

**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. 10202300355P filed February 13, 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] One of the pain points of optical wireless communications (Li-Fi) is the lack of solutions to efficiently collect light from wherever the light comes from. Light signals can come from highly controlled sources (e.g., lasers) or more cost-effective alternatives (e.g., light emitting diodes (LEDs), or broadband light).

[0004] For laser sources, the detection (or collection) is extremely alignment critical, as the laser has a narrow beam size, and the detector is typically small. Increasing the detector size will reduce the alignment sensitivity, but will also result in a slow detector response. Current solutions, such as mechanical tracking systems for beam alignment, can address the alignment requirement, but these solutions are expensive and bulky.

[0005] Other types of sources, such as LEDs and broadband light sources, are very attractive as they are cost-effective. However, these sources present another challenge. While they are not as alignment critical as lasers, the light signals they produce are divergent and are sometimes diffused. In addition, photodetectors with small active areas are used for high-speed optical

communications, resulting in poor signal-to-noise ratio. Refractive lenses can be used to collect more light into the small photodetector, but will reduce the field-of-view due to the conservation of etendue. For example, a one-inch lens can collect more light with a gain of 50 but will result in a small field-of-view (FOV) of 24 degrees. FIG. 1A shows a schematic illustrating the field-of-view (FOV) of a conventional lens used to collect light from a laser source. FIG. 1B shows a schematic illustrating the field-of-view (FOV) of a conventional lens used to collect light from a light emitting diode. While the most sophisticated fish-eye-lens system can collect light up to 180 degrees, these lenses have a limited gain of about 2. There is a need to develop a light collection device that can simultaneously achieve high optical gain and a wide field-of-view (FOV) to address the alignment problem faced by current solutions, and eventually enable non-line-of-sight Li-Fi communications.

## SUMMARY

[0006] Various embodiments may relate to a light concentrator. The light concentrator may include a polymeric matrix with embedded luminophores. The light concentrator may also include a wavelength-selective structure such that the polymeric matrix is within a cavity defined by the wavelength-selective structure. The wavelength-selective structure may be configured to substantially allow external light of a predetermined wavelength or range of wavelengths incident onto the wavelength-selective structure at predetermined incident angles to pass through the wavelength-selective structure. The luminophores may be configured to absorb the external light of the predetermined wavelength or range of wavelengths that passes through the wavelength-selective structure, and further configured to emit wavelength-converted light of another predetermined wavelength or range of wavelengths upon absorption of the external light (of the predetermined wavelength or range of wavelengths) that passes through the wavelength-selective structure. The wavelength-selective structure may be further

configured to substantially reflect the wavelength-converted light incident onto the wavelength-selective structure at further predetermined incident angles. The wavelength-selective structure may define an opening configured to allow the wavelength-converted light and/or the reflected wavelength-converted light to pass through.

[0007] Various embodiments may relate to a method of forming a light concentrator. The method may include forming a polymeric matrix with embedded luminophores. The method may also include in forming a wavelength-selective structure such that the polymeric matrix is within a cavity defined by the wavelength-selective structure. The wavelength-selective structure may be configured to substantially allow external light of a predetermined wavelength or range of wavelengths incident onto the wavelength-selective structure at predetermined incident angles to pass through the wavelength-selective structure. The luminophores may be configured to absorb the external light of the predetermined wavelength or range of wavelengths that passes through the wavelength-selective structure, and further configured to emit wavelength-converted light of another predetermined wavelength or range of wavelengths upon absorption of the external light that passes through the wavelength-selective structure. The wavelength-selective structure may be further configured to substantially reflect the wavelength-converted light incident onto the wavelength-selective structure at further predetermined incident angles. The wavelength-selective structure may define an opening configured to allow the wavelength-converted light or the reflected wavelength-converted light to pass through.

#### **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. 1A shows a schematic illustrating the field-of-view (FOV) of a conventional lens used to collect light from a laser source.

FIG. 1B shows a schematic illustrating the field-of-view (FOV) of a conventional lens used to collect light from a light emitting diode.

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

FIG. 3 shows a general illustration of a method of forming a light concentrator according to various embodiments.

FIG. 4A shows a cross-sectional schematic of a light concentrator according to various embodiments.

FIG. 4B is a schematic illustrating the operation of the light concentrator shown in FIG. 4A according to various embodiments.

FIG. 5 shows a schematic of the fabrication process according to various embodiments.

FIG. 6A shows a plot of absorption (in arbitrary units or a.u.) as a function of wavelength (in micrometers or  $\mu\text{m}$ ) illustrating the absorbance spectra of the luminophores according to various embodiments.

FIG. 6B shows a plot of photoluminescence (in arbitrary units or a.u.) as a function of wavelength (in micrometers or  $\mu\text{m}$ ) illustrating the photoluminescence spectra of the luminophores according to various embodiments.

FIG. 7A shows a plot of transmittance (in percent or %) as a function of wavelength (in nanometers or nm) illustrating the angular dependent transmittance of the wavelength-selective Bragg reflector according to various embodiments.

FIG. 7B shows a plot of photoluminescence (in arbitrary units or a.u.) as a function of wavelength (in nanometers or nm) illustrating that the Bragg reflector according to various

embodiments being able to receive incident light of 350 nm – 500 nm and confine wavelength converted light of 500 nm – 600 nm.

FIG. 8A shows a plot of signal strength (in arbitrary units or a.u.) as a function of size (in millimeters or mm) illustrating the signal strength of a concentrator without a Bragg reflector and the light concentrator with a Bragg reflector according to various embodiments.

FIG. 8B shows a plot of efficiency (in percent or %) as a function of size (in millimeters or mm) illustrating the efficiency of the concentrator without the Bragg reflector and the light concentrator with the Bragg reflector according to various embodiments.

FIG. 9 shows a plot of photocurrent (in micro-Amperes or  $\mu\text{A}$ ) as a function of angle (in degree or deg) illustrating the superiority of the light concentrator with the Bragg reflector according to various embodiments over the light concentrator without the Bragg reflector and the bare photodiode.

FIG. 10 shows a polar plot of signal intensity (in milli-Volts or mV) as a function of angle (in degree or deg) comparing a 16 mm cubic light concentrator with Bragg reflector according to various embodiments, a 16 mm cubic light concentrator without Bragg reflector, and a bare photodiode.

FIG. 11 shows a schematic of a cubic omnidirectional light concentrator/collector with a Bragg reflector on the collection surfaces of the cube according to various embodiments placed above a photodiode.

FIG. 12 shows (A) a schematic of an access point (AP) with an array of light (luminescent) concentrators according to various embodiments being used for underwater communications; and (B) a schematic showing the access point (AP) with the array of light concentrators according to various embodiments being used to receive data from multiple nodes (users).

## 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] Various embodiments may address one or more issues faced by conventional optical systems. Various embodiments may relate to a light collector (light collection device) that can efficiently collect light, have a larger field-of-view (FOV), and/or solve the alignment problem.

[0018] FIG. 2 shows a general illustration of a light concentrator according to various embodiments. The light concentrator may include a polymeric matrix 202 with embedded luminophores 204. The light concentrator may also include a wavelength-selective structure 206 such that the polymeric matrix 204 is within a cavity defined by the wavelength-selective structure 206. The wavelength-selective structure 206 may be configured to substantially allow external light of a predetermined wavelength or range of wavelengths incident onto the wavelength-selective structure 206 at predetermined incident angles to pass through the wavelength-selective structure 206. The luminophores 204 may be configured to absorb the external light of the predetermined wavelength or range of wavelengths that passes through the wavelength-selective structure 206, and further configured to emit wavelength-converted light of another predetermined wavelength or range of wavelengths upon absorption of the external light (of the predetermined wavelength or range of wavelengths) that passes through the wavelength-selective structure 206. The wavelength-selective structure 206 may be further configured to substantially reflect the wavelength-converted light incident onto the wavelength-selective structure 206 at further predetermined incident angles. The wavelength-selective structure 206 may define an opening 208 configured to allow the wavelength-converted light

and/or the reflected wavelength-converted light to pass through. The light concentrator may alternatively be referred to as a luminescent concentrator.

[0019] In other words, the light concentrator may include a matrix 202 with luminophores 204 dispersed in the polymeric material of the matrix 202. The light concentrator may also have a wavelength-selective structure 206 on a portion of the external surface of the matrix 202, with the remaining portion of the matrix 202 being devoid of the wavelength-selective structure 206, thereby defining an opening 208.

[0020] During operation, most or all of external light incident onto the wavelength-selective structure 206 at certain angles (i.e. “predetermined incident angles” or  $\theta_1$ ) may be allowed to pass through (i.e. to the matrix 202 with luminophores 204). In various embodiments, most (e.g.  $\geq 80\%$  or  $\geq 90\%$ ) or all of external light (e.g. from about 350 nm to about 500 nm) incident onto the wavelength-selective structure 206 at angles of incidence of more than about 0 degree to about 60 degrees ( $0^\circ \leq \theta_1 \leq 60^\circ$ ) may be allowed to pass through. The external light that passes through may be absorbed by the luminophores 204 which may up-convert or down-convert the external light.

[0021] The light emitted by the luminophores 204 (i.e. “wavelength-converted light”) may travel to the opening 208 to be transmitted out (i.e. to an external device such as a photodetector), or may travel to the wavelength-selective structure 206. The wavelength-selective structure 206 may be designed such that most or all of the wavelength-converted light incident at most angles (i.e. “further predetermined incident angles” or  $\theta_2$ ) may be reflected by the wavelength-selective structure 206 back to the matrix 202. In various embodiments, most (e.g.  $\geq 95\%$  or  $\geq 99\%$ ) or all of the wavelength-converted light (e.g. from about 500 nm to about 600 nm) incident onto the wavelength-selective structure 206 at angles of incidence from about 0 degree to about 75 degrees ( $0^\circ \leq \theta_2 \leq 75^\circ$ ) may be reflected back to the matrix 202.

[0022] These reflected wavelength-converted light may either travel to the opening 208 and be transmitted out to the external device, or may be reflected by another portion of the wavelength-selective structure 206. The wavelength-converted light may thus undergo one or more reflections by the wavelength-selective structure 206 until the wavelength-converted light is transmitted through the opening 208 to the external device. In such a manner, the light concentrator may be able to confine and concentrate most of the wavelength-converted light to be transmitted through the opening 208 to the external device.

[0023] For avoidance of doubt, FIG. 2 seeks to illustrate some features of the light concentrator according to various embodiments, and is not intended to limit, for instance, the shape, size, dimensions, arrangement, orientation, number etc. of the various features. For instance, while FIG. 2 shows three luminophores 204, various embodiments may include any suitable number of luminophores 204. Also, while FIG. 2 shows a rectangular cuboid matrix 202, the polymeric matrix 202 may be of any suitable shape. In various embodiments, the polymeric matrix 202 may be of a shape selected from a group consisting of a cube, a prism, a cylinder, a sheet, and a fiber.

[0024] In various embodiments, the wavelength-selective structure 206 may be a Bragg reflector. The wavelength-selective structure 206 or Bragg reflector may be a stacked arrangement including alternate layers of a first refractive index and layers of a second refractive index different from the first refractive index. For instance, the wavelength-selective structure 206 or Bragg reflector may include a layer of the first refractive index between (and adjoining) two layers of the second refractive index, or a layer of the second refractive index between (and adjoining) two layers of the first refractive index.

[0025] As mentioned above, the luminophores 204 may up-convert or down-convert the external light that has passed through the wavelength-selective structure 206. In various embodiments, the luminophores may be or may include fluorophores (fluorescent material),

while in various other embodiments, the luminophores may be or may include phosphors (phosphorescent material). In various embodiments, the luminophores may include quantum dots and/or an organic dye, which may up-convert the external light. For instance, the quantum dots may be or may include copper indium sulfide (CIS), indium phosphide, or cadmium selenide. The organic dye may be or may include Coumarin and its derivatives, Perylene and its derivatives, or F8BT. In various embodiments, the luminophores 204 may include perovskites. In various embodiments, the luminophores 204 may include lanthanides. In various embodiments, the wavelength-converted light emitted by the luminophores 204 may be diffused and may be isotropically scattered to all directions.

[0026] Each of the luminophores 204 may be of any suitable dimension. For instance, each of the luminophores 204 may have a diameter or dimension selected from a range from about 1 nm to about 100 nm.

[0027] For avoidable of doubt, the luminophores 204 may be of any suitable shape. For instance, the luminophores 204 may consist of molecules or particles in spherical, elliptical, cylindrical, or may have an irregular shape.

[0028] In various embodiments, the luminophores 204 may alternatively or additionally include perovskites. The perovskites may down-convert the external light. In various embodiments, the luminophores 204 may alternatively or additionally include lanthanides. The lanthanides may up-convert the external light.

[0029] In various embodiments, the wavelength-selective structure 206 may form a coating on or in contact with a surface of the polymeric matrix 202. In various embodiments, the wavelength-selective structure 206 may be on or in contact with the polymeric matrix 202. The wavelength-selective structure 206 may alternatively be referred to as a wavelength-selective coating or layer. The opening 208 may be an uncoated part of the surface of the polymeric matrix 202. The uncoated part of the polymeric matrix 202 may be used as a channel to allow

the wavelength-converted light and/or the reflected wavelength-converted light to exit to the external device, e.g. a photodetector.

[0030] In various embodiments, the polymeric matrix 202 may include any suitable polymer. For instance, the polymeric matrix 202 may include an epoxy or an acrylate.

[0031] In various embodiments, the polymeric matrix 202 may be of any suitable shape. For instance, the polymeric matrix 202 may include a shape selected from a group consisting of a cube, a prism, a cylinder, a sheet, and a fiber. The polymeric matrix 202 may be of any suitable dimension. For instance, the polymeric matrix may have a diameter or dimension selected from a range from about 5 mm to about 50 mm. Generally, the bigger the size of the polymeric matrix, the larger the effective collection area which allows the collection of more light.

[0032] In various embodiments, the light concentrator may further include the external device, e.g. a photodetector such as a photodiode configured to detect the wavelength-converted light or the reflected wavelength-converted light.

[0033] In various embodiments, the external light may be omnidirectional light. In other words, various embodiments may be able to capture external light from virtually all directions (0 degree to 360 degrees) without an extensive alignment process.

[0034] The external light may be emitted by any suitable external light source. For instance, the external light may be emitted by a laser device/source, a light emitting diode or a broadband white light source. As mentioned above, the external light may be of any suitable predetermined wavelength or range of wavelengths. For instance, the external light may be infrared light in the visible spectrum and near-infrared spectrum, e.g. from about 350 nm to about 1800 nm.

[0035] FIG. 3 shows a general illustration of a method of forming a light concentrator according to various embodiments. The method may include, in 302, forming a polymeric matrix with embedded luminophores. The method may also include in, in 304, forming a wavelength-selective structure (e.g. a coating) such that the polymeric matrix is within a cavity

defined by the wavelength-selective structure. The wavelength-selective structure may be formed, by any suitable deposition technique, such as coating or sputtering etc. The wavelength-selective structure may be configured to substantially allow external light of a predetermined wavelength or range of wavelengths incident onto the wavelength-selective structure at predetermined incident angles to pass through the wavelength-selective structure. The luminophores may be configured to absorb the external light of the predetermined wavelength or range of wavelengths that passes through the wavelength-selective structure, and further configured to emit wavelength-converted light of another predetermined wavelength or range of wavelengths upon absorption of the external light that passes through the wavelength-selective structure. The wavelength-selective structure may be further configured to substantially reflect the wavelength-converted light incident onto the wavelength-selective structure at further predetermined incident angles. The wavelength-selective structure may define an opening configured to allow the wavelength-converted light or the reflected wavelength-converted light to pass through.

[0036] In other words, the method may involve forming a polymeric matrix with dispersed luminophores, and forming a wavelength-selective structure almost surrounding the polymeric matrix except for an opening to allow the wavelength-converted light and/or the reflected wavelength-converted light generated by the dispersed luminophores to pass through. The uncoated opening in the wavelength-selective structure may be configured for the light (i.e. wavelength-converted light and/or the reflected wavelength-converted light generated by the dispersed luminophores) to enter an external device, such as a photodetector.

[0037] In various embodiments, forming the polymeric matrix with embedded luminophores may include mixing a polymeric resin precursor and the luminophores to form a mixture, and casting the mixture in a mold, i.e. providing the mixture in a mold such that the mixture is allowed to be cured, thereby forming the polymeric matrix with embedded luminophores. The

polymeric resin precursor may, for instance, be or include bisphenol A diglycidyl ether (BADGE) and/or isophorone diamine (IPDA). The luminophores may, for instance, be or include Coumarin, Perylene, F8BT, quantum dots (QDs). In various embodiments, the mixture may be allowed to cure at any suitable temperature, e.g. a temperature selected from a range from about 10 °C to about 30 °C. In various embodiments, the mixture may have a viscosity of less than 1000 cP.

[0038] In various embodiments, forming the polymeric matrix with embedded luminophores may include removing any excess solvent and air bubbles from the mixture prior to casting, i.e. providing the mixture in the mold.

[0039] In various embodiments, forming the wavelength-selective structure may include applying or coating the polymeric matrix with alternate layers of a first refractive index and layers of a second refractive index different from the first refractive index. The alternate layers may form a Bragg reflector.

[0040] As mentioned above, the polymeric matrix may be of any suitable shape. For instance, the polymeric matrix may include a shape selected from a group consisting of a cube, a prism, a cylinder, a sheet, and a fiber.

[0041] In various embodiments, the method may also include providing an external device, e.g., a photodetector such as a photodiode, configured to detect the wavelength-converted light or the reflected wavelength-converted light.

[0042] FIG. 4A shows a cross-sectional schematic of a light concentrator according to various embodiments. The light concentrator (alternatively referred to as a luminescent concentrator) may be made of a matrix 402 embedded with luminophores (having a luminescent material) 404. The matrix 404 may be surrounded by a wavelength-selective structure 406. Upon incident light (e.g. a laser or broadband light) from any direction the luminophores 404 embedded in the matrix 402 may absorb the light, and may convert the light into longer

wavelengths that will be trapped within the light concentrator through wavelength-selective reflection from the wavelength-selective structure 406 (e.g. a Bragg reflector). The wavelength-selective structure 406 may play a significant role in allowing transmission of incident light wavelengths and in the three-dimensional (3D) confinement of the converted light within the concentrator. The converted light may then be preferentially channeled to an opening 408 (e.g. an uncoated section), and may be collected externally, e.g. by a device 410 such as a photodiode. For optimum light collection and less light leakage, the wavelength-selective structure 406 may be required to transmit the incident light and reflect the converted light at most of the angles. Various embodiments may relate to a compact and robust solution to efficiently capture broadband light omnidirectionally, and to effectively redirect the light into an output channel. Various embodiments may relate to or utilize wavelength-conversion and scattering, wavelength selective light confinement, and preferential channeling of light.

[0043] FIG. 4B is a schematic illustrating the operation of the light concentrator shown in FIG. 4A according to various embodiments. In order to improve clarity and avoid clutter, not all like elements in FIGS. 4A-B have been labelled. In (i) shown in FIG. 4B, external light source (e.g. a laser source, LED or broadband white light source) may radiate light in the visible to near infra-red spectrum (from about 350 nm to about 1800 nm). The light concentrator with a matrix 402 of a polymer material may be able to capture the incident light (i.e. external light) from virtually all directions (0 degree to 360 degrees) without an extensive alignment process. The incident light may penetrate the polymeric matrix 402, and the embedded luminophores 404 may absorb the incident light. As shown in (ii), the luminophores 404 may then convert and emit the light as other wavelengths (i.e. wavelength-converted light), that is better detected by the coupled photodetector or photodiode 410. The emission from the luminophores 404 may be, by nature, diffused and isotropically scattered to all directions.

[0044] The wavelength-selective structure 406 may be a multilayer stack consisting of alternating high and low index films with quarter-wavelength thicknesses of  $t_H = \lambda/(4n_H)$  and  $t_L = \lambda/(4n_L)$  respectively.  $n_H$  and  $n_L$  are indices of refraction of the high- and low-index films, respectively, and  $\lambda$  is the center wavelength of the wavelength-selective structure 406. The wavelength-selective structure 406 may be a Bragg reflector. The wavelength-selective structure 406 may act like a one-dimensional photonic crystal, whereby light of certain wavelengths reflects constructively by the Bragg reflector 406, as shown in (iii). Various embodiments may allow incident light (selected range of wavelength) to efficiently penetrate the light concentrator, and may reflect the range of converted wavelengths emitted by the luminophores 404. Various embodiments may allow a strong confinement of converted light inside the light concentrator by virtue of wavelength-selective confinement. A small section 408 of the light concentrator may be designed not to be coated and may act as an exit channel. The wavelength converted light may preferentially exit through this channel, which may be coupled to an external device 410, such as a photodiode, through butt coupling.

[0045] Prototyping

[0046] A light concentrator may be fabricated by homogeneously dispersing luminophores in polymeric resins through a wet processing method. The luminophores may be quantum dots (QDs) (including a material such as copper indium sulfide (CIS) and indium phosphide (InP)) of varying sizes, and/or organic dyes of desired optical absorption and emission properties. The polymeric resins may be specially formulated to ensure compatibility with the luminescent material, and may have desirable optical properties (e.g. high transmittance, high refractive index) and processability (e.g. pot life, curing conditions, net shape shrinkage and warpage).

[0047] For the prototypes, two main resin systems are evaluated: (1) an epoxy-based system via nucleophilic ring opening; and (2) a modified acrylate system via an addition click reaction. Both systems may be cured at room temperature and post-cured at an elevated temperature (i.e.

above room temperature). Both may be chosen to ensure minimal shrinkage of the final product and scalability to produce a variety of shapes and sizes. It is noted that a variety of precursors may be used and are not limited. Below lists a few options used in the described prototypes:

|                 |                                                                        |
|-----------------|------------------------------------------------------------------------|
| Polymeric Resin | Bisphenol A Diglycidyl Ether (BADGE) + Isophorone Diamine (IPDA)       |
| Luminophores    | Coumarin, Perylene, F8BT, quantum dots (QDs), perovskites, lanthanides |
| Bragg Reflector |                                                                        |

[0048] FIG. 5 shows a schematic of the fabrication process according to various embodiments. The fabrication of the light concentrator may include a low cost, solution processing method, and may be compatible with subsequent casting. Luminophores such as organic dyes and quantum dots (QDs) may be mixed homogeneously with the liquid precursors of the polymeric resin, ensuring all the luminophores are completely solvated/suspended. In this process, any residual solvent (e.g. from QD suspension) and air bubbles may be completely removed before casting. A suitable mold, such as a silicone well, may be used for casting the flowable mixture (e.g. <1000 cP). The cast may then be left to cure at room temperature to obtain the final three-dimensional (3D) matrix. Subsequently, the Bragg reflector may be applied or coated onto desired surfaces of the matrix. For ease of fabrication, the prototype concentrator may be designed with straight/faceted edges for subsequent easy application of the Bragg reflector.

[0049] Performance Testing Through Simulation and Experiments

[0050] The luminophores may absorb blue light well (400 nm – 500 nm) and may down convert the energy to emit longer wavelength green (500 nm - 600nm). FIG. 6A shows a plot of absorption (in arbitrary units or a.u.) as a function of wavelength (in micrometers or  $\mu\text{m}$ ) illustrating the absorbance spectra of the luminophores according to various embodiments. FIG.

6B shows a plot of photoluminescence (in arbitrary units or a.u.) as a function of wavelength (in micrometers or  $\mu\text{m}$ ) illustrating the photoluminescence spectra of the luminophores according to various embodiments.

[0051] While the performance of the Bragg reflector is angle dependent, the Bragg reflector may operate optimally to receive and transmit blue light (at 350 nm – 500 nm) and confine/concentrate the wavelength-converted light (at 500 nm – 600 nm) as shown in FIGS. 7A – B. FIG. 7A shows a plot of transmittance (in percent or %) as a function of wavelength (in nanometers or nm) illustrating the angular dependent transmittance of the wavelength-selective Bragg reflector according to various embodiments. It can be seen that at steeper angles, the transmittance may drop from over 90% to about 60%. FIG. 7B shows a plot of photoluminescence (in arbitrary units or a.u.) as a function of wavelength (in nanometers or nm) illustrating that the Bragg reflector according to various embodiments being able to receive incident light of 350 nm – 500 nm and confine wavelength converted light of 500 nm – 600 nm.

[0052] The light concentrating ability of the light concentrator according to various embodiments is also evaluated using ray tracing simulations. FIG. 8A shows a plot of signal strength (in arbitrary units or a.u.) as a function of size (in millimeters or mm) illustrating the signal strength of a concentrator without a Bragg reflector and the light concentrator with a Bragg reflector according to various embodiments. FIG. 8B shows a plot of efficiency (in percent or %) as a function of size (in millimeters or mm) illustrating the efficiency of the concentrator without the Bragg reflector and the light concentrator with the Bragg reflector according to various embodiments. The light concentrator with Bragg reflector may be able to concentrate more light compared to the light concentrator without the Bragg reflector. For a 16 mm cube, the light concentrator with Bragg reflector may be able to collect 18x more signal than the light concentrator without the Bragg reflector (FIG. 8A). With the increasing size of the concentrator, more signal may be collected, but the signal may plateau at a size of 40 mm.

This may be caused by the decreasing efficiency of the light concentrator as the size increases (see FIG. 8B). For a 16 mm cube, it has been shown that the light concentrator with Bragg reflector has an efficiency of 8.9% compared to 0.5% of one without a Bragg reflector. This corresponds to 17.8x better efficiency. The efficiency may be defined by the ratio of signal collected at photodiode divided by incident light.

[0053] Prototypes of a light concentrator with a Bragg reflector and a light concentrator without a Bragg reflector are fabricated and experimentally tested. Both concentrators are cubes of length 16 mm. The light concentrator with the Bragg reflector shows better confinement of light compared to the one without. The experiment is performed by measuring the photocurrent received at the photodiode. The light concentrator with the Bragg reflector, the light concentrator without the Bragg reflector and the bare photodiode are tested for light capturing and concentrating ability. The setup is illuminated with a blue light (405 nm) from all angles. FIG. 9 shows a plot of photocurrent (in micro-Amperes or  $\mu\text{A}$ ) as a function of angle (in degree or deg) illustrating the superiority of the light concentrator with the Bragg reflector according to various embodiments over the light concentrator without the Bragg reflector and the bare photodiode. FIG. 9 shows the results of incident angles of -30 degrees to 100 degrees in the polar plane. Taking an average over all angles, the light concentrator with the Bragg reflector has collected 15x higher signal than the light concentrator without the Bragg reflector and 9x more signal than the bare photodiode. The light concentrator with the Bragg reflector has an efficiency of 6.5% compared to an efficiency of 0.36% for the one without the Bragg reflector, which works out to an improvement of at least 18x.

[0054] The optical gain may be defined as follows:

$$\text{Optical Gain} = \frac{A_{FCB}}{A_{Photodiode}} * \eta_{FCB} \quad (1)$$

where  $A_{FCB}$  represents the area of the light (luminescent) concentrator with the Bragg reflector,  $A_{PhotoDiode}$  represents the area of the photodiode, and  $\eta_{FCB}$  represents the efficiency of the light (luminescent) concentrator with the Bragg reflector.

[0055] The optical gain of the light concentrator with the Bragg reflector, as computed by Equation (1), is 11.7, with a field-of-view of 360 degrees.

$$Optical\ Gain = \frac{16 \times 16 \times 5}{3.14 \times 1.5^2} * 6.5\% = 11.7 \quad (2)$$

[0056] FIG. 10 shows a polar plot of signal intensity (in milli-Volts or mV) as a function of angle (in degree or deg) comparing a 16 mm cubic light concentrator with Bragg reflector according to various embodiments, a 16 mm cubic light concentrator without Bragg reflector, and a bare photodiode.

[0057] Use Case

[0058] The omnidirectional light (luminescent) concentrator can be used for optical wireless communications or Li-Fi. FIG. 11 shows a schematic of a cubic omnidirectional light concentrator/collector with a Bragg reflector on the collection surfaces of the cube according to various embodiments placed above a photodiode. Li-Fi is highly sensitive to alignment of transmitter with receiver due to the limited FOV of the receiver. With the light concentrator as shown in FIG. 11, it is possible to capture light from any direction, and communications can be enabled with ease, even at 90 degrees to the incident beam axis, thereby enabling non-line-of-sight Li-Fi communications. FIG. 12 shows (A) a schematic of an access point (AP) with an array of light (luminescent) concentrators according to various embodiments being used for underwater communications; and (B) a schematic showing the access point (AP) with the array of light concentrators according to various embodiments being used to receive data from multiple nodes (users). As shown in FIG. 12, an array of light concentrators can be attached to the access point under the ship. Mobile underwater vehicles may be able to communicate with the access point from any direction using the array of the light concentrators. Various

embodiments may not be limited to underwater wireless communications, and may be applied to other applications in free space. Various embodiments may also be applied for other optical wireless communications in aerospace, satellite, or automotive industry. Beyond optical wireless communication, various embodiments can also be applied for energy harvesting.

[0059] Various embodiments may relate to a light concentrator including a matrix, luminophores, and a wavelength-selective structure/layer/coating. The matrix may have an uncoated section for light redirection.

[0060] The various embodiments may be constructed to allow capturing of light from all directions (0 up 360°), wavelength convert the light, confine the converted light, and preferentially redirect the confine light to a channel (e.g. exit channel).

[0061] The matrix may be made of a polymeric material, and may be embedded with luminophores. The matrix may be coated with the wavelength-selective structure/layer/coating, with an uncoated section. The luminophores embedded matrix may be shaped into various shapes as a cube, a prism, cylinder, flexible sheet or fibre, through process such as casting in molds and cured using low energy methods. The size and shape of the matrix may be designed to achieve high efficiency.

[0062] The luminescent material may be a down-conversion or up-conversion material that emits visible light upon excitation through incident light. The luminescent material may include down-conversion materials such as organic dyes, quantum dots (e.g. InP, CdSe, lead halide perovskites) or up-conversion material such as lanthanides. The luminescent material can be chosen to emit at wavelengths with higher responsivity/sensitivity than the incident beam wavelength. The luminescent material may have a decay time that is faster than the optical modulation speed used in communications. The luminescent material may have a high photoluminescence quantum yield of more than 70%. Concentrations, size, molecular weight,

and/or photoluminescence quantum yield of the luminescent particle dyes can be tuned and chosen to achieve high efficiency.

[0063] The wavelength-selective structure/layer/coating may be a Bragg reflector (on an outer side of the luminophores embedded polymeric matrix). The wavelength-selective structure/layer/coating may be wavelength selective, allowing incident light to go into the matrix, while trapping the wavelength-converted light inside the matrix. In optimum cases, the incident beam can transmit through the concentrator for most of the incident beam angles, and the emitted light can be reflected within the concentrator for most of the emission angles.

[0064] The wavelength-selective structure/layer/coating can be attached or coated on or around straight/faceted edges and cylindrical surfaces of the matrix for three-dimensional (3D) confinement. Conceptually, it can be applied on curved surfaces if there are suitable fabrication technologies.

[0065] The wavelength-selective structure/layer/coating can also be fabricated using electron beam evaporation or ion beam assisted sputtering onto each surface of the concentrator through multiple cycles, to form a Bragg reflector stack.

[0066] The uncoated section (or sections) may be used to redirect the wavelength-converted light. The uncoated section (or sections) may be used as a channel for the wavelength-converted light to exit and be outcoupled to an external device (e.g. photodetector).

[0067] Conventionally, omnidirectional capturing of light can be achieved using total internal reflection. Various embodiments may relate to a luminescent concentrator with wavelength-selective structure/layer/coating for highly efficient, compact, and robust omnidirectional light collection at all incident angles.

[0068] Capturing light from all directions is usually achieved through non-elegant solutions (e.g. bulky lens, placing sensors in all directions, etc.). Various embodiments may provide an elegant solution (compact, robust, and high efficiency) by combining several physical

phenomena that work together to achieve efficient omnidirectional light collection. These phenomena are namely: omnidirectional absorption, wavelength conversion and scattering, and wavelength-selective light confinement. It is found that it is possible to take advantage of the omnidirectional absorption of luminophores to receive light omnidirectionally, which is conceptually different from light collection through lenses and other optical elements. Meanwhile, the scattering characteristic of the luminophores' emission means that it may be possible to redirect the light into all possible directions.

[0069] The challenge now is how to control the redirection of emission, and to minimize the loss of light. Several solutions could work, for example, total-internal-reflection concept, the use of other optical components, or other methods. In contrast, various embodiments may take advantage of the wavelength converting nature of luminophores. This means the light that is absorbed may have a different wavelength than the light that is emitted.

[0070] Therefore, various embodiments may use a wavelength-selective Bragg reflector layer. This Bragg reflector may be engineered to allow light of specific wavelength (i.e. the wavelength of the source) to go through the Bragg reflector, but may confine other specific wavelength (i.e. the emission wavelength of the luminophores).

[0071] Therefore, the Bragg reflector may be invisible to incoming light, but may block outgoing light. Various embodiments may provide a compact, robust, and efficient solution. It may be compact and robust as it has minimum components with no moving parts, and cannot be easily broken by impact. Various embodiments may capture light effectively in all directions, with minimum loss in power, allowing for practical use in commercial applications. Potential applications may include robust wireless optical communications (e.g. aircraft, underwater vessels, automotive), energy harvesting (as a solar light concentrator), and/or signal filtering (in secure data transfer).

Claims

## 1. A light concentrator comprising:

a polymeric matrix with embedded luminophores; and

a wavelength-selective structure such that the polymeric matrix is within a cavity defined by the wavelength-selective structure;

wherein the wavelength-selective structure is configured to substantially allow external light of a predetermined wavelength or range of wavelengths incident onto the wavelength-selective structure at predetermined incident angles to pass through the wavelength-selective structure;

wherein the luminophores are configured to absorb the external light of the predetermined wavelength or range of wavelengths that passes through the wavelength-selective structure, and further configured to emit wavelength-converted light of another predetermined wavelength or range of wavelengths upon absorption of the external light that passes through the wavelength-selective structure;

wherein the wavelength-selective structure is further configured to substantially reflect the wavelength-converted light incident onto the wavelength-selective structure at further predetermined incident angles; and wherein the wavelength-selective structure defines an opening configured to allow the wavelength-converted light or the reflected wavelength-converted light to pass through.

## 2. The light concentrator according to claim 1,

wherein the wavelength-selective structure is a Bragg reflector.

3. The light concentrator according to claim 2,  
wherein the Bragg reflector is a stacked arrangement comprising alternate layers of a first refractive index and layers of a second refractive index different from the first refractive index.
4. The light concentrator according to any one of claims 1 to 3,  
wherein the luminophores comprise quantum dots.
5. The light concentrator according to claim 4,  
wherein the quantum dots comprise copper indium sulfide, indium phosphide, or cadmium selenide.
6. The light concentrator according to claim 4 or claim 5,  
wherein the quantum dots comprise a lead halide perovskite.
7. The light concentrator according to any one of claims 1 to 6,  
wherein the luminophores comprise an organic dye.
8. The light concentrator according to any one of claims 1 to 7,  
wherein the luminophores comprise perovskites.
9. The light concentrator according to any one of claims 1 to 8,  
wherein the luminophores comprise lanthanides.

10. The light concentrator according to any one of claims 1 to 9,  
wherein the wavelength-selective structure forms a coating on a surface of the polymeric matrix; and  
wherein the opening is an uncoated part of the surface of the polymeric matrix.
11. The light concentrator according to any one of claims 1 to 10,  
wherein the polymeric matrix comprises an epoxy or an acrylate.
12. The light concentrator according to any one of claims 1 to 11,  
wherein the polymeric matrix is of a shape selected from a group consisting of a cube, a prism, a cylinder, a sheet, and a fiber.
13. The light concentrator according to any one of claims 1 to 12, further comprising:  
a photodetector configured to detect the wavelength-converted light or the reflected wavelength-converted light.
14. The light according to any one of claims 1 to 13,  
wherein the external light is omnidirectional light.
15. A method of forming a light concentrator, the method comprising:  
forming a polymeric matrix with embedded luminophores; and  
forming a wavelength-selective structure such that the polymeric matrix is within a cavity defined by the wavelength-selective structure;  
wherein the wavelength-selective structure is configured to substantially allow external light of a predetermined wavelength or range of wavelengths incident

onto the wavelength-selective structure at predetermined incident angles to pass through the wavelength-selective structure;

wherein the luminophores are configured to absorb the external light of the predetermined wavelength or range of wavelengths that passes through the wavelength-selective structure, and further configured to emit wavelength-converted light of another predetermined wavelength or range of wavelengths upon absorption of the external light that passes through the wavelength-selective structure;

wherein the wavelength-selective structure is further configured to substantially reflect the wavelength-converted light incident onto the wavelength-selective structure at further predetermined incident angles; and

wherein the wavelength-selective structure defines an opening configured to allow the wavelength-converted light or the reflected wavelength-converted light to pass through.

16. The method according to claim 15,

wherein forming the polymeric matrix with embedded luminophores comprises mixing a polymeric resin precursor and the luminescent particles to form a mixture; and

wherein forming the polymeric matrix with embedded luminophores further comprises providing the mixture in a mold such that the mixture is allowed to be cured, thereby forming the polymeric matrix with embedded luminophores.

17. The method according to claim 16,

wherein forming the polymeric matrix with embedded luminescent particles comprises removing any excess solvent and air bubbles from the mixture prior to providing the mixture in the mold.

18. The method according to claim 16 or claim 17,

wherein the mixture has a viscosity of less than 1000 cP.

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

wherein forming the wavelength-selective structure comprises applying or coating the polymeric matrix with alternate layers of a first refractive index and layers of a second refractive index different from the first refractive index.

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

wherein the polymeric matrix is of a shape selected from a group consisting of a cube, a prism, a cylinder, a sheet, and a fiber.

21. The method according to any one of claims 15 to 20, further comprising:

providing a photodetector configured to detect the wavelength-converted light or the reflected wavelength-converted light.