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(54) **Title**: METHOD FOR DISTRIBUTING A UNIFORM RADIATIVE SPECTRUM AND DEVICE FOR IMPLEMENTING SAID METHOD

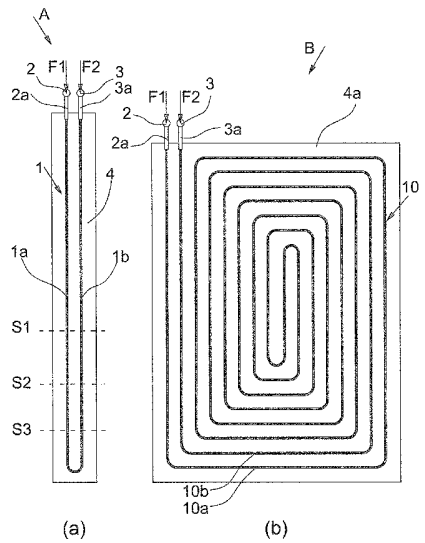

Fig. 1

(57) **Abstract**: This invention relates to a method and to a device for the implementation of said method, to spread homogeneously a radiative spectrum in substrates (solid, liquid and gaseous), saturating volumes in a pervasive and distributed way, with one or two inlet points, fitted to ensure constancy of diffusion, said two inlet points being able to be supplied simultaneously or in following times. The method is characterized by the fact to use one or more side emitting optical fibers (1, 10) submerged in said solids, liquids, vapours or gaseus mediums, said one or more optical fibers (1, 10) being arranged in such a way that a signal constituted by said radiative spectrum, which is introduced into said one or more optical fibers (1, 10), is distributed in a substantially uniform manner in said solids, liquids, vapours or gaseus mediums. The device is characterized in that it comprises one or more side emitting optical fibers (1, 10), each one of said optical fibers (1, 10) comprising two parallel branches, of outward (1a, 10a) and of return (1b, 10b) located at a close distance, said parallel branches being enclosed in a sandwich (4, 4a) made with a pair of sheets transparent to the radiative spectrum of interest, said one or more optical fibers (1, 10) being provided with at least one inlet (2 or 3) through which a signal (F1 or F2) is inserted, said signal (F1 or F2) spreading in said solids, liquids, vapours or gaseus mediums through the lateral emission of said one or more optical fibers (1, 10).

WO 2016/092576 A1

METHOD FOR DISTRIBUTING A UNIFORM RADIATIVE SPECTRUM AND DEVICE FOR IMPLEMENTING SAID METHOD

DESCRIPTION

This invention refers to a method and to a device for the implementation of said method, to spread homogeneously a radiative spectrum in substrates (solid, liquid and gaseous), saturating volumes in a pervasive and distributed way, with one or two inlet points, fitted to ensure constancy of diffusion, said two inlet points being able to be supplied simultaneously or in following times.

The power can be supplied using natural and/or artificial sources.

It is strongly felt the need to have systems for the uniform diffusion of light sources, in several industrial and residential processes, also functional to produce high safety conditions. Existing technologies employ various types of modules using plates of consolidated type in lighting technology, according to various geometries, to encourage reflection and dispersion of the light beams from punctiform sources (incandescent, fluorescent, LEDs, ...). The most widespread solution consists in a pervasive distribution of lighting fixtures, connected by a suitable and expensive electrical system, that often must be designed to operate at low voltage (for safety reasons), losing the necessary sections (on the same operating power). Panels in coloured materials with characteristics of dispersion/distribution complete the lighting installations, with any informative and/or advertising messages. In some industrial and/or agronomic processes, the illumination favours peculiar processes of growth and improve the productivity, supporting the processes of photosynthesis needed (Visible and IR) or that have to be stopped (by UV). These issues relate to various sectors including anaerobic digestion, the algal crops, the antibacterial treatments in different biological processes in purification plants or in general in the industry.

They are not even known devices fitted to illuminate, from different sources (natural and/or artificial) and integrated between them or to saturate volumes in a pervasive and distributed way.

In summary, at present, it is not possible to distribute, in pervasive and

distributed mode, an electromagnetic source in a medium substantially opaque to said electromagnetic radiation.

In particular it is not possible with a single device, enlighten and spread from different sources, natural and/or artificial complementary to each other in the time and in the type of radiation spectrum.

The purpose of this invention is to propose a method and a device for the implementation of said method, respectively conform to claims 1 and 2, to spread homogeneously a radiative spectrum, with pervasive and distributed mode fitted to saturate a volume even if large.

The method is characterized by the fact to use one or more side emitting optical fibers submerged in said solids, liquids, vapours or gaseous mediums, said one or more optical fibers being arranged in such a way that a signal constituted by said radiative spectrum, which is introduced into said one or more optical fibers, is distributed in a substantially uniform manner in said solids, liquids, vapours or gaseus mediums.

The device is characterized in that it comprises one or more side emitting optical fibers, each one of said optical fibers comprising two parallel branches, of outward and of return located close together, said parallel branches being enclosed in a sandwich made with a pair of sheets transparent to the radiative spectrum of interest, said one or more optical fibers being provided with at least one inlet through which a signal is inserted, said signal spreading in said solids, liquids, vapours or gaseus mediums through the lateral emission of said one or more optical fibers.

Other characteristics, such as for example the possibility to organize the fiber in stretches of differentiated emission for the composition of the spectrum, will be the subject of the dependent claims.

The use of a device according to the invention allows, for example, to spray in any volume in a pervasive and distributed mode, a radiative spectrum for the development or the correction of processes (e.g. crops vegetable and not, land or sea, or industrial processes).

The pervasive and distributed mode is achieved thanks to the possibility

to prepare the optical fiber of the device, inside the volume occupied by said solids, liquids, vapours or gaseus mediums, then to distribute anywhere the radiative spectrum of interest, with density at will and compatible with the levels of transparency of said solids, liquids, vapours or gaseus mediums with reference to the radiative spectrum of interest.

The invention will now be described for illustrative and not limitative purpose, according to a preferred embodiment and with reference to figures 1 (a, b) enclosed, that show two possible realizations of the device according to the invention.

With reference to figures 1 (a, b), with (A) and (B) are indicated two possible realizations of the device according to the invention. In particular the device (A) includes an optical fiber (1), with two terminals (2) and (3), arranged according to two parallel straight lines. The optical fiber (1) includes two parallel branches, outward (1a) and return (1b) located close together, enclosed in a sandwich (4) formed with a pair of sheets transparent to the radiative spectrum of interest.

The optical fiber (1) is of the type side emitting, so a first signal (F1), suitably dosed that enters from the first terminal, for example the terminal (2), is laterally dispersed until the signal is exhausted in proximity of the second terminal (3). Both the intensity of the signal, both the lateral emission, decrease progressively starting from the first terminal (2). However the geometry of the optical fiber (1) is such that in each section (S1,S2,S3), remains constant the sum of emissions the outward branch (1a) and of the return branch (1b).

In order not to disperse the first signal (F1) in useless zones, the stretches (2a) and (3a) of the optical fiber (1) are of the point-to-point type.

The optical fiber (1) can be supplied with a second signal (F2) also from the second terminal (3), said second signal (F2) can be provided at the same time or at different times with respect to said first signal (F1).

The device (A) is suitable to diffuse uniformly a signal (F) along a strip, that is along a surface having a predominant dimension.

In the case of surfaces with dimensions of the same order of magnitude,

the device according to the invention assumes the shape indicated with (B), in which a fiber (10) having a outward branch (10a) and a return branch (10b), enclosed in a sandwich (4a), of sheets transparent to the radiative spectrum of interest, has a course such as to uniformly cover the surface to be irradiated on both faces of said sandwich (4a), for example a spiral course circular or elliptical or polygonal.

Also the optical fiber (10) of the device (B) can be supplied by a second signal (F2) also from the second terminal (3), said second signal (F2) can be provided at the same time or at different times with respect to said first signal (F1).

Said first and said second signal (F1) and (F2) can have the same spectrum of frequencies or different spectra. Furthermore they can come from a natural source and/or artificial.

In function of the composition and the input mode of the signals (F1) and (F2), the devices (A) and (B) according to the invention have different applications.

The first signal (F1) composed of a mix of frequencies which are useful to the development of vegetables (for example red and blue light obtained from natural sources) and the second signal (F2), equal to the first signal (F1), but artificially obtained. The second signal (F2), with suitable intensity, can be introduced simultaneously or at different times to complement the first signal (F1), if it is not enough, or to replace if it is absent.

The first signal (F1), consisting of a mix of frequencies which are useful to the development of vegetables, and the second signal (F2), to contrast the development of bacteria and/or virus. In this case both signals can advantageously be obtained from artificial sources, in order to be able to be supplied and measured out also during the night hours.

According to a preferred embodiment, the lateral emission capacity of the optical fibers (1, 10) is not constant along the fibers themselves. In this way the lateral emission can be measured out according to specific needs.

Since the devices (A) and (B) radiate also outside their plane, identified by

sandwich (4) and (4a), they are suitable to saturate the volumes. In particular this can be achieved, for example, by shaping said devices (A) and (B) following circular, elliptical or polygonal courses, or by arranging in parallel, with an appropriate distance, a plurality of said devices (A) and/or (B). Obviously they can be combined one each other, both the shaping of a single device (A) and/or (B), and the use of multiple devices (A) and/or (B).

The invention finds application in various sectors:

- algal crops, in which it is needed a radiative spectrum which favours the development of vegetables (marine or terrestrial), in greenhouses or spaces of culture such as hydroponic and aeroponic cultivation;
- anaerobic digestion processes where it is needed the contrast to specific products (e.g. hydrogen sulphide) implementing the production of carbohydrates that have to be converged in the production of biofuels;
- correction and contrast to biochemical beings and chemical agents in general, by means of suitable spectra (for example with infrared or ultraviolet);
- carrying a specific radiative spectrum in solids, liquids, vapours or gaseus in a pervasive and distributed way at depths not otherwise achievable;
- carrying a radiative spectrum, in a uniform manner in operational environments, residential and non;

the invention allows diffusion actions, during 24 hours, allowing uniformity, integration in time and in quality, in particular, when they are used natural sources (using processes supported by sun and wind) on one side, allows to preserve the propagation by artificial feeding modulated on the complementary side.

The invention has been described for illustrative and not limitative purposes, according to some preferred embodiments. The person skilled in the art could find many other embodiments, all included within the scope of protection of the enclosed claims.

CLAIMS

1. Method to spread a radiative spectrum in pervasive and distributed mode in solids, liquids, vapours or gaseus mediums, characterized by the fact to use one or more side emitting optical fibers (1, 10) submerged in said solids, liquids, vapours or gaseus mediums, said one or more optical fibers (1, 10) being arranged in such a way that a signal (F1 or F2) formed by said radiative spectrum, which is introduced into said one or more optical fibers (1, 10), is distributed in a substantially uniform manner in said solids, liquids, vapours or gaseus mediums.

2. Device (A, B), fitted to spread homogeneously a radiative spectrum, in solids, liquids, vapours or gaseus mediums, with pervasive and distributive mode, characterized in that it comprises one or more side emitting optical fibers (1, 10), each one of said optical fibers (1, 10) comprising two parallel branches, of outward (1a, 10a) and of return (1b, 10b), located at a close distance, said parallel branches being enclosed in a sandwich (4, 4a) made with a pair of sheets transparent to the radiative spectrum of interest, said one or more optical fibers (1, 10) being provided with at least one inlet (2 or 3), through which a signal (F1 or F2) is inserted, said signal (F1 or F2) spreading in said solids, liquids, vapours or gaseus mediums through the lateral emission of said one or more optical fibers (1, 10).

3. Device (A, B), according to claim 2, characterized in that said one or more optical fibers (1, 10) are provided with a first inlet (2), in such a way that a first signal (F1), which is inserted in said first inlet (2), is dissipated thanks to the lateral emission of said one or more optical fibers (1, 10).

4. Device (A, B), according to claim 3, characterized in that said one or more optical fibers (1, 10) are also provided with a second inlet (3), in such a way that a second signal (F2), which is inserted in said second inlet (3), is dissipated thanks to the lateral emission of said one or more optical fibers (1, 10), said second signal being fed simultaneously to said first signal (F1).

5. Device (A, B), according to at least one of claims from 2 to 4, characterized in that said one or more optical fibers (1, 10) have a differentiated lateral emissive capacity.

6. Device (A, B), according to at least one of claims from 2 to 5, characterized in that the stretch of said one or more optical fibers (1, 10) between said sandwich (4, 4a) and said inputs (2, 3) is of the point-to-point type.

7. Device (A, B), according to at least one of claims from 2 to 6, characterized by the fact that it can be shaped according to circular, elliptical or polygonal courses.

8. Device (A, B), according to at least one of claims from 2 to 7, characterized in that two or more of said devices (A, B) are arranged parallel to each other, the said arrangement being produced both by planes devices (A, B) and by shaped devices (A, B).

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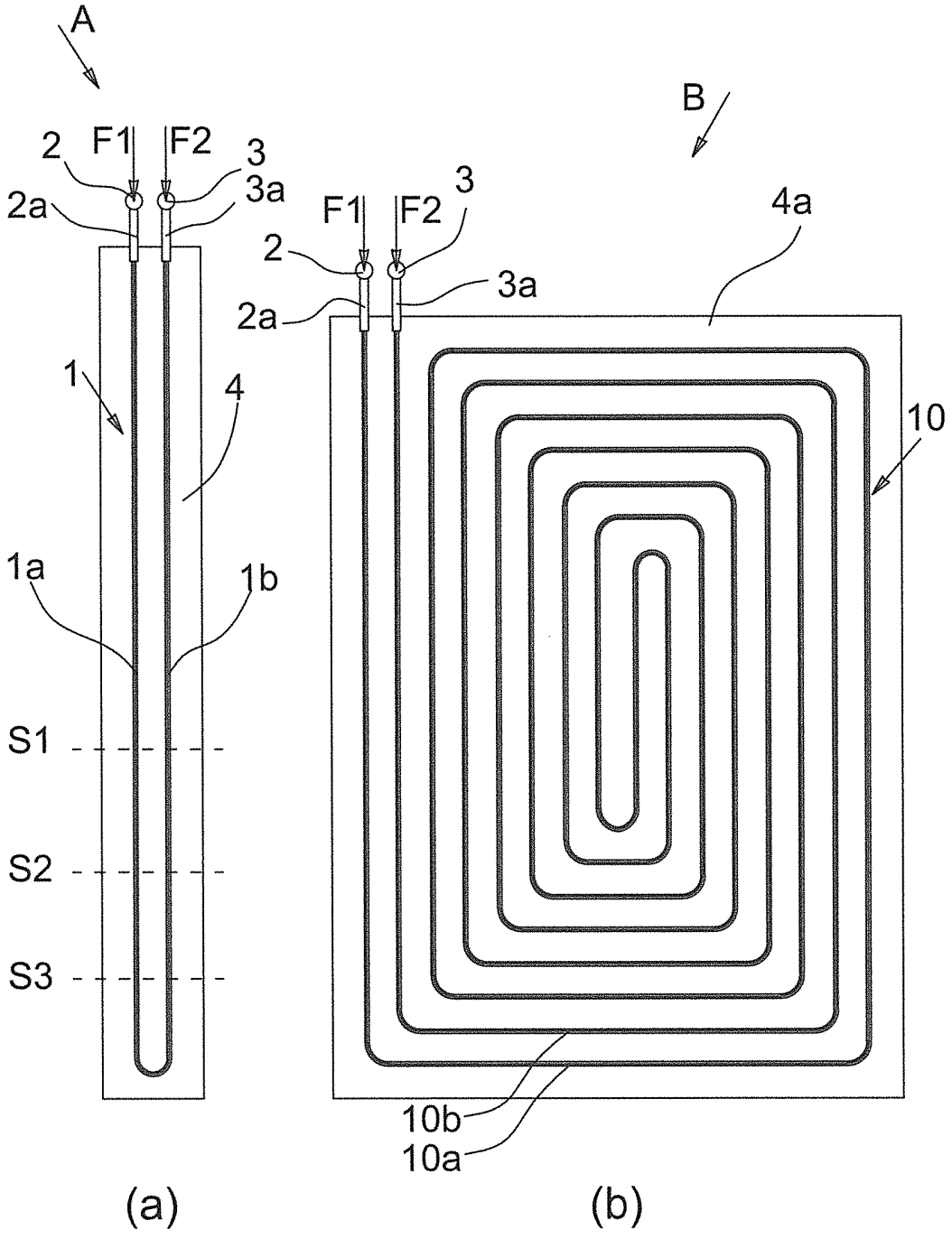

Fig. 1

INTERNATIONAL SEARCH REPORT

International application No
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A. CLASSIFICATION OF SUBJECT MATTER
INV. F21V8/00
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According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F21V G02B A01G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

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Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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Name and mailing address of the ISA/	Authorized officer
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INTERNATIONAL SEARCH REPORT

International application No
PCT/IT2015/000296

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Information on patent family members

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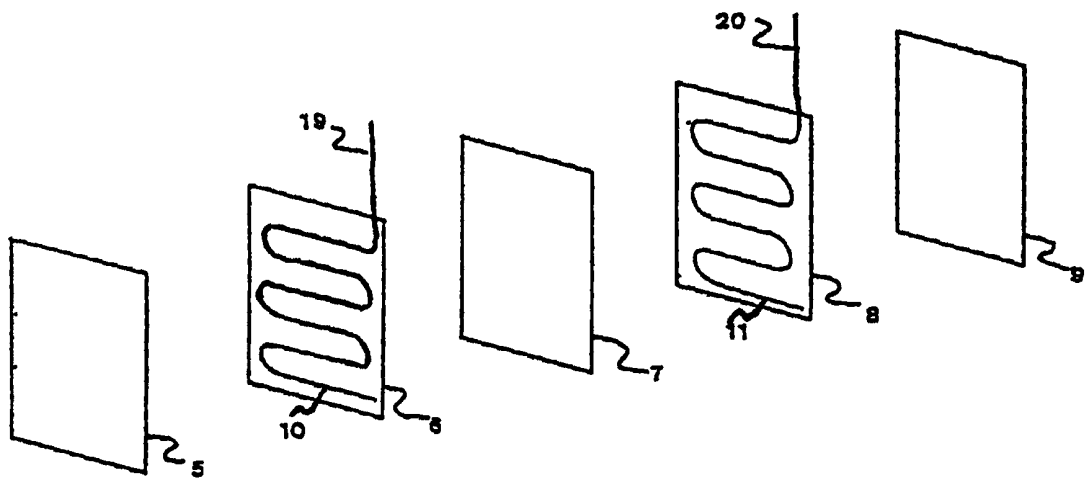
(54) Title: OPTICAL PANEL WITH AN OPTICAL ARRANGED IN A SERPENTINE FASHION



(57) Abstract

The present invention relates to an optical surface device especially usefully integrated into multi layer optical laminations for the diffusing of light as illumination or for the concentrating of light. The device of the present invention is comprised of (a) at least one side emitting optical fiber and the fiber is convoluted to effectively cover a surface area, and (b) means for holding the fiber in the surface area covering convolution. Furthermore, at least one of each of the fibers' end portions either is accessible for receiving light from at least one light source unit (for the illuminator embodiments) or is accessible for transferring light to at least one light emitting unit (for the concentrator embodiments).

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OPTICAL PANEL WITH AN OPTICAL ARRANGED IN A SERPENTINE FASHION

FIELD OF THE INVENTION

The present invention generally relates to an optical surface device, which is especially usefully integrated into multi layer optical laminations for the diffusing of light as illumination or for the concentrating of light. More specifically, the present invention relates to an optical surface device having held-in-place convoluted (effectively surface covering) side emitting optical fiber(s).

The device of the present invention is useful as an illumination device when artificial light from a light source is aligned into the fibers for diffusing the light out from the surface (spatial dimensional lighting).

The device of the present invention is also useful for the collection of light (especially sun light) which illuminates the convoluted surface covering fiber(s) and is transferred by these fibers into a region of optical concentration (being a cross-section without certain properties of a focal point).

BACKGROUND OF THE INVENTION

The device of the present invention in general relates to two symmetrically opposite functional embodiments. These embodiments are the optical surface for the diffusion of light (the "illuminator" embodiment) and the optical surface for the collection of (ambient) light (the "concentrator" embodiment). Each of these two general embodiments requires a different basis of understanding in order to recognize their operating principles and to appreciate their useful applications.

The illuminator embodiment allows large surface area to be used as environmental lighting sources. This has (in the past) been done either by installing a plurality of small light sources (e.g. electric bulbs) onto a substrate (often behind an opaque screen) or by projecting the light from a high intensity light source onto a substrate (screen) using an apparatus of mirrors and/or lenses. Prior art methods have not allowed for the cost efficient uniform illumination of very large surfaces (e.g. entire ceilings, inter-folded hanging draperies, or complex aerodynamic manifolds), while the device of the present invention easily accommodates such applications.

The concentrator embodiment allows large surface areas to be used for the collection of ambient radiation, especially sun light. This has (in the past) been accomplished using expensive lens or mirror apparatus, often with complex computer controlled engines for correcting the tracking angles of the optical element in order to optimize focusing of the collected light. Prior art methods have not allowed for the cost efficient use of large surface collectors (e.g. the exterior wall of a building, or the fixed angle support of a roof), while the device of the present invention easily accomplishes such applications (without any need for sun tracking engines and the like).

Today, multi layer optical laminations include such diverse products as:

(a) Safety glass (made from alternate bonding of glass and plastic layers).

(b) Rear surface mirrors (made from a reflective layer deposited onto a transparent glass or plastic layer).

(c) Dichroic surfaces (made from the deposition of two different color tints onto opposite sides of a layer of glass or plastic; or made from two layers of glass or plastic which are tinted in different colors and which have been bonded together).

(d) Non-glare glass (made by coating a glass or plastic layer with a intermediary optic index material).

(e) Frenel lenses or diffraction gratings (made by the regular geometric convolution etching of surface distortion onto an optical surface substrate).

(f) Morie interference surface optical elements (usually made by bonding together two similar layers of Frenel lenses or diffraction gratings - according to the aforesaid general definition)

(g) Complex chromatic aberration reducing lenses (made by bonding together the convex side of a lens of optical index "A" with the mated concave side of a lens of optical index "B"), sun screens (made by bonding together thin films of differing optical properties).

The preferred embodiments of the device of the present invention introduces a surface like element of side emitting optical fiber(s) (especially into the interstitial bonding region of multi layer optical laminations) in order to accomplish the illuminator and concentrator application embodiments. This use of side emitting optical fibers as an active element in optical laminations has not heretofore been exploited for either type of embodiment. Furthermore, the device of the present invention finds novel cost efficient usefulness in these numerous applications.

SUMMARY OF THE INVENTION

The present invention relates to an optical surface device especially usefully integrated into multi layer optical laminations for the diffusing of light as illumination or for the concentrating of light. The device of the present invention is comprised of (a) at least one side emitting optical fiber and the fiber is convoluted to effectively cover a surface area, and (b) means for holding the fiber in the surface area covering convolution. Furthermore, at least one of each of the fibers' end portions either is accessible for receiving light from at least one light source unit (for the illuminator embodiments) or is accessible for transferring light to at least one light emitting unit (for the concentrator embodiments).

DETAILED DESCRIPTION OF THE INVENTION

For purposes of the present invention (when the device of the present invention is embodied for illumination), a "side emitting optical fiber" is any optical fiber which will transmit a desired frequency of light from one end to the other (using internal reflection of the fiber), and simultaneously allows some portion of the transmitted light to escape from the fiber during the transmission along the length. This escape of light preferably is continuous along the entire length of the fiber, but may be restricted to a plurality of ("exposed") locations along the fiber.

For purposes of the present invention (when the device of the present invention is embodied for light collection), it is equivalent to define the side emitting optical fiber as any optical fiber which will transmit a desired frequency of light from one end to the other (using internal reflection of the fiber), and simultaneously allows some portion of ambient light to enter the fiber and there to be transmitted internally along the length. This entry of light into the fiber preferably is continuous along the entire length of the fiber, but may be restricted to an ensemble (very large number)

of ("exposed") locations along the fiber or to a plurality of ("exposed") locations along the fiber which are positioned at predictable, periodic, or geometrically significant co-ordiantes of the optical surface.

Furthermore, in the context of the present invention "convoluted to effectively cover a surface area" generally relates to a pattern of parallel fibers where the average distance between the fibers is selected according to the maximum optical flux density of the embodiment.

For example, in the context of an optical surface device for illumination, a zig-zag pattern of fiber across the entire surface, a spiral pattern of fiber across the entire surface, and a spiral of zig-zaging fiber across the entire surface all constitute an effective coverage. The spatial frequency of this effective coverage (being the average distance between a fiber portion and it's nearest neighbor fiber portions - within predetermined tolerance limits) determines the relative optical flux density of each fiber portion with respect to the total length of fiber (for continuous side emitting fibers).

A randomized distribution of fiber over a surface area within predetermined spatial frequency limits also constitutes effective coverage, especially for embodiments using fibers having a plurality of exposed locations.

In the context of an optical surface device for the collection (and subsequent concentration) of light, the tolerance of spatial frequency extrema generally demands that the resultant convolution more closely resemble an actual surface (with only tiny holes or slits). However, where the collection embodiment is only for the purposes of filtering (regardless of the desired concentration efficiency), then the convolutions may be identical to those of the illumination embodiment.

For purposes of the present invention "multi layer optical laminations" relates to bonding together optical materials (e.g. glass or plastic layers which are, transparent, opaque, frosted, tinted, partially reflective, diffraction grated, interference producing, holographic, phosphorescent, or fluorescent) using heat, pressure, adhesives, or structural relative-position stabilizing members. These layers may be rigid (e.g. flat, corrugated, parabola shaped, sphere shaped, complex surfaces, surfaces having a plurality of protruding members, etc.) or flexible (e.g. thin films stored or distributed rolled up onto cylinders).

The present invention relates to an optical surface device, which is especially usefully integrated into multi layer optical laminations for the diffusing of light as illumination or for the concentrating of light. The optical surface device of the present invention is comprised of at least one side emitting optical fiber and the fiber is convoluted to effectively cover a surface area, and means for holding the fiber in the surface area covering convolution, wherein at least one of each of the fibers' end portions either is accessible for receiving light from at least one light source unit or is accessible for transferring light to at least one light emitting unit.

According to the preferred embodiment of the illuminator embodiment of the present invention, the optical surface device has at least one light source for aligning light into the optical fibers' end portion.

According to a basic embodiment of the device of the present invention, the side emitting optical fiber is laminated onto a rigid or flexible optical surface. According to the preferred embodiments (both illuminator and concentrator) of the present invention, the side emitting optical fiber is laminated between two optical surfaces. These optical surface may be glass or plastic. These optical surfaces may be transparent, opaque, frosted, tinted, partially reflective, diffraction grated, interference producing, holographic, phosphorescent, or fluorescent. In laminations having two optical surfaces, the two optical surfaces may be tinted in different

frequencies forming a dichroic mirror. According to another basic embodiment of the device of the present invention, the side emitting optical fiber is laminated onto a reflective optical surface.

Furthermore, according to the preferred basic embodiments of the device of the present invention, the means for holding (the fiber in the surface area covering convolution) is using an adhesive or an integrating binder. According to the preferred embodiment of the optical surface device, the optical fiber is a graded index fiber.

An example of the formation of an illuminator embodiment according to the present invention relates to integrating the convoluted held-in-place surface layer of side emitting optical fiber(s) between two layers of thin plastic film, wherein one of these film layers has a deposition of anodized aluminum. This active reflector film laminate embodiment of the device of the present invention may then be used as wall paper, as curtains, or may even be "shrink wrapped" onto sports cars or aircraft wings. When the laminate's accessible incorporated fibers' end portions are connected for receiving light from at least one light source unit, then the entire laminate serves to distribute the light from the source unit into the regions opposite the transparent layer of the laminate.

Another example of the formation of an illuminator embodiment according to the present invention relates to the use a rigid layer in addition to (or as a substitution for at least one of the thin film layers of the previous example. This embodiment results in rigid illuminator members which may be used as interior partitions, windows, ceilings, or walls.

An example of the formation of a concentrator embodiment according to the present invention relates to a stationary flat plate solar energy collector for placement on roof tops (being normally oriented about toward the equator at about a latitude

determined angle). This embodiment is comprised of a first slightly opaque layer, a surface covering convolution of side emitting optical fiber layer, a second slightly opaque layer, a reflective layer, and a structural support layer if the prior layers are not collectively rigid.

Sun light enters the first slightly opaque layer and the angle of the sun light is randomized because of the opacity. Most of the sun light then proceeds into the fiber layer where a portion of the sun light enters into the fiber through the fiber walls at an angle sufficient for this light to proceed within the fiber along the fiber's axis (core). Most of the sun light which does not enter the fiber then proceeds into the second slightly opaque layer where the angle is again randomized. Most of this light is then bounced off of the reflective layer, is again randomized by the second slightly opaque layer, and is given a second chance to enter into the fiber at an acceptable angle. This optical process scenario also has many harmonics, cycles, and other second order interactions.

The majority of the sun light which enters into the side emitting optical fiber is then concentrated at the fibers' end portion where it is accessible for transfer to at least one light emitting unit (often using a standard end emitting optical fiber).

Another example of the formation of a concentrator embodiment according to the present invention relates to a transparent dichroic filter window laminate comprising a exterior layer of ultra-violet filtering glass, a surface covering convolution of side emitting optical fiber central layer, and an interior layer of infra-red filtering glass.

The result for the observer from the interior side of the window is a window which only allows visible light to enter and which has slight optical distortions due to the central fiber layer.

The result from the perspective of the fibers' end portion is an accessible concentration of visible and infra-red light for transfer to at least one light emitting unit (often using a standard end emitting optical fiber).

This concentrated visible and infra-red light may be distributed elsewhere (e.g. in the building's interior) using one of the illuminator embodiments of the device of the present invention. The use of a collector embodiment shunting it's concentrated light into an illuminator embodiment is the preferred hybrid embodiment of the device of the present invention.

Another example of the formation of a hybrid concentrator-illuminator embodiment according to the present invention relates to the use of a high efficiency light source for the illumination of a very large area (such as an entire amphitheater, shopping center, convention center, etc.). This hybrid embodiment is comprised of a high efficiency light source projecting its light through a plurality of surface covering convolution of side emitting optical fiber layers (collectors), with the accessible end portion of each fiber layer shunting it's concentrated light into a corresponding illuminator (at remote locations).

This hybrid embodiment allows (a) energy savings which results from the use of a high efficiency light source, (b) savings due to the reduced cost of illuminator installation without any electricity installation, and (c) eliminates the cumbersome maintenance costs heretofore required for the changing of light bulbs in a plurality of lighting fixtures.

The present invention will be further described and clarified in detail by Figures 1-3. These figures are solely intended to illustrate the preferred embodiment of the invention and are not intended to limit the scope of the invention in any manner.

Figure 1 illustrates a schematic perspective view of an optical laminate containing a central optical fiber surface covering layer.

Figure 2 illustrates a schematic exploded perspective view of an optical laminate containing two optical fiber surface covering layers.

Figure 3 illustrates a schematic exploded perspective view of an optical laminate containing a central optical fiber surface covering layer.

Figure 1 illustrates a schematic perspective view of an optical laminate containing a central optical fiber surface covering layer. At least one side emitting optical fiber (1) is convoluted to effectively cover a surface area. This fiber is held in the surface area covering convolution by adhesive to a substrate glass plate (2). One end portion (18) of the fiber is accessible either for receiving light from at least one light source unit (illuminator embodiment) or for transferring light to at least one light emitting unit (concentrator embodiment). The glass substrate forms the central layer of an optical surface lamination, being between a plastic plate (3) and a mirror-like reflective plate (4). This figure also helps to visualize the constructor of a basic illuminator embodiment or a transparent dichroic filtering window embodiment.

Figure 2 illustrates a schematic exploded perspective view of an optical laminate containing two optical fiber surface covering layers. An exploded five layer laminate is shown having a three transparent glass layers (5) (7) (9) and two thin film substrate layers (6) (8) The first substrate layer (6) has a surface covering side emitting optical fiber (10) with an exposed end portion (19). The second substrate layer (8) has a surface covering side emitting optical fiber (11) with an exposed end

portion (20). This figure also helps to visualize a collector embodiment for use with a high efficiency light source.

Figure 3 illustrates a schematic exploded perspective view of an optical laminate containing a central optical fiber surface covering layer. A five layer laminate is shown having a first protective coating layer (12), a second opaque layer (13), a third thin film substrate layer (14), a forth opaque layer (15), and a fifth reflective layer. The third layer's surface is covered with a high density of side emitting optical fiber (21) having an exposed end portion (17). This illustration helps to visualize a solar radiation collector concentrator embodiment, or a complex illuminator embodiment. In the context of a complex illuminator embodiment, the second layer may be completely or partially diffraction grated, interference producing, holographic, phosphorescent, or fluorescent. This modified second surface layer is useful as an artistic illuminated advertisement sign. Alternatively, having a first layer including a large frenel lens allows a flat illuminator embodiment to be used as a spot light.

CLAIMS

1. An optical surface device especially usefully integrated into multi layer optical laminations for the diffusing of light as illumination or for the concentrating of light comprising at least one side emitting optical fiber and said fiber is convoluted to effectively cover a surface area, and means for holding the fiber in the surface area covering convolution, wherein at least one of each of said fibers' end portions either is accessible for receiving light from at least one light source unit or is accessible for transferring light to at least one light emitting unit.

2. A device according to claim 1 having at least one light source for aligning light into the optical fibers' end portion.

3. A device according to claim 1 wherein the side emitting optical fiber is laminated onto a rigid or flexible optical surface.

4. A device according to claim 1 wherein the side emitting optical fiber is laminated between two optical surfaces.

5. A device according to claims 3 or 4 wherein the optical surface is glass or plastic.

6. A device according to claims 3 or 4 wherein the optical surface is transparent, opaque, frosted, tinted, partially reflective, diffraction grated, interference producing, holographic, phosphorescent, or fluorescent.

7. A device according to claim 4 wherein the two optical surfaces are tinted in different frequencies forming a dichroic mirror.

8. A device according to claim 1 wherein the side emitting optical fiber is laminated onto a reflective optical surface.

9. A device according to claim 1 wherein the means for holding is using an adhesive or an integrating binder.

10. A device according to claim 1 wherein the optical fiber is a graded index fiber.

11. An illumination device according to claim 1 wherein a convoluted held-in-place surface layer of side emitting optical fiber(s) between two layers of thin plastic film, and one of these film layers has a deposition of anodized aluminum.

12. An illumination device according to claim 11 wherein a convoluted held-in-place surface layer of side emitting optical fiber(s) between a thin plastic film layer and a rigid layer of glass or plastic, and one of these layers has a deposition of anodized aluminum.

13. A concentrator device according to claim 1 having a first slightly opaque layer, a surface covering convolution of side emitting optical fiber layer, a second slightly opaque layer, and a reflective layer.

14. A concentrator device according to claim 13 having a structural support layer.

15. A concentrator device according to claim 1 useful as a transparent dichroic filter window laminate comprising a exterior layer of ultra-violet filtering glass, a surface covering convolution of side emitting optical fiber central layer, and an interior layer of infra-red filtering glass.

16. An optical surface device especially usefully integrated into multi layer optical laminations for the diffusing of light as illumination or for the concentrating of light, substantially as hereinbefore described and illustrated.

17. An illuminator device substantially as hereinbefore described and illustrated.

18. An concentrator device substantially as hereinbefore described and illustrated.

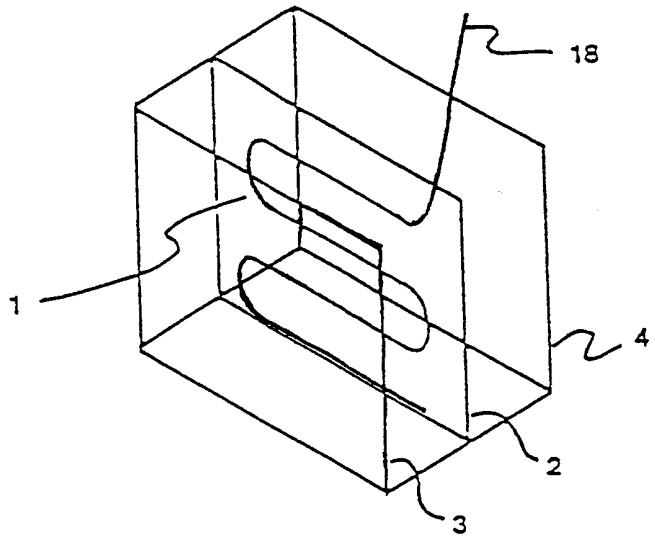

FIG.1

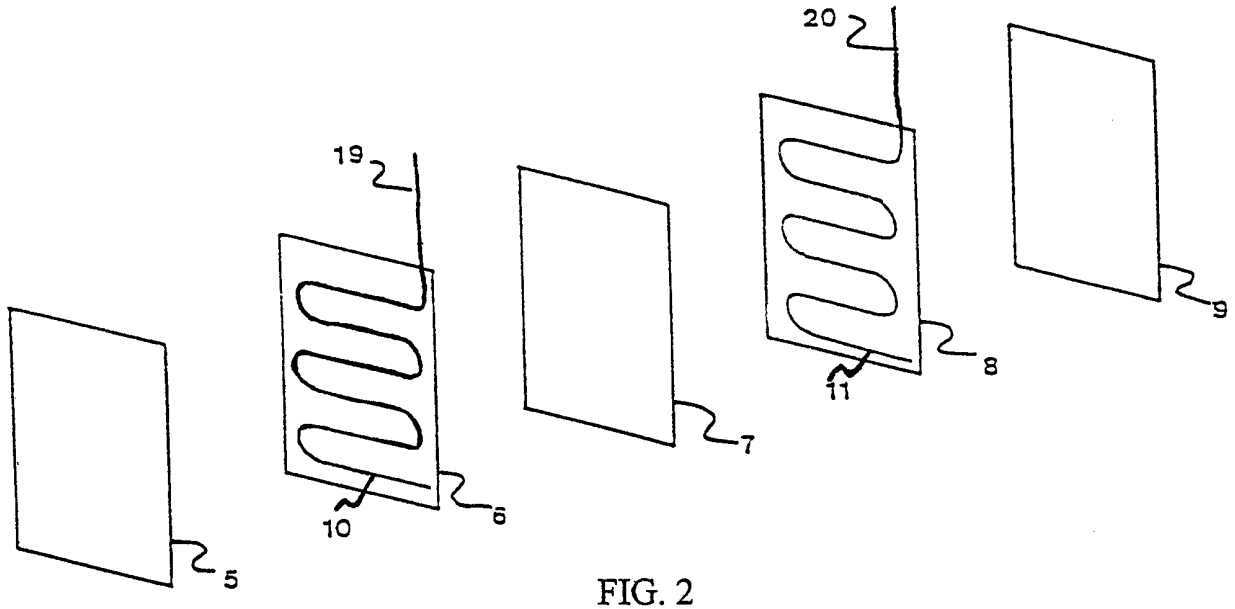

FIG. 2

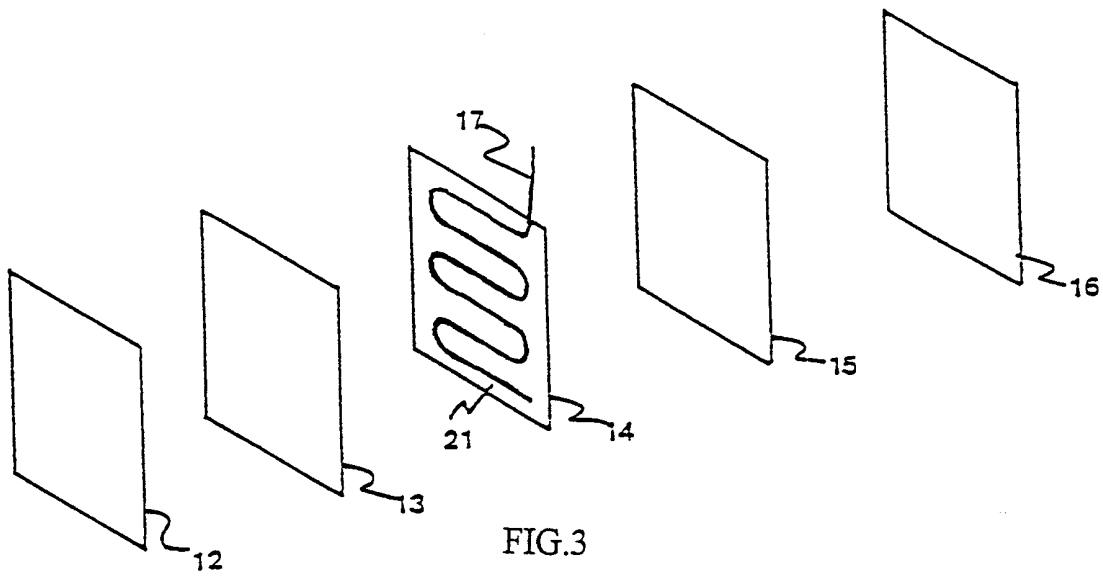

FIG.3

INTERNATIONAL SEARCH REPORT

Ir ational Application No
PCT/IL 98/00587

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 F21V8/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 F21V

Documentation searcned other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 542 016 A (KASCHKE KEVIN D) 30 July 1996 see abstract; figures 2,7,9-12 see column 2, line 40 - column 3, line 32 see column 4, line 27 - column 5, line 14 ---	1-6,8,9
X	US 4 510 555 A (MORI KEI) 9 April 1985 see abstract; figures 3,4 see column 2, line 60 - column 3, line 25 ---	1-4,8
X	US 5 690 408 A (DE LA PENA ALEX T ET AL) 25 November 1997 see abstract; figures 4,5 see column 4, line 11-37 --- -/--	1-4,6,8

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 March 1999	26/03/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Beaven, G

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/IL 98/00587

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 431 742 A (KLEINERMAN MARCOS Y) 11 July 1995 see abstract; figure 2 see column 3, line 38 - column 4, line 68	1,3,5,6
X	US 4 885 663 A (PARKER JEFFREY R) 5 December 1989 see abstract; figure 3 see column 5, line 43 - column 6, line 23	1,2,4,6, 8
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INTERNATIONAL SEARCH REPORT

Information on patent family members

I. ıational Application No
PCT/IL 98/00587

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(19) Europäisches Patentamt
European Patent Office
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(11) Publication number: **0 195 431**
A2

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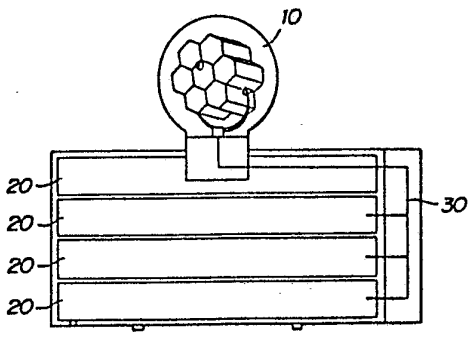
(54) A nurturing device for living organisms.

(57) A nurturing device for effectively nurturing living organisms such as plants, fish, etc. in desert areas of tropical regions by use of unused second-hand containers and a solar ray collecting device. The device comprises a plurality of containers and a solar ray collecting device. The solar rays collected by use of the solar ray collecting device are guided into the containers respectively through optical conductor cables for the purpose of nurturing living organisms therein.

FIG. 1



EP 0 195 431 A2

0195431

A NURTURING DEVICE FOR LIVING ORGANISMS

BACKGROUND OF THE INVENTION

The present invention relates to a nurturing device for living organisms i. e. a nurturing device for effectively nurturing living organisms such as plants, fish, etc. by use of second-hand containers and a solar ray collecting device.

The present applicant has previously proposed various ways to focus solar rays by use of lenses or the like, to guide the same into an optical conductor cable, and thereby to transmit the solar rays onto an optional desired place through the optical conductor cable. The solar rays transmitted in such a way are employed for use in illumination or for other like purposes, for instance to cultivate chlorella, to grow tomatoes or the other plants, and to breed fish.

Furthermore, as in the case of guiding solar rays into an optical conductor cable and transmitting the same therethrough as mentioned above, specific kinds of light rays contained in solar rays, for instance infrared, ultraviolet, or X-rays are harmful to living organisms and can be removed and only visible light rays component of the solar rays can be supplied to living organisms. Furthermore, since the infrared rays component thereof is cut out, the possible heat build-up is eliminated, allowing plants and animals to be effectively nurtured.

On the other hand, in desert areas of tropical regions, a sufficient number of the solar rays are supplied to living organisms. However, plants, fish, etc., cannot be nurtured

because of the harmful rays which are present in unfiltered solar rays and too strong in intensity. Usually an excessive number of solar rays exist on the ground where living organisms are nurtured. In addition to harmful solar rays, there exists a great difference between the lowest temperature and the highest temperature.

SUMMARY OF THE INVENTION

A primary object of the present invention is to effectively utilize solar rays in desert areas of tropical regions.

Another object of the present invention is to nurture plants and fish, to cultivate chlorella, or to promote human body's health and perform medical treatment, by effectively utilizing second-hand container.

Still another object of the present invention is to nurture plants and fish, to cultivate chlorella, or to promote human body's health and perform medical treatment, by effectively utilizing the solar rays collecting device and the second-hand containers.

BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1 and 2 are, respectively, structural views for explaining embodiments according to the present invention;

Fig. 3 is a structural view for explaining an embodiment of a solar ray collecting device which is employed for bringing the present invention into operation;

Fig. 4 is a construction view for explaining an

embodiment of a light focusing lens capable of effectively taking out the light rays component of the desired wave length among the solar rays;

Figs. 5 through 9 are views showing embodiments of the respective devices employed in the containers shown in Figs. 1 and 2;

Fig. 5 is a view showing an embodiment of a device for cultivating plants;

Fig. 6 is a view showing an embodiment of a device for cultivating plants and mushrooms;

Fig. 7 is a view showing an embodiment of a device for nurturing plants and fish;

Fig. 8 is a view showing an embodiment of a device for cultivating chlorella and breeding fish; and

Fig. 9 is a view showing an embodiment of a device for promoting human body's health or giving a patient medical treatment for a wounded portion or the like.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Fig. 1 is a structural view for explaining an embodiment of a nurturing device for living organisms according to the present invention. In Fig. 1, 10 is a solar ray collecting device 20 a plurality of containers, and 30 optical conductor cables. The primary object of the present invention is to make effective use of unused second-hand containers. As is well known, the afore-mentioned containers are constructed with adiabatic (heat-proof) and air-tight materials. Consequently, although such containers are installed on the ground-level in desert areas

of tropical regions, the temperature inside the containers can be kept at a suitable level for nurturing living organisms. Therefore plants or fish can be nurtured inside the containers by guiding the light rays into them. In the case of installing the containers by piling them up on top of each other as shown in Fig. 1, the solar rays are not supplied directly to the lower containers. As a result, the rising temperature can be suppressed effectively. Furthermore, in the case of installing the solar ray collecting device on the uppermost container and by putting a part of the lower portion of the solar ray collecting device in the uppermost container, the solar ray collecting device can be prevented from being over-heated.

In such a manner, plants, fish, or mushrooms, etc. can be nurtured inside of the container 20. In the case of nurturing plants, since the containers are constructed with air-tight material, etc. carbon dioxide CO_2 necessary for photo synthesis can be supplied to the plants inside of the containers. Plants absorb carbon dioxide CO_2 and produce oxygen O_2 through the process of photo synthesis, and fish, or mushrooms absorb oxygen O_2 and discharge carbon dioxide CO_2. Therefore, it is necessary to prepare both of the container for nurturing plants and the other container for nurturing fish or mushrooms. If those containers are connected with each other in such a manner that carbon dioxide CO_2 can be exchanged for oxygen O_2, it will be possible to nurture those living organisms much more effectively.

Fig. 2 is a structural, perspective view for explaining another embodiment of a nurturing device for living organisms,

according to the present invention, in which the containers as mentioned above are piled up in a radial state. In such a construction, the solar ray collecting device 10 is installed on the central portion of the containers arranged in a radial state so that solar rays can be supplied to living organisms by use of a large number of containers and short optical conductor cables 30.

Furthermore, if inlet opening and outlet opening are provided at the central portion side of the respective containers arranged in a radial state, the conditions in the containers can be easily observed. The upper portion of the space formed at the central portion of the radially arranged containers is closed by the solar ray collecting device 10, and the side portions of the same space are closed by the respective containers 20. As a result, a shaded area can be created in the above-mentioned space in order to provide a suitable place for an observer to stay therein.

As is apparent from the foregoing description, according to the present invention, living organisms such as plants, fish, or mushrooms, can be much more effectively nurtured in desert areas of the tropical regions by effective use of unused second-hand containers.

Fig. 3 is a detailed structural view for explaining a solar ray collecting device 10 shown in Figs. 1 and 2. The solar ray collecting device 10 comprises a large number of lenses 11 (nineteen lenses in the embodiment shown in Fig. 3), a solar rays direction sensor 12 for detecting the direction of the solar rays, a support frame 13 for unitarily sustaining the lenses 11

and the solar rays direction sensor 12, a first motor 14 for rotatably moving in a direction shown by an arrow A the unitarily combined lenses 11, sensor 12, and support frame 13, a support art 15 for supporting the afore-mentioned lenses 11, sensor 12, support frame 13, and motor 14, a rotatable shaft 16 installed so as to meet at a right angle with the rotatable shaft of the afore-mentioned motor 14, and a second motor not shown in Fig. 3 for rotating the rotatable shaft 16 in a direction shown by an arrow B.

The direction of the solar rays is detected by the afore-mentioned solar rays direction sensor 12. The signal generated by the sensor 12 controls the first motor and the second motor so as to direct the lenses 11 toward the sun at all times. The solar rays focused by the lenses 11 are guided into the optical conductor cable shown in Fig. 1 (not shown in Fig. 3), the light receiving end portion of which is located at the focus position of the lenses 11. And further, the solar rays are transmitted through the optical conductor cable into the container 20.

The present applicant has previously proposes various ways to focus solar rays by use of lenses or the like, to guide the same into an optical conductor, and thereby to transmit them onto an optional desired place through the optical conductor for use in illumination or for other like purposes.

However, in the case of employing the light energy transmitted through the optical conductor in such a manner as mentioned above as a photo-synthesis light source for nurturing chlorella or intensively cultivate the plants, a light source for breeding fish, a light source for promoting human health, and a

light source utilized for various other purposes, there are many cases in which only a desired light component fitted in the purpose of utilization needs to be selectively separated and employed among the light components contained in the light energies.

However, although various techniques of cutting off infrared rays, ultraviolet rays, or the like have already been proposed up to now, a technique of taking out a light component of the specially designated wave length among the while light rays has not yet been proposed at all.

Fig. 4 is a construction view for explaining a method for introducing the solar rays collected by a lens into the optical conductor cable. In Fig. 4, 11 is a Fresnel lens, and 11a is a light intercepting membrane mounted on the central portion of the Fresnel lens 11. The solar rays or the artificial light rays arrive directly at the points; a, b, c and d, of the lens 11 are focused, respectively, as shown in Fig. 4.

Moreover, in Fig. 4, the green light rays are shown by solid lines, the red light rays by dotted lines, and the blue light rays by two-dots-and-dash lines, respectively. Therefore, at the portion A of the plane I in Fig. 4 comparatively pure green light rays are concentrated, at the portion B of the plane II comparatively pure red light rays, and at the portion E of the plane III comparatively pure blue light rays. Consequently, if each light-receiving edge of the optical conductor is put at those portions; A, B and E, respectively, the light rays having only the desired light component can be guided into the optical conductor.

Moreover, on the plane II, the portion C is a blue light component area, and the portion D is a green light component area. It has been described, heretofore, that the light-receiving edge of the optical conductor is moved to the direction of the lens' optical axis so as to take out the light component of a desired wave length. However, the light component guided into the optical conductor can be also changed in accordance with the diameter of the optical conductor. For instance, if the diameter of the optical conductor is equal to F on the plane I, the visible light rays containing the light components from red to blue are guided into the optical conductor.

Fig. 5 is an overall structural view for explaining an embodiment of a plant cultivating device employed in the container 20 as shown in Figs. 1 and 2. In Fig. 5, 40 is a plant cultivating device which is constructed with a dark room 41 for accommodating a root portion of plant P and an air-tight room 42 for accommodating a stem-and-leaf portion of plant P.

Supply tubes 43 having a large number of holes for supplying nutritious substance, oxygen, etc. necessary for growing the plant P are set up in the dark room 41. Culture fluid and air or the like supplied through an inlet pipe 44 to the above-mentioned multiple-holes tube 43 are discharged into the dark room 41 through the holes of the multiple-holes tubes 43 in order to supply necessary nutritious substance and oxygen to plants P.

In such a manner, after supplying nutritious substance and oxygen to plant P, drainage is exhausted from an outlet pipe 45. Being replenished with nutritious substance and air, it

circulates and is supplied again through the inlet pipe 44 into the dark room 41. Air is exhausted outside through an air exhaust pipe 46.

On the other hand, a large number of light sources L necessary for causing a photo synthesis reaction are provided in the air-tight room 42. And further, an inlet pipe 47 and an outlet pipe 48 are attached to the air-tight room 42 for circulatingly supplying carbon dioxide, high-temperature and high-humidity air, etc. into the air-tight room 42. The environmental condition is adjusted in accordance with the characteristics of plant to be cultivated. For instance, the relative humidity is kept at 70%, the density of contained carbon dioxide at 3%, and the temperature at 25°C through 28°C.

Moreover, any light rays of wave length necessary for causing photo synthesis reaction can be employed as the light source L. For instance, a xenon lamp can be employed. If possible, a cool light source generating no heat is preferable, because heat is not necessary for causing photo synthesis reaction. Concerning such the cool light source, a light-passing substance 32 having a refractive index larger than that of an optical fiber 31 is attached to the surface of the same fiber 31 as shown in Fig. 5. In such a construction, the light rays transmitted in the optical fiber 31 may be preferably discharged through the light-passing substance 32.

Furthermore, 30 is an optical conductor cable connected with the solar ray collecting device 20, and 33 is a photo coupling junction for connecting the optical conductor cable 30 with the plural optical fibers 31. A lens (or lenses) for focusing

the solar rays is installed at the end portion of the optical conductor cable 30 not shown in Fig. 5 as mentioned before. The light rays (solar rays) focused by the lens are guided into the optical conductor cable 30, pass through the optical conductor cable 30, and are further transmitted to the optical fibers 31. The same light rays propagating in the optical fiber 31 are discharged through the light-passing substance 32.

The air-tight receptacle 42 is constructed with transparent material and therefore the interior space thereof can be seen from outside. Fruits of plant P nurtured as mentioned above can be harvested in the air-tight room after exchanging high-temperature and high-humidity air therein containing gases for normal clean air, for example. Or otherwise, a large number of windows capable of being opened and closed are provided on the circumferential wall portion, and the fruits of plant P can be harvested by hands from the windows.

Moreover, the present applicant has previously proposed a device for effectively nurturing plants, funguses, or fish by profitably combining a plant cultivating device absorbing carbon dioxide CO_2 and producing oxygen O_2 with a funguses cultivating device or a fish breeding device absorbing oxygen O_2 and producing carbon dioxide CO_2. Those devices as mentioned above can be employed in the container 20.

Fig. 6 is a cross-sectional structural view for explaining an embodiment of a device for nurturing funguses such as mushrooms or the like and nurturing plants such as tomatoes or the like in the afore-mentioned containers 20. In Fig. 6, 30 is optical conductor cables connected with the solar ray collecting

device 10 as mentioned before, 51 a first air-tight receptacle for nurturing plants absorbing carbon dioxide CO_2 and producing oxygen O_2, 52 a second air-tight receptacle for nurturing funguses M such as, for instance, bracket fungus absorbing oxygen O_2 and producing carbon dioxide CO_2, 53 a first pumping device for supplying oxygen O_2 produced in the first air-tight receptacle 51 into the second air-tight receptacle 52, and 54 a second pumping device for supplying carbon dioxide CO_2 produced in the second air-tight receptacle 52 into the first air-tight receptacle 51.

Oxygen O_2 produced in the first air-tight receptacle 51 and carbon dioxide CO_2 produced in the second air-tight receptacle 52 are exchanged for each other in order to supply a sufficient amount of oxygen O_2 to plants in the first air-tight receptacle 51 and supply a sufficient amount of carbon dioxide CO_2 to funguses in the second air-tight receptacle 52.

And further, in the afore-mentioned living thing nurturing device the temperature in the air-tight receptacle 51 for nurturing plants is kept at 20°C approximately and the relative humidity therein is kept below 60% approximately while the temperature in the air-tight receptacle 52 for nurturing funguses or the like is kept at 30°C approximately and the relative humidity therein is kept above 80% approximately. Therefore, both of plants and funguses can be nurtured effectively. On that occasion, if air contained in the air-tight receptacle 51 is merely guided into the air-tight receptacle 52, the temperature in the receptacle 52 drops and the relative humidity therein also drops. On the contrary, air contained in

the air-tight receptacle 52 is guided into the air-tight receptacle 51, the temperature in the receptacle 51 rises and the relative humidity therein also rises. In order to settle the problems as mentioned above, as shown in Fig. 6, a water tank 55 is installed in the air-tight receptacle 51 and another water tank 56 is installed in the air-tight receptacle 52. The temperature of the water tank 55 is controlled at a value, for instance, 15°C approximately which is a little lower than the temperature suitable for nurturing plants in the air-tight receptacle 51, and the temperature of the water tank 52 is controlled at a value, for instance, 35°C approximately which is a little higher than the temperature in the air-tight receptacle 52. Air contained in the air-tight receptacle 52 is supplied into the air-tight receptacle 51 through the water tank 55, while air contained in the air-tight receptacle 51 is supplied into the air-tight receptacle 52 through the water tank 56.

In such a manner, air of high temperature and high humidity in the air-tight receptacle 52 is supplied into the air-tight receptacle 51 by passing through the water tank 55, and the temperature in the receptacle 51 is kept at 20°C approximately and the relative humidity therein is kept less than 60% approximately. On the contrary, air of low temperature and low humidity in the air-tight receptacle 51 is supplied into the air-tight receptacle 52 by passing through the water tank 56, and the temperature in the receptacle 52 is kept at 30°C approximately and the relative humidity therein is kept more than 80% approximately.

In consequence, the temperature and the humidity in the

air-tight receptacle 51 are always kept respectively at the values suitable for nurturing plants in the air-tight receptacle 51, and a sufficient amount of carbon dioxide CO_2 necessary for nurturing plants is supplied to plants. At the same time, the temperature and the humidity in the air-tight receptacle 52 are also kept respectively at the values suitable for nurturing funguses in the air-tight receptacle 52 at all times, and a sufficient amount of oxygen O_2 necessary for nurturing funguses is supplied to funguses.

Fig. 7 is a cross-sectional structural view for explaining another embodiment of a device for breeding fishes and nurturing plants. In this embodiment, fishes are employed as the living organisms absorbing oxygen O_2 and producing carbon dioxide CO_2. Namely, fishes F are employed instead of funguses M of the embodiment shown in Fig. 6. In Fig. 7, 61 is an air-tight receptacle for breeding fishes. Concerning the other reference numerals, the same reference numeral as that of Fig. 6 is attached to the part performing same action as that of the device shown in Fig. 6. As is the case of the embodiment shown in Fig. 6, carbon dioxide CO_2 produced by fishes is utilized for nurturing plants and oxygen produced by plants is utilized for breeding fishes, in this embodiment.

Furthermore, although only oxygen O_2, carbon dioxide CO_2, the temperature and the humidity have been described heretofore, various conditions other than the above-mentioned, for instance, nutritious substance, light rays, etc. are needed for nurturing plants, funguses, fish or the like. Concerning the light rays, the solar rays collected by the solar ray collecting

device 10 are supplied to plants or the others through the optical conductor cables 30 as mentioned before.

Fig. 8 is a cross-sectional structural view showing an embodiment of a device in which chlorella is cultivated in the above-mentioned container 20 and utilized as a bait for breeding fishes.

The device shown in Fig. 8 is constructed by effectively combining a photo synthesis tub for cultivating funguses and a fish breeding tub together. Stated in more detail, a product produced by the process of photo synthesis is supplied to fishes as nutritious substance source. And further, oxygen O_2 discharged from the photo synthesis tub for cultivating funguses is supplied to fishes while excrement excreted by fishes is supplied to chlorella as nutritious substance source and carbon dioxide CO_2 discharged by fishes is also supplied thereto. Furthermore, a chlorella cultivating light source can be commonly used for fish breeding light source.

In Fig. 8, 71 is a fish breeding tub, 72 a chlorella cultivating tub, 73 a chlorella harvesting device for taking out chlorella produced in the chlorella cultivating tub 72, and 74 a transparent partition wall for separating water-tightly the chlorella cultivating tub 72 from the fish breeding tub 71. All of those elements are installed in the afore-mentioned container 20. And further, the quality of water contained in the fish breeding tub 71 is changed in accordance with the kind of fish to be bred therein. For instance, fresh water is used for breeding fresh water fish and sea-water is used for breeding sea-water fish.

Solar rays collected by the solar ray collecting device 10

are focused by the lenses or the like and guided into the optical conductor cable 30 as mentioned before, and further transmitted through the optical conductor cable 30 are supplied to the chlorella cultivating tub 72 as a photo synthesis light source. At the same time, carbon dioxide CO_2 is supplied to the same. Chlorella is cultivated in liquid containing carbon dioxide CO_2. Chlorella produced in such a manner is harvested at a proper time, and supplied into the fish breeding tub 71 as a bait for breeding fishes. On the other hand, oxygen O_2 produced by cultivating chlorella is supplied into the fish breeding tub 71 through a pipe 75 having a filter therein.

For breeding fishes in the fish breeding tub 71, the bait and oxygen O_2 are supplied to fishes as mentioned before. On that occasion, carbon dioxide CO_2 discharged by fishes is supplied into the chlorella cultivating tub 72 through a pipe 76 and used for cultivating chlorella. At this time, dung evacuated by fishes is also supplied into the chlorella cultivating tub through the pipe 76 for the purpose of using it as nutritious substance source for chlorella. In such a way, not only cultivation of chlorella can be performed much more effectively but also the inside of the fish breeding tub 71 can be kept clean.

Light rays for causing photo synthesis reaction are supplied into the chlorella cultivating tub 72 through the optical conductor cable 30 from the light source, as mentioned before. If the outside wall of the chlorella cultivating tub 72 is constructed with transparent material, light rays in the chlorella cultivating tub 72 leak outside thereof and are supplied into the fish breeding tub 71. In such a manner, the light rays can be

also used as a light source for breeding fish. On that occasion, when both of the chlorella cultivating tub 72 and the fish breeding tub 71 are separated from each other by use of the transparent partition wall 74, withdrawal of chlorella, maintenance and checking of the chlorella cultivating tub 72, etc. can be easily done.

Fig. 9 is a structural view of a device in which solar rays collected by the solar ray collecting device 10 as mentioned above are guided into the container 20 through the optical conductor cable 30 for the purpose of utilizing those solar rays to promote human body's health and perform medical treatment.

In the recent years, a large number of persons suffer from incurable diseases such as arthritis, neuralgia and rheumatism, or a pain of an injury scar or a bone fracture scar, or a pain of an ill-defined disease. Furthermore, any person cannot avoid growing-old of one's skin which makes progress gradually since comparatively young ages. On the other hand, as mentioned before, the present applicant has previously proposed to focus solar rays by use of lenses or the like, to guide solar rays into an optical conductor cable, and to transmit solar rays onto an optional desired place through the optical conductor cable. Those solar rays transmitted in such a way are employed for use in illuminating or for other like purposes, for example, to cultivate plants, chlorella, or the like. On the process thereof, visible light rays not containing ultraviolet and infrared promote a living body reaction, and those visible light rays promote human body's health, or prevent human body's skin from growing old. And further, those visible

light rays have noticeable effects of curing and stopping a pain of arthritis, neuralgia, bedsore (decubitus), sheumatism, injury scar, bone fracture scar, or the like. Such effects obtained by use of the device according to the present invention have been already found out by the present applicant.

Fig. 9 is a structural view showing an embodiment of a device for promoting human body's health, preventing skin of human body from growing old, or curing and stopping a pain of arthritis, neuralgia, bedsore, sheumatism, injury scar, bone fracture scar, in such a manner as described heretofore. In Fig. 9, 30 is an optical conductor cable, into which solar rays collected by the solar ray collecting device 10 shown in Fig. 1 are guided, as mentioned before. Those guided solar rays are transmitted onto the container shown in Fig. 1 through the optical conductor cable 30. As previously proposed by the present applicant, white rays corresponding to a visible light rays component contained in solar rays are transmitted therethrough. The numeral 80 represents a hood member installed at the light emitting end portion 30a of the optical conductor cable 30, and the numeral 81 represents a medical treatment chair. When a patient is placed under medical care, the patient is put on the medical treatment chair 81 and the light rays comprising of visible light rays component transmitted through the optical conductor cable 30 as mentioned before are applied to the diseased part of the patient. As described heretofore, the light rays applied to the diseased part of the patient are corresponding to the visible light rays component of solar rays and contain neither ultraviolet rays nor infrared

rays. By use of such light rays, medical treatment can be performed without being exerted any harmful influence on the human body by ultraviolet rays or infrared rays.

As described heretofore, since only the visible light rays component of solar rays is applied to the diseased part of the patient by use of the afore-mentioned device, there is no harmful influence thereon by ultraviolet rays and infrared rays. Especially, in the case of containing ultraviolet rays, a cancer grows under the influence of ultraviolet rays accumulation. And further, in the case of containing infrared rays, the temperature rises up to the extremé degree under the influence of infrared rays accumulation so that a desired amount of light cannot be radiated. According to the above-mentioned device, such harmful influence doesn't exist at all so that a desired amount of light can be radiated for a desired period. Furthermore, the outlined condition of the light rays component can be known at this time.

CLAIMS

(1) A nurturing device for living organisms, characterized in that said device comprises a plurality of containers and a solar ray collecting device, and solar rays collected by use of said solar ray collecting device are guided into said containers respectively through an optical conductor cable for the purpose of nurturing living organisms therein.

(2) A nurturing device for living organisms, as defined in claim 1, characterized in that a plurality of said containers are piled up on the top of each other and said solar ray collecting device is installed on the uppermost portion of said set of piled-up containers.

(3) A nurturing device for living organisms, as defined in claims 1 or 2, characterized in that a plurality of said containers are arranged in a radial fashion and said solar ray collecting device is installed on the central portion of said radial containers arrangement.

(4) A nurturing device for living organisms, as defined in any one of claims 1 through 3, characterized in that said living organisms absorb carbon dioxide CO_2 and produce oxygen O_2 by the process of photo synthesis.

(5) A nurturing device for living organisms, as defined in any one of claims 1 through 3, characterized in that said living organisms absorb oxygen O_2 and discharge carbon dioxide CO_2.

(6) A nurturing device for living organisms as defined in any one of claims 1 through 3, characterized in that said device comprises a container for nurturing therein said living

organisms which absorb carbon dioxide CO_2 and produce oxygen O_2 and another container for nurturing therein said living organisms which absorb oxygen O_2 and discharge carbon dioxide CO_2, and both containers are connected with each other in such a manner that said oxygen O_2 can be exchanged for said carbon dioxide CO_2.

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FIG. 1

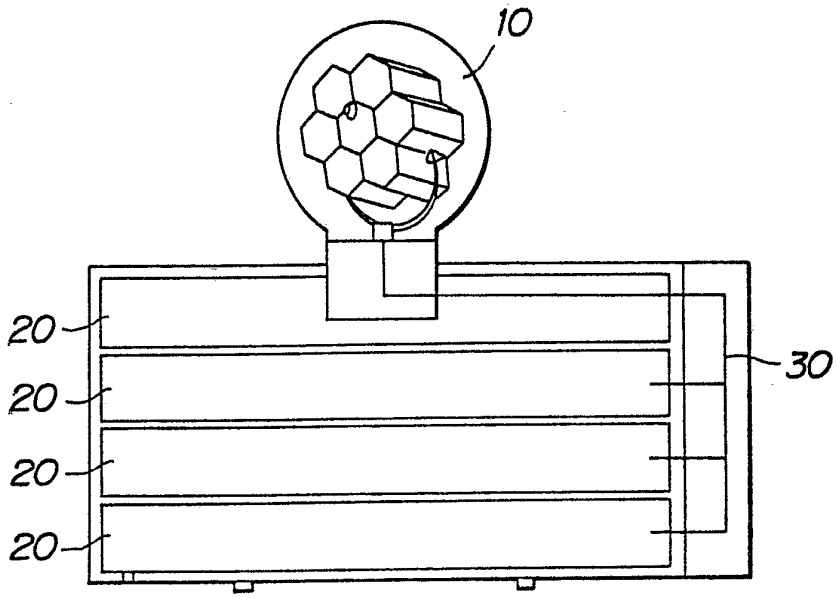

FIG. 2

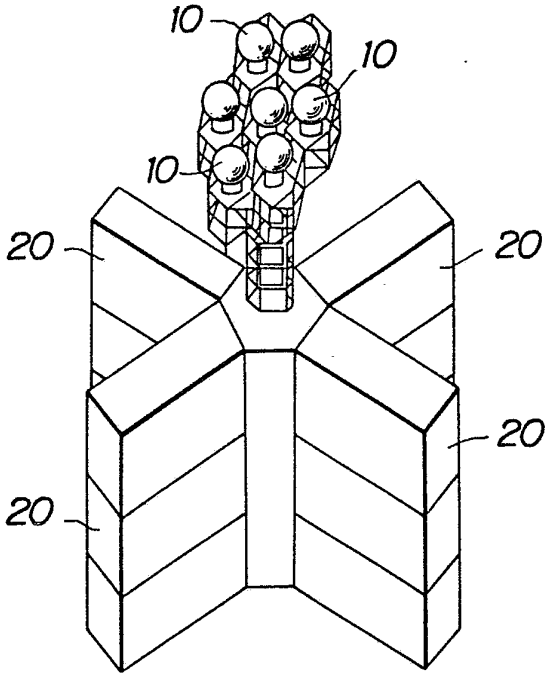

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FIG.3

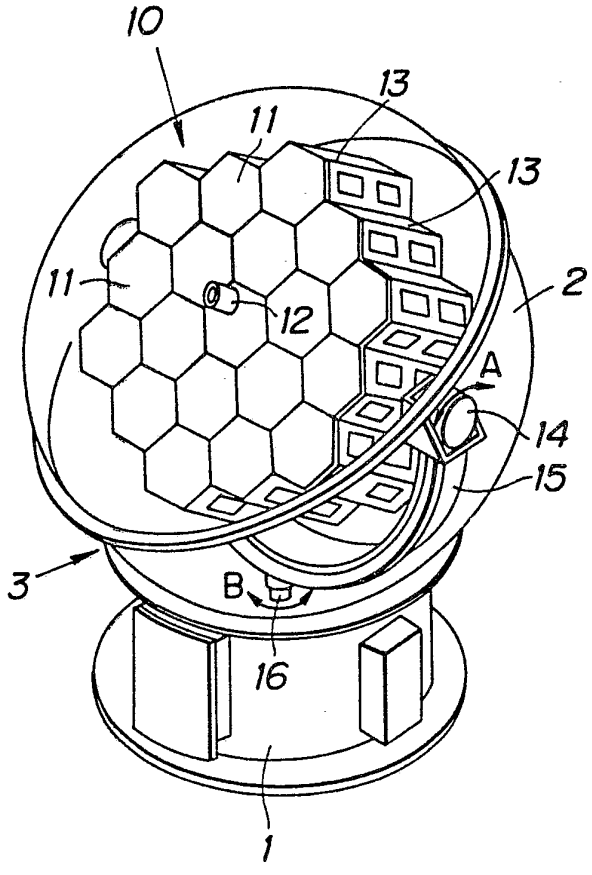

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FIG.4

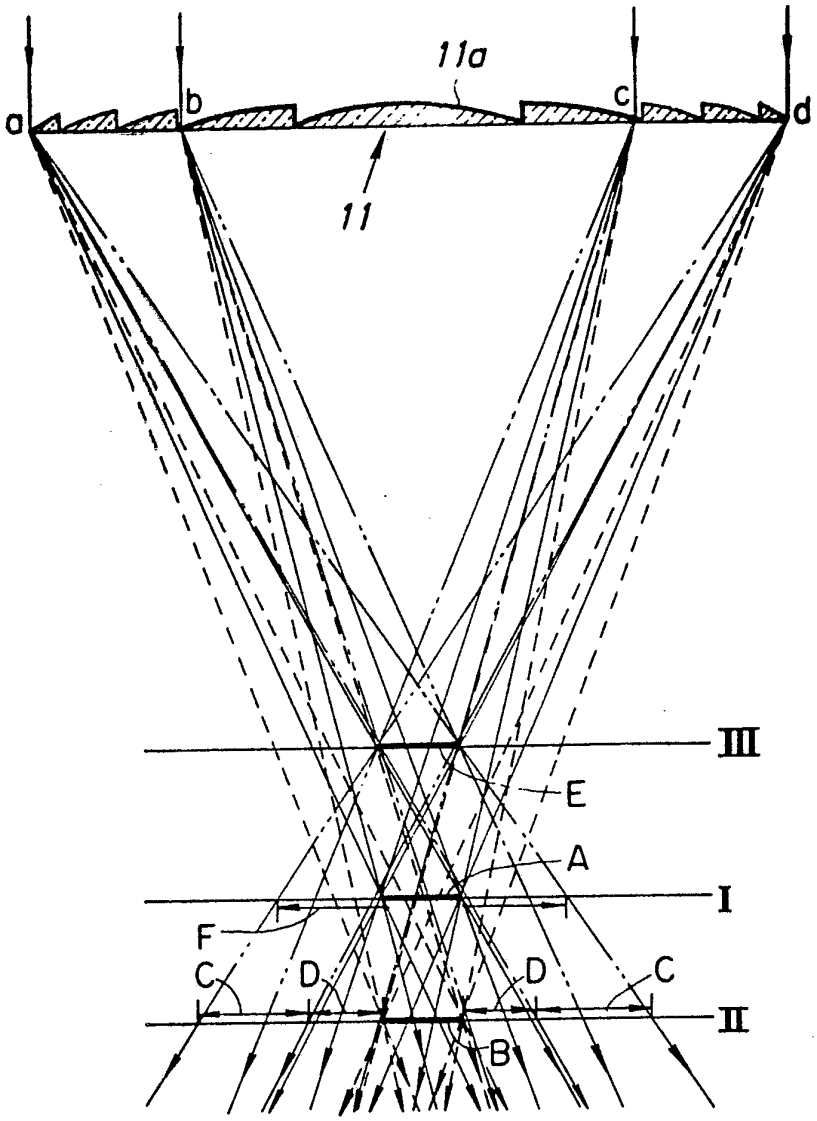

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FIG.5

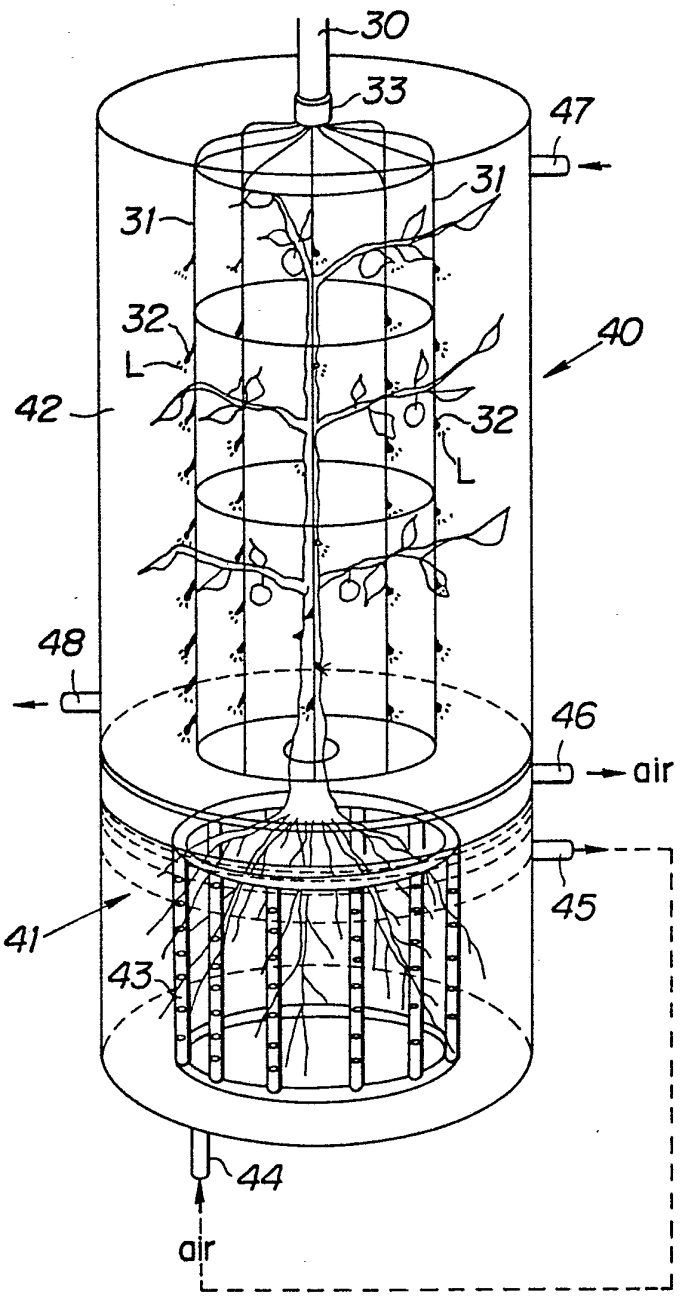

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FIG.6

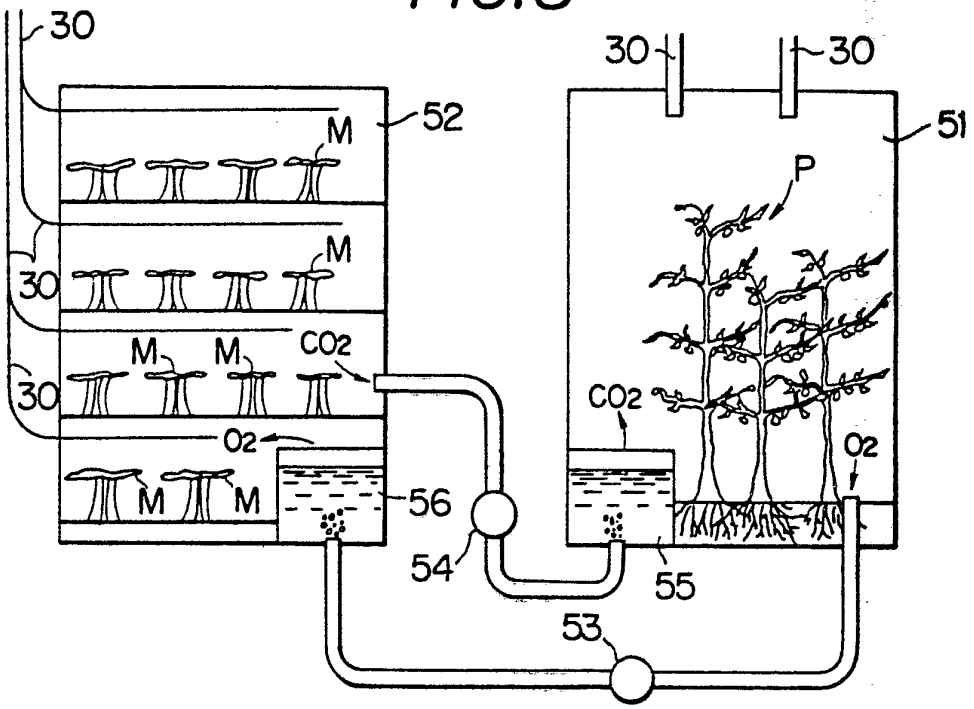

FIG.7

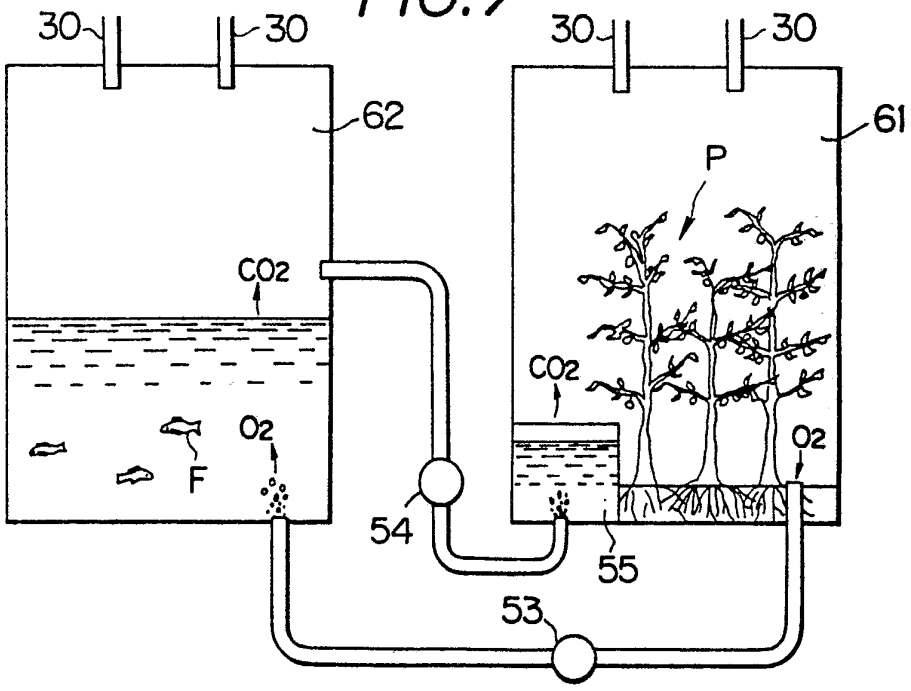

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FIG.8

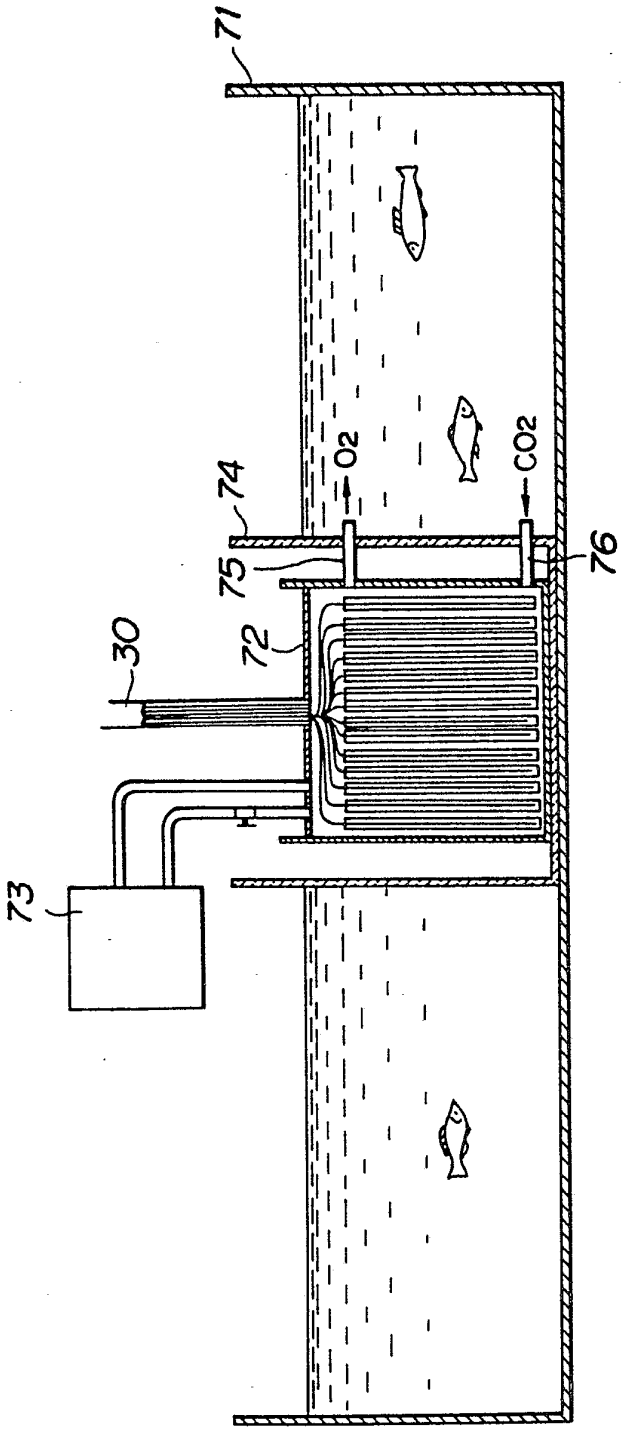

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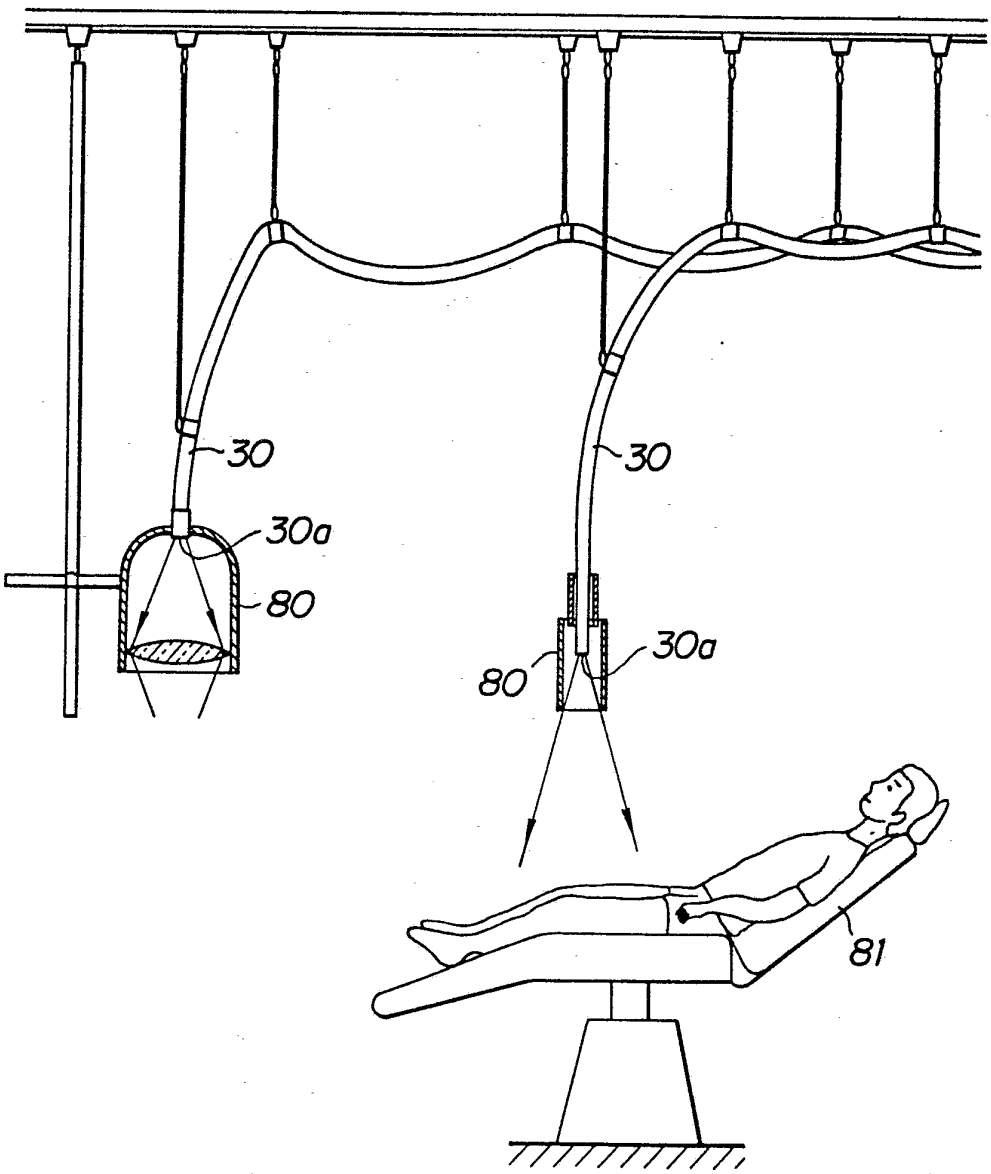
FIG.9



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(19) United States

(12) Patent Application Publication

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Im et al.

(54) **MICROALGAE FERMENTATION USING CONTROLLED ILLUMINATION**

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(73) Assignee: **PHYCOIL BIOTECHNOLOGY INTERNATIONAL, INC.**, Menlo Park, CA (US)

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(86) PCT No.: **PCT/US10/49347**

§ 371 (c)(1),
(2), (4) Date: **Mar. 8, 2012**

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C12P 5/00	(2006.01)
C12P 1/00	(2006.01)
C12P 19/04	(2006.01)

(52) **U.S. Cl.** **435/101**; 435/257.1; 435/41; 435/166; 435/292.1

(57) **ABSTRACT**

Bioreactors and methods for cultivating microalgae are provided herein. The bioreactor and methods include features and modifications to improve heterotrophic growth efficiency by providing a light signal.

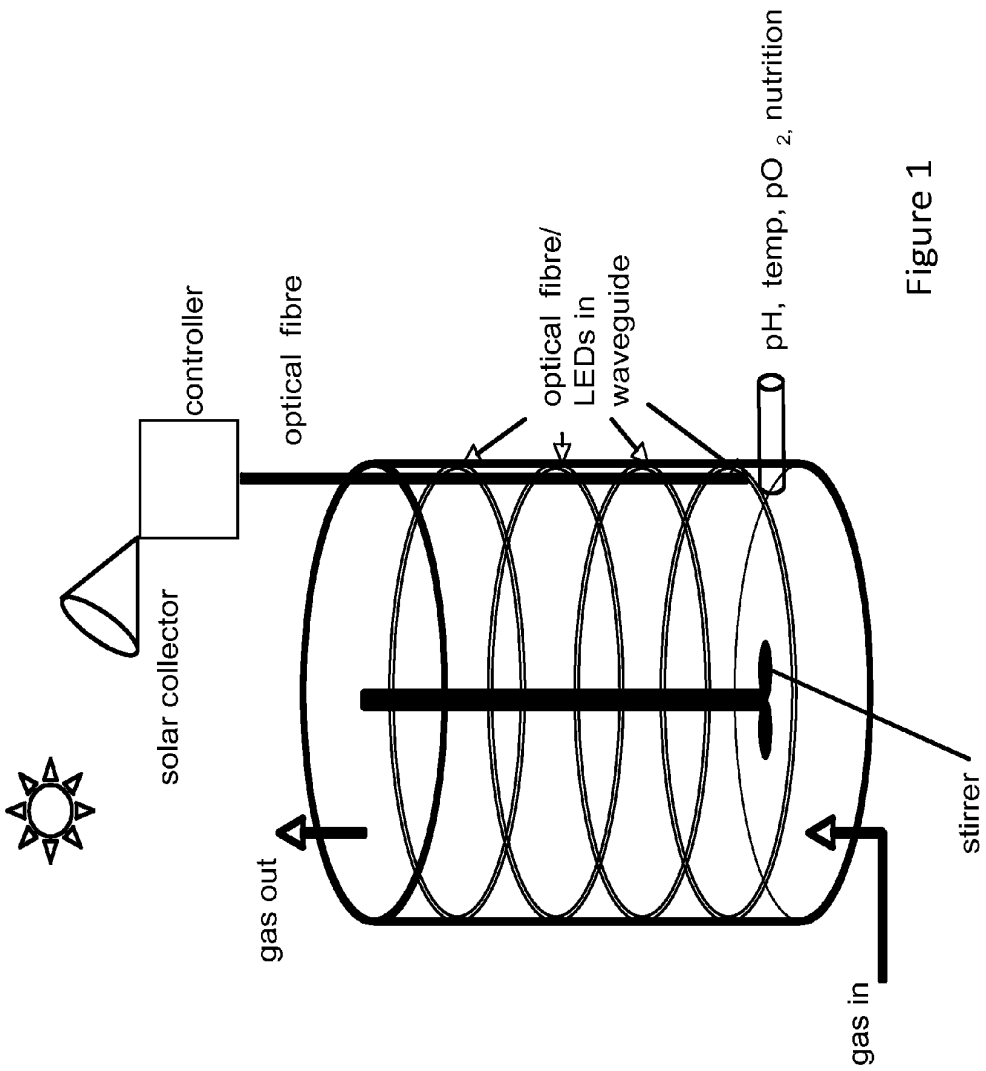
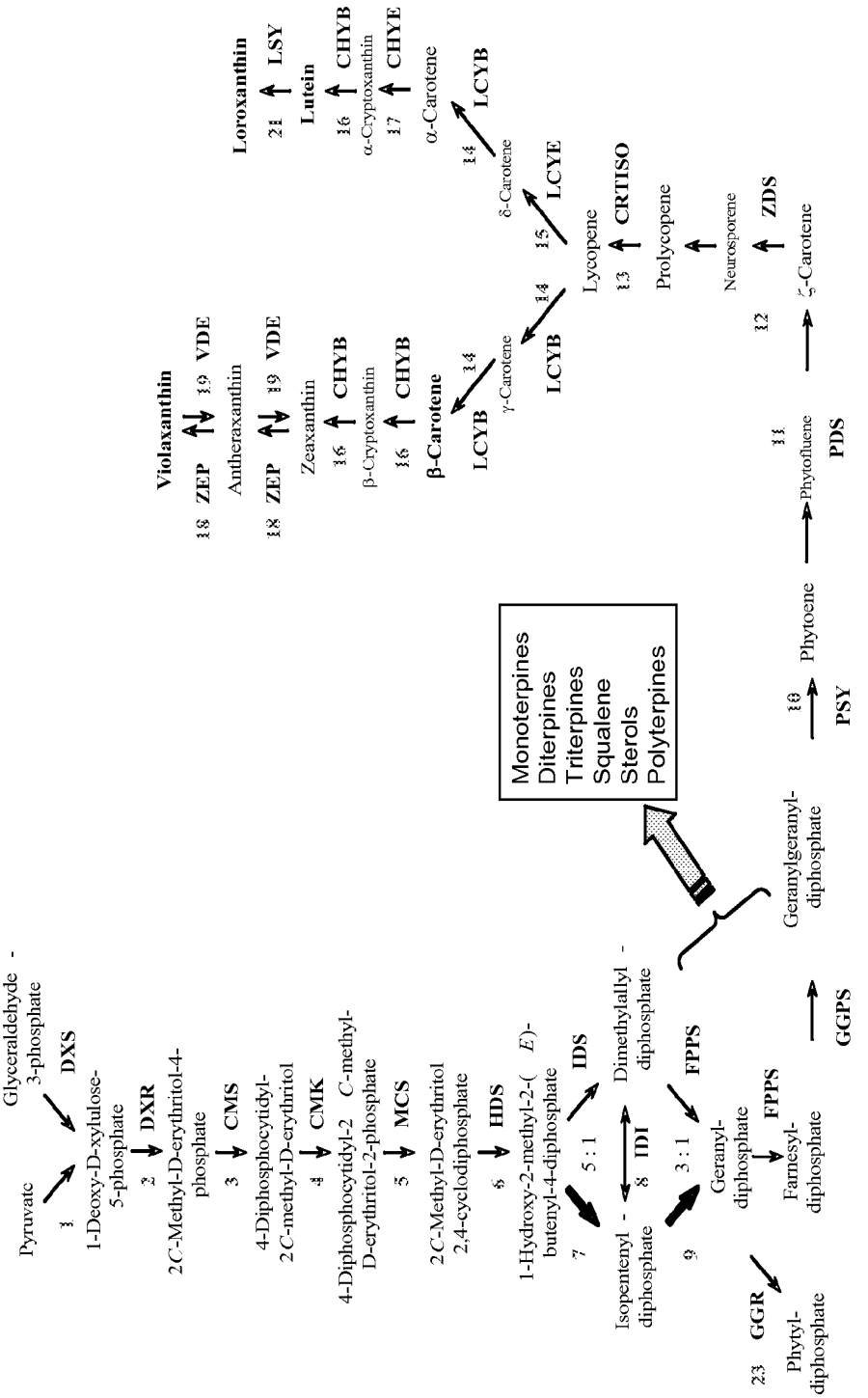

controller
optical fibre
optical fibre/
LEDs in
waveguide
pH, temp, pO 2, nutrition
solar collector
gas out
stirrer
gas in

Figure 1


Pyruvate
Glyceraldehyde - 3-phosphate
1
DXS
1-Deoxy-D-xylulose-5-phosphate
2
DXR
2C-Methyl-D-erythritol-4-phosphate
3
CMS
4-Diphosphocytidyl-2C-methyl-D-erythritol
4
CMK
4-Diphosphocytidyl-2-C-methyl-D-erythritol-2-phosphate
5
MCS
2C-Methyl-D-erythritol 2,4-cyclodiphosphate
6
HDS
1-Hydroxy-2-methyl-2-(E)-butenyl-4-diphosphate
7
5 : 1
IDS
Isopentenyl - diphosphate
8
IDI
Dimethylallyl - diphosphate
9
3 : 1
FPPS
Geranyl-diphosphate
FPPS
Farnesyl-diphosphate
GGPS
Geranylgeranyl-diphosphate
10
Phytoene
PSY
11
Phytofluene
PDS
12
ζ-Carotene
ZDS
Neurosporene
13
CRTISO
Prolycopene
Lycopene
14
15
LCYE
δ-Carotene
LCYB
γ-Carotene
14
LCYB
β-Carotene
16
CHYB
β-Cryptoxanthin
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CHYE
α-Carotene
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LCYB
α-Cryptoxanthin
16
CHYB
Zeaxanthin
18
ZEP
19
VDE
Antheraxanthin
18
ZEP
19
VDE
Violaxanthin
21
LSY
Lutein
16
CHYB
Loroxanthin
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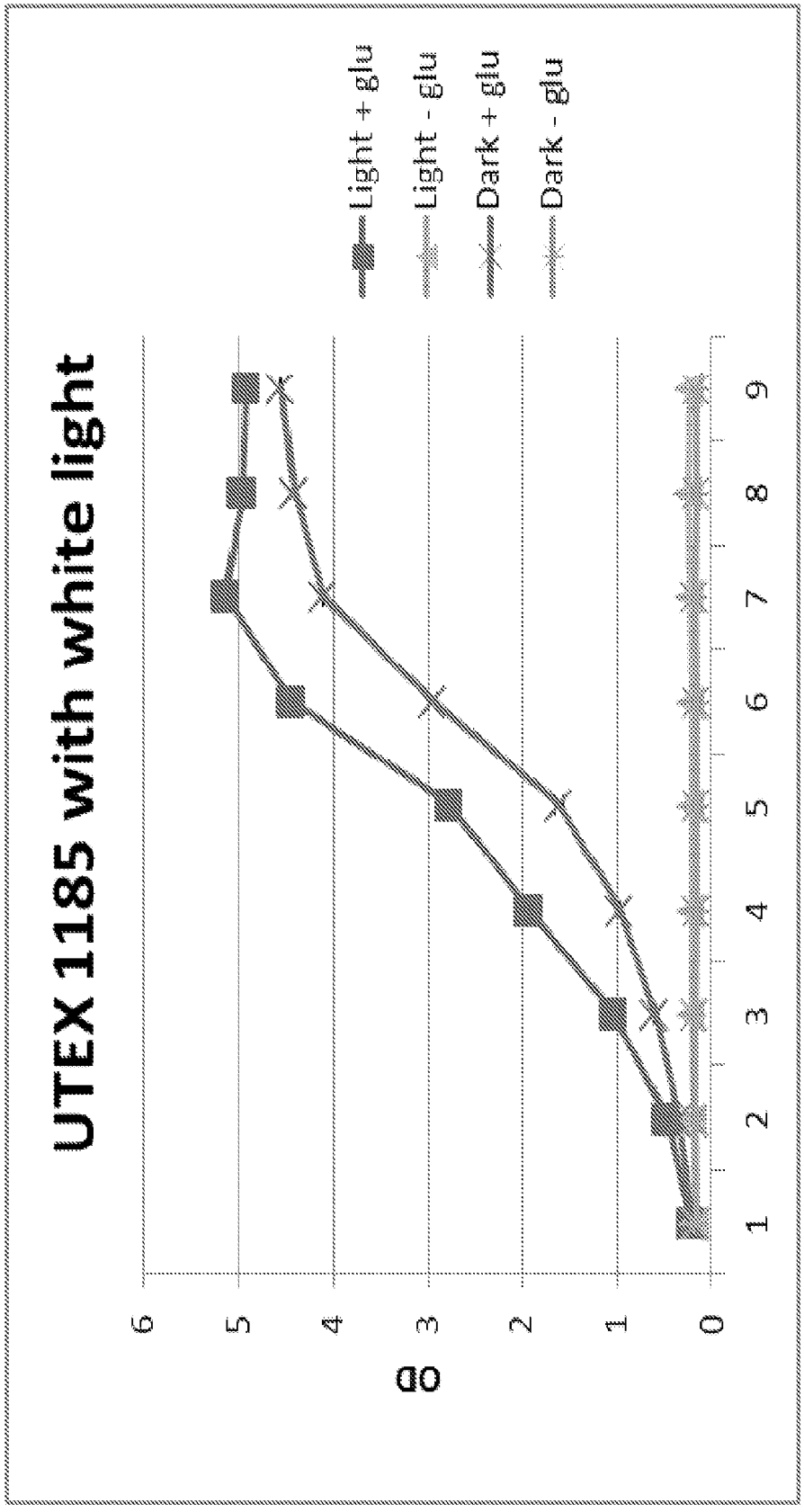
Monoterpines
Diterpines
Triterpines
Squalene
Sterols
Polyterpines

Figure 2


UTEX 1185 with white light
Light + glu
Light - glu
Dark + glu
Dark - glu
OD
0
1
2
3
4
5
6
1
2
3
4
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6
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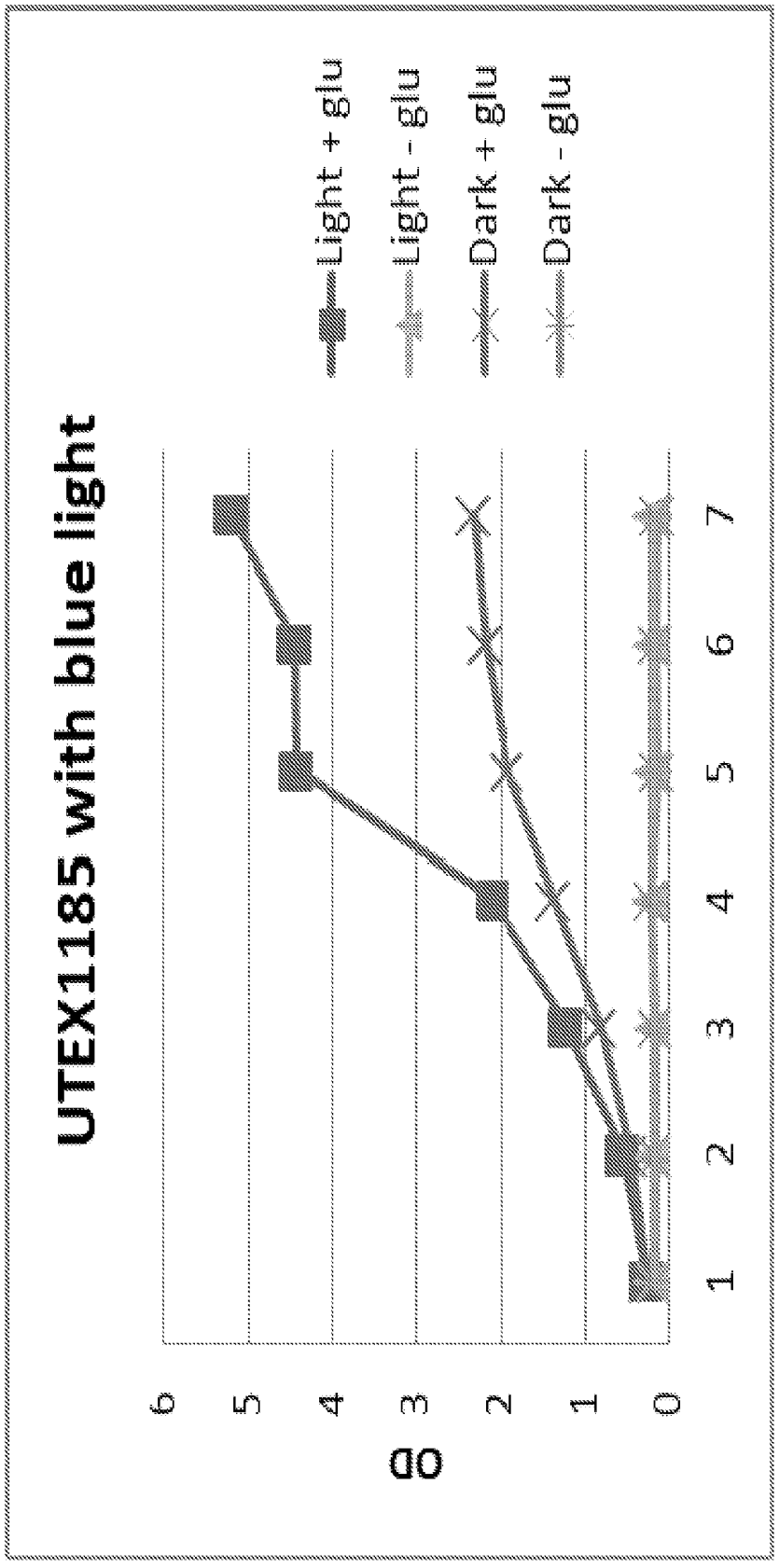
8
9

Figure 3A


UTEX1185 with blue light
Light + glu
Light - glu
Dark + glu
Dark - glu
OD
0
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3
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1
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3
4
5
6
7

Figure 3B

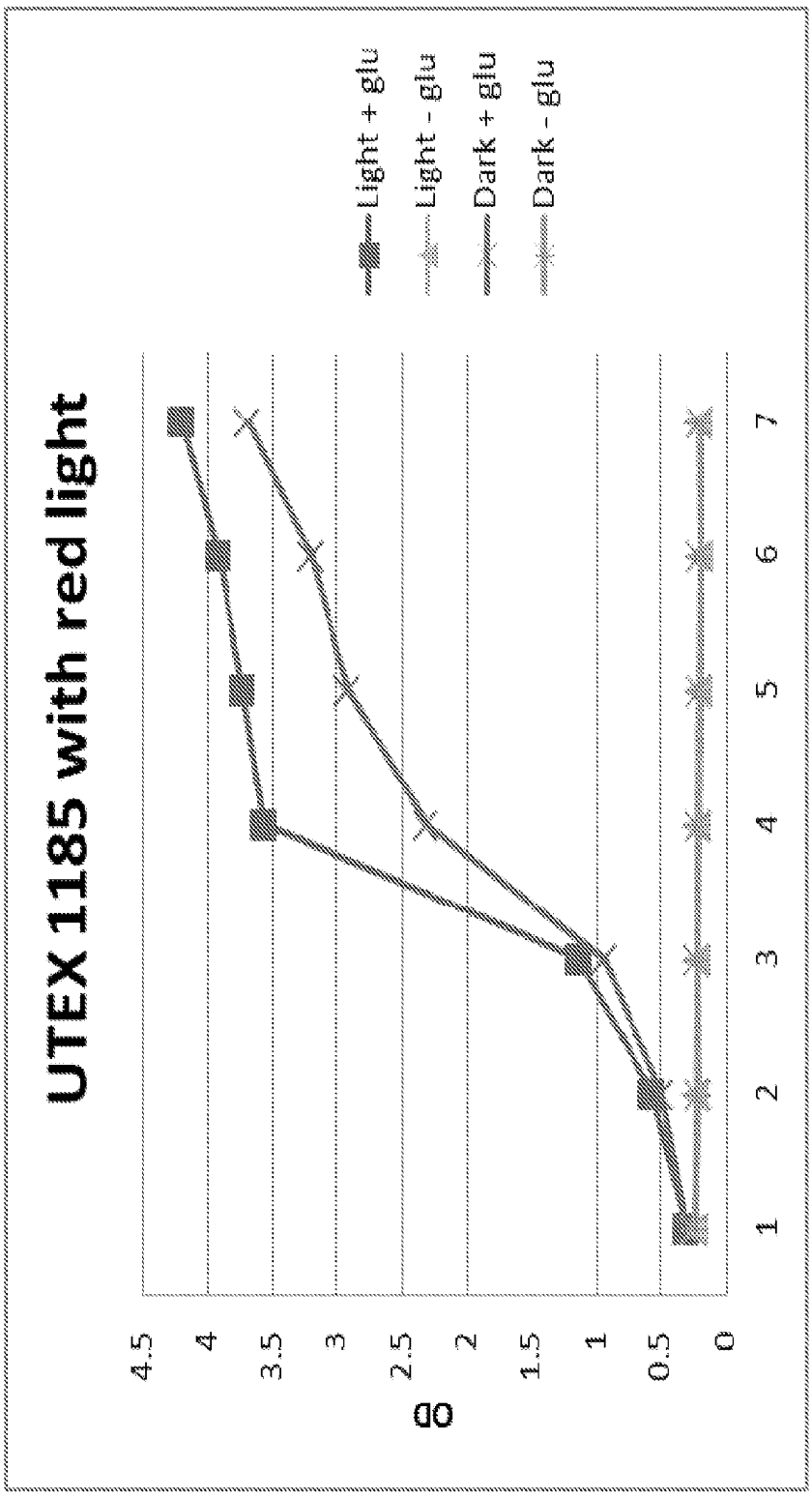
UTEX 1185 with red light
Light + glu
Light - glu
Dark + glu
Dark - glu
OD
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1
2
3
4
5
6
7

Figure 3C

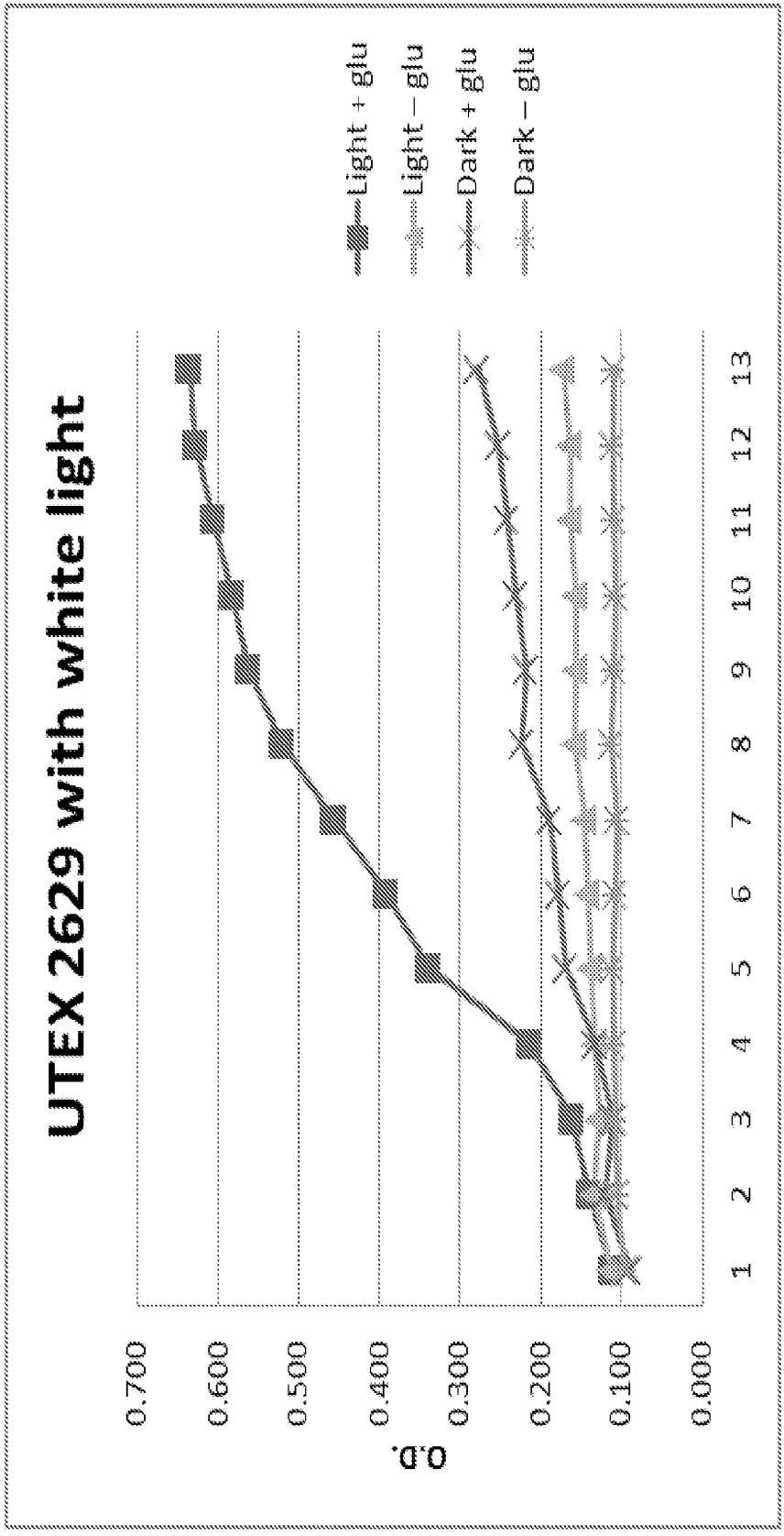
UTEX 2629 with white light
Light + glu
Light – glu
Dark + glu
Dark – glu
O.D.
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
1
2
3
4
5
6
7
8
9
10
11
12
13

Figure 4A

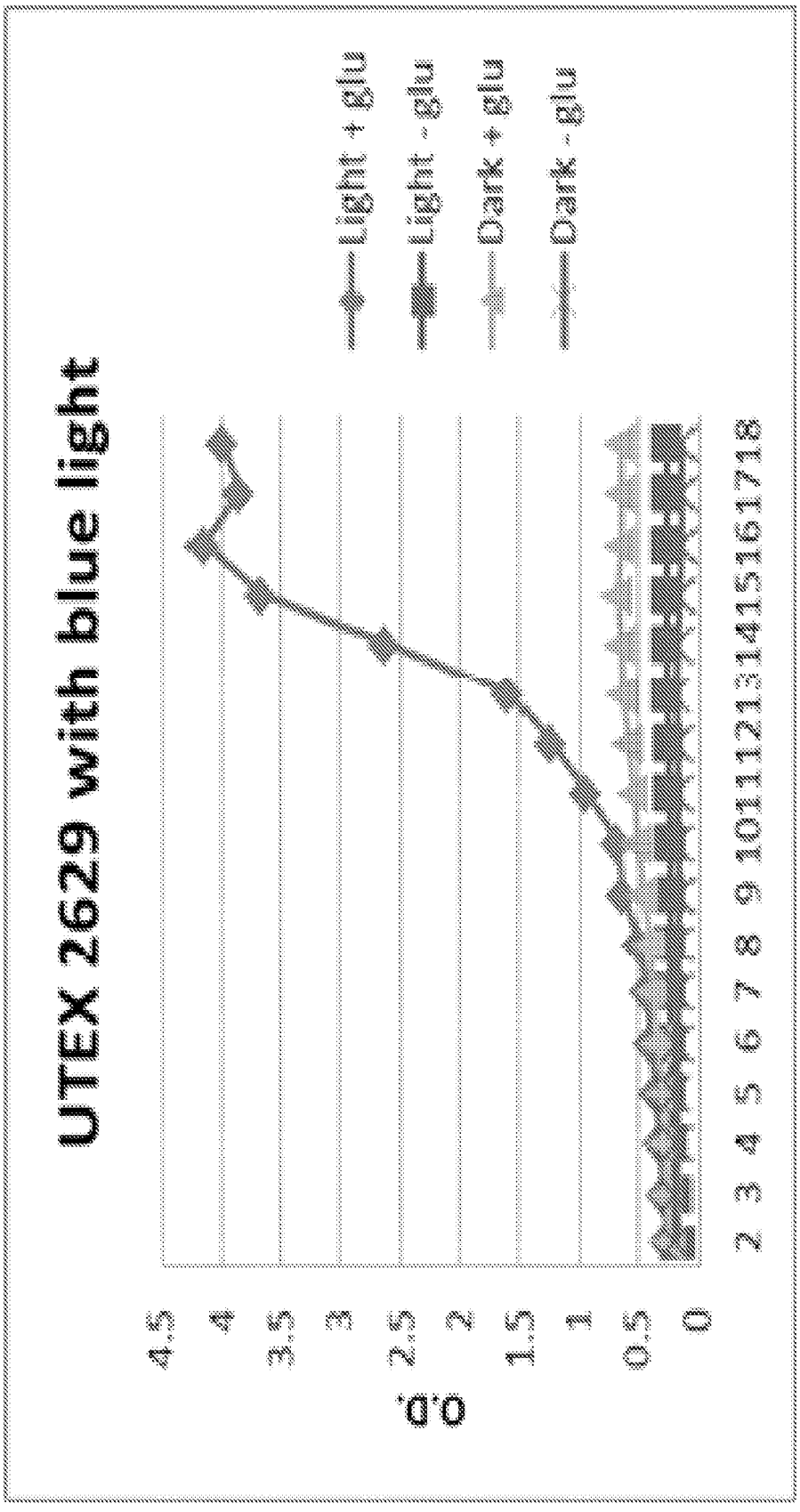
UTEX 2629 with blue light
Light + glu
Light - glu
Dark + glu
Dark - glu
O.D.
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

Figure 4B

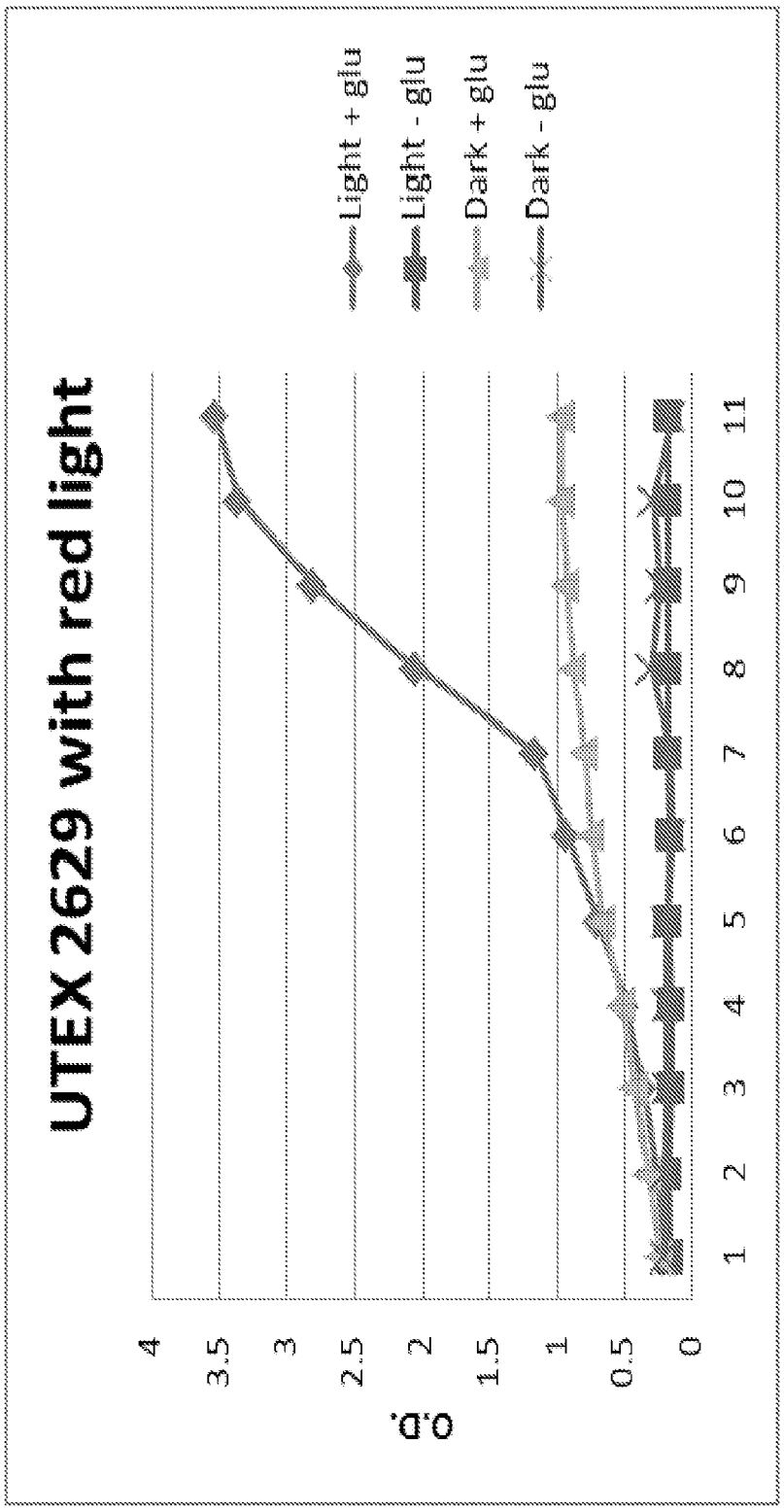
UTEX 2629 with red light
Light + glu
Light - glu
Dark + glu
Dark - glu
O.D.
0
0.5
1
1.5
2
2.5
3
3.5
4
1
2
3
4
5
6
7
8
9
10
11

Figure 4C

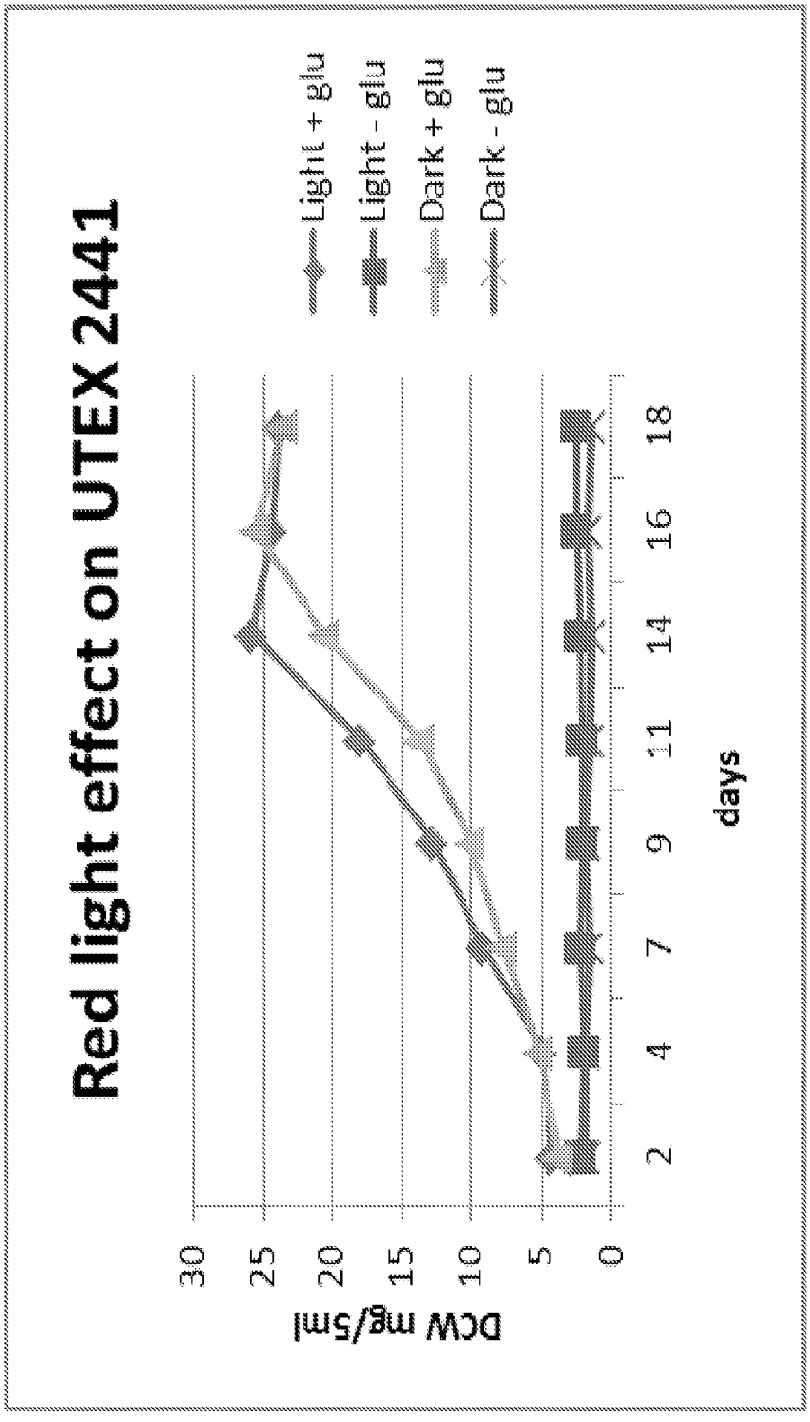
Red light effect on UTEX 2441
Light + glu
Light - glu
Dark + glu
Dark - glu
DCW mg/5ml
0
5
10
15
20
25
30
days
2
4
7
9
11
14
16
18

Figure 5A

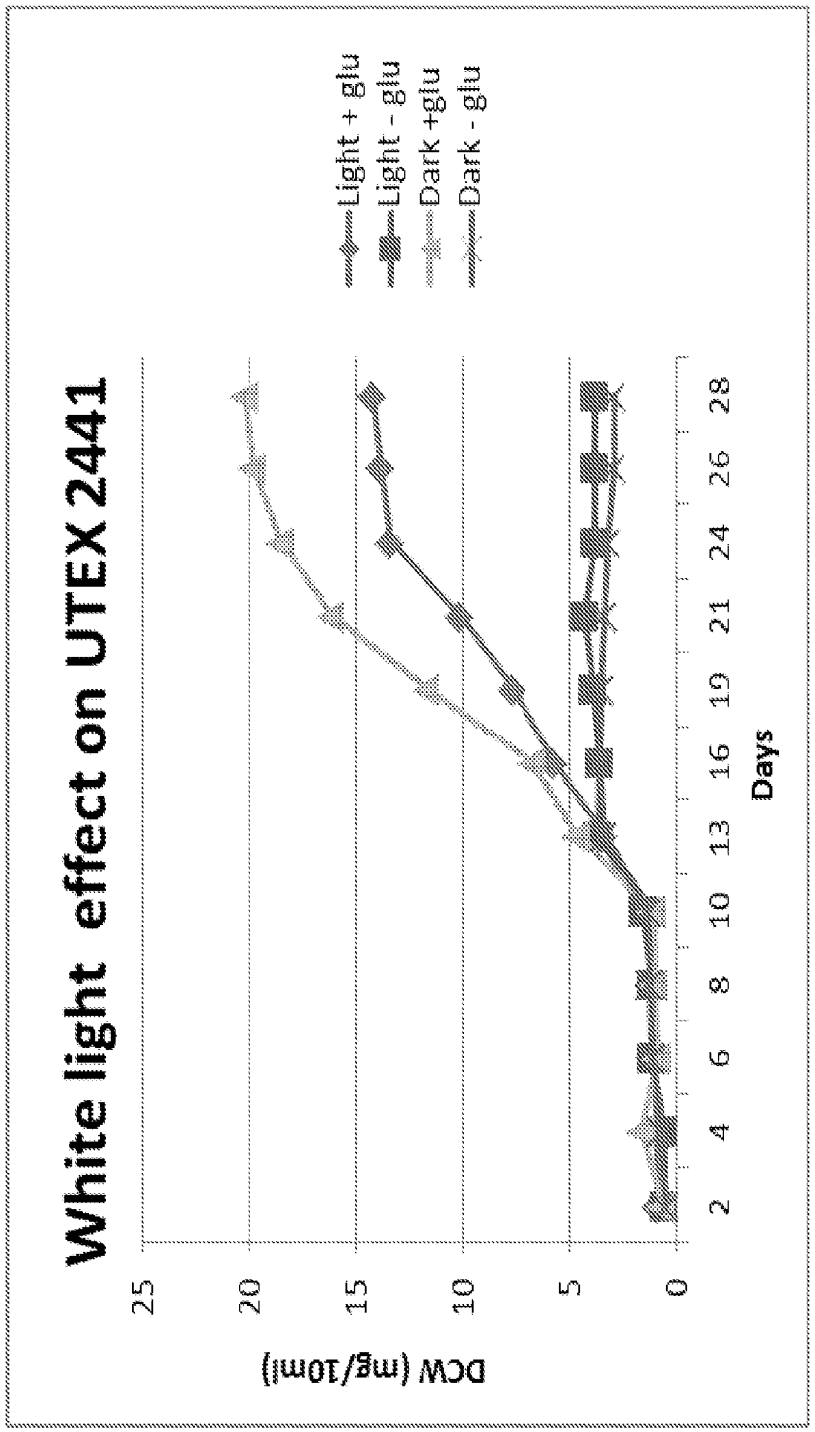
White light effect on UTEX 2441
Light + glu
Light - glu
Dark +glu
Dark - glu
DCW (mg/10ml)
25
20
15
10
5
0
2
4
6
8
10
13
16
19
21
24
26
28
Days

Figure 5B

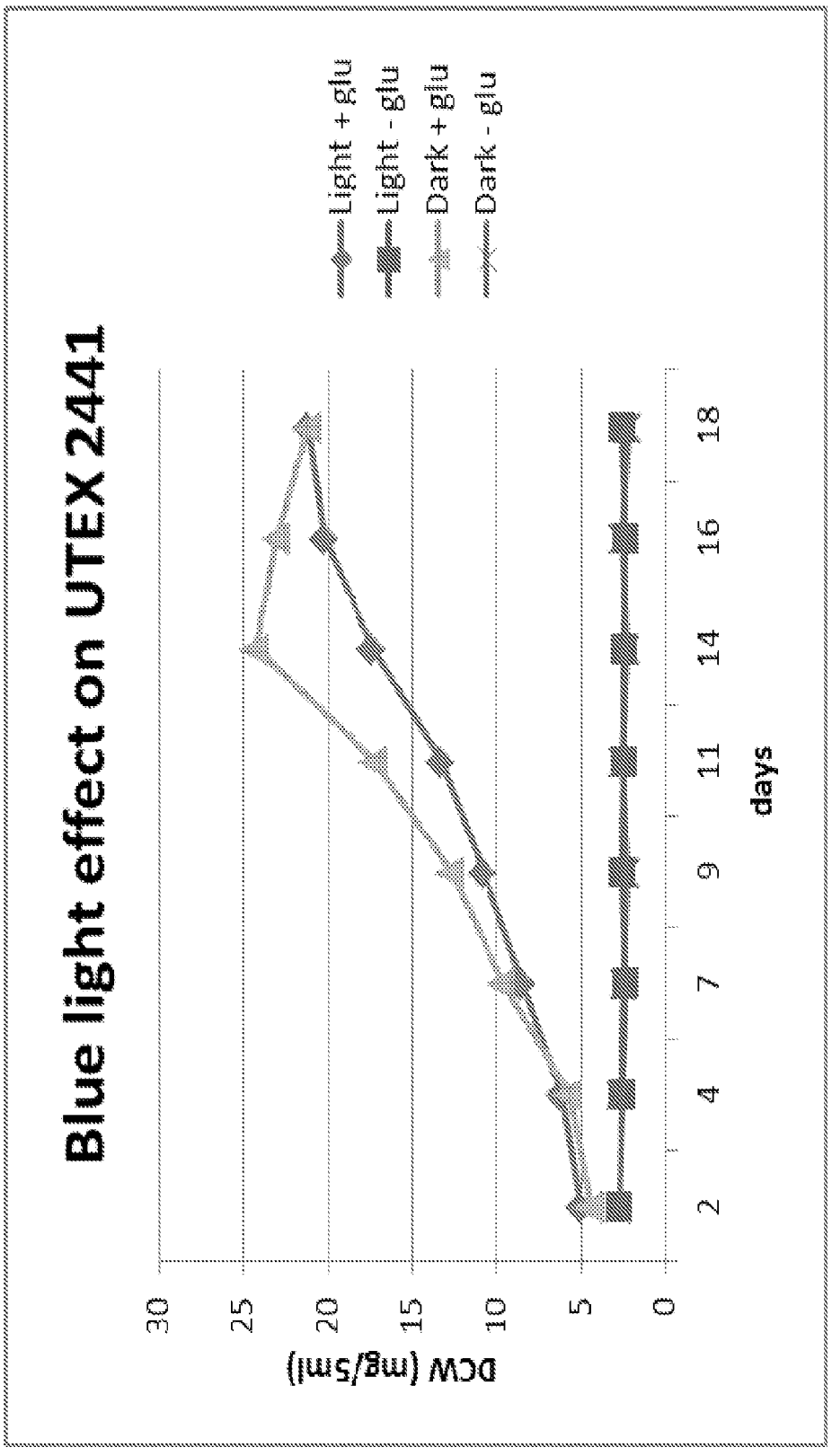
Blue light effect on UTEX 2441
Light + glu
Light - glu
Dark + glu
Dark - glu
DCW (mg/5ml)
0
5
10
15
20
25
30
days
2
4
7
9
11
14
16
18

Figure 5C

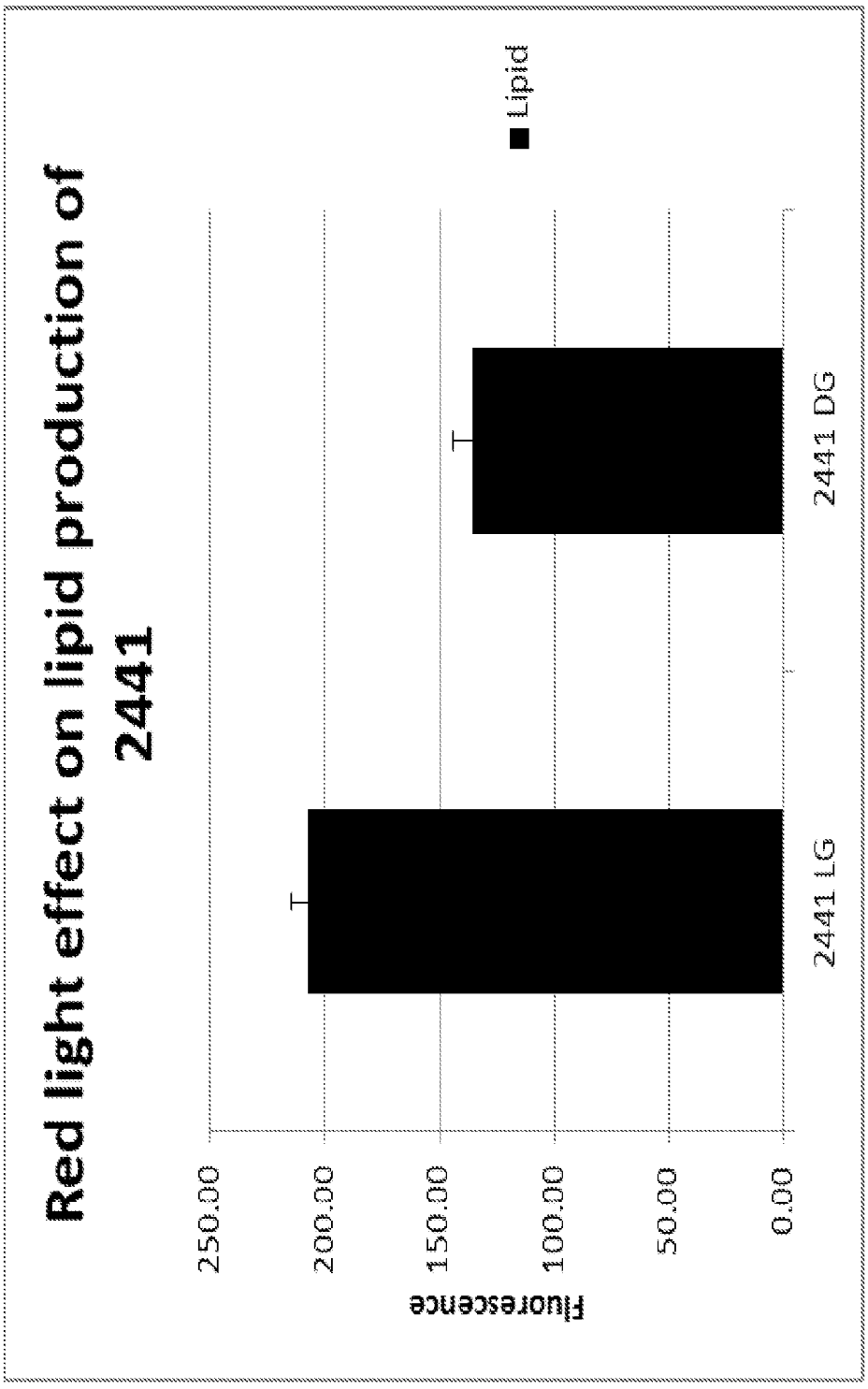
Red light effect on lipid production of 2441
Lipid
Fluorescence
250.00
200.00
150.00
100.00
50.00
0.00
2441 LG
2441 DG

Figure 6

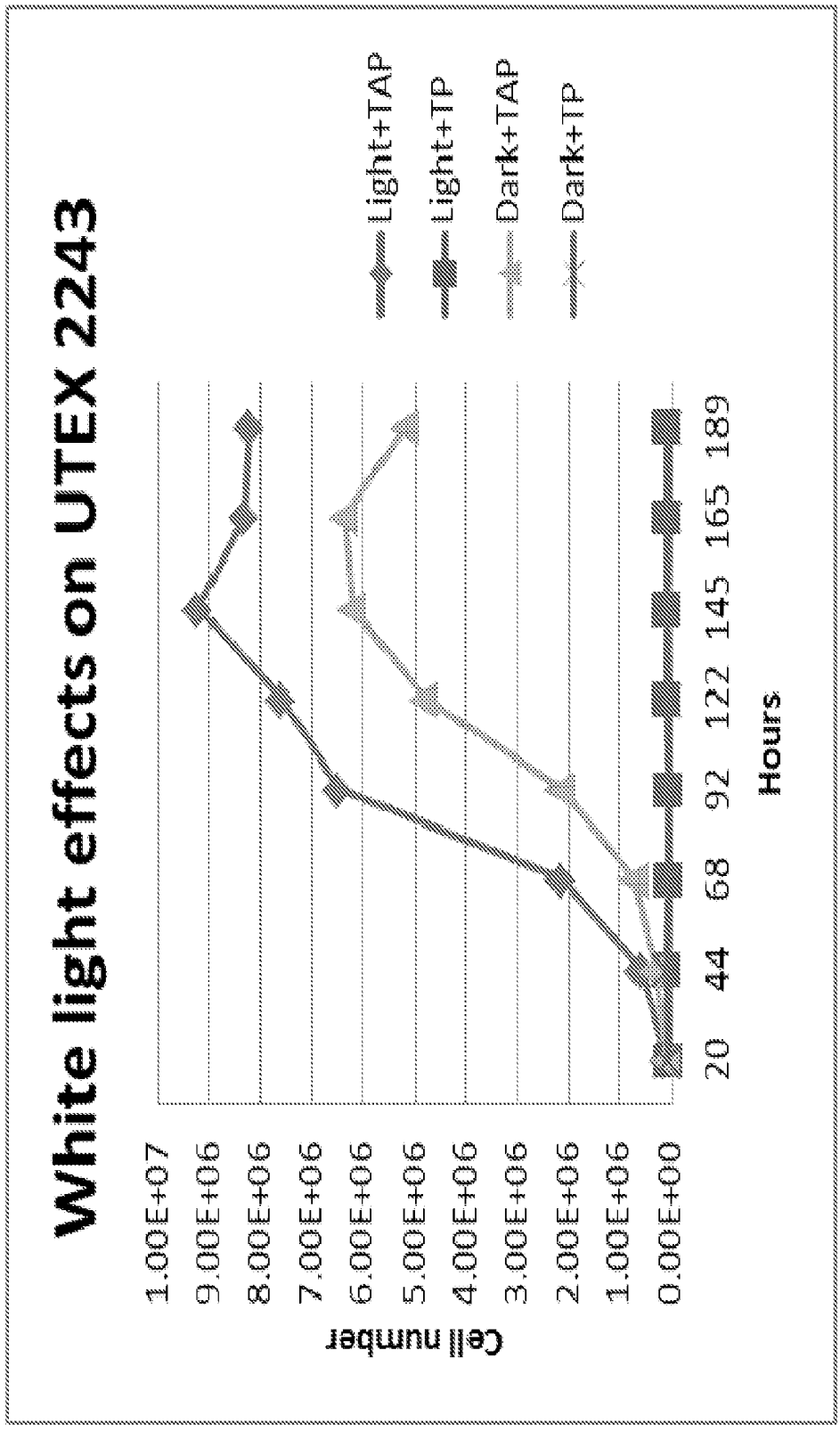
White light effects on UTEX 2243
Light+TAP
Light+TP
Dark+TAP
Dark+TP
Cell number
1.00E+07
9.00E+06
8.00E+06
7.00E+06
6.00E+06
5.00E+06
4.00E+06
3.00E+06
2.00E+06
1.00E+06
0.00E+00
Hours
20
44
68
92
122
145
165
189

Figure 7

MICROALGAE FERMENTATION USING CONTROLLED ILLUMINATION

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 61/243,593, filed Sep. 18, 2009, and U.S. Provisional Application No. 61/359,726, filed Jun. 29, 2010, the entire disclosures of which are hereby incorporated by reference in their entirety for all purposes.

FIELD

[0002] The invention relates to methods, means, and systems of fermentation of microorganisms, e.g., microalgae. The invention can be used in pharmaceutical, cosmetic and food industries, as well as for obtaining oil and biofuel from microalgae.

BACKGROUND

[0003] Recently, attention has been directed to the application of microalgae to the production of a variety of materials including lipids, hydrocarbons, oil, polysaccharides, pigments, and biofuels.

[0004] One of the conventional methods to grow microalgae is to heterotrophically culture it in an enclosed, light-free system. Techniques have been developed for the large-scale production of aquatic microalgae under heterotrophic growth conditions by utilizing organic carbon instead of light as an energy source. For example, U.S. Pat. Nos. 3,142,135 and 3,882,635 describe processes for the heterotrophic production of proteins and pigments from algae such as *Chlorella, Spongiococcum*, and *Prototheca*. In addition, heterotrophic algal cultures can attain much higher densities than photoautotrophic cultures.

[0005] However, the above application cannot be applied to all microalgae because only a limited number of microalgae strains can grow in heterotrophic conditions. Attempts to grow microalgae in heterotrophic conditions often involve either screening for strains that can grow in heterotrophic conditions or genetic modification of organisms to allow growth under such conditions.

[0006] Microalgae that contain both a proper transportation system for sugar and that can grow naturally in heterotrophic conditions often show slow growth rates or low production of materials of commercial interest since they have evolved many years to utilize sunlight as an environmental signal to control aspects of metabolism as well as energy generated through photosynthesis.

[0007] Most of the photosynthetic organisms, including microalgae, use light as an environmental signal to optimize themselves for growth and survival. Light signals are sensed by different photoreceptors including red/far-red photoreceptors (phytochromes) and blue light photoreceptors (cryptochromes and NPHs). Light serves as an environmental signal that regulates physiological and developmental processes and provides the energy that fuels the reduction of inorganic carbon. However, under certain conditions light also has the potential to be toxic. Photoinhibition occurs either when the photon flux absorbed by chloroplasts is very high (under high light conditions) or when the light energy influx exceeds the consumption capability (under mixotrophic conditions where a cell uses reduced carbon as an energy source). In mixotrophic conditions, photosynthetic organisms show photoinhibition at a much lower light intensity than autotrophic conditions since the electrons absorbed through the photosynthetic apparatus cannot be efficiently used due to a feedback mechanism in the Calvin cycle.

[0008] Absorbed light energy can result in the accumulation of excited chlorophyll molecules within the pigment bed and damage of the photosystem. Excited chlorophyll molecules that accumulate in the pigment bed as a consequence of excess excitation can also stimulate the production of active oxygen species such as superoxides, hydroxyl radicals and singlet oxygen.

SUMMARY

[0009] Disclosed herein is a method for cultivating a microalgae capable of heterotrophic growth, including: incubating the microalgae under a heterotrophic growth condition for a period of time sufficient to allow the microalgae to grow, wherein the heterotrophic growth condition includes a media including a carbon source, and wherein the heterotrophic growth condition further includes a low irradiance of light.

[0010] In some embodiments, the microalgae is a *Botryococcus* strain, the carbon source is glucose, and the low irradiance of light is between 1-10 μmol photons $m^{-2}s^{-1}$.

[0011] In some embodiments, the microalgae is a *Botryococcus sudeticus* strain. In some embodiments, the microalgae is a *Botryococcus* strain. In some embodiments, the microalgae is a UTEX 2629 strain. In some embodiments, the microalgae is a *Botryococcus braunii* strain. In some embodiments, the microalgae is a UTEX 2441 strain. In some embodiments, the microalgae is a *Neochloris oleabundans* strain. In some embodiments, the microalgae is a *Neochloris* strain. In some embodiments, the microalgae is a UTEX 1185 strain. In some embodiments, the microalgae is a *Chlamydomonas reinhardtii* strain. In some embodiments, the microalgae is a *Chlamydomonas* strain. In some embodiments, the microalgae is a UTEX 2243 strain. In some embodiments, the microalgae comprises a photoreceptor.

[0012] In some embodiments, the carbon source is glucose. In some embodiments, the carbon source is selected from the group consisting of a fixed carbon source, glucose, fructose, sucrose, galactose, xylose, mannose, rhamnose, N-acetylglucosamine, glycerol, floridoside, glucuronic acid, corn starch, depolymerized cellulosic material, sugar cane, sugar beet, lactose, milk whey, and molasses.

[0013] In some embodiments, the light is produced by a natural light source. In some embodiments, the light is natural sun light. In some embodiments, the light comprises full spectrum light or a specific wavelength of light. In some embodiments, the light is produced by an artificial light source. In some embodiments, the light is artificial light. In some embodiments, the intensity of the low irradiance of light is between 0.01-1 μmol photons m^{-2} s^{-1}. In some embodiments, the intensity of the low irradiance of light is between 1-10 μmol photons $m^{-2}s^{-1}$. In some embodiments, the intensity of the low irradiance of light is between 10-100 μmol photons $m^{-2}s^{-1}$. In some embodiments, the intensity of the low irradiance of light is between 100-300 μmol photons $m^{2}s^{-1}$. In some embodiments, the intensity of the low irradiance of light is between 100-300 μmol photons $m^{-2}s^{-1}$. In some embodiments, the intensity of the low irradiance of light is 3-4 $\mu mol/m^{2}s^{-1}$ photons, 2-3 $\mu mol/m^{2}s^{-1}$ photons, 1-2 $\mu mol/m^{2}s^{-1}$ photons, or 3-5 $\mu mol/m^{2}s^{-1}$ photons.

[0014] In some embodiments, the method further includes producing a material from the microalgae. In some embodi-

ments, the material is a polysaccharide, a pigment, a lipid, or a hydrocarbon. In some embodiments, the material is a hydrocarbon.

[0015] In some embodiments, the method further includes recovering the material. In some embodiments, the method further includes extracting the material.

[0016] In some embodiments, the method further includes processing the material. In some embodiments, the processing of the material produces a processed material. In some embodiments, the processed material is selected from the group consisting of a fuel, biodiesel, jet fuel, a cosmetic, a pharmaceutical agent, a surfactant, and a renewable diesel.

[0017] In some embodiments, the growth rate of the microalgae in the above methods is higher than a second microalgae incubated under a second heterotrophic growth condition for a period of time sufficient to allow the microalgae to grow, wherein the second heterotrophic growth condition includes a growth media comprising a carbon source, and wherein the second heterotrophic growth condition does not include a low irradiance of light.

[0018] Also described herein is a method of culturing microalgae, including placing a plurality of microalgae cells in the presence of a carbon source and a low irradiance of light.

[0019] Also described herein is a method of manufacturing a material, including: providing a microalgae capable of producing the material; culturing the microalgae in a media, wherein the media includes a carbon source; applying a low irradiance of light to the microalgae; and allowing the microalgae to accumulate at least 10% of its dry cell weight as the material. In some embodiments, the method further includes recovering the material.

[0020] Also described herein is a bioreactor system, including: a bioreactor; a culture media including a carbon source, wherein the culture media is located inside the bioreactor; a microalgae adapted for heterotrophic growth, wherein the microalgae is located in the culture media; and a light source, wherein the light source produces a low irradiance of light, and wherein the light source is operatively coupled to the bioreactor.

[0021] In some embodiments, light from the light source includes full spectrum light or a specific wavelength of light. In some embodiments, light from the light source includes natural sunlight collected by a solar energy collector operatively coupled to the bioreactor, and wherein the light is transmitted to the interior of the bioreactor through an optical fiber operatively coupled to the solar collector and the bioreactor. In some embodiments, light from the light source includes artificial light, wherein the artificial light is produced by a light emitted diode (LED) or a fluorescent light. In some embodiments, the system further includes a power supply sufficient to power the LED or fluorescent light, wherein the power supply is operatively coupled to the bioreactor; and a light controller operatively coupled to the power supply, wherein the light controller is adapted to control the intensity and wavelength of light emitted by the LED or fluorescent light. In some embodiments, the optical fibre is mounted in a transparent and protective light structure. In some embodiments, the LED is mounted in a transparent and protective light structure.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0022] These and other features, aspects, and advantages of the present invention will become better understood with regard to the following description, and accompanying drawings, where:

[0023] FIG. **1** is one embodiment of a bioreactor.

[0024] FIG. **2** illustrates the isoprenoid/carotenoid pathway.

[0025] FIGS. **3**A-C show the growth of UTEX 1185 under white, blue, and red light conditions. The X-axis is shown in days. Glu stands for glucose.

[0026] FIGS. **4**A-C show the growth of UTEX 2629 under white, blue, and red light conditions. The X-axis is shown in days. Glu stands for glucose.

[0027] FIGS. **5**A-C show the growth of UTEX 2441 under white, blue, and red light conditions. Glu stands for glucose.

[0028] FIG. **6** shows the production of lipid by UTEX 2441 under red light conditions. LG stands for light+glucose; DG stands for dark+glucose.

[0029] FIG. **7** shows the growth of UTEX 2243 under white light conditions.

DETAILED DESCRIPTION

[0030] Terms used in the claims and specification are defined as set forth below unless otherwise specified.

[0031] "Axenic" means a culture of an organism that is free from contamination by other living organisms.

[0032] "Biodiesel" is a biologically produced fatty acid alkyl ester suitable for use as a fuel in a diesel engine.

[0033] The term "biomass" refers to material produced by growth and/or propagation of cells. Biomass may contain cells and/or intracellular contents as well as extracellular material. Extracellular material includes, but is not limited to, compounds secreted by a cell.

[0034] "Bioreactor" means an enclosure or partial enclosure in which cells are cultured, optionally in suspension. FIG. **1** is an example of a bioreactor. "Photobioreactor" refers to a container, at least part of which is at least partially transparent or partially open, thereby allowing light to pass through, in which one or more microalgae cells are cultured. Photobioreactors may be closed, as in the instance of a polyethylene bag or Erlenmeyer flask, or may be open to the environment, as in the instance of an outdoor pond.

[0035] As used herein, a "catalyst" refers to an agent, such as a molecule or macromolecular complex, capable of facilitating or promoting a chemical reaction of a reactant to a product without becoming a part of the product. A catalyst thus increases the rate of a reaction, after which, the catalyst may act on another reactant to form the product. A catalyst generally lowers the overall activation energy required for the reaction such that it proceeds more quickly or at a lower temperature. Thus reaction equilibrium may be more quickly attained. Examples of catalysts include enzymes, which are biological catalysts, heat, which is a non-biological catalyst, and metal catalysts used in fossil oil refining processes.

[0036] "Cellulosic material" means the products of digestion of cellulose, including glucose and xylose, and optionally additional compounds such as disaccharides, oligosaccharides, lignin, furfurals and other compounds. Nonlimiting examples of sources of cellulosic material include sugar cane bagasses, sugar beet pulp, corn stover, wood chips, sawdust and switchgrass.

[0037] The term "co-culture", and variants thereof such as "co-cultivate", refer to the presence of two or more types of cells in the same bioreactor. The two or more types of cells may both be microorganisms, such as microalgae, or may be a microalgal cell cultured with a different cell type. The culture conditions may be those that foster growth and/or propagation of the two or more cell types or those that facili-

tate growth and/or proliferation of one, or a subset, of the two or more cells while maintaining cellular growth for the remainder.

[0038] The term "cofactor" is used herein to refer to any molecule, other than the substrate, that is required for an enzyme to carry out its enzymatic activity.

[0039] The term "cultivated", and variants thereof, refer to the intentional fostering of growth (increases in cell size, cellular contents, and/or cellular activity) and/or propagation (increases in cell numbers via mitosis) of one or more cells by use of intended culture conditions. The combination of both growth and propagation may be termed proliferation. The one or more cells may be those of a microorganism, such as microalgae. Examples of intended conditions include the use of a defined medium (with known characteristics such as pH, ionic strength, and carbon source), specified temperature, oxygen tension, carbon dioxide levels, and growth in a bioreactor. The term does not refer to the growth or propagation of microorganisms in nature or otherwise without direct human intervention, such as natural growth of an organism that ultimately becomes fossilized to produce geological crude oil.

[0040] As used herein, the term "cytolysis" refers to the lysis of cells in a hypotonic environment. Cytolysis is caused by excessive osmosis, or movement of water, towards the inside of a cell (hyperhydration). The cell cannot withstand the osmotic pressure of the water inside, and so it explodes.

[0041] As used herein, the terms "expression vector" or "expression construct" refer to a nucleic acid construct, generated recombinantly or synthetically, with a series of specified nucleic acid elements that permit transcription of a particular nucleic acid in a host cell. The expression vector can be part of a plasmid, virus, or nucleic acid fragment. Typically, the expression vector includes a nucleic acid to be transcribed operably linked to a promoter.

[0042] "Exogenous gene" refers to a nucleic acid transformed into a cell. A transformed cell may be referred to as a recombinant cell, into which additional exogenous gene(s) may be introduced. The exogenous gene may be from a different species (and so heterologous), or from the same species (and so homologous) relative to the cell being transformed. In the case of a homologous gene, it occupies a different location in the genome of the cell relative to the endogenous copy of the gene. The exogenous gene may be present in more than one copy in the cell. The exogenous gene may be maintained in a cell as an insertion into the genome or as an episomal molecule.

[0043] "Exogenously provided" describes a molecule provided to the culture media of a cell culture.

[0044] "Fixed carbon source" means molecule(s) containing carbon, e.g. organic, that are present at ambient temperature and pressure in solid or liquid form.

[0045] "Homogenate" means biomass that has been physically disrupted.

[0046] As used herein, "hydrocarbon" refers to: (a) a molecule containing only hydrogen and carbon atoms wherein the carbon atoms are covalently linked to form a linear, branched, cyclic, or partially cyclic backbone to which the hydrogen atoms are attached; or (b) a molecule that only primarily contains hydrogen and carbon atoms and that can be converted to contain only hydrogen and carbon atoms by one to four chemical reactions. Nonlimiting examples of the latter include hydrocarbons containing an oxygen atom between one carbon and one hydrogen atom to form an alcohol molecule, as well as aldehydes containing a single oxygen atom. Methods for the reduction of alcohols to hydrocarbons containing only carbon and hydrogen atoms are well known. Another example of a hydrocarbon is an ester, in which an organic group replaces a hydrogen atom (or more than one) in an oxygen acid. The molecular structure of hydrocarbon compounds varies from the simplest, in the form of methane (CH_4), which is a constituent of natural gas, to the very heavy and very complex, such as some molecules such as asphaltenes found in crude oil, petroleum, and bitumens. Hydrocarbons may be in gaseous, liquid, or solid form, or any combination of these forms, and may have one or more double or triple bonds between adjacent carbon atoms in the backbone. Accordingly, the term includes linear, branched, cyclic, or partially cyclic alkanes, alkenes, lipids, and paraffin. Examples include propane, butane, pentane, hexane, octane, triolein, and squalene.

[0047] The term "hydrogen:carbon ratio" refers to the ratio of hydrogen atoms to carbon atoms in a molecule on an atom-to-atom basis. The ratio may be used to refer to the number of carbon and hydrogen atoms in a hydrocarbon molecule. For example, the hydrocarbon with the highest ratio is methane CH_4 (4:1).

[0048] "Hydrophobic fraction" refers to the portion, or fraction, of a material that is more soluble in a hydrophobic phase in comparison to an aqueous phase. A hydrophobic fraction is substantially insoluble in water and usually nonpolar.

[0049] As used herein, the phrase "increase lipid yield" refers to an increase in the productivity of a microbial culture by, for example, increasing dry weight of cells per liter of culture, increasing the percentage of cells that constitute lipid, or increasing the overall amount of lipid per liter of culture volume per unit time.

[0050] An "inducible promoter" is one that mediates transcription of an operably linked gene in response to a particular stimulus.

[0051] As used herein, the phrase "in operable linkage" refers to a functional linkage between two sequences, such a control sequence (typically a promoter) and the linked sequence. A promoter is in operable linkage with an exogenous gene if it can mediate transcription of the gene.

[0052] The term "in situ" means "in place" or "in its original position". For example, a culture may contain a first microalga secreting a catalyst and a second microorganism secreting a substrate, wherein the first and second cell types produce the components necessary for a particular chemical reaction to occur in situ in the co-culture without requiring further separation or processing of the materials.

[0053] A "limiting concentration of a nutrient" is a concentration in a culture that limits the propagation of a cultured organism. A "non-limiting concentration of a nutrient" is a concentration that supports maximal propagation during a given culture period. Thus, the number of cells produced during a given culture period is lower in the presence of a limiting concentration of a nutrient than when the nutrient is non-limiting. A nutrient is said to be "in excess" in a culture, when the nutrient is present at a concentration greater than that which supports maximal propagation.

[0054] As used herein, a "lipase" is a water-soluble enzyme that catalyzes the hydrolysis of ester bonds in water-insoluble, lipid substrates. Lipases catalyze the hydrolysis of lipids into glycerols and fatty acids.

[0055] "Lipids" are a class of hydrocarbon that are soluble in nonpolar solvents (such as ether and chloroform) and are

relatively or completely insoluble in water. Lipid molecules have these properties because they consist largely of long hydrocarbon tails which are hydrophobic in nature. Examples of lipids include fatty acids (saturated and unsaturated); glycerides or glycerolipids (such as monoglycerides, diglycerides, triglycerides or neutral fats, and phosphoglycerides or glycerophospholipids); nonglycerides (sphingolipids, sterol lipids including cholesterol and steroid hormones, prenol lipids including terpenoids, fatty alcohols, waxes, and polyketides); and complex lipid derivatives (sugar-linked lipids, or glycolipids, and protein-linked lipids). "Fats" are a subgroup of lipids called "triacylglycerides."

[0056] The term "low irradiance of light" refers to the irradiance of light that can be applied to a microorganism while avoiding significant photoinhibition under heterotrophic conditions and the irradiance of light needed to initiate a light-activated metabolism in the microorganism. Light-activated metabolisms include, but are not limited to, a life cycle, a circadian rhythm, cell division, a biosynthetic pathway, and a transport system.

[0057] As used herein, the term "lysate" refers to a solution containing the contents of lysed cells.

[0058] As used herein, the term "lysis" refers to the breakage of the plasma membrane and optionally the cell wall of a biological organism sufficient to release at least some intracellular content, often by mechanical, viral or osmotic mechanisms that compromise its integrity.

[0059] As used herein, the term "lysing" refers to disrupting the cellular membrane and optionally the cell wall of a biological organism or cell sufficient to release at least some intracellular content.

[0060] "Microalgae" means a eukaryotic microbial organism that contains a chloroplast, and optionally that is capable of performing photosynthesis, or a prokaryotic microbial organism capable of performing photosynthesis. Microalgae include obligate photoautotrophs, which cannot metabolize a fixed carbon source as energy, as well as heterotrophs, which can live solely off of a fixed carbon source. Microalgae can refer to unicellular organisms that separate from sister cells shortly after cell division, such as *Chlamydomonas*, and can also refer to microbes such as, for example, Volvox, which is a simple multicellular photosynthetic microbe of two distinct cell types. "Microalgae" can also refer to cells such as *Chlorella* and *Dunaliella*. "Microalgae" also includes other microbial photosynthetic organisms that exhibit cell-cell adhesion, such as *Agmenellum, Anabaena*, and *Pyrobotrys*. "Microalgae" also includes obligate heterotrophic microorganisms that have lost the ability to perform photosynthesis, such as certain dinoflagellate algae species. Other examples of microalgae are described below.

[0061] The terms "microorganism" and "microbe" are used interchangeably herein to refer to microscopic unicellular organisms, e.g., microalgae.

[0062] As used herein, the term "osmotic shock" refers to the rupture of cells in a solution following a sudden reduction in osmotic pressure. Osmotic shock is sometimes induced to release cellular components of such cells into a solution.

[0063] "Polysaccharides" (also called "glycans") are carbohydrates made up of monosaccharides joined together by glycosidic linkages. Cellulose is an example of a polysaccharide that makes up certain plant cell walls. Cellulose can be depolymerized by enzymes to yield monosaccharides such as xylose and glucose, as well as larger disaccharides and oligosaccharides.

[0064] "Port", in the context of a bioreactor, refers to an opening in the bioreactor that allows influx or efflux of materials such as gases, liquids, and cells. Ports are usually connected to tubing leading from the bioreactor.

[0065] A "promoter" is defined as an array of nucleic acid control sequences that direct transcription of a nucleic acid. As used herein, a promoter includes necessary nucleic acid sequences near the start site of transcription, such as, in the case of a polymerase II type promoter, a TATA element. A promoter also optionally includes distal enhancer or repressor elements, which can be located as much as several thousand base pairs from the start site of transcription.

[0066] As used herein, the term "recombinant" when used with reference, e.g., to a cell, or nucleic acid, protein, or vector, indicates that the cell, nucleic acid, protein or vector, has been modified by the introduction of an exogenous nucleic acid or protein or the alteration of a native nucleic acid or protein, or that the cell is derived from a cell so modified. Thus, e.g., recombinant cells express genes that are not found within the native (non-recombinant) form of the cell or express native genes that are otherwise abnormally expressed, under expressed or not expressed at all. By the term "recombinant nucleic acid" herein is meant nucleic acid, originally formed in vitro, in general, by the manipulation of nucleic acid, e.g., using polymerases and endonucleases, in a form not normally found in nature. In this manner, operably linkage of different sequences is achieved. Thus an isolated nucleic acid, in a linear form, or an expression vector formed in vitro by ligating DNA molecules that are not normally joined, are both considered recombinant for the purposes of this invention. It is understood that once a recombinant nucleic acid is made and reintroduced into a host cell or organism, it will replicate non-recombinantly, i.e., using the in vivo cellular machinery of the host cell rather than in vitro manipulations; however, such nucleic acids, once produced recombinantly, although subsequently replicated non-recombinantly, are still considered recombinant for the purposes of the invention. Similarly, a "recombinant protein" is a protein made using recombinant techniques, i.e., through the expression of a recombinant nucleic acid as depicted above.

[0067] As used herein, the term "renewable diesel" refers to alkanes (such as C:10:0, C12:0, C:14:0, C16:0 and C18:0) produced through hydrogenation and deoxygenation of lipids.

[0068] As used herein, the term "sonication" refers to a process of disrupting biological materials, such as a cell, by use of sound wave energy.

[0069] "Species of furfural" refers to 2-Furancarboxaldehyde or a derivative thereof which retains the same basic structural characteristics.

[0070] As used herein, "stover" refers to the dried stalks and leaves of a crop remaining after a grain has been harvested.

[0071] "Wastewater" is watery waste which typically contains washing water, laundry waste, feces, urine and other liquid or semi-liquid wastes. It includes some forms of municipal waste as well as secondarily treated sewage.

[0072] It must be noted that, as used in the specification and the appended claims, the singular forms "a," "an" and "the" include plural referents unless the context clearly dictates otherwise.

[0073] Microorganisms

[0074] Any species of organism that produces suitable lipid or hydrocarbon can be used, although microorganisms that

naturally produce high levels of suitable lipid or hydrocarbon are preferred. Production of hydrocarbons by microorganisms is reviewed by Metzger et al. Appl Microbiol Biotechnol (2005) 66: 486-496 and A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae, NREL/TP-580-24190, John Sheehan, Terri Dunahay, John Benemann and Paul Roessler (1998).

[0075] Considerations affecting the selection of microorganisms for use in the invention include, in addition to production of suitable lipids or hydrocarbons for production of oils, fuels, and oleochemicals, include: (1) high lipid content as a percentage of cell weight; (2) ease of growth; (3) ease of genetic engineering; and (4) ease of biomass processing. In particular embodiments, the wild-type or genetically engineered microorganism yields cells that are at least 40%, at least 45%, at least 50%, at least 55%, at least 60%, at least 65%, or at least 70% or more lipid. Preferred organisms grow heterotrophically or can be engineered to do so using, for example, methods disclosed herein. The ease of transformation and availability of selectable markers and promoters, constitutive and/or inducible, that are functional in the microorganism affect the ease of genetic engineering. Processing considerations can include, for example, the availability of effective means for lysing the cells.

[0076] In one embodiment, microorganisms include natural or engineered microorganisms that can grow under heterotrophic condition and use light as signal to control cellular processes. These can include alga such as *Cyanophyta, Chlorophyta, Rhodophyta, Cryptophyta, Chlorarachniophyta, Haptophyta, Euglenophyta, Heterokontophyta,* and *Diatoms.*

[0077] Algae

[0078] In one embodiment of the present invention, the microorganism is a microalgae. Nonlimiting examples of microalgae that can be used in accordance with the present invention are described below.

[0079] More specifically, algal taxa belonging to the Cyanophyta, including Cyanophyceae, are those being Prokaryotae, which have the ability of oxygen evolution-type photosynthesis and are classified into the following orders and families. Chroococcales include Microcystaceae, Chroococcaceae, Entophysalidaceae, Chamaesiphoniaceae, Dermocarpellaceae, Xenococcaceae, and Hydrococcaceae, Oscillatoriales includes Borziaceae, Pseudanabaenaceae, Schizotrichaceae, Phormidiaceae, Oscillatoriaceae, and Homoeotrichaceae, Nostocales includes Scytonemataceae, Microchaetaceae, Rivulariaceae, and Nostocaceae, and Stigonematales includes Chlorogloeopsaceae, Capsosiraceae, Stigonemataceae, Fischerellaceae Borzinemataceae, Nostochopsaceae, and Mastigocladaceae.

[0080] Chlorophyta include Chlorophyceae, Prasinophyceae, Pedinophyceae, Trebouxiophyceae, and Ulvophyceae. More specifically, Chlorophyceae includes *Acetabularia, Acicularia, Actinochloris, Amphikrikos, Anadyomene, Ankistrodesmus, Ankyra, Aphanochaete, Ascochloris, Asterococcus, Asteromonas, Astrephomene, Atractomorpha, Axilococcus, Axilosphaera, Basichlamys, Basicladia, Binuclearia, Bipedinomonas, Blastophysa, Boergesenia, Boodlea, Borodinella, Borodinellopsis, Botryococcus, Brachiomonas, Bracteacoccus, Bulbochaete, Caespitella, Capsosiphon, Carteria, Centrosphaera, Chaetomorpha, Chaetonema, Chaetopeltis, Chaetophora, Chalmasia, Chamaetrichon, Characiochloris, Characiosiphon, Characium, Chlamydella, Chlamydobotrys, Chlamydocapsa, Chlamydomonas, Chlamydopodium, Chloranomala, Chlorochydridion, Chlorochytrium, Chlorocladus, Chlorocloster, Chlorococcopsis, Chlorococcum, Chlorogonium, Chloromonas, Chlorophysalis, Chlorosarcina, Chlorosarcinopsis, Chlorosphaera, Chlorosphaeropsis, Chlorotetraedron, Chlorothecium, Chodatella, Choricystis, Cladophora, Cladophoropsis, Cloniophora, Closteriopsis, Coccobotrys, Coelastrella, Coelastropsis, Coelastrum, Coenochloris, Coleochlamys, Coronastrum, Crucigenia, Crucigeniella, Ctenocladus, Cylindrocapsa, Cylindrocapsopsis, Cylindrocystis, Cymopolia, Cystococcus, Cystomonas, Dactylococcus, Dasycladus, Deasonia, Derbesia, Desmatractum, Desmodesmus, Desmotetra, Diacanthos, Dicellula, Dicloster, Dicranochaete, Dictyochloris, Dictyococcus, Dictyosphaeria, Dictyosphaerium, Didymocystis, Didymogenes, Dilabifilum, Dimorphococcus, Diplosphaera, Draparnaldia, Dunaliella, Dysmorphococcus, Echinocoleum, Elakatothrix, Enallax, Entocladia, Entransia, Eremosphaera, Ettlia, Eudorina, Fasciculochloris, Fernandinella, Follicularia, Fottea, Franceia, Friedmannia, Fritschiella, Fusola, Geminella, Gloeococcus, Gloeocystis, Gloeodendron, Gloeomonas, Gloeotila, Golenkinia, Gongrosira, Gonium, Graesiella, Granulocystis, Gyorffiana, Haematococcus, Hazenia, Helicodictyon, Hemichloris, Heterochlamydomonas, Heteromastix, Heterotetracystis, Hormidiospora, Hormidium, Hormotila, Hormotilopsis, Hyalococcus, Hyalodiscus, Hyalogonium, Hyaloraphidium, Hydrodictyon, Hypnomonas, Ignatius, Interfilum, Kentrosphaera, Keratococcus, Kermatia, Kirchneriella, Koliella, Lagerheimia, Lautosphaeria, Leptosiropsis, Lobocystis, Lobomonas, Lola, Macrochloris, Marvania, Micractinium, Microdictyon, Microspora, Monoraphidium, Muriella, Mychonastes, Nanochlorum, Nautococcus, Neglectella, Neochloris, Neodesmus, Neomeris, Neospongiococcum, Nephrochlamys, Nephrocytium, Nephrodiella, Oedocladium, Oedogonium, Oocystella, Oocystis, Oonephris, Ourococcus, Pachycladella, Palmella, Palmellococcus, Palmellopsis, Palmodictyon, Pandorina, Paradoxia, Parietochloris, Pascherina, Paulschulzia, Pectodictyon, Pediastrum, Pedinomonas, Pedinopera, Percursaria, Phacotus, Phaeophila, Physocytium, Pilina, Planctonema, Planktosphaeria, Platydorina, Platymonas, Pleodorina, Pleurastrum, Pleurococcus, Ploeotila, Polyedriopsis, Polyphysa, Polytoma, Polytomella, Prasinocladus, Prasiococcus, Protoderma, Protosiphon, Pseudendocloniopsis, Pseudocharacium, Pseudochlorella, Pseudochlorococcum, Pseudococcomyxa, Pseudodictyosphaerium, Pseudodidymocystis, Pseudokirchneriella, Pseudopleurococcus, Pseudoschizomeris, Pseudoschroederia, Pseudostichococcus, Pseudotetracystis, Pseudotetradron, Pseudotrebouxia, Pteromonas, Pulchrasphaera, Pyramimonas, Pyrobotrys, Quadrigula, Radiofilum, Radiosphaera, Raphidocelis, Raphidonema, Raphidonemopsis, Rhizoclonium, Rhopalosolen, Saprochaete, Scenedesmus, Schizochlamys, Schizomeris, Schroederia, Schroederiella, Scotiellopsis, Siderocystopsis, Siphonocladus, Sirogonium, Sorastrum, Spermatozopsis, Sphaerella, Sphaerellocystis, Sphaerellopsis, Sphaerocystis, Sphaeroplea, Spirotaenia, Spongiochloris, Spongiococcum, Stephanoptera, Stephanosphaera, Stigeoclonium, Struvea, Tetmemorus, Tetrabaena, Tetracystis, Tetradesmus, Tetraedron, Tetrallantos, Tetraselmis, Tetraspora, Tetrastrum, Treubaria, Triploceros, Trochiscia, Trochisciopsis, Ulva, Uronema, Valonia, Valoniopsis, Ventricaria, Viridiella, Vitreochlamys, Volvox, Volvulina, Westella, Willea, Wislouchiella, Zoochlorella, Zygnemopsis, Hyalotheca, Chlorella,*

Pseudopleurococcum and *Rhopalocystis*. Prasinophyceae includes *Heteromastix, Mammella, Mantoniella, Micromonas, Nephroselmis, Ostreococcus, Prasinocladus, Prasinococcus, Pseudoscourfielda, Pycnococcus, Pyramimonas, Scherffelia. Pedinophyceae includes Marsupiomonas, Pedinomonas, Resultor. Trebouxiophyceae includes Apatococcus, Asterochloris, Auxenochlorella, Chlorella, Coccomyxa, Desmococcus, Dictyochloropsis, Elliptochloris, Jaagiella, Leptosira, Lobococcus, Makinoella, Microthamnion, Myrmecia, Nannochloris, Oocystis, Prasiola, Prasiolopsis, Prototheca, Stichococcus, Tetrachlorella, Trebouxia, Trichophilus, Watanabea* and *Myrmecia*. Ulvophyceae includes *Acrochaete, Bryopsis, Cephaleuros, Chlorocystis, Enteromorpha, Gloeotilopsis, Halochlorococcum, Ostreobium, Pirula, Pithophora, Planophila, Pseudendoclonium, Trentepohlia, Trichosarcina, Ulothrix, Bolbocoleon, Chaetosiphon, Eugomontia, Oltmannsiellopsis, Pringsheimiella, Pseudodendroclonium, Pseudulvella, Sporocladopsis, Urospora*, and *Wittrockiella.*

[0081] Rhodophyta include *Acrochaetium, Agardhiella, Antithamnion, Antithamnionella, Asterocytis, Audouinella, Balbiania, Bangia, Batrachospermum, Bonnemaisonia, Bostrychia, Callithamnion, Caloglossa, Ceramium, Champia, Chroodactylon, Chroothece, Compsopogon, Compsopogonopsis, Cumagloia, Cyanidium, Cystoclonium, Dasya, Digenia, Dixoniella, Erythrocladia, Erythrolobas, Erythrotrichia, Flintiella, Galdieria, Gelidium, Glaucosphaera, Goniotrichum, Gracilaria, Grateloupia, Griffithsia, Hildenbrandia, Hymenocladiopsis, Hypnea, Laingia, Membranoptera, Myriogramme, Nemalion, Nemnalionopsis, Neoagardhiella, Palmaria, Phyllophora, Polyneura, Polysiphonia, Porphyra, Porphyridium, Pseudochantransia, Pterocladia, Pugetia, Rhodella, Rhodochaete, Rhodochorton, Rhodosorus, Rhodospora, Rhodymenia, Seirospora, Selenastrum, Sirodotia, Solieria, Spermothamnion, Spyridia, Stylonema, Thorea, Trailiella* and *Tuomeya.*

[0082] Cryptophyta include Cryptophycease. More specifically, *Campylomonas, Chilomonas, Chroomonas, Cryptochrysis, Cryptomonas, Goniomonas, Guillardia, Hanusia, Hemiselmis, Plagioselmis, Proteomonas, Pyrenomonas, Rhodomonas* and *Stroreatula.*

[0083] Chlorarachniophyta include *Chlorarachnion, Lotharella* and *Chattonella.*

[0084] Haptophyta include *Apistonema, Chrysochromulina, Coccolithophora, Corcontochrysis, Cricosphaera, Diacronema, Emiliana, Pavlova, Ruttnera, Cruciplacolithus, Prymnesium, Isochrysis, Calyptrosphaera, Chrysotila, Coccolithus, Dicrateria, Heterosigma, Hymenomonas, Imantonia, Gephyrocapsa, Ochrosphaera, Phaeocystis, Platychrysis, Pseudoisochrysis, Syracosphaera* and *Pleurochrysis.*

[0085] Euglenophyta include *stasia, Colacium, Cyclidiopsis, Distigma, Euglena, Eutreptia, Eutreptiella, Gyropaigne, Hyalophacus, Khawkinea Astasia, Lepocinclis, Menoidium, Pamidium, Phacus, Rhabdomonas, Rhabdospira, Tetruetreptia* and *Trachelomonas*

[0086] Heterokontophyta include Bacillariophyceae, Phaeophyceae, Pelagophyceae, Xanthophyceae, Eustigmatophyceae, Syanurophyceae, Phaeothamniophyceae and Raphidophyceae. More specifically, Bacillariophyceae includes *Achnanthes, Amphora, Chaetoceros, Bacillaria, Nitzschia, Navicula*, and *Pinnularia*. Phaeophyceae includes *Ascoseira, Asterocladon, Bodanella, Desmarestia, Dictyocha, Dictyota, Ectocarpus, Halopteris, Heribaudiella, Pleurocladia, Porterinema, Pylaiella, Sorocarpus, Spermatochnus, Sphacelaria* and *Waerniella*. Pelagophyceae includes *Aureococcus, Aureoumbra, Pelagococcus, Pelagomonas, Pulvinaria* and *Sarcinochrysis*. Xanthophyceae includes *Chloramoebales, Rhizochloridales, Mischococcales, Tribonematales*, and *Vaucheriales.* Eustigmatophyceae includes *Chloridella, Ellipsoidion, Eustigmatos, Monodopsis, Monodus, Nannochloropsis, Polyedriella, Pseudocharaciopsis, Pseudostaurastrum* and *Vischeria* Syanurophyceae includes *allomonas, Synura* and *Tessellaria*. Phaeothamniophyceae includes *haeobotrys* and *Phaeothamnion*. Raphidophyceae includes *Olisthodiscus, Vacuolaria* and *Fibrocapsa.*

[0087] Diatoms include Bolidophyceae, Coscinodiscophyceae, Dinophyceae and Alveolates. Bolidophyceae include *Bolidomonas, Chrysophyceae, Giraudyopsis, Glossomastix, Chromophyton, Chrysamoeba, Chrysochaete, Chrysodidymus, Chrysolepidomonas, Chrysosaccus, Chrysosphaera, Chrysoxys, Cyclonexis, Dinobryon, Epichrysis, Epipyxis, Hibberdia, Lagynion, Lepochromulina, Monas, Monochrysis, Paraphysomonas, Phaeoplaca, Phaeoschizochlamys, Picophagus, Pleurochrysis, Stichogloea* and *Uroglena*. Coscinodiscophyceae include *Bacteriastrum, Bellerochea, Biddulphia, Brockmanniella, Corethron, Coscinodiscus, Eucampia, Extubocellulus, Guinardia, Helicotheca, Leptocylindrus, Leyanella, Lithodesmium, Melosira, Minidiscus, Odontella, Planktoniella, Porosira, Proboscia, Rhizosolenia, Stellarima, Thalassionema, Bicosoecid, Symbiomonas, Actinocyclus, Amphora, Arcocellulus, Detonula, Diatoma, Ditylum, Fragilariophyceae, Asterionellopsis, Delphineis, Grammatophora, Nanofrustulum, Synedra* and *Tabularia*. Dinophyceae includes *Adenoides, Alexandrium, Amphidinium, Ceratium, Ceratocorys, Coolia, Crypthecodinium, Exuviaella, Gambierdiscus, Gonyaulax, Gymnodinium, Gyrodinium, Heterocapsa, Katodinium, Lingulodinium, Pfiesteria, Polarella, Protoceratium, Pyrocystis, Scrippsiella, Symbiodinium, Thecadinium, Thoracosphaera*, and *Zooxanthella*. Alveolates include *Cystodinium, Glenodinium, Oxyrrhis, Peridinium, Prorocentrum*, and *Woloszynskia.*

[0088] Methods of Culturing Microorganisms and Bioreactors

[0089] Microorganisms are generally cultured both for purposes of conducting genetic manipulations and for subsequent production of hydrocarbons (e.g., lipids, fatty acids, aldehydes, alcohols, and alkanes). The former type of culture is generally conducted on a small scale and initially, at least, under conditions in which the starting microorganism can grow. Culture for purposes of hydrocarbon production is usually conducted on a large scale. Preferably a fixed carbon source (e.g. a feedstock) is present. The culture can also be exposed to light some or all of the time.

[0090] Bioreactor

[0091] Microalgae can be cultured in liquid media. The culture can be contained within a bioreactor. Microalgae can also be cultured in photobioreactors that contain a fixed carbon source and allow light to strike the cells. Exposure of microalgae cells to light, even in the presence of a fixed carbon source that the cells transport and utilize, can accelerate growth compared to culturing cells in the dark. Culture condition parameters can be manipulated to optimize total hydrocarbon production, the combination of hydrocarbon species produced, and/or production of a hydrocarbon species.

[0092] FIG. **1** is one embodiment of a bioreactor of the invention. In one aspect a bioreactor is a photobioreactor. In

one aspect, a bioreactor system can be used for cultivating microalgae. The bioreactor system can include a container and an irradiation assembly, where the irradiation assembly is operatively coupled to the container.

[0093] In one aspect, a bioreactor is a fermentation tank used for industrial fermentation processes.

[0094] In some embodiments, a bioreactor includes glass, metal or plastic tanks, equipped with, e.g., gauges and settings to control aeration, stir rate, temperature, pH, and other parameters of interest. Generally the gauges and settings are operatively coupled to the bioreactor.

[0095] In one aspect, a bioreactor can be small enough for bench-top applications (5-10 L or less) or up to 120,000 L or larger in capacity for large-scale industrial applications.

[0096] In some embodiments, the bioreactor system can include a light-diffusing structure or a plurality of light-diffusing structures. In some embodiments, one or more of the light-diffusing structures from the plurality of light-diffusing structures are located along the interior surface of the bioreactor. In some embodiments, the light-diffusing structure is operatively coupled to the bioreactor.

[0097] The bioreactor system can include one or more optical fibers and/or a plurality of light sources and/or a light source. In some embodiments, the one or more optical fibres are mounted in protective and optically transparent lighting structures. In some embodiments, the optical fiber is operatively coupled to the bioreactor. In some embodiments, the light source is operatively coupled to the bioreactor.

[0098] In some embodiments, the bioreactor system can include a lighting structure operatively coupled to a bioreactor. In certain embodiments herein a lighting structure can have any shape or form as it directs light signal to the interior of a bioreactor. The bioreactor system may also include at least one optical fiber extending from a first end of at least one of the one or more optical fibers to a portion of a solar energy collector. In some embodiments, the solar energy collector is operatively coupled to the bioreactor. The optical fiber can be adapted to optically couple the solar energy collector to the bioreactor. The optical fiber may be optically coupled (directly or indirectly) to the solar energy collector.

[0099] In some embodiments, the bioreactor system includes a plurality of light sources operatively coupled to the bioreactor. The plurality of light sources can include multiple LEDs. The plurality of light sources comprising multiple LEDs can be operable to supply full spectrum or a specific wavelength of artificial light to a bioreactor.

[0100] In one embodiment, an LED is mounted in protective and optically transparent lighting structures. In one embodiment the LED is an array of LEDs.

[0101] In some embodiments, microalgae can be grown and maintained in closed bioreactors made of different types of transparent or semitransparent material. Such material can include Plexiglass™ enclosures, glass enclosures, bags made from substances such as polyethylene, transparent or semi-transparent pipes, and other materials. Microalgae can be grown and maintained in open bioreactors such as raceway ponds, settling ponds, and other non-enclosed containers.

[0102] The gas content of a bioreactor to grow microorganisms like microalgae can be manipulated. Part of the volume of a bioreactor can contain gas rather than liquid. Gas inlets can be used to pump gases into the bioreactor. Any gas can be pumped into a bioreactor, including air, air/O_2 mixtures, noble gases such as argon and others. The rate of entry of gas into a bioreactor can also be manipulated. Increasing gas flow into a bioreactor increases the turbidity of a culture of microalgae. Placement of ports conveying gases into a bioreactor can also affect the turbidity of a culture at a given gas flow rate. Air/O_2 mixtures can be modulated to generate optimal amounts of O_2 for maximal growth by a particular organism. Microalgae grow significantly faster in the light under, for example, 3% O_2/97% air than in 100% air. 3% O_2/97% air is approximately 100-fold more O_2 than found in air. For example, air:O_2 mixtures of about 99.75% air:0.25% O_2, about 99.5% air:0.5% O_2, about 99.0% air:1.00% O_2, about 98.0% air:2.0% O_2, about 97.0% air:3.0% O_2, about 96.0% air:4.0% O_2, and about 95.00% air:5.0% O_2 can be infused into a bioreactor or bioreactor.

[0103] Microalgae cultures can also be subjected to mixing using devices such as spinning blades and impellers, rocking of a culture, stir bars, infusion of pressurized gas, and other instruments.

[0104] Bioreactors can have ports allowing entry of gases, solids, semisolids and liquids into the chamber containing the microalgae. Ports are usually attached to tubing or other means of conveying substances. Gas ports, for example, convey gases into the culture. Pumping gases into a bioreactor can serve to both feed cells O_2 and other gases and to aerate the culture and therefore generate turbidity. The amount of turbidity of a culture varies as the number and position of gas ports is altered. For example, gas ports can be placed along the bottom of a cylindrical polyethylene bag. Microalgae grow faster when O_2 is added to air and bubbled into a bioreactor.

[0105] Bioreactors preferably have one or more ports that allow media entry. It is not necessary that only one substance enter or leave a port. For example, a port can be used to flow culture media into the bioreactor and then later can be used for sampling, gas entry, gas exit, or other purposes. In some instances a bioreactor is filled with culture media at the beginning of a culture and no more growth media is infused after the culture is inoculated. In other words, the microalgal biomass is cultured in an aqueous medium for a period of time during which the microalgae reproduce and increase in number; however quantities of aqueous culture medium are not flowed through the bioreactor throughout the time period. Thus in some embodiments, aqueous culture medium is not flowed through the bioreactor after inoculation.

[0106] In other instances culture media can be flowed though the bioreactor throughout the time period during which the microalgae reproduce and increase in number. In some embodiments media is infused into the bioreactor after inoculation but before the cells reach a desired density. In other words, a turbulent flow regime of gas entry and media entry is not maintained for reproduction of microalgae until a desired increase in number of said microalgae has been achieved.

[0107] Bioreactors preferably have one or more ports that allow gas entry. Gas can serve to both provide nutrients such as O_2 as well as to provide turbulence in the culture media. Turbulence can be achieved by placing a gas entry port below the level of the aqueous culture media so that gas entering the bioreactor bubbles to the surface of the culture. One or more gas exit ports allow gas to escape, thereby preventing pressure buildup in the bioreactor. Preferably a gas exit port leads to a "one-way" valve that prevents contaminating microorganisms from entering the bioreactor. In some instances cells are cultured in a bioreactor for a period of time during which the microalgae reproduce and increase in number, however a turbulent flow regime with turbulent eddies predominantly

throughout the culture media caused by gas entry is not maintained for all of the period of time. In other instances a turbulent flow regime with turbulent eddies predominantly throughout the culture media caused by gas entry can be maintained for all of the period of time during which the microalgae reproduce and increase in number. In some instances a predetermined range of ratios between the scale of the bioreactor and the scale of eddies is not maintained for the period of time during which the microalgae reproduce and increase in number. In other instances such a range can be maintained.

[0108] Bioreactors preferably have at least one port that can be used for sampling the culture. Preferably a sampling port can be used repeatedly without altering compromising the axenic nature of the culture. A sampling port can be configured with a valve or other device that allows the flow of sample to be stopped and started. Alternatively a sampling port can allow continuous sampling. Bioreactors preferably have at least one port that allows inoculation of a culture. Such a port can also be used for other purposes such as media or gas entry.

[0109] In one embodiment, a bioreactor with an irradiation system can be used to produce hydrocarbon from Botryococcus. Botryococcenes are unbranched isoprenoid triterpenes having the formula C_nH_{2n-10}. The A race produces alkadienes and alkatrienes (derivatives of fatty acids) wherein n is an odd number 23 through 31. The B race produces botryococcenes wherein n is in the range 30 through 40. These can be biofuels of choice for hydrocracking to gasoline-type hydrocarbons.

[0110] Media

[0111] Microalgal culture media typically contains components such as a fixed nitrogen source, trace elements, optionally a buffer for pH maintenance, and phosphate. Other components can include a fixed carbon source such as acetate or glucose, and salts such as sodium chloride, particularly for seawater microalgae. Examples of trace elements include zinc, boron, cobalt, copper, manganese, and molybdenum in, for example, the respective forms of $ZnCl_2$, H_3BO_3, $CoCl_2.6H_2O$, $CuCl_2.2H_2O$, $MnCl_2.4H_2O$ and $(NH_4)_6Mo_7O_24.4H_2O$.

[0112] For organisms able to grow on a fixed carbon source, the fixed carbon source can be, for example, glucose, fructose, sucrose, galactose, xylose, mannose, rhamnose, N-acetylglucosamine, glycerol, floridoside, and/or glucuronic acid. The one or more carbon source(s) can be supplied at a concentration of less than 50 μM, at least about 50 μM, at least about 100 μM, at least about 500 μM, at least about 5 mM, at least about 50 mM, at least about 500 mM, and more than 500 mM of one or more exogenously provided fixed carbon source(s). The one or more carbon source(s) can be supplied at a less than 1%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, 10%, 11%, 12%, 13%, 14%, 15%, 16%, 17%, 18%, 19%, 20%, 21%, 22%, 23%, 24%, 25%, 26%, 27%, 28%, 29%, 30%, 31%, 32%, 33%, 34%, 35%, 36%, 37%, 38%, 39%, 40%, 41%, 42%, 43%, 44%, 45%, 46%, 47%, 48%, 49%, 50%, 51%, 52%, 53%, 54%, 55%, 56%, 57%, 58%, 59%, 60%, 61%, 62%, 63%, 64%, 65%, 66%, 67%, 68%, 69%, 70%, 71%, 72%, 73%, 74%, 75%, 76%, 77%, 78%, 79%, 80%, 81%, 82%, 83%, 84%, 85%, 86%, 87%, 88%, 89%, 90%, 91%, 92%, 93%, 94%, 95%, 96%, 97%, 98%, 99%, or 100% of the media. The one or more carbon source(s) can also be supplied at a percentage of the media between the above noted percentages, e.g., 2.5% or 3.7% of the media.

[0113] Some microorganisms naturally grow on or can be engineered to grow on a fixed carbon source that is a heterogeneous source of compounds such as municipal waste, secondarily treated sewage, wastewater, and other sources of fixed carbon and other nutrients such as sulfates, phosphates, and nitrates. The sewage component serves as a nutrient source in the production of hydrocarbons, and the culture provides an inexpensive source of hydrocarbons.

[0114] Other culture parameters can also be manipulated, such as the pH of the culture media, the identity and concentration of trace elements and other media constituents.

[0115] Microorganisms useful in accordance with the methods of the present invention are found in various locations and environments throughout the world. As a consequence of their isolation from other species and their resulting evolutionary divergence, the particular growth medium for optimal growth and generation of lipid and/or hydrocarbon constituents can vary. In some cases, certain strains of microorganisms may be unable to grow on a particular growth medium because of the presence of some inhibitory component or the absence of some essential nutritional requirement required by the particular strain of microorganism.

[0116] Solid and liquid growth media are generally available from a wide variety of sources, and instructions for the preparation of particular media that is suitable for a wide variety of strains of microorganisms can be found, for example, online at a site maintained by the University of Texas at Austin for its culture collection of algae (UTEX).

[0117] Process conditions can be adjusted to increase the yield of lipids suitable for a particular use and/or to reduce production cost. For example, in certain embodiments, a microbe (e.g., microalgae) is cultured in the presence of a limiting concentration of one or more nutrients, such as, for example, carbon and/or nitrogen, phosphorous, or sulfur, while providing an excess of fixed carbon energy such as glucose. Nitrogen limitation tends to increase microbial lipid yield over microbial lipid yield in a culture in which nitrogen is provided in excess. In particular embodiments, the increase in lipid yield is at least about: 10%, 20%, 30%, 40%, 50%, 75%, 100%, 200%, 300%, 400%, or 500%. The microbe can be cultured in the presence of a limiting amount of a nutrient for a portion of the total culture period or for the entire period. In particular embodiments, the nutrient concentration is cycled between a limiting concentration and a non-limiting concentration at least twice during the total culture period.

[0118] Heterotrophic Growth and Light

[0119] Microorganisms can be cultured under heterotrophic growth conditions in which a fixed carbon source provides energy for growth and lipid accumulation.

[0120] Standard methods for the heterotrophic growth and propagation of microalgae are known (see for example Miao and Wu, J Biotechnology, 2004, 11:85-93 and Miao and Wu, Biosource Technology (2006) 97:841-846).

[0121] For hydrocarbon production, cells, including recombinant cells of the invention described herein, can be cultured or fermented in large quantities. The culturing may be in large liquid volumes, such as in suspension cultures as an example. Other examples include starting with a small culture of cells which expand into a large biomass in combination with cell growth and propagation as well as hydrocarbon production. Bioreactors or steel fermentors can be used to accommodate large culture volumes. A bioreactor can include a fermentor. A fermentor similar those used in the

production of beer and/or wine can be suitable, as are extremely large fermentors used in the production of ethanol.

[0122] Appropriate nutrient sources for culture in a fermentor are provided. These include raw materials such as one or more of the following: a fixed carbon source such as glucose, corn starch, depolymerized cellulosic material, sucrose, sugar cane, sugar beet, lactose, milk whey, or molasses; a fat source, such as fats or vegetable oils; a nitrogen source, such as protein, soybean meal, cornsteep liquor, ammonia (pure or in salt form), nitrate or nitrate salt, or molecular nitrogen; and a phosphorus source, such as phosphate salts. Additionally, a fermentor allows for the control of culture conditions such as temperature, pH, oxygen tension, and carbon dioxide levels. Optionally, gaseous components, like oxygen or nitrogen, can be bubbled through a liquid culture. Other Starch (glucose) sources such as wheat, potato, rice, and sorghum. Other carbon sources include process streams such as technical grade glycerol, black liquor, organic acids such as acetate, and molasses. Carbon sources can also be provided as a mixture, such as a mixture of sucrose and depolymerized sugar beet pulp.

[0123] A fermentor can be used to allow cells to undergo the various phases of their growth cycle. As an example, an inoculum of hydrocarbon-producing cells can be introduced into a medium followed by a lag period (lag phase) before the cells begin growth. Following the lag period, the growth rate increases steadily and enters the log, or exponential, phase. The exponential phase is in turn followed by a slowing of growth due to decreases in nutrients and/or increases in toxic substances. After this slowing, growth stops, and the cells enter a stationary phase or steady state, depending on the particular environment provided to the cells.

[0124] Hydrocarbon production by cells disclosed herein can occur during the log phase or thereafter, including the stationary phase wherein nutrients are supplied, or still available, to allow the continuation of hydrocarbon production in the absence of cell division.

[0125] Preferably, microorganisms grown using conditions described herein and known in the art comprise at least about 20% by weight of lipid, preferably at least about 40% by weight, more preferably at least about 50% by weight, and most preferably at least about 60% by weight.

[0126] In an alternate heterotrophic growth method in accordance with the present invention, microorganisms can be cultured using depolymerized cellulosic biomass as a feedstock. Cellulosic biomass (e.g., stover, such as corn stover) is inexpensive and readily available; however, attempts to use this material as a feedstock for yeast have failed. In particular, such feedstock has been found to be inhibitory to yeast growth, and yeast cannot use the 5-carbon sugars produced from cellulosic materials (e.g., xylose from hemi-cellulose). By contrast, microalgae can grow on processed cellulosic material. Accordingly, the invention provides a method of culturing microalgae in the presence of a cellulosic material and/or a 5-carbon sugar.

[0127] Suitable cellulosic materials include residues from herbaceous and woody energy crops, as well as agricultural crops, i.e., the plant parts, primarily stalks and leaves, not removed from the fields with the primary food or fiber product. Examples include agricultural wastes such as sugarcane bagasse, rice hulls, corn fiber (including stalks, leaves, husks, and cobs), wheat straw, rice straw, sugar beet pulp, citrus pulp, citrus peels; forestry wastes such as hardwood and softwood thinnings, and hardwood and softwood residues from timber operations; wood wastes such as saw mill wastes (wood chips, sawdust) and pulp mill waste; urban wastes such as paper fractions of municipal solid waste, urban wood waste and urban green waste such as municipal grass clippings; and wood construction waste. Additional cellulosics include dedicated cellulosic crops such as switchgrass, hybrid poplar wood, and miscanthus, fiber cane, and fiber sorghum. Five-carbon sugars that are produced from such materials include xylose.

[0128] In still another alternative heterotrophic growth method in accordance with the present invention, which itself may optionally be used in combination with the methods described above, sucrose, produced by example from sugar cane or sugar beet, is used as a feedstock.

[0129] Heterotrophic growth can include the use of both light and fixed carbon source(s) for cells to grow and produce hydrocarbons. Heterotrophic growth can be conducted in a photobioreactor.

[0130] Bioreactors can be exposed to one or more light sources to provide microalgae with a light signal. A light signal can be provided via light directed to a surface of the bioreactor by a light source. Preferably the light source provides an intensity that is sufficient for the cells to grow, but not so intense as to cause oxidative damage or cause a photoinhibitive response. In some instances a light source has a wavelength range that mimics or approximately mimics the range of the sun. In other instances a different wavelength range is used. Bioreactors can be placed outdoors or in a greenhouse or other facility that allows sunlight to strike the surface. In some embodiments, photon intensities for species of the genus *Botryococcus* are between 25 and 500 μmE $m^{-2}s^{-1}$ (see for example Photosynth Res. 2005 June; 84(1-3): 21-7).

[0131] The number of photons striking a culture of microalgae cells can be manipulated, as well as other parameters such as the wavelength spectrum and ratio of dark:light hours per day. Microalgae can also be cultured in natural light, as well as simultaneous and/or alternating combinations of natural light and artificial light. For example, microalgae can be cultured under natural light during daylight hours and under artificial light during night hours.

[0132] In one aspect of the invention, a microorganism is exposed to about 0.1% to about 1% of light irradiance required for photosynthesis, preferably about 0.3% to about 0.8% of light irradiance required for photosynthesis by the organism. Typical light irradiance can be between 0.1-300 μmol photons $m^{-2}s^{-1}$ including less than 0.1, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51 to 99, 100, 101 to 149, 150, 151, to 199, 200, 201 to 249, 250, or greater than 250 μmol photons $m^{-2}s^{-1}$. Light irradiance can be about 0.01-1 μmol photons m^2s^{-1}, preferably between 1-10 μmol photons $m^{-2}s^{-1}$, or between 10-100 μmol photons m^2s^{-1}, or between 100-300 μmol photons $m^{-2}s^{-1}$, or between 100-300 μmol photons m^2s^{-1}. Also included are light irradiances between the above noted light irradiances, e.g., 1.1, 2.1, 2.5, or 3.5 μmol photons m^2s^{-1}.

[0133] In one aspect, different light spectrums (e.g. 360-700 nm) can be used. Light spectrums can be less than 300, 300, 350, 400, 450, 500, 550, 600, 650, 700, or 750 nm or more. Also included are light spectrums between the above noted light spectrums, e.g., 360 or 440 nm.

[0134] In one embodiment, the irradiation can be applied in a continuous manner. In another embodiment, the irradiation can be applied in a cyclic pattern with an appropriate period of lighting including but not limited to 12 h light:12 h dark or 16 h light:8 h dark. Light patterns can include less than 1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, or 24 h of light and/or less than 1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, or 23 hours (h) of dark. Also included are light patterns between the above noted light patterns, e.g., 7.5 h of light or 7.5 h of dark.

[0135] In one embodiment, the irradiation can be natural sunlight collected by a solar collector and transmitted to the interior of a bioreactor through an optical fiber.

[0136] In another embodiment, artificial light, such as light emitted diodes (LEDs) or fluorescent light can be used as light source. In another embodiment, natural sunlight and artificial light can be used together.

[0137] In one embodiment, the irradiation is a full spectrum of light.

[0138] In another embodiment, the irradiation is a specific wavelength of light or a range of spectrum light transmitted through a specific filter.

[0139] Methods of Recovering Lipids and Hydrocarbons

[0140] Hydrocarbons (e.g., lipids, fatty acids, aldehydes, alcohols, and alkanes) produced by cells of the invention can be harvested, or otherwise collected, by any convenient means. For example, hydrocarbons secreted from cells can be centrifuged to separate the hydrocarbons in a hydrophobic layer from contaminants in an aqueous layer and optionally from any solid materials as a precipitate in after centrifugation. Material containing cell or cell fractions can be treated with proteases to degrade contaminating proteins before or after centrifugation. In some instances the contaminating proteins are associated, possibly covalently, to hydrocarbons or hydrocarbon precursors which form hydrocarbons upon removal of the protein. In other instances the hydrocarbon molecules are in a preparation that also contains proteins. Proteases can be added to hydrocarbon preparations containing proteins to degrade proteins (for example, the protease from *Streptomyces griseus* can be used (SigmaAldrich catalog number P5147). After digestion, the hydrocarbons are preferably purified from residual proteins, peptide fragments, and amino acids. This purification can be accomplished, for example, by methods listed above such as centrifugation and filtration.

[0141] Extracellular hydrocarbons can also be extracted in vivo from living microalgae cells which are then returned to a bioreactor by exposure of the cells, in an otherwise sterile environment, to a non-toxic extraction solvent, followed by separation of the living cells and the hydrophobic fraction of extraction solvent and hydrocarbons, wherein the separated living cells are then returned to a culture container such as a stainless steel fermentor or photobioreactor (see Biotechnol Bioeng. 2004 Dec. 5; 88(5):593-600 and Biotechnol Bioeng. 2004 Mar. 5; 85(5):475-81).

[0142] Hydrocarbons can also be isolated by whole cell extraction. The cells are first disrupted and then intracellular and cell membrane/cell wall-associated hydrocarbons as well as extracellular hydrocarbons can be collected from the whole cell mass, such as by use of centrifugation as described above.

[0143] Various methods are available for separating hydrocarbons and lipids from cellular lysates produced by the above methods. For example, hydrocarbons can be extracted with a hydrophobic solvent such as hexane (see Frenz et al. 1989, Enzyme Microb. Technol., 11:717). Hydrocarbons can also be extracted using liquefaction (see for example Sawayama et al. 1999, Biomass and Bioenergy 17:33-39 and Inoue et al. 1993, Biomass Bioenergy 6(4):269-274); oil liquefaction (see for example Minowa et al. 1995, Fuel 74(12): 1735-1738); and supercritical CO_2 extraction (see for example Mendes et al. 2003, Inorganica Chimica Acta 356: 328-334).

[0144] Miao and Wu describe a protocol of the recovery of microalgal lipid from a culture in which the cells were harvested by centrifugation, washed with distilled water and dried by freeze drying. The resulting cell powder was pulverized in a mortor and then extracted with n-hexane. Miao and Wu, Biosource Technology (2006) 97:841-846.

[0145] Lysing Cells

[0146] Intracellular lipids and hydrocarbons produced in microorganisms are, in some embodiments, extracted after lysing the cells of the microorganism. Once extracted, the lipids and/or hydrocarbons can be further refined to produce, e.g., oils, fuels, or oleochemicals.

[0147] After completion of culturing, the microorganisms can be separated from the fermentation broth. Optionally, the separation is effected by centrifugation to generate a concentrated paste. Centrifugation does not remove significant amounts of intracellular water from the microorganisms and is not a drying step. The biomass can then be washed with a washing solution (e.g., DI water) to get rid of the fermentation broth and debris. Optionally, the washed microbial biomass may also be dried (oven dried, lyophilized, etc.) prior to cell disruption. Alternatively, cells can be lysed without separation from some or all of the fermentation broth when the fermentation is complete. For example, the cells can be at a ratio of less than 1:1 v:v cells to extracellular liquid when the cells are lysed.

[0148] Microorganisms containing a lipid and/or hydrocarbon can be lysed to produce a lysate. As detailed herein, the step of lysing a microorganism (also referred to as cell lysis) can be achieved by any convenient means, including heat-induced lysis, adding a base, adding an acid, using enzymes such as proteases and polysaccharide degradation enzymes such as amylases, using ultrasound, mechanical lysis, using osmotic shock, infection with a lytic virus, and/or expression of one or more lytic genes. Lysis is performed to release intracellular molecules which have been produced by the microorganism. Each of these methods for lysing a microorganism can be used as a single method or in combination simultaneously or sequentially.

[0149] The extent of cell disruption can be observed by microscopic analysis. Using one or more of the methods described herein, typically more than 70% cell breakage is observed. Preferably, cell breakage is more than 80%, more preferably more than 90% and most preferred about 100%.

[0150] In particular embodiments, the microorganism is lysed after growth, for example to increase the exposure of cellular lipid and/or hydrocarbon for extraction or further processing. The timing of lipase expression (e.g., via an inducible promoter) or cell lysis can be adjusted to optimize the yield of lipids and/or hydrocarbons. Below are described a number of lysis techniques. These techniques can be used individually or in combination.

[0151] Heat-Induced Lysis

[0152] In a preferred embodiment of the present invention, the step of lysing a microorganism comprises heating of a cellular suspension containing the microorganism. In this

embodiment, the fermentation broth containing the microorganisms (or a suspension of microorganisms isolated from the fermentation broth) is heated until the microorganisms, i.e., the cell walls and membranes of microorganisms degrade or breakdown. Typically, temperatures applied are at least 50 C. Higher temperatures, such as, at least 30 C, at least 60 C, at least 70 C, at least 80 C, at least 90 C, at least 100 C, at least 110 C, at least 120 C, at least 130 C or higher are used for more efficient cell lysis.

[0153] Lysing cells by heat treatment can be performed by boiling the microorganism. Alternatively, heat treatment (without boiling) can be performed in an autoclave. The heat treated lysate may be cooled for further treatment.

[0154] Cell disruption can also be performed by steam treatment, i.e., through addition of pressurized steam. Steam treatment of microalgae for cell disruption is described, for example, in U.S. Pat. No. 6,750,048.

[0155] Lysis Using a Base

[0156] In another preferred embodiment of the present invention, the step of lysing a microorganism comprises adding a base to a cellular suspension containing the microorganism.

[0157] The base should be strong enough to hydrolyze at least a portion of the proteinaceous compounds of the microorganisms used. Bases which are useful for solubilizing proteins are known in the art of chemistry. Exemplary bases which are useful in the methods of the present invention include, but are not limited to, hydroxides, carbonates and bicarbonates of lithium, sodium, potassium, calcium, and mixtures thereof. A preferred base is KOH. Base treatment of microalgae for cell disruption is described, for example, in U.S. Pat. No. 6,750,048.

[0158] Acidic Lysis

[0159] In another preferred embodiment of the present invention, the step of lysing a microorganism comprises adding an acid to a cellular suspension containing the microorganism. Acid lysis can be affected using an acid at a concentration of 10-500 mN or preferably 40-160 nM. Acid lysis is preferably performed at above room temperature (e.g., at 40-160, and preferably a temperature of 50-130. For moderate temperatures (e.g., room temperature to 100 C and particularly room temperature to 65, acid treatment can usefully be combined with sonication or other cell disruption methods.

[0160] Lysing Cells Using Enzymes

[0161] In another preferred embodiment of the present invention, the step of lysing a microorganism comprises lysing the microorganism by using an enzyme. Preferred enzymes for lysing a microorganism are proteases and polysaccharide-degrading enzymes such as hemicellulase (e.g., hemicellulase from *Aspergillus niger*; Sigma Aldrich, St. Louis, Mo.; #H2125), pectinase (e.g., pectinase from *Rhizopus* sp.; Sigma Aldrich, St. Louis, Mo.; #P2401), Mannaway 4.0 L (Novozymes), cellulase (e.g., cellulose from *Trichoderma viride*; Sigma Aldrich, St. Louis, Mo.; #C9422), and driselase (e.g., driselase from *Basidiomycetes* sp.; Sigma Aldrich, St. Louis, Mo.; #D9515.

[0162] Cellulases

[0163] In a preferred embodiment of the present invention, a cellulase for lysing a microorganism is a polysaccharide-degrading enzyme, optionally from *Chlorella* or a *Chlorella* virus.

[0164] Proteases

[0165] Proteases such as *Streptomyces griseus* protease, chymotrypsin, proteinase K, proteases listed in Degradation of Polylactide by Commercial Proteases, Oda Y et al., Journal of Polymers and the Environment, Volume 8, Number 1, January 2000, pp. 29-32(4), and other proteases can be used to lyse microorganisms. Other proteases that can be used include Alcalase 2.4 FG (Novozymes) and Flavourzyme 100 L (Novozymes).

[0166] Combinations

[0167] Any combination of a protease and a polysaccharide-degrading enzyme can also be used, including any combination of the preceding proteases and polysaccharide-degrading enzymes.

[0168] Lysing Cells Using Ultrasound

[0169] In another preferred embodiment of the present invention, the step of lysing a microorganism is performed by using ultrasound, i.e., sonication. Thus, cells can also by lysed with high frequency sound. The sound can be produced electronically and transported through a metallic tip to an appropriately concentrated cellular suspension. This sonication (or ultrasonication) disrupts cellular integrity based on the creation of cavities in cell suspension.

[0170] Mechanical Lysis

[0171] In another preferred embodiment of the present invention, the step of lysing a microorganism is performed by mechanical lysis. Cells can be lysed mechanically and optionally homogenized to facilitate hydrocarbon (e.g., lipid) collection. For example, a pressure disrupter can be used to pump a cell containing slurry through a restricted orifice valve. High pressure (up to 1500 bar) is applied, followed by an instant expansion through an exiting nozzle. Cell disruption is accomplished by three different mechanisms: impingement on the valve, high liquid shear in the orifice, and sudden pressure drop upon discharge, causing an explosion of the cell. The method releases intracellular molecules.

[0172] Alternatively, a ball mill can be used. In a ball mill, cells are agitated in suspension with small abrasive particles, such as beads. Cells break because of shear forces, grinding between beads, and collisions with beads. The beads disrupt the cells to release cellular contents. Cells can also be disrupted by shear forces, such as with the use of blending (such as with a high speed or Waring blender as examples), the french press, or even centrifugation in case of weak cell walls, to disrupt cells.

[0173] Lysing Cells by Osmotic Shock (Cytolysis)

[0174] In another preferred embodiment of the present invention, the step of lysing a microorganism is performed by applying an osmotic shock.

[0175] Infection with a Lytic Virus

[0176] In a preferred embodiment of the present invention, the step of lysing a microorganism comprises infection of the microorganism with a lytic virus. A wide variety of viruses are known to lyse microorganisms suitable for use in the present invention, and the selection and use of a particular lytic virus for a particular microorganism is within the level of skill in the art.

[0177] For example, paramecium bursaria chlorella virus (PBCV-1) is the prototype of a group (family Phycodnaviridae, genus *Chlorovirus*) of large, icosahedral, plaque-forming, double-stranded DNA viruses that replicate in, and lyse, certain unicellular, eukaryotic chlorella-like green algae. Accordingly, any susceptible microalgae can be lysed by infecting the culture with a suitable chlorella virus. See for example Adv. Virus Res. 2006; 66:293-336; Virology, 1999 Apr. 25; 257(1):15-23; Virology, 2004 Jan. 5; 318(1):214-23;

Nucleic Acids Symp. Ser. 2000; (44):161-2; J. Virol. 2006 March; 80(5):2437-44; and Annu Rev. Microbiol. 1999; 53:447-94.

[0178] Autolysis (Expression of a Lytic Gene)

[0179] In another preferred embodiment of the present invention, the step of lysing a microorganism comprises autolysis. In this embodiment, a microorganism according to the invention is genetically engineered to produce a lytic protein that will lyse the microorganism. This lytic gene can be expressed using an inducible promoter so that the cells can first be grown to a desirable density in a fermentor, followed by induction of the promoter to express the lytic gene to lyse the cells. In one embodiment, the lytic gene encodes a polysaccharide-degrading enzyme.

[0180] In certain other embodiments, the lytic gene is a gene from a lytic virus. Thus, for example, a lytic gene from a *Chlorella* virus can be expressed in an algal cell of the genus *Chlorella*, such as *C. protothecoides*.

[0181] Suitable expression methods are described herein with respect to the expression of a lipase gene. Expression of lytic genes is preferably done using an inducible promoter, such as a promoter active in microalgae that is induced by a stimulus such as the presence of a small molecule, light, heat, and other stimuli. For example, see Virology 260, 308-315 (1999); FEMS Microbiology Letters 180 (1999) 45-53; Virology 263, 376-387 (1999); and Virology 230, 361-368 (1997).

[0182] Extraction of Lipids and Hydrocarbons

[0183] Lipids and hydrocarbons generated by the microorganisms of the present invention can be recovered by extraction with an organic solvent. In some cases, the preferred organic solvent is hexane. Typically, the organic solvent is added directly to the lysate without prior separation of the lysate components. In one embodiment, the lysate generated by one or more of the methods described above is contacted with an organic solvent for a period of time sufficient to allow the lipid and/or hydrocarbon components to form a solution with the organic solvent. In some cases, the solution can then be further refined to recover specific desired lipid or hydrocarbon components. Hexane extraction methods are well known in the art.

[0184] Methods of Processing Lipids and Hydrocarbons

[0185] Enzymatic Modification

[0186] Hydrocarbons (e.g., lipids, fatty acids, aldehydes, alcohols, and alkanes) produced by cells as described herein can be modified by the use of one or more enzymes, including a lipase. When the hydrocarbons are in the extracellular environment of the cells, the one or more enzymes can be added to that environment under conditions in which the enzyme modifies the hydrocarbon or completes its synthesis from a hydrocarbon precursor. Alternatively, the hydrocarbons can be partially, or completely, isolated from the cellular material before addition of one or more catalysts such as enzymes. Such catalysts are exogenously added, and their activity occurs outside the cell or in vitro.

[0187] Thermal and Other Catalytic Modification

[0188] Hydrocarbons produced by cells in vivo, or enzymatically modified in vitro, as described herein can be optionally further processed by conventional means. The processing can include "cracking" to reduce the size, and thus increase the hydrogen:carbon ratio, of hydrocarbon molecules. Catalytic and thermal cracking methods are routinely used in hydrocarbon and triglyceride oil processing. Catalytic methods involve the use of a catalyst, such as a solid acid catalyst. The catalyst can be silica-alumina or a zeolite, which result in the heterolytic, or asymmetric, breakage of a carbon-carbon bond to result in a carbocation and a hydride anion. These reactive intermediates then undergo either rearrangement or hydride transfer with another hydrocarbon. The reactions can thus regenerate the intermediates to result in a self-propagating chain mechanism. Hydrocarbons can also be processed to reduce, optionally to zero, the number of carbon-carbon double, or triple, bonds therein. Hydrocarbons can also be processed to remove or eliminate a ring or cyclic structure therein. Hydrocarbons can also be processed to increase the hydrogen:carbon ratio. This can include the addition of hydrogen ("hydrogenation") and/or the "cracking" of hydrocarbons into smaller hydrocarbons.

[0189] Thermal methods involve the use of elevated temperature and pressure to reduce hydrocarbon size. An elevated temperature of about 80° C. and pressure of about 700 kPa can be used. These conditions generate "light," a term that is sometimes used to refer to hydrogen-rich hydrocarbon molecules (as distinguished from photon flux), while also generating, by condensation, heavier hydrocarbon molecules which are relatively depleted of hydrogen. The methodology provides homolytic, or symmetrical, breakage and produces alkenes, which may be optionally enzymatically saturated as described above.

[0190] Catalytic and thermal methods are standard in plants for hydrocarbon processing and oil refining. Thus hydrocarbons produced by cells as described herein can be collected and processed or refined via conventional means. See Hillen et al. (Biotechnology and Bioengineering, Vol. XXIV: 193-205 (1982)) for a report on hydrocracking of microalgae-produced hydrocarbons. In alternative embodiments, the fraction is treated with another catalyst, such as an organic compound, heat, and/or an inorganic compound. For processing of lipids into biodiesel, a transesterification process is used as described in Section IV herein.

[0191] Hydrocarbons produced via methods of the present invention are useful in a variety of industrial applications. For example, the production of linear alkylbenzene sulfonate (LAS), an anionic surfactant used in nearly all types of detergents and cleaning preparations, utilizes hydrocarbons generally comprising a chain of 10-14 carbon atoms. See, for example, U.S. Pat. Nos. 6,946,430; 5,506,201; 6,692,730; 6,268,517; 6,020,509; 6,140,302; 5,080,848; and 5,567,359. Surfactants, such as LAS, can be used in the manufacture of personal care compositions and detergents, such as those described in U.S. Pat. Nos. 5,942,479; 6,086,903; 5,833,999; 6,468,955; and 6,407,044.

[0192] Methods of Producing Fuels Suitable for Use in Diesel Vehicles and Jet Engines

[0193] Increasing interest is directed to the use of hydrocarbon components of biological origin in fuels, such as biodiesel, renewable diesel, and jet fuel, since renewable biological starting materials that may replace starting materials derived from fossil fuels are available, and the use thereof is desirable. There is a need for methods for producing hydrocarbon components from biological materials. The present invention fulfills this need by providing methods for production of biodiesel, renewable diesel, and jet fuel using the lipids generated by the methods described herein as a biological material to produce biodiesel, renewable diesel, and jet fuel.

[0194] Traditional diesel fuels are petroleum distillates rich in paraffinic hydrocarbons. They have boiling ranges as broad as 370 to 780 F, which are suitable for combustion in a

compression ignition engine, such as a diesel engine vehicle. The American Society of Testing and Materials (ASTM) establishes the grade of diesel according to the boiling range, along with allowable ranges of other fuel properties, such as cetane number, cloud point, flash point, viscosity, aniline point, sulfur content, water content, ash content, copper strip corrosion, and carbon residue. Technically, any hydrocarbon distillate material derived from biomass or otherwise that meets the appropriate ASTM specification can be defined as diesel fuel (ASTM D975), jet fuel (ASTM D1655), or as biodiesel (ASTM D6751).

[0195] After extraction, lipid and/or hydrocarbon components recovered from the microbial biomass described herein can be subjected to chemical treatment to manufacture a fuel for use in diesel vehicles and jet engines.

[0196] Biodiesel

[0197] Biodiesel is a liquid which varies in color—between golden and dark brown—depending on the production feedstock. It is practically immiscible with water, has a high boiling point and low vapor pressure. Biodiesel refers to a diesel-equivalent processed fuel for use in diesel-engine vehicles. Biodiesel is biodegradable and non-toxic. An additional benefit of biodiesel over conventional diesel fuel is lower engine wear.

[0198] Typically, biodiesel comprises C14-C18 alkyl esters. Various processes convert biomass or a lipid produced and isolated as described herein to diesel fuels. A preferred method to produce biodiesel is by transesterification of a lipid as described herein. A preferred alkyl ester for use as biodiesel is a methyl ester or ethyl ester.

[0199] Biodiesel produced by a method described herein can be used alone or blended with conventional diesel fuel at any concentration in most modern diesel-engine vehicles. When blended with conventional diesel fuel (petroleum diesel), biodiesel may be present from about 0.1% to about 99.9%. Much of the world uses a system known as the "B" factor to state the amount of biodiesel in any fuel mix. For example, fuel containing 20% biodiesel is labeled B20. Pure biodiesel is referred to as B100.

[0200] Biodiesel can also be used as a heating fuel in domestic and commercial boilers. Existing oil boilers may contain rubber parts and may require conversion to run on biodiesel. The conversion process is usually relatively simple, involving the exchange of rubber parts for synthetic parts due to biodiesel being a strong solvent. Due to its strong solvent power, burning biodiesel will increase the efficiency of boilers.

[0201] Biodiesel can be used as an additive in formulations of diesel to increase the lubricity of pure Ultra-Low Sulfur Diesel (ULSD) fuel, which is advantageous because it has virtually no sulfur content.

[0202] Biodiesel is a better solvent than petrodiesel and can be used to break down deposits of residues in the fuel lines of vehicles that have previously been run on petrodiesel.

[0203] Production of Biodiesel

[0204] Biodiesel can be produced by transesterification of triglycerides contained in oil-rich biomass. Thus, in another aspect of the present invention a method for producing biodiesel is provided. In a preferred embodiment, the method for producing biodiesel comprises the steps of (a) cultivating a lipid-containing microorganism using methods disclosed herein (b) lysing a lipid-containing microorganism to produce a lysate, (c) isolating lipid from the lysed microorganism, and (d) transesterifying the lipid composition, whereby biodiesel is produced.

[0205] Methods for growth of a microorganism, lysing a microorganism to produce a lysate, treating the lysate in a medium comprising an organic solvent to form a heterogeneous mixture and separating the treated lysate into a lipid composition have been described above and can also be used in the method of producing biodiesel.

[0206] Lipid compositions can be subjected to transesterification to yield long-chain fatty acid esters useful as biodiesel. Preferred transesterification reactions are outlined below and include base catalyzed transesterification and transesterification using recombinant lipases.

[0207] In a base-catalyzed transesterification process, the triacylglycerides are reacted with an alcohol, such as methanol or ethanol, in the presence of an alkaline catalyst, typically potassium hydroxide. This reaction forms methyl or ethyl esters and glycerin (glycerol) as a byproduct.

[0208] General Chemical Process

[0209] Animal and plant oils are typically made of triglycerides which are esters of free fatty acids with the trihydric alcohol, glycerol. In transesterification, the glycerol in a triacylglyceride (TAG) is replaced with a short-chain alcohol such as methanol or ethanol.

[0210] Using Recombinant Lipases

[0211] Transesterification has also been carried out experimentally using an enzyme, such as a lipase instead of a base. Lipase-catalyzed transesterification can be carried out, for example, at a temperature between the room temperature and 80 C, and a mole ratio of the TAG to the lower alcohol of greater than 1:1, preferably about 3:1.

[0212] Lipases suitable for use in transesterification are found in, e.g. U.S. Pat. Nos. 4,798,793; 4,940,845 5,156,963; 5,342,768; 5,776,741 and WO89/01032.

[0213] One challenge to using a lipase for the production of fatty acid esters suitable for biodiesel is that the price of lipase is much higher than the price of sodium hydroxide (NaOH) used by the strong base process. This challenge has been addressed by using an immobilized lipase, which can be recycled. However, the activity of the immobilized lipase must be maintained after being recycled for a minimum number of cycles to allow a lipase-based process to compete with the strong base process in terms of the production cost. Immobilized lipases are subject to poisoning by the lower alcohols typically used in transesterification. U.S. Pat. No. 6,398,707 (issued Jun. 4, 2002 to Wu et al.) describes methods for enhancing the activity of immobilized lipases and regenerating immobilized lipases having reduced activity.

[0214] In particular embodiments, a recombinant lipase is expressed in the same microorganisms that produce the lipid on which the lipase acts. DNA encoding the lipase and selectable marker is preferably codon-optimized cDNA. Methods of recoding genes for expression in microalgae are described in U.S. Pat. No. 7,135,290.

[0215] Standards

[0216] The common international standard for biodiesel is EN 14214. ASTM D6751 is the most common biodiesel standard referenced in the United States and Canada. Germany uses DIN EN 14214 and the UK requires compliance with BS EN 14214.

[0217] Basic industrial tests to determine whether the products conform to these standards typically include gas chro-

matography, HPLC, and others. Biodiesel meeting the quality standards is very non-toxic, with a toxicity rating (LD_{50}) of greater than 50 mL/kg.

[0218] Renewable Diesel

[0219] Renewable diesel comprises alkanes, such as C16:0 and C18:0 and thus, are distinguishable from biodiesel. High quality renewable diesel conforms to the ASTM D975 standard.

[0220] The lipids produced by the methods of the present invention can serve as feedstock to produce renewable diesel. Thus, in another aspect of the present invention, a method for producing renewable diesel is provided. Renewable diesel can be produced by at least three processes: hydrothermal processing (hydrotreating); hydroprocessing; and indirect liquefaction. These processes yield non-ester distillates. During these processes, triacylglycerides produced and isolated as described herein, are converted to alkanes.

[0221] In a preferred embodiment, the method for producing renewable diesel comprises (a) cultivating a lipid-containing microorganism using methods disclosed herein (b) lysing the microorganism to produce a lysate, (c) isolating lipid from the lysed microorganism, and (d) deoxygenating and hydrotreating the lipid to produce an alkane, whereby renewable diesel is produced. Lipids suitable for manufacturing renewable diesel can be obtained via extraction from microbial biomass using an organic solvent such as hexane, or via other methods, such as those described in U.S. Pat. No. 5,928,696.

[0222] In some methods, the microbial lipid is first cracked in conjunction with hydrotreating to reduce carbon chain length and saturate double bonds, respectively. The material is then isomerized, also in conjunction with hydrotreating. The naptha fraction can then be removed through distillation, followed by additional distillation to vaporize and distill components desired in the diesel fuel to meet a D975 standard while leaving components that are heavier than desired for meeting a D 975 standard. Hydrotreating, hydrocracking, deoxygenation and isomerization methods of chemically modifying oils, including triglyceride oils, are well known in the art. See for example European patent applications EP1741768 (A1); EP1741767 (A1); EP1682466 (A1); EP1640437 (A1); EP1681337 (A1); EP1795576 (A1); and U.S. Pat. Nos. 7,238,277; 6,630,066; 6,596,155; 6,977,322; 7,041,866; 6,217,746; 5,885,440; 6,881,873.

[0223] Hydrotreating

[0224] In a preferred embodiment of the method for producing renewable diesel, treating the lipid to produce an alkane is performed by hydrotreating of the lipid composition. In hydrothermal processing, typically, biomass is reacted in water at an elevated temperature and pressure to form oils and residual solids. Conversion temperatures are typically 300 to 660 F, with pressure sufficient to keep the water primarily as a liquid, 100 to 170 standard atmosphere (atm). Reaction times are on the order of 15 to 30 minutes. After the reaction is completed, the organics are separated from the water. Thereby a distillate suitable for diesel is produced.

[0225] Hydroprocessing

[0226] A renewable diesel, referred to as "green diesel," can be produced from fatty acids by traditional hydroprocessing technology. The triglyceride-containing oils can be hydroprocessed either as co-feed with petroleum or as a dedicated feed. The product is a diesel fuel that conforms to the ASTM D975 specification. Thus, in another preferred embodiment of the method for producing renewable diesel, treating the lipid composition to produce an alkane is performed by hydroprocessing of the lipid composition.

[0227] In some methods of making renewable diesel, the first step of treating a triglyceride is hydroprocessing to saturate double bonds, followed by deoxygenation at elevated temperature in the presence of hydrogen and a catalyst. In some methods, hydrogenation and deoxygenation occur in the same reaction. In other methods deoxygenation occurs before hydrogenation. Isomerization is then optionally performed, also in the presence of hydrogen and a catalyst. Naphtha components are preferably removed through distillation. For examples, see U.S. Pat. Nos. 5,475,160 (hydrogenation of triglycerides); 5,091,116 (deoxygenation, hydrogenation and gas removal); 6,391,815 (hydrogenation); and 5,888,947 (isomerization).

[0228] Petroleum refiners use hydroprocessing to remove impurities by treating feeds with hydrogen. Hydroprocessing conversion temperatures are typically 300 to 700 F. Pressures are typically 40 to 100 atm. The reaction times are typically on the order of 10 to 60 minutes.

[0229] Solid catalysts are employed to increase certain reaction rates, improve selectivity for certain products, and optimize hydrogen consumption.

[0230] Hydrotreating and hydroprocessing ultimately lead to a reduction in the molecular weight of the feed. In the case of triglyceride-containing oils, the triglyceride molecule is reduced to four hydrocarbon molecules under hydroprocessing conditions: a propane molecule and three heavier hydrocarbon molecules, typically in the C8 to C18 range.

[0231] Indirect Liquefaction

[0232] A traditional ultra-low sulfur diesel can be produced from any form of biomass by a two-step process. First, the biomass is converted to a syngas, a gaseous mixture rich in hydrogen and carbon monoxide. Then, the syngas is catalytically converted to liquids. Typically, the production of liquids is accomplished using Fischer-Tropsch (FT) synthesis. This technology applies to coal, natural gas, and heavy oils. Thus, in yet another preferred embodiment of the method for producing renewable diesel, treating the lipid composition to produce an alkane is performed by indirect liquefaction of the lipid composition.

[0233] Jet Fuel

[0234] Aeroplane fuel is clear to straw colored. The most common fuel is an unleaded/paraffin oil-based fuel classified as Aeroplane A-1, which is produced to an internationally standardized set of specifications. Aeroplane fuel is a mixture of a large number of different hydrocarbons, possibly as many as a thousand or more. The range of their sizes (molecular weights or carbon numbers) is restricted by the requirements for the product, for example, freezing point or smoke point. Kerosone-type Aeroplane fuel (including Jet A and Jet A-1) has a carbon number distribution between about 8 and 16 carbon numbers. Wide-cut or naphta-type Aeroplane fuel (including Jet B) typically has a carbon number distribution between about 5 and 15 carbons.

[0235] Both Aeroplanes (Jet A and jet B) may contain a number of additives. Useful additives include, but are not limited to, antioxidants, antistatic agents, corrosion inhibitors, and fuel system icing inhibitor (FSII) agents. Antioxidants prevent gumming and usually, are based on alkylated phenols, for example, AO-30, AO-31, or AO-37. Antistatic agents dissipate static electricity and prevent sparking Stadis 450 with dinonylnaphthylsulfonic acid (DINNSA) as the

active ingredient is an example. Corrosion inhibitors, e.g., DCI-4A are used for civilian and military fuels and DCI-6A is used for military fuels. FSII agents, include, e.g., Di-EGME.

[0236] A solution is blending algae fuels with existing jet fuel. The present invention provides such a solution. The lipids produced by the methods of the present invention can serve as feedstock to produce jet fuel. Thus, in another aspect of the present invention, a method for producing jet fuel is provided. Herewith two methods for producing jet fuel from the lipids produced by the methods of the present invention are provided: fluid catalytic cracking (FCC); and hydrodeoxygenation (HDO).

[0237] Fluid Catalytic Cracking

[0238] Fluid Catalytic Cracking (FCC) is one method which is used to produce olefins, especially propylene from heavy crude fractions. There are reports in the literature that vegetable oils such as canola oil could be processed using FCC to give a hydrocarbon stream useful as a gasoline fuel.

[0239] The lipids produced by the method of the present invention can be converted to olefins. The process involves flowing the lipids produced through an FCC zone and collecting a product stream comprised of olefins, which is useful as a jet fuel. The lipids produced are contacted with a cracking catalyst at cracking conditions to provide a product stream comprising olefins and hydrocarbons useful as jet fuel.

[0240] In a preferred embodiment, the method for producing jet fuel comprises (a) cultivating a lipid-containing microorganism using methods disclosed herein, (b) lysing the lipid-containing microorganism to produce a lysate, (c) isolating lipid from the lysate, and (d) treating the lipid composition, whereby jet fuel is produced.

[0241] In a preferred embodiment of the method for producing a jet fuel, the lipid composition can be flowed through a fluid catalytic cracking zone, which, in one embodiment, may comprise contacting the lipid composition with a cracking catalyst at cracking conditions to provide a product stream comprising C_2-C_5 olefins.

[0242] In certain embodiments of this method it may be desirable to remove any contaminants that may be present in the lipid composition. Thus, prior to flowing the lipid composition through a fluid catalytic cracking zone, the lipid composition is pretreated. Pretreatment may involve contacting the lipid composition with an ion-exchange resin. The ion exchange resin is an acidic ion exchange resin, such as Amberlyst™-15 and can be used as a bed in a reactor through which the lipid composition is flowed, either upflow or downflow. Other pretreatments may include mild acid washes by contacting the lipid composition with an acid, such as sulfuric, acetic, nitric, or hydrochloric acid. Contacting is done with a dilute acid solution usually at ambient temperature and atmospheric pressure.

[0243] The lipid composition, optionally pretreated, is flowed to an FCC zone where the hydrocarbonaceous components are cracked to olefins. Catalytic cracking is accomplished by contacting the lipid composition in a reaction zone with a catalyst composed of finely divided particulate material. The reaction is catalytic cracking, as opposed to hydrocracking, and is carried out in the absence of added hydrogen or the consumption of hydrogen. As the cracking reaction proceeds, substantial amounts of coke are deposited on the catalyst. The catalyst is regenerated at high temperatures by burning coke from the catalyst in a regeneration zone. Coke-containing catalyst, referred to herein as "coked catalyst", is continually transported from the reaction zone to the regeneration zone to be regenerated and replaced by essentially coke-free regenerated catalyst from the regeneration zone. Fluidization of the catalyst particles by various gaseous streams allows the transport of catalyst between the reaction zone and regeneration zone. Methods for cracking hydrocarbons, such as those of the lipid composition described herein, in a fluidized stream of catalyst, transporting catalyst between reaction and regeneration zones, and combusting coke in the regenerator are well known by those skilled in the art of FCC processes. Exemplary FCC applications and catalysts useful for cracking the lipid composition to produce C_2-C_5 olefins are described in U.S. Pat. Nos. 6,538,169, 7,288,685, which are incorporated in their entirety by reference.

[0244] In one embodiment, cracking the lipid composition of the present invention, takes place in the riser section or, alternatively, the lift section, of the FCC zone. The lipid composition is introduced into the riser by a nozzle resulting in the rapid vaporization of the lipid composition. Before contacting the catalyst, the lipid composition will ordinarily have a temperature of about 149 C to about 316 C (300 F to 600 F). The catalyst is flowed from a blending vessel to the riser where it contacts the lipid composition for a time of abort 2 seconds or less.

[0245] The blended catalyst and reacted lipid composition vapors are then discharged from the top of the riser through an outlet and separated into a cracked product vapor stream including olefins and a collection of catalyst particles covered with substantial quantities of coke and generally referred to as "coked catalyst." In an effort to minimize the contact time of the lipid composition and the catalyst which may promote further conversion of desired products to undesirable other products, any arrangement of separators such as a swirl arm arrangement can be used to remove coked catalyst from the product stream quickly. The separator, e.g. swirl arm separator, is located in an upper portion of a chamber with a stripping zone situated in the lower portion of the chamber. Catalyst separated by the swirl arm arrangement drops down into the stripping zone. The cracked product vapor stream comprising cracked hydrocarbons including light olefins and some catalyst exit the chamber via a conduit which is in communication with cyclones. The cyclones remove remaining catalyst particles from the product vapor stream to reduce particle concentrations to very low levels. The product vapor stream then exits the top of the separating vessel. Catalyst separated by the cyclones is returned to the separating vessel and then to the stripping zone. The stripping zone removes adsorbed hydrocarbons from the surface of the catalyst by counter-current contact with steam.

[0246] Low hydrocarbon partial pressure operates to favor the production of light olefins. Accordingly, the riser pressure is set at about 172 to 241 kPa (25 to 35 psia) with a hydrocarbon partial pressure of about 35 to 172 kPa (5 to 25 psia), with a preferred hydrocarbon partial pressure of about 69 to 138 kPa (10 to 20 psia). This relatively low partial pressure for hydrocarbon is achieved by using steam as a diluent to the extent that the diluent is 10 to 55 wt-% of lipid composition and preferably about 15 wt-% of lipid composition. Other diluents such as dry gas can be used to reach equivalent hydrocarbon partial pressures.

[0247] The temperature of the cracked stream at the riser outlet will be about 510 C. to 621 C (950 F to 1150 F). However, riser outlet temperatures above 566 C (1050 F) make more dry gas and more olefins. Whereas, riser outlet temperatures below 566 C (1050 F) make less ethylene and

propylene. Accordingly, it is preferred to run the FCC process at a preferred temperature of about 566 C to about 63° C., preferred pressure of about 138 kPa to about 240 kPa (20 to 35 psia). Another condition for the process is the catalyst to lipid composition ratio which can vary from about 5 to about 20 and preferably from about 10 to about 15.

[0248] In one embodiment of the method for producing a jet fuel, the lipid composition is introduced into the lift section of an FCC reactor. The temperature in the lift section will be very hot and range from about 700 C (1292 F) to about 760 C (1400 F) with a catalyst to lipid composition ratio of about 100 to about 150. It is anticipated that introducing the lipid composition into the lift section will produce considerable amounts of propylene and ethylene.

[0249] Gas and liquid hydrocarbon products produced can be analyzed by gas chromatography, HPLC, etc.

[0250] Hydrodeoxygenation

[0251] In another embodiment of the method for producing a jet fuel using the lipid composition or the lipids produced as described herein, the structure of the lipid composition or the lipids is broken by a process referred to as hydrodeoxygenation (HDO).

[0252] HDO means removal of oxygen by means of hydrogen, that is, oxygen is removed while breaking the structure of the material. Olefinic double bonds are hydrogenated and any sulphur and nitrogen compounds are removed. Sulphur removal is called hydrodesulphurization (HDS). Pretreatment and purity of the raw materials (lipid composition or the lipids) contribute to the service life of the catalyst.

[0253] Generally in the HDO/HDS step, hydrogen is mixed with the feed stock (lipid composition or the lipids) and then the mixture is passed through a catalyst bed as a co-current flow, either as a single phase or a two phase feed stock. After the HDO/MDS step, the product fraction is separated and passed to a separate isomerzation reactor. An isomerization reactor for biological starting material is described in the literature (FI 100 248) as a co-current reactor.

[0254] The process for producing a fuel by hydrogenating a hydrocarbon feed, e.g., the lipid composition or the lipids herein, can also be performed by passing the lipid composition or the lipids as a co-current flow with hydrogen gas through a first hydrogenation zone, and thereafter the hydrocarbon effluent is further hydrogenated in a second hydrogenation zone by passing hydrogen gas to the second hydrogenation zone as a counter-current flow relative to the hydrocarbon effluent. Exemplary HDO applications and catalysts useful for cracking the lipid composition to produce C_2-C_5 olefins are described in U.S. Pat. No. 7,232,935, which is incorporated in its entirety by reference.

[0255] Typically, in the hydrodeoxygenation step, the structure of the biological component, such as the lipid composition or lipids herein, is decomposed, oxygen, nitrogen, phosphorus and sulphur compounds, and light hydrocarbons as gas are removed, and the olefinic bonds are hydrogenated. In the second step of the process, i.e. in the so-called isomerization step, isomerzation is carried out for branching the hydrocarbon chain and improving the performance of the paraffin at low temperatures.

[0256] In the first step i.e. HDO step of the cracking process, hydrogen gas and the lipid composition or lipids herein which are to be hydrogenated are passed to a HDO catalyst bed system either as co-current or counter-current flows, said catalyst bed system comprising one or more catalyst bed(s), preferably 1-3 catalyst beds. The HDO step is typically operated in a co-current manner. In case of a HDO catalyst bed system comprising two or more catalyst beds, one or more of the beds may be operated using the counter-current flow principle.

[0257] In the HDO step, the pressure varies between 20 and 150 bar, preferably between 50 and 100 bar, and the temperature varies between 200 and 500 C, preferably in the range of 300-400 C.

[0258] In the HDO step, known hydrogenation catalysts containing metals from Group VII and/or VIB of the Periodic System may be used. Preferably, the hydrogenation catalysts are supported Pd, Pt, Ni, NiMo or a CoMo catalysts, the support being alumina and/or silica. Typically, $NiMo/Al_2O_3$ and $CoMo/Al_2O_3$ catalysts are used.

[0259] Prior to the HDO step, the lipid composition or lipids herein may optionally be treated by prehydrogenation under milder conditions thus avoiding side reactions of the double bonds. Such prehydrogenation is carried out in the presence of a prehydrogenation catalyst at temperatures of 50 400 C and at hydrogen pressures of 1 200 bar, preferably at a temperature between 150 and 250 C and at a hydrogen pressure between 10 and 100 bar. The catalyst may contain metals from Group VIII and/or VIB of the Periodic System. Preferably, the prehydrogenation catalyst is a supported Pd, Pt, Ni, NiMo or a CoMo catalyst, the support being alumina and/or silica.

[0260] A gaseous stream from the HDO step containing hydrogen is cooled and then carbon monoxide, carbon dioxide, nitrogen, phosphorus and sulphur compounds, gaseous light hydrocarbons and other impurities are removed therefrom. After compressing, the purified hydrogen or recycled hydrogen is returned back to the first catalyst bed and/or between the catalyst beds to make up for the withdrawn gas stream. Water is removed from the condensed liquid. The liquid is passed to the first catalyst bed or between the catalyst beds.

[0261] After the HDO step, the product is subjected to an isomerization step. It is substantial for the process that the impurities are removed as completely as possible before the hydrocarbons are contacted with the isomerization catalyst. The isomerization step comprises an optional stripping step, wherein the reaction product from the HDO step may be purified by stripping with water vapor or a suitable gas such as light hydrocarbon, nitrogen or hydrogen. The optional stripping step is carried out in counter-current manner in a unit upstream of the isomerization catalyst, wherein the gas and liquid are contacted with each other, or before the actual isomerization reactor in a separate stripping unit utilizing counter-current principle.

[0262] After the stripping step the hydrogen gas and the hydrogenated lipid composition or lipids herein, and optionally an n-paraffin mixture, are passed to a reactive isomerization unit comprising one or several catalyst bed(s). The catalyst beds of the isomerization step may operate either in co-current or counter-current manner.

[0263] It is important for the process that the counter-current flow principle is applied in the isomerization step. In the isomerization step this is done by carrying out either the optional stripping step or the isomerization reaction step or both in counter-current manner.

[0264] The isomerization step and the HDO step may be carried out in the same pressure vessel or in separate pressure vessels. Optional prehydrogenation may be carried out in a

separate pressure vessel or in the same pressure vessel as the HDO and isomerization steps.

[0265] In the isomerization step, the pressure varies in the range of 20 150 bar, preferably in the range of 20 100 bar, the temperature being between 200 and 500 C, preferably between 300 and 400 C.

[0266] In the isomerization step, isomerization catalysts known in the art may be used. Suitable isomerization catalysts contain molecular sieve and/or a metal from Group VII and/or a carrier. Preferably, the isomerization catalyst contains SAPO-11 or SAPO41 or ZSM-22 or ZSM-23 or ferrierite and Pt, Pd or N1 and Al_2O_3 or SiO_2. Typical isomerization catalysts are, for example, Pt/SAPO-11/Al_2O_3, Pt/ZSM-22/Al_2O_3, Pt/ZSM-23/Al_2O_3 and Pt/SAPO-11/SiO_2.

[0267] As the product, a high quality hydrocarbon component of biological origin, useful as a diesel fuel or a component thereof, is obtained, the density, cetane number and performance at low temperate of said hydrocarbon component being excellent.

[0268] Microbe Engineering

[0269] As noted above, in certain embodiments of the present invention it is desirable to genetically modify a microorganism to enhance lipid production, modify the properties or proportions of components generated by the microorganism, or to improve or provide de novo growth characteristics on a variety of feedstock materials.

[0270] Promoters, cDNAs, and 3'UTRs, as well as other elements of the vectors, can be generated through cloning techniques using fragments isolated from native sources (see for example Molecular Cloning: A Laboratory Manual, Sambrook et al. (3d edition, 2001, Cold Spring Harbor Press; and U.S. Pat. No. 4,683,202). Alternatively, elements can be generated synthetically using known methods (see for example Gene. 1995 Oct. 16; 164(1):49-53). Microbial engineering methods are generally known in the art, e.g., U.S. Pat. App. No. 20090011480, herein incorporated by reference in its entirety, for all purposes.

EXAMPLES

[0271] Below are examples of specific embodiments for carrying out the present invention. The examples are offered for illustrative purposes only, and are not intended to limit the scope of the present invention in any way. Efforts have been made to ensure accuracy with respect to numbers used (e.g., amounts, temperatures, etc.), but some experimental error and deviation should, of course, be allowed for.

[0272] The practice of the present invention will employ, unless otherwise indicated, conventional methods of protein chemistry, biochemistry, recombinant DNA techniques and pharmacology, within the skill of the art. Such techniques are explained fully in the literature. See, e.g., T. E. Creighton, *Proteins: Structures and Molecular Properties* (W.H. Freeman and Company, 1993); A. L. Lehninger, *Biochemistry* (Worth Publishers, Inc., current addition); Sambrook, et al., *Molecular Cloning: A Laboratory Manual* (2nd Edition, 1989); *Methods In Enzymology* (S. Colowick and N. Kaplan eds., Academic Press, Inc.); *Remington's Pharmaceutical Sciences,* 18th Edition (Easton, Pa.: Mack Publishing Company, 1990); Carey and Sundberg *Advanced Organic Chemistry 3rd Ed.* (Plenum Press) Vols A and B (1992).

Example 1

Biomass Increase by Low Intensity-Illumination Application to Microalgae Fermentation

[0273] *Botryococcus* naturally synthesizes and tolerates hydrocarbon mixtures and produces as much as 85% hydrocarbon by weight, and in many cases the major hydrocarbon is botryococcenes. It is also known to be an obligate phototroph, but it seems to have the ability to uptake glucose (Reference: "Biosynthesis of the triterpenoids, botryococcenes and tetramethylsqualene in the B race of *Botryococcus braunii* via the non-mevalonate pathway" Sato et al. 2003. Tetrahedron Letter 44:7035-7037).

[0274] *Botryococcus* culture is grown on BG11 media (Reference: "Autotrophic cultivation of *Botryococcus braunii* for the production of hydrocarbons and exopolysaccharides in various media". Dayananda et al. 2007. Biomass and Bioenergy. 31: 87-93) at 25-35° C. in a bioreactor with 10-30% of dissolved oxygen. The effects of light signal on heterotrophic growth of *Botryococcus* are tested by comparing the cellular dry weight of the cultures from different conditions (dark+no glucose, dark+glucose, light+no glucose, and light+glucose). Optimum light intensity (0.01-300 μmol photons $m^{-2}s^{-1}$) and different light spectrum (360-700 nm) as well as different light periods (9-16 hr) are tested. Combination of low irradiance of light and glucose results in a) improved growth rate, b) increased products such as carotenoids, lipids, and botryococcenes.

Example 2

Light Regulation of Isoprenoid Pathway

[0275] Isoprene, monoterpenes and sesquiterpenes are synthesized and emitted by some plant and microalgal species, but not all species have this ability. These volatile, nonessential isoprenoid compounds share the same biochemical precursors as larger commercially useful isoprenoids such as carotenoids and hydrocarbons. Two separate pathways operate in plant cells to synthesize prenyl diphosphate precursors common to all isoprenoids.

[0276] Cytosolic and mitochondrial precursors are produced by the mevalonic acid (MVA) pathway whereas the recently discovered methylerythritol phosphate (MEP) pathway is located in plastids. *Botryococcus braunii* produces hydrocarbon by the non-mevalonic, MEP pathway (FIG. **2**).

[0277] Light is the most important environmental factor for regulation of MEP pathway. 1-deoxy-d-xylulose 5-phosphate reductoisomerase (DXR) is the rate limiting step, and the expression of the gene encoding DXR is regulated by light (Reference: "Expression and molecular analysis of the *Arabidopsis* DXR gene encoding 1-deoxy-d-xylulose 5-phosphate reductoisomerase, the first committed enzyme of the 2-c-methyl-d-erythritol 4-phosphate pathway". Carretero-Paulet et al. Plant Physiology. 2002. 129:1581-1591).

[0278] Another example is blue-light activation of genes encoding carotenoid biosynthetic enzymes in *Chlamydomonas reinhardtii*, an unicellular green alga. Microarray and quantitative PCR experiments showed the genes encoding carotenoid biosynthetic enzymes such as PDS, HDS, PSY, and ZDS are activated by very low irradiance of white light (0.01 μmol photons $m^{-2}s^{-1}$) and blue light. Further evidence suggested phototropin, a blue light receptor, is involved in blue-light activated gene expression for carotenoid biosynthesis (Reference: "Phototropin involvement in the expression of genes encoding chlorophyll and carotenoid biosynthesis enzymes and LHC apoproteins in *Chlamydomonas reinhardtii*". Im et al. The Plant Journal. 2006. 48:1-16).

[0279] One example is the increase of hydrocarbon production from Botryococcus. Various light intensity (0.01-300 μmol photons $m^{-2}s^{-1}$) and different light spectrum (360-700

nm) are applied to a *Botryococcus* culture, and the amount of different hydrocarbon species are measured by GC-MS.

Example 3

Growth of *Neochloris oleabundans* Under Different Light Conditions

[0280] Materials and Methods

[0281] Microalgae and Culture Condition

[0282] *Neochloris oleabundans* strain UTEX 1185 was obtained from the culture collection of algae at the University of Texas (Austin, Tex. USA). Initial culture of the microalgae was grown in Erlenmeyer 250 ml flask containing 120 ml modified bold 3 N medium with 2% glucose at 25° C. room temperature with an aluminum foil loosely covering the flask on an orbital shaker at 130 rpm under alternating two 40 W natural sunshine (392316, Philips) and two 40 W plant and aquarium (392282, Philips) fluorescent light bulbs. The culture medium (modified MB3N) contained the following components per 1 L of deionized water: 0.75 g $NaNO_3$, 0.075 g K_2HPO_4, 0.074 g $MgSO_4$ $7H_2O$, 0.025 g $CaCl_2$ $2H_2O$, 0.176 g KH_2PO_4, 0.025 g NaCl, 6 ml of P-IV metal solution (0.75 g Na_2EDTA $2H_2O$, 0.097 g $FeCl_3$ $6H_2O$, 0.041 g $MnCl_2$ $4H_2O$, 0.005 g $ZnCl_2$, 0.002 g $CoCl_2$ $6H_2O$, 0.004 g Na_2MoO4 $2H_2O$ in 1 L dI water), 1 ml of each three vitamins (0.1 mM vitamin B12, 0.1 mM biotin, 6.5 mM thiamine dissolved separately in 50 mM HEPES pH7.8). Final pH of the medium was adjusted to 7.5 with 20% KOH before autoclaving the medium. The vitamin solutions were added to cool down the autoclaved medium. Once the initial culture reached certain confluence, its concentration was measured using optical density (OD) at 680 nm and 750 nm using Genesys 10 UV spectrophotometer (Thermo Scientific).

[0283] Experimental Procedure and Growth Measurement

[0284] Three different wavelengths of light (white, blue, and red) were tested. LED lights were purchased from Super Bright LEDs, Inc. (white: RL5-W3030, blue: RL5-B2430, red: RL5—R1330). For each light wavelength, four different conditions were set up in duplicate as follows:

[0285] 1-2. Modified MB3N+no glucose+dark

[0286] 3-4. Modified MB3N+no glucose+dim light

[0287] 5-6. Modified MB3N+2% glucose+dark

[0288] 7-8. Modified MB3N+2% glucose+dim light

[0289] A total of eight 250 ml Erlenmeyer flasks containing a final volume of 120 ml cell culture were prepared with an initial cell concentration of OD 0.1 at 750 nm (~1.1×10^6 cells/ml) for each condition. Intensity of light was set at 3-4 $\mu mol/m^2s^{-1}$ photons for white, 2-3 $\mu mol/m^2s^{-1}$ photons for blue, and 1-2 $\mu mol/m^2s^{-1}$ photons for red. The speed of the orbital shaker was set at 135 rpm. The experiment was carried out at room temperature for two weeks. 1 ml of cell culture was obtained from each flask every 24 hrs to evaluate cell concentrations by measuring OD at 680 nm and 750 nm using Genesys 10 UV spectrophotometer from Thermo Fisher Scientific (Waltham, Mass. USA). Specific growth rate was determined by plotting the logarithm of culture optical density against time (FIG. **3**). The combination of a low irradiance of red, white, or blue light and glucose resulted in an improved growth rate compared to controls.

Example 4

Growth of *Botryococcus sudeticus* Under Different Light Conditions

[0290] Materials and Methods

[0291] Strains and Media

[0292] *Botryococcus sudeticus* strain UTEX 2629 was obtained from the algae culture collection at the University of Texas (Austin, Tex. USA). Stock culture was grown in Erlenmeyer 250 ml flasks containing 120 ml modified BG11 medium with 2% glucose at 25° C. room temperature with dim light (4-5 $\mu mol/m^2s^{-1}$ photons) on an orbital shaker at 130 rpm. Dim lighting is composed of two different bulbs, 40 W natural sunshine (392316 Philips) and 40 W plant and aquarium fluorescent light bulbs (392282 Philips). 1 L of culture medium (Modified BG-11) contained: 10 mM HEPES (pH 7.8), 1.5 g $NaNO_3$, 0.04 g K_2HPO_4, 0.06 g $MgSO_4$ $7H_2O$, 0.036 g $CaCl_2$ $2H_2O$, 0.006 g Citric acid H_2O, 0.0138 g Ammonium Ferric Citrate, 0.001 g Na_2EDTA $2H_2O$, 0.02 g Na_2CO_3, 2.86 mg H_3BO_3, 1.81 mg $MnCl_2$ $4H_2O$, 0.22 mg $ZnSO_4$ $7H_2O$, 0.39 mg Na_2MoO_4 $2H_2O$, 0.079 mg $CuSO_45H_2O$, 0.0494 mg $Co(NO_3)_2$ $6H_2O$, 0.5 g casein hydrolysate, and 1 ml of each three vitamins (0.1 mM vitamin B12, 0.1 mM biotin, 6.5 mM thiamine dissolved separately in 50 mM HEPES pH7.8). Final pH of the medium was adjusted to 7.8 with 20% KOH.

[0293] Experimental Procedure and Growth Measurement

[0294] Three different wavelengths of light (white, blue, and red) were tested. LED lights were purchased from Super Bright LEDs, Inc. (white: RL5-W3030, blue: RL5-B2430, red: RL5—R1330). For each light wavelength, four different conditions were set up in duplicate as follows:

[0295] 1-2. Modified BG-11+no glucose+dark

[0296] 3-4. Modified BG-11+no glucose+dim light

[0297] 5-6. Modified BG-11+2% glucose+dark

[0298] 7-8. Modified BG-11+2% glucose+dim light

[0299] A total of eight 250 ml Erlenmeyer flasks containing a final volume of 120 ml cell culture were prepared with an initial cell concentration of OD 0.1 at 750 nm (~1.1×10^6 cells/ml) for each condition. Intensity of light was set at 3-4 $\mu mol/m^2s^{-1}$ photons for white, 2-3 $\mu mol/m^2s^{-1}$ photons for blue, and 1-2 $\mu mol/m^2s^{-1}$ photons for red. The speed of the orbital shaker was set at 135 rpm. The experiment was carried out at room temperature for two weeks. 1 ml of cell cultures was obtained from each flask everyday to evaluate cell concentrations by measuring OD at 680 nm and 750 nm using Genesys 10 UV spectrophotometer from Thermo Fisher Scientific (Waltham, Mass. USA). Specific growth rate was determined by plotting the logarithm of culture optical density against time (FIG. **4**). The combination of a low irradiance of red, white, or blue light and glucose resulted in an improved growth rate compared to controls.

Example 5

Botryococcus braunii: Fermentation with Controlled Illumination

[0300] Materials and Methods

[0301] Strains and Media

[0302] *Botryococcus braunii* strain UTEX 2441 was obtained from the algae culture collection at the University of Texas (Austin, Tex. USA). Stock culture was grown in Erlenmeyer 250 ml flasks containing 120 ml modified BG11 medium with 2% glucose at 25° C. room temperature with

dim light (4-5 μmol/m^2s^{-1} photons) on an orbital shaker at 130 rpm. Dim lighting was composed of two different bulbs, 40 W natural sunshine (392316 Philips) and 40 W plant and aquarium fluorescent light bulbs (392282 Philips). 1 L of culture medium (Modified BG-11) contained: 10 mM HEPES (pH 7.8), 1.5 g $NaNO_3$, 0.04 g K_2HPO_4, 0.06 g $MgSo_4$ $7H_2O$, 0.036 g $CaCl_2$ $2H_2O$, 0.006 g Citric acid H_2O, 0.0138 g Ammonium Ferric Citrate, 0.001 g Na_2EDTA $2H_2O$, 0.02 g Na_2CO_3, 2.86 mg H_3BO_3, 1.81 mg $MnCl_2$ $4H_2O$, 0.22 mg $ZnSO_4$ $7H_2O$, 0.39 mg Na_2MoO_4 $2H_2O$, 0.079 mg $Cu50_45H_2O$, 0.0494 mg $Co(NO_3)_2$ $6H_2O$, 0.5 g casein hydrolysate, and 1 ml of each three vitamins (0.1 mM vitamin B12, 0.1 mM biotin, 6.5 mM thiamine dissolved separately in 50 mM HEPES pH7.8). Final pH of the medium was adjusted to 7.8 with 20% KOH.

[0303] Experimental Procedure and Growth Measurement

[0304] Three different wavelengths of lights (white, blue, and red) were tested. LED lights were purchased from Super Bright LEDs, Inc. (white: RL5-W3030, blue: RL5-B2430, red: RL5—R1330). For each light wavelength, four different conditions were set up in duplicate as follows:

[0305] 1-2 Modified BG-11+no glucose+dark

[0306] 3-4 Modified BG-11+no glucose+dim light

[0307] 5-6 Modified BG-11+2% glucose+dark

[0308] 7-8 Modified BG-11+2% glucose+dim light

[0309] A total of eight 250 ml Erlenmeyer flasks containing a final volume of 120 ml cell culture were prepared with an initial cell concentration of O.D 0.1 at 750 nm (~1.1×10^6 cells/ml) for each condition. The intensity of light was set at 3-4 μmol/m^2s^{-1} photons for white, 2-3 μmol/m^2s^{-1} photons for blue, and 1-2 μmol/m^2s^{-1} photons for red. The speed of the orbital shaker was set at 150 rpm. The experiment was carried out at room temperature for two weeks. 5 ml of each cell culture was obtained from each flask every two days to evaluate cell growth by dry cell weight (DCW). Specific growth rate was determined by plotting the culture DCW against time (FIG. **5**).

[0310] Fluorescence Measurement of Neutral Lipid by Using Nile Red

[0311] In 1 ml of algal suspension, 4 ul of Nile Red solution in acetone (250 ug/ml) was added. The mixture was vortexed 2 times during a 10 minute incubation at room temperature. After incubation, 200 ul of stained algal samples were transferred into individual wells in a 96-well plate. Fluorescence was measured on a Molecular Devices 96 well plate spectrofluorometer with a 490 nm excitation and 585 nm emission wavelength with 530 emission filter cut off. In order to determine the relative fluorescence intensity of algal samples, blank (Nile Red alone in the medium) was subtracted from the fluorescence intensity.

[0312] Results

[0313] Red light+glucose increased the growth rate of UTEX 2441 by 35% compared to heterotrophic culture in the dark (Dark+glu) (FIG. **5**). Lipid levels also increased by 52% under red light conditions compared to controls (FIG. **6**).

Example 6

Chlamydomonas reinhardtii: Fermentation with Controlled Illumination

[0314] Materials and Methods

[0315] Strains and Media

[0316] *Chlamydomonas reinhardtii* strain UTEX 2243 was obtained from the algae culture collection at the University of Texas (Austin, Tex. USA). Stock cultures were grown separately in Erlenmeyer 250 ml flasks containing 120 ml TAP medium at 25° C. room temperature with dim light (4-5 μmol/m^2s^{-1} photons) on an orbital shaker at 130 rpm. Dim lighting was composed of two different bulbs (40 W natural sunshine (392316 Philips) and 40 W plant and aquarium fluorescent light bulbs (392282 Philips)). 1 L of culture medium (TAP) contained: 2.42 g Tris, 25 ml of TAP salts solution (15 g NH4Cl, 4 g $MgSO_4$ $7H_2O$, 2 g $CaCl_2$ $2H_2O$), 0.375 ml Phosphate solution (28.8 g K_2HPO_4, 14.4 g KH2PO_4 in 100 ml of water), 1 ml Hutner's trace elements solution (1 L of Trace metal solution contains 50 g EDTA disodium Salt, 22 g $ZnSO_4$ $7H_2O$, 11.4 g H_3BO_4, 5.06 g $MnCl_2$ $4H_2O$, 1.61 g $CoCl_2$ $6H_2O$, 1.57 g $CuSO_4$ $5H_2O$, 1.10 $(NH_4)_6Mo_7O_{24}$ $4H_2O$, 4.99 g $FeSO_4$ $7H_2O$ with pH 7.0 using either KOH or HCl) and 1 ml of glacial acetic acid. Final pH of medium is 7.0 adjusted with glacier acetic acid. Tris minimal medium (TP) was made with all components listed above except acetic acid. The medium's pH was adjusted to 7.0 with HCl.

[0317] Experimental Procedure and Growth Measurement

[0318] LED lights were purchased from Super Bright LEDs, Inc. (RL5-W3030). Four different conditions were set up in duplicate as follows:

[0319] 1-2. TP (no acetic acid)+dark

[0320] 3-4. TP (no acetic acid)+dim light

[0321] 5-6. TAP (acetic acid)+dark

[0322] 7-8. TAP (acetic acid)+dim light

[0323] A total of eight 250 ml Erlenmeyer flasks containing a final volume of 120 ml cell culture were prepared with an initial cell concentration of 1.0×10^5 cells/ml for each condition. The intensity of light was set at 3-5 μmol/m^2s^{-1} photons. The speed of the orbital shaker was set at 140 rpm. The experiment was carried out at room temperature for one week. 500 ul of cell culture was obtained from each flask every day to evaluate cell growth by counting cell numbers. Cells were deflagellated using lugol solution (1:20) prior to counting. Specific growth rate was determined by plotting the cell number against time. The combination of a low irradiance of white light and TAP resulted in an improved growth rate compared to controls (FIG. **7**).

Example 7

Cultivation of Microalgae with a Low Irradiance of Light

[0324] Materials and Methods

[0325] Strains and Media

[0326] Microalgae strains (e.g., *Chlamydomonas, Botryococcus, Neochloris, Cyanophyta, Chlorophyta, Rhodophyta, Cryptophyta, Chlorarachniophyta, Haptophyta, Euglenophyta, Heterokontophyta, Diatoms* and/or those described in the description above) are obtained from, e.g., the algae culture collection at the University of Texas (Austin, Tex. USA). Stock culture is grown, e.g., in Erlenmeyer 250 ml flasks containing the appropriate medium (see, e.g., manufacturer's instructions) at about 25° C. room temperature with dim light (e.g., 4-5 μmol/m^2s^{-1} photons) on an orbital shaker at about 130 rpm. An appropriate carbon source is used in the culture media, e.g., glucose. Dim lighting can be composed of two different bulbs, e.g., 40 W natural sunshine (392316 Philips) and 40 W plant and aquarium fluorescent light bulbs (392282

Philips). The final pH of the medium is adjusted as appropriate for the particular strain. See, e.g., manufacturer's instructions.

[0327] Experimental Procedure and Growth Measurement

[0328] Three different wavelengths of light (white, blue, and red) are tested. LED lights are purchased from, e.g., Super Bright LEDs, Inc. (white: RL5-W3030, blue: RL5-B2430, red: RL5—R1330). For each light wavelength, four different conditions are set up in duplicate as follows:

[0329] 1-2 no carbon+dark

[0330] 3-4 no carbon+dim light

[0331] 5-6 carbon+dark

[0332] 7-8 carbon+dim light

[0333] A total of eight 250 ml Erlenmeyer flasks containing a final volume of 120 ml cell culture are prepared with an initial cell concentration of, e.g., O.D 0.1 at 750 nm (~1.1×10^6 cells/ml) for each condition. Optimum light intensity (e.g., 0.01-300 μmol photons $m^{-2}s^{-1}$) and different light spectrums (e.g., 360-700 nm) as well as different light periods (e.g., 9-16 hr of light) are tested. The intensity of light is set at, e.g., 3-4 μmol/m^2s^{-1} photons for white, 2-3 μmol/m^2s^{-1} photons for blue, and 1-2 μmol/m^2s^{-1} photons for red. Various carbon sources at various concentrations are tested, e.g., glucose, sucrose, fructose at a concentration of, e.g., 1%, 2%, or 3% of culture media. The speed of the orbital shaker is set at, e.g., 150 rpm. The experiment is carried out at room temperature for less than one, one, two, three, or more weeks. An aliquot of each cell culture is obtained from each flask every one to two days to evaluate cell growth by, e.g., dry cell weight (DCW). Specific growth rate is determined by plotting the culture DCW against time.

[0334] Measurement of Material of Interest

[0335] The amount of material of interest (hydrocarbon, lipid, etc.) in the media is measured using standard means known in the art, e.g., GC-MS or Nile Red as described above. For example, in 1 ml of algal suspension, 4 ul of Nile Red solution in acetone (250 ug/ml) is added. The mixture is vortexed during incubation at room temperature. After incubation, 100-200 ul of stained algal samples are transferred into individual wells in a 96-well plate. Fluorescence is measured on, e.g., a Molecular Devices 96 well plate spectrofluorometer with a 490 nm excitation and 585 nm emission wavelength with 530 emission filter cut off. In order to determine the relative fluorescence intensity of algal samples, blank (Nile Red alone in the medium) is subtracted from the fluorescence intensity.

[0336] Results

[0337] Red, white, and/or blue light in combination with a carbon source increase the growth rate of the microalgae strain compared to controls. Material of interest (e.g., hydrocarbon or lipid) levels produced by the experimental microalgae strain (red, white, and/or blue light in combination with a carbon source) increase compared to controls.

[0338] While the invention has been particularly shown and described with reference to a preferred embodiment and various alternate embodiments, it will be understood by persons skilled in the relevant art that various changes in form and details can be made therein without departing from the spirit and scope of the invention.

[0339] All references, issued patents and patent applications cited within the body of the instant specification are hereby incorporated by reference in their entirety, for all purposes.

1. A method for cultivating a microalgae capable of heterotrophic growth, comprising:

incubating the microalgae under a heterotrophic growth condition for a period of time sufficient to allow the microalgae to grow, wherein the heterotrophic growth condition comprises a media comprising a carbon source, and wherein the heterotrophic growth condition further comprises a low irradiance of light.

2. The method of claim **1**, wherein the microalgae is a *Botryococcus* strain, wherein the carbon source is glucose, and wherein the low irradiance of light is between 1-10 μmol photons $m^{-2}s^{-1}$.

3. The method of claim **1**, wherein the microalgae is a *Botryococcus sudeticus* strain, a *Botryococcus* strain, a UTEX 2629 strain, a *Botryococcus braunii* strain, a UTEX 2441 strain, a *Neochloris oleabundans* strain, a *Neochloris* strain, a UTEX 1185 strain, a *Chlamydomonas reinhardtii* strain, a *Chlamydomonas* strain, a UTEX 2243 strain, or a strain comprising a photoreceptor.

4. (canceled)

5. The method of claim **2**, wherein the microalgae is a UTEX 2629 strain or a UTEX 2441 strain.

6. (canceled)

7. (canceled)

8. (canceled)

9. (canceled)

10. (canceled)

11. (canceled)

12. (canceled)

13. (canceled)

14. (canceled)

15. The method of claim **1**, wherein the carbon source is glucose.

16. The method of claim **1**, wherein the carbon source is selected from the group consisting of a fixed carbon source, glucose, fructose, sucrose, galactose, xylose, mannose, rhamnose, N-acetylglucosamine, glycerol, floridoside, glucuronic acid, corn starch, depolymerized cellulosic material, sugar cane, sugar beet, lactose, milk whey, and molasses.

17. The method of claim **1**, wherein the light is produced by a natural light source, the light is natural sun light, the light comprises full spectrum light or a specific wavelength of light, the light is produced by an artificial light source, or the light is artificial light.

18. (canceled)

19. (canceled)

20. (canceled)

21. (canceled)

22. The method of claim **1**, wherein the intensity of the low irradiance of light is between 0.01-1 μmol photons $m^{-2}s^{-1}$, between 1-10 μmol photons $m^{-2}s^{-1}$, between 10-100 μmol photons $m^{-2}s^{-1}$, between 100-300 μmol photons $m^{-2}s^{-1}$, 3-4 μmol/m^2s^{-1} photons, 2-3 μmol/m^2s^{-1} photons, 1-2 μmol/m^2s^{-1} photons, or 3-5 μmol/m^2s^{-1} photons.

23. (canceled)

24. (canceled)

25. (canceled)

26. (canceled)

27. (canceled)

28. The method of claim **1**, further comprising producing a material from the microalgae.

29. The method of claim **28**, wherein the material is a polysaccharide, a pigment, a lipid, or a hydrocarbon.

30. The method of claim **28**, wherein the material is a hydrocarbon.

31. The method of claim **28**, further comprising recovering the material.

32. The method of claim **28**, further comprising extracting the material.

33. The method of claim **28**, further comprising processing the material.

34. The method of claim **31**, further comprising processing the material.

35. The method of claim **33**, wherein the processing of the material produces a processed material.

36. The method of claim **35**, wherein the processed material is selected from the group consisting of a fuel, biodiesel, jet fuel, a cosmetic, a pharmaceutical agent, a surfactant, and a renewable diesel.

37. The method of claim **1**, wherein the growth rate of the microalgae is higher than a second microalgae incubated under a second heterotrophic growth condition for a period of time sufficient to allow the microalgae to grow, wherein the second heterotrophic growth condition comprises a growth media comprising a carbon source, and wherein the second heterotrophic growth condition does not comprise a low irradiance of light.

38. (canceled)

39. A method of manufacturing a material, comprising:

providing a microalgae capable of producing the material;

culturing the microalgae in a media, wherein the media comprises a carbon source;

applying a low irradiance of light to the microalgae; and

allowing the microalgae to accumulate at least 10% of its dry cell weight as the material.

40. (canceled)

41. A bioreactor system, comprising:

a bioreactor;

a culture media comprising a carbon source, wherein the culture media is located inside the bioreactor;

a microalgae adapted for heterotrophic growth, wherein the microalgae is located in the culture media; and

a light source, wherein the light source produces a low irradiance of light, and wherein the light source is operatively coupled to the bioreactor.

42. (canceled)

43. (canceled)

44. (canceled)

45. (canceled)

46. (canceled)

47. (canceled)

* * * * *

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(56) Für die Beurteilung der Patentfähigkeit in Betracht gezogene Druckschriften:

US	2008/01 05 535	A1
US	2007/01 81 508	A1
EP	1 753 831	B1
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CN	1 012 54 463	A
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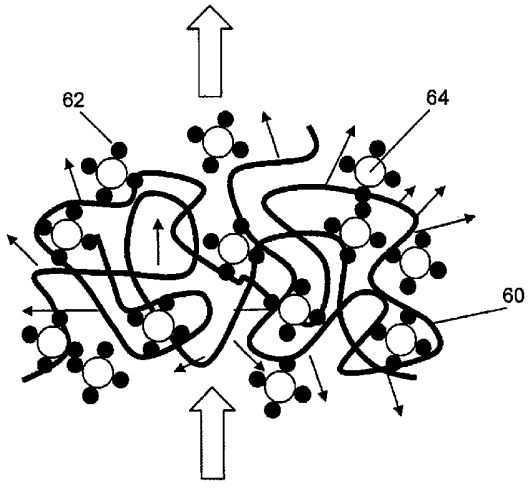
Eberl,J., Kisch,H.: Visible light photo-oxidations in the presence of α-Bi2O3. In: Photochem. Photobiol. Sci., 2008, 7, 1400-1406

Wang,C., et.al.: Photocatalytic properties BiOCl and Bi2O3 nanofibers prepared by electrospinning. In: Scripta Materialia 59 (2008) 332-335

Die folgenden Angaben sind den vom Anmelder eingereichten Unterlagen entnommen

Prüfungsantrag gemäß § 44 PatG ist gestellt.

(54) Bezeichnung: **Photokatalysatoreinrichtung**



(57) Zusammenfassung: Die Erfindung betrifft eine Photokatalysatoreinrichtung mit einem Lichtelement und einer auf dem Lichtelement angeordneten photokatalytischen Substanz. Sie ist dadurch gekennzeichnet, dass die photokatalytische Substanz Bi_2O_3 und/oder N-dotiertes TiO_2 und/oder C-dotiertes TiO_2 und/oder S-dotiertes TiO_2 aufweist.

Beschreibung

[0001] Die Erfindung betrifft eine Photokatalysatoreinrichtung mit einem Lichtelement und einer auf dem Lichtelement angeordneten photokatalytischen Substanz.

[0002] Die Photokatalyse und genauer photoassistierte katalytische Reaktion, bei der unter Einwirkung von Licht geeigneter Wellenlänge eine Katalysator-Substanz in einen angeregten Zustand gebracht wird, der dann die notwendige Energie für eine anschließende Reduktion und/oder Oxidation bereitstellt, ist in der Literatur vielfach beschrieben. Als photokatalytische Substanz wird Titandioxid (TiO_2), insbesondere in der Form von Anatas eingesetzt. Bekannte Anwendungen sind beispielsweise die Abwasser- oder Abgasreinigung, die Photovoltaik, die photokatalytische Selbstreinigung oder die künstliche Photosynthese.

[0003] Die eingangs genannten Photokatalysatoreinrichtungen zur Zersetzung organischer Verbindungen, insbesondere zur Abgasnachbehandlung sind aus zahlreichen Druckschriften bekannt. Beispielhaft wird auf die Patentschrift US 5,564,065 hingewiesen, in der eine Filteranordnung zur Oxidation von Kohlenmonoxid in Abgasen beschrieben wird. Die Filteranordnung weist ein Gewebe eines mit Titandioxid beschichteten Fasermaterials, einen daneben angeordneten Lichtwellenleiter zum Aussenden von Streulicht, eine UV-Lichtquelle, die mit dem Lichtwellenleiter verbunden ist und eine Abgasleitung zum Hindurchführen von Abgas durch das Gewebe des Fasermaterials auf.

[0004] Aus der Patentschrift US 6,324,329 B1 ist eine Photokatalysatoreinrichtung bekannt, bei der eine mehrschichtige Lichtleiterstruktur auf einem Substrat mit einer Titandioxid-Photokatalysatorschicht versehen ist. Licht mit einem Intensitätsmaximum bei einer Wellenlänge von etwa 400 nm wird ausgehend von einer künstlichen Lichtquelle in eine Lichtleiterschicht aus Ta_2O_5 oder Polymetylmethacrylat (PMMA) eingekoppelt. Das Licht tritt entlang der Lichtleiterschicht in eine entweder unmittelbar auf der Lichtleiterschicht angeordneten TiO_2-Photokatalysatorschicht oder über eine zwischengeschaltete Pufferschicht in die Photokatalysatorschicht, begünstigt durch Anpassung der Schichtdicken und der Brechungsindizes, ein und bringt das Titandioxid in einen angeregten Zustand für eine folgende katalytische Reaktion.

[0005] Auch aus der EP 1 008 565 A1 ist eine Photokatalysatoreinrichtung basierend auf einer TiO_2-Beschichtung bekannt. Die photokatalytische Substanz wird in einem Sol-Gel-Prozess in mehreren Tauch- und Trockenschritten auf einer Glasfaser aufgetragen. Die Glasfaser wird zu einem Faden, einem Seil oder einem Gewebe verarbeitet, welches als Photokatalysatoreinrichtung zur Zersetzung organischer Substanzen verwendet werden kann.

[0006] Auch in der US 6,468,428 B1 wird ein Titandioxid-Film in einem Sol-Gel-Prozess auf ein Fasersubstrat aus einem Aluminiumsilicat-Glas aufgetragen, welches entlang seiner Umfangsfläche eine Vielzahl von Vorsprüngen oder Noppen aufweist. Mehrere solcher Fasern werden zu einem Bündel zusammengefasst, wobei die Noppen die Glasfasern in der Gestalt auf Abstand halten, dass ein hinreichend großer Hohlraum zum Durchleiten von Abgasen entsteht. Anstelle des Glasfaserbündels kann die Glasfaser auch zu einem Netz geflochten, zu einem Gewebe verarbeitet oder zu einem Knäuel geformt werden. Ferner wird eine wabenförmige Lichtleiterstruktur sowie eine Anordnung paralleler Lichtleiterplatten vorgestellt. Die Photokatalysatoreinrichtung ist zum Einsatz in einem Dieselpartikelfilter (DPF) vorgesehen.

[0007] Eine Weiterbildung der Photokatalysatoreinrichtung mit gebündelten. Glasfasern ist aus der US 6,764,655 B1 bekannt, wobei die Glasfasern von granularen Abstandshaltern umgeben sind und parallel in einem länglichen Gehäuse angeordnet sind, das in Längsrichtung von Abgas durchströmt wird.

[0008] Die US-Patentschrift 6,685,889 B1 stellt einen photochemischen Katalysator auf Basis einer lichtleitenden Faser vor, welche in einem Sol-Gel-Tauchbeschichtungsverfahren mit einer Zeolith-Schicht als katalytische Substanz beschichtet ist. Ist die lichtleitende Faser ummantelt, so wird der Mantel zumindest auf einem Abschnitt der lichtleitenden Faser entfernt, auf dem dann die Zeolith-Kristallschicht aufgebracht wird.

[0009] Die Eignung von Titandioxid als photokatalytische Substanz ist auf dessen Halbleitereigenschaft mit einer Bandlücke zurückzuführen, deren Energieabstand einer Licht-Wellenlänge von etwa 390 nm entspricht. Licht mit dieser oder einer kürzeren Wellenlänge vermag in dem Material Elektron-Loch-Paare, also einen inneren photoelektrischen Effekt zu erzeugen, der die Ausgangsbasis zur Erzeugung von Radikalen für die Zersetzung organischer Substanzen bildet. Somit kommt als Anregungsenergie überwiegend nur ultraviolettes Licht in Frage, welches gemessen an dem sichtbaren Anteil der terrestrischen Sonnenstrahlung nur einen sehr geringen Anteil ausmacht. Für eine effiziente photokatalytische Wirkung wird deshalb eine künstliche

Lichtquelle benötigt. Desweiteren hat die Verwendung von UV-Licht den Nachteil, dass für die Lichtleitung nur Quarzgläser zur Anwendung kommen können und eine Vielzahl kostengünstigere Lichtleitermaterialien in diesem Spektralbereich ungeeignet ist.

[0010] Die Aufgabe vor dem Hintergrund des vorstehenden Stands der Technik ist es, eine Photokatalysatoreinrichtung der eingangs genannten Art bereitzustellen, die auch unter der Verwendung von Licht anderer Wellenlänge, insbesondere von sichtbarem Licht, eine effiziente photokatalytische Zersetzung organischer Substanzen ermöglicht und die zudem kostengünstig in ihrer Herstellung ist.

[0011] Die Aufgabe wird erfindungsgemäß durch eine Photokatalysatoreinrichtung mit den Merkmalen des Patentanspruchs 1 gelöst. Vorteilhafte Weiterbildungen der Erfindung sind Gegenstand der Unteransprüche.

[0012] Als photokatalytische Reaktion im Sinne dieser Schrift werden sogenannte photosensibilisierte Reaktionen verstanden. Bei Reaktionen dieser Art wird die als Photokatalysator oder photokatalytisch (aktiv) bezeichnete Substanz durch Licht in einen elektronisch angeregten Zustand überführt, in dem sie dann katalytisch aktiv ist. Bei einigen der im Folgenden als photokatalytisch bezeichneten Substanzen gibt es Hinweise darauf, dass es sich hierbei nicht um Katalysatoren im strengen Sinne handeln könnte, da sie sich im Laufe der Reaktion umsetzen bzw. umwandeln, wobei ihre photokatalytische Aktivität verloren geht. Hierbei müsste man streng genommen von einer durch diese Substanzen „assistierten Photoreaktion" sprechen. Im Rahmen dieser Anmeldung werden unter photokatalytischen Reaktionen sowohl die klassischen photosensibilisierten katalytischen Reaktionen als auch die in vorstehendem Sinne assistierten Photoreaktionen verstanden.

[0013] Erfindungsgemäß weist die photokatalytische Substanz Bi_2O_3 und/oder N-dotiertes TiO_2 und/oder C-dotiertes TiO_2 und/oder S-dotiertes TiO_2 und/oder eine binäre Bismut-Metalloxid-Verbindung auf, insbesondere eine Verbindung aus der Gruppe $MBiO_3 \cdot xH_2O$, mit M = Alkali, $x \geq 0$, $BiVO_4$, Bi_2MoO_6 und Bi_2WO_6.

[0014] Bismutoxid weist einen elektronischen Bandabstand von 2,3 bis 2,9 eV in Abhängigkeit von der Präparation des Bismutoxid-Pulvers auf und ist somit hinsichtlich seiner photokatalytischen Aktivität wesentlich weniger begrenzt als TiO_2, dessen Bandlücke deutlich größer als 3,0 eV ist. Dies entspricht einer Lichtwellenlänge von 540 nm bis 427 nm und somit in jedem Fall einer Anregungsenergie, die vollständig im Bereich des sichtbaren Lichts liegt. Es hat sich konkret herausgestellt, dass Bismutoxid als photokatalytische Substanz unter Verwendung von Licht mit einer Wellenlänge größer als 420 nm eine äußerst hohe Photoaktivität aufweist. Dies ermöglicht eine effiziente photokatalytisch assistierte Zersetzungsreaktion von organischen Substanzen unter Verwendung von terrestrischer Sonnenstrahlung und somit ohne Bedarf einer zusätzlichen UV-Lichtquelle. Eine ähnlich hohe Photoaktivität konnte auch unter Verwendung von C-dotiertem TiO_2 verzeichnet werden, während N-dotiertes TiO_2 eine um etwa 30% reduzierte Photoaktivität aufweist. Auch eine Dotierung des Titandioxides mit Schwefel führt zu einer Verringerung der Bandlücke und damit im Vergleich zu undotiertem TiO_2 zu einer erhöhten photokatalytischen Aktivität.

[0015] Bevorzugt weist die photokatalytische Substanz α-Bi_2O_3 und/oder β-Bi_2O_3 auf.

[0016] Als vorteilhaft hat sich herausgestellt, dass das Lichtleitelement wenigstens eine Lichtleitfaser, insbesondere eine brechwertangepasste Lichtleitfaser mit einem lichtleitenden Kern ist, entlang dessen Außenumfangsfläche Streuzentren und die photokatalytische Schicht angeordnet sind.

[0017] Als brechwertangepasste Lichtleitfaser wird im Sinne dieser Schrift eine lichtleitende Faser verstanden, die entweder aus einem Faserkern alleine oder aber aus einem Faserkern und zumindest einem den Kern entlang der Faserachse umschließenden Mantel besteht. Im ersten Fall erfolgt die Lichtleitung in dem Faserkern durch Totalreflexion des in dem Kern geleiteten Lichts an der Grenzfläche zwischen dem Faserkern und dem umgebenden Medium, im zweiten Fall durch Totalreflexion an der Grenzfläche zwischen Mantel und dem umgebenden Medium, sofern das umgebende Medium einen kleineren Brechungsindex als der Mantel aufweist.

[0018] Ist der Faserkern entlang der Faserachse von zumindest einem Mantel umgeben, tritt die Totalreflexion und somit die Lichtleitung dann auf, wenn der Mantel einen im wesentlichen zumindest gleich großen Brechungsindex wie der Faserkern aufweist, damit das Licht überhaupt erst aus dem Kern in den Mantel auskoppeln kann. Das Licht wird demnach in dem System als Kern und Mantel geführt. Man spricht in diesem Fall auch von einer brechwertangepassten Kern-Mantel-Faser.

[0019] Da im allgemeinen eine möglichst gute Führung des Lichts in der Faser angestrebt wird, d. h. dass möglichst wenig Licht bei der Einkopplung in die Faser verlorengeht, wird eine Anpassung des Brechungsindex

des Faserkerns (im Fall der Kernfaser) bzw. des Mantels (im Fall der Kern-Mantel-Faser) durch geeignete Materialwahl vorgenommen, so dass der Grenzwinkel, bei dem noch Totalreflexion an der Grenzfläche zum umgebenden Medium stattfindet in geeigneter Weise eingestellt wird.

[0020] Seitenemittierend im Sinne dieser Schrift heißt, dass die Faser in der Lage ist, Licht seitlich zu emittieren, unabhängig davon, ob sie in Betrieb ist, d. h. ob tatsächlich eine Lichtquelle angeschlossen und das Licht eingeschaltet ist.

[0021] Eine seitenemittierende brechwertangepasste Faser ist dementsprechend eine brechwertangepasste Faser, bei der absichtlich Licht aus der Faser ausgekoppelt wird. Dies erfolgt durch die entlang der Außenumfangsfläche der Lichtleitfaser angeordneten Streuzentren. Im Falle der Kernfaser sind die Streuzentren also auf der Außenumfangsfläche des Kerns und im Falle der Kern-Mantel-Faser auf der Außenumfangsfläche des Mantels angeordnet.

[0022] Im Sinne der Erfindung werden als Streuzentren insbesondere Streupartikel verstanden, die, gleich welcher Form, welchen Materials und/oder welcher Größe, das geleitete Licht streuen können. Streupartikel können durch klassische Streuung, insbesondere Rayleigh- und/oder Mie-Streuung, ebenso wie durch Beugung und/oder Reflexion sowie Mehrfachprozesse vorgenannter Art untereinander ihre streuende Wirkung entfalten. Ihre Aufgabe ist, individuell oder in ihrer Summe auftreffendes Licht dergestalt abzulenken, dass es die Faser verlässt.

[0023] Da im allgemeinen eine gleichmäßige Auskopplung entlang der gesamten Länge der Lichtleitfaser erwünscht ist, welche eine seitenemittierende brechwertangepasste Lichtleitfaser im Idealfall als ein gleichmäßig leuchtendes Band oder eine gleichmäßig leuchtende Linie erscheinen lässt, werden die Streuzentren bevorzugt möglichst homogen auf der Außenumfangsfläche verteilt angeordnet.

[0024] Gemäß einer alternativen Ausführungsform ist die Lichtleitfaser vorteilhafterweise eine seitenemittierende Stufenindexfaser mit einem den Kern umschließenden transparenten und/oder transluzenten Mantel, wobei Streuzentren zwischen dem Mantel und dem Kern und die photokatalytische Schicht auf dem Mantel angeordnet sind.

[0025] Als Stufenindexfaser im Sinne dieser Schrift werden Fasern verstanden, bei denen die Lichtleitung in dem Faserkern durch Totalreflexion des im Kern geleiteten Lichts an der Grenzfläche zu dem umschließenden Mantel erfolgt. Diese Totalreflexion tritt dann auf, wenn der Mantel einen niedrigeren Brechungsindex aufweist als der des lichtleitenden Faserkerns und das auch nur bis zu einem Grenzwinkel β_{min} des auf den Mantel treffenden Lichts, der gemäß $\sin(\beta_{min}) = n_2/n_1$ mit n_1 = Brechungsindex des Faserkerns und n_2 = Brechungsindex des Mantels ermittelt werden kann, wobei β_{min} ausgehend von einer Ebene senkrecht zur Faserachse gemessen wird.

[0026] Der Effekt der Seitenemission wird bei dieser Ausgestaltung der Erfindung durch Streuung des in dem Kern geleiteten Lichts in einem im Verhältnis zum Kerndurchmesser dünnen Streubereich zwischen Kern und Mantel erzeugt. Verantwortlich für die Streuung sind die Streuzentren, welche in den Streubereich eingelagert sind. Im Sinne dieser Ausführungsform sind Streuzentren alle Gebilde gleich welcher Form, welchen Materials und/oder welcher Größe, die das geleitete Licht streuen können und die durch inhomogene Bereiche des Glases, in welches sie eingelagert sind, oder durch Streupartikel aus einem anderen Material als das Glas in welches sie eingebettet sind, gebildet werden. Ihre Aufgabe ist, wie vorstehend beschrieben, individuell oder in ihrer Summe auftreffendes Licht abzulenken, so dass es die Lichtleitfaser in das umgebende Medium verlassen kann. Konkret kommen als Streuzentren beispielsweise Streupartikel in Frage, welche in dem Streubereich zwischen dem Kern und dem Mantel beispielsweise in eine Glasschicht eingelagert sind. Alternativ können die Streuzentren durch inhomogene Bereiche eines zwischen dem Kern und dem Mantel eingelagerten Glases gebildet werden. Im ersteren Fall ist der Brechungsindex des den Streubereich bildenden Glases nach Möglichkeit gleich dem Brechungsindex des Kerns, damit das Licht ungehindert zu den darin eingelagerten Streupartikeln gelangen kann.

[0027] Im letzteren Fall kann der Brechungsindex der eingelagerten Glasschicht mit Inhomogenitäten von dem des Kerns und/oder dem des Mantels abweichen.

[0028] Auf dem Weg in das umgebende Medium trifft das seitenemittierte Licht dann auf die entlang der Außenumfangsfläche der Lichtleitfaser bzw. des Mantels angeordnete photokatalytische Substanz und regt diese zur Bildung eines Elektron-Loch-Paares an.

[0029] Das Lichtleitelement aus Glasfaser bestehend aus einem Kernglas und einem Mantelglas hat besonders bevorzugt eine der folgenden Zusammensetzungen:

Kernglas Variante 1 mit Brechungsindex n_1 von 1,65 bis 1,75, beinhaltend (in Mol% auf Oxidbasis)

SiO_2	25 bis 45
B_2O_3	13 bis 25
CaO	0 bis 16
SrO	0 bis 8
BaO	17 bis 35
La_2O_3	2 bis 12
Ta_2O_5	0,1 bis 6
ZrO_2	0,1 bis 8
ZnO	0,1 bis 8
CaO + SrO + BaO + ZnO	> 33
Al_2O_3	0 bis 5

Kernglas Variante 2 mit Brechungsindex n_1 von 1,65 bis 1,75, beinhaltend (in Mol% auf Oxidbasis)

SiO_2	54,5 bis 65
ZnO	18,5 bis 30
Summe der Alkalioxide	8 bis 20
La_2O_3	0 bis 3
ZrO_2	2 bis 5
HfO_2	0,02 bis 5
$ZrO_2 + HfO_2$	2,02 bis 5
BaO	0,4 bis 6
SrO	0 bis 6
MgO	0 bis 2
CaO	0 bis 2
Summe der Erdalkalioxide	0,4 bis 6
Li_2O	0,5 bis 3, jedoch nicht mehr als 25 Mol% der Summe der Alkalioxide
$SiO_2 + ZrO_2 + HfO_2$	> 58,5

Verhältnis ZnO:Summe der Erdalkalioxide > 3,5:1

Kernglas Variante 3 mit Brechungsindex n_1 von 1,58 bis 1,65, beinhaltend (in Mol% auf Oxidbasis)

SiO_2	50 bis 60
B_2O_3	0 bis 15
BaO	10 bis 35
SrO	0 bis 18
Sr + Ba	10 bis 35
ZnO	0 bis 15
Sr + Ba + Zn	10 bis 40
$B_2O_3 + ZnO$	5 bis 35

Al_2O_3	0,1 bis 1,9
ZrO_2	0 bis 4
La_2O_3	0 bis 4
Y_2O_3	0 bis 4
Nb_2O_5	0 bis 4
$La_2O_3 + Y_2O_3 + Nb_2O_5$	0 bis 4
Na_2O	4,5 bis 10
K_2O	0,1 bis 1
Rb_2O	0 bis 1,5
Cs_2O	0 bis 1,5
$Rb_2O + Cs_2O$	0 bis 1,5
Summe der Erdalkalioxide	4,8–11
MgO	0 bis 6
CaO	0 bis < 5

Kernglas Variante 4 beinhaltend (in Gew.% auf Oxidbasis)

SiO_2	42 bis 53
ZnO	30 bis 38
Na_2O	< 14
K_2O	< 12
$Na_2O + K_2O$	≥ 2
BaO	< 0,9

Kernglas Variante 5 beinhaltend (in Gew.% auf Oxidbasis)

SiO_2	30 bis 45
B_2O_3	< 12
ZnO	< 10
BaO	25 bis 40
Na_2O	< 10
K_2O	< 2
Al_2O_3	< 1
La_2O_3	< 10

Mantelglas Variante 1 (in Gew.% auf Oxidbasis), beinhaltend

SiO_2	70 bis 78
Al_2O_3	0 bis 10
B_2O_3	5 bis 14
Na_2O	0 bis 10
K_2O	0 bis 10
Mg0	0 bis 1
Ca0	0 bis 2
SrO	0 bis 1

BaO	0 bis 1
F	0 bis 1

und im wesentlichen kein Li_2O.

Mantelglas Variante 2 (in Gew.% auf Oxidbasis), beinhaltend

SiO_2	63 bis 75
Al_2O_3	1 bis 7
B_2O_3	0 bis 3
Na_2O	8 bis 20
K_2O	0 bis 6
MgO	0 bis 5
CaO	1 bis 9
BaO	0 bis 5
F	0 bis 1

und im wesentlichen kein Li_2O.

Mantelglas Variante 3 (in Gew.% auf Oxidbasis), beinhaltend

SiO_2	75 bis 85
Al_2O_3	1 bis 5
B_2O_3	10 bis 14
Na_2O	2 bis 8
K_2O	0 bis 1

und im wesentlichen kein Li_2O und MgO.

Mantelglas Variante 4 (in Gew.% auf Oxidbasis), beinhaltend

SiO_2	62 bis 70
B_2O_3	> 15
Li_2O	> 0.1
Na_2O	0 bis 10
K_2O	0 bis 10
MgO	0 bis 5
CaO	0 bis 5
SrO	0 bis 5
BaO	0 bis 5
ZnO	0 bis 5
F	0 bis 1

Mantelglas Variante 5 (in Gew.% auf Oxidbasis), beinhaltend

SiO_2	60 bis 72
B_2O_3	< 20
Al_2O_3	< 10
Na_2O	< 18

K_2O	< 15
Li_2O	< 5
F	≤ 1

Mantelglas Variante 6 (in Gew.% auf Oxidbasis), beinhaltend

SiO_2	72–78
B_2O_3	5 bis 15
Al_2O_3	5 bis 10
Na_2O	< 10
K_2O	< 10
Li_2O	< 5
F	≤ 1

Mantelglas Variante 7 (in Gew.% auf Oxidbasis), beinhaltend

SiO_2	70–80
B_2O_3	< 5
Al_2O_3	< 10
La_2O_3	< 2
Na_2O	< 10
K_2O	< 10
ZrO_2	< 2

[0030] Die Gläser sind als solche in der Literatur bekannt und können beispielsweise der SCHOTT-Schriftenreihe „SCHOTT Series on Glass and Glass Ceramics – Science, Technology and Applications", The Properties of Optical Glass (1995, 2., korr. Ausg., 1998), Bach, Neuroth (Eds.), sowie den hier aufgeführten Verweisen entnommen werden.

[0031] In einer weiteren Ausführungsform weist das Lichtleitelement ein plattenförmiges Substrat, besonders bevorzugt aus einem Flach- oder Floatglas auf Kalknatron- oder Borosilicatbasis auf. Auch ist es möglich, durch die parallele Anordnung mehrerer Lichtleitfasern ein aus Fasern bestehendes plattenförmiges Lichtleitelement zu bilden.

[0032] Alternativ kann als Substrat für das Lichtleitelement bevorzugt auch einer der nachfolgend aufgezählten Kunststoffe verwendet werden:
Polycarbonat (PC), Polyacrylat (P), Polymethylmethacrylat (PMMA), Cycloolefinisches Copolymer (COC), Ethylen-Vinylacetat-Copolymer (EVA), Polystyrol (PS), Styrol-Acrylnitril (SAN), fluorierte Polymere, wie z. B. Polyvinylidenfluorid (PVDF), Perflouralkoxy-Copolymer (PFA), oder teilweise fluorierte Polymere der vorgenannten Kunststoffe.

[0033] Wie auch bei den Gläsern kann ein Lichtleitelement aus Kunststoff aus mehreren Schichten zusammengesetzt sein, um eine Brechwertanpassung vorzunehmen. Auch der Wellenleiter aus Kunststoff kann als Platte oder als Faser ausgebildet sein.

[0034] Darüber hinaus sind auch Kombinationen von Kunststoffen und anorganischen Materialien möglich. Dies ist insbesondere dann vorteilhaft, wenn der Kunststoff durch die hohe photokatalytische Aktivität der aktiven Substanz selbst zersetzt werden würde. Besonders vorteilhaft ist es hierbei, wenn der Kunststoff durch eine anorganische Schutzschicht vom photokatalytischen Material getrennt ist. Als Materialien für eine solche Schutzschicht kommen beispielsweise SiO_2, Al_2O_3, TiO_2, ZrO_2 sowie weitere Metalloxide in Frage. Die Schutzschichten können durch übliche Beschichtungsverfahren wie Aufdampfen, Sputtern, Beflammung oder Flüssigbeschichtung, insbesondere nach dem Sol-Gel-Verfahren, aufgebracht werden.

[0035] Lichtleitfasern eignen sich besonders zur Formung eines Substrats, da sie in bekannter Weise mit großen Längen und somit mit einer große Oberfläche in einem relativ kostengünstigen Prozess hergestellt werden können.

[0036] Vorzugsweise ist die wenigstens eine Lichtleitfaser des Lichtleitelements zu einem Netz, Gewebe oder Knäuel geformt.

[0037] Auf diese Weise kann in einem relativ kleinen Volumen eine große Länge an Lichtleitfasern und somit eine große Reaktionsoberfläche des Lichtleitelements zur Aufbringung der photokatalytischen Substanz bereitgestellt werden. Gleichzeitig ist ein solches Netz, Gewebe oder Knäuel hinreichend offenmaschig bzw. offenporig, so dass es, wenn es in einem Gehäuse eingebettet ist, das Hindurchleiten von zu reinigenden Fluiden (Abgas oder Abwasser) erlaubt.

[0038] Nach einem bevorzugten Aspekt der Erfindung ist die photokatakytische Substanz in Form von Partikeln, insbesondere Nanopartikeln an Trägerpartikel angelagert und dieser Partikelverbund als loses Pulver in dem Netz, Gewebe oder Knäuel der Lichtleitfaser eingebettet.

[0039] Diese nur lose Einbettung der photokatalytisch aktiven Substanz als Pulver hat den Vorteil, dass das photokatalytisch aktive Material nach der Herstellung des Lichtleitelements aufgebracht wird und aufwendige Beschichtungsschritte unterbleiben. Zusätzlich kann das das Lichtleitelement bildende Material ohne Rücksicht auf eine eventuelle Beschädigung der Beschichtung verarbeitet werden, so dass man hier in der Gestaltung und Formgebung sehr flexibel ist.

[0040] Bei dem Trägerpartikelmaterial handelt es sich um Materialien, die üblicherweise als Träger für katalytisch aktive Materialien eingesetzt werden, also beispielsweise Metalloxide wie SiO_2, Al_2O_3, TiO_2, ZrO_2. Der besondere Vorteil dieser Ausführungsform liegt in der Wechselwirkung zwischen Trägermaterial und katalytisch aktiver Substanz: Bei geträgerten Katalysatoren kommt es in der Regel bei geeigneter Reaktionsführung zu einer Steigerung der Aktivität, da sich die katalytisch aktive Substanz hier besonders feinverteilt abscheidet und so besonders reaktiv ist.

[0041] Alternativ oder zusätzlich kann das Lichtleitelement mit Partikeln, insbesondere mit Nanopartikel der photokatalytischen beschichtet sein.

[0042] Unter Nanopartikeln werden im Sinne der Anmeldung Partikel mit einer Größe von 1 bis 300 nm in Frage, besonders bevorzugt von 1 bis 100 nm. Der Vorteil der Verwendung von Partikeln, bevorzugt Nanopartikeln, besteht darin, dass man damit die dem System zur Verfügung gestellte katalytisch wirksame Oberfläche gezielt einstellen kann. Bei der Verwendung von Nanopartikeln hat man darüber hinaus den Vorteil, dass aufgrund des hohen Oberfläche-zu-Volumenverhältnisses das photokatalytische Material in einem besonders energiereichen und somit aktiven Zustand vorliegt.

[0043] Als Beschichtungsverfahren für die Beschichtung mit der photokatalytisch aktiven Substanz kommt beispielsweise die Flüssigbeschichtung in einem Sol-Gel-Prozess, die physikalische Gasphasenabscheidung (PVD), insbesondere Sputtern, die chemische Gasphasenabscheidung (CVD) oder Plasmasprühen in Frage.

[0044] Die photokatalytische Substanz kann auf die ein oder andere Weise in einer Schicht, direkt auf die äußerste Schicht des Lichtleitelementes (Mantel oder Schutzschicht) aufgebracht werden. Hierbei ist es sowohl möglich, dass eine homogene Schicht ausschließlich aus dem photokatalytisch aktiven Material gebildet wird oder eine Trägerschicht, in die vereinzelte Partikel, bevorzugt Nanopartikeln, der photokatalytischen Substanz eingebettet sind. Als Matrixmaterialien für die Trägerschicht kommen insbesondere wiederum SiO_2, Al_2O_3, TiO_2, ZrO_2 sowie weitere Metalloxide in Betracht.

[0045] Besonders bevorzugt ist es, wenn die Partikel oder Nanopartikel nur zu einem Teil in die Trägerschicht eingebettet sind, beispielsweise nur zu ¼ bis einem ½ ihres Durchmessers, und im übrigen aus der Oberfläche der Trägerschicht herausragen.

[0046] Im weiteren Verlauf werden die so hergestellten Lichtleitfasern zu dem Netz, Gewebe oder Knäuel verarbeitet.

[0047] Alternativ oder zusätzlich kann zunächst aus der unbehandelten oder der in der vorstehend beschriebenen Weise beschichteten Lichtleitfasern das Netz, Gewebe oder Knäuel gebildet werden, das dann anschlie-

ßend als ganzes (nochmals) mit einer Schicht aus photokatalytisch aktiven Material versehen wird. Auch diese kann wiederum als homogene Beschichtung aus dem gewünschten Photokatalysatormaterial oder als Trägerschicht mit Partikeln, bevorzugt Nanopartikeln, der photokatalytisch aktiven Substanz ausgebildet sein. Und ach hierbei ist es besonders bevorzugt, wenn die Partikel nur zu einem Teil in die Trägerschicht eingebettet sind und im übrigen aus der Oberfläche der Trägerschicht herausragen.

[0048] Wenn die photokatalytisch aktive Substanz in Form von Partikeln oder Nanopartikeln in das System eingebracht wird, besteht eine weitere bevorzugte Ausführungsform darin, dass die Partikel oder Nanopartikel direkt auf die Oberfläche des Lichtleitelements aufgebracht werden und direkt in dieser haften. Dies kann beispielsweise bei Lichtleitfasern während der Beschlichtung der Fasern erfolgen oder bei flachen Glassubstraten im Anschluss an die Heißformgebung, wenn die Oberfläche des Glases noch relativ warm ist und die Partikel oder Nanopartikel gut an ihr haften, sowie bei Kunststoffe im Rahmen der Formgebung. Auf diese Weise wird ein besonders guter Haftverbund zwischen den photokatalytisch aktiven Partikeln und dem lichtleitenden Substrat ermöglicht. Auch hierbei ist eine Ausführung besonders bevorzugt, bei der die Partikel oder Nanopartikel zu einem Teil aus der Substratoberfläche herausragen, da dies eine Vergrößerung der dem System für die Katalyse zur Verfügung stehenden Oberfläche bedeutet.

[0049] Vorzugsweise weist das Lichtleiterelement eine aufgeraute Oberfläche auf.

[0050] Durch diese Maßnahme werden auf einfache und kostengünstige Weise Streuzentren erzeugt, die das in dem Lichtleiterelement geführte Licht teilweise aus dem Lichtleitelement herausstreuen. Die photokatalytische Substanz wird folgerichtig auf die aufgeraute Oberfläche aufgebracht.

[0051] Alternativ zu einer aufgerauten Oberfläche kann das Lichtleitelement im allgemeinen (also nicht nur eine Lichtleitfaser) eine Außenoberfläche aufweisen, auf der Streuzentren angeordnet oder in die Streuzentren eingebettet sind.

[0052] Die Streuzentren können in Form von Partikeln also wie bei den seitenemittierenden Lichtleitfasern auf der Außenoberfläche oder in einer brechwertangepassten Mantelschicht des Lichtleitelements angeordnet sein.

[0053] In einer anderen vorteilhaften Ausführungsform besteht das Lichtleiterelement aus einem Bündel von Lichtleitfasern, die in Längsrichtung des Faserbündels an unterschiedlicher Position Bruchstellen aufweisen.

[0054] Durch eine Vielzahl von Lichtleitfasern kann somit bewirkt werden, dass das gesamte Bündel über einen größeren Abschnitt in Längsrichtung des Bündels je nach Bedarf gleichmäßig oder konzentriert auf bestimmte Abschnitte Licht emittiert. An entsprechenden Stellen sind dann auch die Partikel der photokatalytischen Substanz aufzubringen.

[0055] Bevorzugt weist die Photokatalysatoreinrichtung eine künstliche Lichtquelle mit Strahlungsmaximum im sichtbaren Spektrum auf. Die künstliche Lichtquelle steht in lichtleitender Verbindung mit dem Lichtleitelement.

[0056] Die künstliche Lichtquelle weist besonders bevorzugt wenigstens eine LED, Glühlampe oder Gasentladungslampe auf.

[0057] Vorgenannte Lichtquellen sind kostengünstig bei hoher Effizienz, insbesondere im Vergleich mit UV-Lichtquellen.

[0058] In einer besonders bevorzugten Ausführungsform wird die Lichtquelle durch Sonnenlicht gebildet. Dementsprechend weist die Photokatalysatoreinrichtung Mittel zum Einsammeln von Sonnenlicht auf, die in lichtleitender Verbindung mit dem Lichtleitelement stehen.

[0059] Weitere Aufgaben, Merkmale und Vorteile der Erfindung werden nachfolgend anhand von Ausführungsbeispielen mit Hilfe der Zeichnungen näher erläutert.

[0060] Es zeigen:

[0061] Fig. 1 ein erstes Ausführungsbeispiel der erfindungsgemäßen photokatalytischen Reinigungsvorrichtung unter Verwendung mehrerer Lichtleitfasern als Lichtleitelemente;

[0062] Fig. 2 einen Ausschnitt eines plattenförmigen Lichtleitelementes mit einseitiger Lichtauskopplung;

[0063] Fig. 3 einen vergrößerten Ausschnitt einer seitenemittierenden Lichtleitfaser als Lichtleitelement;

[0064] Fig. 4 das Ende eines Faserbündels mit Lichtaustritt an Bruchstellen der einzelnen Lichtleitfasern;

[0065] Fig. 5 eine zweite Ausführungsform der erfindungsgemäßen photokatalytischen Reinigungseinrichtung mit plattenförmigen Lichtleitelementen und

[0066] Fig. 6 einen Ausschnitt aus einer Ausführungsform der erfindungsgemäßen Photokatalysatoreinrichtung mit mehreren zu einem Knäuel geformten Lichtleitfasern und einer photokatalytischen Substanz in Form eines losen Partikelverbundes.

[0067] Gemäß dem Ausführungsbeispiel aus Fig. 1 bildet die erfindungsgemäße Photokatalysatoreinrichtung bestehend aus einem Lichtleitelement in Form mehrerer Lichtleitfasern **10**, einer mit den Lichtleitfasern in lichtleitender Verbindung stehenden Lichtquelle **12** und einer auf den Lichtleitfasern angeordneten photokatalytischen Substanz (nicht dargestellt), nämlich Bi_2O_3 und/oder N-dotiertes TiO_2 und/oder C-dotiertes TiO_2 und/oder S-dotiertes TiO_2 und/oder eine binäre Bismut-Metalloxid-Verbindung, eine photokatalytische Reinigungsvorrichtung zur Reinigung eines die Lichtleitfasern durchströmenden Fluides. Die Fluidströmung ist indiziert durch die Pfeile **14**. Die Lichtleitfasern **10** sind in einem würfelförmigen Reaktionsraum **16** in Form eines Knäuels angeordnet. Der Reaktionsraum **16** kann beispielsweise durch ein Gehäuse mit einer Aus- und Eintrittsöffnung zum Durchleiten der Fluidströmung gebildet werden.

[0068] In Fig. 2 ist eine Ausführungsform der erfindungsgemäßen Photokatalysatoreinrichtung schematisch im Querschnitt dargestellt, in der das Lichtleitelement ein einseitig emittierendes plattenförmiges Substrat **20** ist. Das Substrat kann aus einer Glasplatte, vorzugsweise aus Borosilicat-Floatglas oder aus einem plattenförmigen Kalknatron-Glassubstrat, oder aus einem der vorgenannten Kunststoffe gebildet sein, in das von einer oder mehreren Stirnflächen **22** Licht eingekoppelt wird, markiert durch den Pfeil **24**. Auf einer Seitenfläche weist das Substrat **20** eine aufgeraute Oberfläche **26** auf. Durch die aufgeraute Oberfläche wird je nach Grad der Rauheit ein bestimmter Anteil des in dem Substrat **20** geleiteten Lichts seitlich ausgekoppelt, da an den Rauheitsstellen mit statistischer Signifikanz der minimale Winkel, bei dem noch Totalreflexion stattfindet, unterschritten wird. Die Seite der aufgerauten Oberfläche des Substrats **20** ist mit der photokatalytischen Substanz, dargestellt als regelmäßige Anordnung von Partikeln **28**, aufgebracht. Die photokatalytische Substanz kann durch eines der vorstehend genannten Beschichtungsverfahren in Partikelform, vorzugsweise in Form von Nanopartikeln, tatsächlich zu einer mehr oder weniger gleichmäßigen, die gesamte Oberfläche bedeckenden Schicht aufgetragen werden.

[0069] Abweichend von der in Fig. 2 dargestellten Ausführungsform können auch beide Seitenflächen des Substrats **20** aufgeraut und mit der photokatalytischen Substanz beschichtet sein.

[0070] In der Ausführungsform gemäß Fig. 3 ist als Lichtleitelement eine seitenemittierende Stufenindexfaser **30** vorgesehen. Im Schnitt ist zu erkennen, dass diese einen Kern **32** und einen diesen umfänglich umschließenden transparenten und/oder transluzenten Mantel **34** aufweist. Eine die seitliche Lichtemission bewirkende Streuung des in der Stufenindexfaser geleiteten Lichts findet an (nicht dargestellten) Streuzentren zwischen dem Mantel **34** und dem Kern **32** statt. Auf dem äußeren Umfang des Mantels ist die photokatalytische Substanz angeordnet, hier wieder dargestellt als gleichmäßige Anordnung von Partikeln **38**.

[0071] In dem Ausführungsbeispiel gemäß Fig. 4 ist auf der linken Seite ein Bündel **40** aus mehreren normalen, d. h. nicht seitenemittierenden, Lichtleitfasern **42** als Lichtleitelement dargestellt. Auf der rechten Seite ist ein Ausschnitt einer dieser Lichtleitfasern **42** in vergrößerter Darstellung gezeigt. Das an einem Ende des Faserbündels eingekoppelte Licht, dargestellt durch den Pfeil **44**, tritt bei dieser Ausführungsform an dem gegenüberliegenden stirnseitigen Ende an Bruchstellen **46** der einzelnen Lichtleitfasern **42** aus. Diese Bruchstellen **46** sind in Längsrichtung des Faserbündels **40** an unterschiedlicher Position angeordnet, so dass das Licht über einen bestimmten Längenabschnitt des Faserbündels **40** in gewünschter Form austritt. Die Bruchstellen **46** weisen unterschiedliche Oberflächenstrukturen auf, so dass das Licht statistisch über die Vielzahl der Lichtleitfasern **42** vom Ende des Faserbündels **40** in einen großen Raumwinkelbereich gestreut wird. Bei dieser Ausgestaltung genügt es, wenn die photokatalytische Substanz nur im Bereich dieses bestimmten Längenabschnitts des Faserbündels aufgetragen wird. Zu diesem Zweck können die Lichtleitfasern mit dem Ende der Bruchstellen einzeln oder das gesamte Bündel beispielsweise in einem Tauchverfahren beschichtet werden.

[0072] In Fig. 5 ist eine zweite Ausführungsform einer erfindungsgemäßen photokatalytischen Reinigungsvorrichtung gezeigt, bei der als Lichtleitelement eine Vielzahl parallel angeordneter lichtleitender Platten **50** vorgesehen sind. Diese Platten können aus Glas oder Kunststoff gefertigt und einseitig oder beidseitig aufgeraut oder mit Streuzentren versehen sein und auf dieser einen bzw. beiden Seiten mit einer photokatalytischen Substanz der erfindungsgemäßen Art beschichtet sein. Das Licht wird von einer künstlichen Lichtquelle **52** mit Strahlungsmaximum im sichtbaren Spektrum erzeugt und über ein lichtleitendes Kabel **53** und eine lichtleitende Verteilerplatte **54** auf die plattenförmigen Lichtleitelemente **50** verteilt. Das Licht tritt seitlich auf der aufgerauten bzw. mit Streuzentren versehenen Fläche der plattenförmigen Lichtleitelemente **50** aus und regt die dort aufgetragene photokatalytische Substanz an.

[0073] Der Stapel der plattenförmigen Lichtleitelemente **50** definiert einen Reaktionsraum **56**, der durch ein hier nicht dargestelltes Gehäuse begrenzt und mit einer Eintritts- und einer Austrittsöffnung versehen sein kann. Ein zu reinigendes bzw. zu zersetzendes Fluid wird durch die Plattenanordnung hindurch geleitet, markiert durch die Richtungspfeile **58**. Die Größe der plattenförmigen Lichtleitelemente, d. h. deren aktive (aufgeraute und beschichtete) Oberfläche, und deren Länge insbesondere in Strömungsrichtung ist auf die Strömungsgeschwindigkeit und somit auf die Verweil- bzw. Reaktionszeit des durchströmenden Fluids in dem Reaktionsraum dergestalt abzustimmen, dass eine möglichst vollständige Umsetzung der organischen Substanz durch die katalytisch angeregte Reaktion stattfinden kann.

[0074] In Fig. 6 ist ein Ausschnitt eines Knäuels aus einer oder mehreren seitenemittierenden Lichtleitfasern **60** dargestellt. Anders als im Beispiel der Fig. 3 sind die Lichtleitfasern **60** hier jedoch nicht gleichmäßig mit der katalytischen Substanz entlang ihrer Außenumfangsfläche beschichtet. Im Beispiel der Fig. 6 ist photokatalytische Substanz in Form von Partikeln **62** an Trägerpartikel **64** angelagert und dieser Partikelverbund als loses Pulver in das Knäuel der Lichtleitfasern **60** eingebettet.

Bezugszeichenliste

10 Lichtleitfaser
12 Lichtquelle
14 Fluidströmung
16 Reaktionsraum
20 plattenförmiges Lichtleitelement
22 Stirnfläche
24 Lichteinkopplung
26 aufgeraute Oberfläche
28 photokatalytische Beschichtung
30 seitenemittierende Lichtleitfaser
32 Kern
34 Mantel
38 photokatalytische Beschichtung
40 Faserbündel
42 Lichtleitfaser
44 Lichteinkopplung
46 Bruchstellen
50 plattenförmiges Lichtleitelement
52 Lichtquelle
53 lichtleitendes Kabel
54 lichtleitende Verteilerplatte
56 Reaktionsraum
58 Fluidströmung
60 seitenemittierende Lichtleitfaser
62 photokatalytische Partikel
64 Trägerpartikel

ZITATE ENTHALTEN IN DER BESCHREIBUNG

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Patentansprüche

1. Photokatalysatoreinrichtung mit einem Lichtleitelement und einer auf dem Lichtleitelement angeordneten photokatalytischen Substanz **dadurch gekennzeichnet**, dass die photokatalytische Substanz Bi_2O_3, und/oder N-dotiertes TiO_2 und/oder C-dotiertes TiO_2 und/oder S-dotiertes TiO_2 und/oder eine binäre Bismut-Metalloxid-Verbindung aufweist.

2. Photokatalysatoreinrichtung nach Anspruch 1, dadurch gekennzeichnet, dass, die binäre Bismut-Metalloxid-Verbindung eine Verbindung aus der Gruppe $MBiO_3 \cdot xH_2O$, mit M = Alkali und $x \geq 0$, $BiVO_4$, Bi_2MoO_6 und Bi_2WO_6 ist.

3. Photokatalysatoreinrichtung nach Anspruch 1, dadurch gekennzeichnet, dass, die photokatalytische Substanz α-Bi_2O_3 und/oder β-Bi_2O_3 aufweist.

4. Photokatalysatoreinrichtung nach einem der vorstehenden Ansprüche, dadurch gekennzeichnet, dass das Lichtleitelement wenigstens eine Lichtleitfaser (**10**, **42**) aufweist.

5. Photokatalysatoreinrichtung nach Anspruch 4, dadurch gekennzeichnet, dass die Lichtleitfaser (**10**, **42**) eine seitenemittierende brechwertangepasste Lichtleitfaser (**30**, **60**) ist, entlang deren Außenumfangsfläche Streuzentren und die photokatalytische Substanz angeordnet sind.

6. Photokatalysatoreinrichtung nach Anspruch 5, dadurch gekennzeichnet, dass die Streuzentren durch Streupartikel auf der Außenumfangsfläche gebildet werden.

7. Photokatalysatoreinrichtung nach Anspruch 5 oder 6, dadurch gekennzeichnet, dass die Streuzentren in eine Glasschicht eingebettet sind, die die Außenumfangsfläche zumindest auf einem Abschnitt umgibt.

8. Photokatalysatoreinrichtung nach Anspruch 4, dadurch gekennzeichnet, dass die Lichtleitfaser (**10**, **42**) eine seitenemittierende Stufenindexfaser mit einem den Kern (**32**) umschließenden transparenten und/oder transluzenten Mantel (**34**) ist, wobei Streuzentren zwischen dem Mantel (**34**) und dem Kern (**32**) und die photokatalytische Substanz auf dem Mantel (**34**) angeordnet sind.

9. Photokatalysatoreinrichtung nach Anspruch 8, dadurch gekennzeichnet, dass die Streuzentren durch Streupartikel auf der Außenumfangsfläche des Kerns (**32**) gebildet werden.

10. Photokatalysatoreinrichtung nach Anspruch 8 oder 9, dadurch gekennzeichnet, dass die Streuzentren in eine Glasschicht eingebettet sind, die den Kern (**32**) zumindest auf einem Abschnitt umgibt.

11. Photokatalysatoreinrichtung nach einem der Ansprüche 9 bis 9, dadurch gekennzeichnet, dass die Streuzentren durch Inhomogenitäten des Lichtleitfasermaterials im Außenumfangsbereich des Kerns (**32**) gebildet werden.

12. Photokatalysatoreinrichtung nach einem der Ansprüche 4 bis 11, dadurch gekennzeichnet, dass die wenigstens eine Lichtfaser (**10**, **42**) zu einem Netz, Gewebe oder Knäuel geformt ist.

13. Photokatalysatoreinrichtung nach Anspruch 12, dadurch gekennzeichnet, dass die photokatalytische Substanz in Form von Partikeln (**62**) an Trägerpartikeln (**64**) angelagert und dieser Partikelverbund als loses Pulver in dem Netz, Gewebe oder Knäuel eingebettet ist.

14. Photokatalysatoreinrichtung nach einem der Ansprüche 1 bis 3, dadurch gekennzeichnet, dass das Lichtleitelement ein plattenförmiges Substrat aufweist.

15. Photokatalysatoreinrichtung nach Anspruch 14, dadurch gekennzeichnet, dass das Substrat aus Kalknatron- oder Borosilicat-Floatglas besteht.

16. Photokatalysatoreinrichtung nach einem der vorstehenden Ansprüche, dadurch gekennzeichnet, dass das Lichtleitelement mit Partikeln (**62**) der photokatalytischen Substanz beschichtet ist.

17. Photokatalysatoreinrichtung nach Anspruch 16, dadurch gekennzeichnet, dass die Partikel (**62**) mittels eines Sol-Gel-Prozesses auf das Lichtleitelement aufgebracht sind.

18. Photokatalysatoreinrichtung nach einem der vorstehenden Ansprüche, dadurch gekennzeichnet, dass die photokatalytische Substanz in Form von Nanopartikeln auf dem Lichtleitelement angeordnet ist.

19. Photokatalysatoreinrichtung nach einem der vorstehenden Ansprüche, dadurch gekennzeichnet, dass das Lichtleitelement eine aufgeraute Oberfläche aufweist.

20. Photokatalysatoreinrichtung nach einem der vorstehenden Ansprüche, dadurch gekennzeichnet, dass das Lichtleitelement eine Außenoberfläche aufweist, auf der Streuzentren angeordnet oder in die Streuzentren eingebettet sind.

21. Photokatalysatoreinrichtung nach einem der vorstehenden Ansprüche, dadurch gekennzeichnet, dass das Lichtleitelement aus einem Bündel von Lichtleitfasern (**10**, **42**) besteht, die in Längsrichtung des Faserbündels (**40**) an unterschiedlicher Position Bruchstellen (**46**) aufweisen.

22. Photokatalysatoreinrichtung nach einem der vorstehenden Ansprüche, gekennzeichnet durch eine künstliche Lichtquelle mit Strahlungsmaximum im sichtbaren Spektrum, die in lichtleitender Verbindung mit dem Lichtleitelement steht.

23. Photokatalysatoreinrichtung nach einem der vorstehenden Ansprüche, dadurch gekennzeichnet, dass die künstliche Lichtquelle wenigstens eine LED, Glühlampe oder Gasentladungslampe aufweist.

24. Photokatalysatoreinrichtung nach einem der vorstehenden Ansprüche, gekennzeichnet durch Mittel zum Einsammeln von Sonnenlicht, die in lichtleitender Verbindung mit dem Lichtleitelement stehen.

Es folgen 2 Blatt Zeichnungen

Anhängende Zeichnungen

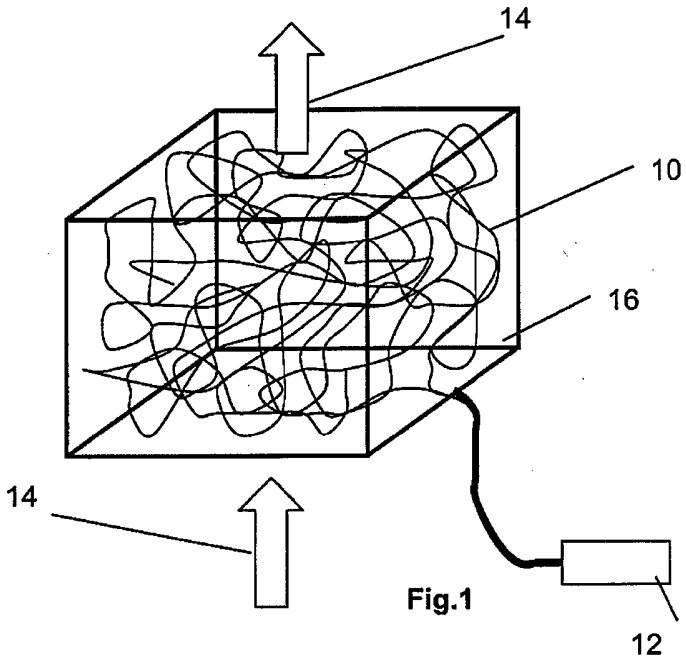


Fig.1

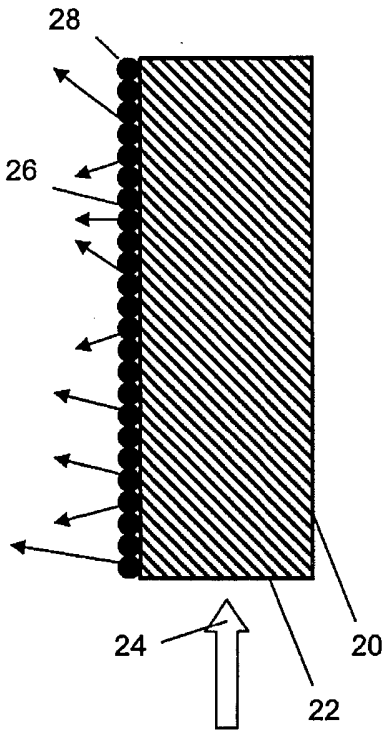


Fig. 2

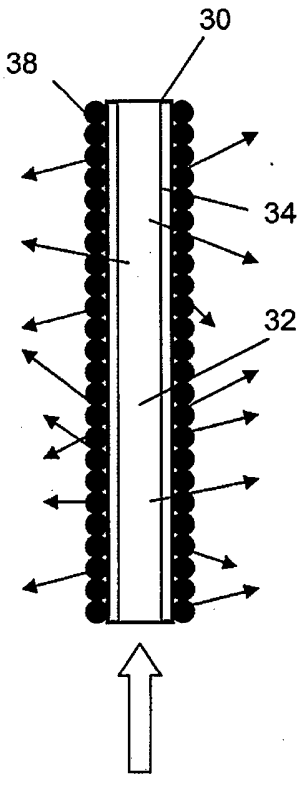


Fig. 3

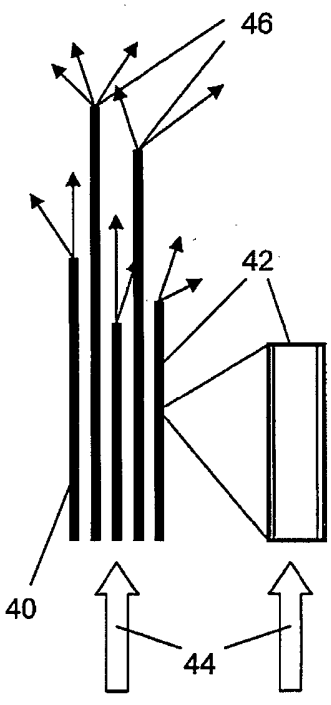


Fig. 4

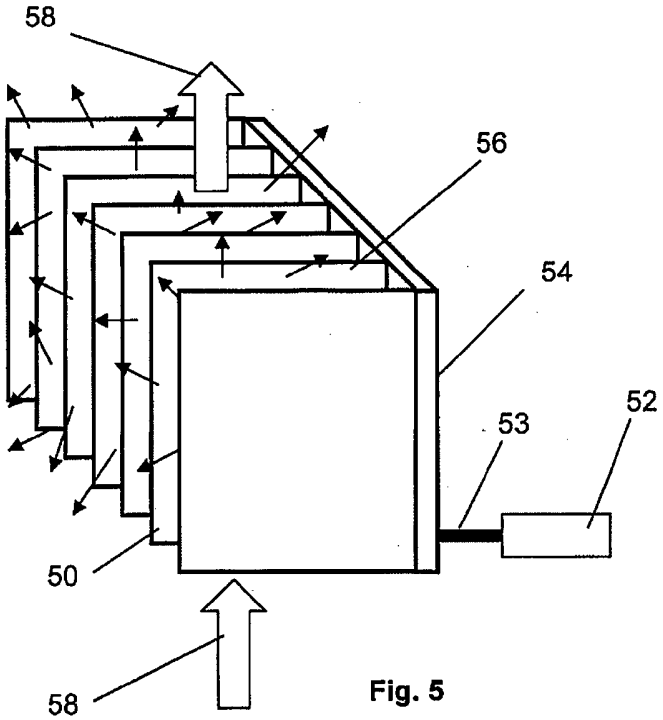


Fig. 5

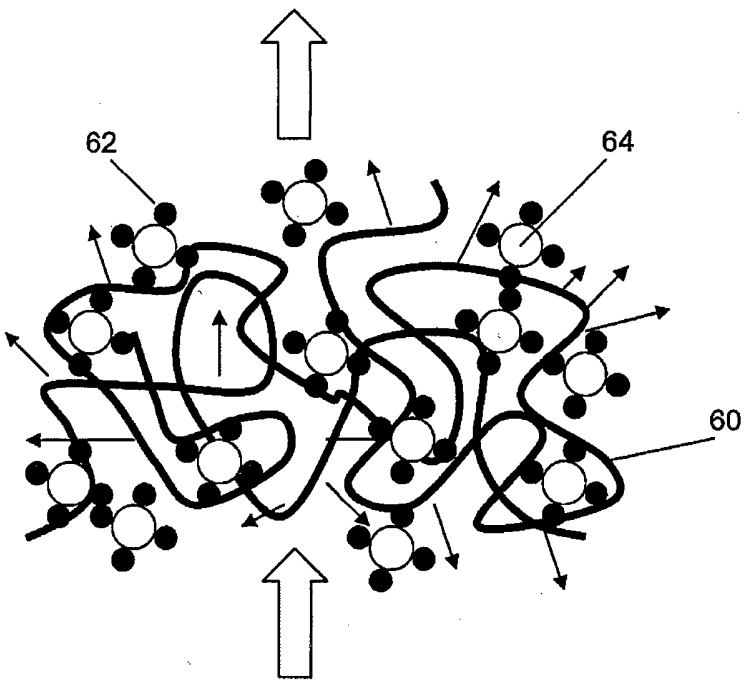


Fig. 6

US 20120275178A1

(19) **United States**

(12) **Patent Application Publication**

Logunov

(10) **Pub. No.: US 2012/0275178 A1**

(43) **Pub. Date: Nov. 1, 2012**

(54) **LIGHT-COUPLING OPTICAL SYSTEMS AND METHODS EMPLOYING LIGHT-DIFFUSING OPTICAL FIBERT**

(76) Inventor: **Stephan Lvovich Logunov**, Corning, NY (US)

(21) Appl. No.: **13/269,733**

(22) Filed: **Oct. 10, 2011**

Related U.S. Application Data

(63) Continuation-in-part of application No. 13/094,221, filed on Apr. 26, 2011.

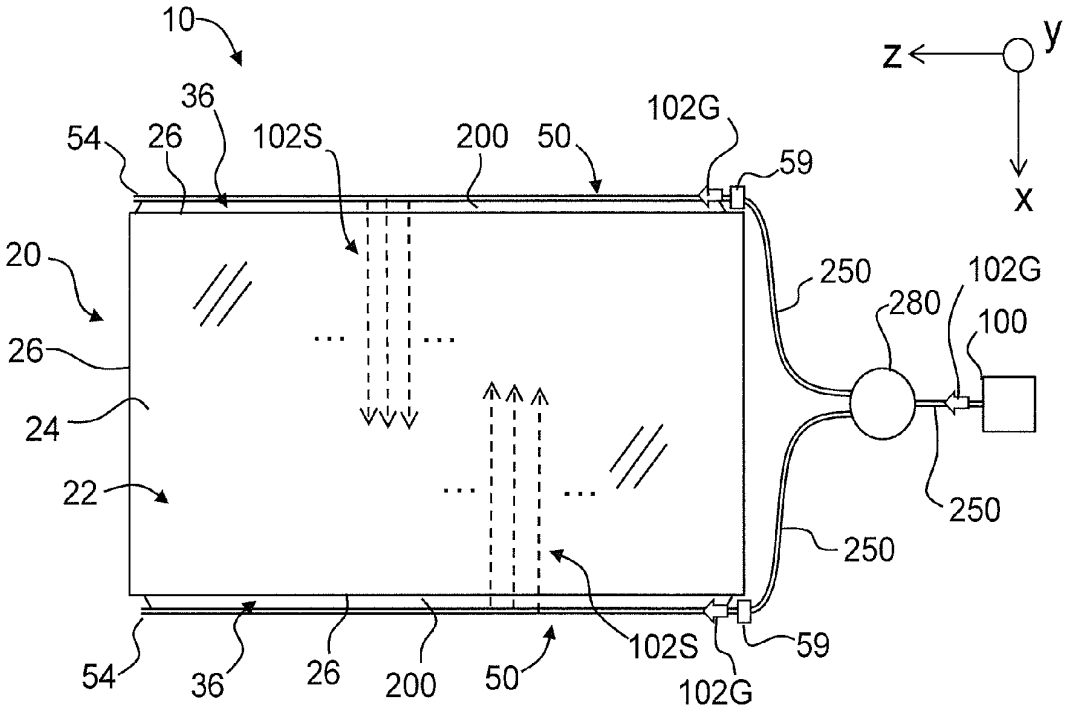
Publication Classification

(51) **Int. Cl.**
F21V 13/02 (2006.01)
F21V 8/00 (2006.01)

(52) **U.S. Cl.** **362/552**; 362/551; 362/582; 362/583

(57) **ABSTRACT**

Light-coupling systems and methods that employ light-diffusing optical fiber are disclosed. The systems include a light source and a light-diffusing optical fiber optically coupled thereto. The light-diffusing optical fiber has a core, a cladding and a length. At least a portion of the core comprises randomly arranged voids configured to provide substantially spatially continuous light emission from the core and out of the cladding along at least a portion of the length. A portion of the light-diffusing optical is embedded in an index-matching layer disposed adjacent a lower surface of a transparent sheet. Light emitted by the light-diffusing optical fiber is trapped within the transparent sheet and index-matching layer by total internal reflection and is scattered out of the upper surface of the transparent sheet by at least one scattering feature thereon.



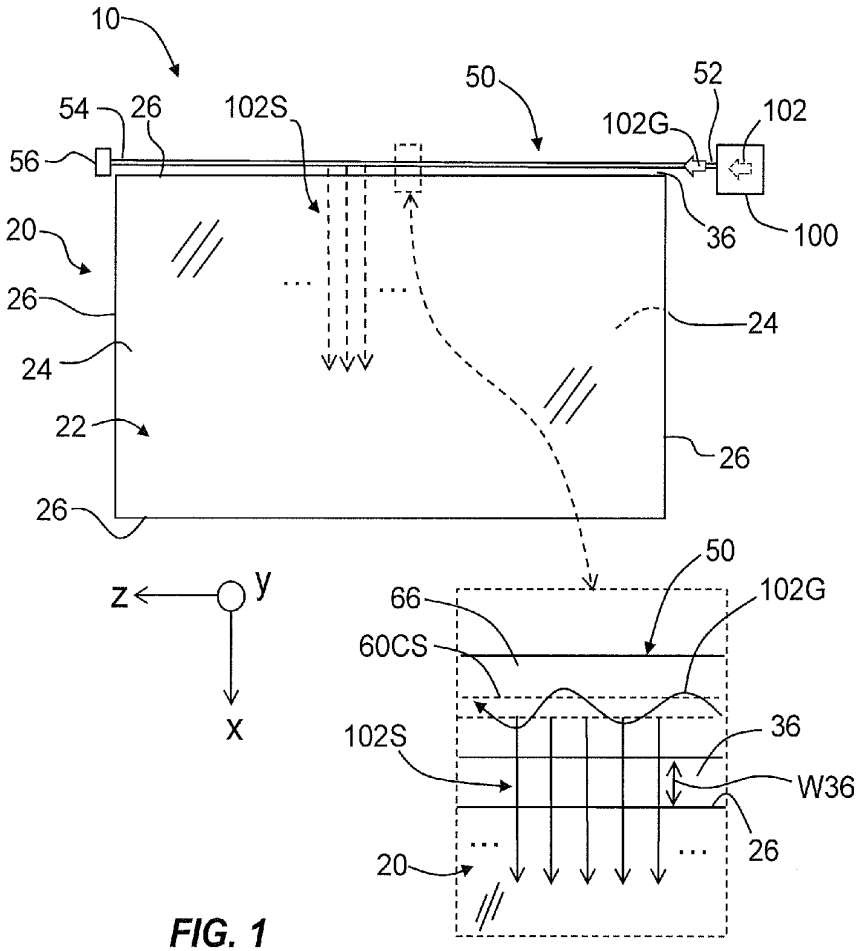

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FIG. 1

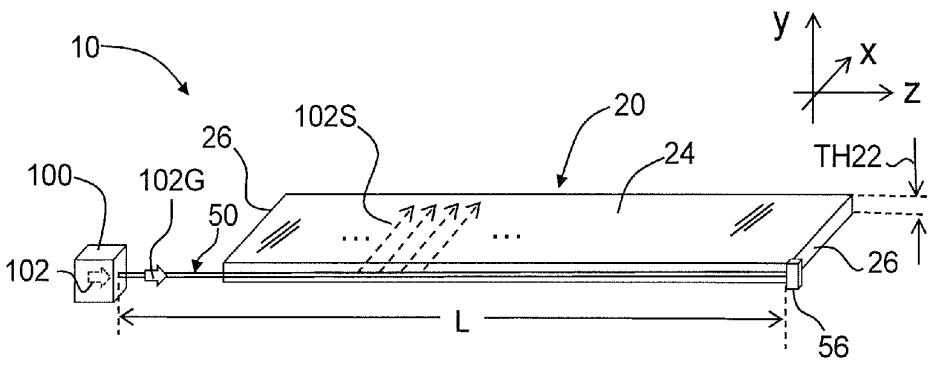
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FIG. 2

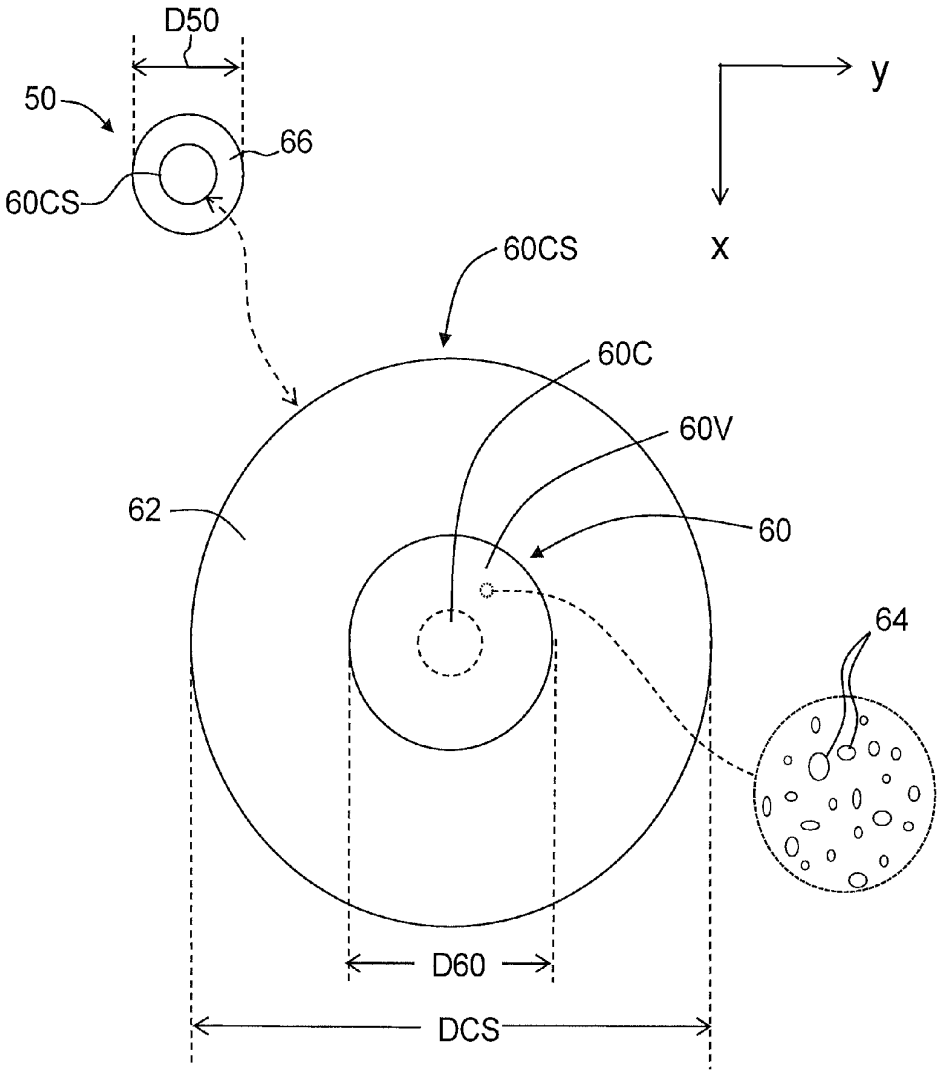

FIG. 3A

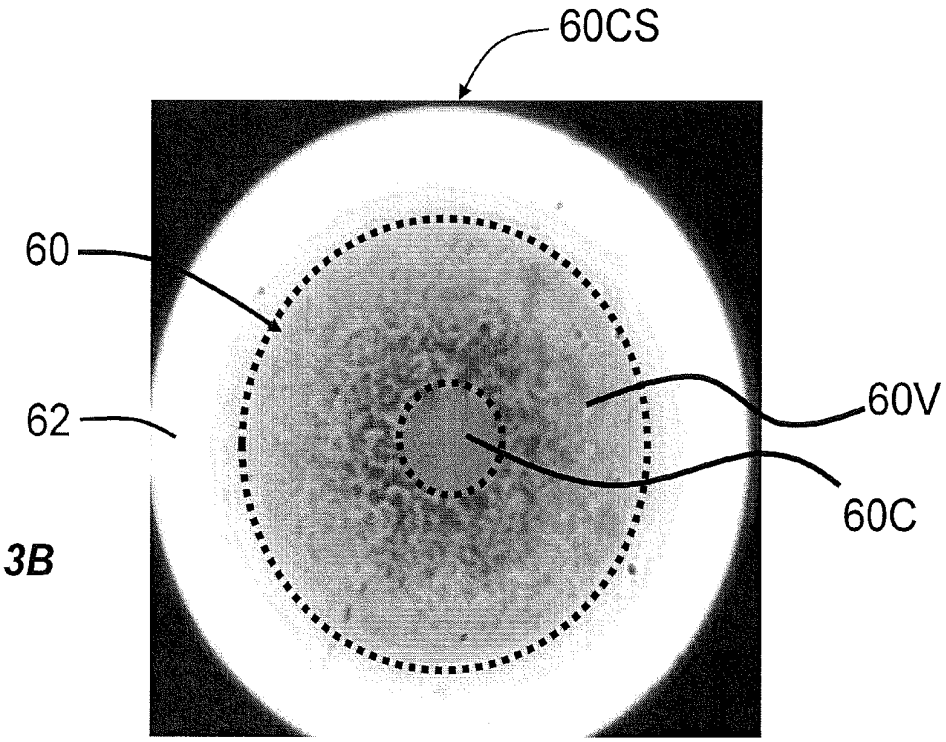

FIG. 3B

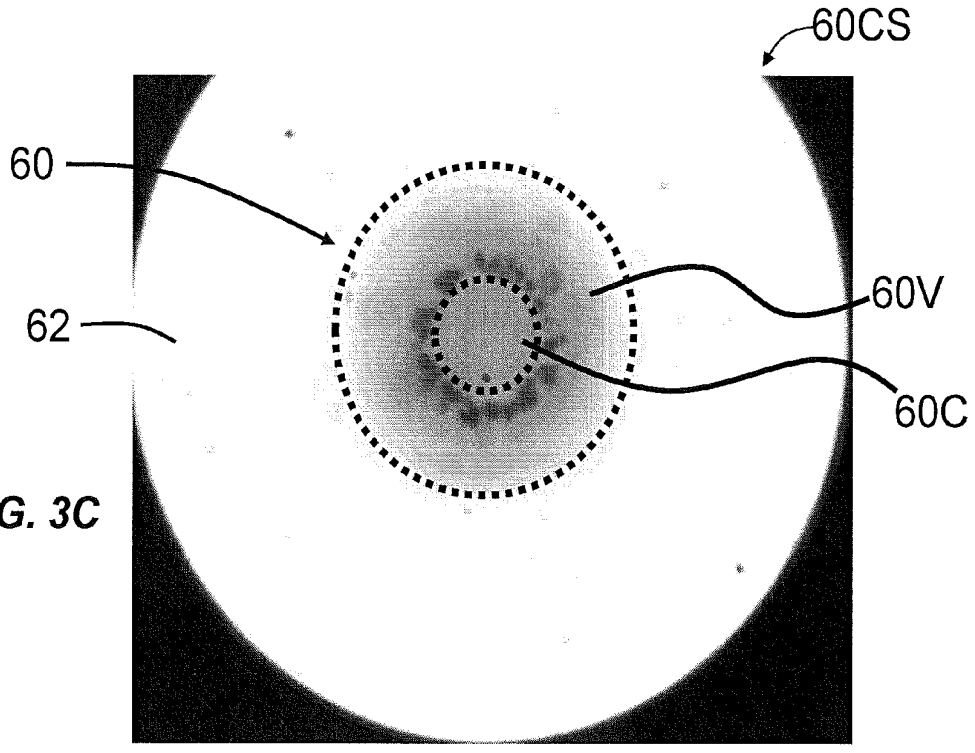

FIG. 3C

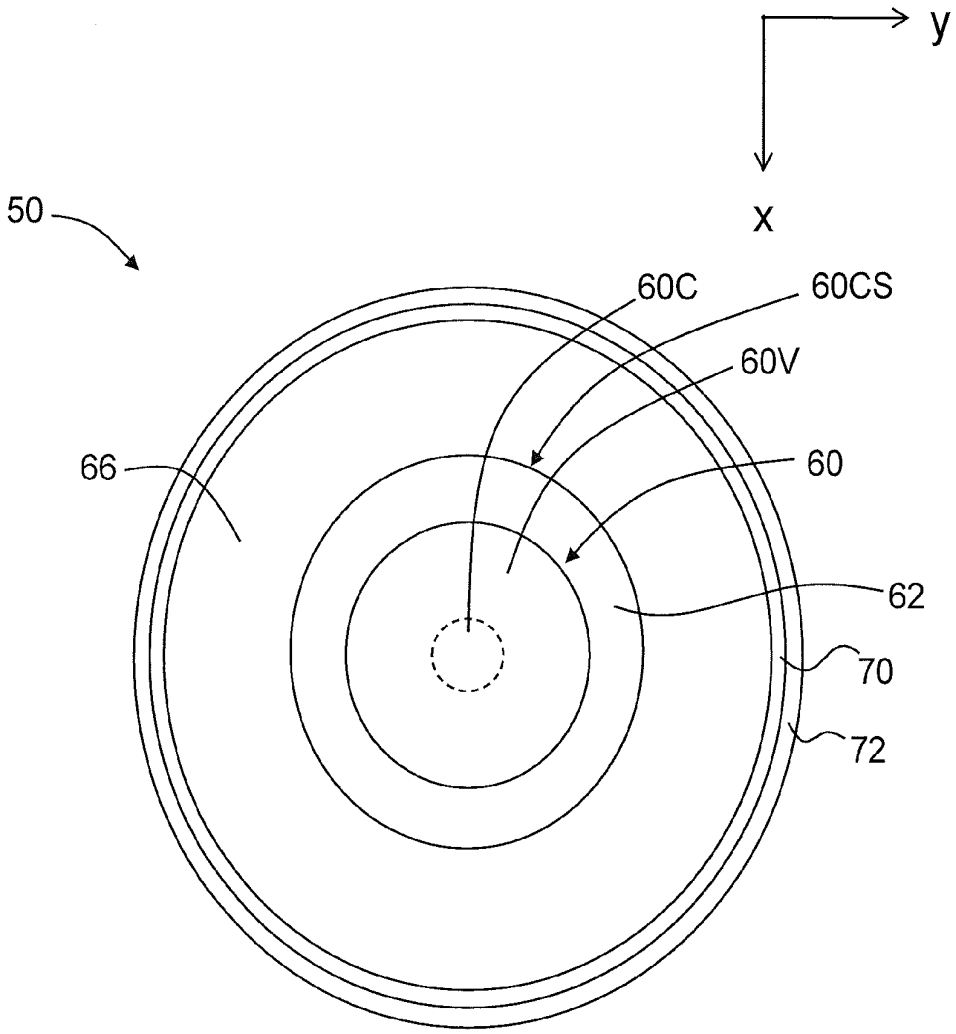

FIG. 3D

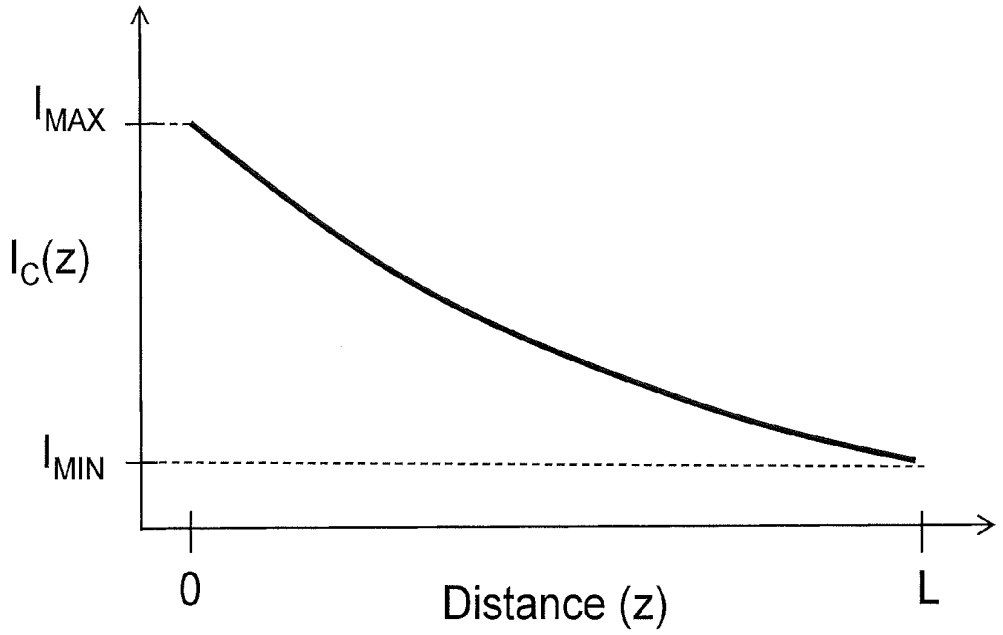

FIG. 4A

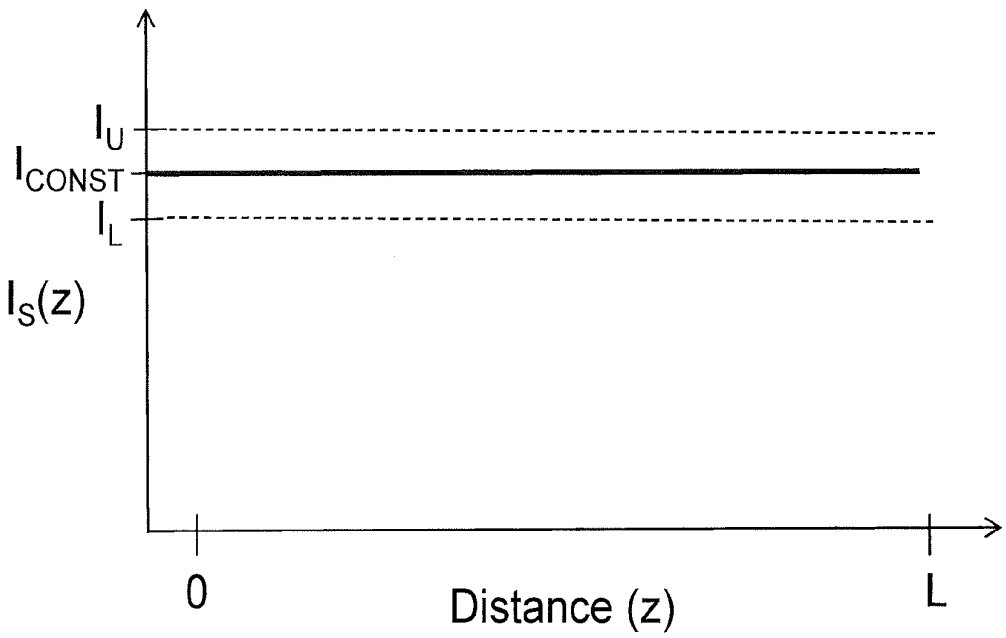

FIG. 4B

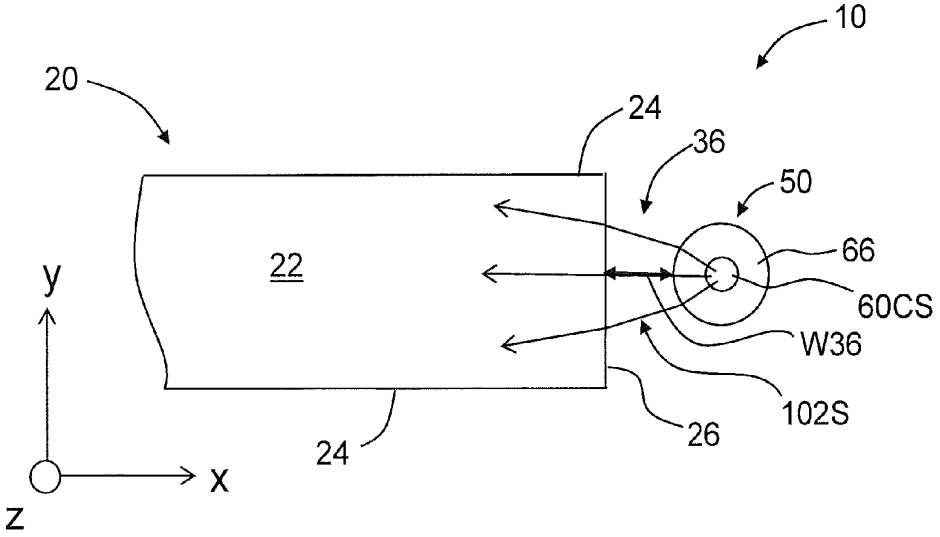
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FIG. 5A

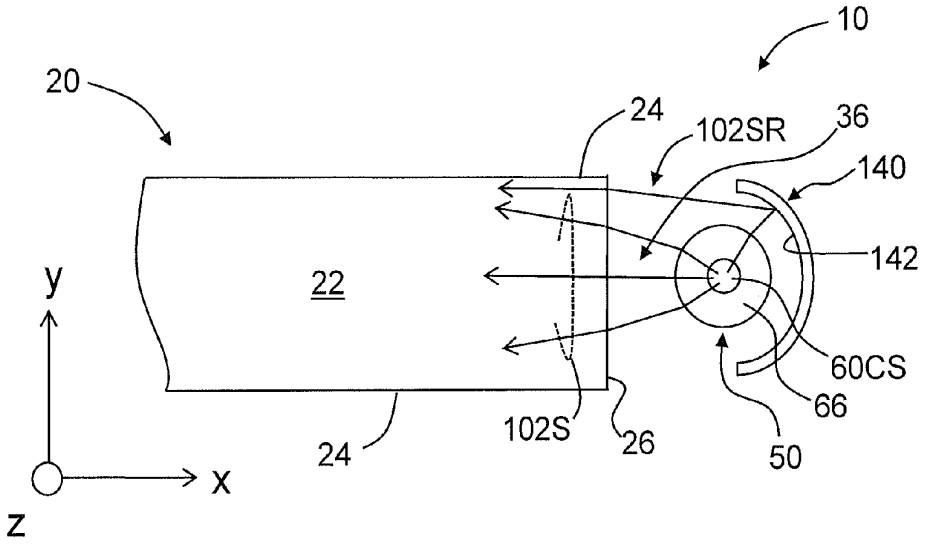
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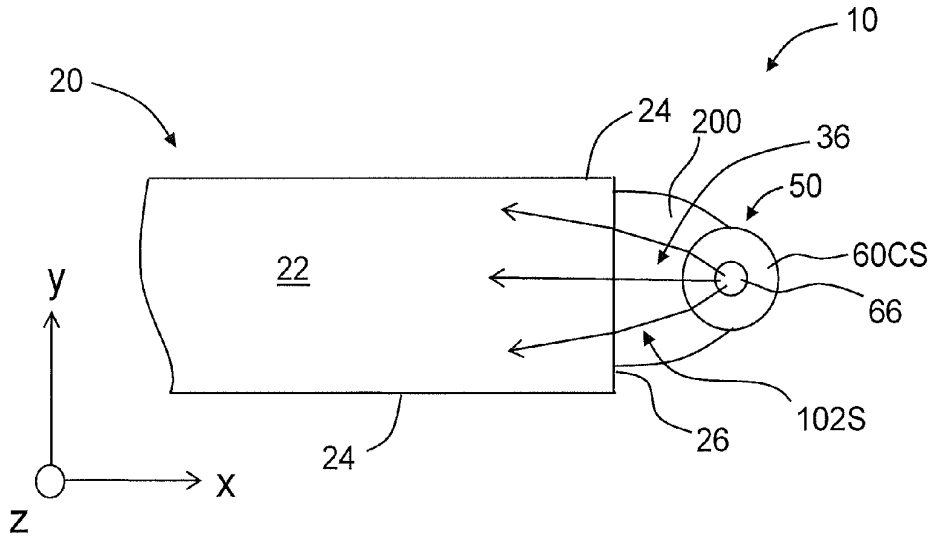
FIG. 5B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102S

FIG. 5C

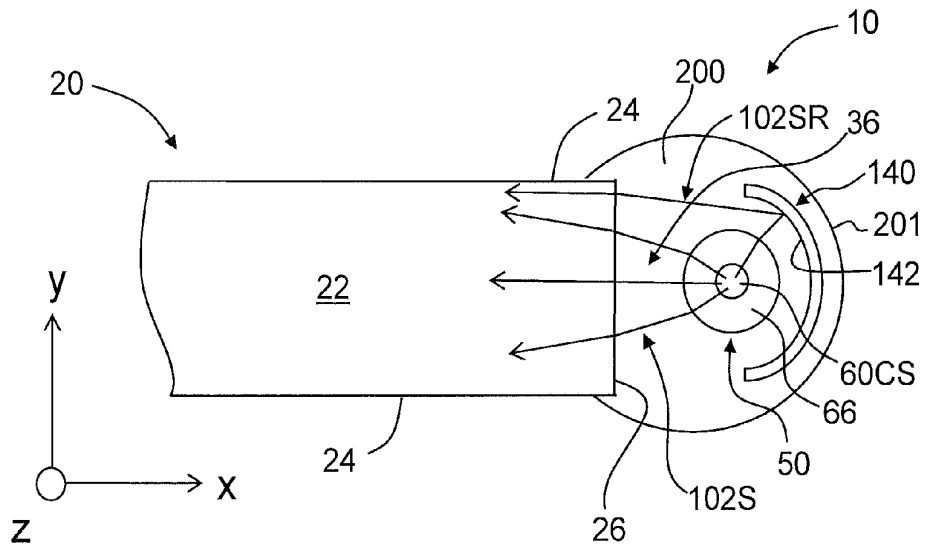
10
20
200
24
102SR
36
140
201
142
22
y
x
z
60CS
66
50
24
26
102S

FIG. 5D

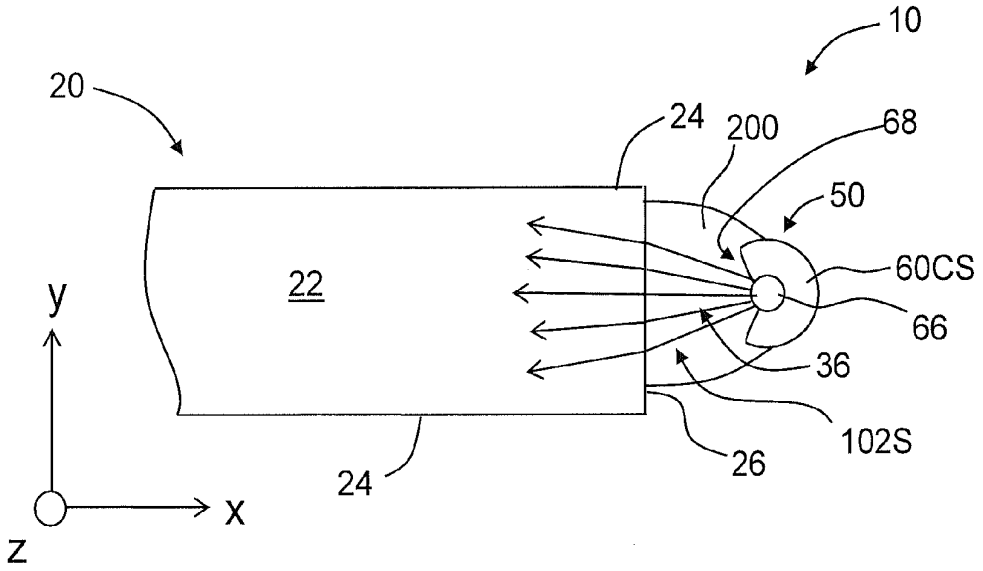
10
20
24
200
68
50
60CS
66
36
102S
26
22
24
y
x
z

FIG. 5E

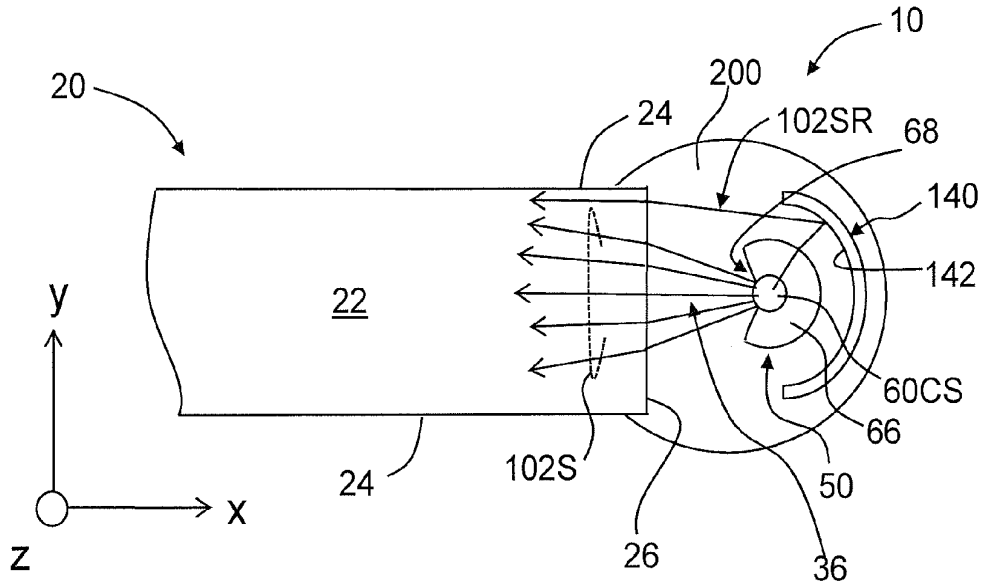
10
20
200
24
102SR
68
140
142
60CS
66
50
36
26
102S
22
24
y
x
z

FIG. 5F

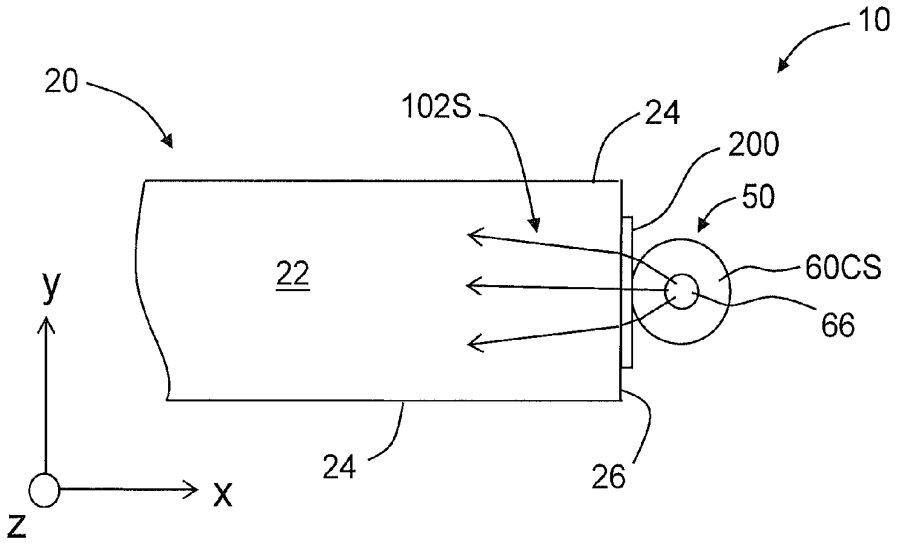
10
20
102S
24
200
50
60CS
66
22
y
x
z
24
26

FIG. 5G

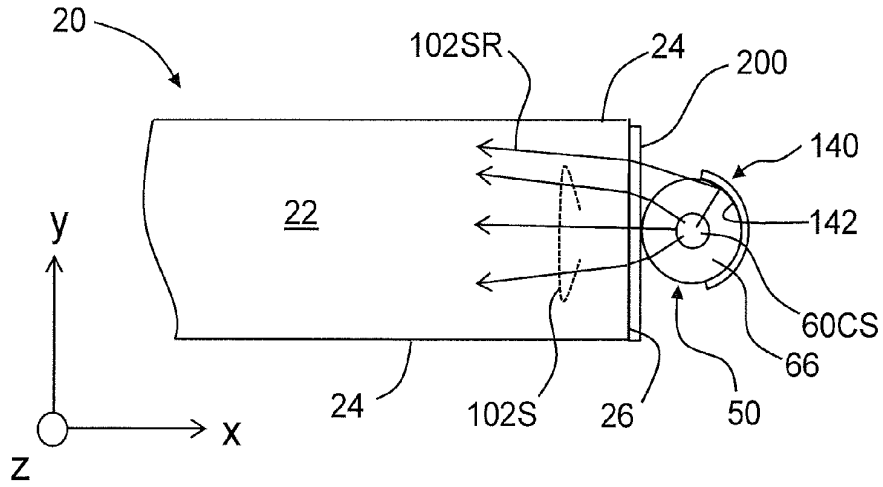
20
102SR
24
200
140
142
60CS
66
22
y
x
z
24
102S
26
50

FIG. 5H

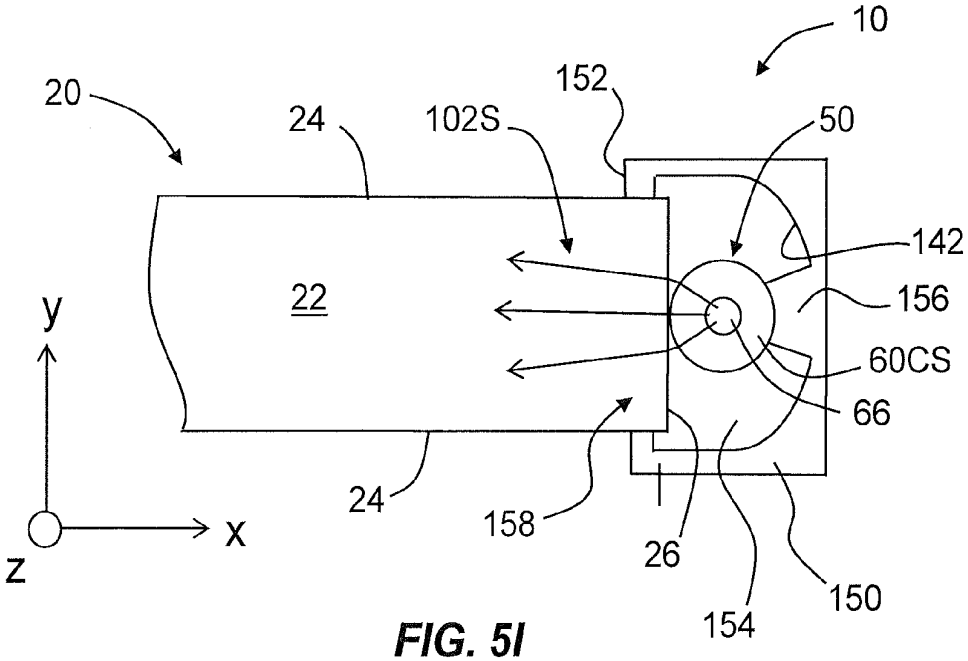
10
20
24
102S
152
50
142
156
60CS
66
22
y
x
z
24
158
26
154
150

FIG. 5I

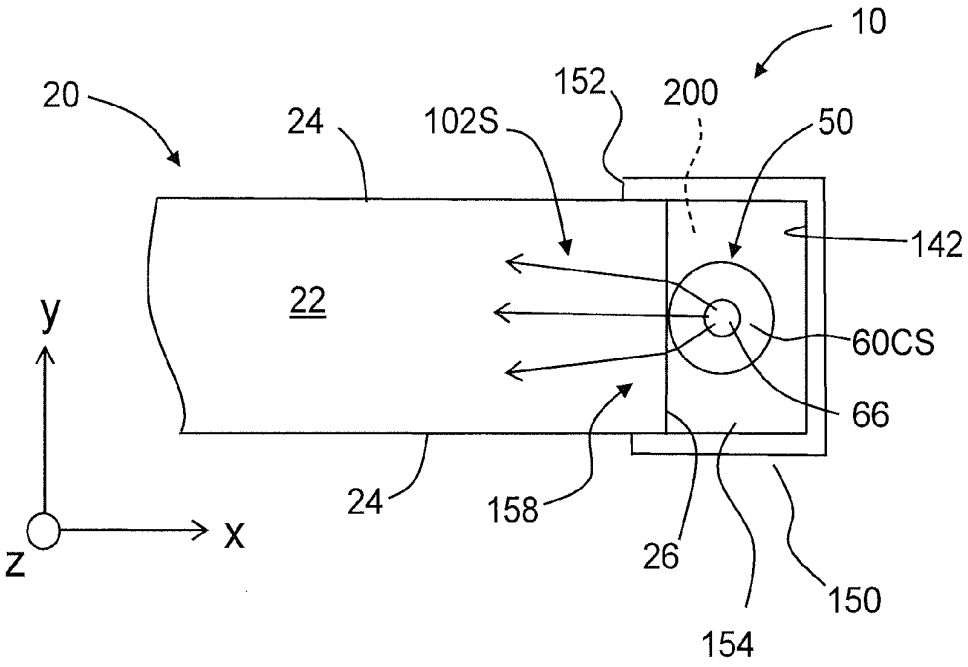
10
20
24
102S
152
200
50
142
60CS
66
22
y
x
z
24
158
26
154
150

FIG. 5J

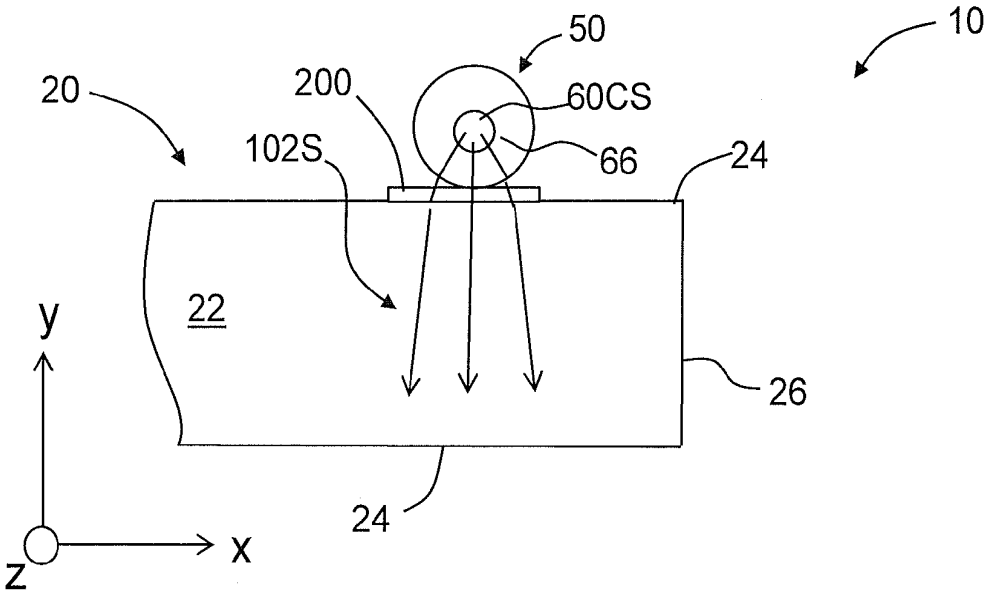
10
50
20
200
60CS
102S
66
24
22
26
y
24
x
z

FIG. 5K

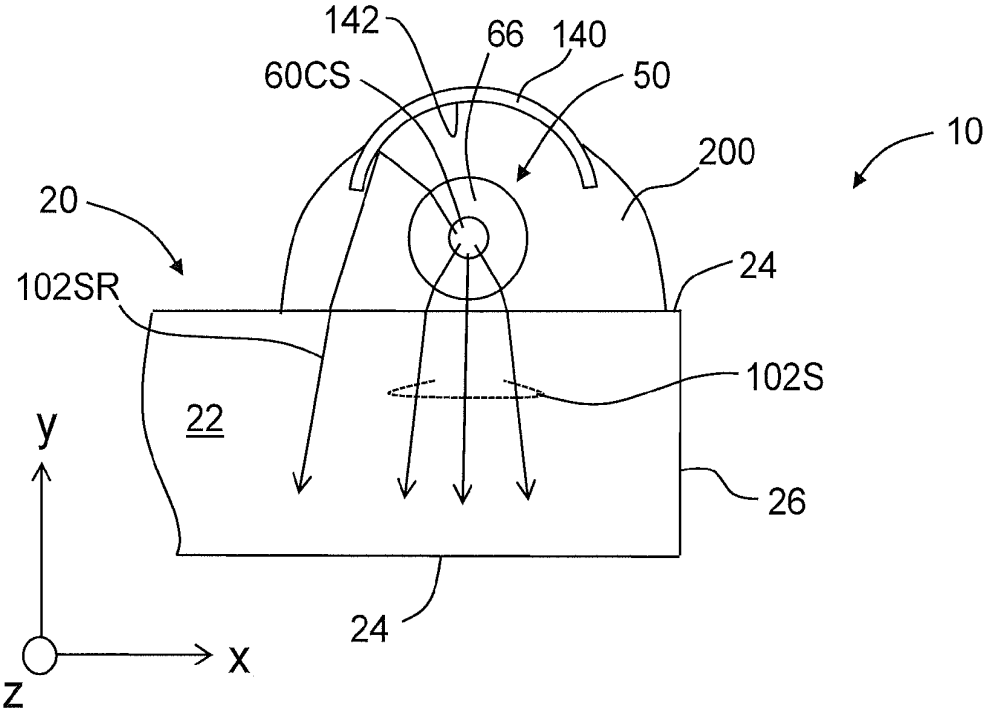
142
66
140
60CS
50
10
200
20
24
102SR
102S
22
y
26
24
x
z

FIG. 5L

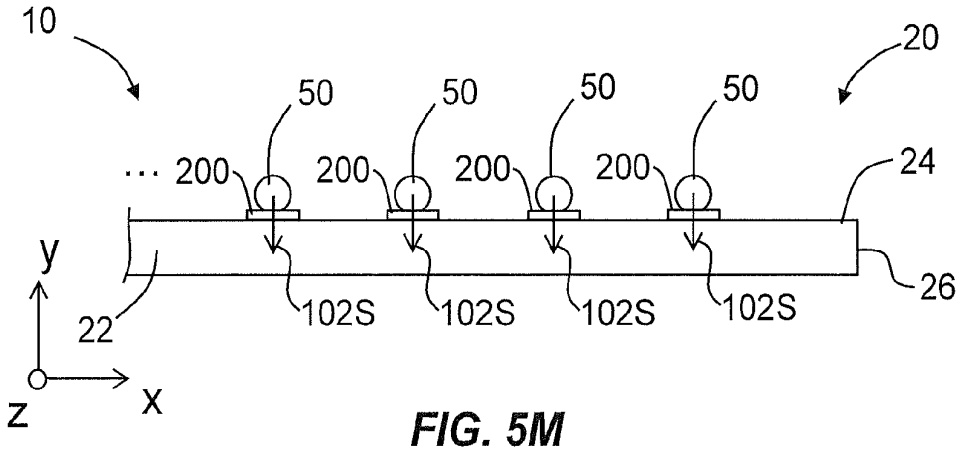

FIG. 5M

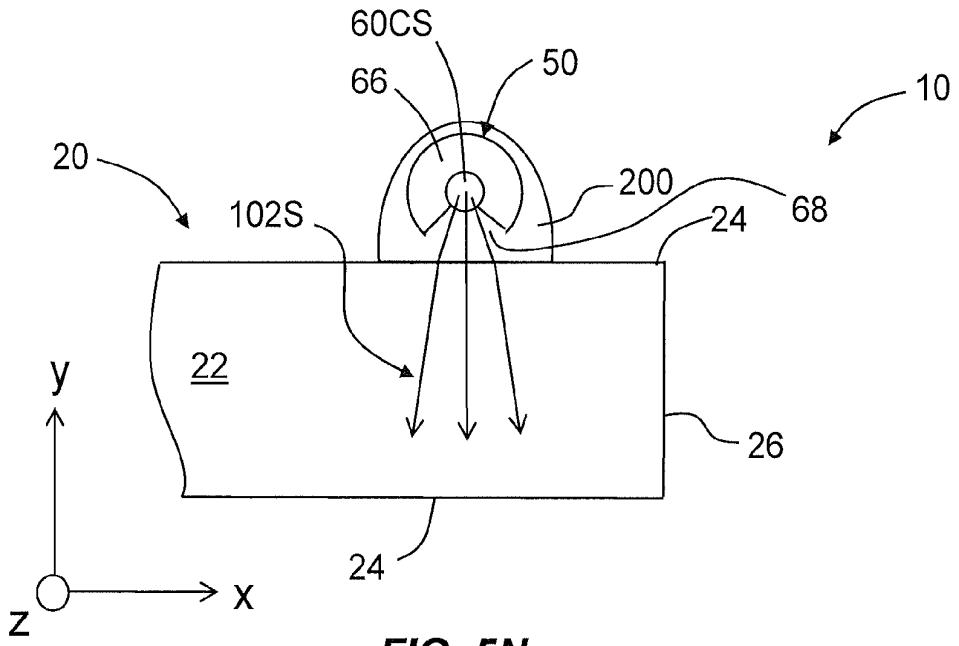

FIG. 5N

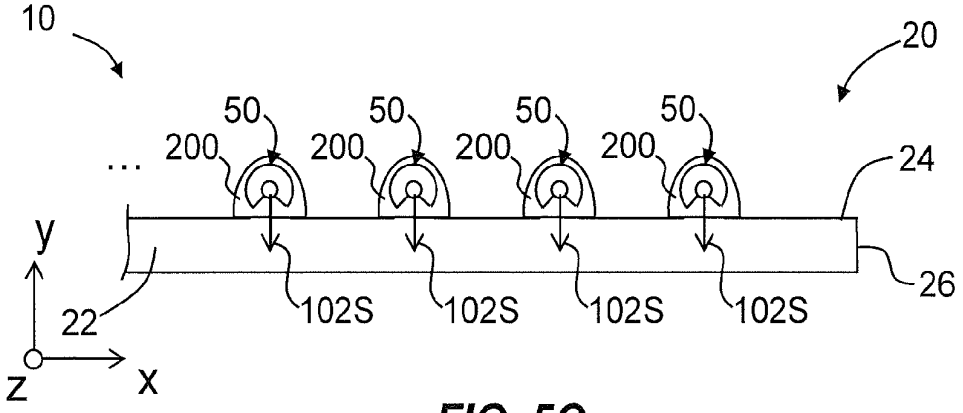

FIG. 5O

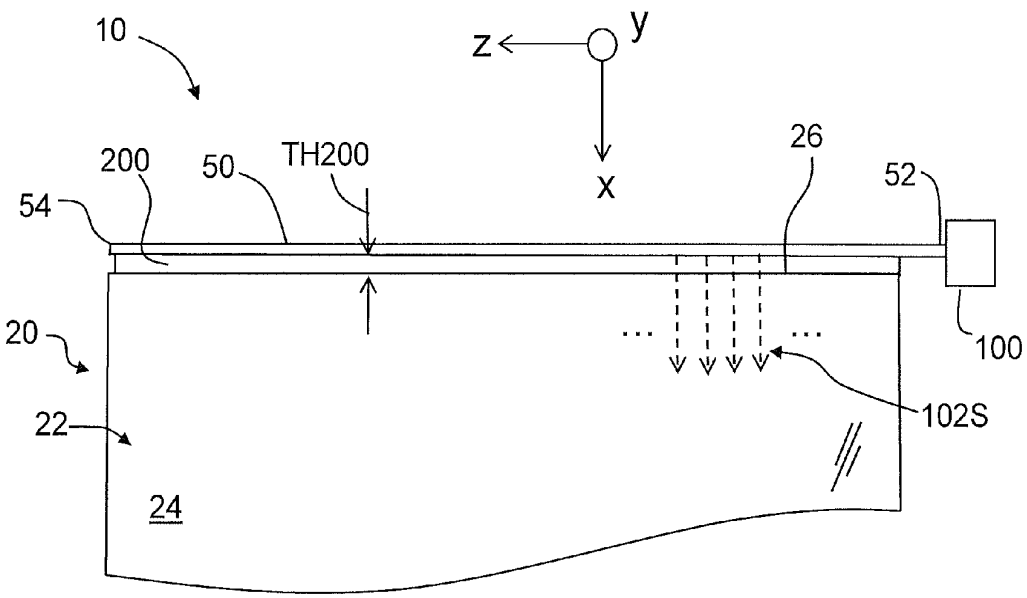

FIG. 6A

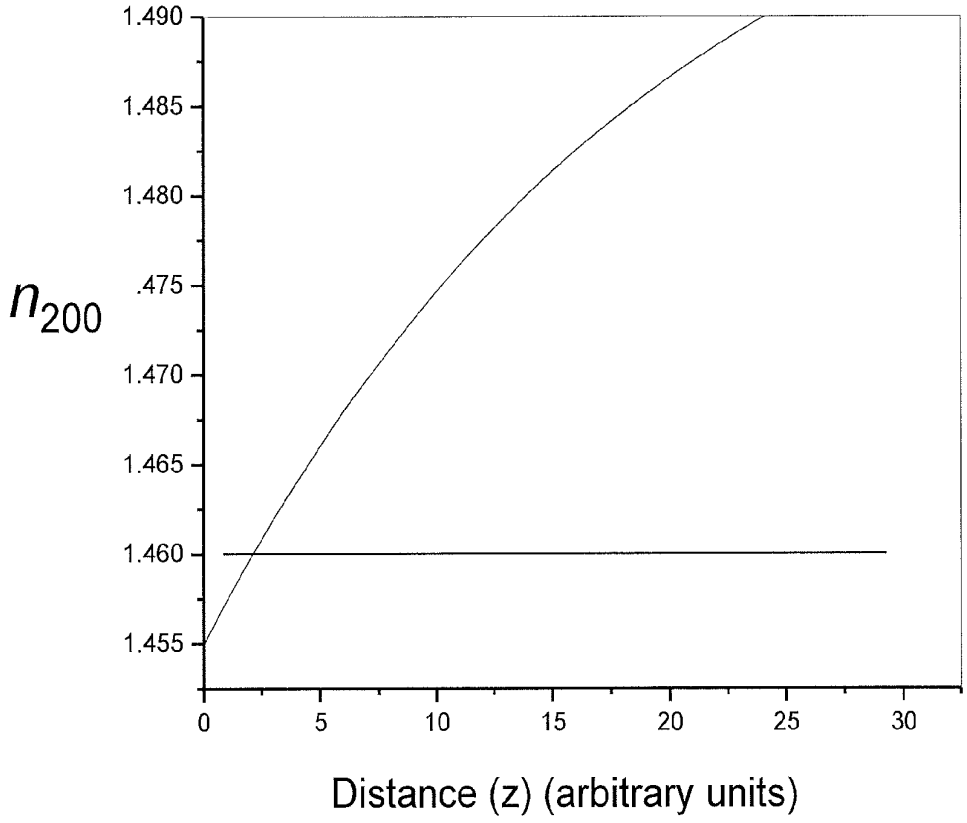
1.490
1.485
1.480
.475
1.470
1.465
1.460
1.455
n_{200}
0
5
10
15
20
25
30
Distance (z) (arbitrary units)

FIG. 6B

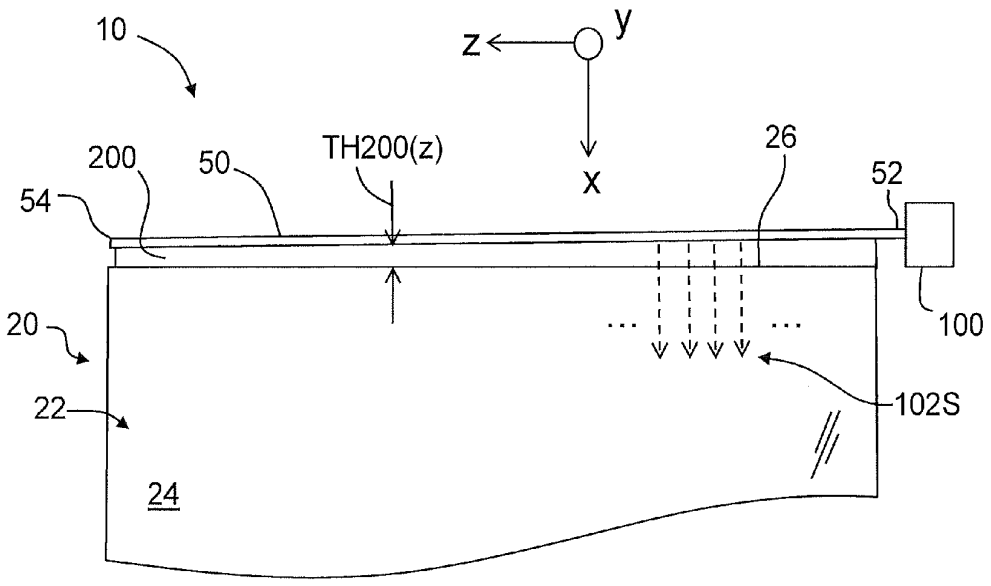
10
z
y
x
200
50
TH200(z)
26
52
54
100
20
22
102S
24

FIG. 6C

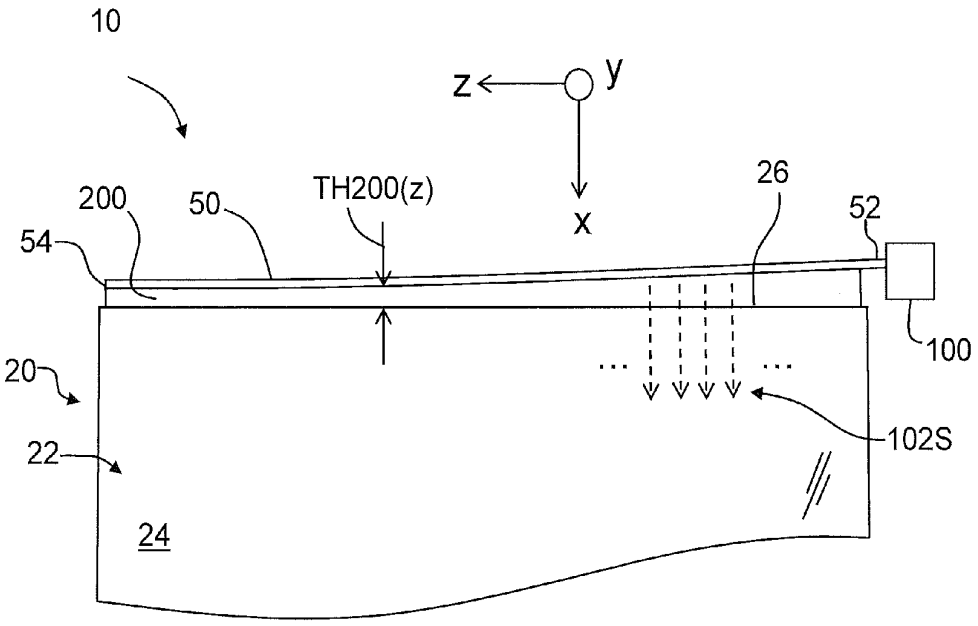
10
z
y
x
200
50
TH200(z)
26
52
54
100
20
22
102S
24

FIG. 6D

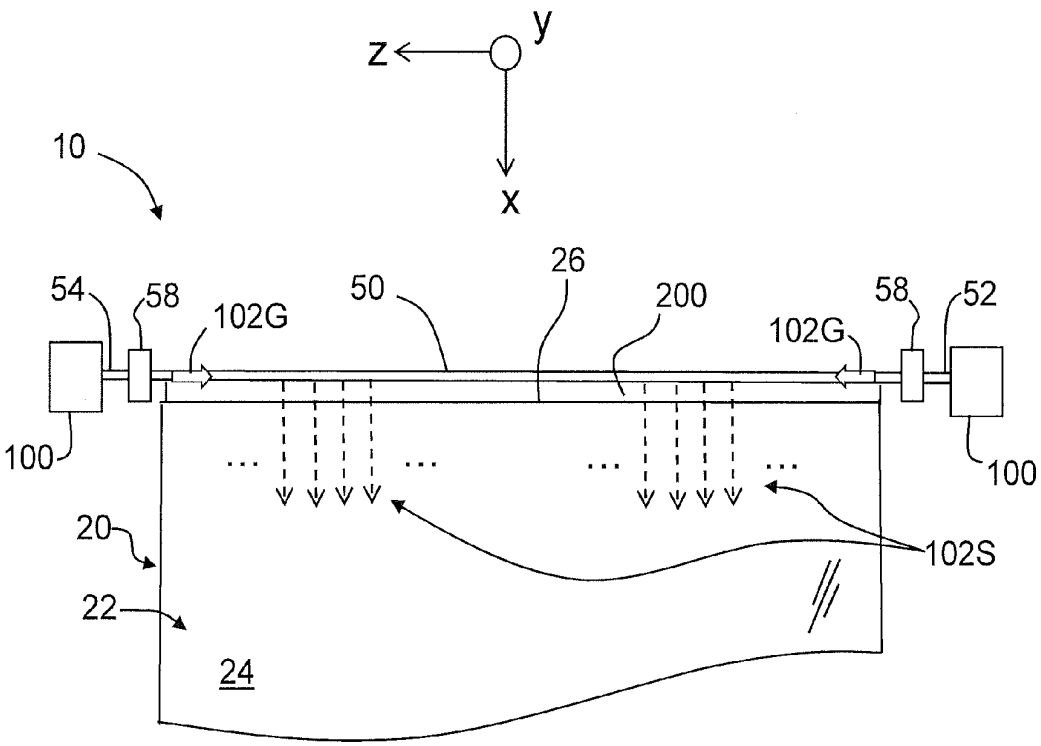

FIG. 6E

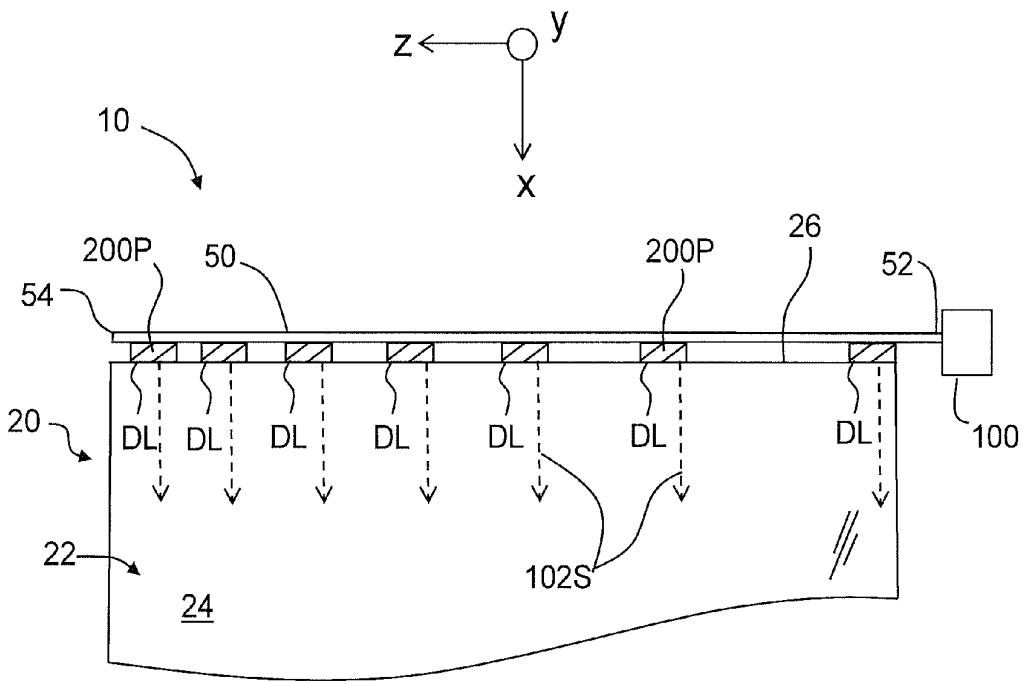

FIG. 6F

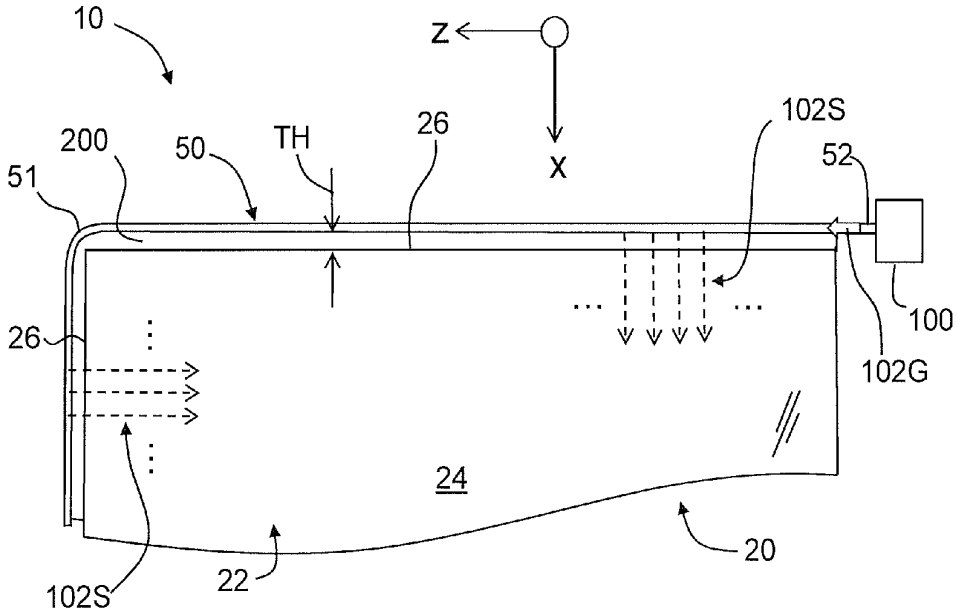
10
z
x
200
50
TH
26
102S
52
51
26
100
102G
24
20
22
102S

FIG. 7A

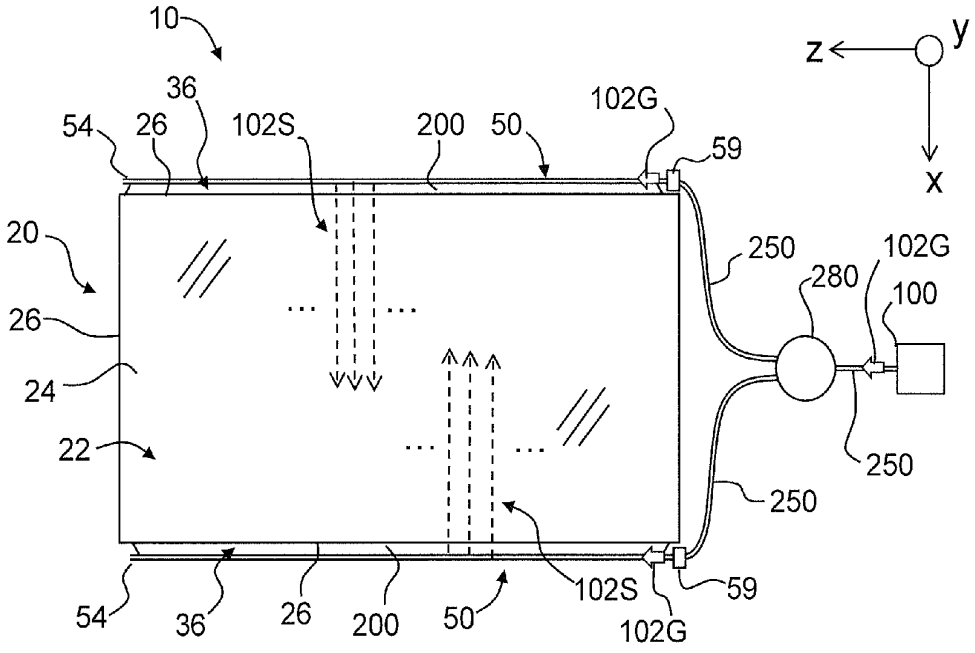
10
y
z
x
36
54
26
102S
200
50
102G
59
20
250
280
102G
100
26
24
22
250
250
54
36
26
200
50
102S
102G
59

FIG. 7B

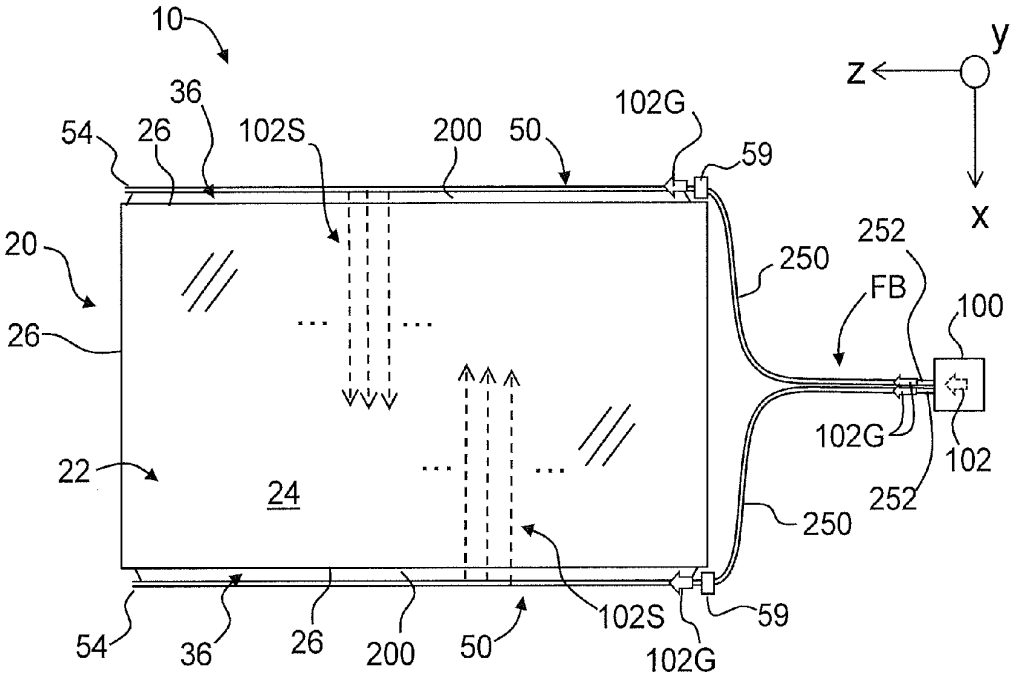
10
36
54
26
102S
200
50
102G
59
z
y
x
20
26
252
250
FB
100
102G
102
252
22
24
250
54
36
26
200
50
102S
59
102G

FIG. 7C

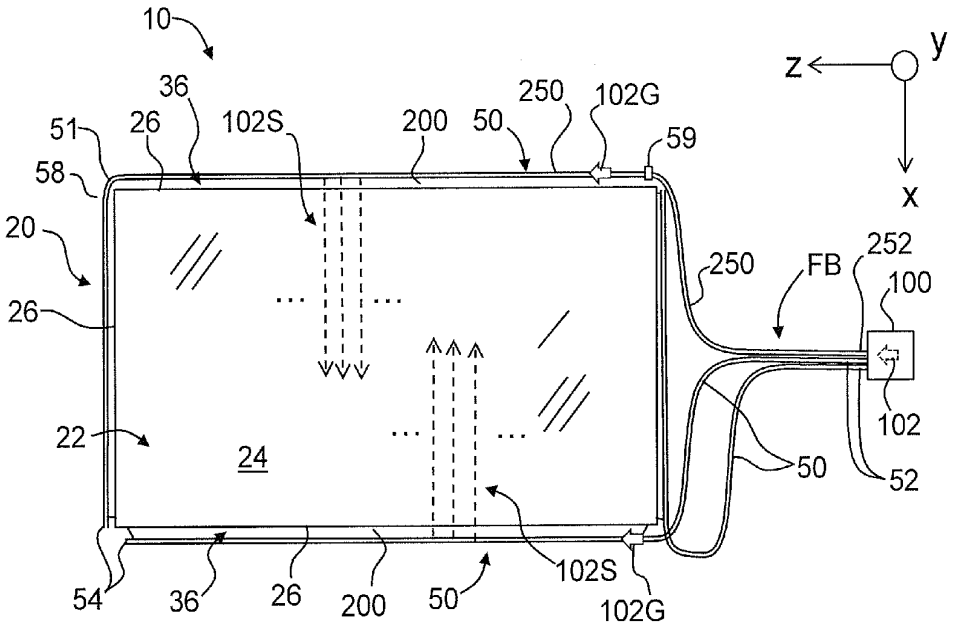
10
36
51
26
102S
200
50
250
102G
59
58
z
y
x
20
26
250
FB
252
100
22
24
102
50
52
54
36
26
200
50
102S
102G

FIG. 7D

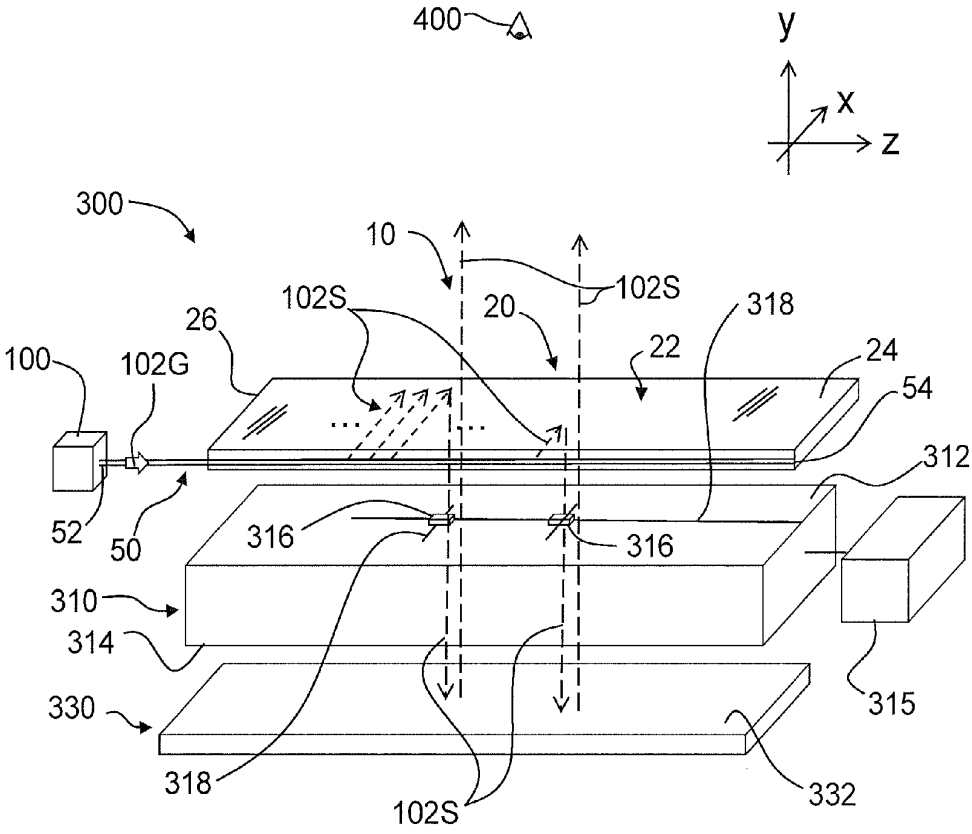
400
y
x
z
300
10
102S
102S
20
318
26
22
24
100
102G
54
312
52
50
316
316
310
314
330
315
318
102S
332

FIG. 8

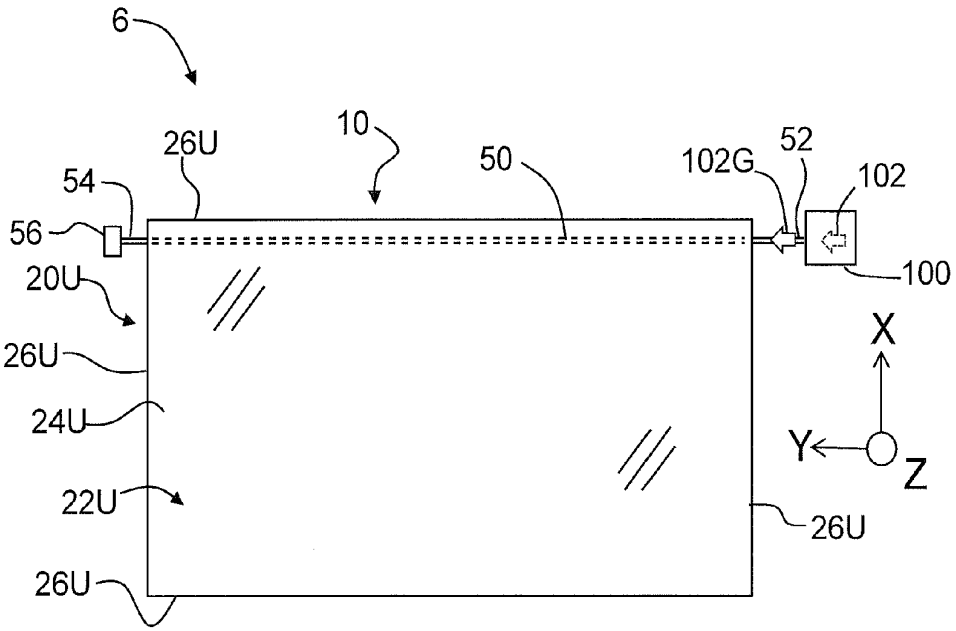
6
10
26U
50
54
102G
52
102
56
100
20U
26U
24U
22U
26U
26U
X
Y
Z

FIG. 9A

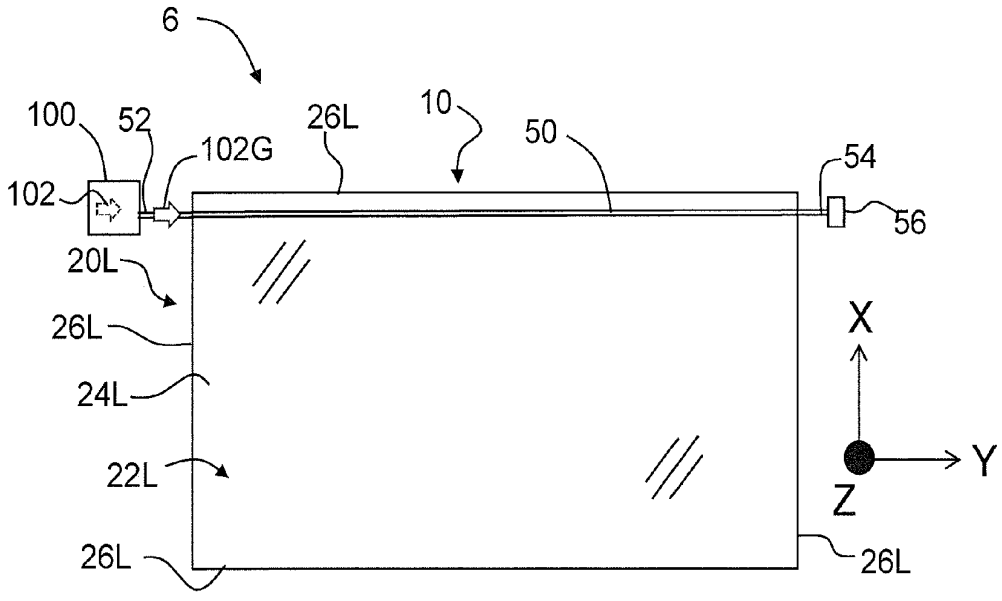
6
100
52
102G
26L
10
50
54
102
56
20L
26L
24L
22L
26L
26L
X
Y
Z

FIG. 9B

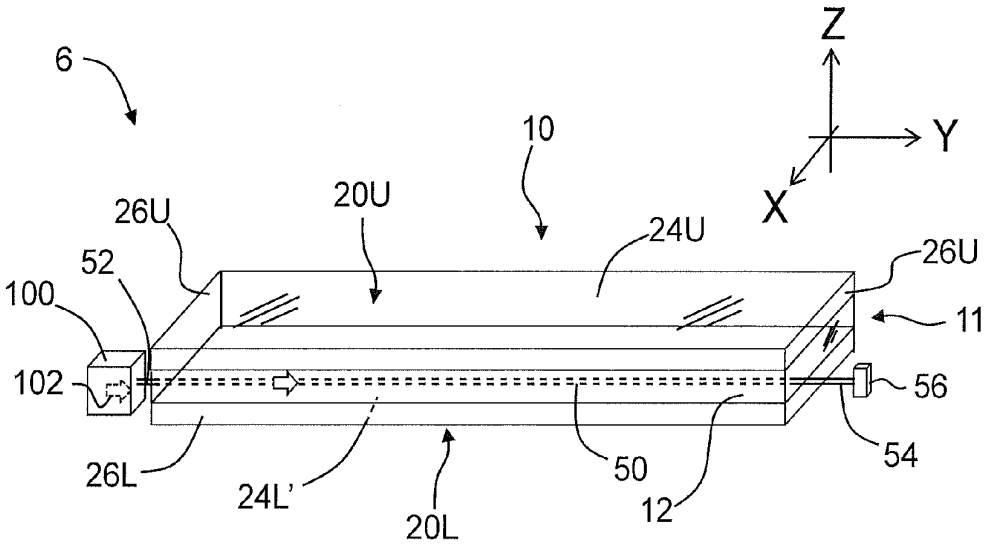
6
Z
Y
X
10
20U
26U
24U
26U
52
100
11
102
56
54
26L
24L'
20L
50
12

FIG. 10

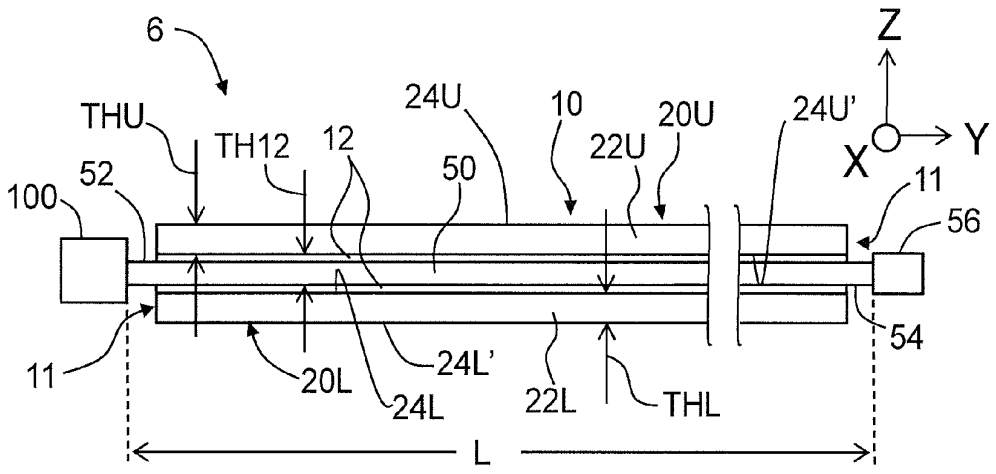
6
Z
Y
X
THU
TH12
12
24U
10
20U
22U
24U'
52
50
100
11
56
54
11
20L
24L'
24L
22L
THL
L

FIG. 11

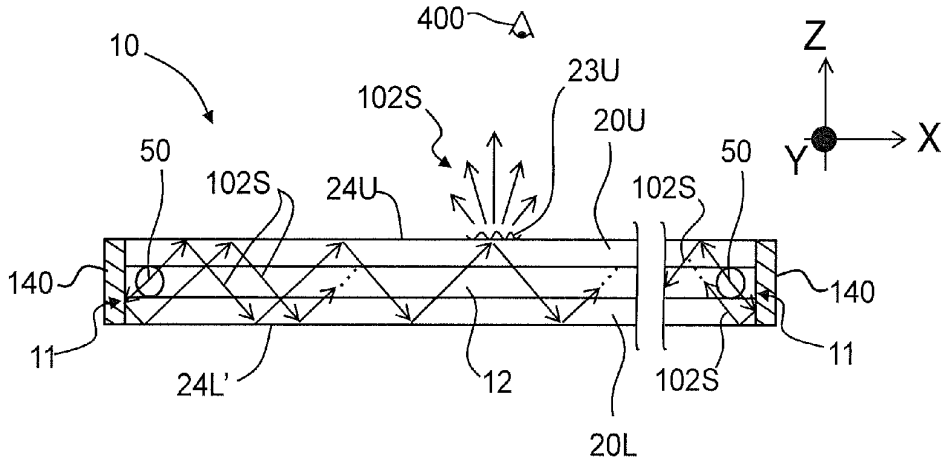

FIG. 12A

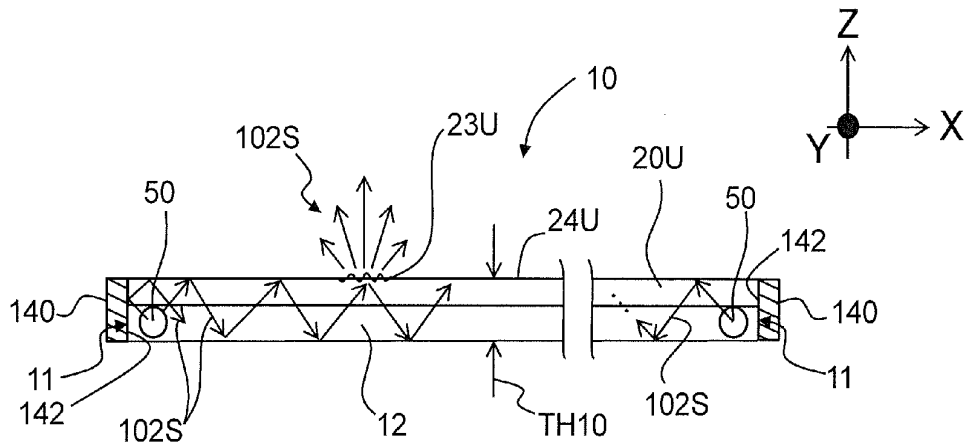

FIG. 12B

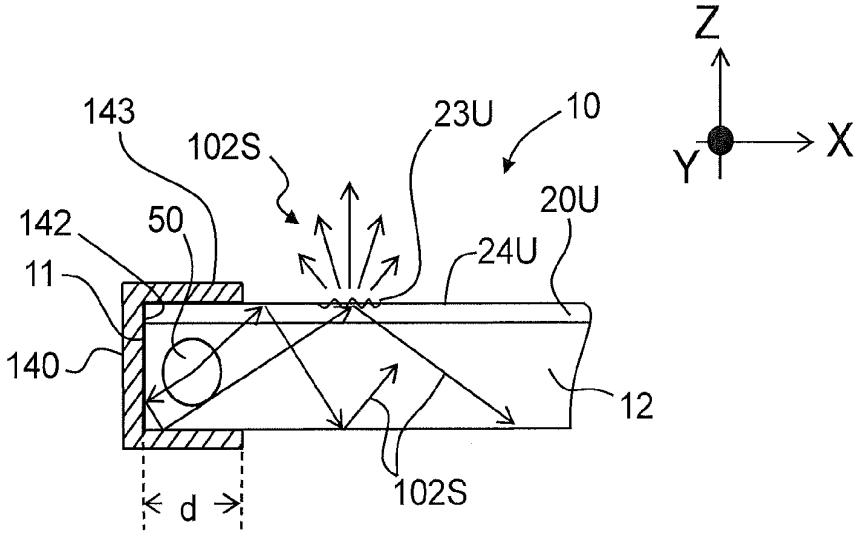

FIG. 12C

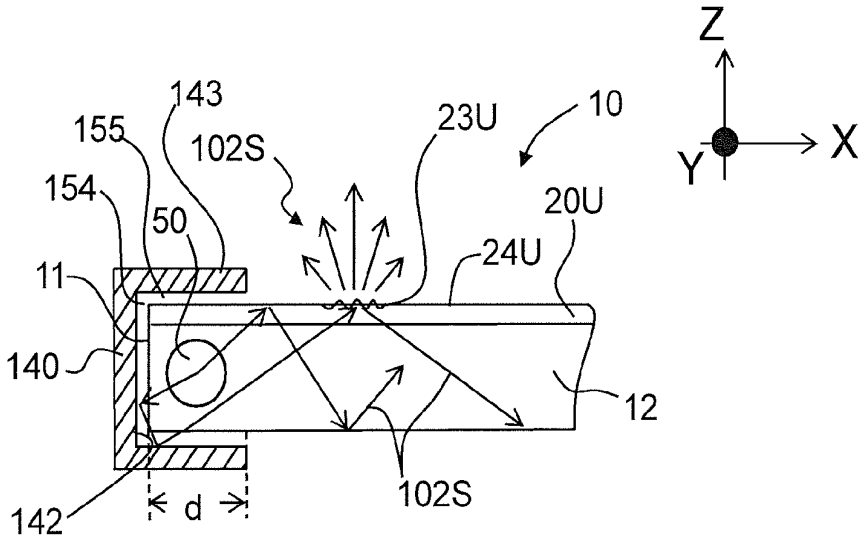

FIG. 12D

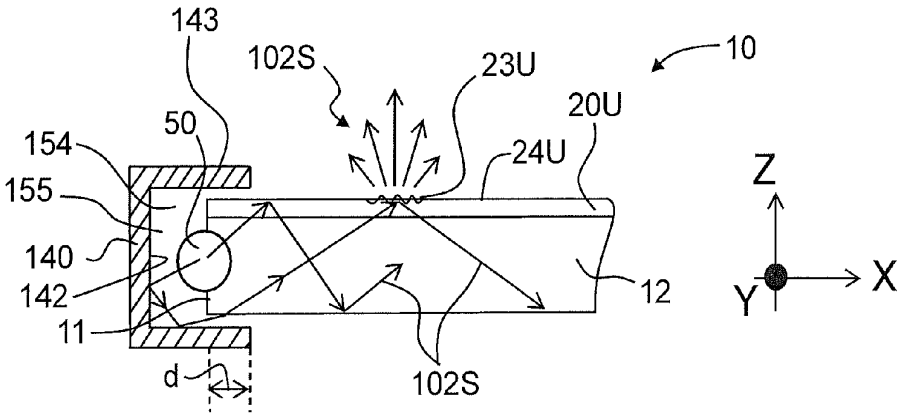

FIG. 12E

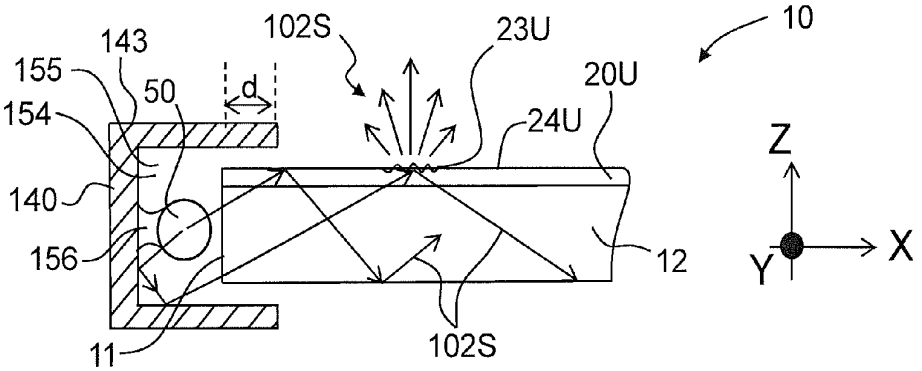

FIG. 12F

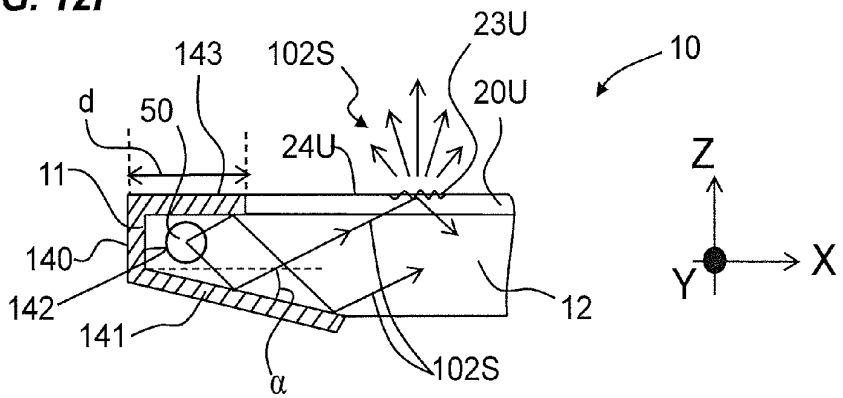

FIG. 12G

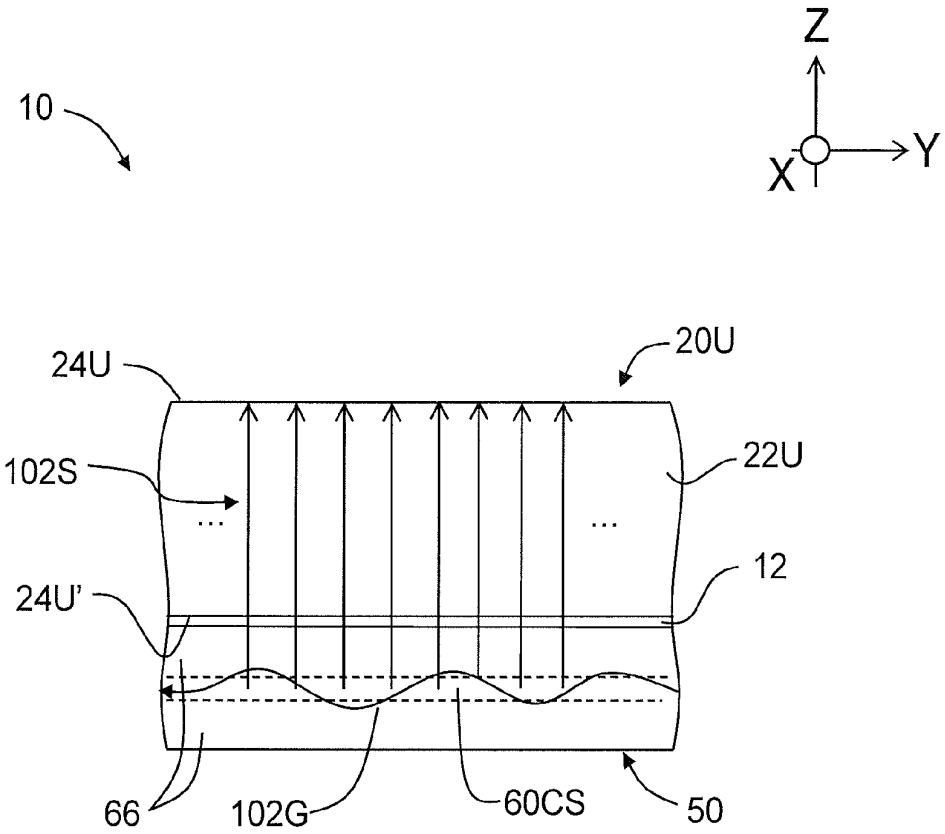

FIG. 13

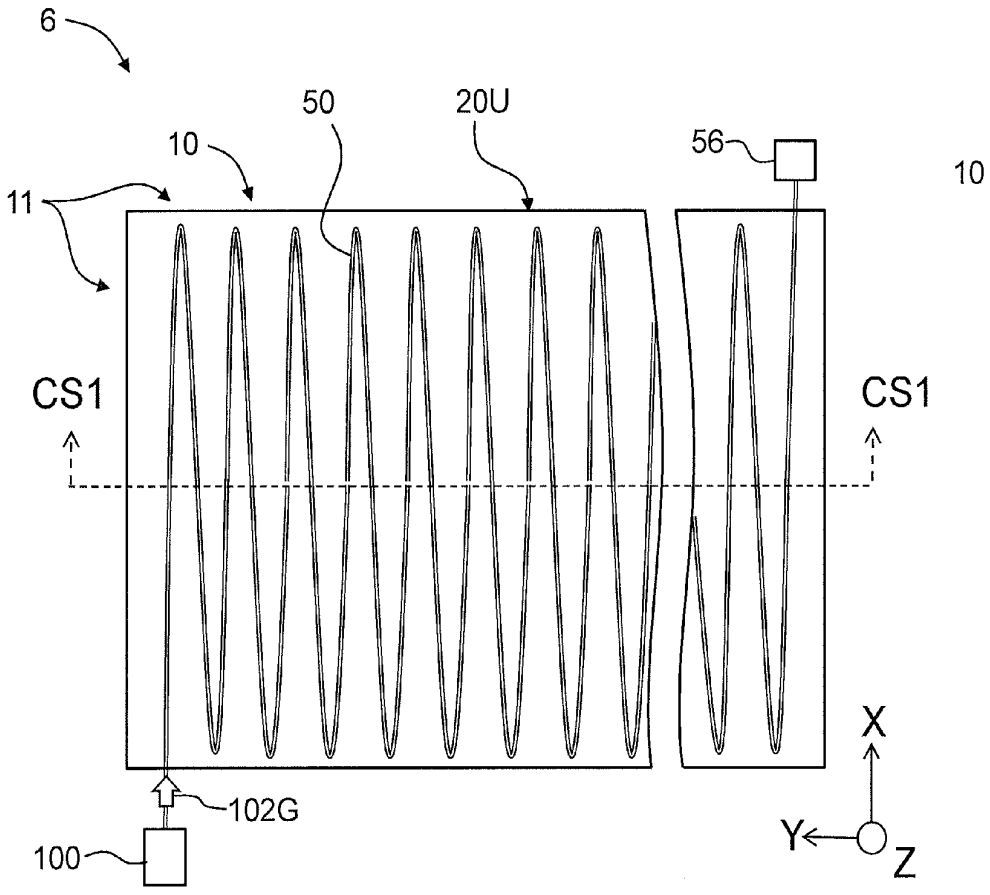

FIG. 14

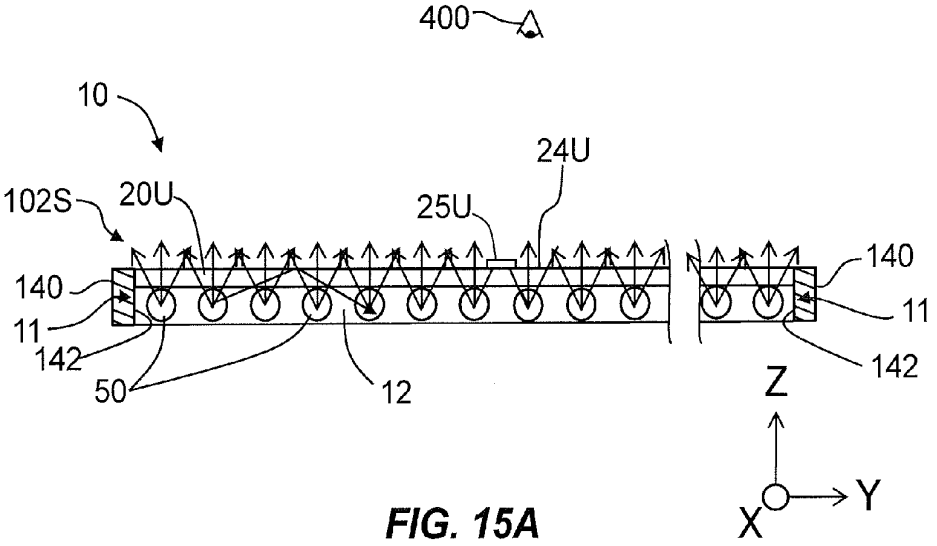

FIG. 15A

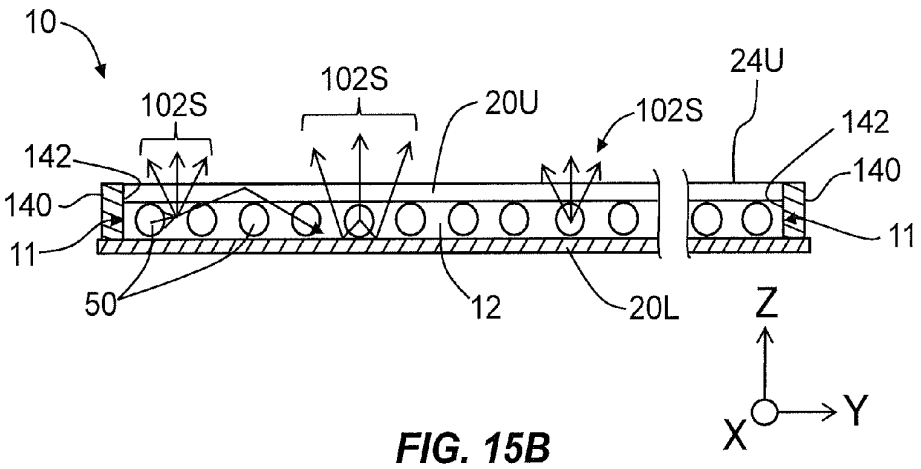

FIG. 15B

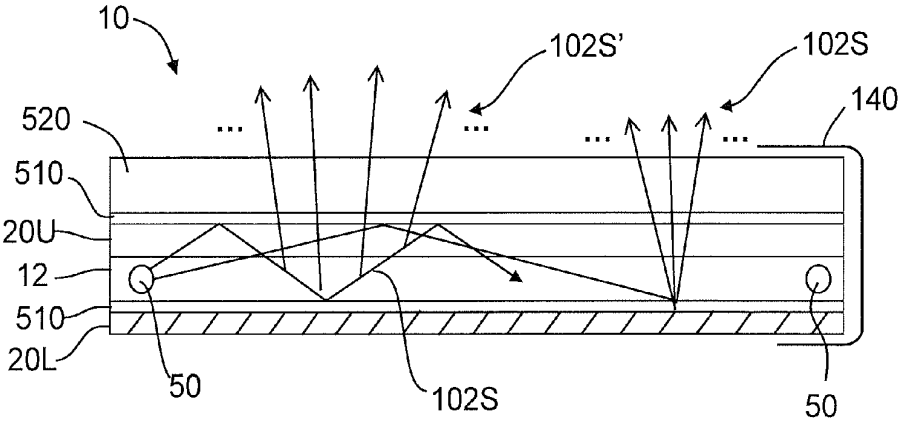

FIG. 16A

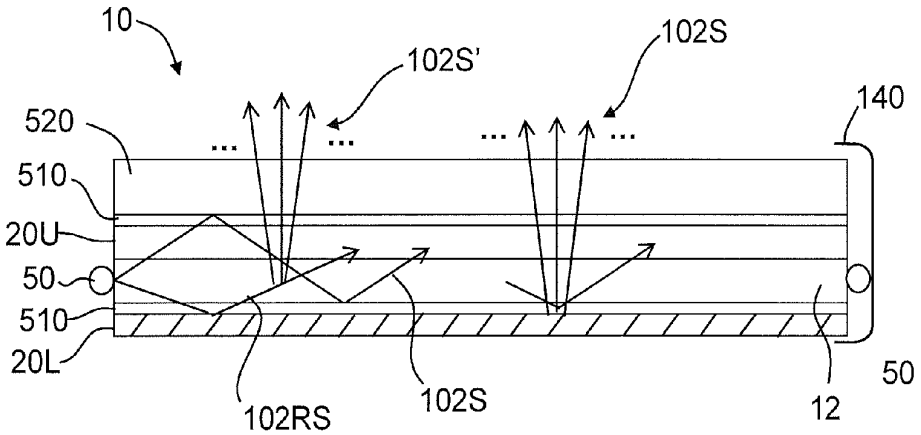

FIG. 16B

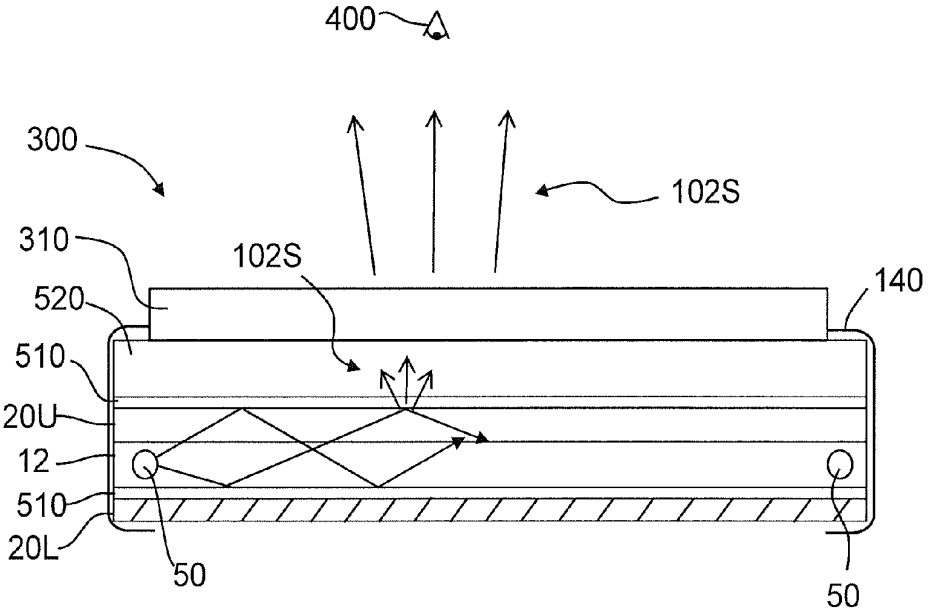

FIG. 17

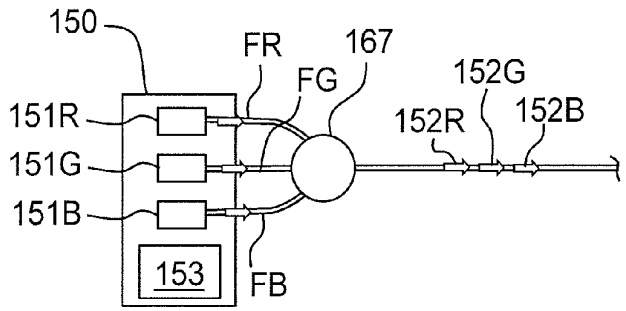

FIG. 18A

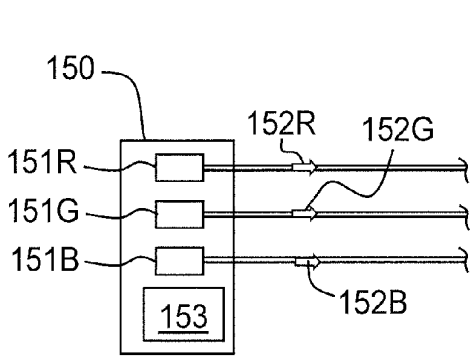

FIG. 18B

LIGHT-COUPLING OPTICAL SYSTEMS AND METHODS EMPLOYING LIGHT-DIFFUSING OPTICAL FIBERT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of U.S. patent application Ser. No. 13/094,221, filed on Apr. 26, 2011, and entitled, "Systems and methods for coupling light into a transparent sheet," which application is incorporated by reference herein.

FIELD

[0002] The disclosure is generally directed light-coupling optical systems, and in particular to light-coupling optical systems and methods that employ light-diffusing optical fiber.

BACKGROUND

[0003] There is an increasing variety of electronic-based devices that utilize flat-screen displays. Such devices range in size from the largest flat-screen televisions to the smallest hand-held devices such as cell-phones.

[0004] In certain types of flat-screen displays, an internal light source provides the light needed to view the display. For example, in one type of liquid-crystal display, an addressable liquid-crystal display structure is backlit with an internal light source and employs crossed polarizers on either side of the structure. Other types of flat-screen displays are reflective displays (e.g., reflective liquid crystal displays) that operate without backlighting or other internal light source and instead use ambient light from an external light source, such as room light.

[0005] While reflective displays that utilize ambient light are appealing for certain applications (e.g., so-called e-book applications), these displays are not functional in a dark environment and require an internal light source. However, the internal light source should be configured to maintain the compact and planar nature of the display while also providing illumination of sufficient uniformity and intensity to make the display readable.

SUMMARY

[0006] An embodiment of the disclosure is a light-coupling optical system. The light-coupling system includes a transparent sheet having substantially parallel opposite upper and lower surfaces and a first refractive index. An index-matching layer is disposed in contact with the lower surface of the transparent sheet and has a second refractive index that is substantially the same as the first refractive index. The light-coupling system has at least one light-diffusing optical fiber with a glass core, a cladding that surrounds the glass core, and a length. The glass core has randomly arranged voids configured to provide substantially spatially continuous light emission from the glass core and out of the cladding and into the transparent sheet along at least a portion of the length. The at least one light-diffusing optical fiber is at least partially disposed within the index-matching layer. The light-coupling optical system has at least one light source optically connected to the at least one light-diffusing optical fiber and that emits light into the at least one light-diffusing optical fiber, with the light traveling therein as guided light scattering therefrom as scattered light. The at least one light-diffusing optical fiber is arranged so that the scattered light travels within the transparent sheet and the index-matching layer via total internal reflection and is scattered out of the upper surface of the transparent sheet by at least one scattering feature of the transparent sheet.

[0007] Another embodiment is a method of providing illumination from a substantially planar surface of a transparent sheet having upper and lower surfaces. The method includes disposing at least a portion of at least one light-diffusing optical fiber within an index-matching layer that is immediately adjacent the lower surface of the transparent sheet. The at least one light-diffusing optical fiber has a core, a cladding and a length. At least a portion of the glass core includes randomly arranged voids configured to provide substantially continuous light emission from the core and out of the cladding along said portion of the light-diffusing optical fiber. The method also includes sending light down the glass core of at least one light-diffusing optical fiber as guided light to cause said light emission, with the emitted light traveling within the transparent sheet and the index-matching layer by total internal reflection. The method also includes scattering at least a portion of the light traveling within the transparent sheet and the index-matching layer out of the upper surface of the transparent sheet.

[0008] Another embodiment is a light-coupling optical system that has a transparent sheet with substantially parallel opposite upper and lower surfaces and a first refractive index. An index-matching layer is disposed in contact with the lower surface of the transparent sheet and has a second refractive index substantially the same as the first refractive index. A light source that emits light is optically coupled to a light diffusing optical fiber that is at least partially disposed within the index-matching layer. The light-diffusing optical fiber carries the light as guided light. The light-diffusing optical fiber has randomly arranged voids configured to provide substantially spatially continuous light emission due to scattering of the guided light from an outer surface of the light-diffusing optical fiber. The light-diffusing optical fiber is arranged so that the scattered light travels within the transparent sheet and the index-matching layer via total internal reflection and is scattered out of the upper surface of the transparent sheet by at least one scattering feature of the transparent sheet.

[0009] Another embodiment is a light-coupling optical system having a transparent sheet with upper and lower surfaces and a first refractive index. An index-matching layer is disposed in contact with the lower surface of the transparent sheet and has a second refractive index substantially the same as the first refractive index. The light-coupling optical system includes a light source that emits light. A light-diffusing optical fiber that is at least partially disposed within the index-matching layer and that is optically coupled to the light source to carry the light as guided light. The light-diffusing optical fiber has randomly arranged voids configured to provide substantially spatially continuous light emission due to scattering of the guided light from an outer surface of the light-diffusing optical fiber. The light-diffusing optical fiber is arranged so that the scattered light travels within the transparent sheet and the index-matching layer via total internal reflection and is scattered out of the upper surface of the transparent sheet by at least one scattering feature of the transparent sheet.

[0010] Additional features and advantages will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the same as described herein,

including the detailed description that follows, the claims, as well as the appended drawings.

[0011] It is to be understood that both the foregoing general description and the following detailed description present embodiments that are intended to provide an overview or framework for understanding the nature and character of the claims. The accompanying drawings are included to provide a further understanding of the disclosure, and are incorporated into and constitute a part of this specification. The claims are incorporated into and constitute part of this specification. The drawings illustrate various embodiments and together with the description serve to explain the principles and operation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] FIG. **1** is a top-down view of an example light-coupling optical system according to the disclosure;

[0013] FIG. **2** is an elevated view of the light-coupling optical system of FIG. **1**;

[0014] FIG. **3**A is a cross-sectional view of an example light-diffusing optical fiber, including a detailed cross-sectional view of the central core section;

[0015] FIG. **3**B and FIG. **3**C are cross-sectional photographs of example light-diffusing optical fibers having different core and cladding geometries;

[0016] FIG. **3**D is similar to FIG. **3**A and illustrates another example embodiment of a light-diffusing optical fiber that includes an outer layer of light-scattering material;

[0017] FIG. **4**A is a schematic plot of the light intensity $I_C(z)$ in the core section as a function of the distance z along the length of an example light-diffusing optical fiber from the coupling end to the terminal end, illustrating the drop in light intensity within the core section due to scattering loss;

[0018] FIG. **4**B is a schematic plot of the idealized scattered light intensity $I_S(z)$ from the light-diffusing optical fiber, illustrating a desired constant intensity I_{CONST} of the scattered light as a function of distance z;

[0019] FIG. **5**A is a close-up, cross-sectional view (X-Y plane) of an edge portion of the transparent sheet and the light-diffusing optical fiber operably arranged adjacent the edge of the transparent sheet;

[0020] FIG. **5**B is similar to FIG. **5**A and further includes a reflecting member operably arranged relative to the light-diffusing optical fiber so that at least a portion of the scattered light that would not otherwise be coupled into the transparent sheet at the edge is coupled into the transparent sheet;

[0021] FIG. **5**C is similar to FIG. **5**A, and further includes an index-matching material disposed between the light-diffusing optical fiber and the transparent sheet so that the scattered light travels through the index-matching material;

[0022] FIG. **5**D is similar to FIG. **5**B and illustrates an example embodiment where the index-matching material is used to support the light-diffusing optical fiber and the reflecting member;

[0023] FIG. **5**E is similar to FIG. **5**C, and illustrates an example embodiment wherein a portion of the cladding is removed from the light-diffusing optical fiber along at least a portion of its length to define a cladding gap, with the cladding gap filled with an index-matching material;

[0024] FIG. **5**F is similar to FIG. **5**D and illustrates an example embodiment where the light-diffusing optical fiber includes a cladding gap filled with an index-matching material;

[0025] FIG. **5**G is similar to FIG. **5**A, and illustrates an example embodiment wherein the index-matching material is in the form of an adhesive strip applied to the edge of the transparent sheet;

[0026] FIG. **5**H is similar to FIG. **5**G and further includes a reflective member operably disposed on a portion of the cladding;

[0027] FIG. **5**I and FIG. **5**J are similar to FIG. **5**G, and illustrate example embodiments that include a support member configured to support the light-diffusing optical fiber relative to the transparent sheet;

[0028] FIG. **5**K is similar to FIG. **5**G, except that the index-matching adhesive strip and the light-diffusing optical fiber reside adjacent the upper surface of the transparent sheet;

[0029] FIG. **5**L is similar to FIG. **5**K, with the index-matching material supporting both the light-diffusing optical fiber and an operably arranged reflecting member;

[0030] FIG. **5**M is similar to FIG. **5**K, and illustrates multiple light-diffusing optical fibers adhered to the upper surface of the transparent sheet;

[0031] FIG. **5**N is similar to FIG. **5**L, except that there is no reflecting member, and a light-diffusion optical fiber has a cladding gap;

[0032] FIG. **5**O is similar to FIG. **5**K, and illustrates multiple light-diffusing optical fibers as configured in FIG. **5**M adhered to the upper surface of the transparent sheet;

[0033] FIG. **6**A is similar to FIG. **1** and illustrates an example embodiment wherein index-matching material has an index of refraction n_{200} that varies as a function of distance z along the length of the light-diffusing optical fiber;

[0034] FIG. **6**B is a plot of an example profile of the index of refraction n_{200} of the index-matching material versus the distance z along the length of the light-diffusing optical fiber;

[0035] FIG. **6**C and FIG. **6**D are similar to FIG. **6**A and illustrate example embodiments where the thickness of the index-matching material varies with distance z along the length of the optical fiber;

[0036] FIG. **6**E is similar to FIG. **6**A and illustrates an example embodiment where the light-diffusing optical fiber is optically coupled to two light sources;

[0037] FIG. **6**F is similar to FIG. **6**A and illustrates an example embodiment where the index-matching material (shown in cross-hatch for ease of viewing) is not continuous and is provided in discrete portions at discrete locations along the length of the light-diffusion optical fiber between the optical fiber and the transparent sheet;

[0038] FIG. **7**A is similar to FIG. **6**A, and illustrates an embodiment wherein the light-diffusing optical fiber includes a bend that allows the optical fiber to reside adjacent two edges of the transparent sheet;

[0039] FIG. **7**B is similar to FIG. **7**A and illustrates an example embodiment that employs multiple light-diffusing optical fibers along different edges of the transparent sheet;

[0040] FIG. **7**C is similar to FIG. **7**B and illustrates an example embodiment where the ends of the non-light-diffusing optical fibers are brought together to form a fiber bundle;

[0041] FIG. **7**D illustrates an embodiment similar to FIG. **7**C where three light-diffusing optical fibers and one non-light-diffusing optical fiber converge to form a fiber bundle, and where the three light-diffusing optical fibers are configured to provide coverage of all four edges of the transparent sheet;

[0042] FIG. **8** is an exploded elevated view of an example flat-screen device that includes the light-coupling optical system of the disclosure;

[0043] FIGS. **9**A and **9**B are top-down views of an example light-coupling optical system according to the disclosure;

[0044] FIG. **10** is a side elevated view of the light-coupling optical system of FIG. **1**;

[0045] FIG. **11** is a cross-sectional view of the light-coupling optical system of FIG. **2** as taken in the Y-Z plane;

[0046] FIG. **12**A is cross-sectional view of embodiments of the optical assembly of the light-coupling optical system of FIG. **9**A as taken in the X-Z plane, with the optical assembly having upper and lower transparent sheets sandwiching an index-matching layer;

[0047] FIG. **12**B is similar to FIG. **12**A and illustrates an example embodiment where the optical assembly includes upper sheet and an index-matching layer and no lower sheet;

[0048] FIG. **12**C is a close-up cross-sectional view of an end portion of the optical assembly illustrating an example embodiment where the reflecting member has a U-shape and is arranged in contact with the perimeter, the upper sheet and the index-matching layer;

[0049] FIG. **12**D is similar to FIG. **12**C and illustrates an example embodiment where the reflecting member is spaced apart from the perimeter, the upper sheet and the index matching layer by an air gap;

[0050] FIG. **12**E is similar to FIG. **12**D, except that a portion of the light-diffusing optical fiber extends from the perimeter;

[0051] FIG. **12**F is similar to FIG. **12**E, except that the light-diffusing optical fiber resides outside of the index matching layer and adjacent the perimeter;

[0052] FIG. **12**G is similar to FIG. **12**C and illustrates an example embodiment wherein the reflecting member has an angled portion;

[0053] FIG. **13** is close-up cross-sectional view of an optical assembly, showing how guided light traveling in the light-diffusing optical fiber is emitted from the sides of the light-diffusing optical fiber and travels through the upper transparent sheet;

[0054] FIG. **14** is a top-down view of an example embodiment of the light-coupling optical system wherein the light-diffusing optical fiber has a serpentine configuration in the X-Y plane;

[0055] FIG. **15**A is a cross-sectional view of the example embodiment of light-coupling optical system of FIG. **14** as taken along the line CS**1** therein and showing the scattered light from the light-diffusing optical fiber passing through the upper transparent sheet;

[0056] FIG. **15**B is similar to FIG. **15**A and illustrates an example embodiment wherein the light-coupling optical system includes a reflective lower sheet as well as side reflectors;

[0057] FIG. **16**A is a cross-sectional view similar to that of FIG. **12**B and illustrates another example embodiment of an optical assembly that includes additionally includes low-index layers that sandwich the upper sheet and the index-matching layer, and wherein the lower sheet comprises a diffuse reflector;

[0058] FIG. **16**B is similar to FIG. **16**A and illustrates an example where the light-diffusing optical fibers reside outside of and adjacent the index-matching layer;

[0059] FIG. **17** is a cross-sectional view of an example embodiment of a display screen device that includes the optical assembly of FIG. **16**A;

[0060] FIG. **18**A is a close-up view of an example light source assembly wherein the light source includes red, green and blue light emitters that are optically coupled to the light-diffusing optical fiber via a multiplexing device; and

[0061] FIG. **18**B is similar to FIG. **18**A, except that the three different light-diffusing optical fibers are optically coupled directly to the respective red, green and blue light emitters.

DETAILED DESCRIPTION

[0062] Reference is now made in detail to the preferred embodiments of the disclosure, examples of which are illustrated in the accompanying drawings. Whenever possible, like reference numbers are used to refer to like components or parts. Cartesian coordinates are shown in some of the Figures by way of reference.

[0063] FIG. **1** is a top-down view of an example light-coupling optical system **6** according to the disclosure. FIG. **2** is an elevated view of the light-coupling optical system **6** of FIG. **1**. System **6** generally includes a transparent sheet **20**, a light-diffusing optical fiber **50** operably disposed adjacent the transparent sheet, and a light source **100** optically coupled to the light-diffusing optical fiber. In an example, light source **100** comprises at least one light-emitting diode (LED) or at least one diode laser. Light source **100** emits light **102** that in one example is in the wavelength range from 350 nm to 1,000 nm, while in another example is in the visible wavelength range, e.g., nominally from 380 nm (violet) nm to 750 nm (red).

[0064] Transparent sheet **20** has a body **22** that defines a thickness TH**22**, opposite upper and lower (i.e., top and bottom) substantially planar and substantially parallel surfaces **24**, and one or more edges **26**, such as four edges **26** for a rectangular transparent sheet. Transparent sheet **20** can be made of, for example, glass, plastic, display glass such as Corning's EAGLE XG®, EAGLE®, GORILLA® and PYREX® glasses, as well as fused silica, plastic materials like PPMA or any other transparent material. Here, the term "transparent" generally means that the transparent sheet transmits light **102** at least in the visible wavelength range, and transmits more light than it absorbs for the given thickness TH**22** of transparent sheet body **22**.

[0065] In an example, the thickness TH**22** of transparent sheet body **22** is 0.3 mm or greater, and in another example is 0.7 mm or greater. In an example, transparent sheet body **22** has a refractive index of about 1.5 or greater at 550 nm. Also in an example, one or more of upper and lower surfaces **24** may be rough surfaces with a roughness designed to scatter light **102**.

[0066] System **6** includes at least one light-diffusing optical fiber **50**. The term "light-diffusing" means that light scattering is substantially spatially continuous along at least a portion of the length of the light-diffusing optical fiber **50**, i.e., there are no substantial jumps or discontinuities such as those associated with discrete (e.g., point) scattering. Thus, the concept of substantially continuous light emission or substantially continuous light scattering as set forth in the present disclosure refers to spatial continuity.

[0067] In an example, light-diffusing optical fiber **50** includes a coupling end **52** and a terminal end **54**. Coupling end **52** and terminal end **54** define a length L for light-diffusing optical fiber **50**. Coupling end **52** is optically coupled to light source **100** so that light **102** from the light source travels in light-diffusing optical fiber **50** as guided light **102**G. Light-

diffusing optical fiber **50** is disposed adjacent at least one of transparent sheet edge **26** and transparent sheet surface **24**. In an example, a terminal optical member **56** is operably disposed adjacent terminal end **54** of light-diffusing optical fiber **50**. In one example, terminal optical member **56** is an optical absorber that absorbs light **102**, while in another example it is an optical reflector that reflects light **102** (e.g., guided light **102**G) so that the reflected guided light travels down the optical fiber **50** in the opposite direction, i.e., toward light source **100**. In such an example, an optical isolator (not shown) may be employed (e.g., adjacent light source **100**) to prevent light **102** from returning to light source **100**.

[0068] FIG. **3**A is a cross-sectional view of an example light-diffusing optical fiber **50** having a central core section ("core") **60**CS, and an outer cladding **66**, and showing in detail an example configuration for the core. Light-diffusing optical fiber **50** includes a center (or inner) core region **60** having a diameter D**60**, and an outer core region **62** that at least partially surrounds the center core region. The center core region **60** includes a central clear (solid) region **60**C surrounded by an annular void region **60**V that includes randomly arranged and randomly sized voids **64**, as illustrated in the lower inset of FIG. **3**A. Light-diffusing optical fiber **50** also includes a cladding region **66** that surrounds core **60**CS. In an example, cladding region **66** is made of low-index polymer while core **60**CS comprises silica.

[0069] Examples of light-diffusing optical fibers having randomly arranged and randomly sized voids **64** (also referred to as "random air lines" or "nanostructures" or "nano-sized structures") is described in U.S. Pat. No. 7,450,806, and in U.S. patent application Ser. No. 12/950,045, which patent and patent application are incorporated by reference herein.

[0070] In an example, central clear region **60**C has a nominal refractive index of about 1.46 at a wavelength of 550 nm. Also in an example, core diameter DCS is in the range from about 125 microns to 300 microns. Further in an example, the diameter D**50** of light-diffusing optical fiber **50** is in the range from 0.2 mm (200 microns) to 0.25 mm (250 microns).

[0071] FIG. **3**B and FIG. **3**C are cross-sectional photographs of actual optical fiber cores **60**CS illustrating two different configurations for the optical fiber center core region **60** and outer core region **62**. Dotted circles have been added to the photographs to highlight the distinctions between the different regions. Optical fiber core **60**CS of FIG. **3**B has a relatively large annular void region **60**V with relatively small voids **64** and has a loss of about 1.2 dB/m. Optical fiber core **60**CS of FIG. **3**C has a relatively small annular void region **60**V that includes relatively large voids **64** and has a loss of about 0.4 dB/m. For both of the cores **60**CS shown in FIG. **3**B and FIG. **3**C, central and outer core regions **60** and **62** are silica and cladding **66** is a low-refractive-index polymer. This provides light-diffusing optical fiber **50** with a relatively high NA suitable for optical coupling to light sources such as LED and laser diodes.

[0072] Light-diffusing optical fiber **50** can have a loss due to scattering that varies from 0.2 to 60 dB/m, depending on the particular configuration of center core region **60** and outer core region **62**. However, as described in greater detail below, embodiments of the disclosure involve modifying light-diffusing optical fiber **50** to obtain a greater loss, e.g., up to about 300 dB/m. Thus, in an example, light-diffusing optical fiber **50** can have a loss in the range from about 0.2 dB/m to about 300 dB/m, wherein the loss is substantially spectrally uniform in the wavelength range from 250 nm to 2,000 nm and in another example is substantially spectrally uniform over the visible wavelength or "white light" spectral range (e.g., nominally from 380 nm to 750 nm).

[0073] FIG. **3**D is similar to FIG. **3**A and illustrates an example embodiment of a light-diffusing optical fiber **50**. Light-diffusing optical fiber **50** of FIG. **3**D includes central core region **60** having clear and void sections **60**C and **60**V, and outer core region **62**. Cladding **66** surrounds outer core region **62**. Core **60**CS comprises silica, while cladding **66** is comprised of low-refractive-index polymer.

[0074] Light-diffusing optical fiber **50** further includes coating layer **70**, such as acrylate polymer material, that surrounds cladding **66**. Light-diffusing optical fiber **50** also includes a light-scattering layer **72** that surrounds coating layer **70**. Light-scattering layer **72** comprises a light-scattering material, such as any solid particle, liquid droplet or gas bubble, or combination thereof, sized to scatter light. Specific examples of light-scattering materials include phosphorous, TiO_2 particles, and doped polymers, such as white acrylate inks for efficient scattering in angular space (i.e., uniform angular scattering).

[0075] With reference again to FIG. **1** and FIG. **2** and also to the cross-sectional view of FIG. **5**A, in an example, light-diffusing optical fiber **50** is operably disposed adjacent edge **26** of transparent sheet **20**, and can be in contact with the edge or can be spaced apart therefrom to define a gap **36**. In an example, gap **36** can have a width W**36** in the range from 0 mm (i.e., light-diffusing optical fiber **50** in contact with edge **26**) up to 5 mm.

[0076] In the general operation of system **10** of FIG. **1** and FIG. **2**, light source **100** generates light **102**, which is coupled into light-diffusing optical fiber **50** at coupling end **52**, thereby forming guided light **102**G that travels down the light-diffusing optical fiber toward its terminal end **54**. However, as guided light **102**G travels down light-diffusing optical fiber **50**, the light-diffusing property of the optical fiber generates diffused or scattered light **102**S that leaves core **60** and (in one embodiment) exits cladding **66**, thereby providing substantially continuous light emission of scattered light **102**S along at least a portion of the optical fiber length. In an example, the aforementioned portion of the length of the light-diffusing optical fiber **50** is defined by the length of the corresponding edge **26** of transparent sheet **20**.

[0077] FIG. **4**A is a schematic plot of the intensity $I_C(z)$ of guided light **102**G traveling in core **60** versus the distance z along light-diffusing optical fiber **50**. The intensity $I_C(z)$ monotonically decreases from a maximum value I_{MAX} at the coupling end **52** of light-diffusing optical fiber **50** to a minimum value I_{MIN} at terminal end **54**. The intensity $I_S(z)$ of the scattered light **102**S from core **60** has a similar shape when the light scattering is uniform over the length of the light-scattering optical fiber **50**. The shape of the plot of FIG. **4**A is determined by the loss characteristics of the particular light-diffusing optical fiber **50**.

[0078] FIG. **4**B is a schematic plot of the idealized intensity $I_S(z)$ of the scattered light **102**S illustrating a desired constant intensity I_{CONST} of scattered light as a function of distance z, i.e., along the length of light-diffusing optical fiber **50**. In an example, I_{CONST} can vary with a tolerance range, i.e., a narrow range of intensities having an upper bound I_U and a lower bound I_L. The plot of FIG. **4**B can also be the amount of scattered light **102**S coupled into transparent sheet **20**, so that even with a non-uniform scattered light intensity profile from

light-diffusing optical fiber **50**, techniques can be used to condition the scattered light before it enters transparent sheet **20**. Example methods for at least partially compensating for the reduction in the intensity I_S of the scattered light and the intensity I_C of guided light **102**G with distance along light-diffusing optical fiber **50** are described below.

[0079] In an example, the light scattering is isotropic so that a portion of scattered light **102**S is directed towards transparent sheet edge **26** and is coupled into transparent sheet body **22** at the sheet edge, while the remaining portion misses the transparent sheet edge and thus is not coupled into the transparent sheet body. In the Figures, only the portion of scattered light **102**S that is coupled into transparent sheet body **22** is shown for ease of illustration. The portion of scattered light **102**S that is coupled into transparent sheet body **22** can serve as illumination light for a variety of applications, including flat-screen displays, such as described in greater detail below.

[0080] FIG. **5**B is similar to FIG. **5**A, and further includes a reflecting member **140** having a reflecting surface **142**. Reflecting member **140** is disposed adjacent light-diffusing optical fiber **50** opposite transparent sheet **20**. Reflecting member **140** is configured (e.g., via the shape of reflecting surface **142**) to receive scattered light **102**S that would otherwise miss transparent sheet **20**, and direct (reflect) at least a portion of this scattered light toward edge **26** of the transparent sheet as scattered and reflected light **102**SR. Thus, reflecting member **140** serves to increase the amount of scattered light reflected) light **102**SR that would otherwise be lost due to the isotropic nature of the scattering process within light-diffusing optical fiber **50**.

[0081] FIG. **5**C is similar to FIG. **5**A, and further includes an index-matching material **200** disposed between light-diffusing optical fiber **50** and transparent sheet **20** so that scattered light **102**S travels through the index-matching material (i.e., the index-matching material is disposed in the optical path). Index-matching material **200** has, in an example, a refractive index n_{200} between that of core **60** (n_{60}) of light-diffusing optical fiber **50** and that of transparent sheet **20** (n_{20}), e.g., $(0.99)n_{60}<n_{200}<n_{20}$.

[0082] In an example, index-matching material **200** also serves to support light-diffusing optical fiber **50** relative to transparent sheet **20**. In an example, index-matching material **200** has an adhesive property. An example value for n_{60} is 1.46 at a wavelength 550 nm, and an example value for n_{200} is in the range from 1.45 to 1.55 at a wavelength of 550 nm. Example index-matching materials include polymer-based glues, photo-curable polymers, and epoxy glues.

[0083] FIG. **5**D is similar to FIG. **5**B and illustrates an example embodiment where index-matching material **200** is used to support light-diffusing optical fiber **50** and reflecting member **140**. In an example, reflecting member **140** may be supported on an outside surface **201** of index-matching material **200**.

[0084] FIG. **5**E is similar to FIG. **5**C, and illustrates an example embodiment wherein a portion of cladding **66** is removed from light-diffusing optical fiber **50** along at least a portion of its length so that core **60**CS is exposed or the thickness of the cladding is substantially reduced. The removed portion of cladding **66** forms a gap **68** that is shown as being filled with index-matching material **200**. In an example where core **60**CS is exposed, silane may be applied to the exposed portion of the core to protect the core surface.

[0085] The configuration illustrated in FIG. **5**E increases the amount of scattered light **102**S that is emitted from core **60**CS of light-diffusing optical fiber **50**, with the increased amount of scattered light being directed substantially radially outward from the core and into gap **68**. This configuration allows for the scattering loss in light-diffusing optical fiber **50** to be relatively high, e.g., up to the aforementioned 300 dB/m.

[0086] FIG. **5**F is similar to FIG. **5**D and illustrates an example embodiment where light-diffusing optical fiber **50** includes gap **68** filled with index-matching material **200**. Note that even though the light scattering is no longer isotropic, there is still a benefit to having reflecting member **140** reflect at least a portion of the scattered light back into transparent sheet **20** as scattered and reflected light **102**SR.

[0087] FIG. **5**G is similar to FIG. **5**A, and illustrates an example embodiment wherein index-matching material **200** is in the form of an adhesive strip applied to edge **26** of transparent sheet **20**. Index-matching adhesive strip **200** serves to support light-diffusing optical fiber **50** relative to edge **26** and also serves the above-described index-matching function that enhances the coupling of scattered light **102**S into transparent sheet body **22** through edge **26**.

[0088] FIG. **5**H is similar to FIG. **5**G and further includes reflective member **140** operably disposed on or adjacent a portion of cladding **66** opposite transparent sheet **20**. In an example, reflective member **140** comprises reflective tape or a reflective film deposited directly onto the portion of cladding **66**.

[0089] FIG. **5**I is similar to FIG. **5**G, and illustrates an example embodiment that includes a support member **150** configured to support light-diffusing optical fiber **50** relative to transparent sheet **20**. Support member **150** has a front end **152** and an internal cavity **154** open at front end **152**. In an example, cavity **154** includes a reflective rear surface **142** that can be curved as shown, or can be planar. In an example, support member **150** is a unitary structure formed by molding. In an example, support member **150** includes a support mount or stem **156** to which light-diffusing optical fiber **50** can be mounted. Also in an example, support member **150** can be configured to support multiple light-diffusing optical fibers **50**.

[0090] In an example, front end **152** of support member **150** defines an aperture **158** sized to the thickness TH**20** of transparent sheet **20** so that support member **150** can slidingly and snugly engage a portion of transparent sheet at edge **26** by gripping upper and lower surfaces **24**. In an example, front end **152** is compliant to facilitate gripping upper and lower surfaces **24** of transparent sheet **20**. FIG. **5**J is similar to FIG. **5**I and illustrates an example support member **150** formed, for example, using reflective tape. In an example, internal cavity **154** can optionally be filled with index-matching material **200** to operably support light-diffusing optical fiber **50** within the internal cavity.

[0091] FIG. **5**K is similar to FIG. **5**G, except that index-matching adhesive strip **200** and light-diffusing optical fiber **50** reside adjacent upper surface **24** of transparent sheet **20**. FIG. **5**L is similar to FIG. **5**K, except that index-matching material **200** is used to support both light-diffusing optical fiber **50** and reflecting member **140**.

[0092] FIG. **5**M is similar to FIG. **5**K, and illustrates multiple light-diffusing optical fibers **50** adhered to transparent sheet upper surface **24** via respective index-matching adhesive strips **200**. In an alternative example, a single index-matching adhesive strip **200** can be employed. This configuration provides multiple locations for coupling scattered light **102**S into transparent sheet body **22** through upper surface **24**.

In examples, this same configuration can be formed on lower surface **24** in addition to or as an alternative to the upper-surface configuration.

[0093] FIG. **5**N is similar to FIG. **5**L, except that there is no reflecting member **140**, and a portion of cladding **66** has been removed to form the aforementioned cladding gap **68**. This configuration allows for scattered light **102**S to exit light-diffusing optical fiber **50** at cladding gap **68** and enter transparent sheet body **22** from upper surface **24**.

[0094] FIG. **5**O is similar to FIG. **5**K and FIG. **5**M, and illustrates multiple light-diffusing optical fibers **50** adhered to transparent sheet upper surface **24** via respective index-matching material portions **200**. In an alternative example, a single index-matching layer **200** can be employed. This configuration provides another method of providing multiple locations for coupling scattered light **102**S into transparent sheet body **22** via one or both of upper and lower surfaces **24** (upper surface **24** is shown by way of illustration).

[0095] FIG. **6**A is similar to FIG. **1** and illustrates an example embodiment wherein index-matching material **200** has an index of refraction n_{200} that varies as a function of distance z (i.e., distance along the light-diffusing optical fiber **50**) that at least partially compensates for the decrease in the intensity I_S of scattered light **102**S from the light-diffusing optical fiber **50** with distance along the optical fiber. FIG. **6**B is a plot of an example profile of index of refraction n_{200} versus distance z. The thickness TH**200** of the index-matching material **200** is about 10 microns. The (effective) refractive index of core **60** is n_{60}=1.46, as indicated by the solid horizontal line in the plot. Transparent sheet **20** is made of glass having a refractive index n_{20}=1.5. The varying refractive index profile $n_{200}(z)$ for the index-matching material **200** has a value of 1.455, which is just below the core index n_{60} of 1.460 at or near the coupling end **52** of light-diffusing optical fiber **50**, and increases to a value of 1.49 towards the terminal end **54**. As the refractive index n_{200} of the index-matching material **200** increases, and increasing amount of light is scattered from core **60**. This serves to at least partially counteract the diminished amount of light scattering with distance inherent in light-diffusing optical fiber **50**.

[0096] FIG. **6**C and FIG. **6**D are similar to FIG. **6**A and illustrate example embodiments where the thickness TH**200** of index-matching material **200** varies with distance (z), i.e., TH**200**=TH**200**(*z*). A greater thickness TH**200** corresponds to a greater amount of attenuation of scattered light **102**S. Thus, at or near coupling end **52** of light-diffusing optical fiber **50**, the thickness TH**200**(*z*) is greatest and it monotonically decreases to a minimum thickness at or near terminal end **54**. FIG. **6**C illustrates an example linearly varying thickness profile TH**200**(*z*), while FIG. **6**D illustrates an example curved thickness profile TH**200**(*z*). The particular thickness profile TH**200**(*z*) is determined by the loss characteristics of light-diffusing optical fiber **50**.

[0097] In an example embodiment, thickness profile TH**200**(*z*) is configured to substantially compensate for the variation in intensity I_S of the scattered light **102**S with distance along at least a portion of light-diffusing optical fiber **50** so that the scattered light intensity I_S is substantially uniform along the portion of the length of the light-diffusing optical fiber.

[0098] In another example embodiment, light-diffusing optical fiber **50** is configured so that the scattered light intensity I_S is substantially constant as a function of distance along the light-diffusing optical fiber. This can be accomplished, for example, by changing the temperature during the optical fiber drawing process, which serves to change the size of voids **64** in core void region **60**V. The smaller the voids **64** are, the greater the loss in the optical fiber **50**. Thus, in an example embodiment, light-diffusing optical fiber **50** is configured so that it emits scattered light **102**S with substantially constant intensity I_S over at least a portion of its length. Example methods of forming such a light-diffusing optical fiber **50** are disclosed in U.S. patent application Ser. No. 12/950,045, which application is incorporated by reference herein. Example methods of forming optical fibers with randomly arranged voids are disclosed in U.S. Pat. No. 7,450,806, which patent is incorporated by reference herein.

[0099] FIG. **6**E is similar to FIG. **6**A and illustrates an example embodiment where light-diffusing optical fiber **50** is optically coupled to two light sources **100** at respective ends **52** and **54**. Optical isolators **58** are optionally employed adjacent each light source **100** to prevent light from one light source **100** entering the other light source. The symmetry of this two-source configuration results in substantially uniform intensity I_S of scattered light **102**S.

[0100] FIG. **6**F is similar to FIG. **6**A and illustrates an example embodiment where the index-matching material **200** (shown now in cross-hatch for ease of viewing) is not continuous and light diffusing optical fiber **50** is optically coupled to (an in one example, is attached to) transparent sheet **20** (e.g., at edge **26**, as shown) using a number of portions **200**P of index-matching material **200** at a number of discrete locations DL. In an example, the density of the discrete locations DL where index-matching material portions **200**P resides changes along the length of light-diffusing optical fiber **50** from input end **52**, with a relatively low density towards coupling end **52** and relatively high density towards terminal end **54**. The portions **200**P of index-matching material **200** at each discrete location DL are shown in one embodiment as being essentially the same for ease of illustration. However, different sized portions **200**P of index-material material **200** can also be used at different discrete locations DL. In an example, the particular configuration of index-matching material portions **200**P and discrete locations DL is selected to provide for substantially uniform amounts (i.e., intensity I_S) of scattered light **102**S entering transparent sheet body **22** along the corresponding portion of the length of light-diffusing optical fiber **50**.

[0101] FIG. **7**A is similar to FIG. **6**A, and illustrates an embodiment of system **6** wherein light-diffusing optical fiber **50** includes a bend **51** that allows the optical fiber to reside adjacent two edges **26** of transparent sheet **20**, as shown. This allows for scattered light **102**S to enter transparent sheet **26** at the both edges **26**, thereby coupling more light into transparent sheet **20**. Generally, one or more bends **51** can be employed in a single light-diffusing optical fiber **50** so that portions of the optical fiber can reside adjacent corresponding two or more edges **26** of transparent sheet **20**.

[0102] FIG. **7**B is similar to FIG. **7**A and illustrates an example embodiment of system **6** that employs multiple light-diffusing optical fibers **50** along different edges **26** of transparent sheet **20**. System **6** of FIG. **7**B employs three sections of non-light-diffusing optical fiber **250**. A first section of optical fiber **250** optically connects light source **100** to a 1×2 coupler **280**. The second and third sections of optical fiber **250** optically connect the optical coupler **280** to first and second light-diffusing optical fibers **50** that are operably arranged on opposite edges **26** of transparent sheet **20**. In an

example, the second and third sections of optical fiber **250** are optically connected to the respective light-diffusing optical fibers **50** via splicing members **59**, which can be mechanical connectors.

[0103] In an alternate embodiment illustrated in FIG. **7**C, rather than use a single non-light-diffusing optical fiber **250** and a circulator **280**, two non-light-diffusing optical fibers **250** are brought together to form an optical fiber bundle FB at light source **100**. Light **102** is then coupled directly into the two optical fiber ends **252**. Likewise, in another embodiment, multiple light sources **100** can be used, one for each non-light-diffusing optical fiber **250** in optical fiber bundle FB.

[0104] Generally speaking, optical fiber bundle FB can include non-light-diffusing optical fibers **250**, light-diffusing optical fibers **50**, or a combination thereof, with at least portions of two or more light-diffusing optical fibers **50** operably arranged adjacent corresponding respective edges **26** and/or surfaces **24** of transparent sheet **20**. FIG. **7**D illustrates an embodiment similar to FIG. **7**C where two light-diffusing optical fibers **50** and one non-light-diffusing optical fiber **250** converge to form fiber bundle FB. The two light-diffusing optical fibers **50** are configured to provide coverage of all four edges **26** of the rectangular-shaped transparent sheet **20**. A section of the non-light-diffusing optical fiber **250** is optically connected (e.g., via splice **59**) to the light-diffusing optical fiber **50** that includes a bend **51** that allows this particular optical fiber to operably reside adjacent two edges **26** of transparent sheet **20**.

[0105] FIG. **8** is an exploded elevated view of an example flat-screen device **300** that includes system **6** of the present disclosure. Flat-screen device **300** includes a light-modulation display assembly **310** having an upper surface **312** and a lower surface **314**. Light-modulation display assembly **310** is electrically connected to light-modulation electronics **315**. Transparent sheet **20** resides on or adjacent upper surface **312** of light-modulation display assembly **310**. In an example, light-modulation display assembly **310** includes a plurality of pixels **316** that are addressable by light-modulation electronics **315** via transparent electrical connections **318**. Transparent electrical connections **318** typically have a grid-like configuration (e.g., of source and gate bus lines), and only select electrical connections are illustrated for ease of illustration. An example light-modulation display assembly **310** is a liquid-crystal display assembly that includes a liquid-crystal matrix that defines an array of liquid-crystal cells (pixels) sandwiched by cross-polarizers. An example reflective liquid-crystal display assembly is disclosed in U.S. Pat. No. 6,404,471, which is incorporated by reference herein.

[0106] Flat-screen device **300** also includes a reflecting member **330** having a reflective surface **332**. Reflecting member **330** resides adjacent light-modulation assembly lower surface **314**.

[0107] In the operation of flat-screen device **300**, scattered light **102**S is coupled into transparent sheet **20**, say at edge **26**, in the manner described above. In other examples, scattered light **102**S is coupled into transparent sheet **20** using any of the other example embodiments discussed above. At least a portion of this scattered light **102**S is then re-directed by transparent sheet **20**, e.g., by scattering from rough upper surface **24**, to travel to light-modulation display assembly **310**. This scattered light **102**S travels through the light-modulation display assembly **310** and is reflected by reflecting surface **332** of reflecting member **300** to travel back through the light-modulation display assembly, where it exits transparent sheet **20** and is seen by a viewer **400**. Thus, scattered light **102**S is modulated by passing twice through light-modulation display assembly **310**, with the modulation determined by the operation of light-modulation electronics **315**. The result is a display image that is visible to viewer **400**.

Light-Coupling Optical System with Index-Matching Layer

[0108] FIG. **9**A is a top-down view and FIG. **9**B is a bottom-up view of another example embodiment of a light-coupling optical system ("system") **6** according to the disclosure. FIG. **10** is an elevated view of the light-coupling optical system **6** of FIG. **9**A FIG. **11** is a cross-sectional view of system **6** as taken in the Y-Z plane, while FIG. **12**A is a cross-sectional view of the system as taken in the X-Z plane.

[0109] System **6** is similar to that shown in FIG. **1** and FIG. **2** and includes an optical assembly **10** that has at least an upper transparent sheet ("upper sheet") **20**U and optionally includes a lower sheet **20**L, which may also be transparent but that can also be opaque, semi-opaque, partially reflective or substantially reflective. Sheets **20**U and **20**L are arranged spaced apart and substantially parallel to one another.

[0110] Optical assembly **10** includes an index-matching layer **12** sandwiched between upper and lower sheets **20**U and **20**L. In an example embodiment where system **6** includes no lower sheet **20**L, then index-matching layer **12** resides immediately adjacent upper sheet **20**U, as illustrated in the cross-sectional view of FIG. **12**B. Index-matching layer **12** is configured to have a refractive index that substantially matches that of upper sheet **20**U. An example material for index-matching layer **12** is an ultra-violet-(UV)-curable polymer. In an example, index-matching layer **12** is adhesive, e.g., comprises an adhesive polymer. In an example, index-matching layer **12** is configured to scatter light, e.g., includes a light scattering substance (see FIG. **15**B). Example materials for index-matching layer thus include: a polymer, a doped polymer, a polymer having an adhesive property, a polymer with low absorption in the wavelength range between 400 nm and 700 nm, a thermally curable polymer, a photo-curable polymer, or combinations thereof.

[0111] With regard to the embodiment of optical assembly **10** that includes upper and lower sheets **20**U and **20**L, the upper sheet has a body **22**U that defines a thickness THU (see FIG. **11**), opposite upper and lower (i.e., top and bottom) substantially planar and substantially parallel surfaces **24**U and **24**U' (see FIG. **11**) and one or more edges **26**U, such as four edges **26**U for a rectangular transparent sheet. Likewise, lower sheet **20**L has a body **22**L that defines a thickness THL (see FIG. **11**), opposite upper and lower (i.e., top and bottom) substantially planar and substantially parallel surfaces **24**L and **24**L', and one or more edges **26**L, such as four edges **26**L for a rectangular transparent sheet.

[0112] Upper and lower transparent sheets **20**U and **20**L can be made of, for example, glass, plastic, display glass such as Corning's EAGLE XG®, EAGLE®, GORILLA® and PYREX® glasses, as well as fused silica, plastic materials like PPMA, a polymer, or any other transparent material. In an example, upper sheet **20**U can be formed from multiple sheets, such as a sheet of glass coated with a polymer layer. Here, the term "transparent" generally means that the transparent sheet transmits light at least in the visible wavelength range, and transmits more light than it absorbs for the given thickness THU or THL.

[0113] In an example, at least one of the thickness THU of body **22**U of upper sheet **20**U and the thickness THL of body **22**L of lower transparent sheet **20**L is 0.3 mm or greater, and

in another example is 0.7 mm or greater. In an example, at least one of upper sheet body **22**U and lower sheet body **22**L has a refractive index of about 1.5 or greater at 550 nm. In an example, upper sheet **20**U comprises a glass layer as thin as about 100 microns and index-matching layer **12** comprises a polymer and has thickness TH**12** as thin as 200 microns.

[0114] Optical assembly **10** of system **6** also includes at least one light-diffusing optical fiber **50** operably disposed so that a least a portion of the at least one light-diffusing optical fiber is at least partially embedded within index-matching layer **12**. In examples, the at least one light-diffusing optical fiber **50** resides either immediately adjacent or slightly spaced apart from upper transparent sheet **20**U with a portion of the index-matching layer in between. In an example, at least a portion of the at least one light-diffusing optical fiber **50** is entirely embedded within index-matching layer **12**.

[0115] In an example, light-diffusing optical fiber **50** includes the aforementioned coupling end **52** and terminal end **54**. Coupling end **52** and terminal end **54** define a length L (see FIG. **11**) for light-diffusing optical fiber **50**. System **6** also includes the aforementioned light source **100** optically coupled to optical assembly **10** and in particular to coupling end **52** of light-diffusing optical fiber **50**. Light source **100** emits light **102**, which as discussed above travels in light-diffusing optical fiber **50** as guided light **102**G, as illustrated in the close-up cross-sectional view of FIG. **13**. Light-diffusing optical fiber **50** is configured as described above to generate scattered light **102**S from guided light **102**G.

[0116] In an example, system **6** includes the aforementioned terminal optical member **56** operably disposed adjacent terminal end **54** of light-diffusing optical fiber **50**. In one example, terminal optical member **56** is an optical absorber that absorbs light **102**, while in another example it is an optical reflector that reflects light **102** (e.g., reflects guided light **102**G) so that the reflected guided light travels in the opposite direction, i.e., toward light source **100**. In such an example, an optical isolator (not shown) may be employed (e.g., adjacent light source **100**) to prevent light **102** from returning to light source **100**.

[0117] In an example embodiment, optical assembly **10** is configured to be flexible, i.e., is able to be bent to have a substantial curvature. In another example embodiment, optical assembly **10** is configured to be stiff, i.e., so that it is not able to be bent to have a substantial curvature.

[0118] With reference to FIGS. **12**A and **12**B, in an example embodiment, optical assembly **10** includes a perimeter **11** that includes side **26**U of upper sheet **20**U and can include sides **26**L of lower sheet **20**L. In an example embodiment, optical assembly includes at least one reflecting member **140** arranged adjacent at least a portion of perimeter **11**. Reflecting surface **142** of reflecting member **140** may be configured to specularly reflect light or to diffusely reflect light.

[0119] The portion of scattered light **102**S from light-diffusing optical fiber **50** that is within the critical angle as defined by the respective indices of refraction of upper sheet **20** and the surrounding medium (e.g., air, or a low-index layer, as described below), is trapped within optical assembly **10** by total internal reflection. In an example, a light-scattering feature **23**U on upper surface **24**U of upper sheet **20**U serves to further scatter scattered light **102**S that is trapped within optical assembly **10**. This allows observer **400** to see scattered light **102**S while viewing upper surface **24**U of upper sheet **20**U.

[0120] In an example, light-scattering feature **23**U is localized while in another example covers substantially all of upper surface **24**U. In an example, light-scattering feature **23**U comprises a rough feature. In an example, light-scattering feature **23**U is etched into upper surface **24**U of upper sheet **20**U using, for example, a laser (e.g., by laser etching). In an example, light-scattering feature **23**U is added to upper sheet **20**U as a light-scattering element rather than being integrally formed in upper surface **24** of the upper sheet.

[0121] FIG. **12**C is a close-up cross-sectional view of an end portion of the optical assembly **10** illustrating an example embodiment where the reflecting member **140** has a U-shape and is arranged in contact with perimeter **11**, upper sheet **20**U and the index-matching layer **12**. A portion of scattered light **102**S from light-diffusing optical fiber **50** is incident upon reflecting member **140** and reflects therefrom, similar to that as described above in connection with FIG. **12**B. This scattered light **102**S also travels within optical assembly **10** via total internal reflection.

[0122] FIG. **12**D is similar to FIG. **12**C and illustrates an example embodiment where the reflecting member **140** is spaced apart from perimeter **11**, upper sheet **20**U and index matching layer **12** by an air gap **155** associated with the internal cavity **154** defined by the reflecting member.

[0123] FIG. **12**E is similar to FIG. **12**D, except that a portion of the light-diffusing optical fiber **50** extends from index-matching layer **12** at perimeter **11**. FIG. **12**F is similar to FIG. **12**E, except that the light-diffusing optical fiber **50** resides entirely outside of the index matching layer **12** and is adjacent perimeter **11**. FIG. **12**G is similar to FIG. **12**C and illustrates an example embodiment wherein reflecting member **140** has an angled portion **141** defined by an angle α relative to the X-direction. Angled portion **141** can be used to reduce the amount of loss as compared to a U-shaped reflecting member **140** used in the same geometry for optical assembly **10**. The top portion of reflecting member **140** can define a bezel **143** having a dimension (length) d.

[0124] In an example, the dimension d of reflecting member **140** as shown in FIGS. **12**C through **12**F can be in the range $0 \leqq d \leqq 4$ mm. In another example, reflecting member **140** is configured so that length d provides a loss of 20% or less. Here, loss is defined as the fraction of the light that is not coupled into optical assembly **10**.

[0125] In an example, optical assembly **10** has a thickness $TH10 \leqq 0.8$ mm and preferably 0.2 mm $\leqq TH10 \leqq 0.25$ mm. Such small values for the thickness TH**10** of optical assembly **10** allows for a flat-screen device **300** (such as shown in FIG. **17** and introduced and discussed in greater detail below) to be very thin and to have a small form factor. Also, the small diameter of light-diffusing optical fiber **50** allows for very narrow bezels **143**.

[0126] In an example, the coupling efficiency ϵ of scattered light **102**S from light-diffusing optical fiber **50** into optical assembly **10** as internally reflected (guided) light is $\epsilon \geqq 70\%$. The coupling efficiency is greater than the typical light coupling efficiencies of convention flat-panel display devices that utilize light conventional light sources, such as LEDs.

[0127] In another example illustrated in FIG. **15**A (introduced and discussed in greater detail below), a light-absorbing feature **25**U can be formed on upper surface **24**U of upper sheet **20**. Light-absorbing feature **25**U can be used to absorb scattered light **102**S in an embodiment where scattered light exits upper surface **24**U. In this case, light-absorbing feature **25**U serves to substantially absorb scattered light **102**S so that

an observer **400** sees a dark feature corresponding to the light-absorbing feature Light-absorbing feature **25**U can be used, for example, to form indicia, text, signage, etc.

[0128] FIG. **14** is a top-down view of an example embodiment of system **6** wherein light-diffusing optical fiber **50** has a serpentine configuration in the X-Y plane. FIG. **15**A is a cross-sectional view of the optical assembly **10** of FIG. **14** as taken along the line CS**1**. The example embodiment of system **6** of FIGS. **14** and **15**A distributes light-diffusing optical fiber **50** so that it can provide scattered light **1025** to a large area of upper sheet **20**U.

[0129] FIG. **15**B is similar to FIG. **15**A and illustrates an example embodiment of the optical assembly **10** of FIG. **14** that includes a reflective lower sheet **20**L as well as side reflectors **140**. Reflective lower sheet **20**L serves to reflect scattered light **1025** back up to upper sheet **20**U. Reflective lower sheet **20**L may be specularly reflecting or diffusely reflecting. Note that some of scattered light **1025** travels through upper sheet **20**U while some of the scattered light may fall within the critical angle and be trapped within upper sheet and index-matching layer **12** via total internal reflection. Also, FIG. **15**B illustrates at the left-most side of the Figure how scattered light **1025** can re-scatter within index-matching layer **12** when the index-matching layer is configured to scatter light, e.g., by the inclusion of particulates.

[0130] FIG. **16**A is a cross-sectional view similar to that of FIG. **12**B and illustrates another example embodiment of optical assembly **10**. Optical assembly **10** of FIG. **16**A include a first low-index layer **510** (e.g., a low-index polymer) immediately adjacent upper surface **24**U of upper sheet **20**U and a second low-index layer **510** between index-matching layer **12** and lower sheet **20**L. Index-matching layer **12** is configured to scatter scattered light **102**S from light-diffusing optical fiber **50** to form twice-scattered light **102**S'.

[0131] In an example, index-matching layer **12** comprises a doped polymer. In an example, index-matching layer **12** has a thickness TH**12**=0.3 mm thick while upper sheet **20**U is made of glass and has a thickness of THU=0.7 mm thick. In an example embodiment, lower sheet **20**L is configured as a diffuse reflector that diffusely reflects scattered light **102**S. In an example, reflecting member **140** serves as a bezel to cover light-diffusing optical fiber **50** at periphery **11**. In an example, the edge of light-diffusing optical fiber **50** closest to periphery **11** is about 2 mm away from the periphery.

[0132] FIG. **16**B is similar to FIG. **16**A and shows an example embodiment where light-diffusing optical fibers **50** are outside of and adjacent index-matching layer **12**. Note that since the diameter of light-diffusing optical fiber **50** is relatively small (e.g., 250 microns), there is no need for a substantial bezel or any bezel.

[0133] With reference to FIGS. **16**A and **16**B, optical assembly **10** further includes a cover film **520**. In an example, cover film **520** is configured as a so-called "brightness enhancement film" (BEF) that increases brightness for a viewer **400** that views the optical assembly at an angle relatively close to normal incidence. In an example, cover film **520** is configured to polarize light, which is needed for liquid crystal displays (LCDs). The optical assembly **10** of FIGS. **16**A and **16**B constitutes a back-lighting unit that can be used in flat-panel displays. FIG. **17** is a schematic diagram of a flat-screen device **300** that employs system **6** that includes optical assembly **10** as described above in connection with FIGS. **16**A and **16**B. Flat-screen device **300** includes a light-modulation display assembly **310** operably arranged with optical assembly **10**.

[0134] With reference to FIG. **18**A, in an example embodiment, light source **150** is part of a light source assembly **149** and is configured with red (R), green (G) and blue (B) light emitters **151**, i.e., **151**R, **151**G and **151**B, respectively, such as laser diodes. Light emitters **151**R, **151**G and **151**B are optically connected to respective ports of a multiplexing device **167** via respective optical fiber sections FR, FG and FB, which in an example are low-loss optical fibers rather than light-diffusing optical fibers. Light emitters **151**R, **151**G and **151**B respectively emit light **152**R, **152**G and **152**B.

[0135] Light-diffusing optical fiber **50** is also connected to multiplexing device. In an example, light source **150** includes control electronics **153** configured to control the operation of light source **150**, including the sequential activation of light emitters **151**R, **151**G and **151**B. In another example, control electronics **153** are separate from but operably connected to light source **150**.

[0136] Light source **150** is configured via control electronics **153** to time-multiplex the light emitters **151**R, **151**G and **151**B to generate red light **152**R, green light **152**G and blue light **152**B, respectively. This light travels over the respective optical fiber sections FR, FG and FB and to multiplexing device **167**, which multiplexes the light onto light-diffusing optical fiber **50**, which as described above resides within or adjacent index-matching layer **12**.

[0137] This arrangement for light source assembly **149** can be used to generate field-sequential color in optical assembly **10** as part of flat-screen device **300**. It is noted that such a configuration obviates the need for a color filters used with white-light LEDs, and also allows for the use of lasers rather than LEDs as the light emitters **151**. This results in an improved color gamut as compared to conventional LCD flat-screen devices. In an example, the color gamut improves by up to a factor of about 1.9. It also allows for improved energy efficiency, e.g., up to about a 3× improvement (i.e., an energy reduction of about 3×).

[0138] FIG. **18**B is similar to FIG. **18**A, but illustrates an example where light source assembly **149** includes three light-diffusing optical fibers **50**R, **50**G and **50**B respectively optically connected directly to respectively light emitters **151**R, **151**G and **151**B. Portions of the three light-diffusing optical fibers **50** reside within or adjacent index-matching layer **12** as described above in connection with the various embodiments described by way of example as using a single index-matching optical fiber. This configuration can also be used to form field-sequential color in flat-panel display **300**.

[0139] Although the disclosure has been illustrated and described herein with reference to embodiments and specific examples thereof, it will be readily apparent to those of ordinary skill in the art that other embodiments and examples can perform similar functions and/or achieve like results. All such equivalent embodiments and examples are within the spirit and scope of the disclosure and are intended to be covered by the appended claims. It will also be apparent to those skilled in the art that various modifications and variations can be made to the present disclosure without departing from the spirit and scope of the same. Thus, it is intended that the present disclosure cover the modifications and variations of this disclosure provided they come within the scope of the appended claims and their equivalents.

We claim:

1. A light-coupling optical system, comprising:

a transparent sheet having substantially parallel opposite upper and lower surfaces and a first refractive index;

an index-matching layer disposed in contact with the lower surface of the transparent sheet and having a second refractive index substantially the same as the first refractive index;

at least one light-diffusing optical fiber having a glass core, a cladding surrounding the core, and a length, the glass core having randomly arranged voids configured to provide substantially spatially continuous light emission from the glass core and out of the cladding and into the transparent sheet along at least a portion of the length, the at least one light-diffusing optical fiber being at least partially disposed within the index-matching layer;

at least one light source optically connected to the at least one light-diffusing optical fiber and that emits light into the at least one light-diffusing optical fiber, with the light traveling therein as guided light which scatters therefrom as scattered light; and

wherein the at least one light-diffusing optical fiber is arranged so that the scattered light travels within the transparent sheet and the index-matching layer via total internal reflection and is scattered out of the upper surface of the transparent sheet by at least one scattering feature of the transparent sheet.

2. The system according to claim **1**, wherein a portion of the at least one light-scattering optical fiber resides entirely within the index-matching layer.

3. The system according to claim **1**, where the transparent sheet constitutes an upper transparent sheet, and further comprising a lower sheet disposed adjacent the index matching layer opposite the upper transparent sheet, the lower sheet configured to be either reflective or transparent.

4. The system according to claim **1**, wherein the transparent sheet and index-matching layer define a perimeter, and further comprising a reflecting member disposed adjacent at least a portion of the perimeter, the reflecting member being configured to diffusely or specularly reflect the scattered light.

5. The system according to claim **1**, wherein the index-matching layer comprises a material selected from the group of materials comprising: a polymer, a doped polymer, a polymer having an adhesive property, and a polymer with low absorption in the wavelength range between 400 nm and 700 nm, a thermally curable polymer and a photo-curable polymer.

6. The system according to claim **1**, wherein the at least one light-diffusing optical fiber includes a serpentine portion that resides substantially within the index-matching layer.

7. The system according to claim **1**, wherein the transparent sheet includes an upper surface that includes at least one light-scattering feature.

8. The system according to claim **1**, further comprising:

a first low-index layer disposed immediately adjacent the transparent sheet opposite the index-matching layer, with the first low-index layer having an index of refraction less than the first refractive index of the transparent sheet; and

a second low-index layer disposed immediately adjacent the index-matching layer opposite the transparent sheet, with the second low-index layer having an index of refraction less than the second index of refraction of the index-matching layer.

9. The system according to claim **8**, further comprising:

a reflective layer disposed immediately adjacent the second low-index layer opposite the index-matching layer; and

a cover layer disposed immediately adjacent the first low-index layer opposite the transparent sheet, the cover layer configured to increase an amount of brightness as seen by a viewer viewing the system at substantially normal incidence to the cover layer.

10. An optical display, comprising:

the system according to claim **9**; and

a light-modulating display assembly operably arranged adjacent the system.

11. The system according to claim **1**, further comprising a terminal optical member disposed at an end of the at least one light-diffusing optical fiber opposite the light source and configured to either absorb or reflect guided light.

12. The system according to claim **1**, further comprising a reflecting member disposed adjacent the at least one light-diffusing optical fiber.

13. The system of claim **1**, wherein the transparent sheet and index matching layer define a thickness TH**10**, wherein TH**10**≦0.8 mm.

14. The system of claim **13**, wherein 0.2 mm≦TH**10**≦0.25 mm.

15. The system of claim **1**, further comprising:

the light source including a red light emitter, a green light emitter and a blue light emitter, with each of the light emitters being optically coupled to the at least one light-diffusing optical fiber; and

control electronics operably connected to the light source or included therein and configured to control the sequential activation of the red, green and blue light emitters to emit red, green and blue light, respectively, which red, green and blue light is sequentially transmitted down the at least one light-diffusing optical fiber to form sequentially emitted red, green and blue scattered light.

16. The system of claim **1**, further comprising a coupling efficiency ϵ of scattered light coupled into the transparent sheet and index-matching layer, wherein ϵ>70%.

17. A method of providing illumination through a transparent sheet having upper and lower surfaces, comprising:

disposing at least a portion of at least one light-diffusing optical fiber within an index-matching layer that is immediately adjacent the lower surface of the transparent sheet, wherein the at least one light-diffusing optical fiber has a core, a cladding and a length, with at least a portion of the glass core comprising randomly arranged voids configured to provide substantially continuous light emission from the core and out of the cladding along said portion of the light-diffusing optical fiber when guided light travels down the glass core;

sending light down the glass core of at least one light-diffusing optical fiber as guided light to cause said light emission, with the emitted light traveling within the transparent sheet and the index-matching layer by total internal reflection; and

scattering at least a portion of the light traveling within the transparent sheet and the index-matching layer out of the upper surface of the transparent sheet.

18. The method according to claim **17**, wherein the transparent sheet and the index-matching layer define a periphery,

and further comprising reflecting light emitted from the at least one light-diffusing optical fiber to the periphery back into the index-matching layer or the transparent sheet.

19. The method according to claim **17**, wherein the substantially continuous light emission is substantially wavelength-independent over a wavelength range from 250 nm to 2,000 nm.

20. The method according to claim **17**, further comprising performing said scattering of light out of the upper surface of the transparent sheet using at least one light-scattering feature of the transparent sheet.

21. The method of claim **17**, wherein the transparent sheet and index matching layer define a thickness TH**10**, wherein TH**10**≦0.8 mm.

22. The method of claim **21**, wherein 0.2 mm≦TH**10**≦0.25 mm.

23. The method of claim **17**, wherein sending light down the glass core includes sequentially sending red, green and blue light down the glass core, thereby generating sequentially emitted red, green and blue scattered light.

24. The system of claim **17**, further comprising a coupling efficiency ϵ of scattered light coupled into the transparent sheet and index-matching layer, wherein ϵ>70%.

25. A light-coupling optical system, comprising:

a transparent sheet having upper and lower surfaces and a first refractive index;

an index-matching layer disposed in contact with the lower surface of the transparent sheet and having a second refractive index substantially the same as the first refractive index;

a light source that emits light;

a light-diffusing optical fiber that is at least partially disposed within the index-matching layer and that is optically coupled to the light source to carry the light as guided light, the light-diffusing optical fiber having randomly arranged voids configured to provide substantially spatially continuous light emission due to scattering of the guided light out of an outer surface of the light-diffusing optical fiber; and

wherein the light-diffusing optical fiber is arranged so that the scattered light travels within the transparent sheet and the index-matching layer via total internal reflection and is scattered out of the upper surface of the transparent sheet by at least one scattering feature of the transparent sheet.

26. The light-coupling optical system according to claim **25**, wherein the transparent sheet constitutes an upper sheet and further comprising a lower sheet disposed adjacent the index matching layer opposite the upper transparent sheet, the lower sheet configured to be either reflective or transparent.

27. The light-coupling optical system according to claim **25**, further comprising at least one reflecting element operably disposed adjacent a perimeter of the system and configured to reflect scattered light back into either the transparent sheet or the index-matching layer.

28. The light-coupling optical system according to claim **25**, further comprising at least one reflecting member operably disposed adjacent the outer surface of at least a portion of the light-diffusing optical fiber.

29. The light-coupling optical system according to claim **25**, wherein a portion of the at least one light-scattering optical fiber resides entirely within the index-matching layer.

* * * * *

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(54) **REFRIGERATOR HAVING PHOTOCATALYST**

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TOKYO 175-0092 (JP)

(21) Appl. No.: **12/156,623**

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(52) **U.S. Cl.** **62/264**; 362/92

(57) **ABSTRACT**

A refrigerator having photocatalyst comprises: a photocatalytic light guide member, composed of a light guide member and a photocatalyst; the light guide member having a light entrance portion and a light leaking portion; the photocatalyst being composed of visible light responsive photocatalytic material, disposed on or adjacent to the light leaking portion; at least one visible light emitting type light emitting element, for emitting visible light which is directed or incident to the light entrance portion; and wherein the visible light responsive photocatalytic material is excited by visible light which is leaked from the light leaking portion. Thereby, the photocatalyst indicates a photocatalytic decomposition activity and at least a shelf and a store room can be kept clean.

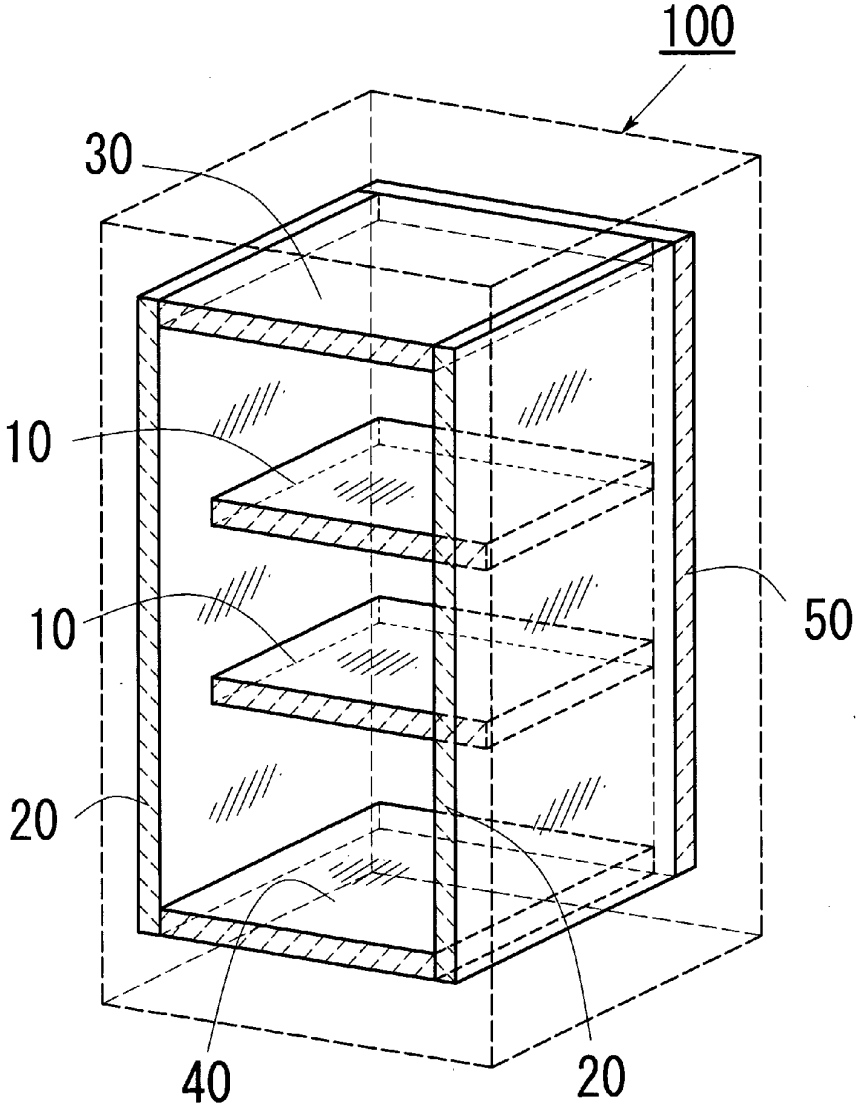


FIG. 1

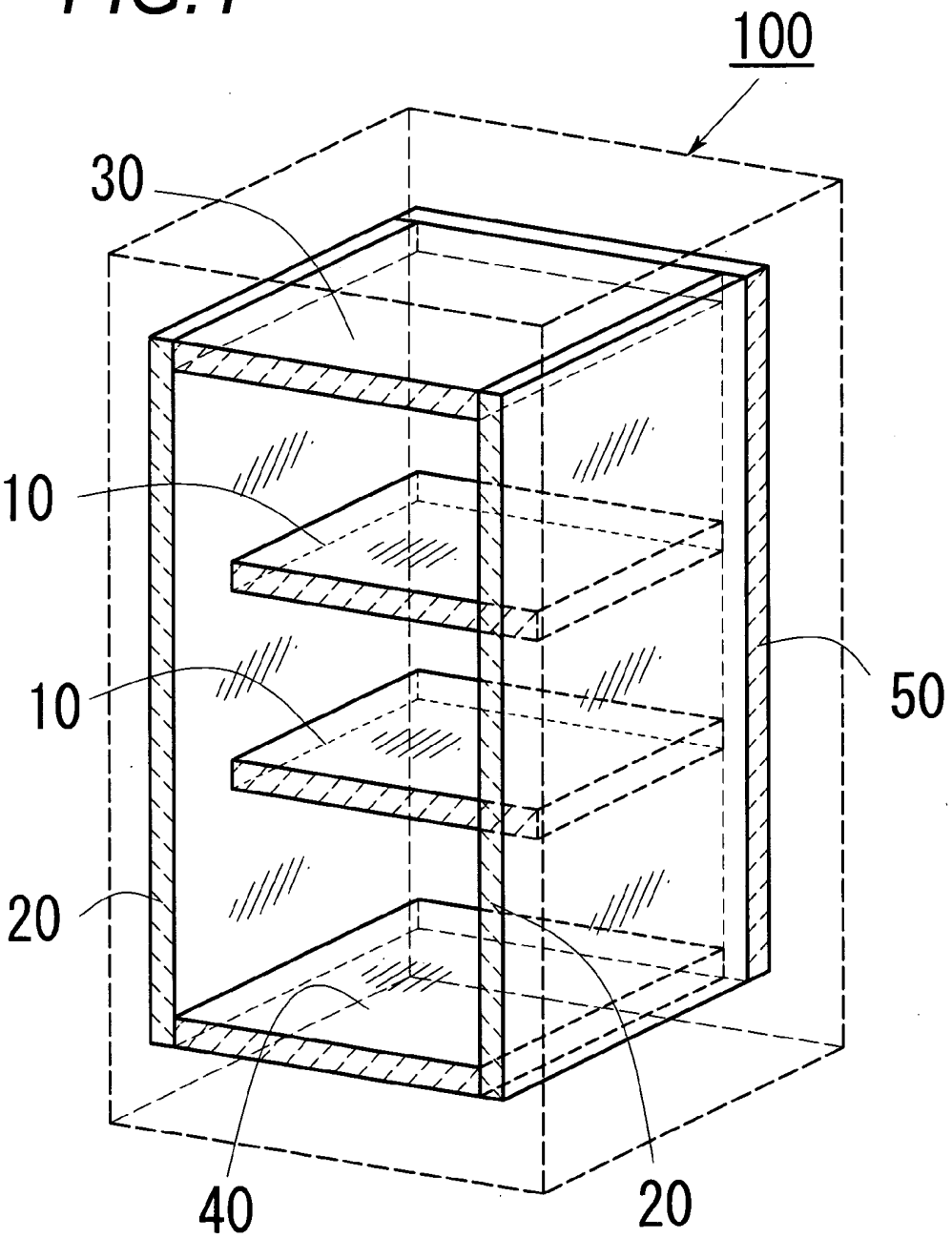


FIG.2

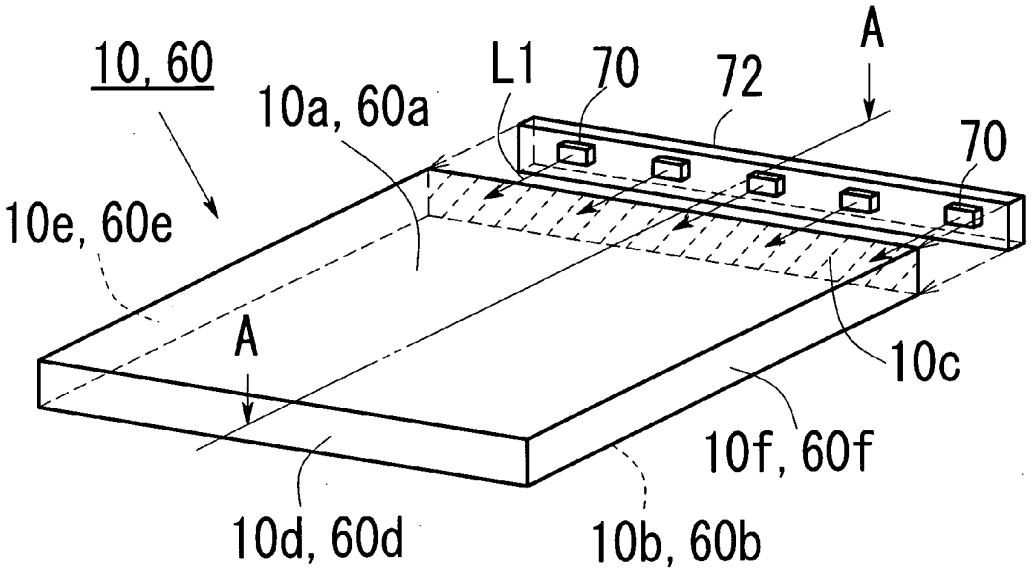


FIG.3

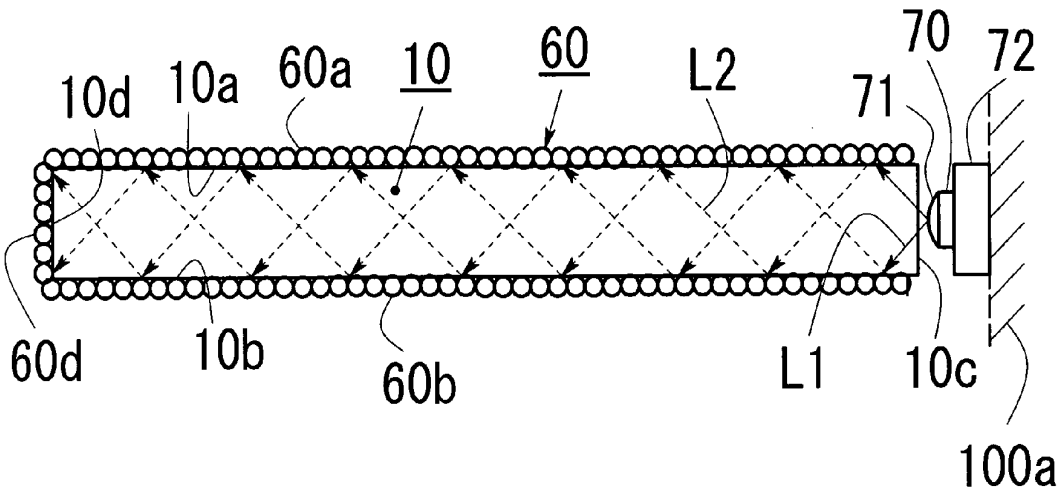
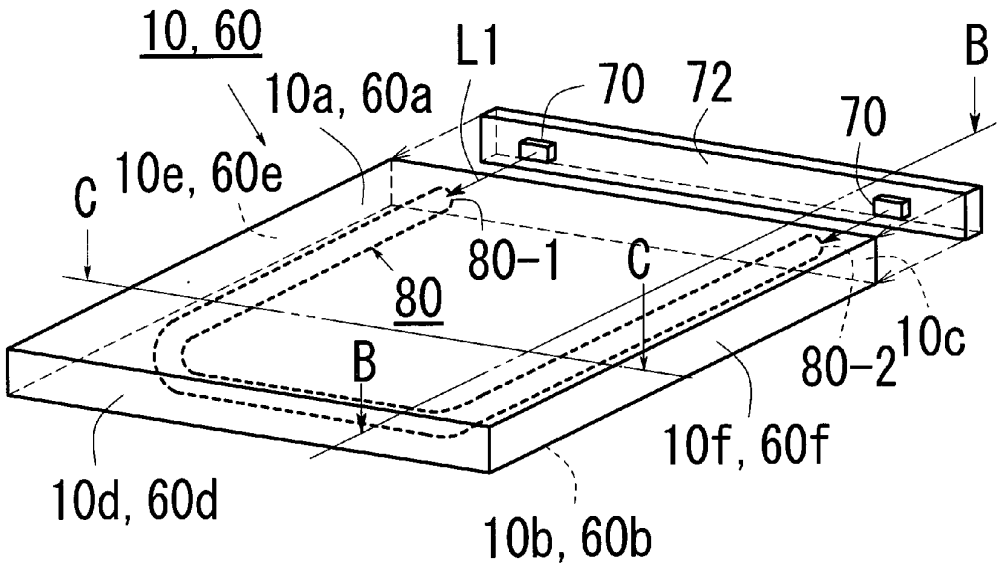


FIG.4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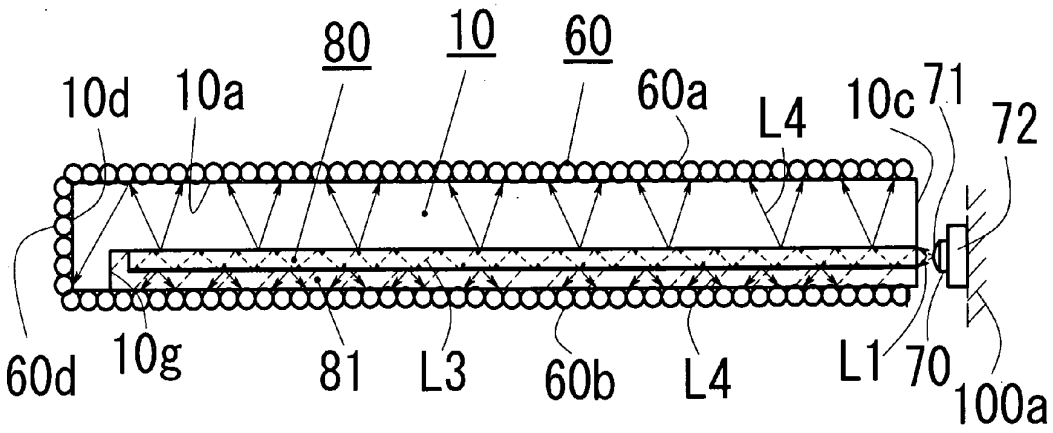
10d, 60d
10b, 60b

FIG.5A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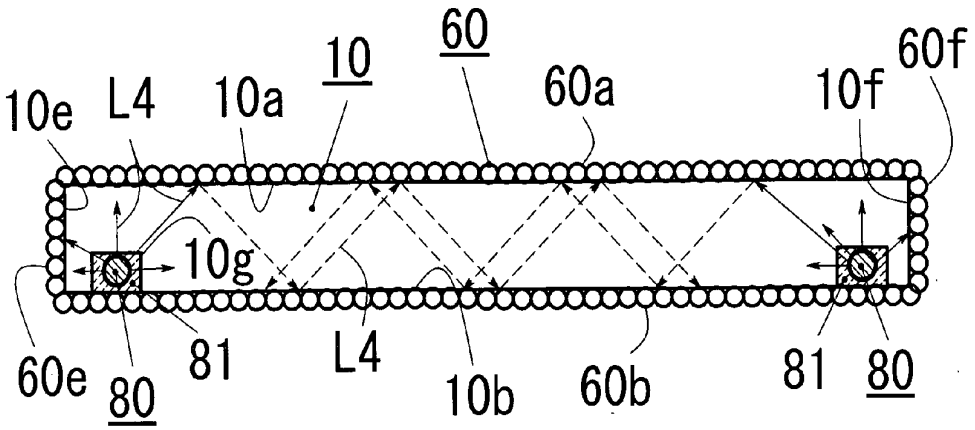
100a

FIG.5B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L4
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81
80

FIG.6A

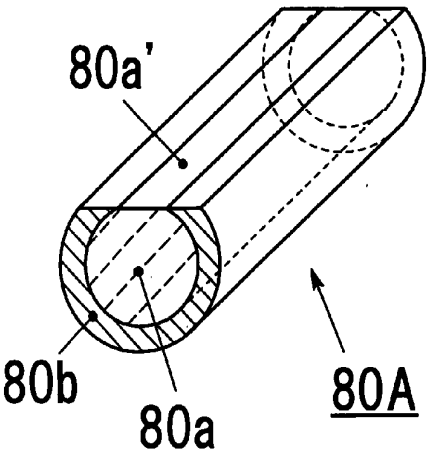

FIG.6B

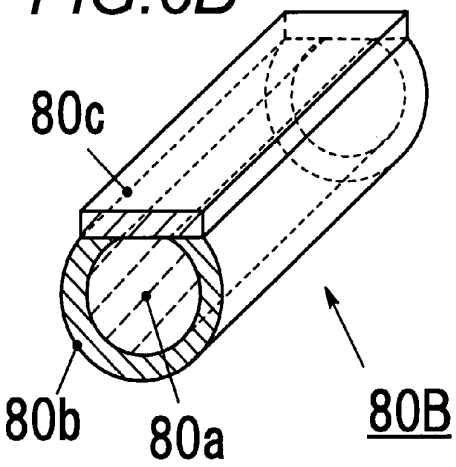

FIG.6C

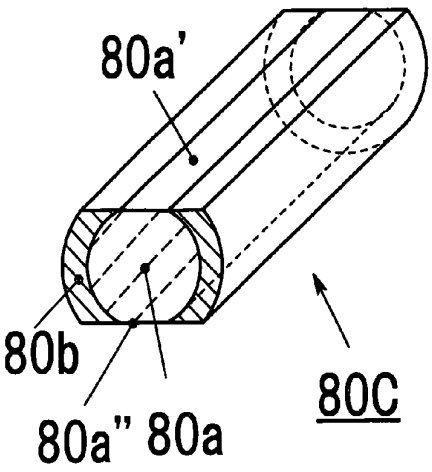

FIG.6D

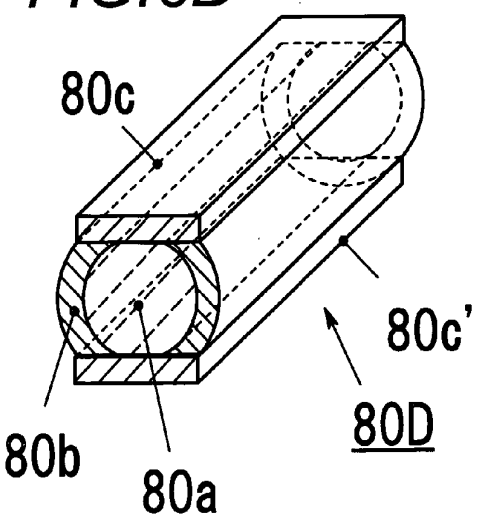

FIG.7A

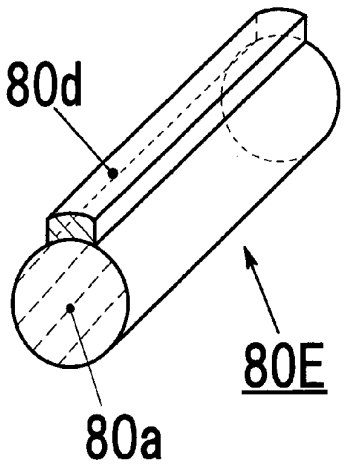

FIG.7B

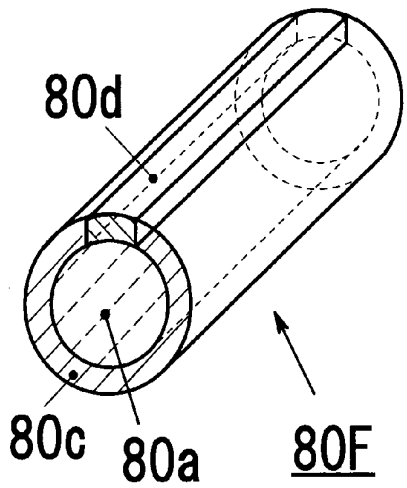

FIG.7C

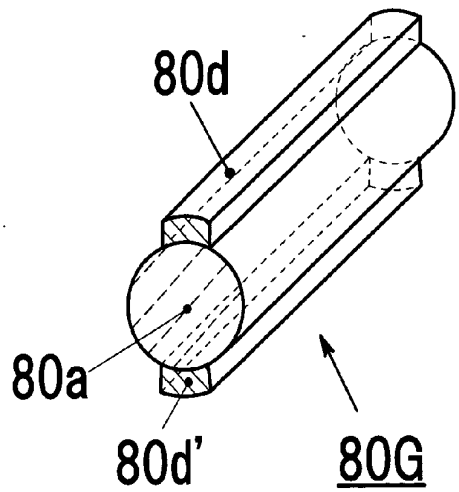

FIG.7D

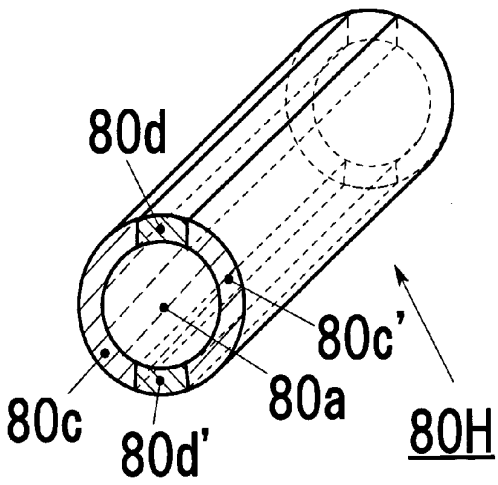

FIG.8

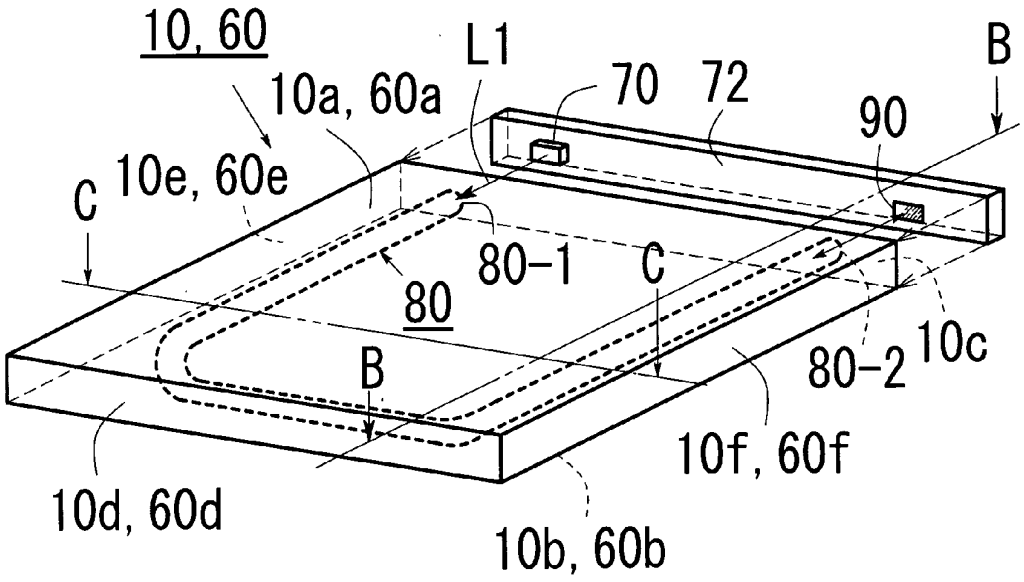
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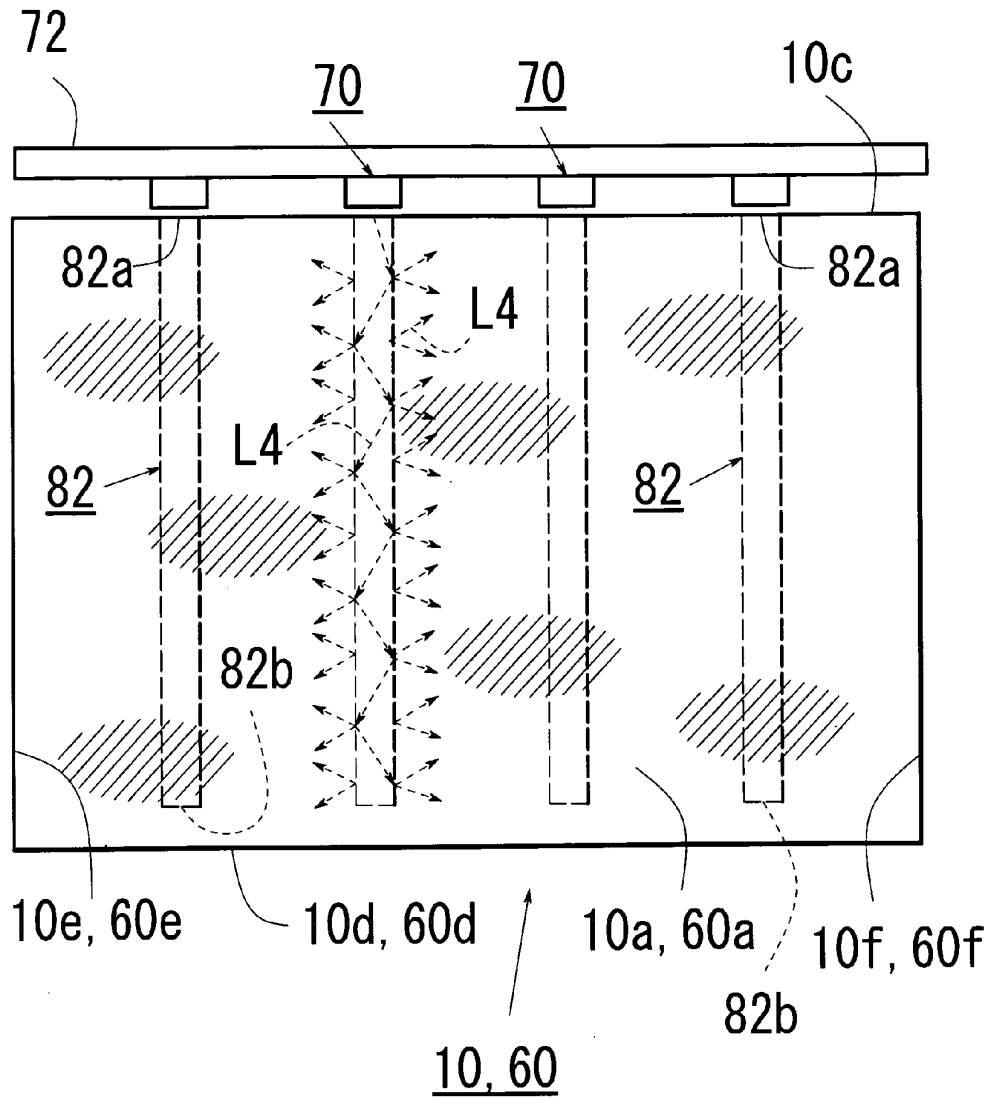
FIG.9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82b
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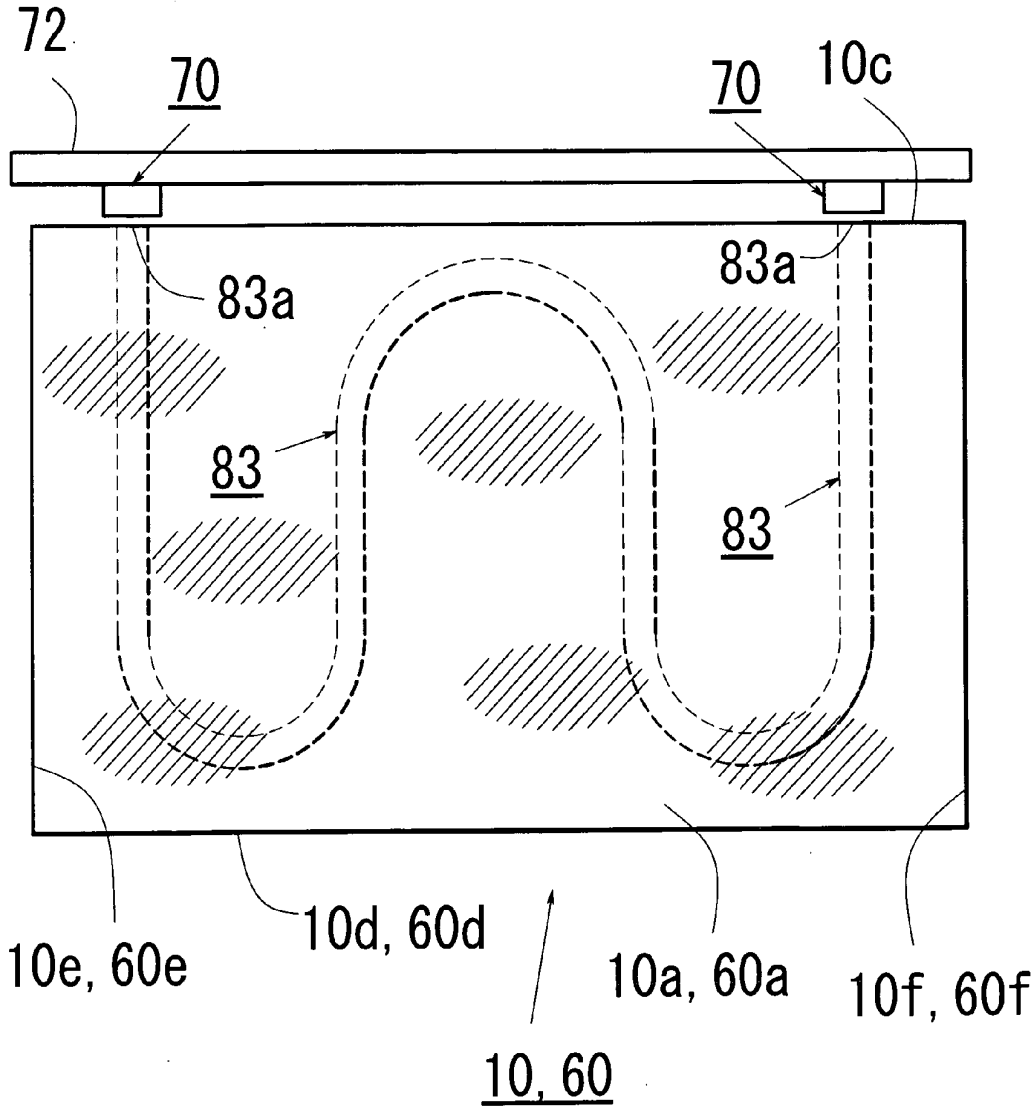
FIG.10



REFRIGERATOR HAVING PHOTOCATALYST

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is based on the prior Japanese Patent application No. 2005-330284 filed on Nov. 15, 2005 which is published on Jun. 7, 2007 as Japanese Patent Laid-Open No. 2007-139230, and the entire disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention is related to a refrigerator having a photocatalyst that exhibit an optical antibacterial function.

[0004] The present invention is related to a refrigerator having lighting and an optical antibacterial function.

[0005] 2. Description of the Related Art

[0006] A refrigerator is disclosed in the patent documents 1 (Japanese Patent Laid-Open No. 05-039978) as follows.

[0007] PURPOSE: To improve the visual workability in a storage room of a refrigerator by providing lighting system which prevents foods from casting shadows on the wall.

[0008] CONSTITUTION: A lighting system is composed of a light guide **1**, a light source **2**, a reflector **3**, a shielding plate **4** and a slit **5**. Most of the light generated from the light source **2** is reflected and converged on the reflector **3** and transmitted to the light guide **1**. Apart of the light leaks out of the vertical slit **5** and evenly lights the wall surface. The light transmitted to the light guide **1** is irregularly reflected on the coated surface and transmitted and diffused. Thus, foods placed below the light guide **1** are evenly lighted. The light leaked out of the slit **5** lights evenly the wall surface so that the storage space looks wide and deep. In this way, a lighting condition superior in visual workability without casting shadows of foods is realized.

[0009] An illuminator for refrigerator is disclosed in the patent documents 2 (Japanese Patent Laid-Open No. 09-203582) as follows.

[0010] PROBLEM TO BE SOLVED: To fasten the starting of a luminous flux with high efficiency, long life and excellent starting characteristics at a low temperature and to incorporate deodorizing function of long life by attempting to increase the storage space in a refrigerator.

[0011] SOLUTION: The illuminator for a refrigerator comprises a bulb with a three band fluorescent layer overlying the inner surface, discharging medium containing rare gas containing xenon as a main body and sealed in the bulb, a fluorescent lamp **17** having a pair of electrodes for generating discharge in the bulb and disposed in a refrigerator body **12**, and a light guiding plate **16** having a light emitting surface **15** receiving the light from the lamp **17** from the side end to emit a light in a surface state and opposed in the body **12**.

[0012] PROBLEM TO BE SOLVED: To reduce power consumption and to illuminate a cold storage chamber and deep freezing chamber irrespective of an amount of food by constituting by a light diverging means provided at an outer surface of a light transmitting means to emit a light transmitted via the transmitting means in a predetermined direction out of the transmitting means.

[0013] SOLUTION: An illuminating means **13** comprises a plurality of light diffusing members **23** for distributing a light from a light transmitting means **15** to a predetermined area and connected to a protrusion of the means **15** to perform a role of a shelf, and light diverging means **25** provided at outer surfaces of the members **23** to emit the light distributed in the members **23** in a predetermined direction out of the members **23**. An optical fiber has a core for transmitting the light, and a clad for totally reflecting the light of the core. The clad of the fiber is removed so that light introduced into the core is transmitted along the core by total reflection but the light is not emitted to front sides of the members **23**.

[0014] The illuminator for refrigerator is disclosed in the patent documents 4 (Japanese Patent Laid-Open No. 11-159953) as follows.

[0015] PROBLEM TO BE SOLVED: To provide an interior illuminator for refrigerator which does not spoil the freshness of the foodstuffs stored in a refrigerator for a long period.

[0016] SOLUTION: An interior illuminator for refrigerator which illuminates the foodstuffs stored in a refrigerator at a low temperature is provided with a mounted board **1** and a plurality of semiconductor light emitting elements **2** which are arranged on the board **1** in parallel with each other and only emits light having a wavelength which falls within a visible light domain between about 420 nm and about 780 nm.

[0017] A refrigerator is disclosed in the patent documents 5 (Japanese Patent Laid-Open No. 2001-501295) and the patent documents 6 (U.S. Pat. No. 6,210,013 corresponding to the patent documents 5) as follows.

[0018] A refrigerator capable of being internally illuminated wherein the illumination is provided by an edge-lit panel of a substantially transparent material having two opposed surfaces of which at least one is within the refrigerator and on which a matrix of dots is applied so as to produce a light piping effect internally in to the refrigerator and wherein the light source of the edge-lit panel is located within the enclosed space of the refrigerator.

[0019] One or more edge-lit panels may be used, which may be shelf of the refrigerator, or its side panels, back panel or roof panel. The edge-lit panel may be form from a transparent acrylic sheet, preferably containing an optical brightener. Protective transparent or translucent layer and a light diffuser may be applied to the surface carrying the matrix of dots.

[0020] A visible light responsive photocatalyst is disclosed in the patent documents 7 (Japanese Patent Laid-Open No. 2004-988) and the patent documents 8 (Japanese Patent No. 3,601,532 corresponding to the patent documents 7) as follows.

[0021] PROBLEM TO BE SOLVED: To obtain a photocatalytic substance which develops a photocatalytic function by visible light.

[0022] SOLUTION: A Ti—O—N film **12**, wherein nitrogen is added to titanium oxide crystals by substituting a part of the oxygen site of titanium oxide crystals with a nitrogen atom, is formed on an SiO2 substrate **10**. As a result, a chemical bond is present between Ti and N atoms in the crystals and the Ti—O—N film absorbs visible light to develop a photocatalytic function. For example, the thin Ti—O—N film with a thickness of 10 μm or less is formed on the substrate.

[0023] Another visible light responsive photocatalyst is disclosed in the patent documents 9 (Japanese Patent Laid-Open No. 2002-239395) and the patent documents 10 (Japanese Patent Laid-Open No. 2004-73910) as follows.

[0024] PROBLEM TO BE SOLVED: To provide a photocatalyst excited by the irradiation with visible light and stably developing high photocatalytic activity and a method for manufacturing the photocatalyst industrially, economically and advantageously.

[0025] SOLUTION: The photocatalyst is obtained by adding a platinum halide compound to the surfaces of photocatalyst particles comprising titanium oxide or the like. Further, photocatalyst particles and a platinum halide compound are heated in a liquid medium or an accelerator containing hypophosphorous acid or the like is further added to the liquid medium at the time of heating to manufacture the photocatalyst.

[0026] A still another visible light responsive photocatalyst is disclosed in the patent documents 11 (Japanese Patent Laid-Open No. 2002-239395) and the patent documents 12 (Japanese. Patent Laid-Open No. 2004-73910) as follows.

[0027] PROBLEM TO BE SOLVED: To provide a photocatalyst excited by the irradiation with visible light and stably developing high photocatalytic activity and a method for manufacturing the photocatalyst industrially, economically and advantageously.

[0028] SOLUTION: The photocatalyst is obtained by adding a platinum halide compound to the surfaces of photocatalyst particles comprising titanium oxide or the like. Further, photocatalyst particles and a platinum halide compound are heated in a liquid medium or an accelerator containing hypophosphorous acid or the like is further added to the liquid medium at the time of heating to manufacture the photocatalyst.

[0029] A leaky optical fiber is disclosed in the patent documents 13 (Japanese Patent Laid-Open No. 2001-108856) and the patent documents 14 (Japanese Patent Laid-Open No. 2002-202415) as follows.

[0030] The patent documents 13 discloses an optical fiber as follows:

[0031] PROBLEM TO BE SOLVED: To provide an optical fiber of a flank emission type which has constant quality and can uniformly emit light outside with excellent reproducibility.

[0032] SOLUTION: The optical fiber having a core in the central part and a clad which is disposed at the peripheral edge of this core and has a refractive index lower than the refractive index of the core is so constituted that a rugged structure is imparted between the core and the clad along the circumferential and longitudinal directions of the fiber.

[0033] The patent documents 14 discloses a side face light emitting optical fiber as follows:

[0034] PROBLEM TO BE SOLVED: To provide a side face light emitting optical fiber capable of improving uniformity of side face light emitting luminance over the longitudinal direction even in an optical fiber having a relatively long core length.

[0035] SOLUTION: In the side face light emitting optical fiber having a core at the central part and a clad arranged around the core, the clad is composed of a first transparent layer which comes into contact with the core and a second light diffusing layer which is formed in the outside of the first layer, and moreover both layers are integrally formed.

[0036] A list of cited documents by the applicant are as follows:

Patent document 1; Japanese Patent Laid-Open No. JPO5-039978,
Patent document 2; Japanese Patent Laid-Open No. JPO9-203582,
Patent document 3; Japanese Patent Laid-Open No. JP10-141845,
Patent document 4; Japanese Patent Laid-Open No. JP11-159953,
Patent document 5; Japanese Patent Laid-Open No. JP2001-501295,
Patent document 6; U.S. Pat. No. 6,210,013,
Patent document 7; Japanese Patent Laid-Open No. JP2004-988,
Patent document 8; Japanese Patent No. JP3601532,
Patent document 9; Japanese Patent Laid-Open No. JP2002-239395,
Patent document 10; Japanese Patent Laid-Open No. JP2004-73910,
Patent document 11; Japanese Patent Laid-Open No. JP2002-239395,
Patent document 12; Japanese Patent Laid-Open No. JP2004-73910,
Patent document 13; Japanese Patent Laid-Open No. JP2001-108856, and
Patent document 14; Japanese Patent Laid-Open No. JP2002-202415,

[0037] The patent documents 1 and the patent documents 3 to 6 disclose the lighting in the room (warehouse) of a refrigerator, and are not disclosed about photocatalyst at all.

[0038] The patent documents 8 to 12 disclose a visible light response type photocatalyst, and can be used as one component of this invention.

[0039] The patent documents 2 (JP 09-203582) discloses a refrigerator having a light guide member of a glass plate, a fluorescent lamp to emit light including ultraviolet (UV) and an UV responsive photocatalyst film disposed on the glass plate.

[0040] However, this refrigerator disclosed in the patent documents 2 (JP 09-203582) has following disadvantages based on a use of ultraviolet light:

[0041] If a photocatalyst film is coated entirely on the light exit surfaces of the light guide member, it is not restricted that most ultraviolet rays are absorbed by the photocatalyst film, but there is a possibility that some ultraviolet rays may be emitted from the light guide member to the room of the refrigerator.

[0042] After long-term of use or frequent contacts with articles housed in the room, the photocatalyst film partially or entirely wears out and exfoliates from the light exit surface of the light guide member and ultraviolet rays exits from an exposed portion of the light exit surface without absorbing in the photocatalyst film to the room.

[0043] The light guide member made of polymer or plastic material cannot be used for ultraviolet irradiated device, for instance, a typical transparent polymer or plastic material of acryl resin (PMMA) or polycarbonate resin (PC) is easy to decompose or tint to e.g. yellow color due to long-term of irradiation of ultraviolet light. Therefore, the patent documents 2 discloses to use a glass plate as the light guide member.

[0044] If the articles, typically foodstuffs stored in the room of the refrigerator receives ultraviolet rays leaked from the light exit surface of the light guide member, the articles may be decomposed.

[0045] In this refrigerator disclosed in the patent documents 2, the light guide member with the photocatalyst film

and the fluorescent lamp to emit light containing visible light and UV light is used in lighting and an antibacterial function, therefore users may receive UV light leaked from the light guide member at the times of opening/closing the door of the refrigerator and that may give a bad influence by the ultraviolet rays to human body such as eyes.

BRIEF SUMMARY OF THE INVENTION

[0046] A major purpose of the present invention is to eliminate the disadvantages of the prior art described hereinbefore.

[0047] A first aspect of the present invention is a refrigerator which comprises: 1) a photocatalytic light guide member, composed of light guide member and a photocatalyst; the light guide member having a light entrance portion and a light leaking portion, 2) the photocatalyst being composed of visible light responsive photocatalytic material, disposed on or adjacent to the light leaking portion; 3) at least one visible light emitting type light emitting element, for emitting visible light which is directed or incident to the light entrance portion; and 4) wherein the visible light responsive photocatalytic material is excited by visible light which is leaked from the light leaking portion.

[0048] A second aspect of the present invention is a refrigerator which comprises: 1) a photocatalytic light guide member, composed of light guide member and a photocatalyst; the light guide member having a light entrance portion and a light leaking portion, 2) the photocatalyst being composed of visible light responsive photocatalytic material, disposed on or adjacent to the light leaking portion; 3) at least one visible light emitting type light emitting element, for emitting visible light which is directed or incident to the light entrance portion; 4) at least one leaky optical fiber disposed in/on or adjacent to the light guide member and 5) wherein the visible light responsive photocatalytic material is excited by visible light which is leaked from the light leaking portion.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

[0049] For a more complete understanding of the present invention and the advantage thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0050] FIG. **1** is a schematic perspective view showing a refrigerator;

[0051] FIG. **2** is a schematic enlarged perspective view showing a first embodiment of the invention;

[0052] FIG. **3** is a schematic enlarged cross sectional view taken along the line A-A of FIG. **2**;

[0053] FIG. **4** is a schematic enlarged perspective view showing a second embodiment of the invention;

[0054] FIG. **5**A is a schematic enlarged cross sectional view taken along the line B-B of FIG. **4**;

[0055] FIG. **5**B is a schematic enlarged cross sectional view taken along the line C-C of FIG. **4**;

[0056] FIG. **6**A, FIG. **6**B, FIG. **6**C and FIG. **6**D are schematic perspective views showing several structures of leaky optical fibers for use in the second embodiments of the invention;

[0057] FIG. **7**A, FIG. **7**B, FIG. **7**C and FIG. **7**D are schematic perspective views showing several structures of other leaky optical fibers for use in the second embodiments of the invention;

[0058] FIG. **8** is a schematic enlarged perspective view showing a third embodiment of the invention;

[0059] FIG. **9** is a schematic enlarged perspective view showing a fourth embodiment of the invention; and

[0060] FIG. **10** is a schematic enlarged perspective view showing a fifth embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0061] At first, visible light responsive photocatalyst and a visible light emitting type light emitting element e.g. light emitting diode (LED) which can be used in several embodiments are explained below.

[0062] (Visible Light Responsive Photocatalyst)

[0063] Visible light responsive photocatalyst materials which can be used in several embodiments are, for example, the photocatalyst materials disclosed in the patent documents 7 (Japanese Patent Application Publication No. JP2004-988), the patent documents 8(Japanese Patent No. 3601532), the patent documents 9 (Japanese Patent Application Publication No. 2002-239395), the patent documents 10 (Japanese Patent Application Publication No. 2004-73910), the patent documents 11 (Japanese Patent Application Publication No. 2002-239395), the patent documents 12 (Japanese Patent Application Publication No. 2004-73910) and other patent documents.

[0064] Visible light responsive photocatalyst materials which can be used for this invention, for example, the following (a), (b) are (c) are commercially available as follows. These photocatalyst materials can be excited by blue light.

[0065] (a): Photocatalyst materials are available from Ishihara Sangyo Kaisha, ltd. Japan (brand MPT-621, MPT-623, etc.) which are composed of titanium oxide having platinum compound.

[0066] (b): A photocatalyst material was developed by Toyota Central R&D Labs. Japan, which is composed of Nitrogen doped titanium oxide (TiO—N).

[0067] (c) Photocatalyst materials are available from Sekisui Jushi Corporation, Japan, which are composed of sulfur-cation doped titanium oxide having iron.

[0068] (Visible Light Emitting Type Light Emitting Diode)

[0069] Visible light emitting type Light Emitting Diodes (LEDs) which can be used in several embodiments is the LEDs to emit light having a blue wavelength range.

[0070] These blue light emitting LEDs use semiconductor tips for emitting mainly blue visible light which are typically composed of gallium nitride (GaN), indium gallium nitride (InGaN) or zinc oxide (ZnO).

[0071] As blue visible light emitting type LED, a LED package which is composed of a near-ultraviolet light emitting semiconductor chip (e.g. GaN and InGaN) and a blue phosphor can be used for the invention, in which the blue phosphor receives the near UV light from the semiconductor chip and convert a short wavelength of the near light to a long wavelength of blue light.

[0072] For example, the near UV emitting chip is embedded in a transparent resin capsule containing blue phosphor particles or the near UV emitting chip is covered with a lens in which blue phosphor is coated on a top or bottom surface.

[0073] Blue light emitting type LEDs suitably used for embodiments of the invention are commercially available

from Toyoda Gosei Co., Ltd, Japan, Nichia Chemical Industries, Japan, Lumileds Lighting U.S., LLC, U.S.A., Cree, Inc. U.S.A.

A FIRST EMBODIMENT OF THE INVENTION

[0074] An embodiment of the invention is described referring to FIG. **1**, FIG. **2** and FIG. **3**.

[0075] A refrigerator **100** generally comprises a thermally insulated box and a cooling/freezing device, in which the box is provided with at least one storage room to store typically foodstuffs and the cooling/freezing device is for cooling/freezing the foodstuffs.

[0076] The storage room is provided with a top wall (top panel) **30**, a bottom wall (bottom panel) **40**, a back wall (back panel) **50**, left and right side walls (left and right panels) **20** and at least one shelf (shelf plate) **10**.

[0077] In the first embodiment, the shelf (shelf plate) **10** is composed of a light guide member.

[0078] The light guide panel (light guide shelf) **10** is composed of a substantially rectangular light transmissive (transparent or semi-transparent) panel or plate made of a light transmissive synthetic resin or glass.

[0079] The light guide shelf **10** may be made of light transmissive synthetic resin materials such as acrylic resin, polycarbonate resin, polypropylene resin, polyethylene terephthalate resin, ABS resin and epoxy resin.

[0080] The light guide shelf **10** may be made of light transmissive glass materials such as tempered glass and quartz.

[0081] As shown in FIG. **2** and FIG. **3**, the light guide shelf **10** is a panel-like sheet-like member composed of a front surface **10***a*, a rear surface **10***b* opposed to the front surface **10***a*, opposed side faces **10***c*, **10***d* and opposed side faces **10***e*, **10***f*.

[0082] A printed-circuit board **72** is arranged at a wall **100***a*, in which at least one visible light emitting type semiconductor light emitting element, typically Light Emitting Diode (LED) **70** is mounted on the printed-circuit board **72**.

[0083] Blue light emitting LED/LEDs **70** are suitably used in the invention, in which the LED/LEDs **70** emit light having a blue peak wavelength.

[0084] Further, LED/LEDs **70** are preferably used in the invention, in which the LED/LEDs **70** emit light including a blue color and excluding ultraviolet rays (UV).

[0085] The visible color LED **70** is positioned adjacent to the light guide shelf **10**, in such a manner that a light exit window (or lens) **71** of the visible color LED **70** faces a side face **10***c* of the light guide shelf **10**.

[0086] Therefore, light emitting from the light exit window **71** can be directed to the side face **10***c* which acts as a light entrance portion of the light guide shelf **10**.

[0087] Instead, at least one optical fiber for light transmission is interposed between the visible color LED **70** and the light guide shelf **10**, in which the visible color LED **70** can be positioned at any place in the box or room.

[0088] A visible light responsive photocatalyst **60** is carried on at least one portion of the light guide shelf **10**, in which the visible light responsive photocatalyst **60** is excited by light including blue color from the visible color LED **70**

[0089] As shown in FIG. **2** and FIG. **3**, visible light responsive photocatalytic films **60** (**60***a*, **60***b*, **60***c*, **60***d*) containing or consisting of the visible light response type photocatalyst may be formed partially or entirely on the front and rear surfaces **10***a*, **10***b* and the three sides **10***a*, **10***b*, **10***d*, except for the side face **10***c* which is the light entrance portion to receive light from the visible color LED **70**.

[0090] The visible light responsive photocatalytic films **60** (**60***a*, **60***b*, **60***c*, **60***d*) may be composed of a transparent resin film containing a plurality of photocatalyst particles dispersed therein.

[0091] The visible light responsive photocatalytic films **60** (**60***a*, **60***b*, **60***c*, **60***d*) may be composed of a plurality of photocatalyst particles, a plurality of light diffusing particles and a transparent resin as a binder containing the photocatalyst particles and light diffusing particles dispersed therein, in which the light diffusing particles may be composed of transparent polymer beads or glass beads which have a refractive index different from transparent resin.

[0092] As shown in FIG. **3**, visible light L**1** emitted from the light exit window **71** of the visible light emitting type LED **70** enters into the side face **10***c* of the light guide shelf **10**, visible light L**2** entered in the light guide shelf **10** transmits within the light guide shelf **10** and advances from the side face **10***c* (light entrance portion) toward the side face **10***d* opposed to the side face **10***c*, in such a manner that visible light L reflects repeatedly between the front and rear surfaces **10** *a* and **10***b* based on a total internal reflection (TIR).

[0093] Light L**2** transmitted within the light guide **10** leaks gradually on the way of transmission from the front and rear surfaces **10** *a* and **10***b* (and three side faces **10** *d*, **10***e* and **10***f*) to the visible light responsive photocatalytic films **60** (**60***a*, **60***b*, **60***c*, **60***d*).

[0094] At that time, the visible light responsive photocatalytic films **60** (**60***a*, **60***b*, **60***c*, **60***d*). absorb light L**2** leaked from the light guide **10**, so that the photocatalytic films **60** are excited by light L**2**, thereby the photocatalytic films **60** indicate a photocatalytic decomposition activity.

[0095] Therefore, dirt or odor organic components such as bacteria, mold, dirt ingredients of food which are adhered on or contacted with the photocatalyst films **60** (**60***a*, **60***b*, **60***c*, **60***d*) on the light guide shelf **10** are decomposed by the photocatalytic decomposition activity.

[0096] Thereby, the light guide shelf **10** and also air circulating in the room of the refrigerator are kept clean, due to the photocatalytic decomposition activity. showing sterilization, disinfection, antibacterial and deodorizing properties.

[0097] In the first embodiment of the invention, the photocatalyst film **60** is formed on the shelf **10** of the refrigerator **100**, however, the photocatalyst film **60** may be formed on an exposed surface of at least one of the left and right side plates **20**, the top plate **30**, the bottom plate **40**, the rear plate **50** (see FIG. **1**) which are composed of the light guide member.

[0098] These light guide plates **20**, **30**, **40** and/or **50** with the photocatalyst **60** are positioned adjacent to walls (left and right side walls, a top wall, a bottom wall and/or a rear wall) of the box of the refrigerator **100**.

[0099] Instead, the walls (left and right side walls, a top wall, a bottom wall and/or a rear wall) themselves may be composed of the light guide plates **20**, **30**, **40** and/or **50** with the photocatalyst **60**.

A SECOND EMBODIMENT OF THE INVENTION

[0100] Referring to second embodiment of the invention is described with reference to FIG. **4**, FIG. **5**A, FIG. **5**B and FIG. **6**.

[0101] A light guide member (e.g. light guide shelf) **10** is composed of a light transmissive plate or panel made of polymer or glass.

[0102] As shown in FIG. **4**, FIG. **5**A and FIG. **5**B, the light guide shelf **10** is composed of a substantially rectangular light guide panel or plate having opposed front and rear surfaces **10***a*, **10***b*, one set of opposed side faces **10***c*, **10***d* and another set of opposed side faces **10***e*, **10***f* and visible light responsive photocatalytic films **60** are formed on the front and rear surfaces **10***a*, **10***b* and the side faces **10***d*, **10***e* and **10***d*.

[0103] In the second embodiment, a leaky optical fiber **80** is provided, which is positioned on/in or adjacent to the light guide shelf **10**.

[0104] The light guide shelf **10** is provided with a groove (i.e. ditch) **10***g* in the rear surface **10***b*, in which the groove **10***g* may have a shape corresponding to the shape of the leaky optical fiber **80**.

[0105] As shown in FIG. **4**, t FIG. **5**A and FIG. **5**B, the groove **10***g* may have a "U" shape and the leaky optical fiber **80** bent to the "U" shape is placed in the groove **10***g*.

[0106] At least one light entrance end of the leaky optical fiber **80** is positioned so as to expose at the side face **10***c* of the leaky optical fiber **10**.

[0107] At least one visible color LED **70** mounted on a printed circuit board **72** is positioned at a wall, LED **70** faces to the light entrance end of the leaky optical fiber **80** with a gap, visible light L**1** emitting from the LED **70** is incident to the light entrance end so that light L**3** transmits within the leaky optical fiber **10** and leaks gradually on the way of transmission.

[0108] The leaky optical fiber **10** leaks light L**4** from a light leaking side along an elongated length of the leaky optical fiber **10**.

[0109] The visible light responsive photocatalytic films **60** on the light guiding shelf **10** receives light L**4** leaked from the leaky optical fiber **10** and the photocatalytic films **60** is excited by the light L**4** so as to exhibit a photocatalytic decomposition activity.

[0110] (Leaky Optical Fiber)

[0111] A leaky optical fiber (i.e. side emitting light fiber) **30** used in the second embodiment is composed of an optical fiber having a light exit side face along a length of the optical fiber and first and/or second light entrance ends.

[0112] Two kinds of the leaky optical fibers may be selectively used in the invention, in which a first kind of the leaky optical fiber exits light from all peripheral portions on the side face along the length and a second kind of the leaky optical fiber exits light from a linear portion on the side face along the length.

[0113] The leaky optical fiber **80** preferably used in the invention is available from 3M, United States and SUMITOMO 3M LTD, Japan, in which 3M Light Fiber (trade mark, brand name) is a leaky plastic optical fiber to exit light from a side surface along a length of the fiber.

[0114] Various kinds of the leaky plastic optical fiber are available from 3M and Sumitomo 3M, for example, Product name LF90 (a core diameter of 9 mm and an outer diameter of 10 mm), Product name LF120 (core diameter: 12 mm/outer diameter: 14 mm), Product name LF120RH (core diameter: 12 mm/outer diameter: 14 mm) and Product name LF120HL (core diameter: 12 mm/outer diameter: 14 mm, with a white clad), according to Web catalogue.

[0115] In these leaky plastic optical fibers, a plastic core having acrylic resin is used which is suitable for use of visible light but not suitable for use of UV light.

[0116] These leaky plastic optical fibers are suitably used in the second embodiment of the invention, because a combination of the visible light responsive photocatalyst **80** and the visible light emitting LED/LEDs **70** are used in the second embodiment,

[0117] Other non-leaky plastic fibers may be used in the second embodiment by making a leaky processing, in which the leaky processing changes the non-leaky plastic fibers to leaky plastic fibers.

[0118] The non-leaky plastic fibers are available from Mitsubishi Rayon Co., Ltd. Japan as "ESKA" (trade mark) such as Product name CK-20 (diameter: 0.5 mm), Product name CK-40 (diameter: 1.0 mm), Product name CK-60 (diameter: 1.5 mm), Product name CK-80 (diameter: 2.0 mm), Product name CK-100 (diameter: 2.5 mm) and Product name CK-120 (diameter: 3.0 mm).

[0119] Another non-leaky plastic fibers are available from Asahi Chemical electronics Co. Japan, as "LUMINUS" (trade mark), such as Product name DB-500 (diameter: 0.5 mm), Product name DB-750 (diameter: 0.75 mm), Product name DB-1000 (diameter: 1.0 mm), Product name DB-1500 (diameter: 1.5 mm), Product name DB-2000 (diameter: 2.0 mm) and Product name DB-3000 (diameter: 3.0 mm),

[0120] A still another non-leaky plastic fibers are available from Hitachi Cable, Ltd. Japan, in which the non-leaky plastic fibers have an optical core made of silicone resin such as Product name HLG-Hd/D (core diameter: 5.0 mm to 9.0 mm, outer diameter: 6.0 mm to 10.5 mm, Product name HLG-Sd/D (core diameter: 5.0 mm to 9.0 mm, outer diameter: 6.0 mm to 10.5 mm.

[0121] The leaky processing for changing the non-leaky plastic optical fibers to the leaky plastic optical fibers are made such as by hot stamping, blasting, laser removing so that an optical clad is partially removed along a length of the non-leaky plastic optical fibers so as to expose an optical core.

[0122] Referring to (FIG. **6**A, FIG. **6**B, FIG. **6**C, FIG. **6**D) and (FIG. **7**A, FIG. **7**B, FIG. **7**C, FIG. **7**D), several structures of the leaky optical fiber **80** are explained.

[0123] A leaky optical fiber **80**A shown in FIG. **6**A is made in such a manner that at first, a non-leaky optical fiber composed of a core **80***a* having a first refractive index and a clad **80***b* having a second refractive index smaller than the first refractive index and a clad **80***b* is prepared beforehand, next an upper portion of the clad **80***b* is removed along a length of the optical fiber **80**A by the leaky processing method so that a core exposed portion **80***a*' is formed, from which light transmitted within the optical fiber **80**A is leaked to outside.

[0124] A leaky optical fiber **80**B shown in FIG. **6**B is made such that a transparent resin film **80***c* is coated on the core exposed portion **80***a*' of the leaky optical fiber **80**A shown in FIG. **6**A, in which the transparent resin film **80***c* has a third refractive index equal to or higher than the first refractive index of the core **80***b*.

[0125] The transparent resin film **80***c* preferably contains known white pigments or light diffusing beads made of glass or polymer material having a refractive index different from the transparent resin film **80***c*, so that the transparent resin film **80***c* has a light diffusing function.

[0126] The leaky optical fibers **80**A (see FIG. **6**B) and **80**B (see FIG. **6**B) leak light which is transmitted within the core

80*a* from the upper portion **80***a*' and **80***c* to outside along the length of the fiber **80**A and **80**B.

[0127] As shown in FIG. **6**C, a leaky optical fiber **80**C is a modification of the leaky optical fiber **80**A (see FIG. **6**A), in which the leaky optical fiber **80**C has an upper exposed core portion **80***a*' and a lower exposed core portion **80***a*", and light transmitted within core **80***a* is leaked from the upper and lower exposed core portions **80***a*' and **80***a*".

[0128] As shown in FIG. **6**D, a leaky optical fiber **80**D is a modification of the leaky optical fibers **80**B (see FIG. **6**B) and **80**C (see FIG. **6**C), in which the leaky optical fiber **80**D has upper and lower exposed core portions **80***a*' and **80***a*" (see FIG. **6**C) and upper and lower transparent films **80***c* (see FIG. **6**B) and **80***c*', and light transmitted within core **80***a* is leaked from the upper and lower transparent films **80***c* and **80***c*'.

[0129] As shown in FIG. **7**A, a leaky optical fiber **80**E is composed of a clad-less optical fiber (core) **80***a* and an upper transparent linear film **80***d* formed on the core **80***a* along a length of the clad-less optical fiber (core) **80***a*, in which a refractive index of the upper transparent linear film **80***d* is higher than the core **80***a* so as to enhance a leakage of light.

[0130] The transparent linear film **80***d* preferably contains known white pigments or light diffusing beads made of glass or polymer material having a refractive index different from the transparent linear film **80***d*, so that the transparent linear film **80***d* has a light diffusing function.

[0131] As shown in FIG. **7**C, a leaky optical fiber **80**G is composed of a clad-less optical fiber (core) **80***a* and upper and lower transparent linear films **80***d* and **80***d*' formed on the core **80***a* along a length of the clad-less optical fiber (core) **80***a*, in which a refractive index of the upper and lower transparent linear films **80***d* and **80***d*' is higher than the core **80***a* so as to enhance a leakage of light.

[0132] As shown in FIG. **7**B, a leaky optical fiber **80**F is composed of an optical fiber having a core **80***a* with a higher refractive index and a clad **80***c* with a lower refractive index formed on the core **80***a* except for an upper exposed linear portion, in which an upper linear transparent film **80***d* is formed on the upper exposed linear portion of the core **80***a*.

[0133] The upper linear transparent film **80***d* has a refractive index equal to or higher than the core **80***a* and the clad **80***c*, therefore light transmitted within the core **80***a* is leaked from the upper linear transparent film **80***d* along a length of the leaky optical fiber **80**E.

[0134] As shown in FIG. **7**D, a leaky optical fiber **80**H is composed of an optical fiber having a core **80***a* with a higher refractive index and divided clads **80***c*/**80***c*' with a lower refractive index formed on the core **80***a* except for upper and lower exposed linear portions, in which upper and lower linear transparent film **80***d* and **80***d*' are formed on the upper and lower exposed linear portion of the core **80***a*.

[0135] The upper and lower linear transparent films **80***d* and **80***d*' have a refractive index equal to or higher than the core **80***a* and the clads and the clad **80***c* and **80***c*', therefore light transmitted within the core **80***a* is leaked from the upper and lower linear transparent films **80***d* and **80***d*' along a length of the leaky optical fiber **80**E.

[0136] Referring to FIG. **4**, FIG. **5**A and FIG. **5**B again, two LEDs emitting visible light including a blue wavelength range are mounted on the printed circuit board **72**, in which the printed circuit board **72** may be fixed on the wall **100***a* (see FIG. **5**A).

[0137] The leaky optical fiber **80** is located in the light guide shelf plate **10** so that two end faces **80-1** and **80-2** of the leaky optical fiber **80** is positioned near the side face **10***c* of the light guide shelf plate **10**.

[0138] The two end faces **80-1** and **80-2** of the leaky optical fiber **80** (and optionally the side face **10***c*) are adjacently positioned to face two light emitting windows **71** of the two LEDs **70** with a gap between the two end faces **80-1**/**80-2** and the two LEDs **70**.

[0139] Alternatively, the LED mounted circuit board (**72** and **80**) may be located in any place in a refrigerator box far from the light guide member/leaky optical fiber (**10** and **80**), if at least one optical fiber for light transmission (not shown in Figures) is interposed between the LEDs **72** and the leaky optical fiber **80**.

[0140] As shown in FIG. **4**, FIG. **5**A and FIG. **5**B, visible light responsive photocatalytic films **60** (**60***a*, **60***b*, **60***c*, **60***d*) containing or consisting of the visible light response type photocatalyst may be formed partially or entirely on the front and rear surfaces **10***a*, **10***b* and the three sides **10***a*, **10***b*, **10***d*, except for the side face **10***c* which is the light entrance portion to receive light from the visible color LED **70**.

[0141] As shown in FIG. **4**, FIG. **5**A and FIG. **5**B, visible light L**1** to emit from the window (or lens) **71** of the LED/LEDs **70** is incident to the light entrance end/ends of the leaky optical fiber **80**, the visible light L**3** transmits within the leaky optical fiber **80** and the visible light L**1** also leaks from the leaky optical fiber **80** to the light guide shelf plate **10** through the transparent adhesive **81**.

[0142] Visible light L**4** leaked from the leaky optical fiber **80** advances to expand within the light guide member **10** toward the visible light responsive photocatalytic films **60** (**60***a*, **60***b*, **60***c*, **60***d*) formed partially or entirely on the light guide member **10**, in which the visible light responsive photocatalytic films **60** (**60***a*, **60***b*, **60***c*, **60***d*) absorb the visible light L**4** and the photocatalytic films **60** are excited to indicate a photocatalytic activity.

[0143] Therefore, dirt or odor organic components such as bacteria, mold, dirt ingredients of foodstuff which are adhered on or contacted with the photocatalyst films **60** (**60***a*, **60***b*, **60***c*, **60***d*) on the light guide shelf **10** are decomposed by the photocatalytic decomposition activity.

[0144] Thereby, the light guide shelf **10** and also air circulating in the room of the refrigerator are kept clean, due to the photocatalytic decomposition activity. showing sterilization, disinfection, antibacterial and deodorizing properties.

A THIRD EMBODIMENT OF THE INVENTION

[0145] Referring to FIG. **8**, a third embodiment is explained below.

[0146] Because the third embodiment is a modification of the second embodiment, an explanation of the same portion as the second embodiment is omitted as much as possible.

[0147] As shown in FIG. **8**, visible light responsive photocatalytic films **60** (**60***a*, **60***b*, **60***c*, **60***d*) containing or consisting of a visible light response type photocatalyst may be formed partially or entirely on front and rear surfaces **10***a*, **10***b* and three sides **10***a*, **10***b*, **10***d* of a light guide shelf plate **10**, except for a side face **10***c* which is a light entrance portion to receive light from the visible color LED **70**.

[0148] In the third embodiment, a leaky optical fiber **80** is placed in or adjacent to the light guide shelf **10** similarly to the second embodiment.

[0149] The light guide shelf **10** may be provided with an "U" shaped groove in the rear surface **10***b* and the leaky optical fiber **80** bent to the "U" shape is placed in the groove.

[0150] A pair of end faces **80-1** and **80-2** of the leaky optical fiber **80** is positioned near the side face **10***c* of the he leaky optical fiber **80**.

[0151] In the third embodiment of the invention, the printed circuit board **72** is provided with a LED **70** and a reflector **90**, in which the LED **70** is positioned to face one end face **80-1** of the leaky optical fiber **80** and the reflector **90** is positioned to face another end face **80-2** of the leaky optical fiber **80**.

[0152] Light from the LED **70** is incident to the one end face **80-1**, the light transmits within the leaky optical fiber **80** with "U" shape toward the another end face **80-2** and the light advanced to the another end face **80-2** is reflected back toward the one end face **80-1**.

[0153] Light leaked from the leaky optical fiber **80** on the way of transmission enters into the visible light responsive photocatalytic films **60** (**60***a*, **60***b*, **60***c*, **60***d*) through the light guide shelf plate **10**.

[0154] Instead, the reflector or reflecting film **90** may be positioned on the another end face **80-2** of the leaky optical fiber **80**.

A FOURTH EMBODIMENT OF THE INVENTION

[0155] Referring to FIG. **9**, a fourth embodiment of the invention is described as follows.

[0156] As shown in FIG. **9**, visible light responsive photocatalytic films **60** (**60***a*, **60***b*, **60***c*, **60***d*) may be formed partially or entirely on a front surface **10***a*, a rear surface opposed to the front surfaces **10***a* and three sides **10***d*, **10***e*, **10***f* of a light guide shelf plate **10**, except for a side face **10***c* of the light guide shelf plate **10** and end faces **82***a* of the leaky optical fiber **80**, which are light entrance portions to receive light from a plurality of visible color LEDs **70**.

[0157] A plurality of leaky optical fibers **82** having an "I"-like linear shape is positioned in a plurality of linear grooves (linear slits) formed in the rear surface of the light guide shelf plate **10**, the linear leaky optical fibers **82** (and the linear grooves) are arranged in parallel.

[0158] The visible color LEDs **70** are mounted on a printed circuit board **72**, in which the LED mounted printed circuit board (**70** and **72**) is positioned adjacent to the light entrance portions of the side face **10***c* and the end faces **82***a*.

[0159] Light L**4** from the LEDs **70** is incident to the end faces **82***a*, the light L**4** transmits within the leaky optical fibers **82** toward other end faces **82***b* and the light L**4** leaked from the leaky optical fibers **82** on the way of transmission enters into the visible light responsive photocatalytic films **60** (e.g. **60***a*, **60***d*, **60***e*, **60***f*) through the light guide shelf plate **10**.

A FIFTH EMBODIMENT OF THE INVENTION

[0160] Referring to FIG. **10**, a fifth embodiment of the invention is described below.

[0161] As shown in FIG. **10**, visible light responsive photocatalytic films **60** (**60***a*, **60***b*, **60***c*, **60***d*) may be formed partially or entirely on a light guide shelf plate **10***a* (a front surface **10***a*, a rear surface opposed to the front surfaces **10***a* and three sides **10***d*, **10***e*, **10***f*), except for a side face **10***c* of the light guide shelf plate **10** and end faces **83***a* of the leaky optical fiber **83**, which are light entrance portions to receive light from two visible color LEDs **70**.

[0162] A leaky optical fiber **83** in this embodiment of the invention has a meandered shape such as "W" or "M" shape as a whole and the meandered leaky optical fiber **83** is positioned in a meandered shaped groove formed in the rear surface of the light guide shelf plate **10**.

[0163] The visible color LEDs **70** are mounted on a printed circuit board **72**, in which the LED mounted printed circuit board (**70** and **72**) is positioned adjacent to the light entrance portions of the side face **10***c* and two end faces **83***a* of the leaky optical fiber **83**.

[0164] Light from the LEDs **70** is incident to the end faces **83***a*, the light transmits within the leaky optical fibers **83**, the light leaked from the leaky optical fibers **83** on the way of transmission and enters into the visible light responsive photocatalytic films **60** (e.g. **60***a*, **60***d*, **60***e*, **60***f*) through the light guide shelf plate **10**.

[0165] White color emitting LED can be used for visible light emitting element/elements in all the embodiments of the invention, in which the white color emitting LED/may be composed of a LED having near UV or blue emitting LED and a wavelength converting phosphor to emit white color consisting of blue, green and red color, instead a combination of three separated LEDs having a blue emitting LED, a green emitting LED and a red emitting LED can be used.

[0166] Some volume of blue light from the LED is absorbed in the photocatalyst to excite it, and three colors of light consisting of green light, red light and the rest of the blue light from the LED without absorbing in the photocatalyst can exit from the light guide member so as to illuminate a store room of a refrigerator.

[0167] In some embodiments described hereinbefore, the light guide member and/or the leaky optical fiber are preferably composed of resin material.

[0168] In some embodiments described hereinbefore, the light guide member and/or the leaky optical fiber may contain a plurality of diffusing particles to enhance a leaking capability.

[0169] In some embodiments described hereinbefore, the light guide member may be eliminated, if the photocatalyst is disposed on, or adjacent to the leaky optical fiber, such that a refrigerator having photocatalyst, comprises: at least one leaky optical fiber having a light leaking side surface and at least one light entrance end; a photocatalyst composed of visible light responsive photocatalytic material, disposed on or adjacent to the light leaking side surface; and at least one visible light emitting type light emitting element, for emitting visible light which is directed or incident to the at least one light entrance end.

[0170] Although illustrative embodiments of the present invention have been described referring to the accompanying drawings, it is to be understood that the present invention is not limited to those embodiments and that various changes, modifications or equivalents may be made in the present invention by those skilled in the art without departing from the spirit or the scope of the present invention and the appended claims.

What is claimed is:

1. A refrigerator having photocatalyst, comprising:

a photocatalytic light guide member, composed of a light guide member and a photocatalyst;

the light guide member having a light entrance portion and a light leaking portion;

the photocatalyst being composed of visible light responsive photocatalytic material, disposed on or adjacent to the light leaking portion;

at least one visible light emitting type light emitting element, for emitting visible light which is directed or incident to the light entrance portion; and

wherein the visible light responsive photocatalytic material is excited by visible light which is leaked from the light leaking portion.

2. The refrigerator according to claim **1**, wherein the light guide member comprises at least one shelf plate, a top plate, a back plate, a bottom plate, and/or at least one side plate.

3. The refrigerator according to claim **1**: wherein the light guide member comprises a light transmissive plate or panel having opposed surfaces and opposed sides; wherein a photocatalytic film contains or consists of the photocatalyst, which is disposed partially or entirely on at least one of the opposed surfaces; and wherein the at least one visible light emitting type light emitting element is disposed to face at least one of the opposed sides.

4. The refrigerator according to claim **1**: wherein the light guide member comprises a leaky optical fiber having a light leaking side surface and a light entrance end.

5. The refrigerator according to claim **1**: wherein a photocatalytic film comprises a plurality of photocatalyst particles having the photocatalyst and a transparent binder containing the photocatalyst particles.

6. The refrigerator according to claim **1**: wherein a photocatalytic film comprises a plurality of photocatalyst particles having the photocatalyst, a plurality of light diffusing particles and a transparent binder containing the photocatalyst particles and the light diffusing particles.

7. The refrigerator according to claim **1**: wherein the at least one visible light emitting type light emitting element comprises at least one light emitting diode (LED) to emit blue light and/or white light.

8. The refrigerator according to claim **1**: wherein the at least one visible light emitting type light emitting element comprises at least one light emitting diode (LED) to emit at least blue light; and wherein the photocatalyst is excited by blue light from the LED.

9. The refrigerator according to claim **1**: wherein the light guide member comprises a resin material

10. A refrigerator having photocatalyst, comprising:

a photocatalytic light guide member, composed of a light guide member and a photocatalyst;

at least one leaky optical fiber having a light leaking side surface and a light entrance end, disposed in/on or adjacent to the light guide member;

the photocatalyst being composed of visible light responsive photocatalytic material, disposed on or adjacent to the light guide member; and

at least one visible light emitting type light emitting element, for emitting visible light which is directed or incident to the light entrance end.

11. The refrigerator according to claim **10**: wherein the visible light responsive photocatalytic material is excited by visible light which leaked from the leaky optical fiber through the light guide member.

12. The refrigerator according to claim **10**, wherein the light guide member comprises at least one shelf plate, a top plate, a back plate, a bottom plate, and/or at least one side plate.

13. The refrigerator according to claim **10**: wherein the light guide member comprises a light transmissive plate or panel having opposed surfaces and opposed sides; wherein a photocatalytic film contains or consists of the photocatalyst, which is disposed partially or entirely on at least one of the opposed surfaces; and wherein the at least one visible light emitting type light emitting element is disposed to face at least one of the opposed sides.

14. The refrigerator according to claim **10**: wherein a photocatalytic film comprises a plurality of photocatalyst particles having the photocatalyst and a transparent binder containing the photocatalyst particles.

15. The refrigerator according to claim **10**: wherein a photocatalytic film comprises a plurality of photocatalyst particles having the photocatalyst, a plurality of light diffusing particles and a transparent binder containing the photocatalyst particles and the light diffusing particles.

16. The refrigerator according to claim **10**: wherein the at least one visible light emitting type light emitting element comprises at least one light emitting diode (LED) to emit blue light and/or white light.

17. The refrigerator according to claim **10**: wherein the at least one visible light emitting type light emitting element comprises at least one light emitting diode (LED) to emit at least blue light; and wherein the photocatalyst is excited by blue light from the LED.

18. The refrigerator according to claim **10**: wherein the light guide member and/or the leaky optical fiber comprises a resin material.

19. The refrigerator according to claim **10**: wherein the light guide member and/or the leaky optical fiber contain a plurality of diffusing particles.

20. A refrigerator having photocatalyst, comprising:

at least one leaky optical fiber having a light leaking side surface and at least one light entrance end;

a photocatalyst composed of visible light responsive photocatalytic material, disposed on or adjacent to the light leaking side surface; and

at least one visible light emitting type light emitting element, for emitting visible light which is directed or incident to the at least one light entrance end.

* * * * *

US005542016A

United States Patent [19]

Kaschke

[11] **Patent Number: 5,542,016**

[45] **Date of Patent: Jul. 30, 1996**

[54] **OPTICAL FIBER LIGHT EMITTING APPARATUS**

[75] Inventor: **Kevin D. Kaschke**, Hoffman Estates, Ill.

[73] Assignee: **Motorola, Inc.**, Schaumburg, Ill.

[21] Appl. No.: **374,385**

[22] Filed: **Jan. 13, 1995**

Related U.S. Application Data

[63] Continuation of Ser. No. 57,394, May 5, 1993, abandoned.

[51] **Int. Cl.**[6] **G02B 6/02**

[52] **U.S. Cl.** **385/123**; 385/31; 385/901; 362/32

[58] **Field of Search** 385/123, 115, 385/116, 117, 120, 147, 901; 362/32

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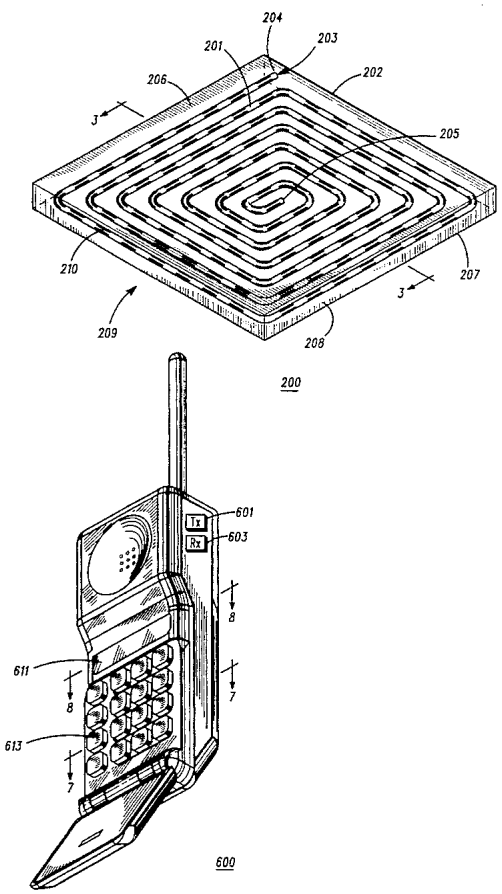
Primary Examiner—John D. Lee
Assistant Examiner—Phan T. H. Palmer
Attorney, Agent, or Firm—Kevin D. Kaschke

[57] **ABSTRACT**

An optical fiber light emitting apparatus (**200**) comprises at least one optical fiber (**201**) arranged in a repeating, recurrent pattern extending substantially throughout a predetermined area (**206**). The optical fiber (**201**) has a plurality of locations along the length thereof permitting light entering at least one end of the optical fiber (**201**) for transmission therein to be selectively emitted by the optical fiber (**201**) at the plurality of locations (**210**) for producing substantially uniform illumination substantially throughout the predetermined area (**206**). The repeating, recurrent pattern may form a spiral or serpentine pattern, for example. The repeating, recurrent pattern eliminates the space required for the fan-in arrangement (**115**) of prior art optical fiber light emitting panels (**100**). The optical fiber light emitting apparatus (**200**) is beneficial for illuminating keypads (**613**) and displays (**611**) in electronic devices (**600**), such as portable radio telephones, having limited space available.

28 Claims, 6 Drawing Sheets



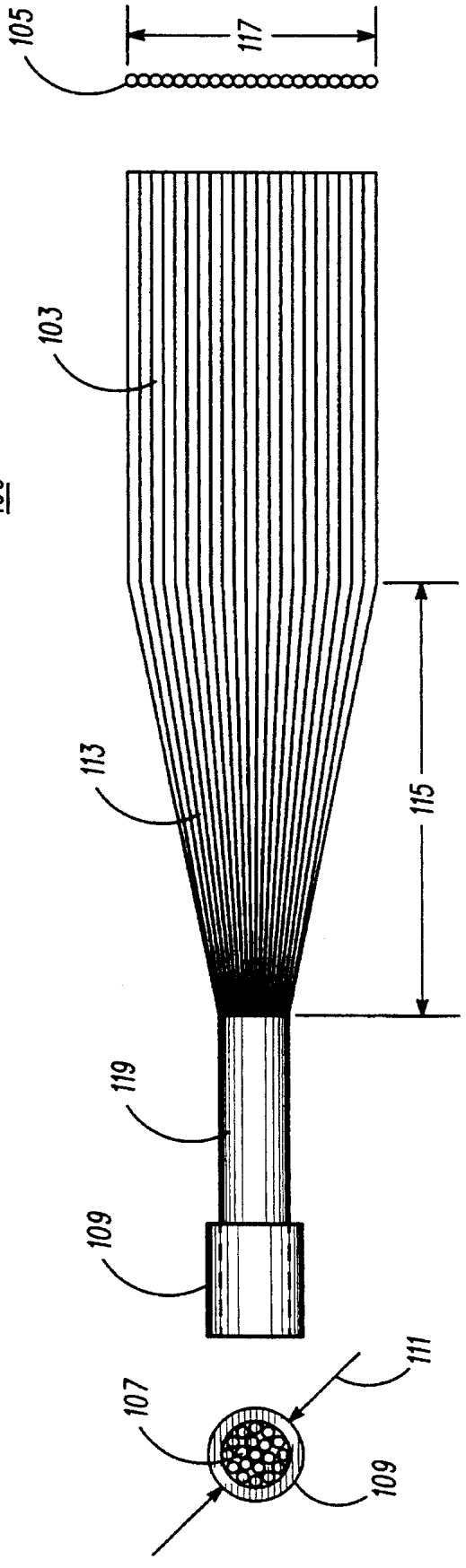


FIG. 1
-PRIOR ART-

FIG. 2

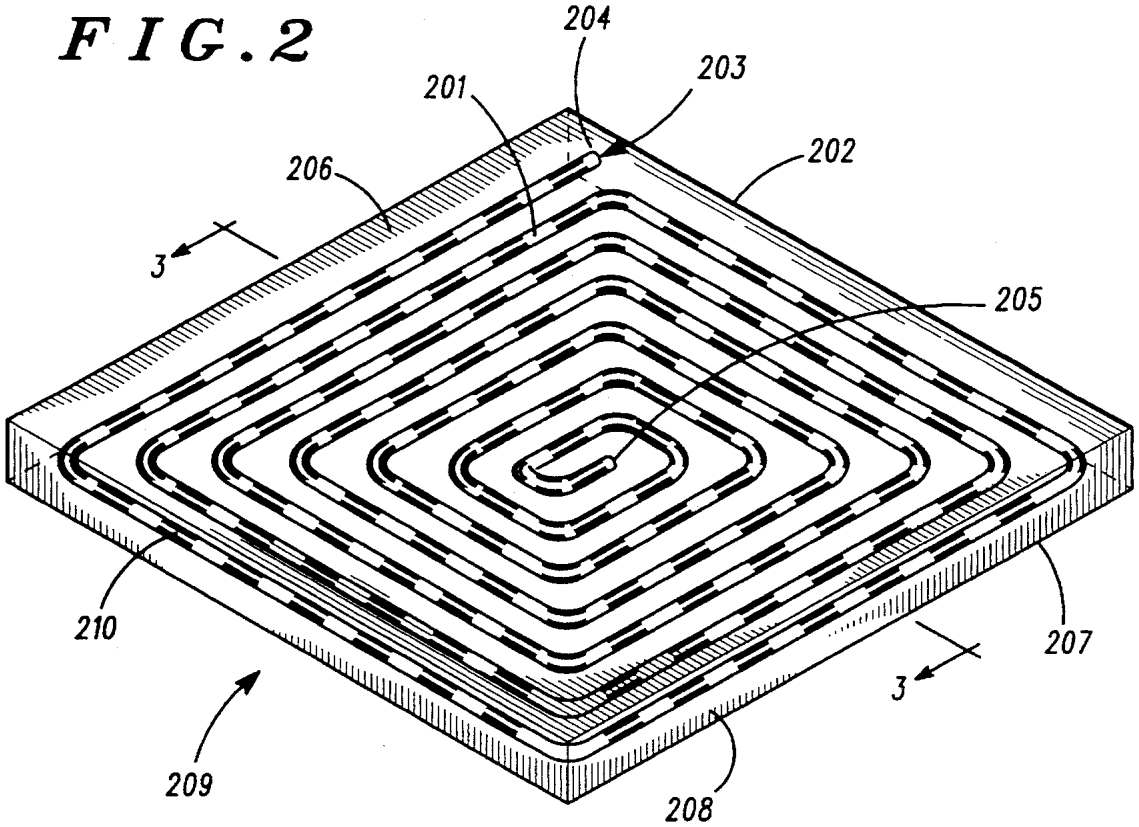
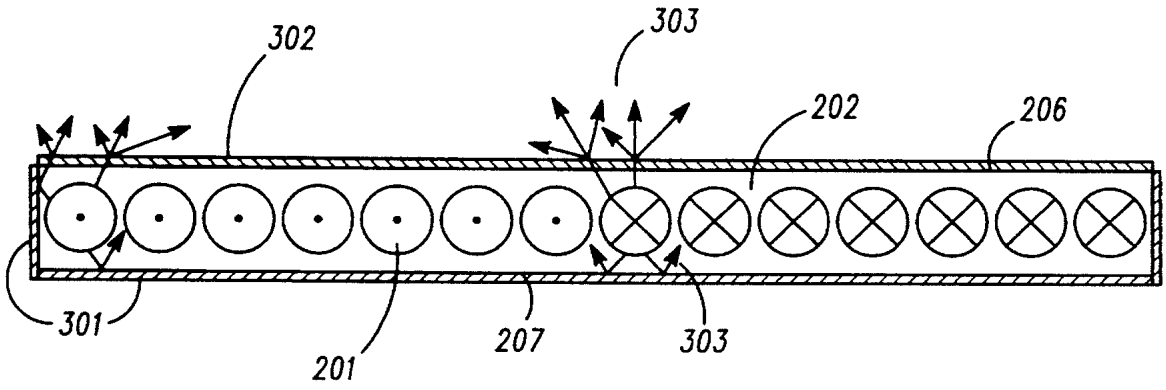


FIG. 3



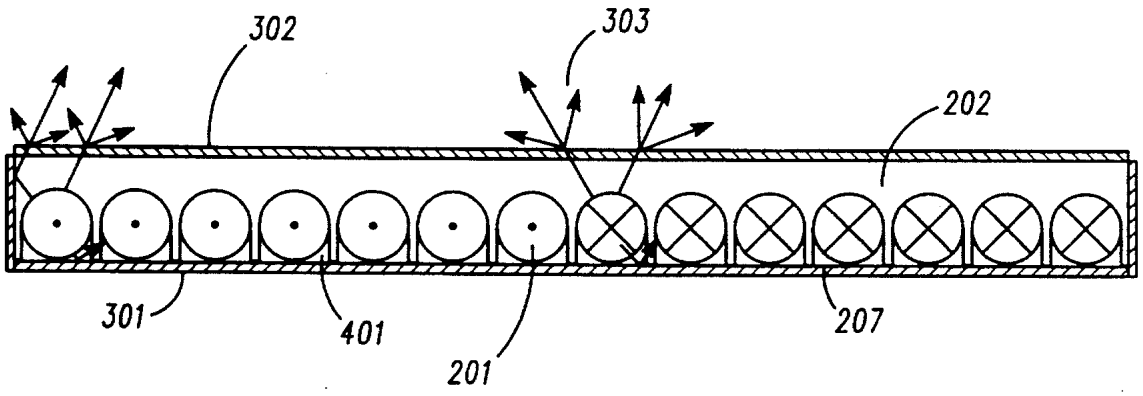
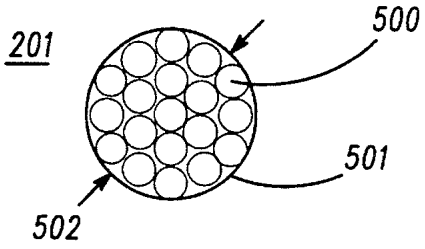


FIG. 4

400

FIG. 5



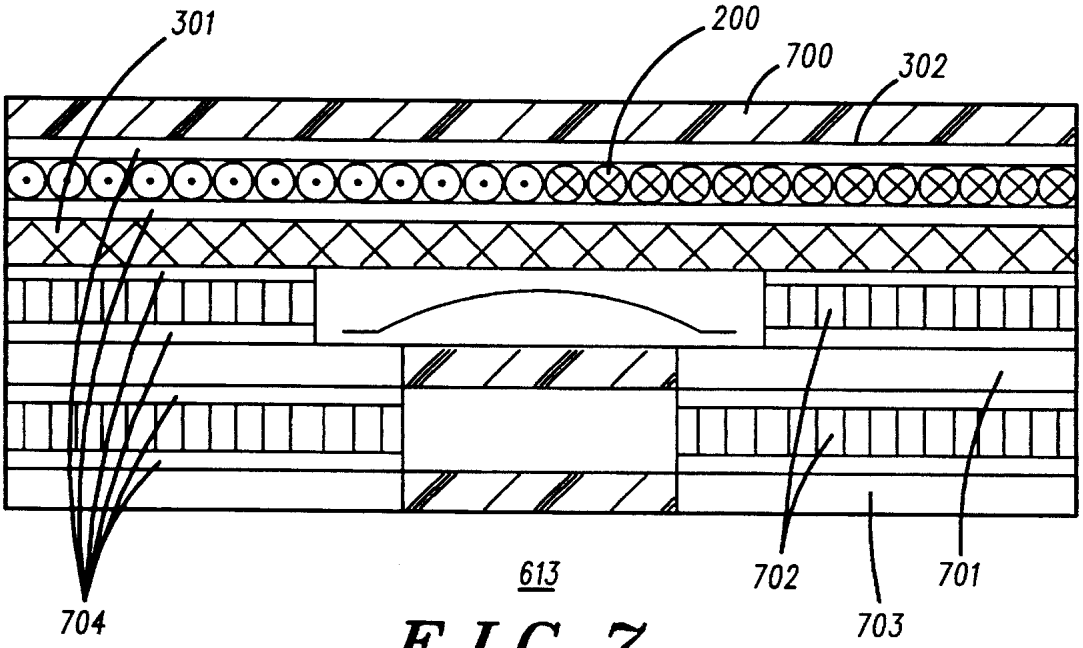


FIG. 7

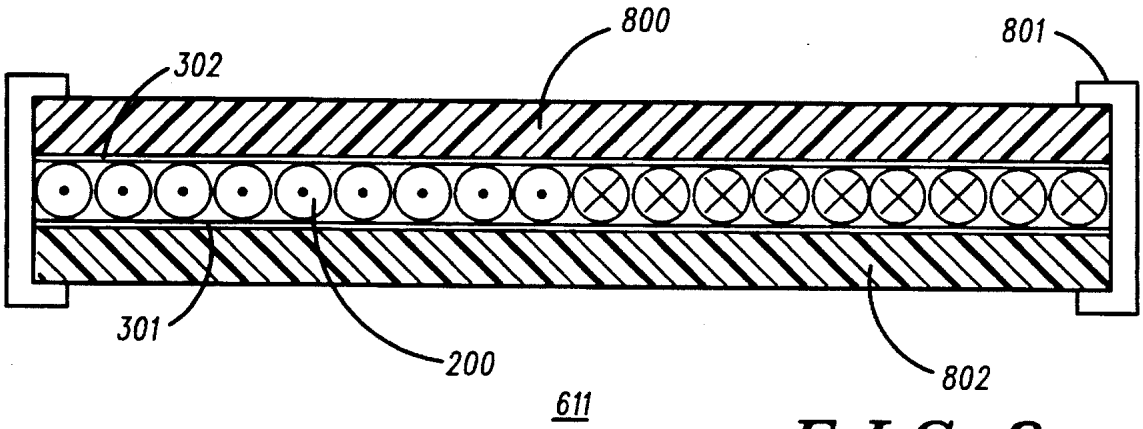


FIG. 8

FIG. 6

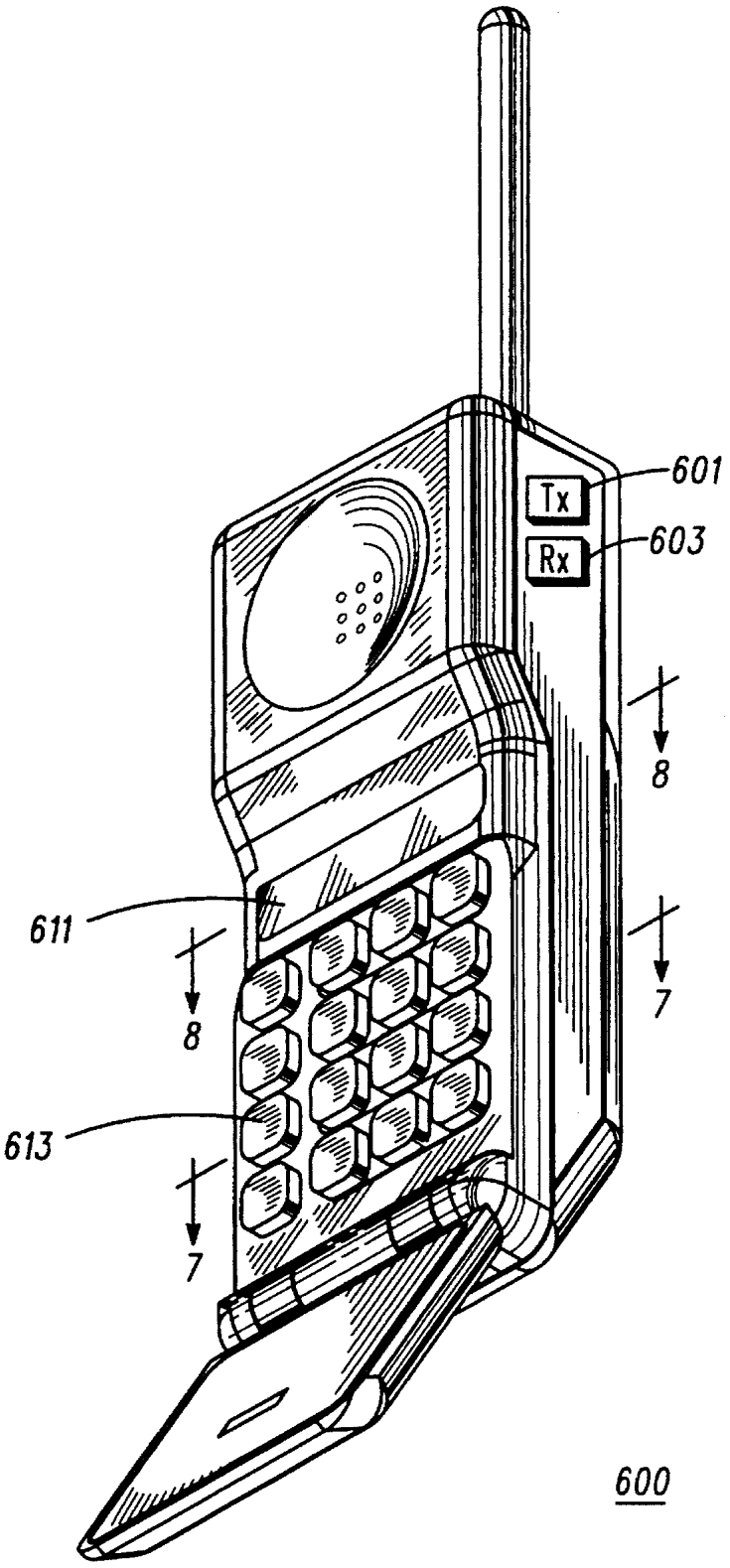


FIG. 9

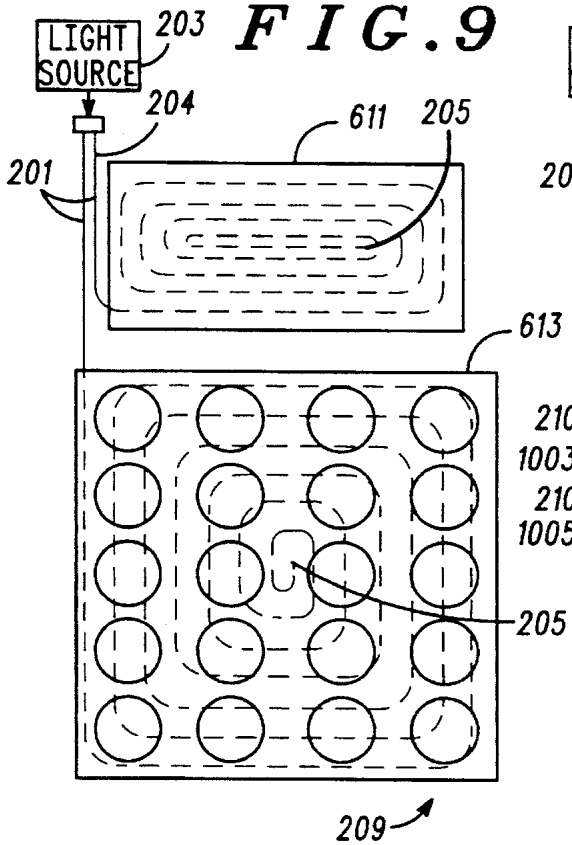


FIG. 10

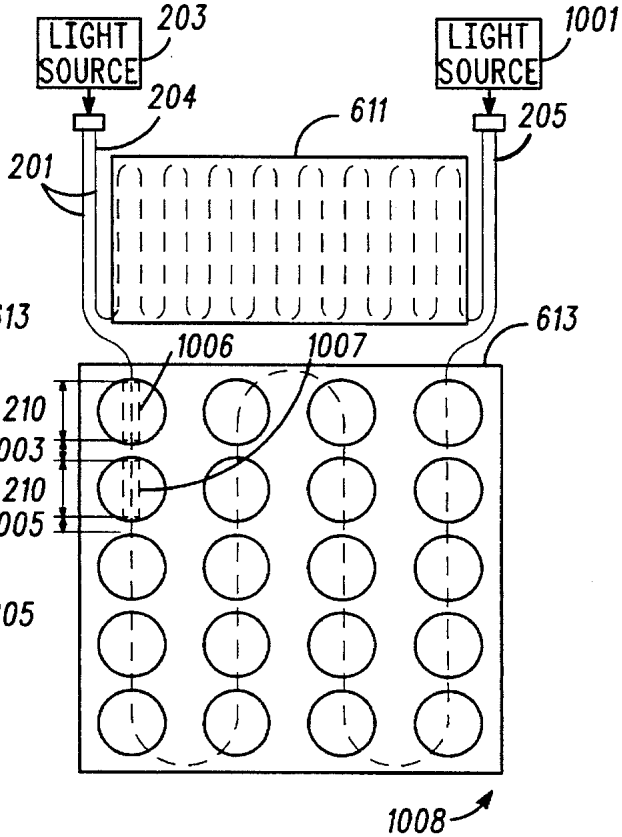


FIG. 11

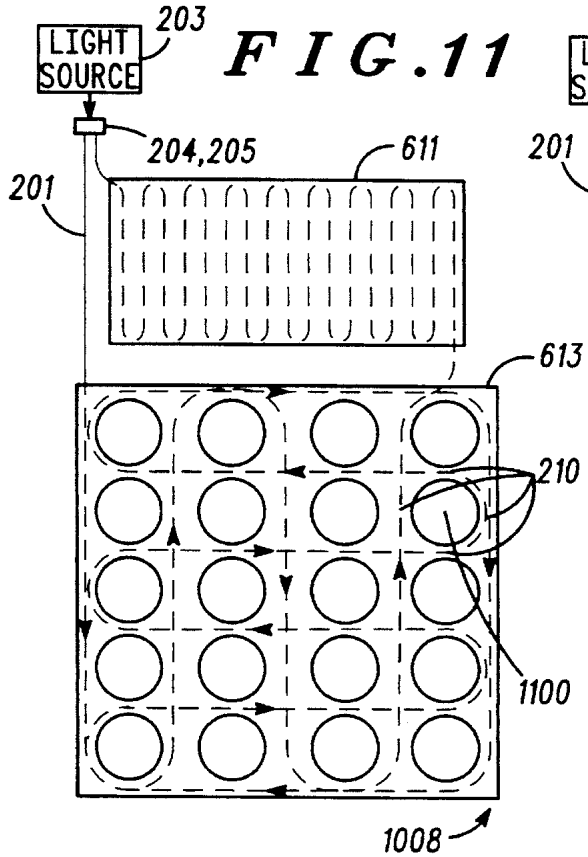
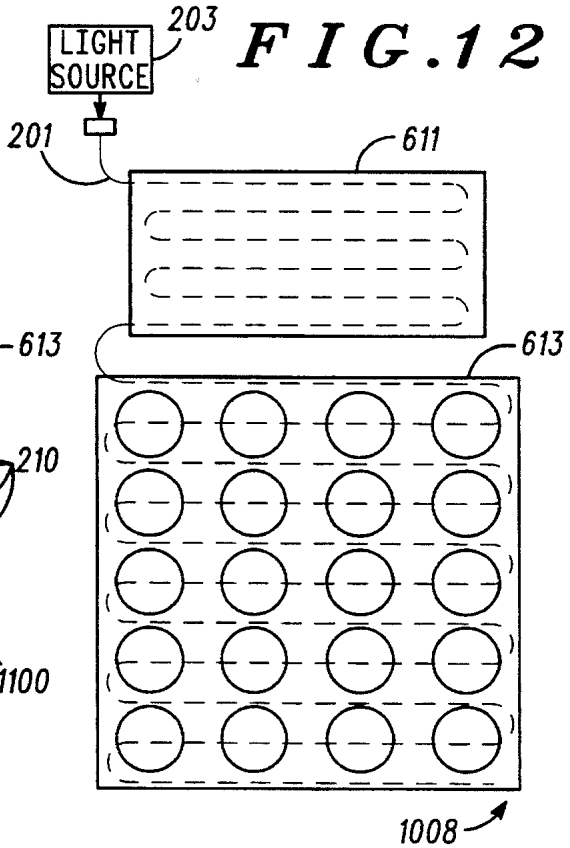


FIG. 12



OPTICAL FIBER LIGHT EMITTING APPARATUS

This is a continuation of U.S. patent application Ser. No. 08/057,394, filed May 5, 1993 and now abandoned.

FIELD OF THE INVENTION

The present invention relates generally to light emitting apparatus and more particularly to optical fiber light emitting apparatus.

BACKGROUND OF THE INVENTION

It is generally known to form optical fibers into a panel or the like and make the panel luminous in one or more selected areas by altering the total internal reflection character of the optical fibers in such areas. Illumination in these areas is caused by allowing light transmitted into the optical fibers from a remote light source to emerge from the optical fibers in the selected areas.

Normally the light entering one end of an optical fiber passes out the other end thereof after a certain amount of loss takes place. However, if the surface of the optical fiber is disrupted as by scratching or otherwise deformed as by bending the optical fiber at a plurality of discrete locations along its length such that the angle of bend approximately exceeds the angle of-internal reflection light will be emitted at these locations.

A conventional optical fiber light emitting panel **100** is shown in FIG. **1**. The panel is formed of a plurality of cladded optical fibers arranged in an abutting side-by-side essentially parallel relationship and extending over a predetermined area **103**. The distal ends **105** of the optical fibers are typically cut and polished. The proximal ends **107** of the optical fibers are bundled together with a band **109** such that a single light source may be used to illuminate the panel. The diameter **111** of the bundle increases with the number and diameter of the individual optical fibers. The gradual gathering of the optical fibers from their essentially parallel relationship to a bundle produces a fan-in arrangement **113**. Typically, the length of the fan-in arrangement **115** is one and one-half times the distance across the essentially parallel optical fibers **117**. The optical fibers may optionally be bundled into a cable **119** for routing to a remote location.

A problem with the conventionally formed optical fiber light emitting panel **100** is the space consumed by the fan-in arrangement **115**. Although optical fiber light emitting panels provide certain advantages over other lighting apparatus, some lighting applications, such as portable electronics, simply cannot use the conventional optical light emitting panel because of the amount of space available for the fan-in arrangement.

Therefore, there is a need for an improved optical fiber light emitting panel providing essentially the same advantages as the conventional optical fiber light emitting panel but consuming less space.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a top and end view of a prior art optical fiber light emitting panel.

FIG. **2** illustrates a top perspective view of an optical fiber light emitting apparatus including an optical fiber in accordance with the present invention.

FIG. **3** illustrates a cross-sectional view of the optical fiber light emitting apparatus of FIG. **2** in accordance with the present invention.

FIG. **4** illustrates an alternate cross-sectional view of the optical fiber light emitting apparatus of FIG. **2** in accordance with the present invention.

FIG. **5** illustrates a cross-sectional view of plurality of optical fiber strands forming the optical fiber of FIG. **2** in accordance with the present invention.

FIG. **6** illustrates an electronic device including a keypad and a display in accordance with the present invention.

FIG. **7** illustrates a cross-sectional view of the keypad of FIG. **6** incorporating the optical fiber light emitting apparatus of FIG. **2** in accordance with the present invention.

FIG. **8** illustrates a cross-sectional view of the display of FIG. **6** incorporating the optical fiber light emitting apparatus of FIG. **2** in accordance with the present invention.

FIG. **9** illustrates a first schematic view of the display and the keypad of FIG. **6** incorporating the optical fiber light emitting apparatus of FIG. **2** in accordance with the present invention.

FIG. **10** illustrates a second schematic view of the display and the keypad of FIG. **6** incorporating the optical fiber light emitting apparatus of FIG. **2** in accordance with the present invention.

FIG. **11** illustrates a third schematic view of the display and the keypad of FIG, **6** incorporating the optical fiber light emitting apparatus of FIG. **2** in accordance with the present invention.

FIG. **12** illustrates a fourth schematic view of the display and the keypad of FIG, **6** incorporating the optical fiber light emitting apparatus of FIG, **2** in accordance with the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Generally, the present invention provides an optical fiber light emitting apparatus comprising at least one optical fiber arranged in a repeating, recurrent pattern extending substantially throughout a predetermined area. The optical fiber has a plurality of locations along the length thereof permitting light entering at least one end of the optical fiber for transmission therein to be selectively emitted by the optical fiber at the plurality of locations for producing substantially uniform illumination substantially throughout the predetermined area. The repeating, recurrent pattern may form a spiral or serpentine pattern, for example. The optical fiber light emitting apparatus is advantageously used to illuminate keypads and displays, for example, within electronic devices having limited space available.

The present invention can be more fully understood with reference to FIGS. **2–12** wherein FIG. **2** illustrates a top perspective view of an optical fiber light emitting apparatus **200** including an optical fiber **201** in accordance with a preferred embodiment of the present invention.

In accordance with the present invention, the optical fiber light emitting apparatus **200** comprises at least one optical fiber **201** arranged in a repeating, recurrent pattern extending substantially throughout a predetermined area **206**. The optical fiber **201** has a plurality of locations **210** along the length thereof permitting light entering at least a first end **204** of the optical fiber **201** for transmission therein to be selectively emitted by the optical fiber **201** at the plurality of

locations **210** for producing substantially uniform illumination substantially throughout the predetermined area **206**.

The repeating, recurrent pattern is preferably a spiral pattern **209** but may also be serpentine pattern or even a random pattern if so desired. The pitch between portions of the optical fiber **201** may be tight or loose as desired. The pattern is repeating in that the pattern occurs more than once. The pattern is recurrent in that it turns back in a direction opposite to a former course.

The optical fiber **201** has the first end **204** and a second end **205**. A light source **203** transmits the light into the first end **204** of the optical fiber **201**. The light source **203** may be remotely located from the optical fiber light emitting apparatus **200** and may supply light for one or more optical fiber light emitting apparatus **200**. A light source **203**, remotely located, may advantageously be used in dangerous, inaccessible locations or where electricity, heat, EMI or RFI are problems. An optional filter (not shown) may be used to filter the light emitted by the light source **203** before it enters the optical fiber **201**. The kind of light source **203** utilized may include light emitting diodes, incandescent bulbs (preferably, for example, T 1 ¼, 5 V/115 mA), arc lamps or even the sun, as is well known in the art.

The second end **205** of the optical fiber **201** is desirably cut and polished and a reflector (not shown) is provided at the second end **205** to reflect light back into the optical fiber **201** thereby increasing its light emitting efficiency, as is well known in the art.

In accordance with the present invention, a carrier **202** forms a support for holding the at least one optical fiber in the repeating, recurrent pattern. The carrier **202** has a top side **206**, thereby defining the predetermined area, essentially opposite a bottom side **207** and a lateral side **208** disposed essentially therebetween.

Individually, the optical fiber **201**, the carrier **202** and the light source **203** are well known in the art and only a brief description will be presented to facilitate the understanding of the present invention.

The optical fiber **201** is preferably made of a plastic material but any suitable light transmitting material such as glass may be used. The optical fiber **201** is available in diameters ranging from 0.25 mm to 2.0 mm, typically. The optical fiber **201** is durable but should not be bent less than approximately five times its diameter to maintain structural integrity and approximately ten times its diameter to maintain its internal reflection properties at the bend, if desirable.

Several techniques for causing the light to be illuminated from the plurality of locations **210** are well known in the art and only a brief description will be presented to facilitate the understanding of the present invention. One technique used to cause the light to be emitted from the plurality of locations **210** involves disrupting the external surface of the optical fiber **201** by bending (weaving, for example) a plurality of optical fiber strands **500** (see FIG. **5**) at a plurality of discrete locations along their lengths such that the angle of each bend approximately exceeds the angle of internal reflection so that a portion of the light will be emitted at each bend. Another technique is used to cause the light to be emitted from the plurality of locations **210** involves varying the lengths of the plurality of optical fiber strands **500** (see FIG. **5**) so that a portion of the light will be emitted at the end faces of each optical fiber strand **500**. Yet another technique, the preferred, used to cause the light to be emitted from the plurality of locations **210** involves scratching, abrading or chemically removing portions of cladding on the surface of the optical fiber **201** or by doping the internal structure of the core of the optical fiber **201** to cause the light to be deflected out through the cladding of the individual fibers without any deformation of the optical fiber **201** itself.

It is advantageous to increase the frequency of plurality of locations **210** as the distance from the first end **204** of the optical fiber **201** increases to permit light emitted from the plurality of locations **210** to be substantially uniform over the length of the optical fiber **201** and therefor over the predetermined area **206**. Several techniques for varying the frequency of light to be illuminated along the length of the optical fiber **201** are well known in the art and only a brief description will be presented to facilitate the understanding of the present invention. One technique for varying the frequency of light to be illuminated along the length of the optical fiber **201** involves varying the shape of the optical fiber disruptions or bends as by varying the tightness of the weave or by varying the proportion of optical fiber strands **500** (see FIG. **5**) to other material in the weave. Another technique for varying the frequency of light to be illuminated along the length of the optical fiber **201** involves decreasing spacing between the plurality of locations **210** having the cladding removed from the surface of the optical fiber **201**. Still another technique for varying the frequency of light to be illuminated along the length of the optical fiber **201** involves decreasing spacing between various lengths of the optical fiber strands **500** (see FIG. **5**).

In accordance with the present invention, the carrier **202** may be fabricated such that it is rigid, flexible, porous or solid and such that it is integrally formed with or separately formed from the optical fiber **201**. For example the carrier may be cast, sprayed or injection molded over the optical fiber **201**. The carrier **202** may be formed as a substantially translucent acrylic light pipe, an elastomeric keypad, a membrane keypad and a, preferred, resin or epoxy-coated film that is heat or radiation cured upon assembly. It should also be understood that the optical fiber light emitting apparatus **200** can be made to emit light from one or both sides of the carrier **202**. The optical fiber light emitting apparatus **200** can also be made in any size or shape. More than one layer of the optical fiber light emitting apparatus **200** may be used to increase the light output over the predetermined area **206**.

FIG. **3** illustrates a cross-sectional view of the optical fiber light emitting apparatus **200** of FIG. **2** in accordance with the preferred embodiment of the present invention. The optical fiber **201** having a dot inside its cross-sectional view represents the optical fiber **201** coming out of the page and a cross inside its cross-sectional view represents the optical fiber **201** going into the page. The optical fiber light emitting apparatus **200** is shown as constructed with an optional, but preferred, reflector **301** and an optional diffuser **302**. Individually, the reflector **301** and the diffuser **302** are well known in the art and only a brief description will be presented to facilitate the understanding of the present invention.

The reflector **301** causes at least a portion of the light **303** emitted by the plurality of locations **210** (see FIG. **2**) towards the bottom side **207** to be redirected towards the top side **206**. Examples of reflectors include inter alia metal foil and white sheets of material disposed adjacent to the bottom side **207**, white paint disposed on the bottom side **207** and a textured surface integrally molded into the bottom side **207**. The reflector **301** advantageously increases the efficiency of the optical fiber light emitting apparatus **200** by increasing the amount of light **303** emitted from the top side **206**. The reflector **301** may also be used to aid in providing a uniform light output from the optical fiber light emitting

apparatus **200** by varying the amount of reflection at each of the plurality of locations **210**. For example, as the light output from the plurality of locations **210** of the optical fiber **201** decreases, the amount of reflection can increase to compensate thereby providing a uniform light output.

The diffuser **302** is formed of a substantially translucent material for diffusing or scattering at least a portion of the light **303** emitted by the selective areas. Examples of diffusers include inter alia ground glass, smoked/etched plastic and diffuser films. The diffuser **302** advantageously disperses the light **303** emitted from the plurality of locations **210** to further provide uniform lighting over the top side **206**.

FIG. **4** illustrates an alternate cross-sectional view of the optical fiber light emitting apparatus **200** of FIG. **2** in accordance with an alternate embodiment of the present invention. The carrier **202** includes channels **401** formed in the bottom side **207**. The optical fiber **201** is held in the channel **401** with the reflector **301** by attaching the reflector **401** to the bottom side **207** of the carrier **202**. The channels **401** advantageously permit the optical fiber to be assembled with the carrier after the carder is formed.

FIG. **5** illustrates a cross-sectional view of plurality of optical fiber strands **500** forming the optical fiber **201** of FIG. **2** in accordance with the present invention.

The optical fiber **201** alternatively comprises the plurality of optical fiber strands **500** bundled together. The plurality of smaller optical fiber strands **500** can advantageously be bent at a sharper radius than a single optical fiber of essentially the same diameter.

A technique for bundling the optical fiber strands **500** for coupling to the light source is well known in the art which uses a connector assembly consisting of a buffer material (not shown) surrounding the gathered optical fiber strands **500** and a ferrule (not shown) crimped onto the buffer material to tightly bundle the ends together. The diameter **502** of the optical fiber strands **500** forming a tight bundle is calculated using the following equation:

$$d_{bundle} = d_{one\ optical\ strand}\left(\sqrt{n} + \frac{\sqrt{n \times 40}}{100}\right)$$

wherein n=the number of optical fiber strands. For example, **120** optical fiber strands **500** having a diameter of 0.25 mm each produces a 3.83 mm diameter bundle **502**.

The ends of the optical fiber strands **500** when bundled, are cut and polished at their end surface and held on a plane essentially perpendicular to the principal axis of the light source to properly receive light from the light source and to transmit the maximum amount of light through the surface and down the length of the optical fiber for illuminating the predetermined area **206**.

A cover **501** made of substantially translucent material is optional but preferably used to surround the optical fiber strands **500** for organizing the optical fiber strands **500**. The cover **501** may extend along substantially the entire length of the optical fiber **201** or be discretely spaced bands. Alternatively, the optical fiber strands **500** may be twisted together.

FIG. **6** illustrates an electronic device **600** including a keypad **613** and a display **611** in accordance with the present invention. In particular, the electronic device **600** is a particular type of communication unit known as a portable radio telephone. The individual elements of the electronic device **600** represented as a communication unit, having a keypad **613** and display **611** are well known in the art and no further discussion will be presented except to facilitate the understanding of the present invention. Examples of communication units include mobile and portable radio telephones, pagers, pocket notebooks, portable control panels, user interface devices.

The electronic device **600** representing a communication unit generally includes at least one of a transmitter **601**, a receiver **603**, and a transceiver **601**, **603** (internal to the device). The receiver **603** receives signals representing received information. A display has information positions for presenting the received information substantially throughout a first predetermined area (typically, within the display lens area). The transmitter **601** transmits signals representing transmitted information. A plurality of keys forming the keypad **613** are positioned substantially throughout a second predetermined area (typically, the keypad area) for inputting the transmitted information. In accordance with the present invention, at least one optical fiber is arranged in a repeating, recurrent pattern extending substantially throughout at least one of the first and second predetermined areas. The at least one optical fiber has a plurality of locations along the length thereof permitting light entering at least a first end of the at least one optical fiber for transmission therein to be selectively emitted by the at least one optical fiber at the plurality of locations for producing substantially uniform illumination for at least one of the information positions and plurality of keys positioned substantially throughout the first and second predetermined areas, respectively.

FIG. **7** illustrates a cross-sectional view of the keypad **613** of FIG. **6** incorporating the optical fiber light emitting apparatus **200** of FIG. **2** in accordance with the present invention. The keypad **613** generally comprises the optical fiber light emitting apparatus **200**, a membrane **700** (with the diffuser **302**), the reflector **301**, the top and bottom switch layers **701** and **703**, the spacers **702** and the adhesive **704**. The keypad construction incorporating the novel optical fiber light emitting apparatus **200** is well known in the art and no further discussion will be given.

FIG. **8** illustrates a cross-sectional view of the display **611** of FIG. **6** incorporating the optical fiber light emitting apparatus **200** of FIG. **2** in accordance with the present invention. The display **611**, represented a liquid crystal display (LCD), generally comprises LCD glass **800**, a bezel **801**, a circuit board **802**, the diffuser **302**, the reflector **301** and the optical fiber light emitting apparatus **200**. The display construction incorporating the novel optical fiber light emitting apparatus **200** is well known in the art and no further discussion will be given.

FIG. **9** illustrates a first schematic view of the display **611** and the keypad **613** of FIG. **6** incorporating the optical fiber light emitting apparatus **200** of FIG. **2** in accordance with the present invention. The display **611** and the keypad **613** each have the optical fiber **201** arranged in a spiral pattern **209**. The optical fibers for the display **611** and the keypad **613** advantageously received light at a first end **204** from the same light source **203**. The second end **205** of the optical fibers are cut, polished and have a reflector to keep the light reaching the second end **205** inside the optical fiber.

FIG. **10** illustrates a second schematic view of the display **611** and the keypad **613** of FIG. **6** incorporating the optical fiber light emitting apparatus **200** of FIG. **2** in accordance with the present invention. The display **611** and the keypad **613** each have the optical fiber **201** arranged in a serpentine pattern **1008**. The optical fiber **201** for each of the display **611** and the keypad **613** advantageously receive light at a first end **204** from the same light source **203** and receives light at a second end **205** from another light source **1001**.

The repeating, recurrent serpentine pattern is advantageously is disposed substantially beneath the keys. Therefore, the optical fiber **201** emits light at the plurality of locations **210** when beneath the keys (**1006** and **1007**, for example) to only emit light where its needed.

FIG. **11** illustrates a third schematic view of the display **611** and the keypad **613** of FIG. **6** incorporating the optical fiber light emitting apparatus **200** of FIG. **2** in accordance with the present invention. The display **611** and the keypad **613** use the same the optical fiber **201** arranged in a serpentine pattern **1008**. Both the first and the second ends **204** and **205** of the optical fiber **201** advantageously receive light from the same light source **203**. The plurality of locations **210** along the optical fiber **201** that emit light from the optical fiber **201** correspond to the position of the keys (**1100**, for example) such that each key is surrounded by light emitted by the locations **210** along the optical fiber **201**.

FIG. **12** illustrates a fourth schematic view of the display **611** and the keypad **613** of FIG. **6** incorporating the optical fiber light emitting apparatus **200** of FIG. **2** in accordance with the present invention. The display **611** and the keypad **613** use the same the optical fiber **201** arranged in a serpentine pattern **1008**. Only the first end **204** of the optical fiber **201** receives light from the light source **203**. The plurality of locations **210** along the optical fiber **201** that emit light from the optical fiber **201** are disposed both between and beneath the keys to advantageously illuminate the entire keypad area. FIGS. **2–4** and FIGS. **7–12** show the pattern of the optical fiber **201** arranged to be substantially parallel to the predetermined area. The optical fiber **201** has a plurality of bends being substantially parallel to a plane of illumination of the predetermined area.

The present invention provides an optical fiber light emitting apparatus **200** suitable where limited space is available. The optical light emitting apparatus **200** has at least one optical fiber **201** arranged in a repeating, recurrent pattern extending substantially throughout a predetermined area **206**. The optic fiber **201** has a plurality of locations **210** along the length thereof permitting light entering at least a first end **204** of the at least one optical fiber **201** for transmission therein to be selectively emitted by the at least one optical fiber **201** at the plurality of locations **210** for producing substantially uniform illumination substantially throughout the predetermined area **206**. For example, the continuous nonlinear pattern may be arranged to form a spiral **209** or serpentine **1008** pattern. The repeating, recurrent pattern eliminates the space required for the fan-in arrangement of the prior art optical fiber light emitting panels. The optical fiber light emitting apparatus **200** is beneficial for illuminating keypads **613** and displays **611** in electronic devices **600**, such as portable radiotelephones, having limited space available.

I claim:

1. An optical fiber light emitting apparatus comprising:

at least one optical fiber arranged in a continuous, nonlinear pattern along a common path so that the at least one optical fiber extends substantially throughout a predetermined area, the pattern arranged to be substantially parallel to the predetermined area, the at least one optical fiber having a plurality of locations along the length thereof permitting light entering at least a first end of the at least one optical fiber for transmission therein to be selectively emitted by the at least one optical fiber at the plurality of locations for producing substantially uniform illumination substantially throughout the predetermined area.

2. An optical fiber light emitting apparatus according to claim **1** further comprising a carrier forming a support for holding the at least one optical fiber in the continuous, nonlinear pattern.

3. An optical fiber light emitting apparatus according to claim **1** wherein the continuous, nonlinear pattern is a spiral pattern.

4. An optical fiber light emitting apparatus according to claim **1** wherein the continuous, nonlinear pattern is a serpentine pattern.

5. An optical fiber light emitting apparatus according to claim **1** wherein the at least one optical fiber further comprises a plurality of optical fiber strands bundled together.

6. An optical fiber light emitting apparatus according to claim **1** further comprising a reflector for redirecting at least a portion of the light emitted by the plurality of locations.

7. An optical fiber light emitting apparatus according to claim **1** further comprising a diffuser for diffusing at least a portion of the light emitted by the plurality of locations.

8. An optical fiber light emitting apparatus according to claim **1** further comprising a light source for transmitting light into the first end of the at least one optical fiber.

9. A keypad comprising:

a plurality of keys positioned substantially throughout a predetermined area;

at least one optical fiber arranged in a repeating, recurrent pattern so that the at least one optical fiber extends substantially throughout the predetermined area, the pattern arranged to be substantially parallel to the predetermined area, the at least one optical fiber having a plurality of locations along the length thereof permitting light entering at least a first end of the at least one optical fiber for transmission therein to be selectively emitted by the at least one optical fiber at the plurality of locations for producing substantially uniform illumination for the plurality of keys positioned substantially throughout the predetermined area;

a reflector for redirecting at least a portion of the light emitted by the plurality of locations; and

a diffuser for diffusing at least a portion of the light emitted by the plurality of locations.

10. A keypad according to claim **9** wherein the repeating, recurrent pattern is disposed substantially between the keys.

11. A keypad according to claim **9** wherein repeating, recurrent pattern is disposed substantially beneath the keys.

12. A keypad according to claim **9** wherein the plurality of locations correspond to the position of the keys.

13. A display comprising:

positions for information to be presented substantially throughout a predetermined area;

at least one optical fiber arranged in a repeating, recurrent pattern so that the at least one optical fiber extends substantially throughout the predetermined area, the pattern arranged to be substantially parallel to the predetermined area, the at least one optical fiber having a plurality of locations along the length thereof permitting light entering at least a first end of the at least one optical fiber for transmission therein to be selectively emitted by the at least one optical fiber at the plurality of locations for producing substantially uniform illumination for the positions for information substantially throughout the predetermined area;

a reflector for redirecting at least a portion of the light emitted by the plurality of locations; and

a diffuser for diffusing at least a portion of the light emitted by the plurality of locations.

14. A display according to claim **13** wherein the plurality of locations correspond to the positions for the information.

15. An electronic device comprising:

a display having positions for presenting information substantially throughout a first predetermined area;

a keypad having a plurality of keys positioned substantially throughout a second predetermined area; and

at least one optical fiber arranged in a repeating, recurrent pattern so that the at least one optical fiber extends substantially throughout at least one of the first and second predetermined areas, the pattern arranged to be substantially parallel to the at least one of the first and second predetermined areas, the at least one optical fiber having a plurality of locations along the length thereof permitting light entering at least a first end of the at least one optical fiber for transmission therein to be selectively emitted by the at least one optical fiber at the plurality of locations for producing substantially uniform illumination for at least one of the positions for presenting the information and the plurality of keys positioned substantially throughout the first and second predetermined areas, respectively.

16. A communication unit comprising:

a receiver for receiving signals representing information;

a display having information positions for presenting the information substantially throughout a predetermined area; and

at least one optical fiber arranged in a repeating, recurrent pattern so that the at least one optical fiber extends substantially throughout the predetermined area, the pattern arranged to be substantially parallel to the predetermined area, the at least one optical fiber having a plurality of locations along the length thereof permitting light entering at least a first end of the at least one optical fiber for transmission therein to be selectively emitted by the at least one optical fiber at the plurality of locations for producing substantially uniform illumination for the information positions substantially throughout the predetermined area.

17. A communication unit comprising:

a transmitter for transmitting signals representing information;

a plurality of keys positioned substantially throughout a predetermined area for inputting the information; and

at least one optical fiber arranged in a repeating, recurrent pattern so that the at least one optical fiber extends substantially throughout the predetermined area, the pattern arranged to be substantially parallel to the predetermined area, the at least one optical fiber having a plurality of locations along the length thereof permitting light entering at least a first end of the at least one optical fiber for transmission therein to be selectively emitted by the at least one optical fiber at the plurality of locations for producing substantially uniform illumination for the plurality of keys positioned substantially throughout the predetermined area.

18. A communication unit comprising:

a receiver for receiving signals representing received information;

a display having information positions for presenting the received information substantially throughout a first predetermined area;

a transmitter for transmitting signals representing transmitted information;

a plurality of keys positioned substantially throughout a second predetermined area for inputting the transmitted information; and

at least one optical fiber arranged in a repeating, recurrent pattern so that the at least one optical fiber extends substantially throughout at least one of the first and second predetermined areas, the pattern arranged to be substantially parallel to the at least one of the first and second predetermined areas, the at least one optical fiber having a plurality of locations along the length thereof permitting light entering at least a first end of the at least one optical fiber for transmission therein to be selectively emitted by the at least one optical fiber at the plurality of locations for producing substantially uniform illumination for at least one of the information positions and plurality of keys positioned substantially throughout the first and second predetermined areas, respectively.

19. An optical fiber light emitting apparatus comprising:

at least one optical fiber for transmitting light therein, the at least one optical fiber having at least one light receiving input for receiving the light from a light source, the at least one optical fiber having a plurality of light emitting outputs for selectively emitting the light transmitted within the at least one optical fiber, the at least one optical fiber arranged in a continuous, nonlinear pattern along a common path so that the at least one optical fiber extends substantially throughout a predetermined area to provide substantially uniform illumination of the predetermined area, the at least one optical fiber having a plurality of bends being substantially parallel to a plane of illumination of the predetermined area.

20. An optical fiber light emitting apparatus according to claim 19 wherein the pattern formed by the arrangement of the at least one optical fiber is a repeating recurrent pattern.

21. An optical fiber light emitting apparatus according to claim 19 wherein the pattern formed by the arrangement of the at least one optical fiber is a spiral pattern.

22. An optical fiber light emitting apparatus according to claim 19 wherein the pattern formed by the arrangement of the at least one optical fiber is a serpentine pattern.

23. An optical fiber light emitting apparatus comprising:

only one optical fiber for transmitting light therein, the only one optical fiber having a light receiving input for receiving the light from a light source, the only one optical fiber having a plurality of light emitting outputs for selectively emitting the light transmitted within the only one optical fiber, the only one optical fiber arranged in a continuous, nonlinear pattern along a common path so that the only one optical fiber extends substantially throughout a predetermined area substantially parallel to the pattern to provide substantially uniform illumination of the predetermined area.

24. An optical fiber light emitting apparatus according to claim 23 wherein the pattern formed by the arrangement of the one optical fiber further comprises a plurality of bends being substantially parallel to the plane of illumination of the predetermined area.

25. An optical fiber light emitting apparatus according to claim 23 wherein the pattern formed by the arrangement of the one optical fiber is a repeating recurrent pattern.

26. An optical fiber light emitting apparatus according to claim 23 wherein the pattern formed by the arrangement of the one optical fiber is a spiral pattern.

27. An optical fiber light emitting apparatus according to claim 23 wherein the pattern formed by the arrangement of the one optical fiber is a serpentine pattern.

28. An optical fiber light emitting apparatus comprising:

at least one optical fiber arranged in a continuous, nonlinear pattern along a common path, repeatedly turning

back in a direction essentially opposite to a former course, so that the at least one optical fiber extends substantially throughout a predetermined area, the pattern arranged to be substantially parallel to the predetermined area, the at least one optical fiber having a plurality of locations along the length thereof permitting light, entering at least a first end of the at least one optical fiber for transmission therein, to be selectively emitted by the at least one optical fiber at the plurality of locations for producing substantially uniform illumination substantially throughout the predetermined area.

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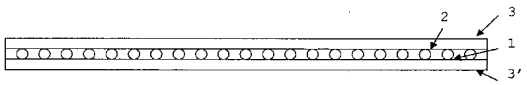
Die folgenden Angaben sind den vom Anmelder eingereichten Unterlagen entnommen

(54) Bezeichnung: **Flächiges Leuchtelement**

(57) Hauptanspruch: Flächiges Leuchtelement in Form eines Verbundsystems aus mindestens zwei unabhängig voneinander aus mindestens einem lichtdurchlässigen oder transluzenten Polymer bestehenden Deckschichten, zwischen denen ein lichtleitende Fasern enthaltendes Gewebe angeordnet ist, wobei die lichtleitenden Fasern an mindestens einem Ende an eine Lichtquelle optisch ankoppelbar sind.



Beschreibung

[0001] Die Erfindung betrifft ein flächiges Leuchtelement in Form eines Verbundsystems, das aus zwei Deckschichten besteht, zwischen denen ein Gewebe aus lichtleitenden Fasern angeordnet ist. Die Deckschichten bestehen dabei aus einem lichtdurchlässigen oder transluzenten Polymer. Durch Einkopplung von Licht an den Faserenden mittels einer Lichtquelle wird ein illuminierender Effekt des Leuchtelementes und damit verbunden eine Beleuchtung der Umgebung ermöglicht. Der Einsatz von Lichtleitfasern findet im Bereich der Lichtinstallation eine immer breitere Verwendung. Das Prinzip beruht darauf, dass mittels eines Projektors Licht in entsprechende Glas- oder Kunststofffasern über deren Kopfende eingekoppelt wird, wobei diese so beschaffen sind, dass das Licht in den umgebenden Raum abgestrahlt werden kann.

[0002] Aus der EP 1 291 160 A2 ist eine derartige Faser bekannt, wobei hier die Faser zu deren Schutz vor mechanischen Belastungen mit einer Ummantelung aus einem Kunststoff versehen ist. Nachteil dieser Technik ist allerdings, dass die Herstellung derartiger Fasern sehr aufwendig ist und eine Verarbeitung zu großflächigen Leuchtelementen aufgrund der geringen Flexibilität nur bedingt möglich ist.

[0003] Es besteht nach wie vor ein Bedarf nach flächigen Leuchtelementen, die stoffähnliche Eigenschaften aufweisen, sodass diese vielseitig verarbeitbar und einsetzbar sind.

[0004] Aufgabe der vorliegenden Erfindung war es daher, ein flächiges Leuchtelementen bereitzustellen, das zum einen eine hohe Stabilität gegenüber mechanischen Belastungen aufweist, gleichzeitig aber auch stoffähnliche Eigenschaften zur besseren Verarbeitbarkeit beibehält.

[0005] Diese Aufgabe wird durch das flächige Leuchtelement mit den Merkmalen des Anspruchs 1 gelöst.

[0006] Erfindungsgemäß wird ein flächiges Leuchtelementen in Form eines Verbundsystems bereitgestellt, das aus mindestens zwei Deckschichten besteht, zwischen denen ein lichtleitende Fasern enthaltendes Gewebe angeordnet ist. Die Deckschichten sind dabei unabhängig voneinander aus mindestens einem lichtdurchlässigen oder transluzenten Polymer gebildet.

[0007] Der illuminierende Effekt wird durch optische Einkopplung von Licht aus einer Lichtquelle an mindestens einem Ende der lichtleitenden Fasern ermöglicht.

[0008] Besonderer Vorteil des erfindungsgemäßen Leuchtelementes ist es, dass durch die Anordnung in Form eines Verbundsystems die lichtleitenden Fasern effizient vor mechanischen Belastungen geschützt werden, da diese in die Deckschichten eingebettet sind. Ein weiter Vorteil beruht darauf, dass die Fasern in einem Gewebe eingewoben werden, wodurch eine sehr regelmäßige parallele Anordnung der Lichtleitfasern ermöglicht wird, eine zusätzliche Stabilisierung erreicht wird und eine einfache Herstellung möglich wird.

[0009] In einer bevorzugten Variante bestehen die lichtleitenden Fasern aus Glas und/oder Polymethylmethacrylat. Es können aber auch andere Materialien eingesetzt werden, mit denen die Herstellung von lichtleitenden Fasern ermöglicht wird.

[0010] Hinsichtlich der Deckschichten ist der Einsatz beliebiger transluzenter oder lichtdurchlässiger Polymere möglich. Hierzu zählen beispielsweise Tetrafluorethylen-Polymer, Ethylen-Tetrafluorethylen-Copolymer, Copolymeren aus Tetrafluorethylen und perfluorierten Comonomeren, Tetrafluorethylen-Hexafluorpropylen-Copolymer, Polyvinylidenfluorid, Tetrafluorethylen-Hexafluorpropylen-Polyvinylenidenfluorid-Copolymer, Polyethylen, Polyvinylchlorid und Polyethylenterephthalat.

[0011] Die Deckschichten liegen dabei vorzugsweise in Form von Folien vor, was das Einlaminieren des lichtleitenden Gewebes zwischen den Deckschichten ermöglicht.

[0012] In einer bevorzugten Variante ist auf der Deckschicht mindestens eine Schicht zur Oberflächenvergütung aufgebracht. Diese Schicht zur Oberflächenvergütung besteht vorzugsweise zumindest teilweise aus Polysi-lazan.

[0013] Eine besonders bevorzugte Variante sieht vor, dass die Deckschichten aus einem schwer entflammbaren oder selbstverlöschenden Material bestehen. Hierzu zählen beispielsweise Materialien, die die DIN 4102, die das Brandverhalten von Baustoffen und Bauteilen betrifft, erfüllen. Insbesondere sollten diese die Klassifizierung B1 oder S4 aus der genannten DIN-Norm erfüllen.

[0014] Besonderer Vorteil des Leuchtelementes ist es, dass dieses die Eigenschaften einer Folie aufweist, was vielfältige Anwendungsbereiche eröffnet.

[0015] Eine weitere bevorzugte Variante des erfindungsgemäßen Leuchtelementes sieht vor, dass die erste Deckschicht Reflektoreigenschaften und die zweite Deckschicht Diffusoreigenschaften besitzt. Dies ermöglicht verbesserte optische Eigenschaften durch die Verwendung einer ersten transparenten Deckschicht und einer z.B. milchig weißen zweiten Deckschicht. Die zweite Deckschicht wirkt dabei als

Reflektor, die erste Deckschicht als Diffusor. Ebenso ist in einer weiteren Variante vorgesehen, dass sowohl die erste als auch die zweite Deckschicht Diffusoreigenschaften besitzen.

[0016] In einer bevorzugten Variante werden die lichtleitenden Fasern mit Hilfe von Kettenfäden zu einem Gewebe verwoben. Das Material dieser Kettenfäden kann dabei beispielsweise aus einem Polyester bestehen. Ein derartiges Gewebe ist besonders vorteilhaft, da so die lichtleitenden Fasern, wie ein Stoff zu einem Gewebe, verarbeitet werden können.

[0017] Neben dem Laminieren des Gewebes mit den Deckschichten kann zusätzlich auch ein Adhäsionsmittel zwischen dem Gewebe und den Deckschichten zumindest bereichsweise aufgetragen sein. Dieses ist dabei vorzugsweise ausgewählt aus Klebstoffen auf Acrylbasis oder Zwei-Komponenten-Polyurethan-Klebstoffen.

[0018] Für eine effiziente Einkopplung von Licht in die lichtleitenden Fasern werden diese vorzugsweise an mindestens einem Ende in einem optischen Verbinder zusammen geführt, der wiederum an eine beliebige Lichtquelle ankoppelbar ist. Eine derartige Ankopplung kann beispielsweise über optische Fasern, z.B. LCPOZ (engl. large-core plastic optical fiber), einen Stab und/oder ein Faserbündel aus Polymethylmethacrylat erfolgen.

[0019] Eine weitere bevorzugte Variante sieht vor, dass die lichtleitenden Fasern an dem nicht für die Lichteinkopplung verwendeten Ende der Fasern so ausgebildet sind, dass eine Totalreflexion von Licht an diesem zweiten Ende ermöglicht wird. Dies kann beispielsweise durch eine Verspiegelung dieser Enden erfolgen.

[0020] Besonderer Vorteil des erfindungsgemäßen Leuchtelementes ist es, dass auf diese Weise großflächige Leuchtelemente herstellbar sind. Aufgrund der Tatsache, dass die lichtleitenden Fasern in Form von Endlosfasern erzeugt werden können, können Leuchtelemente beliebiger Länge hergestellt werden. Die Anpassung an die gewünschte Länge erfolgt dann einfach durch eine Trennung dieser Endlosfasern in Teilstücke. Beispielsweise können so Leuchtelemente mit einer Länge mit 20 bis 400 m hergestellt werden. Auch hinsichtlich der Breite gibt es grundsätzlich keine Limitierungen, sodass Leuchtelemente beispielsweise mit einer Breite von 1 bis 300 cm möglich sind.

[0021] Trotz dieser großflächigen Ausmaße des Leuchtelementes war es besonders überraschend, dass hier besonders geringe Dicken möglich sind, ohne die Stabilität des Leuchtelementes gegenüber mechanischen Beanspruchungen zu gefährden. So kann die Dicke in einem Bereich von 15 µm bis 2 mm, besonders bevorzugt im Bereich von 25 bis 500 µm liegen.

[0022] Das erfindungsgemäße Leuchtelement stellt einen festen Verbund dar, der aus drei Schichten besteht und im Wesentlichen die Folieneigenschaften, die durch die Deckschichten vorgegeben sind, beibehält. Es handelt sich somit um ein Verbundsystem, das einen hervorragenden Schutz für die empfindlichen, nicht witterungsbeständigen und mechanisch nicht belastbaren Lichtleitfasern darstellt. Anhand der nachfolgenden Figuren soll der erfindungsgemäße Gegenstand näher beschrieben werden.

[0023] Fig. 1 zeigt ein erfindungsgemäßes Leuchtelement, das ein Gewebe **1** mit lichtleitenden Fasern **2** aufweist. Dieses Gewebe ist sandwichartig in eine erste Deckschicht **3** und eine zweite Deckschicht **3'** eingebettet.

[0024] Fig. 2 zeigt einen erfindungsgemäßes Leuchtelement in Form eines großflächigen Verbundes. Für die Herstellung kann man sich hier die Vorteile der industriellen Folienproduktion zu Nutze machen, wobei das textile Gewebe wie eine Folie behandelt wird. Dies wird dadurch ermöglicht, dass die beiden Faserenden, beidseitig oder auch nur einseitig, entsprechend fixiert werden. Dies geschieht durch das Aufbringen eines Schutzklebebandes **4**, hier beim Weben des Textils, sowie durch die Einbringung von gemäß dieser Figur vertikal verlaufenden Kettenfäden **5**. Dies erlaubt die Verbindung der Techniken der industriellen Folien- und Textilverarbeitung.

[0025] In Fig. 3 wird schematisch die Herstellung der erfindungsgemäßen Leuchtelemente dargestellt. Die Deckschichten **3** und **3'** werden über Rollen von oben und unten zugeführt, wie es bei einem Laminierprozess für Folien üblich ist. An den Stationen **6** kann eine Beschichtung der Deckschichten **3** und **3'** mit einem Adhäsionsmittel auf den dem Gewebe zugewandten Seiten der Déckschichten versehen werden. Zwischen den Deckschichten **3** und **3'** wird dann das Gewebe **1** über eine weitere Rolle mittig zugeführt, wodurch dann das erfindungsgemäße Leuchtelement erhalten wird. Wichtig bei der Herstellung sind dabei die Kontrolle von Druck und Temperatur auf das Leuchtelement, da dieses eine begrenzte Druck- und Temperaturbeständigkeit bei der Fertigung aufweist, solange es noch nicht durch das Verbundsystem geschützt ist.

Schutzansprüche

1. Flächiges Leuchtelement in Form eines Verbundsystems aus mindestens zwei unabhängig voneinander aus mindestens einem lichtdurchlässigen oder transluzenten Polymer bestehenden Deckschichten, zwischen denen ein lichtleitende Fasern enthaltendes Gewebe angeordnet ist, wobei die licht-

leitenden Fasern an mindestens einem Ende an eine Lichtquelle optisch ankoppelbar sind.

2. Leuchtelement nach Anspruch 1, dadurch gekennzeichnet, dass die lichtleitenden Fasern aus Glas und/oder Polymethylmethacrylat bestehen.

3. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass das transluzente oder lichtdurchlässige Polymer ausgewählt ist aus der Gruppe bestehend aus Tetrafluorethylen-Polymer, Ethylen-Tetrafluorethylen-Copolymer, Copolymeren aus Tetrafluorethylen und perfluorierten Comonomeren, Tetrafluorethylen-Hexafluorpropylen-Copolymer, Polyvinylidenfluorid, Tetrafluorethylen-Hexafluorpropylen-Polyvinylenidenfluorid-Copolymer, Polyethylen, Polyvinylchlorid und Polyethylenterephthalat.

4. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass die Deckschichten in Form von Folien vorliegen.

5. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass auf der Deckschicht mindestens eine Schicht zur Oberflächenvergütung aufgebracht ist.

6. Leuchtelement nach dem vorhergehenden Anspruch, dadurch gekennzeichnet, dass die Schicht zur Oberflächenvergütung zumindest teilweise aus Polysilazan besteht.

7. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass die Deckschichten aus einem schwer entflammbaren oder selbst verlöschenden Material bestehen.

8. Leuchtelement nach dem vorhergehenden Anspruch, dadurch gekennzeichnet, dass das schwer entflammbare oder selbst verlöschende Material die DIN 4102 erfüllt.

9. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass das Leuchtelement die Eigenschaften einer Folie aufweist.

10. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass die erste Deckschicht Reflektoreigenschaften und die zweite Deckschicht Diffusoreigenschaften besitzt.

11. Leuchtelement nach einem der Ansprüche 1 bis 9, dadurch gekennzeichnet, dass die erste und die zweite Deckschicht Diffusoreigenschaften besitzen.

12. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass die lichtleitenden Fasern mit Hilfe von Kettenfäden verwoben sind.

13. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass die Kettenfäden aus einem Polyester bestehen.

14. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass zwischen dem Gewebe und den Deckschichten zumindest bereichsweise ein Adhäsionsmittel aufgetragen ist.

15. Leuchtelement nach dem vorhergehenden Anspruch, dadurch gekennzeichnet, dass das Adhäsionsmittel ein Klebstoff auf Acrylbasis oder eine Zwei-Komponenten-Polyurethan-Klebstoff ist.

16. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass die lichtleitenden Fasern an mindestens einem Ende in einem optischen Verbinder zusammengeführt sind, der an eine Lichtquelle ankoppelbar ist.

17. Leuchtelement nach dem vorhergehenden Anspruch, dadurch gekennzeichnet, dass die Ankopplung über eine optische Faser, z.B. LCPOF, einen Stab und/oder ein Faserbündel aus Polymethylmethacrylat erfolgt.

18. Leuchtelement nach einem der vorhergehenden Anspruch, dadurch gekennzeichnet, dass die lichtleitenden Fasern an dem nicht zur Lichteinkopplung verwendeten Ende so ausgebildet sind, dass eine Totalreflexion von Licht ermöglicht wird.

19. Leuchtelement nach dem vorhergehenden Anspruch, dadurch gekennzeichnet, dass die lichtleitenden Fasern an dem nicht zur Lichteinkopplung verwendeten Ende verspiegelt sind.

20. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass das Leuchtelement eine Dicke von 15 µm bis 2 mm, insbesondere 25 bis 500 µm aufweist.

21. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass das Leuchtelement eine Breite von 1 bis 300 cm, insbesondere von 50 bis 300 cm aufweist.

22. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass das Leuchtelement eine Länge von 20 bis 400 m aufweist.

23. Leuchtelement nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, dass das Leuchtelement als Endlosfaser erzeugt und anschlie-

ßend in Teilstücke zertrennt wird.

Es folgen 2 Blatt Zeichnungen

Anhängende Zeichnungen

Fig. 1

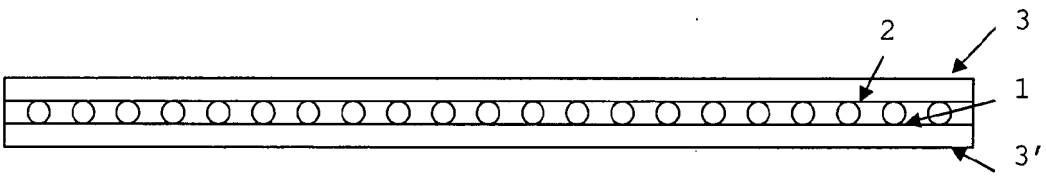


Fig. 2

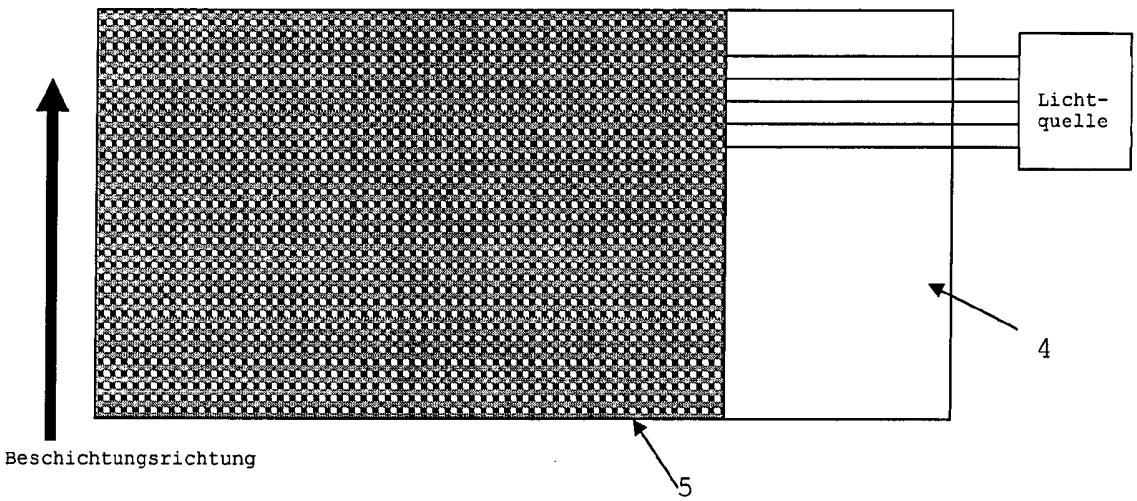
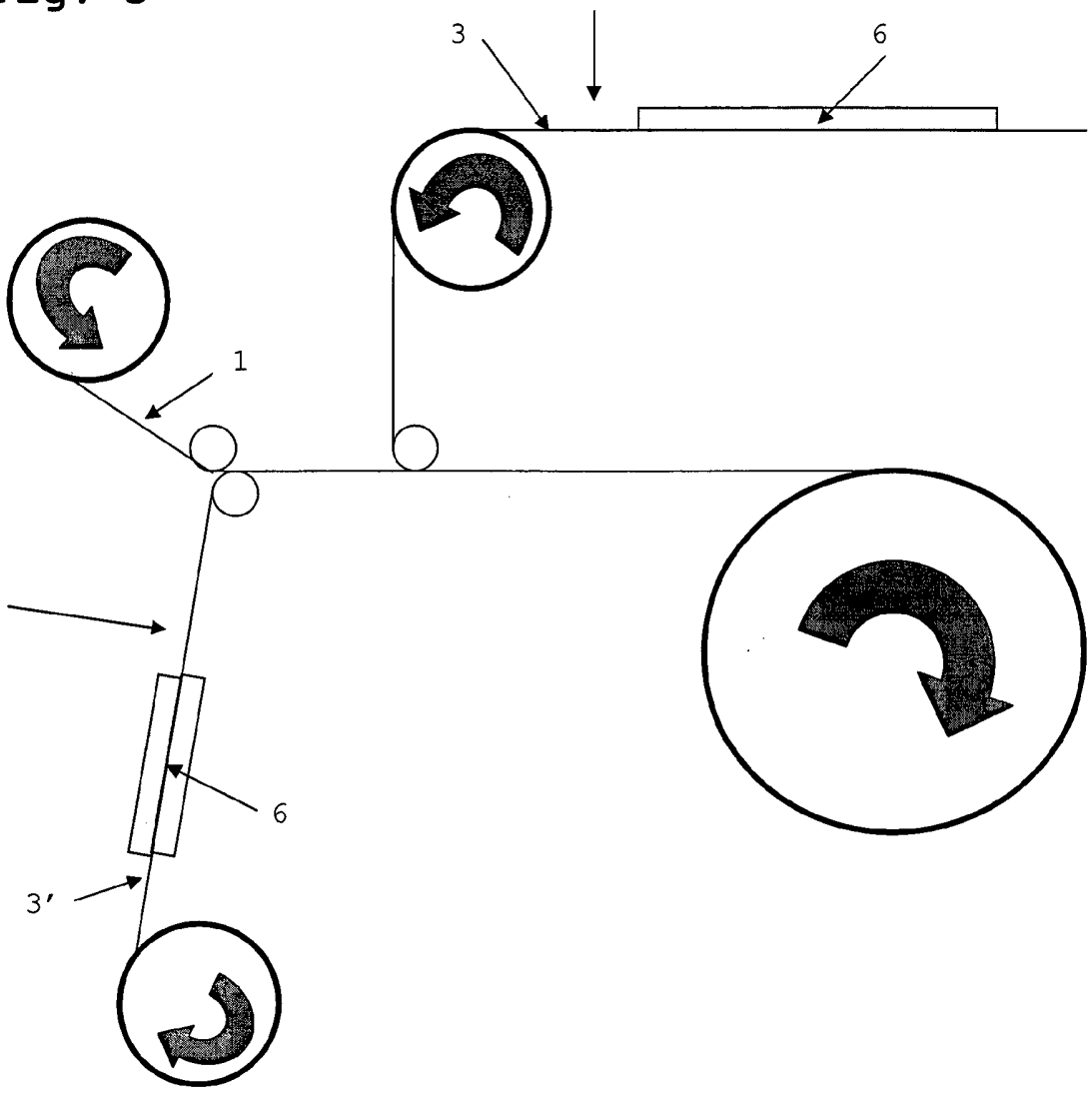


Fig. 3



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(12) **United States Patent**
Weiss

(10) **Patent No.: US 7,329,857 B1**
(45) **Date of Patent: *Feb. 12, 2008**

(54) **SIDE-EMITTING FIBER OPTIC POSITION SENSOR**

(75) Inventor: **Jonathan D. Weiss**, Albuquerque, NM (US)

(73) Assignee: **Sandia Corporation**, Albuquerque, NM (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 74 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **11/389,660**

(22) Filed: **Mar. 24, 2006**

Related U.S. Application Data

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(51) **Int. Cl.**
G01J 1/04 (2006.01)
G01J 1/42 (2006.01)
G01J 5/08 (2006.01)
G02B 6/00 (2006.01)

(52) **U.S. Cl.** **250/227.11**; 385/12

(58) **Field of Classification Search** ..... 250/227.11, 250/483.1, 484.2, 485.1, 361 R; 356/73.1, 356/614, 615, 622; 385/12–14
See application file for complete search history.

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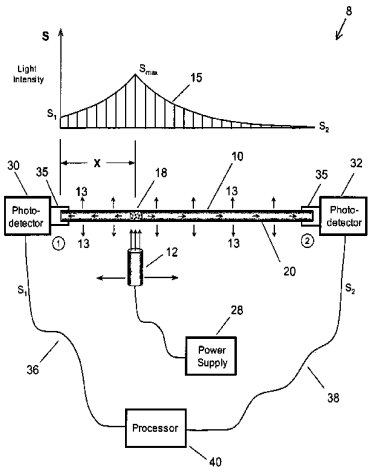
Primary Examiner—Georgia Epps
Assistant Examiner—Suezu Ellis
(74) *Attorney, Agent, or Firm*—Robert D. Watson

(57) **ABSTRACT**

A side-emitting fiber optic position sensor and method of determining an unknown position of an object by using the sensor. In one embodiment, a concentrated beam of light source illuminates the side of a side-emitting fiber optic at an unknown axial position along the fiber's length. Some of this side-illuminated light is in-scattered into the fiber and captured. As the captured light is guided down the fiber, its intensity decreases due to loss from side-emission away from the fiber and from bulk absorption within the fiber. By measuring the intensity of light emitted from one (or both) ends of the fiber with a photodetector(s), the axial position of the light source is determined by comparing the photodetector's signal to a calibrated response curve, look-up table, or by using a mathematical model. Alternatively, the side-emitting fiber is illuminated at one end, while a photodetector measures the intensity of light emitted from the side of the fiber, at an unknown position. As the photodetector moves further away from the illuminated end, the detector's signal strength decreases due to loss from side-emission and/or bulk absorption. As before, the detector's signal is correlated to a unique position along the fiber.

14 Claims, 11 Drawing Sheets



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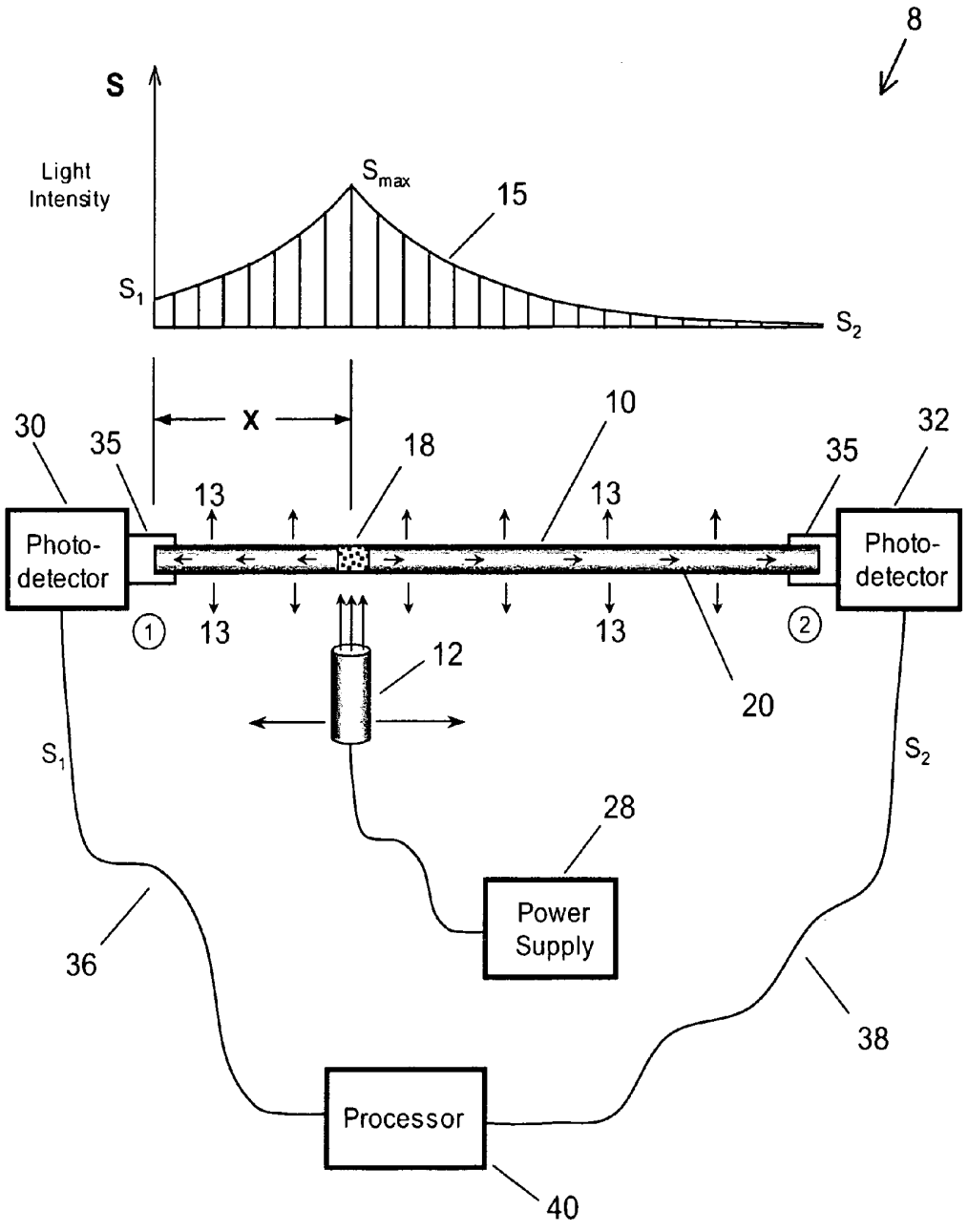
8
S
Light Intensity
S_{max}
15
S_1
S_2
X
30
35
18
10
13
13
32
35
Photo-detector
Photo-detector
1
13
13
2
12
20
S_1
S_2
28
Power Supply
36
38
Processor
40

Fig. 1

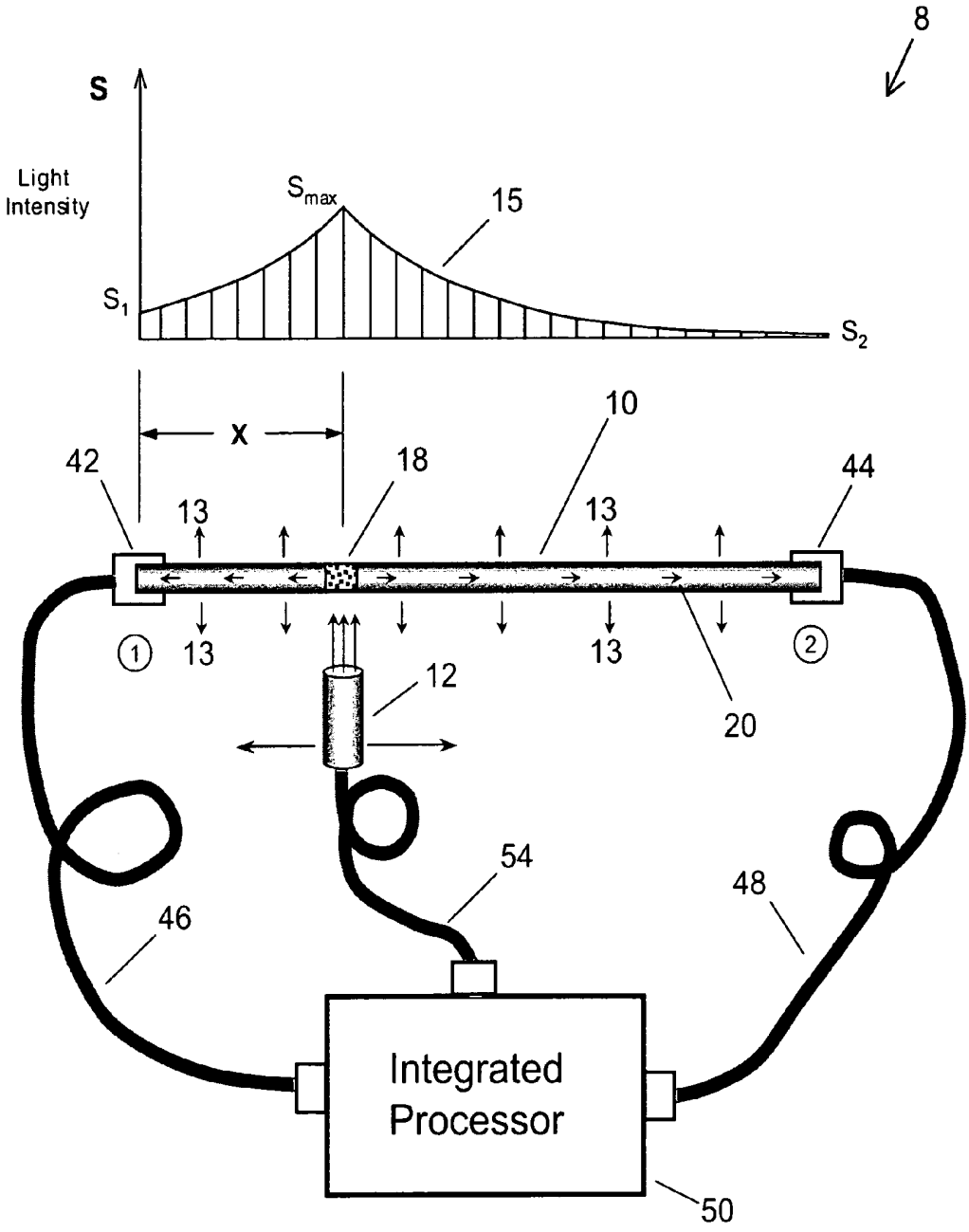
8
S
Light Intensity
S_{max}
15
S_1
S_2
X
10
42
18
44
13
13
1
13
13
2
12
20
54
48
46
Integrated Processor
50

Fig. 2

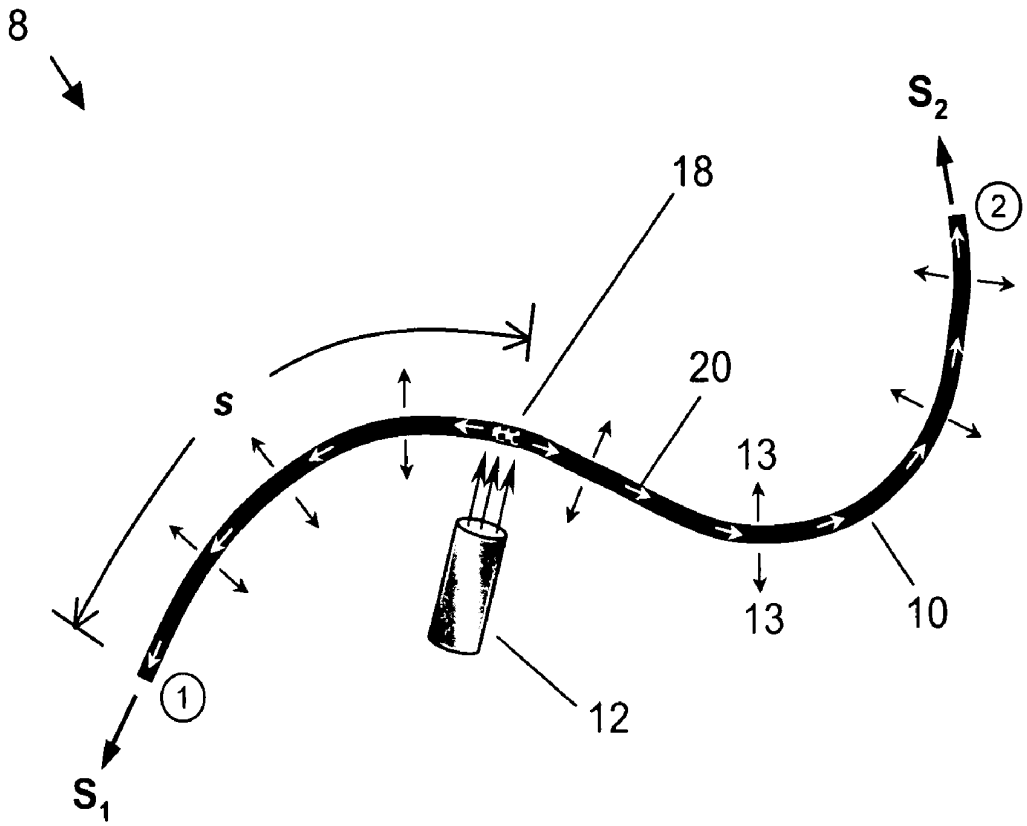

Fig. 3

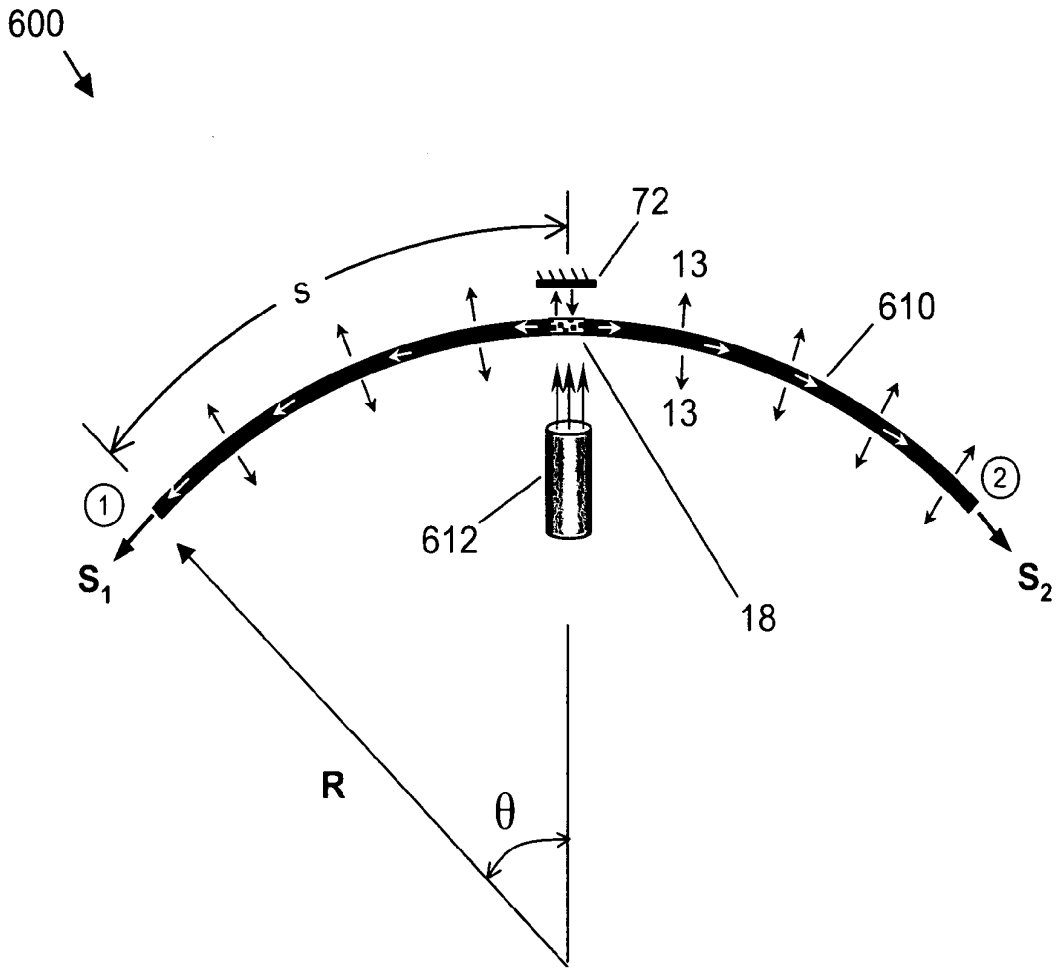

Fig. 4

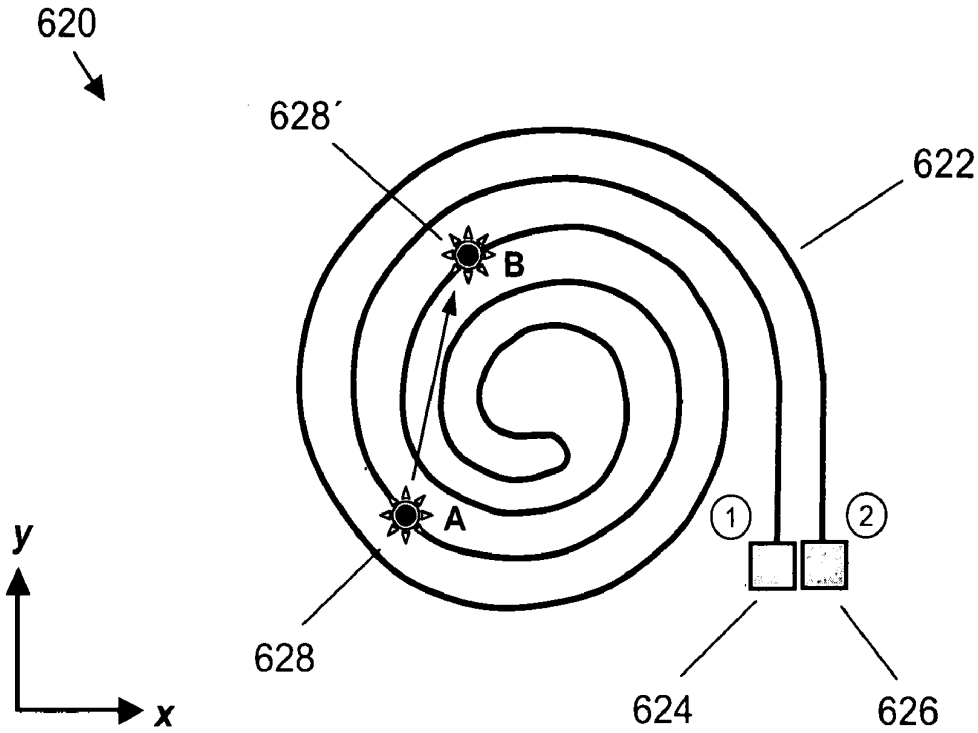

Fig. 5

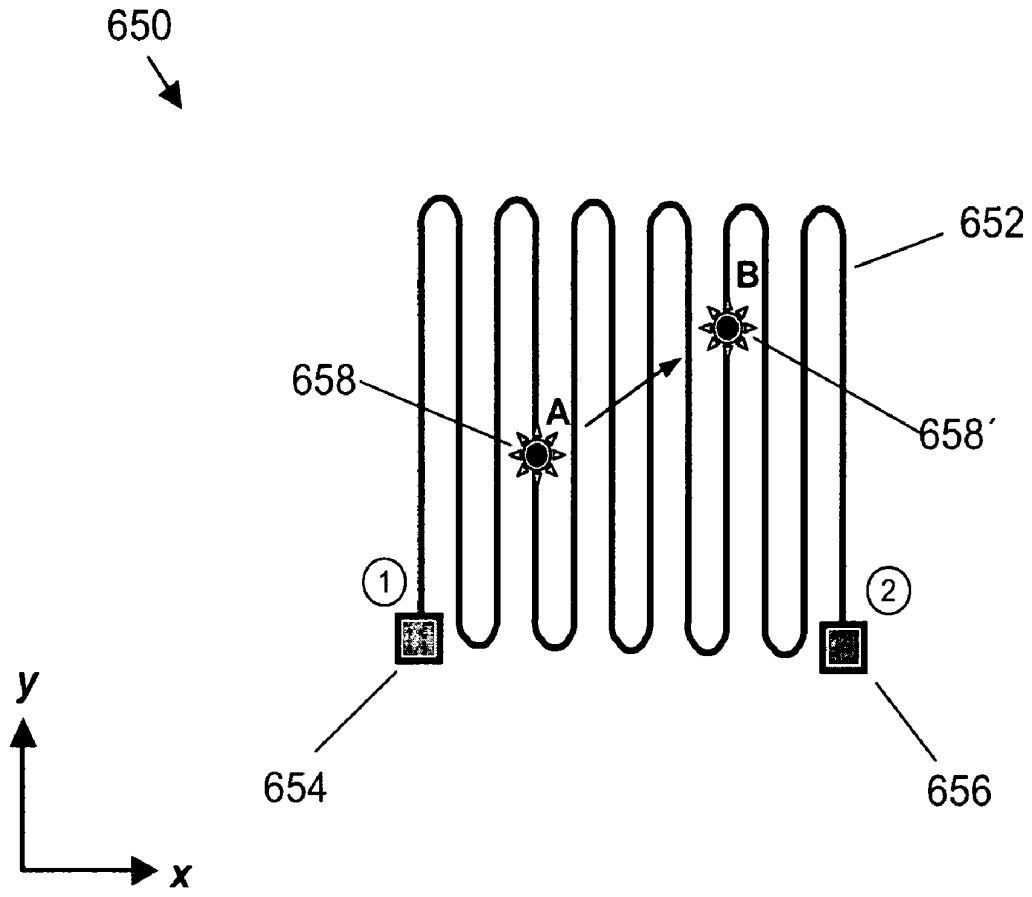

Fig. 6

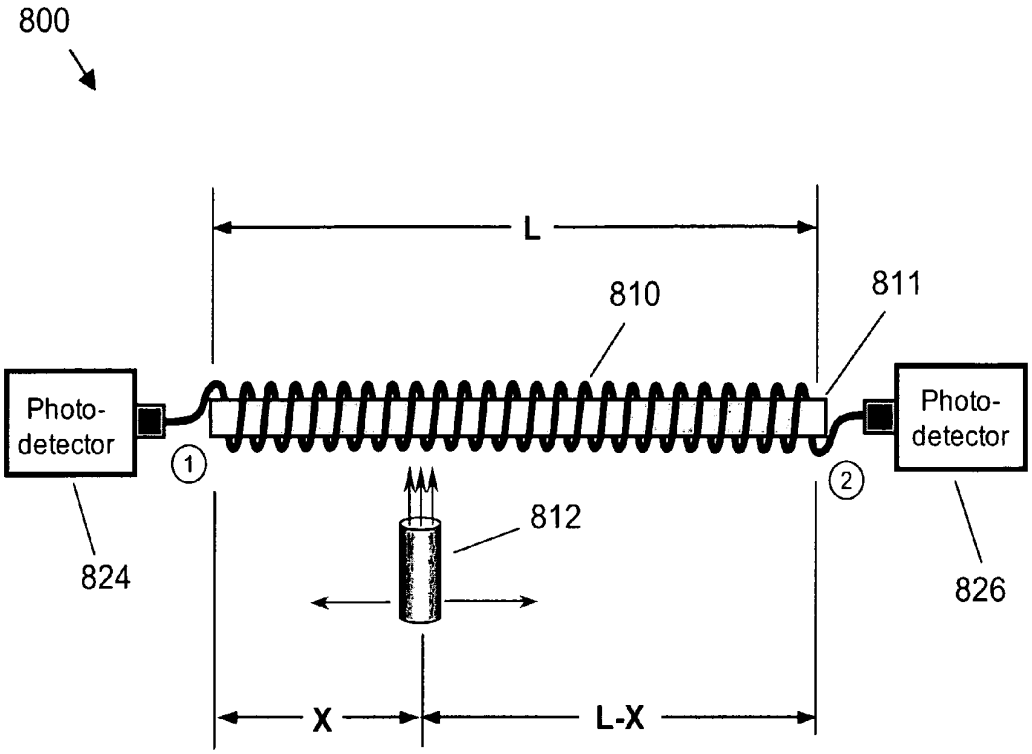
800
L
810
811
Photo-
detector
Photo-
detector
1
2
812
824
826
X
L-X

Fig. 7

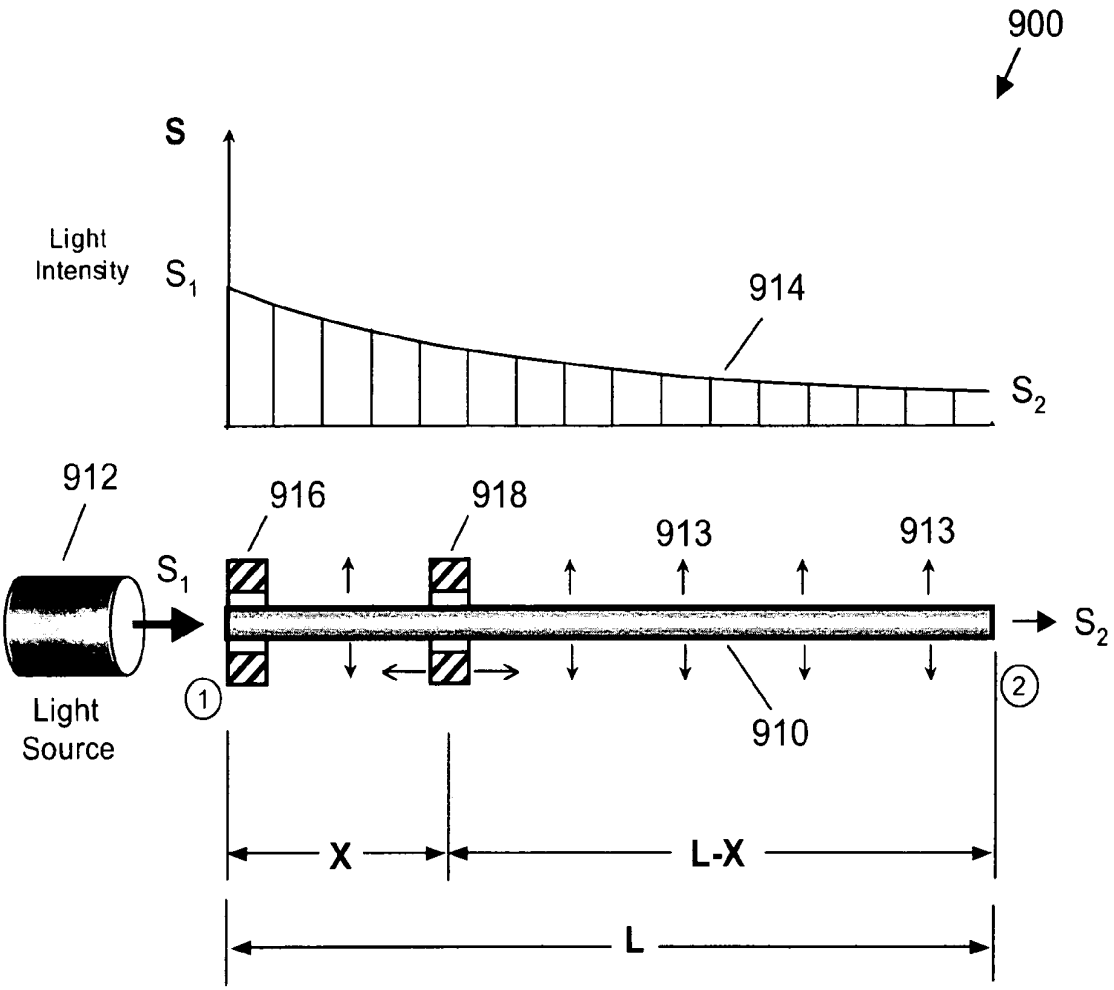
900
S
Light Intensity
S_1
914
S_2
912
916
918
913
913
S_1
S_2
Light Source
1
2
910
X
L-X
L

Fig. 8

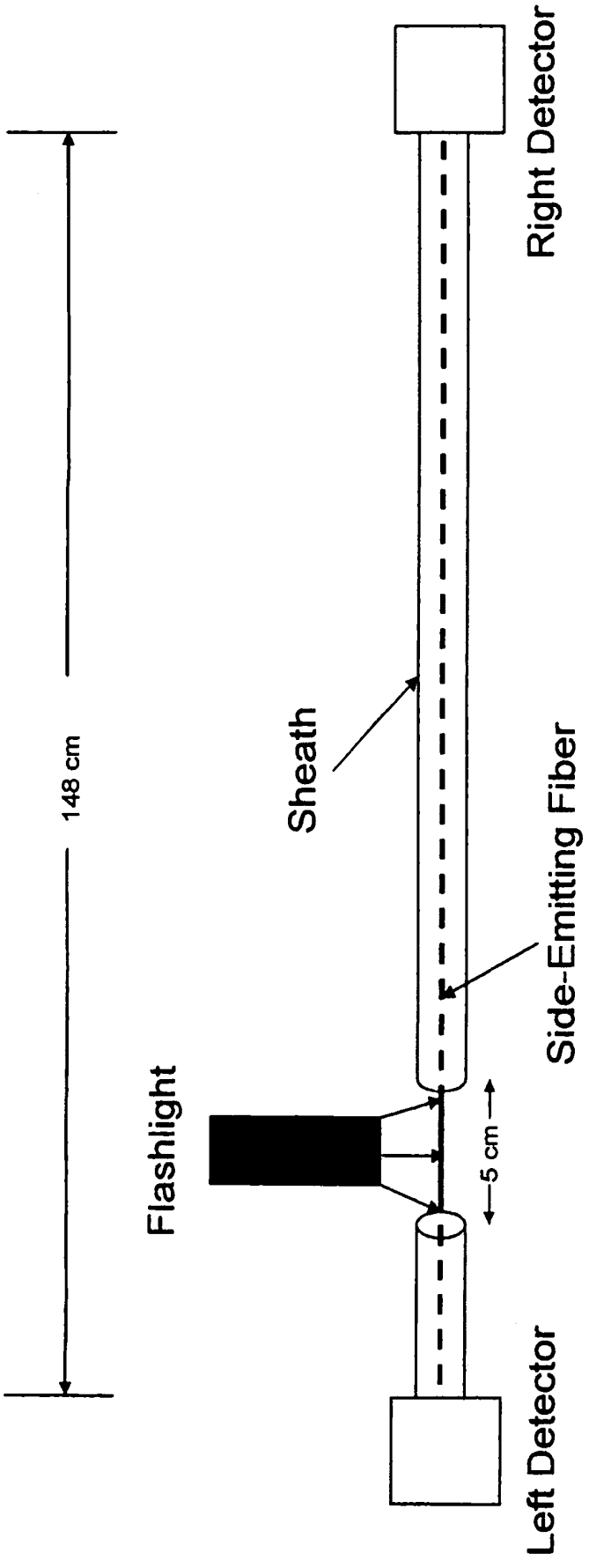
148 cm
Sheath
Right Detector
Side-Emitting Fiber
Flashlight
5 cm
Left Detector

Fig. 9

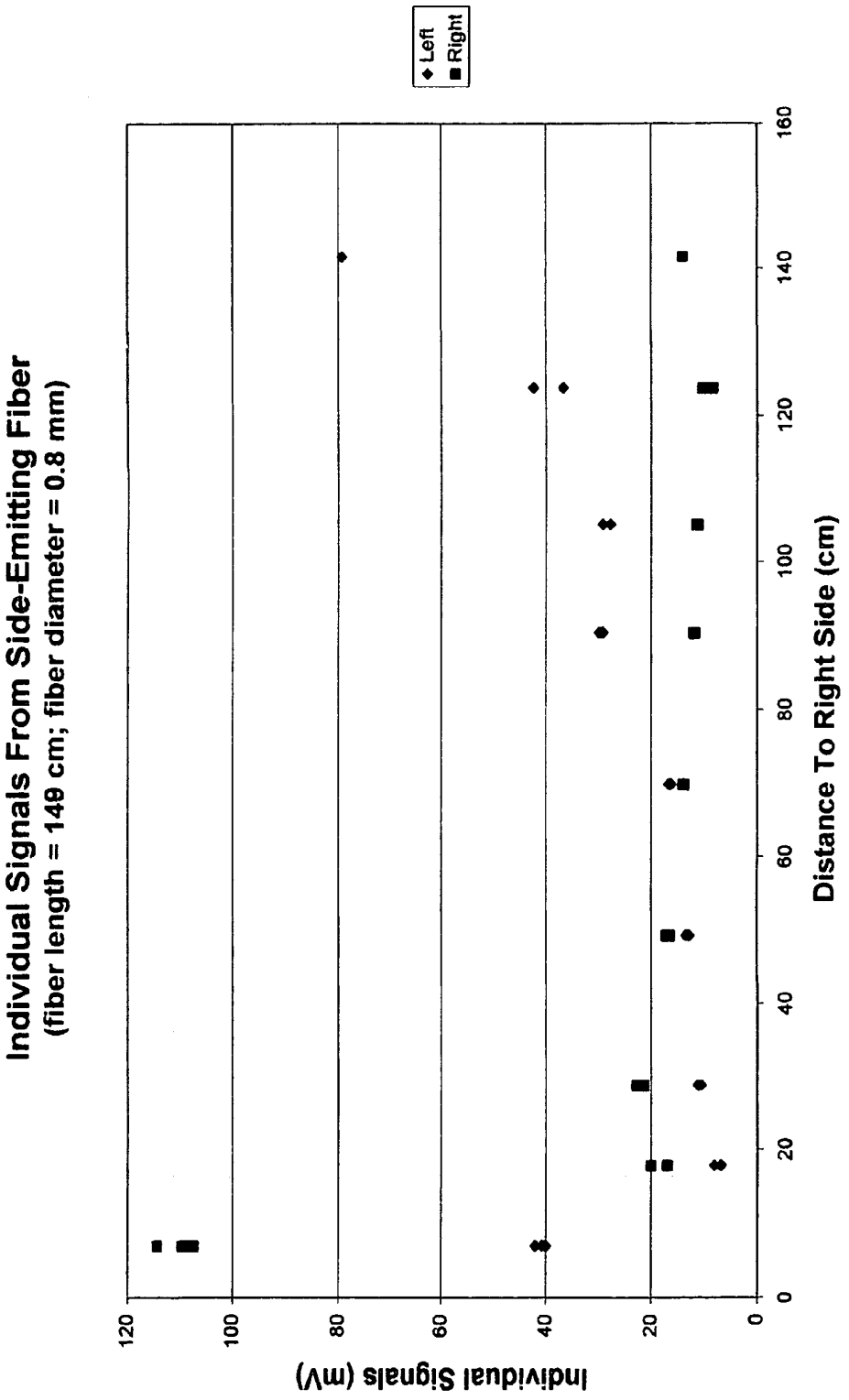
Individual Signals From Side-Emitting Fiber
(fiber length = 149 cm; fiber diameter = 0.8 mm)
Left
Right
Individual Signals (mV)
0
20
40
60
80
100
120
Distance To Right Side (cm)
0
20
40
60
80
100
120
140
160

Fig. 10

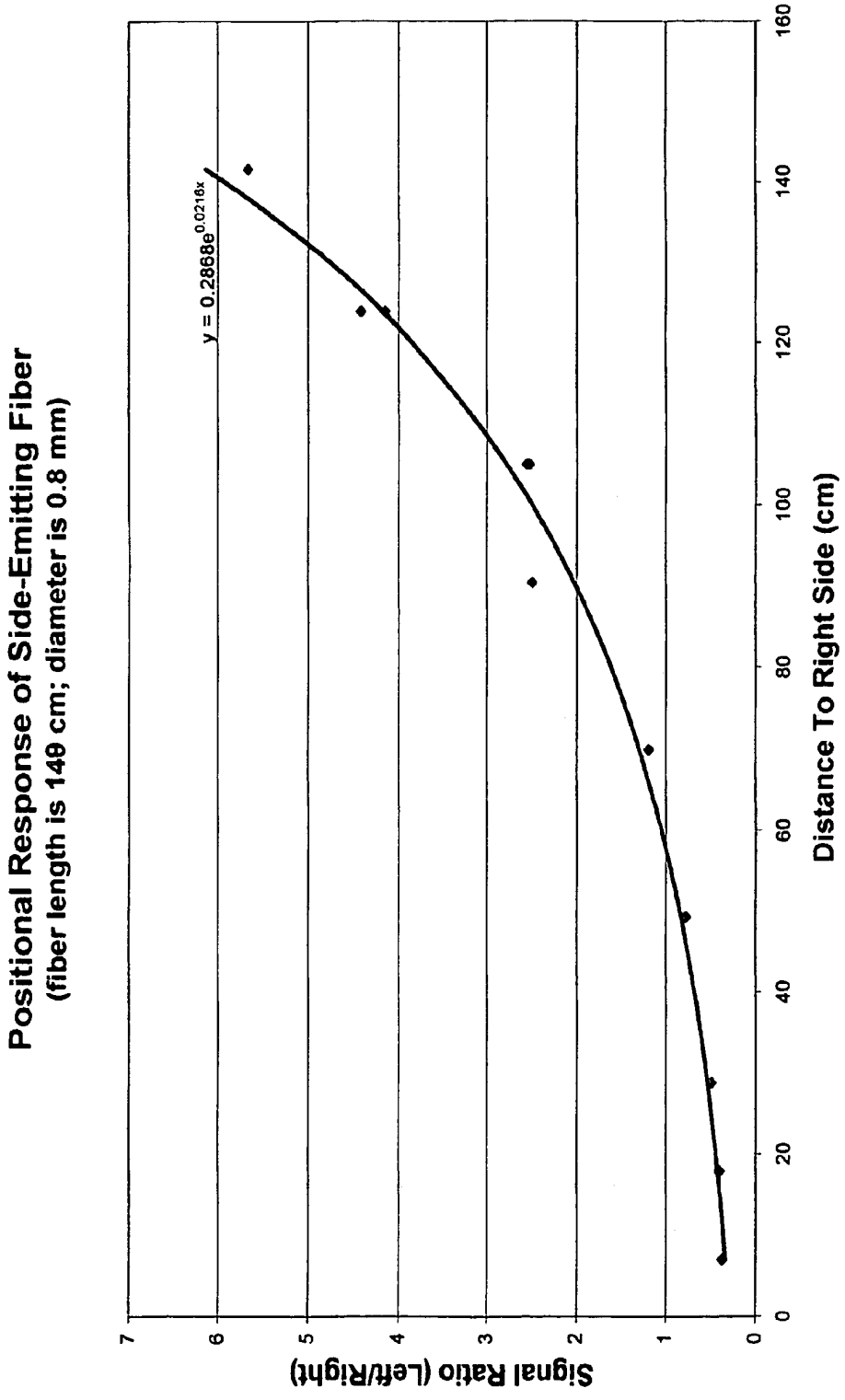
Positional Response of Side-Emitting Fiber
(fiber length is 140 cm; diameter is 0.8 mm)
y = 0.2868e^0.0216x
Signal Ratio (Left/Right)
Distance To Right Side (cm)
0
1
2
3
4
5
6
7
0
20
40
60
80
100
120
140
160

Fig. 11

SIDE-EMITTING FIBER OPTIC POSITION SENSOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of Provisional patent application Ser. No. 60/778,129 filed Mar. 1, 2006, which is incorporated herein by reference.

FEDERALLY SPONSORED RESEARCH

The U.S. Government has rights in this invention pursuant to Department of Energy Contract No. DE-AC04-94AL85000 with Sandia Corporation.

BACKGROUND OF THE INVENTION

The present invention relates generally to a method and apparatus for measuring the position of an object, and more specifically to position sensors that utilize side-emitting optical fibers.

Non-electrical position sensors are desirable for use in hazardous environments, e.g., for measuring the liquid level in gasoline or jet fuel tanks. All-optical position sensors based on the use of fiber optics would be an attractive choice because they would introduce no electrical energy, be insensitive to electromagnetic interference, have few moving parts (if any), and could provide continuous measurements.

Large-scale rotary drilling for oil and gas, minerals, and water wells, have a need for measuring the depth of drill bits and pipe segments. Measuring the length of a cable played out is often inaccurate because the cable stretches under heavy loads. An auxiliary cable under minimal tension can be used, but it can interfere with the drilling operation and is generally considered to be undesirable. Hence, a need exists for a long-range position sensor (e.g., greater than 10 meters), that is non-contact, simple, cheap, reliable, compact, non-electrical, and robust (i.e., able to withstand drilling mud and debris).

One approach is to use optical position sensors based on fluorescent fiber optics (e.g., U.S. Pat. No. 6,965,709 to Weiss). The operation of these sensors depends on the fluorescence generated in the fiber by an external pump source and its subsequent absorption as it is guided toward either end of the fiber. Since the fluorescence is generated isotropically within a small, localized region; and since its subsequent absorption depends on the path length traversed within the fiber, the ratio of optical signals outputted at the two ends can be used to determine the position of the external pump source, regardless of the individual strengths of the output signals.

However, since these types of sensors rely on fluorescence, the wavelength of the excitation (i.e. pump) light is typically limited to a fairly-narrow absorption band where stimulation (i.e., pumping/excitation) occurs. Hence, a needs exists for an optical position sensor that does not require the use of fluorescent dopants; that can operate over a wide range of wavelengths; and that has a reduced cost.

These, and other features, have been achieved in the present invention by replacing the fluorescent fibers with side-emitting fibers, which operate over a much wider range of wavelengths, and at a reduced cost.

SUMMARY OF THE INVENTION

The present invention relates to a side-emitting fiber optic position sensor and method of determining an unknown position of an object by using the sensor. In one embodiment, a concentrated beam of light source illuminates the side of a side-emitting fiber optic at an unknown axial position along the fiber's length. Some of this side-illuminated light is in-scattered into the fiber and captured. As the captured light is guided down the fiber, its intensity decreases due to loss from side-emission away from the fiber and from bulk absorption within the fiber. By measuring the intensity of light emitted from one (or both) ends of the fiber with a photodetector(s), the axial position of the light source is determined by comparing the photodetector's signal to a calibrated response curve, look-up table, or by using a mathematical model. Alternatively, the side-emitting fiber is illuminated at one end, while a photodetector measures the intensity of light emitted from the side of the fiber, at an unknown position. As the photodetector moves further away from the illuminated end, the detector's signal strength decreases due to loss from side-emission and/or bulk absorption. As before, the detector's signal is correlated to a unique position along the fiber.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and form part of the specification, illustrate various embodiments of the present invention and, together with the detailed description, serve to explain the principles of the invention.

FIG. **1** illustrates a schematic view of an embodiment of a side-emitting fiber optic position sensor, according to the present invention.

FIG. **2** illustrates a schematic layout of another embodiment of a side-emitting fiber optic position sensor, according to the present invention.

FIG. **3** illustrates a schematic layout of another embodiment of a side-emitting fiber optic position sensor, according to the present invention.

FIG. **4** illustrates a schematic layout of another embodiment of a side-emitting fiber optic position sensor, according to the present invention.

FIG. **5** illustrates a schematic layout of another embodiment of a side-emitting fiber optic position sensor, according to the present invention.

FIG. **6** illustrates a schematic layout of another embodiment of a side-emitting fiber optic position sensor, according to the present invention.

FIG. **7** illustrates a schematic layout of another embodiment of a side-emitting fiber optic position sensor, according to the present invention.

FIG. **8** illustrates a schematic layout of another embodiment of a side-emitting fiber optic position sensor, according to the present invention.

FIG. **9** illustrates a schematic layout of an experimental test setup of a side-emitting fiber optic position sensor, according to the present invention.

FIG. **10** plots the two individual photodetector signals as a function of distance.

FIG. **11** plots the ratio of the two photodetector signals as a function of distance.

DETAILED DESCRIPTION OF THE INVENTION

As used herein, the words "light" and "optical" include not only the visible spectrum, but also the infrared and near UV spectrum, as well. The term "light" includes both coherent and incoherent light; as well as including both monochromatic and polychromatic or multi-spectral light.

The methods and sensors of the present invention utilize "side-emitting" fiber optics. These fibers, which are commonly referred to as "side-emitting fibers" are commercially available from a number of different manufacturers, e.g. Super Vision International, Inc. (http://www.svision.com); Intelite, Inc. (http://www.intelite.com); Ashai Chemical Industry Col, Ltd. (http://www.asahi-kasei.co.jp), and others. Side-emitting fibers can be as simple as a single plastic or glass core without any cladding or coating. Then, depending on the index of refraction of the surrounding media, light sent into the core is lost through the sides because it is not trapped or internally guided. More typically, however, the plastic or glass core is clad with a different material than the core. To make the fiber "side-emitting", scattering defects are introduced into the fiber at various location. In one method, the core region is doped with small refractive and/or reflective light-scattering particles during manufacture. Alternatively, the surface of the core is modified or treated to have surface features ("defects") that scatter light out of the core. Some examples of light-emitting surface defects include serrations, notches, scratches, texture, roughness, corrugations, etching, abrasion, etc. The entire length of fiber can be modified or treated to have side-emitting properties, or just a portion of the fiber (i.e., a portion along the length or circumference of the fiber, or both). Another technique involves twisting or braiding a bundle of fibers into a "rope" which side-emits light due to the bending of the fibers. Combinations of these techniques can be used, e.g., reflective particles in the core with scratches or notches on the core's surface. Also, the index of refraction of the surrounding media (e.g., dry air, humid air, inert gas, vacuum, a liquid, etc.) can affect the amount of light lost by side-emission from scattering defects. Hence, the rate at which light is lost via side-emission, e.g., per unit length, is highly controllable.

Accordingly, the terms "scattering-out", "out-scattering", "scattering-in", and "in-scattering" are defined herein to include reflection and/or refraction processes, but not fluorescence. For example, the term "in-scattering" includes any combination of the following processes: (1) reflection from internal scattering defects, (2) refraction from internal scattering defects, (3) refraction from bent fibers, and (4) refraction across interfaces between the core and its surrounding media.

The term "side-emitting fibers", as used herein, and as used conventionally in commercial practice, is defined herein as meaning fibers that can "glow" or emit light along their length without requiring the use of fluorescent materials to create the glowing light. This definition is necessary in order to distinguish between fluorescent fibers and side-emitting fibers (and, also, from common end-emitting fibers), even though fluorescent fibers emit light from their sides.

Side-emitting fibers also inherently function in reverse, i.e., as "side-receiving" fibers, because the same defects that "scatter" light out of the fiber (i.e., when illuminated from the end) can also "scatter" light into the fiber (i.e., when illuminated from the side). In this case, side-illuminated light that is "trapped" or "collected" in this way is called "in-scattered" light. Hence, a side-emitting fiber is also a side-receiving fiber. Accordingly, the term "side-emitting fibers"and the term "side-receiving fibers" are used interchangeably herein, unless otherwise stated. Hence, in some embodiments, the side-emitting fiber may be illuminated from both the side and from the end of the fiber, with the same, or different, type of light.

In some embodiments of the present invention, the side-emitting fibers may optionally be doped with one or more fluorescent materials. In this case, the light source used in the position sensor may be chosen to have a wavelength that excites fluorescence in the doped+side-emitting fiber. However, in other embodiments, the side-emitting fibers do not comprise any fluorescent materials.

FIG. **1** illustrates a schematic view of a first embodiment of a side-emitting fiber optic position sensor **8**, according to the present invention. Sensor **8** comprises a side-emitting fiber optic **10**, with a pair of photodetectors **30** and **32** attached to ends "**1**" and "**2**" of fiber **10** via optical couplers **34** and **35**, respectively. Light source **12** is positioned at an unknown distance X from the left end "**1**" of fiber **10**, and is oriented to illuminate the side of fiber **10** with a small, concentrated beam of light. Because side-emitting fiber **10** also behaves as a "side-receiving" fiber, some of the impinging light from source **12** is "in-scattered" into the fiber and captured within a small, localized zone **18**. Note that this zone is analagous to the small, localized zone of fluorescent light that would be generated in a fluorescent fiber optic, (if the wavelength of light source **12** within the fluorescent fiber's excitation band).

The light that is "in-scattered" and captured in zone **18** is then guided along fiber **10** to both ends (note: the light that is guided along fiber **10** is designated "guided light **20**", with reference to FIG. **1**). Photodetectors **30** and **32** measure the intensity, S_1 and S_2, of light emitted from ends "**1**" and "**2**" of fiber **10**. Photodetectors **30**, **32** may comprise photodiodes, CCD elements, etc., as is well known in the art; and can be chosen to detect light not only the visible spectrum, but also the infrared and near UV spectrum, as needed. Power supply **28** provides power to light source **12**. The electrical output from photodetectors **30** and **32** is connected to processor **40** via electrical cables **36** and **38**, respectively. Alternatively (not shown), the photodetector signals may be transmitted wirelessly to processor **40**. Processor **40** comprises analog or digital computer processing means, memory means, etc., for calculating the axial position, X, of light source **12** based on the measured intensity values of either S_1, or S_2, or, both S_1 and S_2. Light source **12** may be coherent, incoherent, monochromatic, or polychromatic/multi-spectral, or combinations thereof. For example, source **12** may be a blue or red LED.

In FIG. **1**, curve **15** schematically illustrates the variation in intensity, S, of guided light **20** inside of fiber **10**, as a function of distance, X, as measured (arbitrarily) from the left end of the fiber. The exponential-like decay in light intensity in both directions away from the peak, S_{max}, at position "X" (i.e., the center of light source **12**) is caused by two effects. First, some of guided light **20** is lost from the core of fiber **10** due to side-emission **13** along the length of fiber **10**. Second, some of guided light **20** is absorbed in the fiber's core itself as it travels down the fiber. This second effect (i.e., bulk absorption) is typically more pronounced in plastic fibers than in glass fibers. Either one, or both of these effects attenuates the intensity of guided light **20** as one travels further and further away from light source **12**, in either direction. Hence, by the time that guided light **20** has reached either end "**1**" or "**2**" of fiber **10**, its intensity, S, at

that end has been attenuated by an amount that depends uniquely on the specific axial location of light source **12**.

Optionally, sensor **8** may comprise a single photodetector (e.g., photodetector **30**) attached to only one end of fiber **10**. In this case, the other end of fiber **10** may have a mirrored surface to reflect light back in the other direction.

It should be clear that any sort of object may be attached to light source **12** in such a manner that the position of the object, relative to the coordinate system of the fiber optic **10**, may be determined by measuring the position of the attached light source **12** in the manner presented herein using sensor **8**.

Any variety of mechanical motion control devices (not shown), including sliding or rolling bearings, tracks, etc. may be used to confine the motion of light source **12** to travel smoothly and continuously along the path defined by the shape of fiber **10**, including straight and curved paths. Such a motion control device may also be used to hold light source **12** at a constant distance (spacing) away from the surface of fiber **10**, and at a constant angle of incidence (e.g., perpendicular). However, it is not required to hold light source **12** at a constant distance (spacing) away from the surface of fiber **10**, or at a constant angle of incidence (e.g., perpendicular), since the ratio of the output signals, S_1/S_2, is independent of the degree of coupling of excitation light into the fiber, as will be discussed shortly.

Light source **12** may be a continuous, steady-state source; or it may be modulated, amplitude modulated, frequency modulated, pulsed, or any combination thereof. Multiple light sources may be used at the same, or different, axial position along fiber **10**; with each source having a unique wavelength, modulation pattern, modulation frequency, etc. Using appropriate filtering and digital processing, the photodetector signals can be de-moldulated to separate out the individual contributions from each independent light source.

If exposed, side-emitting fiber **10** can collect ambient light, such as sunlight or indoor fluorescent lighting. However, if the ambient light is uniform along the length of fiber **10**, then both of the signals S_1 and S_2 will be affected by approximately the same amount. Additionally, a calibrated response curve may be used to account for the effect of ambient light. Alternatively, any undesired signal, S, contributed by ambient light may be effectively eliminated by modulating the output of light source **12** at a high frequency, e.g. greater than 10 KHz, and then electrically or digitally filtering out all signals that are below this frequency (e.g., sunlight is DC, and fluorescent lighting oscillates at 60-120 Hz).

In some embodiments, the side-emission properties (i.e., the loss rate of side-emitted light per unit length) and the bulk absorption properties of the core are uniformly distrubuted along the entire length of fiber **10** (i.e., by having uniformly-distributed scattering defects along the length of the fiber). In this case, the following equations can be used to describe an approximate, simple relationship between the output intensities (S_1 and S_2), and the unknown position, X, of light source **12**.

$$S_1=ke^{-\alpha X} \tag{1}$$

$$S_2=ke^{-\alpha(L-X)} \tag{2}$$

$$S_1/S_2=e^{\alpha L}e^{-2\alpha X} \tag{3}$$

where α=0.23 B, and B=Fiber Attenuation Coefficient (in db/meter).

The Fiber Attenuation Coefficient, B, depends on both the side-emission properties (i.e., the loss rate of side-emitted light per unit length) and the bulk absorption properties of the core. As an example, assume that the fiber attenuation coefficient, B, equals 0.3 db/meter, and the fiber is 30 meters long (L=30), then the signal ratio, S_1/S_2=7.9 when the light source **12** is positioned at the left end (X=0). When the light source **12** is positioned at the far right end (X=30 meters), then S_1/S_2=0.13. When the source is positioned exactly at the middle (X=15 meters), then S_1/S_2 =1.

Solving for X from eq. (3), we get equation (4):

$$X=\frac{L}{2}-\frac{1}{2\alpha}\ln(S_1/S_2) \tag{4}$$

This simple exponential response is called "single-ended" because the origin of the X-coordinate system is located at one end of the fiber. On the other hand, a clear symmetry exists with respect to the center of the fiber. Consequently, if it is desired that the position of light source **12** should be measured from the center of the fiber, then equations (1)-(3) can be appropriately rewritten in a "centered" coordinate system.

It is not a requirement of the present invention that the axial distribution of scattering defects, or of the bulk absorption properties, be uniform along the length of fiber **10**. In these cases, a calibration curve can be generated that provides a unique relationship between the position of light source **12** and the intensity of output signals S_1 and S_2, and/or the ratio of S_1/S_2. Note that when referring to the ratio of output signals, S_1/S_2 we also intend to include equal consideration of the inverse ratio, i.e., S_2/S_1 in the discussion of the method and apparatus of the present invention. However, if the Fiber Attenuation Coefficient, B, is reasonably uniform along the length, then equations (1)-(3) can be used to provide a reasonably accurate prediction of the sensor's response. If the Fiber Attenuation Coefficient is too high for a given fiber length, L, the signal at one or both ends could be too low. Conversely, if the Fiber Attenuation Coefficient is too low, then the output signals at both ends will be large, and will not change much as light source **12** moves along the fiber optic fiber **10**.

Plastic fiber optics generally have high bulk absorption coefficients, and could be appropriate for ranges of less than about 100 feet, while glass fibers could be more appropriate for lengths greater than about 100 feet.

Light source **12** may comprise a variety of sources, including lasers, LED's, Vertical Cavity Surface Emitting Lasers (VCSEL's), monochromatic incoherent light sources (e.g., tungsten, mercury, or sodium vapor), incandescent light sources, sunlight, ultraviolet and microwave sources.

Light source **12** may impinge on the side of fiber **10** at any angle, from normal (i.e., perpendicular) incidence down to a shallow, grazing angle, depending on the application.

FIG. **2** shows a schematic layout of another embodiment of an optical position sensor **8**, according to the present invention. Sensor **8** comprises fiber optic **10** with optical couplers **42** and **44** attached to the ends "**1**" and "**2**" of fiber optic **10**, respectively. Clear, low-loss, non-absorbing fiber optics **46** and **48** are attached to couplers **42** and **44**, respectively, which transmit light emitted from ends **1**" and "**2**" to a pair of photodetectors contained within integrated processor **50**. A clear, low-loss, non-absorbing fiber optic **54** is used to guide light from a light source located inside of integrated processor **50** to the other end of fiber **54**, which side illuminates fiber optic **10**. Light source **12** may comprise an annular, ring-like structure (not illustrated) that

surrounds fiber optic **10** and provides a circumferentially uniform source of illumination light **12** at position=X. Integrated processor **50** may include a power source (including batteries) and other electronic components (not shown) for modulating the light source, amplifying and filtering the photodetector output, displaying, and storing the data and results, analyzing the data and calculating the unknown position, X, etc. All of the electrical components are contained within integrated processor **50**, which can have an electrically-shielded housing. Only optical sensor components are located outside of processor **50**, which allows use of the sensor **8** in explosive environments.

In other embodiments of the present invention, fiber **10** can move relative to a fixed light source **12**, since it is the relative distance, X, between a reference point on fiber **10** and source **12** that is measured by position sensor **8**.

In equations (1) and (2), the proportionality constant "k" that determines the intensity of output signal S_1 and S_2 depends on many different factors, including the concentration (i.e., density) of scattering defects, the electronic gain factors, the photodetector's sensitivity, the optical coupling efficiency from the fiber to the detector, the strength of the light source, and the fraction of light coupled into fiber **10** by in-scattering, the refractive index of the surrounding media, etc. Some of these factors may vary over time, such as the strength of light source **12** as it ages, or the efficiency of receiving light into the side-receiving fiber **10** if the radial separation distance between source **12** and the side of fiber **10** is not constant. However, barring signal-to-noise considerations, these generally unavoidable variations will not affect the ratio of the output signals, S_1/S_2, since the ratio of signals is independent of the constant "k", as can be seen from equation (3).

In another embodiment, position sensor **8** is operated using a single photodetector to measure the light emitted from only one end of fiber **10** (either S_1 or S_2, but not both). From equations (1) and (2), we see that use of a single photodetector requires knowledge of the constant "k" to achieve an absolute measurement of the source's position. Alternatively, a calibrated response curve for S_1 (and/or S_2) may be used to overcome a lack of a measurement for constant "k". Also, a calibrated response curve likely provides a more accurate measurement, since equations (1)-(3) only approximate the response of the system. Having the ability to measure distance with a single photodetector would be useful if a second photodetector coupled to the other end of fiber **10** fails, or is defective.

In another embodiment, a single photodetector may be used for measuring a change i.e., ΔX in the axial position, X, of source **12** relative to a previously measured position. If a first position, X_a, provides an output signal of S_a, and a second position, X_b, provides an output signal of S_b, then equation (5) can be used to calculate the relative change in position, ΔX, as:

$$S_1/S_1' = e^{\alpha \Delta X} \tag{5}$$

where $\Delta X = X_a - X_b$. Solving for ΔX, we get:

$$\Delta X = \frac{1}{\alpha} \ln(S_1 / S_1') \tag{6}$$

where α=0.23 B, and B=Fiber Attenuation Coefficient (in db/meter). Here, we see that the constant "k" and the fiber's total length "L" disappears from equations (5) and (6).

In the previous embodiments shown in FIGS. **1-2**, the coordinate system used is a one-dimensional, Cartesian-type, linear coordinate system. However, the method and apparatus of the present invention can be generalized to a one-dimensional, curvilinear coordinate system, such as the one illustrated schematically in FIG. **3**.

FIG. **3** shows a schematic layout of another embodiment of a side-emitting fiber optic position sensor **8**, according to the present invention. Here, side-emitting fiber **10** is curved in one or more directions. The position of light source **12** can be defined in terms of a one-dimensional, curvilinear coordinate, s, which closely follows the path of the curved shape of fiber **10**. Hence, the curvilinear coordinate variable, S, is the path length from one end of fiber to the location of light source **12**. In a "single-ended" system, equations (1)-(3) could be used equally well for the curved fiber **10** shown in FIG. **3** by simply substituting the curvilinear coordinate variable, s, for the linear Cartesian coordinate variable, X. Note that the shape of fiber **10** is drawn as being confined to the plane in FIG. **3**, however, it is not necessary to confine a curved fiber **10** to lay on a single plane. Fiber **10** may be curved in any three-dimensional space, in a completely general way, and still be characterized by a one-dimensional, curvilinear coordinate, s, which closely follows the path of the curved shape of fiber **10**.

FIG. **4** shows a schematic layout of another embodiment of an optical position sensor **600**, according to the present invention. Sensor **600** comprises side-emitting fiber optic **610**, which is curved in a circular arc with radius=R. By comparing the measured intensity of output signals, S_1 and S_2 (or the ratio of signals S_1/S_2), in the manner presented earlier, the angular position of light source **612** can be determined by simply converting the curvilinear (i.e., circumferential) path length, S, to the angular position, θ. FIG. **4** also illustrates an optional mirror or reflecting surface **72** that can be placed behind fiber **610** to reflect light from source **612** back towards fiber **610** to generate a second pass at being in-scattered into the fiber. Mirror **72** can be flat or curved, as is well known in the art. Mirror **72** may be mechanically coupled to source **612**, so that both elements move together as a single unit, when the source **612** moves along the length of fiber **610**. Alternatively, mirror **72** may extend along the entire length of the fiber, in which case it would not need to be movable.

In general, in any of the different embodiments, a mirror or other reflecting surface may be placed behind the fiber to reflect light from a side-illuminating source back towards the fiber to generate a second pass (i.e. second chance) at being in-scattered into the fiber.

FIG. **5** shows a schematic layout of another embodiment of an optical position sensor **620**, according to the present invention. Sensor **620** comprises a side-emitting fiber optic **622** laid out in a two-dimensional, double-spiral pattern. Movable light source **628** side-illuminates a localized region of fiber **622**. The in-scattered light travels in either direction along fiber **622** towards ends "**1**" and "**2**", where photodetectors **624** and **626** measure the amount of attenuated guided light emitted from ends "**1**" and "**2**", respectively. The unknown curvelinear position, s, along the axis of fiber **622** (i.e., path length) can be determined by comparing the signals output from photodetectors **624** and **626**, in the manner presented earlier. This information, combined with the knowledge of the (x,y) coordinates of the two-dimensional double-spiral pattern, allows a unique mapping to be made between the path length distance, s, and the (x,y) coordinate of light source **628**. Accordingly, the two-dimen-

sional motion of light source **628** as it moves from position "A" to position "B" can be uniquely determined using sensor **620**.

FIG. **6** shows a schematic layout of another embodiment of an optical position sensor **650**, according to the present invention. Sensor **650** comprises a side-emitting fiber optic **652** laid out in a two-dimensional, serpentine (i.e., boustrophedon) pattern. Movable light source **628** side-illuminates a localized region of fiber **652**. The in-scattered light travels in either direction along fiber **652** towards ends "**1**" and "**2**", where photodetectors **654** and **656** measure the amount of attenuated guided light emitted from ends "**1**" and "**2**", respectively. The unknown curvelinear position, s, along the axis of side-emitting fiber optic **652** (i.e., path length) can be determined by comparing the signals output from photodetectors **654** and **656**, as presented earlier. This information, combined with the knowledge of the (x,y) coordinates of the out-out, two-dimensional serpentine pattern, allows a unique mapping to be made between the path length distance, s, and the (x,y) coordinate of light source **658**. Accordingly, the two-dimensional motion of light source **658** as it moves from position "A" to position "B" can be uniquely determined using sensor **650**. It should be noted that the change in photodetector output signal as light source **658** moves along the X-direction is "magnified", as compared to the arrangement illustrated in FIG. **1** (which has a straight fiber **10**). Hence, the path length, s, traversed when light source **658** moves along the X-direction from one segment to another is approximately equal to the vertical length of a single segment (i.e., in the Y-direction) rather than simply the length along the axial coordinate, X, as would be the case for a straight fiber (see, e.g., FIG. **6**). In this sense, a serpentine-type sensor **650** generates a greater change in output signal (i.e., magnified output) for the same amount of change in the position of the light source along the X-direction, relative to a sensor using a straight (unwrapped) fiber. The magnification factor provided by this serpentine/folded shape provides increased resolution, when compared to an unmagnified, straight fiber.

FIG. **7** shows a schematic layout of another embodiment of an optical position sensor **800**, according to the present invention. Sensor **800** comprises a side-emitting fiber optic **810** wrapped in a helical (spiral) pattern about cylinder **811**. Movable light source **812** side-illuminates a localized region of fiber **810**. The in-scattered light travels in either direction along fiber **810** towards ends "**1**" and "**2**", where photodetectors **824** and **826** measure the amount of attenuated guided light emitted from ends "**1**" and "**2**", respectively. The unknown axial position, X, along the longitudinal axis of cylinder **811** can be determined by comparing the signals output from photodetectors **824** and **826**, as presented earlier. Cylinder **811** may be opaque or transparent, solid, hollow, or tubular, depending on the application. It should be noted that the change in photodetector output signal as light source **812** moves along the X-direction, is "magnified" or "enhanced, when compared to the arrangement illustrated in FIG. **1** (which has a straight fiber **10**). This is due to the fact that fiber optic **810** has been coiled or wrapped into a compact, helical shape. Hence, the path length, s, traversed when light source **812** moves axially from one coil to another is given by the circumference of the coil ($2\pi R$), rather than the axial distance, X, as would be the case for a straight fiber (see, e.g., FIG. **1**). In this sense, a spiral-wrapped sensor generates a greater change in output signal (i.e., magnified output) for the same amount of change in the axial position of the light source, relative to a sensor using a straight (unwrapped) fiber. Thus, a spiral-wrapped/coil fiber design provides for enhanced position resolution, as compared to a straight fiber design. Note also that the best accuracy and reproducibility for position sensor **800** can be attained by providing good alignment of light source **812** with respect to the axial centerline of the helical/spiral pattern and cylindrical core **811**, so that any motion perpendicular to the axis of travel (i.e., the primary direction), is minimized. Good concentric axial alignment may be achieved by providing an outer cylindrical tube/housing that closely fits around the outer surface of helically shaped fiber **810** (e.g., a piston/cylinder geometry). Alternatively, cylinder **811** may have a reflective outer surface, in order to produce a second pass of source light **812** through the fiber **810**.

FIG. **8** shows a schematic layout of another embodiment of a side-emitting fiber optic position sensor **900**, according to the present invention. Here, the positions of the light source and photodetectors are reversed from that shown previously in FIGS. **1-7**. Here, in this "inverse" configuration, light source **912** illuminates the left end of side-emitting fiber **910** with an intensity equal to S_1. As the light from source **912** is guided down fiber **910**, some of this light is continuously emitted from the side of the fiber, as well as possibly being absorbed by the bulk core. The intensity, S, of guided light decays in an exponential-fashion as a function of distance, X, as measured from the left end of fiber **910**. This decay in light intensity, S, is illustrated schematically by curve **914**. A pair of photodetectors **916** & **918** measure the intensity of light emitted at two different axial positions along fiber **910**. Specialized ring-type photodetectors may be used, which circumferentially surrounds the fiber. A "reference" photodetector **916** is fixed at a stationary position on fiber **910**, e.g., at the left end where the intensity of side-emitted light is greatest. A second, movable "ring-type" photodetector **918** is located at the unknown, variable position, X, where it measures a reduced, attenuated intensity of side-emitted light. A set of equations similar to equations (1)-(6) can be derived that express the unique relationship between measured light intensity and position along the fiber, in this "reversed" or "inverse" mode of operation. Optionally, the intensity of light, S_2, emitted from the opposite end of fiber **901** (i.e., the right end), may be measured with a third ring photodetector (not shown) located at the right end of fiber **901**. This third photodetector could provide a reference signal. Alternatively, the right end of fiber **910** may be mirrored to reflect guided light backwards.

Ring-type photodetectors **916**, **918** may comprise a loop, or loops, of side-receiving fiber or fibers.

Method of Operation

One embodiment of a method for measuring an unknown position, X, of an object by using a side-emitting fiber optic position sensor may comprise performing the following steps:

a) providing a side-emitting fiber optic position sensor comprising a side-emitting optical fiber having a first end, an opposing second end, a photodetector optically coupled to the first end for measuring a first intensity of light, S_1, emitted from the first end; and a one-dimensional curvilinear coordinate system, x, having an origin at the first end and extending along the fiber towards the second end;

b) side-illuminating the fiber with a concentrated beam of light; wherein the light source is located at an unknown axial position, X, along the fiber, as measured in the curvilinear coordinate system;

c) in-scattering some of the side-illuminating light into the fiber;

d) guiding the in-scattered light along the fiber;

e) attenuating the intensity of the guided light as the guided light travels further and further away from the unknown axial position, X;

f) measuring with the photodetector the intensity of light, S_1, emitted from the first end of the fiber;

g) determining the position, X, of the light source by comparing the measured light intensity, S_1, to a calibrated response curve or look-up table; or by inputting S_1 into a equation that approximately models the sensor's response.

In another embodiment, a second photodetector measures an intensity of light, S_2, emitted from the second end of the fiber; and the ratio of the two light intensities, S_1/S_2, is used to determine the position, X, of the light source. In one embodiment, attenuating the intensity of the guided light can comprise side-emitting light from the side of the fiber. Alternatively, or additionally, attenuating the intensity of the guided light can comprise absorbing light inside the bulk of the fiber.

Experimental Test Results

FIG. **9** shows a schematic layout, uncluttered by detail, of an experimental test setup, according to the present invention. A number of tests were performed that successfully demonstrated the design and principles of operation.

A 148-cm length of side-emitting fiber was connected to two photodetectors, left and right. The core diameter of the fiber was 0.8 mm. For a given measurement, all but about 5 cm of this fiber was sheathed to isolate it from ambient light. A flashlight was used to illuminate the exposed section. Aluminum foil (not shown) was placed beneath the fiber, which produced a second pass of the light from the flashlight through this exposed section. In addition, it was discovered that removing the plastic buffer from the exposed section of fiber increased the photodetector signal.

FIG. **10** shows the individual signals from each photodetector at various positions of the flashlight along the fiber. FIG. **11** shows the ratio of the two signals, at each flashlight position. As was found previously in the case of a fluorescent fiber (see U.S. Pat. No. 6,965,709 to Weiss, which is incorporated herein by reference), the individual detector signals show considerable scatter because the illumination was not particularity consistent. However, the ratio of the two signals produced a rather well-behaved response curve, which could be reasonably fit with an simple exponential function (see FIG. **11**). As expected from previous experiments using fluorescent fibers, the signal ratio (left/right) increases as the distance from the light source to the right end of the fiber increases (i.e., as the light source moves to the left). This is because as the source moves to the left, the intensity of light emitted from the left end increases, while, at the same time, the intensity of light emitted from the right end decreases.

The particular examples and embodiments discussed above are cited to illustrate particular embodiments of the invention. Other applications and embodiments of the apparatus and method of the present invention will become evident to those skilled in the art.

The scope of the invention is defined by the claims appended hereto.

What is claimed is:

1. A method for measuring an unknown position, X, of an object by using a side-emitting fiber optic position sensor, comprising:

a) providing a side-emitting fiber optic position sensor comprising a side-emitting optical fiber having a first end, an opposing second end, a first photodetector optically coupled to the first end for measuring a first intensity of light, S_1, emitted from the first end; and a one-dimensional curvilinear coordinate system, x, having an origin at the first end and extending along the fiber towards the second end;

b) side-illuminating the fiber with a concentrated beam of light; wherein the light source is located at an unknown axial position, X, along the fiber, as measured in the curvilinear coordinate system;

c) in-scattering some of the side-illuminating light into the fiber;

d) guiding the in-scattered light along the fiber;

e) attenuating the intensity of the guided light as the guided light travels further and further away from the unknown axial position, X;

f) measuring with the first photodetector a first intensity of light, S_1, emitted from the first end of the fiber;

g) determining the position, X, of the light source by comparing the measured first light intensity, S_1, to a calibrated response curve or look-up table; or by inputting S_1 into a equation that approximately models the sensor's response;

wherein the fiber does not comprise fluorescent materials; and

wherein the method does not include generating fluorescent light by causing fluorescence of fluorescent materials inside of the fiber.

2. The method of claim **1**, further comprising measuring with a second photodetector coupled to the second end of the fiber a second intensity of light, S_2, emitted from the second end; and then determining the position, X, of the light source by comparing the ratio of the measured light intensities, S_1/S_2 to a calibrated response curve or look-up table; or by inputting S_1/S_2 into an equation that approximately models the sensor's response.

3. A side-emitting fiber optic position sensor, comprising:

a side-emitting optical fiber having a first end and an opposing second end;

a first photodetector optically coupled to the first end for measuring a first intensity of light, S_1, emitted from the first end;

a one-dimensional curvilinear coordinate system, x, having an origin at the first end and extending along the fiber towards the second end;

a movable light source for side-illuminating the fiber with a concentrated beam of light; located at an unknown axial position, X, along the fiber, as measured in the curvilinear coordinate system;

processing means for determining the unknown position, X, of the light source by comparing the measured first light intensity, S_1, to a calibrated response curve or look-up table; or by inputting S_1 into a equation that approximately models the sensor's response;

wherein the optical fiber does not comprise any fluorescent materials.

4. The sensor of claim **3**, further comprising a second photodetector optically coupled to the second end of the fiber for measuring a second intensity of light, S_2, emitted from the second end of the fiber.

5. The sensor of claim 4, wherein said processing means determines the unknown position, X, of the light source based on the ratio, S_1/S_2, of the first and second intensities.

6. The sensor of claim 3, wherein the side-emitting fiber is wrapped in a spiral pattern around a cylindrical core.

7. The sensor of claim 3, wherein the side-emitting fiber is curved.

8. The sensor of claim 7, wherein the side-emitting fiber is curved in the shape of a double-spiral pattern.

9. The sensor of claim 7, wherein the side-emitting fiber is curved in the shape of a serpentine pattern.

10. The sensor of claim 3, wherein said first and second photodetectors are remotely located, and are coupled to their respective fiber via low-loss fiber optic cables; and further wherein the light source comprises a third low-loss fiber optic cable held in close proximity by a support to said fiber and oriented to illuminate the fiber from the side; wherein the distal end of the third fiber optic cable is coupled to a remotely-located source of light.

11. The sensor of claim 3, further comprising a plurality of side-illuminating light sources disposed at a plurality of axial positions along the fiber, wherein each light source is modulated at a different frequency to allow discrimination of individual light sources by frequency filtering the photodetector's output signal.

12. A side-emitting fiber optic position sensor, comprising:

a side-emitting optical fiber having a first end and an opposing second end;

a first photodetector optically coupled to the first end for measuring a first intensity of light, S_1, emitted from the first end;

a one-dimensional curvilinear coordinate system, x, having an origin at the first end and extending along the fiber towards the second end;

a movable light source for side-illuminating the fiber with a concentrated beam of light; located at an unknown axial position, X, along the fiber, as measured in the curvilinear coordinate system;

processing means for determining the unknown position, X, of the light source by comparing the measured first light intensity, S_1, to a calibrated response curve or look-up table; or by inputting S_1 into a equation that approximately models the sensor's response;

wherein the side-emitting fiber comprises one or more scattering defects selected from the group consisting of serrations, notches, scratches, texture, roughness, corrugations, and combinations thereof.

13. The sensor of claim 12, wherein the side-emitting fiber further comprises one or more fluorescent dopants distributed uniformly along the length of the fiber.

14. A side-emitting fiber optic position sensor, comprising;

a side-emitting optical fiber having a first end and an opposing second end;

a first photodetector optically coupled to the first end for measuring a first intensity of light, S_1, emitted from the first end;

a one-dimensional curvilinear coordinate system, x, having an origin at the first end and extending along the fiber towards the second end;

a movable light source for side-illuminating the fiber with a concentrated beam of light; located at an unknown axial position, X, along the fiber, as measured in the curvilinear coordinate system;

processing means for determining the unknown position, X, of the light source by comparing the measured first light intensity, S_1, to a calibrated response curve or look-up table; or by inputting S_1 into a equation that approximately models the sensor's response;

further comprising a reflective surface placed behind the side-emitting fiber, at the axial location of the movable light source, for creating a second pass of side-illumination light through the fiber.

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