

LIGHT CONCENTRATOR AND METHOD OF FORMING THE SAME**CROSS-REFERENCE TO RELATED APPLICATION**

[0001] This application claims the benefit of priority of Singapore application No. 10202303500X filed December 14, 2023, the contents of it being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] Various embodiments of this disclosure may relate to a light concentrator. Various embodiments of this disclosure may relate to a method of forming a light concentrator.

BACKGROUND

[0003] Refractive and reflective optical elements obey the conservation of “étendue”, where the product of the aperture area and the solid angle of acceptance remains constant. Consequently, increasing the optical gain of such elements results in a reduction of field-of-view (FOV). The maximum gain ($G_{\max}$) of a refractive element for a given FOV is defined by equation (1), where FOV is defined as twice the half-angle, $\theta_{\max}$.

$$G_{\max} = \frac{n^2}{\sin^2 \theta_{\max}} \quad (1)$$

[0004] For instance, an optical lens with a refractive index of 1.5 can achieve a high gain of 50, but with a smaller FOV of 24.5°. For a lens with a wide FOV of 180°, the maximum attainable gain will be 2.25. While large FOV detection has been achieved using non-fluorescence techniques such as microlens assemblies, their gains are limited by the conservation of étendue. This limitation constrains their applications in optical wireless communication and energy harvesting, where maximum light collection from any direction is essential.

[0005] A fluorescent light concentrator changes the frequency of the incident light within the fluorescent medium, enabling both high gain and wide FOV, without violating the second law of thermodynamics. The light concentration process in these systems relies not only on reflection and refraction, but also on light absorption and emission with Stokes shift. Consequently, the light reaching a photodiode (PD) through a fluorescent light concentrator is influenced by several factors including absorption efficiency, quantum yield of the fluorophore, scattering, re-absorption, coupling efficiency to the PD, geometrical gain, and total internal reflection. In recent years, there has been significant research interest in utilizing fluorescent concentrators to achieve high geometrical gain and wide FOV. These works have focused on developing optical antennas based on fluorescent materials with FOV of up to 120°. Along with variations in design, such antennas rely on large illuminating surface area for increasing optical gain. Demonstrations of fluorescent slabs with different colors for detecting different wavelengths with high spatial diversity have also been reported. Omnidirectional photodetection (360° FOV) has been established using a scintillating fiber bundle doped with organic dyes. However, achieving compact omnidirectional light collectors with high optical gain and efficiency of more than a few percent from fluorescent concentrators remains challenging. Only a small proportion of the light emitted isotropically within the fluorescent concentrator can be trapped by total internal reflection. Trapped light may be absorbed by self-absorption in the medium before it enters the PD. Imperfect coupling to the photodetector may also contribute to additional light leakage.

SUMMARY

[0006] Various embodiments may relate to a light concentrator. The light concentrator may include a matrix. The matrix may include a matrix material. The matrix may also include a plurality of luminophores in the matrix. The matrix may also include a plurality of optical

scatterers in the matrix. The light concentrator may also include a Bragg reflector layer in contact with an outer surface of the matrix, the Bragg reflector layer defining an opening.

[0007] Various embodiments may relate to a method of forming a light concentrator. The method may include forming a matrix. The matrix may include a matrix material. The matrix may also include a plurality of luminophores in the matrix. The matrix may further include a plurality of optical scatterers in the matrix. The method may also include forming a Bragg reflector layer in contact with an outer surface of the matrix, the Bragg reflector layer defining an opening.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily drawn to scale, emphasis instead generally being placed upon illustrating the principles of various embodiments. In the following description, various embodiments of the invention are described with reference to the following drawings.

FIG. 1 shows a general illustration of a light concentrator according to various embodiments.

FIG. 2 shows a general illustration of a method of forming a light concentrator according to various embodiments.

FIG. 3A show a schematic of a fluorescent concentrator (FC) according to various embodiments.

FIG. 3B shows a schematic illustrating the light detection and emission process in the fluorescent concentrator (FC) shown in FIG. 3A according to various embodiments.

FIG. 4A show a schematic of another fluorescent concentrator (FC) according to various embodiments.

FIG. 4B shows a schematic illustrating the light detection and emission process in the fluorescent concentrator (FC) shown in FIG. 4A according to various embodiments.

FIG. 5A shows a plot of absorbance (in arbitrary units or a.u.) as a function of wavelength (in nanometers or nm) illustrating the absorbance spectra of the resin matrix with the fluorescent dye, as well as the resin matrix with the fluorescent dye and the optical scatterers according to various embodiments.

FIG. 5B shows a plot of photoluminescence (in arbitrary units or a.u.) as a function of wavelength (in nanometers or nm) illustrating the absorbance spectra of the resin matrix with the fluorescent dye, as well as the resin matrix with the fluorescent dye and the optical scatterers according to various embodiments.

FIG. 5C shows a plot of gain / efficiency as a function of scattering particle concentration (in milligrams per milliliter or mg/ml) illustrating the gain and optical detection efficiency of the fluorescent concentrator (FC) with different concentrations of optical scatterers under 0-degree and 45-degrees illumination according to various embodiments.

FIG. 5D shows an azimuthal gain plot illustrating omnidirectional detection by a photodiode attached to a fluorescent concentrator (FC) having the matrix with the fluorescent dye (labelled as “fluorescent cube”), a fluorescent concentrator (FC) having the matrix with the fluorescent dye, as well as the Bragg reflector layer (labelled as “fluorescent cube with Bragg reflector”), and a fluorescent concentrator (FC) having the matrix with the fluorescent dye and optical scatterers, as well as the Bragg reflector layer (labelled as “fluorescent cube with optical scatterers and Bragg reflector”) according to various embodiments.

FIG. 6A shows a plot of transmittance (in percent or %) as a function of wavelength (in nanometers or nm) illustrating the angular-dependent transmittance of the Bragg reflector layer according to various embodiments from 0° to 75°.

FIG. 6B shows a plot of absorption (in arbitrary units or a.u.)/spectral radiant flux (in nano-Watts per nanometer or nW/nm) illustrating the absorbance and photoluminescence spectra of the fluorescent dye according to various embodiments.

FIG. 7A shows a plot of power (in mill-Watts or mW) / photocurrent (in milli-Amperes or mA) as a function of size (in millimeters or mm) illustrating increasing signal strength with increasing size of the fluorescent concentrator (FC) according to various embodiments.

FIG. 7B shows a plot of efficiency as a function of size (in millimeters or mm) illustrating the decreasing optical efficiency with increasing size of the fluorescent concentrator (FC) according to various embodiments.

FIG. 7C shows a plot of power (in milli-Watts or mW) as a function of size (in millimeters or mm) illustrating the simulated signal strength of a bare fluorescent concentrator (FC Bare), a fluorescent concentrator with a Bragg reflector layer (FC Bragg) and a fluorescent concentrator with a Bragg reflector layer and optical scatterers (FC Bragg & Particles) with varying sizes.

FIG. 7D shows a plot of photocurrent efficiency as a function of size (in millimeters or mm) illustrating the efficiency of a bare fluorescent concentrator (FC Bare), a fluorescent concentrator with a Bragg reflector layer (FC Bragg) and a fluorescent concentrator with a Bragg reflector layer and optical scatterers (FC Bragg & Particles) with varying sizes.

FIG. 8A shows a schematic of a polar irradiance setup according to various embodiments.

FIG. 8B shows a polar plot illustrating the gain recorded for each illumination angle for bare fluorescent concentrator (Bare-FC), fluorescent concentrator with Bragg reflector (Bragg-FC), fluorescent concentrator with Bragg reflector and optical scatterers (Bragg-SP-FC), a compound parabolic concentrator (CPC) and a photodiode (PD) according to various embodiments.

FIG. 8C shows a schematic of an azimuthal irradiance setup according to various embodiments. The light source and detector may be positioned at a 90-degree angle to each other. This

configuration may allow the light source to illuminate any facet adjacent to the PD-attached facet at the specified illumination angle.

FIG. 8D shows an azimuthal plot illustrating the gain recorded for each illumination angle for bare fluorescent concentrator (Bare-FC), fluorescent concentrator with Bragg reflector (Bragg-FC), fluorescent concentrator with Bragg reflector and optical scatterers (Bragg-SP-FC), a compound parabolic concentrator (CPC) and a photodiode (PD) according to various embodiments.

FIG. 8E shows a plot of yield as a function of sample measured comparing the signal leakage of the various samples according to various embodiments.

FIG. 9A shows a plot of signal (in decibels or dB) as a function of frequency (in MegaHertz or MHz) illustrating the bandwidth measurement of the fluorescent concentrator (FC) according to various embodiments.

FIG. 9B shows an eye diagram reflecting the detected optical signals of the fluorescent concentrator (FC) according to various embodiments sampled by the oscilloscope.

FIG. 10A shows a schematic of the system tested using a bare silicon photodiode (PD) and without a fluorescent concentrator (FC).

FIG. 10B shows a schematic of the system in which a fluorescent concentrator (FC) according to various embodiments is mounted onto the silicon photodiode (PD).

FIG. 10C shows a plot signal-to-noise ratio (SNR) (in decibels or dB) as a function of distance (in meters or m) illustrating the SNR of the fluorescent concentrator (FC) according to various embodiments compared to a bare photodiode (PD) as a function of distance.

DESCRIPTION

[0009] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be

practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0010] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0011] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0012] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance, e.g. within 10% of the specified value.

[0013] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0014] By “comprising” it is meant including, but not limited to, whatever follows the word “comprising”. Thus, use of the term “comprising” indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0015] By “consisting of” is meant including, and limited to, whatever follows the phrase “consisting of”. Thus, the phrase “consisting of” indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0016] Embodiments described in the context of one of the light concentrators are analogously valid for the other light concentrators, embodiments described in the context of a method are analogously valid for a light concentrator, and vice versa.

[0017] FIG. 1 shows a general illustration of a light concentrator according to various embodiments. The light concentrator may include a matrix 102. The matrix may include a matrix material 102a. The matrix may also include a plurality of luminophores 102b in the matrix 102. The matrix may also include a plurality of optical scatterers 102c in the matrix 102. The light concentrator may also include a Bragg reflector layer 104 in contact with an outer surface of the matrix 102, the Bragg reflector layer 104 defining an opening.

[0018] In other words, various embodiments may relate to a light concentrator (alternatively referred to as a “fluorescent concentrator” or “FC”) including a matrix 102 made of a matrix material 102a, as well as luminophores 102b (e.g., fluorophores or phosphors) and optical scatterers 102c dispersed or embedded in the matrix 102. The light concentrator may include a Bragg reflector layer 104 (also referred to as “Bragg film” or “Bragg reflector coating”) covering the matrix 102, except for an opening (alternatively referred to as an “exit window”, “uncoated exit window” or “exit channel”).

[0019] For avoidance of doubt, FIG. 1 seeks to illustrate various features of the light concentrator according to various embodiments, and is not intended to limit e.g., the orientation, arrangement, shapes, sizes etc. of the various embodiments. For instance, while FIG. 1 shows that the luminophores 102b have triangular shapes and the optical scatterers 102c have circular shapes, these shapes are purely for illustration purposes, and the luminophores 102b and the optical scatterers 102c may be of any suitable shapes.

[0020] In various embodiments, the incident light may be omnidirectional light. In other words, the incident light may be provided to the light concentrator in all directions. In other words, the light may be incident on the light concentrator from multiple directions at the same

time. In various other embodiments, the incident light may be directional light. The incident light may come at certain directions. In other words, the incident light may be provided to the light concentrator at any incident angle.

[0021] In various embodiments, the plurality of luminophores 102b may be configured to absorb incident light of a predetermined wavelength or range of wavelengths, and further configured to emit wavelength-converted light of another predetermined wavelength or range of wavelengths upon absorption of the incident light. The plurality of optical scatterers 102c may be configured to scatter the incident light and/or the wavelength-converted light.

[0022] The Bragg reflector layer 104 may be configured to allow a fraction of the incident light traveling from outside the light concentrator to pass through to the matrix 102, and may be further configured to reflect a fraction of the wavelength-converted light traveling from the matrix 102 towards outside the light concentrator back to the matrix 102. The Bragg reflector layer 104 may be configured to allow a remaining fraction (which may be relatively smaller compared to the fraction that is reflected) of the wavelength-converted light traveling from the matrix 102 to pass through to outside the light concentrator. Generally speaking, the reflectance of the Bragg reflector layer 104 may be dependent on the wavelength of the light passing through the Bragg reflector layer 104 as well as the angle of incidence of the light on the Bragg reflector layer 104. In various embodiments, the fraction of the incident light allowed to pass through to the matrix 102 may be greater than the remaining fraction of the wavelength-converted light allowed to pass through to outside the light concentrator. The opening may be configured to allow the wavelength-converted light to pass through.

[0023] In various embodiments, the other predetermined wavelength or range of wavelengths may be longer than the predetermined wavelength or range of wavelengths. In other words, the incident light may be down-converted or down-shifted. For down-conversion, a high energy photon may be absorbed to emit multiple low energy photons, while for down-

shifting, a high energy photon may be absorbed to emit a low energy photon. In various other embodiments, the other predetermined wavelength or range of wavelengths may be shorter than the predetermined wavelength or range of wavelengths. In other words, the incident light may be up-converted. For up-conversion, multiple low energy photons may be absorbed to emit a high energy photon.

[0024] In various embodiments, the other predetermined wavelength or range of wavelengths may be chosen to have a higher peak photodetection responsivity compared to the predetermined wavelength or range of wavelengths. The responsivity of the photodetector may or may not be higher at the converted wavelengths (i.e., the other predetermined wavelength or range of wavelengths) compared to the incident wavelengths (i.e., the predetermined wavelength or range of wavelengths). In some cases, depending on the wavelengths and the photodetector, a photodetection responsivity of the photodetector at the other predetermined wavelength or range of wavelengths may be higher or lower than a photodetection responsivity of the photodetector at the predetermined wavelength or range of wavelengths.

[0025] The Bragg reflector 104 may be configured to reflect the fraction of the wavelength-converted light (i.e., the down-converted, down-shifted, or up-converted light) via wavelength-selective Bragg reflection and total internal reflection. In other words, assuming that the refractive index of the matrix is higher than the environment/medium external to the light concentrator, the wavelength-converted light from the matrix 102 approaching the outer surface of the matrix 102 at angles greater than the critical angle may be reflected back to the matrix 102 due to total internal reflection. Further, the Bragg reflector 104 may be able to reflect most of the remaining wavelength-converted light traveling from the matrix 102 towards outside the light concentrator back to the matrix 102 via the wavelength-selective Bragg reflection.

[0026] The matrix material 302a may be any suitable material. Generally speaking, the matrix material 302a may be transparent or substantially transparent to the incident light and

the wavelength-converted light. In various embodiments, the matrix material 302a may be a polymeric resin material (also referred to as a “resin medium” or “polymer matrix material”), such as an epoxy based polymer or an acrylic based polymer. The matrix 302 may also be referred to as a “resin matrix”.

[0027] In various embodiments, the optical scatterers 102c may be optical scattering particles. In various embodiments, the plurality of optical scatterers 102c may include silicone resin powder particles, silicon dioxide particles or titanium dioxide particles.

[0028] The plurality of luminophores 102b may be any suitable structures that are configured to absorb incident light of a predetermined wavelength or range of wavelengths, and further configured to emit wavelength-converted light of another predetermined wavelength or range of wavelengths (lapping or non-overlapping with the predetermined range of wavelengths of the incident light) upon absorption of the incident light. In various embodiments, the plurality of luminophores 102b may include organic dyes, quantum structures (e.g., quantum dots), perovskites or lanthanides. The organic dyes may include, for instance, dyes such as Coumarin, Fluorescein, or Rhodamine. The quantum structures may be, for instance, cadmium selenide, indium phosphide, or zinc selenide quantum structures /dots. The perovskites may include, for instance, lead halide perovskites. The lanthanides may include, for instance, erbium ions doped nanocrystals. The Bragg reflector layer 104 may include alternating sub-layers of materials having different refractive indexes. For instance, the Bragg reflector layer 104 may include alternate sublayers of aluminum arsenide (AlAs) and gallium arsenide (GaAs), or alternate sublayers of titanium dioxide (TiO₂) and silica (SiO₂). The luminophores 102b and the Bragg reflector layer 104 selected may be dependent on the wavelength or range of wavelengths of the wavelength converted light required. AlAs/GaAs may be used to confine near infrared light, while TiO₂/SiO₂ may be used to confine visible light.

[0029] In various embodiments, the light concentrator may further include a photodetector, such as a photodiode. In various embodiments, the photodetector may be a p-i-n photodiode (i.e., a photodiode having a p doped region – intrinsic region – n-doped region), an avalanche photodiode, a silicon photomultiplier or a photomultiplier tube.

[0030] FIG. 2 shows a general illustration of a method of forming a light concentrator according to various embodiments. The method may include, in 202, forming a matrix. The matrix may include a matrix material. The matrix may also include a plurality of luminophores in the matrix. The matrix may further include a plurality of optical scatterers in the matrix. The method may also include, in 204, forming a Bragg reflector layer in contact with an outer surface of the matrix, the Bragg reflector layer defining an opening.

[0031] In other words, the method of forming a light concentrator may include forming the matrix including the matrix material, the luminophores and the optical scatterers. The method may also include forming a Bragg reflector layer on an outside of the matrix, except for a predetermined area which serves as an opening.

[0032] In various embodiments, step 204 may occur after step 202.

[0033] In various embodiments, the plurality of luminophores may be configured to absorb incident light of a predetermined wavelength or range of wavelengths, and further configured to emit wavelength-converted light of another predetermined wavelength or range of wavelengths upon absorption of the incident light. The plurality of optical scatterers may be configured to scatter the incident light and the wavelength-converted light. The Bragg reflector layer may be configured to allow a fraction of the incident light traveling from outside the light concentrator to pass through to the matrix, and may be further configured to reflect a fraction of the wavelength-converted light traveling from the matrix towards outside the light concentrator back to the matrix. The Bragg reflector layer may be configured to reflect a higher fraction of the wavelength-converted light to travel within the matrix 102 than to pass through

to outside of the light concentrator. The opening may be configured to allow the wavelength-converted light to pass through.

[0034] In various embodiments, the other predetermined wavelength or range of wavelengths may be longer than the predetermined wavelength or range of wavelengths. In various other embodiments, the other predetermined wavelength or range of wavelengths may be shorter than the predetermined wavelength or range of wavelengths.

[0035] In various embodiments, the other predetermined wavelength or range of wavelengths may be chosen to have a higher peak photodetection responsivity compared to the predetermined wavelength or range of wavelengths.

[0036] In various embodiments, the Bragg reflector may be configured to reflect the fraction of the wavelength-converted light via wavelength-selective Bragg reflection and total internal reflection.

[0037] In various embodiments, the incident light may be omnidirectional light. In various other embodiments, the incident light may be directional.

[0038] In various embodiments, the plurality of optical scatterers may include silicone resin powder particles, silicon dioxide particles or titanium dioxide particles.

[0039] In various embodiments, the plurality of luminophores may include organic dyes, quantum structures, perovskites or lanthanides.

[0040] In various embodiments, the method may further include a photodetector. The photodetector may be a p-i-n photodiode, an avalanche photodiode, a silicon photomultiplier or a photomultiplier tube.

[0041] In various embodiments, the matrix material may be a polymeric resin material.

[0042] FIG. 3A show a schematic of a fluorescent concentrator (FC) according to various embodiments. The fluorescent concentrator (FC) may include a fluorescent dye 302b (i.e., fluorophores) that is mixed with optical scatterers, e.g., scattering particles 302c and

incorporated into the resin matrix including the resin medium 302a. This resin matrix can be molded into various shapes, such as cubes, prisms, or films, according to specific size requirements. Increasing the size of the device may result in a larger effective collection area, which, in turn, may lead to higher signal collection. However, it is important to note that this may also reduce the optical collection efficiency and may increase the overall size of the detector system. Additionally, by embedding optical scatterers 302c in the resin medium 302a, light scattering towards the output and absorption by the fluorescent dye 302b can be enhanced, resulting in higher optical gain and efficiency. The cast matrix may also be coated with a Bragg reflector layer 304 on its surface to improve light confinement. A region of the surface of the resin matrix may be intentionally left uncoated to act as an exit channel or aperture. A photodiode 306 may be arranged or attached to the exit channel to collect or detect light exiting from the exit channel or aperture.

[0043] FIG. 3B shows a schematic illustrating the light detection and emission process in the fluorescent concentrator (FC) shown in FIG. 3A according to various embodiments. A light source (e.g., laser source, light emitting diode (LED), or broadband white light etc.) emitting in the visible to near infra-red spectrum (350 nm to 1800 nm) may be used to illuminate the FC. The FC may interact with the incident light from all directions (0 to 360 degrees) with minimal alignment requirement. The incident light may pass through the resin and may get absorbed by the fluorescent dye embedded in the resin medium. The light that is not directly absorbed by the fluorescent dye may interact with the optical scatterers in the resin matrix. The light thus scattered may also get absorbed by the fluorescent dye along its path. The fluorescent dye may convert the absorbed wavelength to a different wavelength (i.e., wavelength-converted light). The emission from the fluorescent dye may be confined within the resin matrix using Bragg reflection and total internal reflection. The emitted light can further interact with the optical scatterers, while traversing inside the resin matrix, and may get scattered and redirected to the

uncoated exit window after multiple reflections, to be collected by the photodiode attached to the exit window.

[0044] FIG. 4A show a schematic of another fluorescent concentrator (FC) according to various embodiments. The fluorescent concentrator (FC) may be in the form of a cube for omnidirectional light collection and ease of fabrication. The fluorescent concentrator (FC) may include a fluorescent matrix cube 402 including a polymer matrix material 402a, fluorescent particles 402b and optical scatterers, e.g., scattering particles 402c. The fluorescent concentrator (FC) may also include a Bragg reflector coating 404. An uncoated portion (i.e., section of the surface of the fluorescent matrix cube intentionally left uncovered by the Bragg reflector coating) may serve as an exit channel.

[0045] FIG. 4B shows a schematic illustrating the light detection and emission process in the fluorescent concentrator (FC) shown in FIG. 4A according to various embodiments. When exposed to near-ultraviolet (near-UV) light (405 nm), the light may propagate through the Bragg reflector coating and may be absorbed by the embedded fluorescent particles in the matrix cube. The fluorescent particles may then down-convert the absorbed light to a longer green-yellow wavelength (475 nm – 650 nm) and may isotropically emit the down-converted light into the surrounding polymer matrix material. The down-converted light may be confined in the fluorescent concentrator (FC) via total internal reflection (TIR) and wavelength-selective Bragg reflection. When the scattered light hits the internal surface of the FC (i.e., the interface between the fluorescent matrix cube and the Bragg reflector coating) with an angle larger than the critical angle of 40° , the scattered light may be trapped within the FC by TIR. To enhance light confinement, the Bragg reflector coating may be employed, allowing incident near-UV light to pass through while confining the down-converted light within the FC. The Bragg reflector coating may specifically confine scattered light incident on the inner surface at angles smaller than the critical angle of 40° . The exit channel may allow preferential light coupling to

an external photodetector. Consequently, the down-converted light may be preferentially emitted through the exit channel, optimizing its butt coupling into a photodiode (PD). A fluorescent image of the fabricated FC with emission coming out from the exit channel upon the FC being excited with 405 nm wavelength is shown in (v) of FIG. 4B.

[0046] **Experiment 1**

[0047] **Materials**

[0048] An epoxy-based system via nucleophilic ring opening is used as the resin medium. The materials may include epoxy resin 2,2-Bis[4-(glycidyloxy) phenyl] propane (D.E.R 332) and curing agent Isophorone Diamine (IPDA) to form the resin medium, Coumarin 545T as the fluorescent dye, silicone resin powder as optical scatterers, as well as the Bragg reflector layer.

[0049] **Fabrication**

[0050] The fabrication of the fluorescent concentrator may include a low-cost method suitable for casting. The epoxy resin (D.E.R. 332) and the curing agent (IPDA) may be mixed at a proportion that results in minimal shrinkage and warpage, thereby forming the resin medium. The desired concentration of fluorescent dye material may first be solvated in a solvent and may then be dispersed in the resin medium and mixed well to form the fluorescent dye.

[0051] **Measurements And Discussion**

[0052] The scattering particle powder may be measured for the desired concentration of the optical scatterers in the resin medium and may be solvated in a solvent to ensure homogeneous dispersion when the solution is mixed with the resin medium. The resin medium may be mixed with the fluorescent dye and the optical scatterers, and the mixture may be sonicated to ensure uniform mixing and removal of bubbles incorporated during the vigorous mixing process. Any remaining bubbles and residual solvent may be removed by vacuum degassing the mixture before the mixture is poured into a silicone mold. The silicone mold with the mixture may be left undisturbed for curing at room temperature to form the resin matrix. After fully curing, the

Bragg reflector layer may be applied on the surfaces of the resin matrix to form the FC. The FC may be in the form of a cube.

[0053] Coumarin 545T, which is used as the fluorescent dye, may absorb blue light (400 nm – 500 nm) well, and may down convert the energy to emit longer wavelength green (500 nm – 600 nm), as shown by FIGS. 5A – B. FIG. 5A shows a plot of absorbance (in arbitrary units or a.u.) as a function of wavelength (in nanometers or nm) illustrating the absorbance spectra of the resin matrix with the fluorescent dye, as well as the resin matrix with the fluorescent dye and the optical scatterers according to various embodiments. FIG. 5B shows a plot of photoluminescence (in arbitrary units or a.u.) as a function of wavelength (in nanometers or nm) illustrating the absorbance spectra of the resin matrix with the fluorescent dye, as well as the resin matrix with the fluorescent dye and the optical scatterers according to various embodiments. It can be seen that the addition of the optical scatterers to the resin matrix may enhance the absorption and emission characteristics.

[0054] The light concentrating ability of the fluorescent concentrator (FC) is evaluated for varying scattering particle concentration using ray tracing simulations. FIG. 5C shows a plot of gain / efficiency as a function of scattering particle concentration (in milligrams per milliliter or mg/ml) illustrating the gain and optical detection efficiency of the fluorescent concentrator (FC) with different concentrations of optical scatterers under 0-degree and 45-degrees illumination according to various embodiments.

[0055] The fluorescent concentrator (FC) may allow light detection by a photodiode over 360-degree angle of incidence. FIG. 5D shows an azimuthal gain plot illustrating omnidirectional detection by a photodiode attached to a fluorescent concentrator (FC) having the matrix with the fluorescent dye (labelled as “fluorescent cube”), a fluorescent concentrator (FC) having the matrix with the fluorescent dye, as well as the Bragg reflector layer (labelled as “fluorescent cube with Bragg reflector”), and a fluorescent concentrator (FC) having the

matrix with the fluorescent dye and optical scatterers, as well as the Bragg reflector layer (labelled as “fluorescent cube with optical scatterers and Bragg reflector”) according to various embodiments. It can be seen that the fluorescent cube with the optical scatterers shows two times improvement in the gain compared to the fluorescent cube without the optical scatterers for the same dye concentration.

[0056] **Experiment 2**

[0057] **Simulation**

[0058] Ray-tracing simulations may be done using the non-sequential mode of Zemax OpticStudio (Ansys, Inc.) to model the performance of the FC. The FC may be defined as a solid with the refractive index of PMMA (1.5) and may have a Bragg coating defined on all six sides of the cube. A rectangular cutout may be made in the bottom face of the cube to allow the light to escape and be collected by the photodetector. The fluorescence of the dye may be implemented using the Phosphors and Fluorescence model which may take the absorption, emission and quantum yield spectra, extinction coefficient at 405 nm and fluorescent particle density as inputs. The spectra and extinction coefficient may be obtained from experimental photometric measurements of the fluorescent dye, while the fluorescent particle density may be given by the ratio of its density to its molar mass. The source may be defined as a point source with a wavelength of 405 nm and cone divergence of 2.5°. One million rays may be launched for higher accuracy and the simple ray tracing approach used to reduce file size. A two dimensional (2D) planar detector may be placed 0.006 mm below the bottom of the cube to measure the flux of light that escaped from the cube. The simulations may then be repeated for different cube sizes and for bare cubes without a Bragg coating.

[0059] **Fabrication**

[0060] The resin matrix may include D.E.R 332 as the epoxy and isophorone diamine as the crosslinking agent. Coumarin dye may be mixed with silica (SiO₂) optical scatterers into the

resin. The resin mixture may then be sonicated at room temperature to ensure uniform mixing and removal of bubbles incorporated due to the vigorous mixing. Once the resin matrix is free of any bubbles, it may be degassed to remove any left over micro bubbles and the solvents. Then, the resin may then be poured into the silicone molds to form the cubes. The resin filled molds may be allowed to cure at room temperature for 24 hours to ensure that the polymer is fully crosslinked. Once the cube is formed, it may be demolded and attached with Bragg reflector layer on all sides of the cube facets.

[0061] Measurements And Discussion

[0062] FIG. 6A shows a plot of transmittance (in percent or %) as a function of wavelength (in nanometers or nm) illustrating the angular-dependent transmittance of the Bragg reflector layer according to various embodiments from 0° to 75°. The Bragg reflector layer is shown to have a transmission range of about 350 nm to 410 nm. The graph shows that near-ultraviolet (near-UV) light with a wavelength of 405 nm is an ideal source, as it achieves 80% transmission from 0° up to 60° angle of incidence (AOI), and still maintains over 60% transmission at AOI greater than 75°. This high transmission may ensure that more light enters the polymer matrix of the FC. Additionally, at normal incidence, green and red wavelengths (520 nm – 780 nm) are efficiently back-reflected, which may help to confine the down-converted light within the FC before it is preferentially channeled out. The bandgap of the Bragg reflector layer may be observed to blue shift with an increase in the incident angle. Accordingly, there may be a corresponding blue shift in the reflectance band with increasing incident angles, which narrows the optimal reflectance band to 550 nm – 600 nm. Therefore, for effective light confinement within the FC, it may be crucial for the emission wavelength of the fluorescent material to overlap with this range. A coumarin-based fluorophore may be suitable as the fluorescent dye, as it absorbs blue light (400 nm – 500 nm) and down-converts the energy to emit longer wavelengths (500 nm – 600 nm). The absorption and photoluminescence spectra of fluorescent

dye measured with an integrating sphere are shown in FIG. 6B. FIG. 6B shows a plot of absorption (in arbitrary units or a.u.)/spectral radiant flux (in nano-Watts per nanometer or nW/nm) illustrating the absorbance and photoluminescence spectra of the fluorescent dye according to various embodiments. The peak absorbance of the fluorescent dye may be in the near-UV region. The emission band of the fluorescent dye may fall within the stopband of the chosen Bragg reflector, which leads to efficient trapping and harvesting of the emitted radiation at the exit aperture of the FC.

[0063] The light collecting and concentrating ability of the FC was initially assessed using ray tracing methods and subsequently validated experimentally based on three key performance metrics: (a) signal strength, (ii) optical efficiency, and (iii) omnidirectionality. The first two metrics may be illustrated in FIG. 7A – B across a range of different cube sizes.

[0064] Illumination for each cube may be carried out with a 405 nm LED source directed perpendicular to one of its side facets. The light may then be coupled to a photodiode (PD) through an aperture on the bottom facet, ensuring that the incident light is at a 90-degree angle to the PD surface (at this angle, a simple bare PD without the FC would not be able to detect any light). This setup may effectively highlight the FC's capability to collect light from extreme angles and redirect light towards the PD (refer to "Simulation" section above for the details of the setup). To maintain consistency, parameters such as the light source, output channel size (a square uncoated section of the cube measuring 3×3 mm), and PD dimensions (3.6×3.6 mm) are kept constant. The cube length is varied from 8 mm to 24 mm, measuring the power captured by the PD. The output channel may be intentionally designed to be slightly smaller than the PD to optimize coupling.

[0065] FIG. 7A shows a plot of power (in mill-Watts or mW) / photocurrent (in milli-Amperes or mA) as a function of size (in millimeters or mm) illustrating increasing signal strength with increasing size of the fluorescent concentrator (FC) according to various

embodiments. As the surface area of the cube's side facet increases, more light can be collected. However, the ray tracing simulations show that this increase may not be linear, but may instead plateau at a cube length of 22 mm. The result shows that increasing the cube surface area by 9-fold (comparing the surface areas of a 24 mm cube to an 8 mm cube), may correspond to an 8.8-fold increase in incident light intensity. However, as illustrated in FIG. 7A, the signal coupled to the PD may only show a 3.08-fold increase, which is validated by experimental data.

[0066] FIG. 7B shows a plot of efficiency as a function of size (in millimeters or mm) illustrating the decreasing optical efficiency with increasing size of the fluorescent concentrator (FC) according to various embodiments. Optical efficiency may be defined as the ratio of the photocurrent collected at the PD and the equivalent photocurrent incident on the FC. For comparison with the computational simulations, this may be calculated by comparing the power of light collected at the PD to the power of light incident on the surface of the PD, factoring in photon energy and PD responsivity (see Equation 2).

[0067] The result indicates that optical efficiency may decrease as the cube size increases. Despite the larger surface area for light collection, bigger FC sizes may lead to reduced efficiency, which explains the plateaued signal collection observed in FIG. 7A. This reduction in efficiency with increasing cube size can be attributed to increased reabsorption of down-converted light, which diminishes the overall efficiency due to the quantum efficiency (i.e., photoluminescence quantum yield, PLQY) of the fluorescent material. This reabsorption phenomenon may be possible as the absorption and emission spectra of the fluorophore overlap within the wavelength range of 480 nm to 520 nm (FIG. 6B). As the cube size increases, the likelihood of multiple reabsorptions significantly increases, causing a substantial drop in the FC's optical efficiency. FIG. 7B shows that a 27-fold increase in volume (i.e., from an 8 mm cube to a 24 mm cube) results in a 2.85-fold decrease in efficiency – from 35.6% to 12.5%.

Therefore, when selecting the FC size, both signal strength and efficiency may be required to be considered.

$$\eta_{optical} = \eta_{power} * \frac{E_{photon@405\text{ nm}}}{E_{photon@520\text{ nm}}} * \frac{QE_{photodiode@520\text{ nm}}}{QE_{photodiode@405\text{ nm}}} \quad (2)$$

where $\eta_{optical}$ represents optical efficiency, η_{power} represents power efficiency, $E_{photon@405\text{ nm}}$ represents photon energy of light at 405 nm, $E_{photon@520\text{ nm}}$ represents photon energy of light at 520 nm, $QE_{photodiode@405\text{ nm}}$ represents quantum efficiency of light at 405 nm, $QE_{photodiode@520\text{ nm}}$ represents quantum efficiency of light at 520 nm.

[0068] The 16 mm cube is selected as a prototype for further investigation, because it provides sufficient signal strength for optical communication applications, while maintaining high efficiency.

[0069] In the initial investigation, the bare FC, i.e., FC without any coating, exhibited persistently low signal collection and efficiency. The bare FC relied on scattering and total internal reflection (TIR) to gather and redirect/bend light towards the PD, which may not be effective. Subsequently, the FC may be enhanced by applying a Bragg reflector coating, which increased the signal collection significantly in simulations (described below).

[0070] Experimentally, an increase in the received signal of 5 – 7 times was observed. By leveraging color conversion and wavelength-selective confinement, the integration of Bragg reflectors may significantly augment the FC's light collection efficiency and its effectiveness in capturing light compared to FCs without Bragg reflectors, which solely rely on the TIR mechanism. Furthermore, incorporating optical scatterers into the FC medium with Bragg reflectors may be shown to improve signal collection and efficiency. This performance enhancement can be attributed to intensified scattering, which may reduce the mean free path and may promote more efficient color conversion. For a 16 mm cube, the simulations indicate

a 1.99-fold improvement in signal collection, while experimental observations demonstrate a 1.93-fold enhancement.

[0071] The data illustrated in FIGS. 7C – D are in relation to simulation studies of fluorescent cubes. FIG. 7C shows a plot of power (in milli-Watts or mW) as a function of size (in millimeters or mm) illustrating the simulated signal strength of a bare fluorescent concentrator (FC Bare), a fluorescent concentrator with a Bragg reflector layer (FC Bragg) and a fluorescent concentrator with a Bragg reflector layer and optical scatterers (FC Bragg & Particles) with varying sizes. The collected signal power at the PD is illustrated in FIG. 7C. It is notable that the signal collected scales with size, as expected due to the increased surface area of the cube's side facet in capturing the incident light. However, in initial investigations, the bare FC—representing the FC without any coating—exhibits persistently low signal collection despite size increments. The bare FC may rely on scattering and total internal reflection (TIR) to gather and redirect/bend light towards the photodiode. Subsequently, the FC may be enhanced by applying a Bragg coating, which results in a remarkable increase in signal collection. Leveraging color conversion and wavelength-selective confinement, the integration of Bragg reflectors may significantly augment the FC's light collection efficiency and its effectiveness in capturing omnidirectional light compared to FCs without Bragg reflectors, which solely rely on the TIR mechanism. Furthermore, the results reveal that incorporating optical scatterers into the FC-Bragg concentrator may further amplify signal collection. This performance enhancement can be attributed to intensified scattering, which may reduce the mean free path and promotes more efficient color conversion.

[0072] FIG. 7D shows a plot of photocurrent efficiency as a function of size (in millimeters or mm) illustrating the efficiency of a bare fluorescent concentrator (FC Bare), a fluorescent concentrator with a Bragg reflector layer (FC Bragg) and a fluorescent concentrator with a Bragg reflector layer and optical scatterers (FC Bragg & Particles) with varying sizes. As

depicted in FIG. 7D, the efficiency may decrease with increasing cube size. Despite increase in surface area for light collection, larger FC sizes may lead to reduced efficiency, resulting in the plateaued signal collection in FIG. 7C. The reduction in efficiency with increasing cube size can be attributed to a higher occurrence of reabsorption of down-converted light, which may diminish the overall efficiency due to the quantum efficiency (PLQY) of the fluorescent material. This reabsorption phenomenon may become more pronounced as the absorption and emission spectra of the fluorophores overlap within the wavelength range of 480 nm to 520 nm.

[0073] Despite the 8 mm cube demonstrating the highest efficiency, the 16 mm cube is selected as the prototype, as it may allow sufficient signal power for optical communication application. Additionally, corroborating the signal strength data, the FC with Bragg & Particles may exhibit the highest efficiency. Notably, for the 16 mm cube, the optical scatterers may enhance efficiency by 1.99 times, from 27.5% to 54.5%. Experimentally, 1.67 times enhancement from 16% to 26.7% may be observed.

[0074] A quantitative analysis of the omnidirectionality of the FC is conducted by subjecting it to irradiation from various polar and azimuthal angles using a 405 nm LED light source. The resulting photocurrent of the PD due to output light coupled into the PD through the exit aperture may be measured. For this study, the results of various FC configurations based on a 16 mm cube with 0.1 mg/ml fluorophore concentration may be compared. The configurations are bare fluorescent concentrator (Bare-FC), fluorescent concentrator with Bragg reflector (Bragg-FC), and fluorescent concentrator with Bragg reflector and optical scatterers (Bragg-SP-FC). The results may be compared with two other solutions: a compound parabolic concentrator (CPC), and the bare photodiode (PD) only.

[0075] FIG. 8A shows a schematic of a polar irradiance setup according to various embodiments. The illuminating source and PD are aligned on the same optical axis. “0° illumination” indicates the source illuminating the cube face directly opposite to the PD, while

“180° illumination” refers to the face attached to the PD being illuminated. FIG. 8B shows a polar plot illustrating the gain recorded for each illumination angle for bare fluorescent concentrator (Bare-FC), fluorescent concentrator with Bragg reflector (Bragg-FC), fluorescent concentrator with Bragg reflector and optical scatterers (Bragg-SP-FC), a compound parabolic concentrator (CPC) and a photodiode (PD) according to various embodiments. FIG. 8C shows a schematic of an azimuthal irradiance setup according to various embodiments. The light source and detector may be positioned at a 90-degree angle to each other. This configuration may allow the light source to illuminate any facet adjacent to the PD-attached facet at the specified illumination angle. FIG. 8D shows an azimuthal plot illustrating the gain recorded for each illumination angle for bare fluorescent concentrator (Bare-FC), fluorescent concentrator with Bragg reflector (Bragg-FC), fluorescent concentrator with Bragg reflector and optical scatterers (Bragg-SP-FC), a compound parabolic concentrator (CPC) and a photodiode (PD) according to various embodiments. The measurement results are shown in FIG. 8B and FIG. 8D where the optical gains are plotted as a function of incident illumination angle. Omnidirectionality can be seen from both polar and azimuthal gain plots shown in FIG. 8B and FIG. 8D. The optical gain of the FC is defined as the ratio of the photocurrent measured from the FC to the photocurrent measured from the bare PD under normal incidence, at identical illumination distances:

$$G_{optical} = \frac{I_{FC}}{I_{bare\ PD}} = G_{geometrical} \times \eta_{optical} = \frac{Area_{input}}{Area_{output}} \times \eta_{optical} \quad (3)$$

where $G_{optical}$ is the optical gain of the FC, I_{FC} is the photocurrent measured by a PD coupled with FC at a distance d , $I_{bare\ PD}$ is the photocurrent measured by a bare PD at the same distance d with the beam at 0° to the PD normal, $G_{geometrical}$ is the geometrical gain, $\eta_{optical}$ is the optical efficiency, $Area_{input}$ is the total surface area that is capable to collect the light and $Area_{output}$ is the surface area of the PD active region. Hence, high geometrical gain need not necessarily translate to high optical gain as it may be dependent on the optical efficiency. Based on

measurements (at $d = 1.5$ m), it may be observed that the bare PD can detect signals ranging from -60° to 60° (FOV 120°) for polar illumination, while no signals are received for azimuthal illumination (i.e. 90° signal relative to PD normal), whereas the CPC exhibits a maximum gain of 4 when illuminated at 0° with an even smaller FOV of 45° .

[0076] In contrast, the FC may exhibit omnidirectional detection (FOV 360°) across both polar and azimuthal axes. The photodetection may be consistent with an optical gain of 4.88 to 6.39 in azimuthal illumination (i.e. 90° signal relative to PD normal). Even at an extreme angle of 180° polar (i.e. light incident from the back of the PD), it may still show a notable gain of 3.6. In both polar and azimuthal orientation, the highest optical gain (6.39) may occur at a 45-degree illumination angle where the effective illuminated area is maximized. Indeed, the combination of Bragg coating and embedded optical scatterers may play an important role in boosting the efficiency of the FC, and subsequently the gain. Contrary to bare FC that demonstrates the lowest gain of 0.5 (which corresponds to overall signal reduction), Bragg-FC demonstrates an overall signal gain of 2.9 (gain averaged over different illumination angles). Notably, this gain may increase substantially to 5.6 for the Bragg-SP-FC. This may correspond to an optical efficiency of 23.8% for the Bragg-SP-FC (as compared to 2.5% and 12.5% for Bare-FC and Bragg-FC respectively).

[0077] To validate the photodiode-based characterizations, as well as to understand why optical scatterers improve efficiency, integrating sphere measurements may be performed. When converting incident near-UV light to fluorescent emissions, significant light loss can occur through multiple light reflections within the cube that increase the effect of reabsorption loss or light leakage from the Bragg reflectors for specific wavelengths and angles outside the stopband.

[0078] The integrating sphere measurements quantify light exiting the FCs to the surroundings. The emission properties of the fluorescent cube were characterized using an

integrating sphere setup. A 16 mm FC was subjected to irradiation from a 405 nm light source within the integrating sphere, and its emission spectrum was analyzed using a spectrophotometer. FIG. 8E shows a plot of yield as a function of sample measured comparing the signal leakage of the various samples according to various embodiments. Initially, the FC, with a dye concentration of 0.1 mg/ml, exhibited an emission intensity of 74.7%. However, upon applying a Bragg reflector layer and introducing an exit aperture to one of its faces, the emission decreased to 36.9%. FIG. 8E also shows a reduction to a value of 42.4% for the FC with Bragg reflector layer and scattering particles.

[0079] However, these values represent light exiting both through the intended exit channel (desired) and through the unintended leakage from the Bragg imperfections (not desired). A second set of measurements were taken but with a PD is attached at the exit channel this time. By comparing the difference in light leakage, the amount of light entering the PD may be determined. The photon yield entering the PD may be deduced to be approximately 9% for the FC with Bragg reflector layer and significantly increased to 15% for the FC with Bragg reflector layer and scattering particles. These may correspond to an optical efficiency (photon yield/0.609) of 14.8% and 24.6% respectively. These results may confirm that the scattering particles effectively reduce multiple reflections, thereby reducing unintended light leakage, while increasing coupling to the intended PD. In summary, the approach in combining Bragg coating with optical scatterers/scattering particles may be shown to be effective in increasing the efficiency of the FC.

[0080] The bandwidth characteristics of the FC may be examined using a 405 nm laser diode modulated using an arbitrary waveform generator. The emission may then be detected using a high-speed avalanche photodiode (APD). FIG. 9A shows a plot of signal (in decibels or dB) as a function of frequency (in MegaHertz or MHz) illustrating the bandwidth measurement of the fluorescent concentrator (FC) according to various embodiments. Based on the findings

presented in FIG. 9A, the 3dB bandwidth of the FC may be determined to be approximately 37 MHz. Qualitative analysis of the digital signals may also be conducted, by modulating the laser with a pseudorandom bit sequence generated from the waveform generator and repetitively sampling the detected optical signals with an oscilloscope. FIG. 9B shows an eye diagram reflecting the detected optical signals of the fluorescent concentrator (FC) according to various embodiments sampled by the oscilloscope. As seen from FIG. 9B, a distinct open eye can be seen at 40 Mbps. This is an indication of a signal integrity suitable for data communications. With higher data

[0081] The feasibility of non-line-of-sight and omnidirectional optical wireless communications may also be demonstrated. The system under evaluation transmitted audio signals. FIG. 10A shows a schematic of the system tested using a bare silicon photodiode (PD) 1052 and without a fluorescent concentrator (FC). FIG. 10B shows a schematic of the system in which a fluorescent concentrator (FC) 1000 according to various embodiments is mounted onto the silicon photodiode (PD) 1052. Digital audio data stored on a microcontroller (not shown in FIGS. 10A – B) may be sent to a transmitter circuit (not shown in FIGS. 10A – B) to drive the blue light emitting diode (LED) array and encode the data into optical signals. These optical signals may be sent to the photodiode 1052, which acts as a receiver to detect the optical signals. The receiver circuit then converts the optical signals back into audio format, which is then played through a speaker. During testing, a board 1054 may be placed to block the line-of-sight between the transmitter and the photodiode 1052, that is placed near a wall 1058. For the system in FIG. 10A in which only a bare PD 1052 is used without a FC, no signals may be detected as shown in the oscilloscope 1056, and the music stops playing, indicating that the communication is blocked. In FIG. 10B in which the FC 1000 is mounted onto the PD 1052, the FC 1000 may enable the detection of reflected signals from the walls 1058 even when the receiver or PD 1052 is blocked or when the receiver or PD faces 180 degrees away from the

transmitter. This allows the music to continue playing, demonstrating the capability of the system for non-line-of-sight optical wireless communication. Communication can still be maintained even when the line-of-sight is blocked or when the receiver is rotated over all angles.

[0082] FIG. 10C shows a plot signal-to-noise ratio (SNR) (in decibels or dB) as a function of distance (in meters or m) illustrating the SNR of the fluorescent concentrator (FC) according to various embodiments compared to a bare photodiode (PD) as a function of distance. The SNR of the FC was measured with the light incident at 90 degrees to the detector (i.e., from the side facet). It may be observed that the difference in SNR between the FC and the bare PD is approximately 12.5 dB, corresponding to a gain of approximately 4.3 times and a range increase of 2.1 times. For robust communication, an SNR of at least 23 dB may be required. This may not be achievable with a bare PD at distances greater than 45 m. The FC may extend this distance for robust communication beyond 60 m. Although current measurements are limited by experimental conditions (i.e. the corridor length), the fitted plot indicates that robust communication may be maintained beyond 80 m. Additionally, light reflected from ceilings and walls may contribute to the gain, indicating that measurements depend on environmental factors such as indoor vs. outdoor settings, corridor size, and wall and ceiling reflectivity.

[0083] Various embodiments may relate to a compact omnidirectional system based on Bragg-coated optically transparent cube embedded with a fluorescent dye and optical scatterers. By incorporating Bragg reflectors, light confinement may be improved by selectively transmitting incident light from an external source while confining down-converted emitted light within the FC. The inclusion of optical scatterers reduced leakage and reabsorption loss, enhancing coupling into the photodetector or photodiode.

[0084] The system may demonstrate non-line-of-sight optical wireless communication (OWC). While fluorescent concentrators have shown promise of achieving wide field-of-view (FOV) and high gain as compared to conventional optics, achieving high efficiency beyond a

few percent has been difficult, especially with increasing FOV. The fluorescent concentrator described herein may have one of the highest efficiencies (23.8%) reported to date with 360° FOV. Integrating sphere measurements reveal that incorporating Bragg reflectors and optical scatterers may effectively reduce the light leakage from the cube. With the gain of up to 6.3 (average gain is 5.6) and with wavelength selective properties of the FC, there may be significant improvement in the communication range of more than 60 meters, which is independent of the PD's orientation relative to the beam axis, i.e. omnidirectionality. Moreover, the 360-degree light collection capability may allow for the capture of non-line-of-sight optical signals, thereby overcoming alignment limitations and offering new opportunities for robust and mobile visible light communication systems. In contrast, although conventional fiber bundle detectors allow for omnidirectional light collection with a 360 degrees FOV, they had a gain of 0.56 and an efficiency of 0.3%. Various embodiments may provide a combination of omnidirectionality, high gain, and high efficiency, along with wavelength-selective properties, which may enable effective light collection over smaller collection areas. This may provide a viable solution for non-line-of-sight optical wireless communication with long communication range in a compact form factor.

[0085] Various embodiments may allow for 360 degrees signal detection. Various embodiments may support high gain, high efficiency communication channels. Various embodiments may provide a large collection area to relax alignment tolerance and a small outcoupling area into the photodetector, enabling switching speeds in the nanosecond regime. Various embodiments may serve as a compact and efficient transceiver module. Various embodiments may provide an efficient outdoor optical communications means, through the use of wavelength selective characteristics to eliminate noise signals of ambient light.

[0086] Various embodiments may find applications in robust wireless optical communication (OWC), aircraft cockpit wireless optical communications, optical sensors n

agriculture, aerospace, and automotive industries, as solar light concentrators and redirection means for renewal energy or indoor lighting, free-space communications in satellites, and in optical communications modules for autonomous vehicles. Further, arrays of FCs may be used for underwater wireless communications, through integration with multiple access points.

[0087] In future, other complex geometries, materials, and fabrication methods including 3D printing can be explored for tailored applications.

Claims

1. A light concentrator comprising:
 - a matrix comprising:
 - a matrix material;
 - a plurality of luminophores in the matrix; and
 - a plurality of optical scatterers in the matrix; and
 - a Bragg reflector layer in contact with an outer surface of the matrix, the Bragg reflector layer defining an opening.
2. The light concentrator according to claim 1,
 - wherein the plurality of luminophores is configured to absorb incident light of a predetermined wavelength or range of wavelengths, and further configured to emit wavelength-converted light of another predetermined wavelength or range of wavelengths upon absorption of the incident light;
 - wherein the plurality of optical scatterers is configured to scatter the incident light and the wavelength-converted light;
 - wherein the Bragg reflector layer is configured to allow a fraction of the incident light traveling from outside the light concentrator to pass through to the matrix, and is further configured to reflect a fraction of the wavelength-converted light traveling from the matrix towards outside the light concentrator back to the matrix; and
 - wherein the opening is configured to allow the wavelength-converted light to pass through.

3. The light concentrator according to claim 2,
wherein the other predetermined wavelength or range of wavelengths is longer than the predetermined wavelength or range of wavelengths.
4. The light concentrator according to claim 2,
wherein the other predetermined wavelength or range of wavelengths is shorter than the predetermined wavelength or range of wavelengths.
5. The light concentrator according to any one of claims 2 to 4,
wherein the other predetermined wavelength or range of wavelengths is chosen to have a higher peak photodetection responsivity compared to the predetermined wavelength or range of wavelengths.
6. The light concentrator according to any one of claims 2 to 5,
wherein the Bragg reflector is configured to reflect the fraction of the wavelength-converted light via wavelength-selective Bragg reflection and total internal reflection.
7. The light concentrator according to any one of claims 2 to 6,
wherein the incident light is omnidirectional light.
8. The light concentrator according to any one of claims 2 to 6,
wherein the incident light is directional light.
9. The light concentrator according to any one of claims 1 to 8,

wherein the plurality of optical scatterers comprises silicone resin powder particles, silicon dioxide or titanium dioxide particles.

10. The light concentrator according to any one of claims 1 to 9,

wherein the plurality of luminophores comprises organic dyes, quantum structures, perovskites or lanthanides.

11. The light concentrator according to any one of claims 1 to 10, further comprising:

a photodetector.

12. The light concentrator according to claim 11,

wherein the photodetector is a p-i-n photodiode, an avalanche photodiode, a silicon photomultiplier or a photomultiplier tube.

13. The light concentrator according to any one of claims 1 to 12,

wherein the matrix material is a polymeric resin material.

14. A method of forming a light concentrator, the method comprising:

forming a matrix comprising:

a matrix material;

a plurality of luminophores in the matrix; and

a plurality of optical scatterers in the matrix; and

forming a Bragg reflector layer in contact with an outer surface of the matrix,
the Bragg reflector layer defining an opening.

15. The method according to claim 14,

wherein the plurality of luminophores is configured to absorb incident light of a predetermined wavelength or range of wavelengths, and further configured to emit wavelength-converted light of another predetermined wavelength or range of wavelengths upon absorption of the incident light;

wherein the plurality of optical scatterers is configured to scatter the incident light and the wavelength-converted light;

wherein the Bragg reflector layer is configured to allow a fraction of the incident light traveling from outside the light concentrator to pass through to the matrix, and is further configured to reflect a fraction of the wavelength-converted light traveling from the matrix towards outside the light concentrator back to the matrix; and

wherein the opening is configured to allow the wavelength-converted light to pass through.

16. The method according to claim 15,

wherein the other predetermined wavelength or range of wavelengths is longer than the predetermined wavelength or range of wavelengths.

17. The method according to claim 15,

wherein the other predetermined wavelength or range of wavelengths is shorter than the predetermined wavelength or range of wavelengths.

18. The method according to any one of claims 15 to 17,

wherein the other predetermined wavelength or range of wavelengths is chosen to have a higher peak photodetection responsivity compared to the predetermined wavelength or range of wavelengths.

19. The method according to any one of claims 15 to 18,

wherein the Bragg reflector is configured to reflect the fraction of the wavelength-converted light via wavelength-selective Bragg reflection and total internal reflection.

20. The method according to any one of claims 15 to 19,

wherein the incident light is omnidirectional light.

21. The method according to any one of claims 15 to 19,

wherein the incident light is directional light.

22. The method according to any one of claims 14 to 21,

wherein the plurality of optical scatterers comprises silicone resin powder particles, silicon dioxide or titanium dioxide particles.

23. The method according to any one of claims 14 to 22,

wherein the plurality of luminophores comprises organic dyes, quantum structures, perovskites or lanthanides.

24. The method according to any one of claims 14 to 23, further comprising:

a photodetector.

25. The method according to claim 24,
wherein the photodetector is a p-i-n photodiode, an avalanche photodiode, a
silicon photomultiplier or a photomultiplier tube.
26. The method according to any one of claims 14 to 25,
wherein the matrix material is a polymeric resin material.