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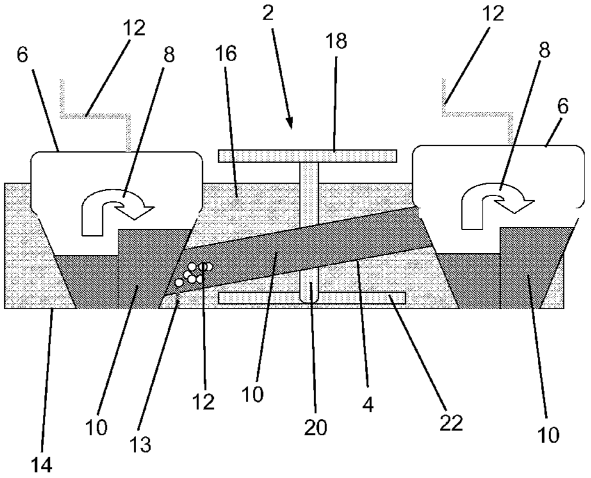

Fig. 1

(57) Abstract: An illumination system (2; 102) for a photobioreactor comprising a luminescent light absorber (18; 1 18) arranged to absorb at least a proportion of the incident solar radiation (126) and to re-emit at least portion of the absorbed radiation, the system further comprising a light diffuser (22; 122) optically coupled to the luminescent light absorber (18; 1 18) and arranged to diffuse the re-emitted radiation (129) for use in the photobioreactor.

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Photobioreactor Illumination System

This invention relates to photobioreactors. In particular this invention relates to systems for illuminating photobioreactors from sunlight.

The cultivation of biocultures such as algae under high growth conditions is increasingly important as a means both for extracting carbon dioxide from effluent gases produced by industrial and power generation processes, and for providing alternative sources of biofuels. Such cultivation is highly efficient in terms of the type of land it can use (poor quality, including deserts), the proportion of useable products that are generated (including high value nutrients, food, animal food and biofuels), and the ability to use brackish or salt water. These alternative sources of biofuels have the potential to reduce the price of production compared to traditional biofuels owing to the increase in productivity for the area of land used, and will also avoid competition with food production as is now the case with biofuels derived from commodities such as wheat, corn and sugar beet.

The cultivation of algae has traditionally been performed in open ponds, where the algae are grown in "race-track" ponds (closed circular channels), and moved around and mixed by a paddle wheel. Such cultivation is low cost, but there is limited control over the dissolved gases, illumination and temperature, with a particular problem of contamination and overgrowth from non-desired algal species. Such problems mean that long term cultivation is only possible for algal species which are able to tolerate very specific growth conditions (e.g. extremes of pH or salinity), unless batch processing is used, with the open pond being periodically cleared completely and restocked from a pure grown culture.

At least some of these problems are overcome by using photobioreactors which give closed growth systems. Here, the algae are grown inside containers, e.g. plastic bags or tubes, which are illuminated by direct or diffuse sunlight, or by artificial lighting, and into which carbon dioxide is introduced. However, as will be appreciated, the cost of operating photobioreactors is greatly increased compared to using open ponds, and, up until now, this has not been outweighed by their increased productivity.

The increase in productivity from using photobioreactors has also been somewhat limited owing to the very specific conditions that need to be obtained for optimal cultivation of algae. Algae photosynthesise most efficiently at light intensities which are significantly below that of direct sunlight at the water surface, because they have evolved to live in conditions such as dirty water or with other algae obscuring the direct light. If the light is too intense, photoinhibition of the algae occurs which reduces the rate of photosynthesis. Prolonged exposure of the algae to high intensity light can also cause photo-oxidation which inflicts irreparable damage to the photosynthesis system in the algae.

Photobioreactors need to be designed to supply light at intensities of around 30-60 Watts per square metre (Wm^{-2}) for optimal growth levels of algae, around 10% of the intensity of direct sunlight. This therefore requires a reduction in the intensity of light from direct illumination which can be achieved in a number of different ways. One approach is to use "temporal averaging" in which algae cells are moved towards and away from the sunlight, e.g. mixed up and down in depth in a container or circulated through thin plastic sheets. However this leads to the algae being exposed to light which is too intense some of the time which can cause photoinhibition and photo-oxidation, and too diffuse for photosynthesis at other times. Another approach is to couple sunlight from solar concentrators, such as Fresnel lenses or parabolic mirrors, to the algae containers, e.g. using optical fibres, light plates or light tubes. This achieves a more uniform illumination of the algae which can be optimised for the desired intensity.

However, when using solar concentrators an expensive tracking system is required to keep them pointing at the sun in order for them to maintain their focus, and they perform poorly on cloudy days when tracking and alignment errors cause problems which leads to a significant reduction in the productivity of the photobioreactor. This significant cost is one of the reasons that photobioreactors are not widely used for producing biofuels, the aim of which is to achieve the maximum yield for minimum capital and running costs.

It is an aim of the present invention to provide an improved photobioreactor which can be illuminated by sunlight.

When viewed from a first aspect the invention provides an illumination system for a photobioreactor comprising a luminescent light absorber arranged to absorb at least a proportion of the incident solar radiation and to re-emit at least portion of the absorbed radiation, the system further comprising a light diffuser optically coupled to the luminescent light absorber and arranged to diffuse the re-emitted radiation for use in the photobioreactor.

The invention also extends to a photobioreactor comprising such an illumination system.

Thus it will be seen by those skilled in the art that an illumination system for a photobioreactor in accordance with the present invention does not require a conventional reflective or refractive solar concentrator with an associated expensive tracking system, but simply provides a luminescent light absorber which is arranged to receive solar radiation some of which it then absorbs and re-emits via the light diffuser for use in the photobioreactor, i.e. for the cultivation of biocultures such as algae. A luminescent light absorber does not need to track the sun as it will absorb incident solar radiation at any angle, and therefore is able to couple radiation into the illumination system which can then be out-coupled from the illumination system by the light diffuser in a uniform manner and in any direction as is required. This is therefore ideal for photobioreactors which require a reliable source of uniform radiation at wavelengths which are suitable for cultivation of biocultures, e.g. which are readily absorbed by chlorophyll and therefore allow efficient photosynthesis. Together, the luminescent light absorber and the light diffuser can be optimised to provide radiation at the desired wavelengths and the desired locations, by virtue of the absorption and re-emission by the luminescent light absorber and the spatial arrangement of the light diffuser which allows the radiation re-emitted by the luminescent light absorber to be directed to a desired location.

It is apparent from the fact that as biocultures, e.g. algae, are coloured green, they do not absorb light over the whole range of the solar emission spectrum, but reflect light in the middle of the visual spectrum, i.e. around the green region of wavelengths. Chlorophyll, which absorbs radiation for use in photosynthesis, has absorption peaks in the blue and the red regions of the visual spectrum. Some types of algae, e.g. red algae, are able to absorb light in the middle of the solar emission spectrum for use in photosynthesis, by using carotenoids and other dyes.

In general the luminescent light absorber will have an emission spectrum which differs from its absorption spectrum. This spectral shifting can be exploited to enable the incident solar radiation to be utilised in a more efficient way for providing radiation for photosynthesis, and to compensate for the spectral mismatch between the solar radiation spectrum and the bioculture absorption spectrum, i.e. at least some of the incident solar radiation which is at wavelengths not available for use in photosynthesis is shifted to wavelengths which can beneficially be used.

In a preferred set of embodiments the luminescent light absorber is arranged to re-emit the incident solar radiation at a wavelength or wavelengths which are maximally used for photosynthesis, e.g. in the red (around 670 - 680 nm) and/or blue (around 470 - 480 nm) regions corresponding to the absorption peaks of chlorophyll. In another, not necessarily mutually exclusive set of embodiments, the luminescent light absorber is arranged to absorb incident solar radiation in the UV region, the green light region, the infrared region and/or the near infrared region. Such radiation is used poorly or not at all by photosynthesis, so if this radiation is absorbed and then the luminescent light absorber is arranged to re-emit it at a wavelength which is preferentially absorbed by chlorophyll, an increased utilisation of the solar radiation spectrum is effected.

The luminescent light absorber could comprise one or more of many different materials to absorb and re-emit the incident solar radiation, for example a dye, nanoparticles, a ceramic material, a crystalline matrix, quantum dots, a protein complex. The material could be a coating or film on the surface of the luminescent light absorber or it could be embedded or combined within the bulk of it. In one set of embodiments the luminescent light absorber comprises a clear plastic film coated with a UV curable suspension, wherein the UV curable suspension comprises a fluorescent material.

In one set of embodiments the luminescent light absorber comprises a fluorescent material, e.g. a fluorescent dye. Fluorescent materials are able to absorb light at one wavelength and emit it at another (generally longer) wavelength. As fluorescent materials generally emit light at wavelengths longer than those which they absorb, preferably the fluorescent material is arranged to absorb incident solar radiation in the UV wavelength range and emit light in the red wavelength range, e.g. at around 670 - 680 nm. 670 - 680 nm corresponds to the red absorption peak for chlorophyll. The fluorescent material used is chosen to have the desired absorption and emission properties. Examples of suitable materials are coumarin (e.g. MACROLEX Fluorescent Red G), perylene (e.g. BASF Lumogen 300 Red) and similar fluorescent dyes. Such materials absorb and emit light in the desired part of the spectrum, e.g. as has been discussed above. These material also have a long lifetime and resistance to bleaching, have a high quantum efficiency in their fluorescent performance, have absorption and emission spectra curves which have minimal overlap, are low cost and can be incorporated into coating materials. Having absorption and emission spectra curves which have minimal overlap is important to avoid light emitted by the fluorescent material being re-absorbed before it has exited the luminescent light absorber.

In one set of embodiments the luminescent light absorber comprises a phosphorescent material. Phosphorescent materials can advantageously be arranged to up-convert light, i.e. emit it at shorter wavelengths than it was absorbed at, compared to fluorescent materials which generally emit light at longer wavelengths than the absorbed wavelength. Up-conversion phosphors can comprise ceramic materials in which rare earth atoms or ions are embedded in a crystalline matrix. The materials generally absorb infrared radiation and up-convert to emit in the visible spectrum. By use of different rare earth dopants, e.g. Er^{3+}, a large number of distinctive emission spectra can be obtained which can be tailored to the photosynthesis absorption spectra. A benefit of using these types of up-conversion phosphors is that they require a much lower excitation intensity for the incident radiation, e.g. about 100 times less, compared to typical organic dyes which require two-photon excitation. They are also resistant to photobleaching, since the transitions come from rare earth atomic orbitals and not from molecular orbitals. A typical up-conversion phosphor, e.g. with Er^{3+} ions, has an absorption maximum around 975 nm, i.e. in the infrared region, and an emission maximum around 650 nm.

In one set of embodiments the luminescent light absorber comprises nanoparticles. Nanoparticles, as with some phosphors, are can be arranged to up-convert radiation, e.g. near infrared radiation to visible light. Examples of materials which can be produced as nanoparticles are silica-coated $NaYF_4$ which are co-doped with lanthanide ions, e.g. Yb and Er. The advantage of being able to up-convert near infrared radiation (or infrared radiation in the case of the phosphorescent materials) is that by absorbing this portion of the spectrum from the incident solar radiation reduces its heating effect as well as providing light in the visible spectrum, e.g. in the red region, which can be used for photosynthesis.

In one set of embodiments the nanoparticles comprise quantum dots. Quantum dots are inorganic nanoparticles which absorb and emit light. The size and shape of the quantum dots can be arranged to absorb light in the near-infrared or infrared wavelength region and emit light in the visible light region, e.g. to coincide at a peak absorption wavelength of chlorophyll. Quantum dots have long lifetimes and resistance to bleaching.

In one set of embodiments the luminescent light absorber comprises a protein complex, e.g. phycobilisomes. Protein complexes such as phycobilisomes are the photosynthetic antennae complexes of red algae and cyanobacteria. Since these exist naturally to convert radiation of wavelengths not used by chlorophyll to those that are, these materials are very suitable to the present invention. Conveniently, the protein complexes could be suspended or stabilised in a matrix within the luminescent light absorber. Studies have indicated that the energy transfer within intact phycobilisomes results in a reduction of re-absorption losses by about 50%.

Where reference is made herein to absorption or emission at a particular wavelength or within a range of wavelengths this should be understood to mean that the corresponding absorption or emission spectrum has a peak at that wavelength or in that band of wavelengths. This does not exclude the spectrum having other peaks, some of which may even be higher.

As well as comprising a luminescent material, in some embodiments the luminescent light absorber comprises an infrared or near infrared reflecting material arranged to reflect incident infrared radiation within the incident solar radiation. This prevents or at least reduces infrared radiation being transmitted through the luminescent light absorber and into any bioculture that the system is arranged to be illuminating. Consequently the heat load on the bioculture is reduced. Additionally or alternatively, as has been discussed previously, the luminescent light absorber could comprise an infrared or near infrared up-conversion material arranged to convert the infrared or near infrared radiation into photosynthetically useable light, e.g. in the red region of the visible spectrum.

The luminescent light absorber could be arranged to absorb all of the incident solar radiation, but in one set of embodiments it is arranged to allow at least a proportion of the incident solar radiation to pass through without being absorbed, e.g. the luminescent light absorber is translucent.

In this set of embodiments, conveniently the system or photobioreactor comprises a chamber for receiving a bioculture arranged to receive the solar radiation which passes through the luminescent light absorber. This chamber may also receive some radiation which is absorbed and re-emitted from the luminescent light absorber but which is not coupled to the light diffuser, i.e. because it is not trapped within the luminescent light absorber but is emitted directly out of the surface. A similar proportion of radiation will be emitted from the surface of the luminescent light absorber which receives the incident solar radiation. By selecting the luminescent material for the luminescent light absorber the amount of light absorbed compared to the amount of light which passes through can be adjusted.

In one set of embodiments the luminescent light absorber comprises an extended waveguide. The extended waveguide could be extended in one dimension, e.g. a light pipe or tube, or in two dimensions, e.g. a sheet or plate. Having the luminescent light absorber extended in two dimensions provides a large area over which incident solar radiation can be absorbed. Furthermore the extended waveguide could be curved (with care being taken that the radius of curvature is great enough to avoid loss of radiation through the curved surface, though mirrored sections could be provided to prevent this), but preferably the extended waveguide is straight (e.g. a straight pipe or tube) or flat (e.g. planar). The extended waveguide is arranged to receive incident solar radiation upon the extended surface, and to trap the re-emitted radiation within the waveguide. Some of the re-emitted radiation may escape from the extended surfaces of the waveguide, though the majority will be contained within the waveguide and be emitted from the ends or edges of the extended waveguide as concentrated radiation. In preferred implementations the luminescent light absorber will be arranged in the system to maximally absorb the incident solar radiation, so there is no need to track the concentrator to face the sun.

Conveniently, therefore, the light diffuser is coupled to the ends or edges of the extended waveguide of the luminescent light absorber and is arranged to receive and diffuse the radiation emitted from the ends or edges of the extended waveguide. The light diffuser could be directly coupled to the extended waveguide or the system could comprise a light transmitter arranged to receive radiation re-emitted from the luminescent light absorber and to transmit the radiation to the light diffuser. The light transmitter could comprise a waveguide, e.g. an extended rigid waveguide (curved or planar as for the luminescent light absorber) or an optical fibre. Providing a light transmitter allows the luminescent light absorber and the light diffuser to be spatially separated, which conveniently allows design flexibility in the arrangement of the system.

In one set of embodiments the light transmitter could simply be an extension of the luminescent light absorber, e.g. a part of it which does not comprise a luminescent material. Conveniently these embodiments could include an extended waveguide which comprises a first region including a luminescent light absorber and a second region including a light transmitter. In a similar set of embodiments the light transmitter could be an extension of the light diffuser, e.g. a part of it which does not comprise means arranged to transmit the received radiation from its surface but rather arranged to transmit the received radiation, e.g. by waveguiding or total internal reflection. Conveniently these embodiments could include an extended waveguide which comprises a first region including a light transmitter and a second region including a light diffuser. As will be appreciated, another set of embodiments could include an extended waveguide which comprises a first region including a luminescent light absorber, a second region including a light transmitter and a third region including a light diffuser. In all of these different sets of embodiments the different regions are defined by their respective properties, i.e. the luminescent light absorber is arranged to receive and re-emit incident solar radiation, the light transmitter is arranged to receive and transmit radiation re-emitted from the luminescent light absorber, and the light diffuser is arranged to receive and diffuse radiation from the light transmitter.

In one set of embodiments the light transmitter comprises reflective portions arranged to reflect the radiation received from the luminescent light absorber. These reflective portions are provided to prevent the light escaping from the light transmitter and/or to direct the light towards the light diffuser. The luminescent light absorber and the light diffuser could also comprise reflective portions arranged to retain light within the structure, e.g. to direct the light towards the desired parts of the system or to prevent the light escaping from the edges of a waveguide.

In general the light diffuser is arranged to out-couple the re-emitted radiation, received from the luminescent light absorber, from the light diffuser into the photobioreactor. Conveniently, the light diffuser comprises means arranged to diffuse the received radiation from a surface thereof, preferably an extended surface, e.g. a planar surface. As has been discussed previously, the light diffuser could be an extended waveguide e.g. planar or curved. This allows the radiation received by the light diffuser to be distributed through its volume and therefore emitted from a relatively large surface area. In one set of embodiments the light diffuser comprises micro-optical structures, e.g. micro-lenses, micro-prisms, micro-pyramids, diffractive grating structures, etc, arranged to diffuse light from the surface of the light diffuser. These micro-optical structures could be formed in the surface of the light diffuser itself, but in a preferred set of embodiments the micro-optical structures are provided on a thin film. The thin film could be laminated to an extended waveguide which could comprise part of the light diffuser or part of the light transmitter. Preferably the light diffuser is arranged to emit light uniformly over at least part of its surface area, e.g. by arranging micro-optical structures across the surface of the light diffuser. The micro-optical structures act as diffractive, refractive and/or reflective structures which are arranged to redirect light out of the light diffuser.

In a preferred set of embodiments the light diffuser comprises a separate structure from the luminescent light absorber, e.g. coupled to it via a light transmitter, but a set of embodiments is contemplated in which the light diffuser comprises an external surface of the luminescent light absorber, e.g. a surface of micro-optical structures which could be formed directly on the surface of the luminescent light absorber or provided on a thin film as discussed above. In this set of embodiments, incident solar radiation would typically be absorbed via one surface of the luminescent light absorber and out-coupled via another surface by the light diffuser.

The light diffuser could comprise any suitable shape, e.g. planar or cylindrical. It could also comprise different sections of different shapes. These could be arranged to conform to the shapes of the bioculture chambers in the photobioreactor. Likewise the illumination system need not be limited to having a single luminescent light absorber, a single light transmitter (if provided) and a single light diffuser; there could be a plurality of any or all of these components. This could be advantageous for larger photobioreactors which require incident solar radiation to be absorbed and distributed over a larger volume, e.g. it could be provided with multiple light diffusers for multiple different bioculture chambers.

In one set of embodiments the luminescent light absorber and/or the light transmitter (if provided) comprises one or more reflecting surfaces, e.g. mirrors, arranged to reflect light from the luminescent light absorber to the light diffuser. Preferably the one or more reflecting surfaces are arranged on or at the outer surfaces of the luminescent light absorber or light transmitter, e.g. the edges of a waveguide. By providing reflecting surfaces, the maximum amount of radiation re-emitted by the luminescent light absorber is coupled into the light diffuser without needing to ensure that every part of the luminescent light absorber from which radiation could escape is optically coupled to the light diffuser (via the light transmitter if provided).

The luminescent light absorber could comprise any suitable shape, e.g. an extended waveguide as discussed previously. In one set of embodiments, however, the luminescent light absorber comprises a triangular waveguide plate. The triangular waveguide plate is arranged to couple radiation re-emitted by the luminescent light absorber into light transmitters at one or more of the vertices of the triangular waveguide plate. Preferably the edges of the triangular waveguide plate comprise reflecting surfaces. The reflecting surfaces are arranged to reflect the radiation re-emitted by the luminescent light absorber so that as much of the re-emitted radiation as possible is coupled into the light transmitter (and then into the light diffuser) as discussed above.

The photobioreactor could simply comprise an open pond into which the illumination system is placed, wherein the illumination system is arranged to provide a uniform light distribution within the pond. However in a preferred set of embodiments the photobioreactor comprises one or more chambers for receiving biocultures, said chambers comprising transparent walls arranged to receive the radiation emitted from the illumination system, e.g. which either passes through the luminescent light absorber as discussed above, or which is emitted from the light diffuser. The chambers could be any suitable shape for cultivating the biocultures, e.g. sheets, plates or tubes. Chambers which have a large surface area arranged to received the radiation emitted from the illumination system and/or a thickness over which the intensity of the incident radiation is attenuated to around 5% (depending on the chosen absolute intensity) across the chamber, e.g. the thickness is the smallest dimension of the chamber, are advantageous for the efficient cultivation of biocultures as they will distribute the light relatively uniformly across the biocultures in the chamber. Two examples of suitable containers are therefore a long flattened tube or a set of spaced plates.

The one or more containers are preferably rigid to contain the biocultures, and preferably also sufficiently impermeable to carbon dioxide so to allow it to be introduced and not immediately diffuse out. A high permeability to oxygen is also desirable, but this is difficult to achieve when low permeability to carbon dioxide is also preferred. Any suitable material could be used for the containers, e.g. low density polyethylene, Poly(methyl methacrylate) (PMMA) or polycarbonate.

In one set of embodiments the one or more chambers comprise one or more channels arranged to allow the biocultures to be passed through the one or more channels. This allows the biocultures to be moved through the system so that the amount of light to which they are exposed can be controlled. Therefore preferably the photobioreactor also comprises a pump arranged to pump the biocultures through the one or more channels.

Conveniently the photobioreactor comprises means for supplying carbon dioxide to the biocultures, e.g. a carbon dioxide injection system, and/or means for removing oxygen gas, e.g. an oxygen gas removal system. The photobioreactor could also comprise a container for receiving a transparent fluid, e.g. water, wherein the transparent fluid receiving container is arranged to receive therewithin the one or more bioculture containers such that in use the one or more bioculture containers are at least partially submerged in the fluid. The fluid can, for example, be used to regulate the temperature of the biocultures. Additionally or alternatively the photobioreactor could comprise means for supplying temperature controlled fluid to the biocultures themselves, e.g. a temperature controlled water supply system. The means for supplying temperature controlled fluid could also be arranged to supply a nutrient solution.

To prevent biofouling of the light diffuser by the biocultures, preferably the light diffuser and/or the containers for the biocultures comprise a surface treatment arranged to minimise biofouling by biocultures, e.g. using polymers, a hydrophilic layer or an ultra-violet surface treatment.

Certain preferred embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Fig. 1 shows a schematic view of a photobioreactor and illumination system;

Fig. 2 shows a schematic view of an illumination system;

Fig. 3 shows a schematic view of two different arrangements for a light transmitter and light emitting surfaces for an illumination system;

Fig. 4 shows a schematic view of an arrangement from above of a luminescent light absorber and light transmitters for an illumination system; and

Fig. 5 shows a schematic view of a side view of the arrangement of Fig. 4.

Fig. 1 shows a schematic view of a photobioreactor and an associated illumination system 2 in accordance with the present invention. The photobioreactor comprises a thin plastic tube 4, e.g. made from low density polyethylene, which is fluidically connected between two end containers 6. Each of the end containers 6 comprises a low shear mixing pump 8 to pump algae 10 through the plastic tube 4, and a one-way gas outlet 12. The mixing pumps 8 are low shear to avoid unnecessary break up of the algae structure. At the lower end of the plastic tube 4 is an gas inlet 13 to inject carbon dioxide 14, e.g. from an industrial process, into the plastic tube 4.

The photobioreactor also comprises a tank 14 filled with water 16 in which the plastic tube 4 is submerged. The temperature of the water 16 is controlled to keep the algae 10 in the plastic tube 4 and the end containers 6 at a temperature which is suitable for optimum growth requirements.

Partially submerged within the water tank 14 is an illumination system 2 for illuminating the algae 10 in the plastic tube 4. The illumination system 2 comprises an upper luminescent light absorber 18 positioned above the plastic tube 4. The luminescent light absorber 18 is optically coupled to a light pipe 20, which in turn is optically coupled to a light diffuser 22 below the plastic tube 4 containing the algae 10.

The luminescent light absorber 18 comprises a planar waveguide coated with a fluorescent dye. The planar waveguide is arranged to be illuminated with solar radiation, with the fluorescent dye absorbing UV radiation which it re-emits as light in the red wavelength region of the visible spectrum. The light pipe 20 is arranged to couple light emitted by the fluorescent dye and trapped within the planar waveguide from the luminescent light absorber 18 to the light diffuser 22. The light diffuser 22 comprises a thin film laminated to the surface of the planar waveguide, with the thin film comprising a plurality of micro-structures which are arranged to out-couple the light from the planar waveguide to illuminate the plastic tube 4 containing the algae 10 from beneath.

In operation, algae 10 is placed into the end containers 6 of the photobioreactor from where it is pumped through the thin plastic tube 4 by the low shear mixing pumps 8. The pumps 8 can be arranged either to alternate the flow of algae from one end container 6 to another, or to circulate the algae through the photobioreactor (if a second tube is provided). Carbon dioxide 14 is injected into the plastic tube 4 through the gas inlet 12 where it mixes with the algae 10 so that it is available for use in photosynthesis. Water 16 in the tank 14 surrounding the end containers 6 and the plastic tube 4 containing the algae 10 is controlled to keep it at a temperature suitable for the chosen strain of algae which could be approximately 20°C to 30°C.

Solar radiation is incident upon the surface of the luminescent light absorber 18 above the plastic tube 4. The fluorescent dye coated onto the luminescent light absorber 18 absorbs UV radiation from the solar radiation spectrum, allowing the remaining radiation, i.e. infrared radiation and visible light, to pass through the luminescent light absorber 18 and be absorbed by the algae 10 for use in photosynthesis. The UV radiation absorbed by the fluorescent dye is re-emitted as red wavelength light, e.g. about 670 nm, of which the majority is trapped within the planar waveguide of the luminescent light absorber 18, with only some leaving the planar waveguide through its upper and lower surfaces.

The red wavelength light is waveguided from the luminescent light absorber 18 via the light pipe 20 to the light diffuser 22. The red light is then out-coupled from the light diffuser 22 via the thin film of micro-structures to be emitted across its surface area towards the plastic tube 4 containing the algae 10. The chlorophyll within the algae 10 has an absorption peak corresponding to red light, so the red light emitted from the light diffuser 22 is easily absorbed by the chlorophyll for efficient use in photosynthesis.

Fig. 2 shows a schematic view of a different embodiment of an illumination system 102 in accordance with the invention adjacent to plastic tubes 104 of a photobioreactor containing algae 110, but in a different configuration to the illumination system shown in Fig. 1. As in Fig. 1, the illumination system comprises a luminescent light absorber 118 optically coupled to a light pipe 120 which in turn is optically coupled to a light diffuser 122. Again, the luminescent light absorber 118 comprises a planar waveguide 124 coated with a fluorescent dye. The planar waveguide 124 is arranged to be illuminated with solar radiation 126, with the fluorescent dye being absorbent to UV radiation which it re-emits as light 129 in the red wavelength region of the visible spectrum. However in this embodiment, the light pipe 120 is simply an extension of the planar waveguide 124 of the luminescent light absorber 118, arranged to couple light emitted by the fluorescent dye and trapped within the planar waveguide 124 from the luminescent light absorber 118 to the light diffuser 122. The light diffuser 122 is a further extension of the planar waveguide 124 and comprises a thin film 128 laminated to the surface of the planar waveguide 124, with the thin film 128 comprising a plurality of micro-structures which are arranged to out-couple the light from the planar waveguide 124 to the plastic tubes 104 containing algae 110.

The illumination system of Fig. 2 operates in much the same way as the illumination system shown and described in Fig. 1.

Fig. 3 shows two schematic views of possible arrangements for the coupling of a light pipe to a light diffuser. In the left hand arrangement the light diffuser is provided by a thin film of micro-structures 30 which is laminated to the outer surface of the light pipe 32 in order to out-couple the light 34. In the right hand arrangement the light diffuser is provided by a planar waveguide 36 which on its surface has a thin film of micro-structures in order to out-couple the light 38 from the light pipe 35.

The embodiments of the light pipes shown in Fig. 3 only differ in the manner in which the light is coupled from the light pipe into the light diffuser and then leaves the light diffuser. In the left hand arrangement the light 34 is out-coupled directly from the light pipe 32 via the cylindrical micro-structured surface 30 of the light diffuser. In the right hand arrangement the light 38 is first coupled from the light pipe 35 into the light diffuser comprising a planar waveguide 36 (as in the other embodiments) from where it leaves via the micro-structured surface.

Figs. 4 and 5 show schematic views from above and the side respectively of another possible arrangement for an illumination system. As seen in Fig. 4, the luminescent light absorber 40 comprises triangular waveguide plates 42 (approximately 30 cm across) tessellated together with light pipes 44 at their common vertices. Each of the triangular waveguide plates 42 comprises mirrored edges 46 apart from at the vertices where the light pipes 44 are coupled. As can be seen from Fig. 5, the triangular waveguide plates 42 are provided above the plastic tube 48 which contains the algae 49, with the light pipes 44 coupling the light emitted by the triangular waveguide plates 42 to light diffusers 50 below the plastic tube 48 (as in Figs. 1 and 3). The light pipes 44 include mirrored surfaces 52 angled so to aid the coupling of light from the triangular waveguide plates 42 into the light pipes 44 and again from the light pipes 44 into the light diffusers 50. The edges 54 of the light diffusers 50, as well as the edges 46 of the triangular waveguide plates 42, are mirrored to retain light within the illumination system before it is emitted.

In the embodiments shown in Figs. 4 and 5, the red light re-emitted by the luminescent light absorber 40 is trapped within the triangular waveguide plates 42. The red light is waveguided from the triangular waveguide plates 42 and coupled into the light pipes 44 by being reflected by the mirrored edges 46 of the triangular waveguide plates 42 and the mirrored surfaces 52 at the top of the light pipes 44. The red light is then coupled into the light diffusers 50 below the plastic tube 48 containing the algae 49 via the mirrored surfaces 52 at the bottom of the light pipes 44. From here the red light leaves the diffusers 50 as in the embodiment shown in Fig. 2. In this embodiment close spatial relationships between respectively the light absorber 40 and the light diffuser with the algae chamber 48 ensures a high efficiency of light transfer.

It will be appreciated by those skilled in the art that many variations and modifications to the embodiments described above may be made within the scope of the various aspects of the invention set out herein. For example, the illumination system could comprise any arrangement of either a single or multiple luminescent light absorbers, which could be a number of different shapes, arranged in order to efficiently capture incident solar radiation. There could also be any arrangement of light diffusers in order to efficiently and uniformly illuminate the algae within the photobioreactor, and therefore with the necessary number of light transmitters, e.g. light pipes.

The specific embodiments described refer to an illumination system for a closed photobioreactor, however embodiments within the scope of the invention are also envisaged in which an illumination system is simply at least partially submerged in an open pond containing algae in order to provide uniform light to cultivate the algae.

Claims

1. An illumination system for a photobioreactor comprising a luminescent light absorber arranged to absorb at least a proportion of the incident solar radiation and to re-emit at least portion of the absorbed radiation, the system further comprising a light diffuser optically coupled to the luminescent light absorber and arranged to diffuse the re-emitted radiation for use in the photobioreactor.

2. An illumination system as claimed in claim 1 wherein the luminescent light absorber comprises an emission spectrum which differs from its absorption spectrum.

3. An illumination system as claimed in claim 1 or 2 wherein the luminescent light absorber comprises an extended waveguide.

4. An illumination system as claimed in claim 3 wherein the extended waveguide is straight or flat.

5. An illumination system as claimed in claim 3 or 4 wherein the light diffuser is coupled to the ends or edges of the extended waveguide of the luminescent light absorber and is arranged to receive and diffuse the radiation emitted from the ends or edges of the extended waveguide.

6. An illumination system as claimed in any preceding claim comprising a light transmitter arranged to receive radiation re-emitted from the luminescent light absorber and to transmit the radiation to the light diffuser.

7. An illumination system as claimed in claim 6 wherein the light transmitter comprises a waveguide.

8. An illumination system as claimed in claim 6 or 7 wherein the light transmitter comprises an extension of the luminescent light absorber.

9. An illumination system as claimed in claim 6, 7 or 8 wherein the light transmitter comprises an extension of the light diffuser.

10. An illumination system as claimed in any of claims 6 to 9 wherein the light transmitter comprises reflective portions arranged to reflect the radiation received from the luminescent light absorber.

11. An illumination system as claimed in any preceding claim wherein the luminescent light absorber and/or the light diffuser comprise reflective portions arranged to retain light within the illumination system.

12. An illumination system as claimed in any preceding claim wherein the light diffuser comprises micro-optical structures arranged to diffuse light from the surface of the light diffuser.

13. An illumination system as claimed in claim 12 wherein the micro-optical structures are provided on a thin film.

14. An illumination system as claimed in any preceding claim wherein the light diffuser is arranged such that light leaves it uniformly over at least part of its surface area.

15. An illumination system as claimed in any preceding claim wherein the light diffuser comprises a separate structure from the luminescent light absorber.

16. An illumination system as claimed in any preceding claim wherein the luminescent light absorber comprises one or more reflecting surfaces arranged to reflect light from the luminescent light absorber to the light diffuser.

17. An illumination system as claimed in claim 16 wherein the one or more reflecting surfaces are arranged on or at the outer surfaces of the luminescent light absorber.

18. An illumination system as claimed in any preceding claim wherein the luminescent light absorber is arranged to re-emit the incident solar radiation at a wavelength or wavelengths which are maximally used for photosynthesis.

19. An illumination system as claimed in any preceding claim wherein the luminescent light absorber comprises a fluorescent material.

20. An illumination system as claimed in claim 19 wherein the fluorescent material is arranged to absorb incident solar radiation in the UV wavelength range and emit light in the red wavelength range.

21. An illumination system as claimed in any preceding claim wherein the luminescent light absorber comprises a phosphorescent material, nanoparticles or a protein complex.

22. An illumination system as claimed in any preceding claim wherein the luminescent light absorber comprises an infrared or near-infrared reflecting material arranged to reflect incident infrared radiation within the incident solar radiation.

23. An illumination system as claimed in any preceding claim wherein the luminescent light absorber is arranged to allow at least a proportion of the incident solar radiation to pass through without being absorbed.

24. A photobioreactor comprising an illumination system as claimed in any preceding claim.

25. A photobioreactor as claimed in claim 24 comprising one or more chambers for receiving biocultures, said chambers comprising transparent walls arranged to receive the radiation emitted from the illumination system.

26. A photobioreactor as claimed in claim 25 wherein the one or more chambers comprises one or more channels arranged to allow the biocultures to be passed through the one or more channels.

27. A photobioreactor as claimed in claim 26 comprising a pump arranged to pump the biocultures through the one or more channels.

28. A photobioreactor as claimed in claim 25, 26 or 27 comprising means for supplying carbon dioxide to the biocultures.

29. A photobioreactor as claimed in any of claims 25 to 28 comprising a container for receiving a transparent fluid wherein container is arranged to receive therewithin the one or more bioculture chambers such that in use the one or more bioculture chambers are at least partially submerged in the fluid.

30. A photobioreactor as claimed in any of claims 25 to 29 wherein the light diffuser and/or the containers for the biocultures comprise a surface treatment arranged to minimise biofouling by biocultures.

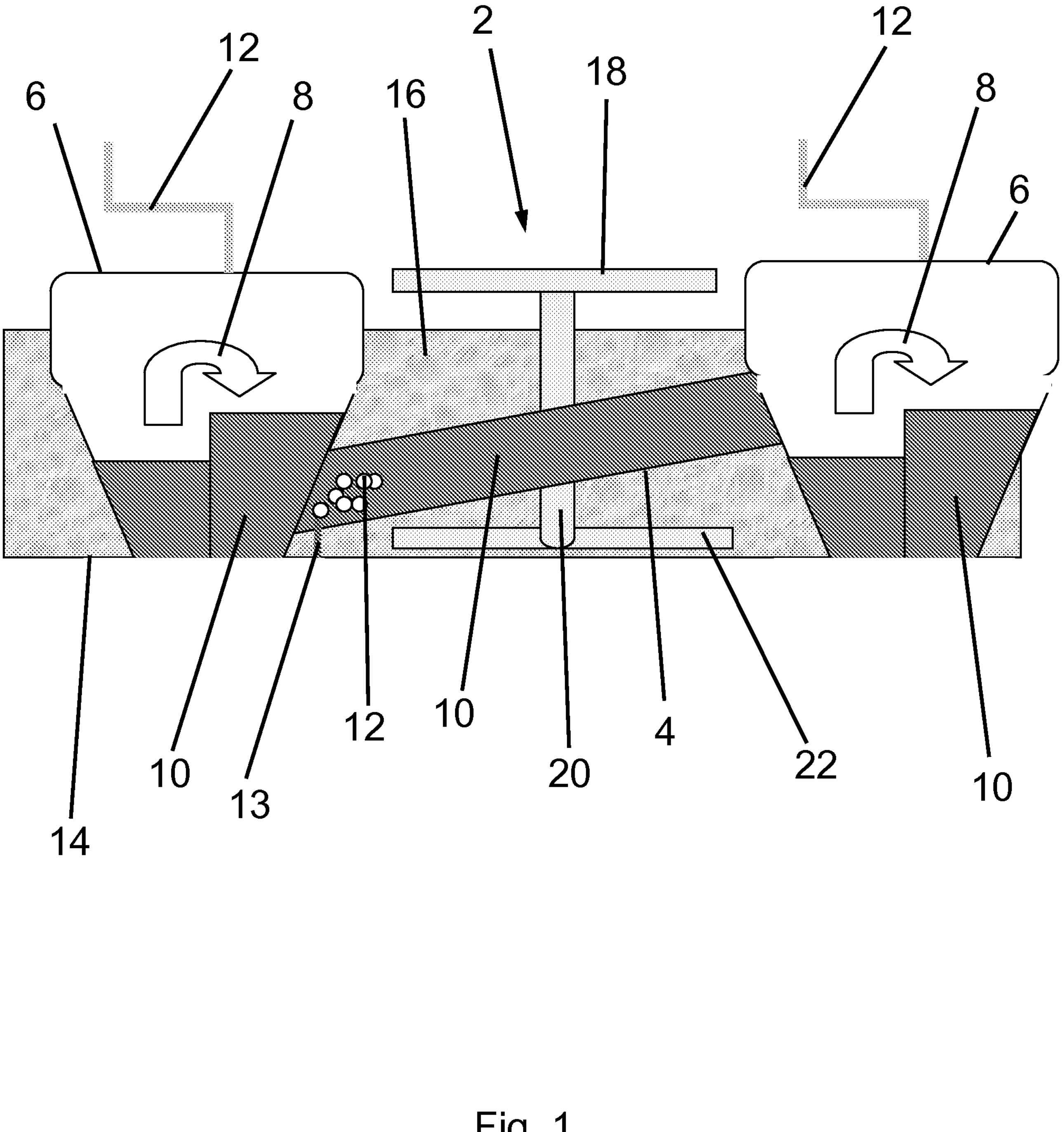

Fig. 1

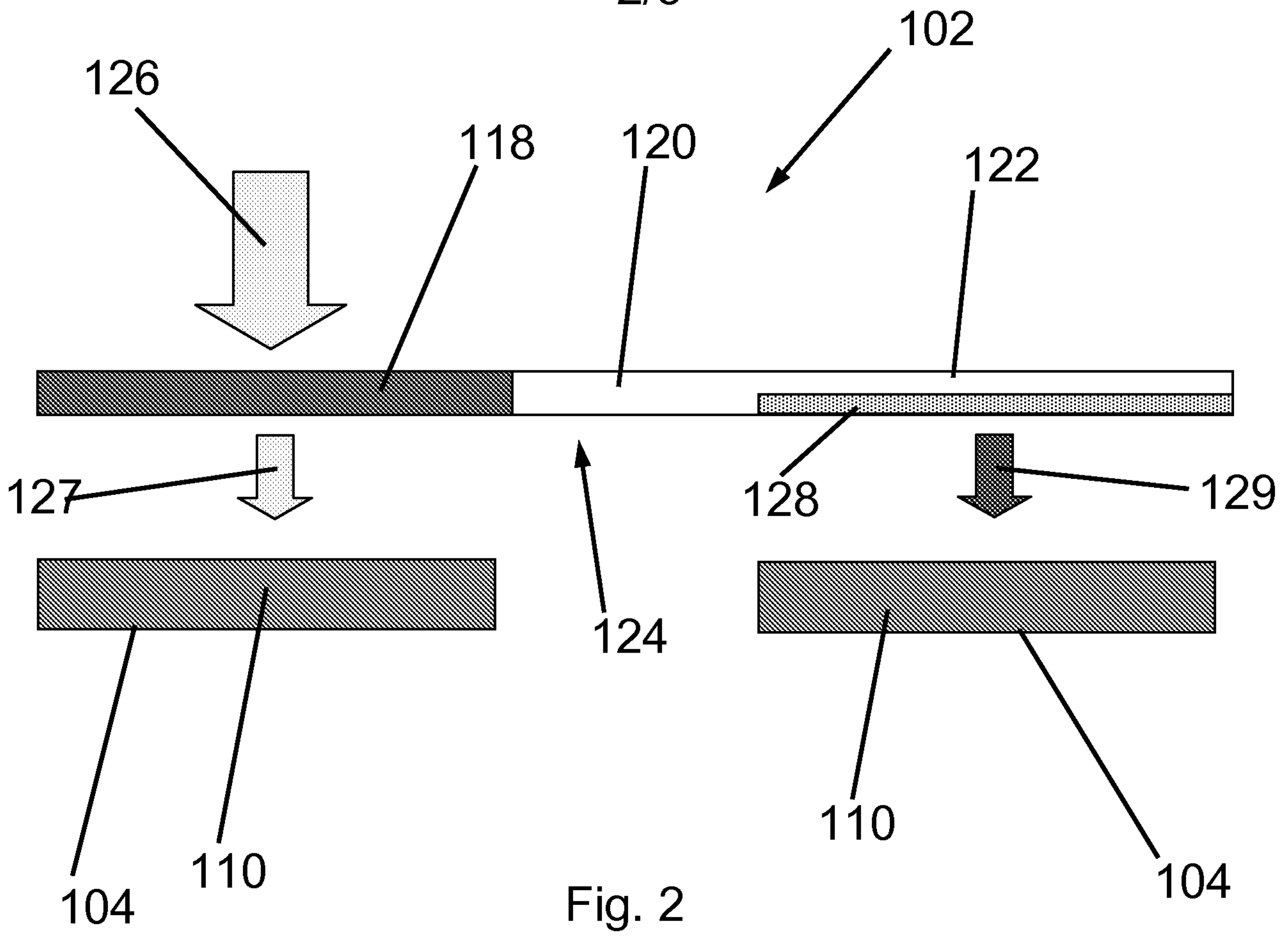
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Fig. 2

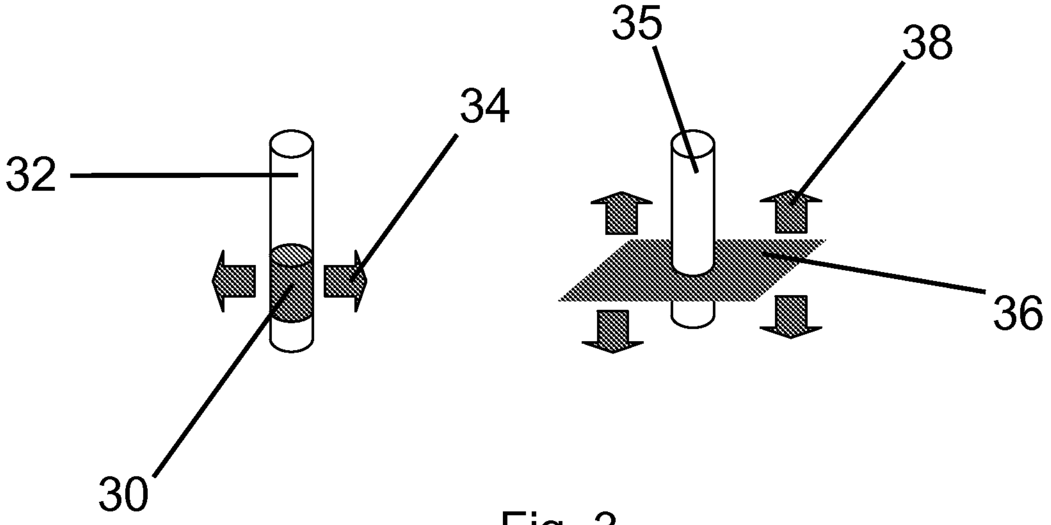
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Fig. 3

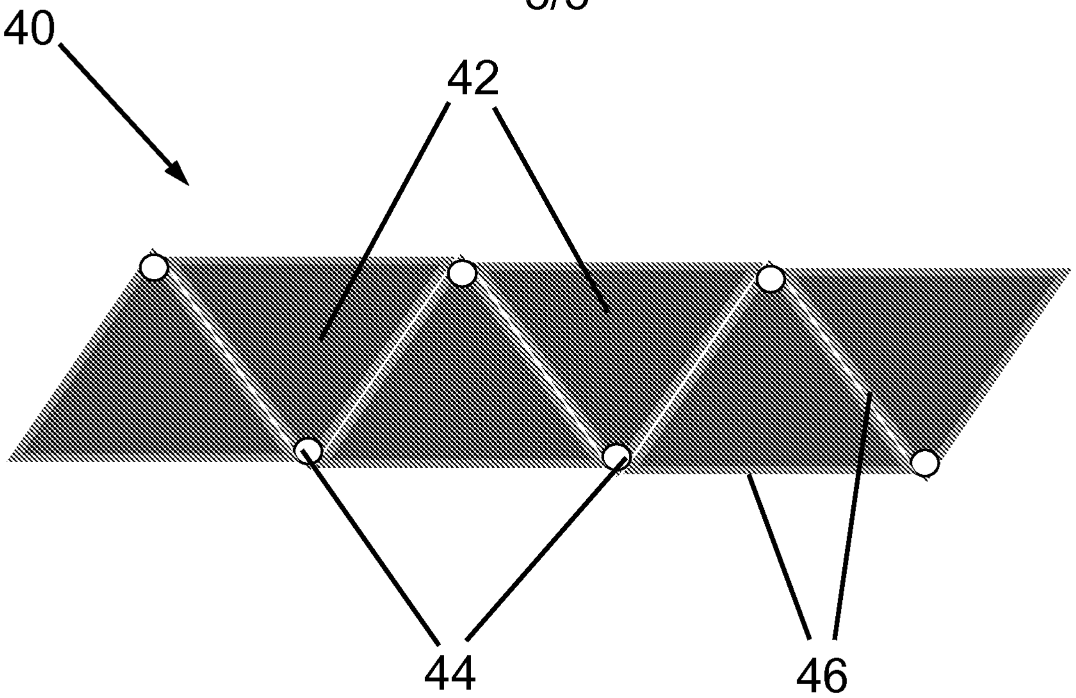

Fig. 4

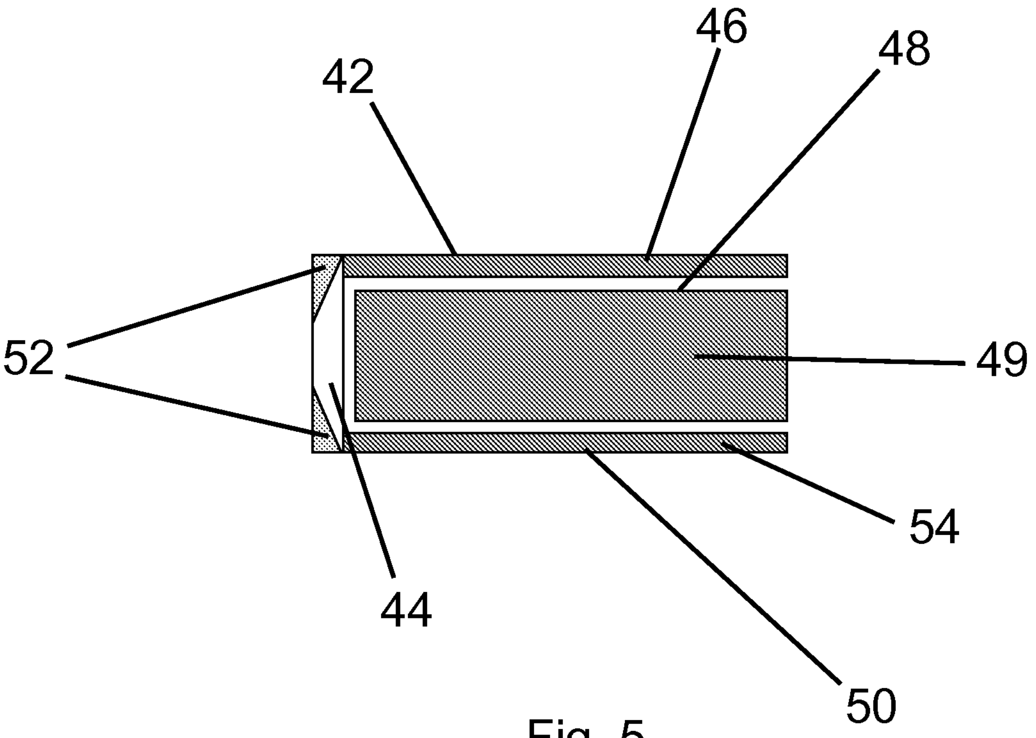

Fig. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2012/050260

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B6/00
ADD.

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)
G02B C12M C12N F21S

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 practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2010/085853 A1 (ZERO DISCHARGE PTY LTD [AU]; FALBER ALEXANDER [AU]) 5 August 2010 (2010-08-05) page 8, line 4 - line 11; figures 4a, 4e, 4f, 4g page 32, line 4 - line 8 page 2, line 32 - page 3, line 6 abstract page 25, line 39 - line 30 page 35, line 20 - line 25 -----	1-29
X	DE 197 46 343 A1 (DEUTSCH ZENTR LUFT & RAUMFAHRT [DE]; FRAUNHOFER GES FORSCHUNG [DE]) 22 April 1999 (1999-04-22) column 2, line 1 - line 15; figure 2 column 3, line 68 - column 4, line 15 abstract figure 1 page 42, line 9 - line 14 -----	1-26,30

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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

"E" earlier document but published on or after the international filing date

"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 18 April 2012	Date of mailing of the international search report 07/05/2012
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Jones, Julian

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2012/050260

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2010085853 A1	05-08-2010	CN 102378811 A	14-03-2012
		EP 2391705 A1	07-12-2011
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