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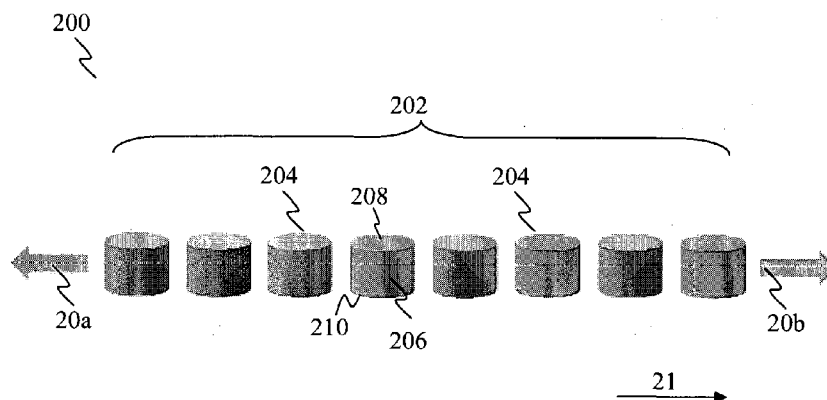


FIG. 2A

(57) Abstract: According to embodiments of the present invention, a light source including a nanoparticle, wherein the nanoparticle is made of a gain material with a refractive index of at least 2 is provided.

LIGHT SOURCE INCLUDING A NANOPARTICLE

Cross-Reference To Related Application

5 [0001] This application claims the benefit of priority of Singapore patent application No. 201308806-7, filed on 27 November 2013, the content of it being hereby incorporated by reference in its entirety for all purposes.

Technical Field

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[0002] Various embodiments relate to a light source including a nanoparticle.

Background

15 [0003] Integration of compact light sources on chip is an important challenge facing nanophotonics, which aims to significantly improve the speed of on-chip interconnects using light-on-chip integration.

[0004] Microdisk, microring and other whispering gallery microcavity (WGM) lasers emit light in the visible and near-infrared (near-IR) spectral ranges with relatively high quality (Q) factors of more than 1000. However, this emission is not directional and additional outcouplers are designed to couple the laser emission into on-chip optical components. Coaxial nanolaser designs also face a similar challenge.

[0005] Another drawback of microdisk and WGM lasers is the reliance on higher-order resonator modes, which are sensitive to the surface quality of the fabricated structures.

25 [0006] Moreover, the device footprint of such microdisk (or WGM) laser is relatively large. In order to lase with lower order modes, decreasing the size of the microdisk (or WGM) laser below 1 micron causes an abrupt decrease in the Q factor, which prevents further laser generation.

[0007] One possible route to make on-chip lasers more compact is to use plasmon-based nanoresonators. In this case, the laser cavities represent a nanoparticle or a nanorod made of both gain medium and plasmonic metals (for example, silver or gold). Surface

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plasmons allow for localization of light energy at sub-wavelength scales, which makes possible to realize visible light emission from cavities with sub-100 nm lateral dimensions.

[0008] However, the Q factor of these cavities is typically low (in the order of one to tens) due to the relatively high losses inherent to plasmonic metals at visible and near-IR frequencies. The losses are also responsible for extensive heating of the cavities, which in turn require substantial cooling for laser operation. Another disadvantage of preferred plasmonic metals (e.g. gold and silver) is their incompatibility with complementary metal-oxide-semiconductor (CMOS) process.

[0009] There is therefore a need for a light source that does not rely on plasmonic metals and thus avoids substantial losses and heating (i.e., having low threshold pumping power for lasing and low energy dissipation into heat), is compact in lateral directions having a low device foot print, and is capable of emitting light in a single (or multiple) preferred direction for ease of coupling light into other on-chip optical components (e.g. waveguides), thereby addressing at least the problems above.

[0010] The involvement of nanoparticles in other optical components has also been explored. For example, a chain of nanoparticles, made of passive high-refractive index materials, forms a waveguide structure capable of transporting electromagnetic energy without radiative losses. In such a waveguide structure, the distance between the centres of neighbouring particles is smaller than half of the particle's resonant wavelength. Further, small particle chains made of passive high-refractive index materials has also been used to form low-loss passive antennas for controlling emission directivity of localized emitters.

Summary

[0011] According to an embodiment, a light source including a nanoparticle is provided. The nanoparticle may be made of a gain material with a refractive index of at least 2.

Brief Description of the Drawings

[0012] In the drawings, like reference characters generally refer to like parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0013] FIG. 1 shows a schematic view of a light source, according to various embodiments.

[0014] FIGs. 2A to 2E show, as schematic views, various examples of nanoparticle lasers, according to various embodiments.

[0015] FIG. 3A shows a plot illustrating the dependence of Q factor on the number of nanoparticles (cylinders), according to various embodiments.

[0016] FIG. 3B shows a plot illustrating a normalized spectrum for a chain of 16 cylinders, according to one embodiment.

[0017] FIG. 3C shows a plot illustrating a normalized spectrum for a chain located on a substrate, according to one embodiment.

[0018] FIG. 3D shows a plot illustrating the dependence of Q factor on the radius of a reflector particle, according to various embodiments.

[0019] FIG. 4A shows a plot illustrating the relationship between average output power and pumping intensity for various chains of nanoparticles, according to various embodiments.

[0020] FIG. 4B shows a schematic view of a mode structure inside the cavity (8-nanoparticle chain), according to one embodiment.

[0021] FIG. 4C shows a plot illustrating a normalized spectrum for a chain of 16 cylinders at different pumping intensities, according to various embodiments.

[0022] FIG. 4D shows the respective energy density plots at the pumping intensities described in FIG. 4C.

[0023] FIG. 4E shows a plot illustrating the relationship between average output power and pumping intensity for a chain of 16 cylinders in air and located on a substrate, according to various embodiments.

[0024] FIG. 4F shows a plot illustrating the relationship between average output and pumping intensity for a chain of 8 cylinders with and without variations, according to various embodiments.

[0025] FIGs. 5A to 5D show emission diagrams of various examples of nanoparticle lasers, according to various embodiments.

Detailed Description

[0026] 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.

[0027] 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.

[0028] 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.

[0029] In the context of various embodiments, the phrase “at least substantially” or “substantially” may include “exactly” and a reasonable variance.

[0030] 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.

[0031] As used herein, the term “and/or” includes any and all combinations of more of the associated listed items.

[0032] As used herein, the phrase of the form of “at least one of A or B” may include A or B or both A and B. Correspondingly, the phrase of the form of “at least one of A or B or C”, or including further listed items, may include any and all combinations of one or more of the associated listed items.

[0033] The same numerals may be assigned to like elements. Further, the description for the elements may be as described in the context of the figures, and such description may be applicable to like elements, even though the corresponding descriptions for like elements may be omitted.

[0034] Various embodiments may provide nanoparticle-based light sources.

[0035] Various embodiments may relate to compact (nano- and micrometer scale) light sources, which may be fabricated directly on chip for light-on-chip integration and emit light at visible and near-IR wavelengths towards preferred spatial directions in or out of the device plane.

[0036] Various embodiments may provide a light source based on coupled chains of resonant nanoparticles. These nanoparticles may be fabricated directly on chip and may emit light of visible and near-IR wavelengths into a single or multiple preferred directions inside or outside the device plane. The Q factor and laser threshold of the light source may depend on the number of nanoparticles inside the resonator of the light source. For example, the higher the number of nanoparticles, the greater the Q factor and the smaller the threshold pumping power required for lasing. Such a relationship may allow the tuning of the light source, for example, in the form of a laser structure, in accordance with particular experimental conditions (such as heating and cooling conditions).

[0037] Various embodiments may provide a nanoparticle laser.

[0038] Various embodiments may relate to the principles of the nanoparticles waveguides and nanoantennas with high-refractive index gain materials for directional compact light sources/lasers which may be fabricated on chip and may emit light in preferred directions in or outside the device plane.

[0039] FIG. 1 shows a schematic view of a light source 100, according to various embodiments. The light source 100 includes a nanoparticle 102. The nanoparticle 102 is

made of a gain material with a refractive index of at least 2. This may mean that the material has a refractive index of at least 2.

[0040] In other words, the nanoparticle 102 may include a gain material with a refractive index of at least 2. In various embodiments, the nanoparticle 102 may consist of or essentially consist of a gain material with a refractive index of at least 2.

[0041] The light source 100 may be fabricated for light-on-chip integration. In some embodiments, the light source 100 may be fabricated directly on a chip for light-on-chip integration.

[0042] In the context of various embodiments, the refractive index may be a value that is measured at a wavelength of operation of the light source 100.

[0043] In various embodiments, the nanoparticle 102 may have a refractive index of more than 2 ($n > 2$), or more than 2.5 ($n > 2.5$), or more than 3 ($n > 3$), or more than 3.5 ($n > 3.5$). For example, the nanoparticle 102 may have a refractive index of about 2.1, about 2.2, about 2.3, about 2.4, about 2.5, about 2.6, about 2.7, about 2.8, about 2.9, about 3, about 3.1, about 3.2, about 3.3, about 3.4, about 3.5, about 3.6, about 3.7, about 3.8, about 3.9, or about 4.

[0044] The phrase “gain material” generally refers to a material that undergoes a reversible fundamental (e.g. physical, chemical) property change when activated by an external stimulus or signal. The gain material is capable of emitting electromagnetic radiation upon stimulation.

[0045] In the context of various embodiments, the gain material may refer to a material that provides optical gain in the light source 100. For example, the gain material, when being pumped or excited appropriately, is capable of amplifying and emitting radiation within a certain spectral range. The gain material may be interchangeably referred to as an active material. It should be appreciated and understood that a gain material (or an active material) is different from a passive material which does not provide optical gain, but instead generates radiation losses. Accordingly, it should be appreciated and understood that with the gain material, the nanoparticle 102 is “active” and is different from passive one described in conventional nanoscale waveguides and nanoantennas. Generally, examples of the gain material may include, but is not limited to, a crystalline compound or a semiconductor compound. The gain material may also be composed of

high refractive index material (e.g. high-refractive index glass, high-refractive index gel material, high-refractive index polymer, and so on) doped by active compounds (e.g. quantum dots, active dyes, and so on).

5 [0046] In various embodiments, the gain material may include a III-V semiconductor material.

[0047] For example, the gain material may be selected from the group consisting of gallium nitride (GaN), aluminum indium nitride (AlInN), aluminum gallium nitride (AlGaIn), gallium phosphide (GaP), indium nitride (InN), gallium arsenide (GaAs), indium phosphide (InP), indium gallium arsenide (InGaAs), indium gallium arsenide phosphide (InGaAsP), and any combination thereof. The gain material may also be any
10 other active semiconductor material (e.g. group III-V, IV or II-VI semiconductor) with a refractive index of at least 2.

[0048] In various embodiments, the light source 100 may have an emission wavelength substantially corresponding to a spectral position of a first Mie resonance exhibited by the
15 nanoparticle 102.

[0049] In the context of various embodiments, the phrase “substantially corresponding to” may refer to having a relationship with, or being equivalent to, or being approximate to, or close to, or being defined by, or being derived from.

[0050] For example, the emission wavelength of the light source 100 may be of a value
20 that is the same as the spectral position of the first Mie resonance exhibited by the nanoparticle 102. The emission wavelength of the light source 100 may also be of a value that is a factor of the spectral position of the first Mie resonance exhibited by the nanoparticle 102. For example, the emission wavelength may be within $\pm 25\%$ from the spectral position of the first Mie resonance. As such, the light source 100 may have an
25 emission wavelength close with about $\pm 25\%$ variance to a spectral position of a first Mie resonance exhibited by the nanoparticle 102.

[0051] Due to the relatively high refractive index of at least 2, the nanoparticle 102 may have well defined scattering Mie resonances. In other words, the nanoparticle 102 may exhibit multiple Mie resonances with measurable (or non-negligible) amplitudes.
30 Accordingly, the well defined Mie resonances may be spectrally separated and observable in a scattering spectrum. The first Mie resonance may refer to the Mie

resonance with the largest wavelength. The first Mie resonance may refer to the $m=0$ dipole resonance.

[0052] In an example of single spherical particle (or spherical nanoparticle) with refractive index $n > 2$ located in air, the wavelength of the first Mie resonance, λ_{res} , may be approximately estimated (e.g. with a variation of about $\pm 10\%$) from the following formula:

$$\lambda_{\text{res}} \approx d \times n \quad (\text{Equation 1})$$

where d is the particle diameter.

[0053] The size and shape of the nanoparticle 102 may be determined such that the spectral position of the first Mie resonance overlaps with the active/ emission region of the gain material, in other words, the wavelength of the first Mie resonance falling within a wavelength range in which the gain material is capable of having light emission.

[0054] It should be appreciated that the size of the nanoparticle 102 may differ depending on the gain material used and may not be limited to the exemplary values/ ranges described herein. As an example for illustrative purposes only, the nanoparticle 102 may include InP and may have a diameter in a range of about 225 nm to about 235 nm.

[0055] More specifically, the nanoparticle 102 may have a diameter in a range of about 226 nm to about 234 nm, or of about 227 nm to about 233 nm, or of about 228 nm to about 232 nm, or of about 229 nm to about 231 nm. The nanoparticle 102 may have a diameter of about 230 nm. The nanoparticle 102 may have a diameter of 230 nm with a variant of 1 % (i.e., $230 \text{ nm} \pm 2.3 \text{ nm}$).

[0056] The term “diameter” generally refers to the length of a straight line passing from side to side through the centre of a body or figure. For example, for a rectangle or a square, the diameter may refer to the length of the diagonal.

[0057] For the abovementioned illustrative examples, the nanoparticle 102 may have a height in a range of about 226 nm to about 234 nm, or of about 227 nm to about 233 nm, or of about 228 nm to about 232 nm, or of about 229 nm to about 231 nm. The nanoparticle 102 may have a height of about 230 nm. The nanoparticle 102 may have a height of 230 nm with a variant of 1 % (i.e., $230 \text{ nm} \pm 2.3 \text{ nm}$).

[0058] In various embodiments, the nanoparticle 102 may include, but is not limited to, a cylindrical nanoparticle, a spherical nanoparticle, a cuboidal nanoparticle, or a prism-shaped nanoparticle.

[0059] In various embodiments, the light source 100 may further include a plurality of nanoparticles. Each of the plurality of nanoparticles may be made of a gain material with a refractive index of at least 2. This may mean that the gain material has a refractive index of at least 2.

[0060] In some embodiments, each of the plurality of nanoparticles may be made of the same gain material. Using the same gain material may allow for easier, faster and more cost effective fabrication. In other embodiments, at least one of the plurality of nanoparticles may be made of a gain material different from another of the plurality of nanoparticles.

[0061] The gain material may include a III-V semiconductor material. For example, the gain material may be selected from the group consisting of GaN, AlInN, AlGaIn, GaP, InN, GaAs, InP, InGaAs, InGaAsP, and any combination thereof. The gain material may also be any other active semiconductor material (e.g. group III-V, IV or II-VI semiconductor) with a refractive index of at least 2.

[0062] The plurality of nanoparticles may include cylindrical nanoparticles, spherical nanoparticles, cuboidal nanoparticles, prism-shaped nanoparticles, or mixtures thereof.

[0063] The light source 100 may have an emission wavelength substantially corresponding to a spectral position of a first Mie resonance exhibited by the plurality of nanoparticles. For example, the emission wavelength may be within $\pm 25\%$ from the spectral position of the first Mie resonance.

[0064] The plurality of nanoparticles may provide a guiding mode where electromagnetic energy may be transported without radiative loss. In this case, the distance between the centres of neighbouring nanoparticles may be smaller than half of the nanoparticle's resonant wavelength. This may be achievable for high-refractive index nanoparticles at their first Mie resonance if their refractive indices are at least 2.

[0065] In various embodiments, each of the plurality of nanoparticles may be described in the context of the nanoparticle 102 of FIG. 1. In other embodiments, at least one of the

plurality of nanoparticles may be described in the context of the nanoparticle 102 o

1.

[0066] In various embodiments, the plurality of nanoparticles may be arranged laterally to form a chain of nanoparticles. In other words, each nanoparticle may be arranged adjacent or side by side to another nanoparticle.

[0067] The chain of nanoparticles may be a linear chain of nanoparticles. A linear chain of nanoparticles may mean the nanoparticles being arranged coaxially, in other words, the centre of each nanoparticle is in line (or forms a line) with the centre of another nanoparticle in the chain of nanoparticles.

[0068] In some embodiments, the chain of nanoparticles may be a non-linear chain of nanoparticles. A non-linear chain of nanoparticles may mean the nanoparticles being arranged in manner such that the centre of each nanoparticle is not in line with the centre of another nanoparticle in the chain of nanoparticles. For example, a non-linear chain of nanoparticles may mean nanoparticles being arranged in a circular manner or along the perimeter of a circle.

[0069] The chain of nanoparticles may be interchangeably referred to as the nanoparticle chain. The chain of nanoparticles may also be simply referred herein as "chain".

[0070] In various embodiments, the light source 100 may further include a reflector particle arranged to at least minimize transmission of light emitted from the plurality of nanoparticles in a predetermined direction.

[0071] For example, the reflector particle may be configured to reflect light from the plurality of nanoparticles. The reflector particle may be a nanoscale reflector particle. The reflector particle may be made of the same material as nanoparticles in the chain or may include an optically reflective material or a mirror that does not allow light transmission.

Reflector particle may be larger (in horizontal or in all directions) than the nanoparticles in the chain or have a different shape. Light (e.g. emitted from the plurality of nanoparticles) incident on the reflector particle may be re-directed or bend back from the reflector particle. This way, transmission of light emitted from the plurality of nanoparticles may be minimized or may not be allowed in a direction through the path of the reflector particle, but instead, transmission of light emitted from the plurality of nanoparticles may be maximized or allowed in another direction which is not through the

path of the reflector particle, for example, in an opposing direction away from the reflector particle.

[0072] In various embodiments, the reflector particle may have a size associated with a directivity of the light source 100. For example, the reflector particle may have an optimal size corresponding to the highest directivity of the light source 100. The size may also be defined by resonant interaction inside the light source 100 similar to a nanoparticle-based Yagi-Uda nanoantenna.

[0073] It should be appreciated that the size of the reflector particle may differ and may not be limited to the exemplary values/ ranges described herein. For illustrative purposes only and based on the abovementioned illustrative examples describing the size of the nanoparticle 102, the reflector particle may have a diameter in a range of about 240 nm to about 440 nm.

[0074] More specifically, the reflector particle may have a diameter in a range of about 250 nm to about 430 nm, or about 260 nm to about 420 nm, or about 270 nm to about 410 nm, or about 280 nm to about 400 nm, or about 290 nm to about 390 nm, or about 300 nm to about 380 nm, or about 310 nm to about 370 nm, or about 320 nm to about 360 nm, or about 330 nm to about 350 nm. The reflector particle may have a diameter of about 355 nm. The reflector particle may have a diameter of 355 nm with a variant of 1 % (i.e., $355 \text{ nm} \pm 3.55 \text{ nm}$).

[0075] The reflector particle may have a height at least substantially similar to the height of the plurality of nanoparticles.

[0076] For the abovementioned illustrative examples, the reflector particle may have a height in a range of about 226 nm to about 234 nm, or of about 227 nm to about 233 nm, or of about 228 nm to about 232 nm, or of about 229 nm to about 231 nm. The reflector particle may have a height of about 230 nm. The reflector particle may have a height of 230 nm with a variant of 1 % (i.e., $230 \text{ nm} \pm 2.3 \text{ nm}$).

[0077] In various embodiments, the reflector particle may include, but is not limited to, a cylindrical reflector particle, a spherical reflector particle, a cuboidal reflector particle, or a prism-shaped reflector particle.

[0078] In various embodiments, the reflector particle may be arranged at one end of the chain of nanoparticles. With the reflector particle positioned at one end of the chain of

nanoparticles, light may be emitted from the opposite end of the chain in one pre direction that may be parallel to the chain's axis.

[0079] For the abovementioned illustrative examples, the reflector particle may be placed at about 400 nm, or about 450 nm, or about 500 nm side-to-side separation from the nanoparticle chain.

[0080] It may be appreciated that by varying the number of reflector particles, the size of the reflector particle, and the separation distances between the reflector particle and the nanoparticle chain, the directivity may be varied.

[0081] In various embodiments, the light source 100 may further include a substrate having a surface on which the plurality of nanoparticles may be disposed. For example, the plurality of nanoparticles may be fabricated on the surface of the substrate.

[0082] The substrate may include, for example, a dielectric substrate. The substrate may be silicon dioxide, glass, sapphire, or any other dielectric material with a refractive index below 2.

[0083] For example, the plurality of nanoparticles may be arranged such that at least one of the plurality of nanoparticles may directly or indirectly be in contact with the surface of the substrate.

[0084] In various embodiments, the chain of nanoparticles may be arranged to extend along a plane substantially parallel to the surface of the substrate.

[0085] The plane substantially parallel to the surface of the substrate may include any plane that may be considered continuously at equidistance from the surface of the substrate. In some embodiments, the plane substantially parallel to the surface of the substrate may also refer to the surface of the substrate itself. In this case, each of the plurality of nanoparticles may be positioned directly on the surface of the substrate to form a chain of nanoparticles on the surface of the substrate.

[0086] Light emission from the chain of nanoparticles arranged to extend along a plane substantially parallel to the surface of the substrate may be described as in-device-plane light emission.

[0087] In various embodiments, the chain of nanoparticles may be arranged to extend along a direction substantially perpendicular to the surface of the substrate.

[0088] Light emission from the chain of nanoparticles arranged to extend along a direction substantially perpendicular to the surface of the substrate may be described as light emission outwardly with respect to the surface of the substrate or out-of-device-plane light emission.

5 [0089] In various embodiments, the plurality of nanoparticles may be spaced apart from one another.

[0090] It should be appreciated that the separation distance between adjacent nanoparticles may differ and may not be limited to the exemplary values/ ranges described herein. For illustrative purposes only and based on the abovementioned
10 illustrative examples describing the size of the nanoparticle 102, the plurality of nanoparticles may be spaced apart from one another with a nanoparticle-to-nanoparticle separation distance ranging from about 45 nm to about 55 nm. The phrase “nanoparticle-to-nanoparticle separation” may mean side-to-side separation.

[0091] More specifically, the plurality of nanoparticles may be spaced apart from one
15 another with a nanoparticle-to-nanoparticle separation distance ranging from about 46 nm to about 54 nm, or from about 47 nm to about 53 nm, or from about 48 nm to about 52 nm, or from about 49 nm to about 51 nm. The plurality of nanoparticles may be spaced apart from one another with a nanoparticle-to-nanoparticle separation distance of about
20 50 nm. The plurality of nanoparticles may be spaced apart from one another with a nanoparticle-to-nanoparticle separation distance of 50 nm with a variant of 10 % (i.e., 50 nm $\pm$ 5 nm).

[0092] In various embodiments, the light source 100 may further include a dielectric material disposed between the spaced apart nanoparticles.

[0093] In various embodiments, the dielectric material may have a refractive index of
25 less than 2. For example, the refractive index of the dielectric material may be about 1.1, or about 1.2, or about 1.3, or about 1.4, or about 1.5, or about 1.6, or about 1.7, or about 1.8, or about 1.9.

[0094] In various embodiments, the plurality of nanoparticles may include 2 or more nanoparticles, 3 or more nanoparticles, 4 or more nanoparticles, 5 or more nanoparticles,
30 6 or more nanoparticles, 7 or more nanoparticles, 8 or more nanoparticles, 9 or more nanoparticles, 10 or more nanoparticles, 11 or more nanoparticles, 12 or more

nanoparticles, 13 or more nanoparticles, 14 or more nanoparticles, 15 or nanoparticles, 16 or more nanoparticles, 20 or more nanoparticles, 30 or more nanoparticles, 50 or more nanoparticles, 100 or more nanoparticles, or 1000 or more nanoparticles.

5 [0095] In various embodiments, the plurality of nanoparticles may include at least 8 nanoparticles.

[0096] In other embodiments, the plurality of nanoparticles may include at least 16 nanoparticles.

10 [0097] In various embodiments, the light source 100 may be a laser. The laser may be an on-chip laser that relies on chains of coupled nanoparticles made of high-refractive index gain material (e.g. III-V semiconductors). The laser may have a laser cavity (or a laser resonator) based on the plurality of nanoparticles. In other words, the cavity of these lasers may consist of closely spaced coupled resonant nanoparticles made of high-refractive index ($n > 2$) gain materials (e.g. III-V semiconductor).

15 [0098] The Q factor and lasing threshold of the laser cavity (or laser resonator) may depend on the number of nanoparticles in the laser cavity (or laser resonator). For example, the higher the number of nanoparticles, the greater the Q factor and the smaller the threshold pumping power required for lasing. More specifically, the Q factor of the laser cavity (or laser resonator) may increase and the threshold pump power required for
20 lasing may decrease with increasing number of nanoparticles inside the laser cavity (or laser resonator).

[0099] The light emission wavelength may be tuned through the visible and near-IR wavelengths by changing the size of the nanoparticles and by altering a gain medium of the laser. Each nanoparticle may have varied geometry (e.g. sphere, cylinder, cuboid,
25 prisms) as long as the spectral position of its first Mie resonance is close to the emission wavelength. The light resonantly emitted by each single nanoparticle may be coupled into the nanoparticle chain forming a collective emission mode inside the laser cavity (or laser resonator). This mode may emit from the end of the nanoparticle chain in a direction defined by the chain geometry.

30 [0100] Examples of chain geometries for the light source 100 in the form of a nanoparticle laser are shown in FIGs. 2A to 2E. It may be noted that different structure

(chain geometries) and nanoparticle geometries may be used, given that the following conditions are observed:-

- the nanoparticles may be made of gain material (or interchangeably referred to as gain medium material) with relatively high refractive index of at least 2;
- 5 • the first Mie resonance of the nanoparticles may overlap with the active region of the gain material;
- the distance between the nanoparticles' centres may be less than half the wavelength of the nanoparticles' first Mie resonance.

[0101] A schematic view 200 illustrating an exemplary linear chain 202 of closely spaced coupled resonant nanoparticles 204 is shown in FIG. 2A. The nanoparticle 204 may be described in the context of the nanoparticle 102 of FIG. 1. Each nanoparticle 204 may be cylindrical (i.e., having a curved surface body 206 with a circular top surface 208 and a circular bottom surface 210). Each nanoparticle 204 may be spaced apart from a neighbouring nanoparticle 204 such that the curved surface body 206 of the nanoparticle 204 may be side by side to the curved surface body 206 of the neighbouring nanoparticle 204. If the nanoparticles 204 are of the same height, the respective circular top surfaces 208 of the nanoparticles 204 may be considered to be aligned along a same plane. Similarly, the respective circular bottom surfaces 210 of the nanoparticles 204 may also be considered to be aligned along a separate same plane. Arrows 20a, 20b show the directions of preferred light emission by the laser design. In this case, since the laser cavity (or laser resonator) may be provided by a linear chain of similar nanoparticles 204, light may be emitted from the ends of the chain (linear chain 202) in two opposite preferred directions 20a, 20b parallel to the chain's axis (as indicated by an arrow 21). The nanoparticles 204 may be located on a substrate (not shown in FIG. 2A). The space between the nanoparticles 204 may be filled by low-refractive index (< 2) transparent dielectric material.

[0102] Each nanoparticle 204 may be made of high refractive index (n being at least 2) gain material. Due to the high refractive index, each nanoparticle 204 may have well defined scattering Mie resonances. The distance between the nanoparticle 204 centres may be chosen to be less than half the wavelength of the first scattering Mie resonance of each nanoparticle 204.

[0103] The size and shape of the nanoparticles 204 may be chosen such that the position of their first Mie resonance overlaps with the active/ emission region of the gain material. In other words, the spectral position of the first Mie resonance may be close to the active region of gain medium. The shape of the nanoparticles 204 may be cylindrical (as shown in FIG. 2A), spherical, or any other arbitrary shape as long as the aforementioned conditions are observed.

[0104] The cylindrical shape is further used herein as an example because it may be directly fabricated by lithography.

[0105] The light emitted by each resonant nanoparticle 204 in the chain 202 may be coupled into the chain 202 by means of resonant interaction. This may form a guiding mode inside the chain 202, which may propagate in both directions (as indicated by arrows 20a, 20b) without radiative losses in the lateral directions. The mode may be reflected from both sides of the chain 202 forming a standing resonator mode. The light may emit from both sides of the chain 202 as shown in FIG. 2A as from the partially transmitting mirrors of conventional resonators.

[0106] In the schematic view 220 of FIG. 2B, an additional reflector particle 222 is added to one side of the nanoparticle chain 202. This reflector particle 222 may significantly increase reflection of the mode propagating inside the nanoparticle chain 202 from its end of the chain 202. This may change the emission diagram of the laser or light source making it aligned along a single direction at the opposite end of the chain 202 (as indicated by an arrow 22). This type of emitters may be considered as single-direction emitters.

[0107] In each particular design, the reflector particle 222 may have an optimal size corresponding to the highest directivity of the laser or light source system. For example, this size may be defined by resonant interaction inside the system similar to nanoparticle-based Yagi-Uda nanoantennas.

[0108] A similar design to that as shown in FIG. 2B is provided in the schematic view 240 of FIG. 2C where light is emitted in the vertical direction (as indicated by an arrow 24) perpendicular to the device plane (as indicated by an arrow 25) instead. In other words, since the laser cavity (or laser resonator) may be provided by a linear nanoparticle chain 242 with a reflector particle 222 at one end, light may be emitted from the opposite

end of the chain 242 in one preferred direction (as indicated by the arrow 24) parallel to the chain 242's axis (as indicated by the arrow 24).

[0109] As seen in FIG. 2C, each nanoparticle 204 is spaced apart from a neighbouring nanoparticle 204 in the chain 242 such that the circular top surface 244 of the nanoparticle 204 is side by side to the circular bottom surface 246 of the neighbouring nanoparticle 204. If the nanoparticles 204 are of the same diameter, the respective curved surface bodies 248 of the nanoparticles 204 may be considered to be aligned along a same plane. Such design (as in FIG. 2C) may be fabricated by lithographic process of a multilayer film, where each layer film may provide each nanoparticle 204. Although it may be appreciated that in another example, the vertically extended chain 242 may be formed with the cylindrical reflector 222 and the cylindrical nanoparticles 204 in FIG. 2C being orientated differently (e.g. as in FIG. 2B) to also emit light in the vertical direction (as indicated by the arrow 24), the fabrication of this exemplary design may be relatively challenging.

[0110] An exemplary laser design with a circular shape resonator 262 consisting of coupled nanoparticles 264 is shown in the schematic top view 260 of FIG. 2D. The nanoparticles 264 may be described in the context of the nanoparticles 204 of FIGs. 2A to 2C. In this case, the Q factor and lasing threshold of the resonator may be expected to be higher and lower, respectively, as compared to the designs shown in FIGs. 2A to 2C. However, the emission from such a resonator 262 may not be regarded as being directional (as indicated by the arrows 26) and just as in the case of disk lasers, an additional outcoupler may be required (not shown in FIG. 2D).

[0111] Efficient lasing may be obtained for a chain of coupled nanoparticles (e.g. cylinders), which may be fabricated by direct lithographic process.

[0112] FIG. 2E shows a schematic view 280 of a chain 202 (as in FIG. 2A) located on a substrate 282. Similar to FIG. 2A, since the laser cavity (or laser resonator) may be provided by a linear chain of similar nanoparticles 204 on the substrate 282, light may be emitted from the ends of the chain (linear chain 202) in two opposite preferred directions 28a, 28b parallel to the chain's axis (as indicated by an arrow 29).

[0113] The emission wavelength of the nanoparticle lasers, e.g. as described in FIGs. 2A to 2E, may be defined by the properties of the gain medium and the spectral position of

the nanoparticles' first Mie resonance, which may in turn be defined by their geometry.

In various examples, it may be tuned through the entire visible and near-IR spectral range by using different III-V semiconductor materials (active material) as a gain medium (such as GaN, AlInN, AlGaIn, GaP, InN, GaAs, InP, InGaAsP, and so on) and by tuning the spectral position of the nanoparticles' first Mie resonance such that it may overlap with the gain region of the active material. The spectral position of the nanoparticles' first Mie resonance may be tuned by changing the size and shape of the nanoparticles.

[0114] In the following, particular realizations of nanoparticle laser designs (e.g. some of which as described above) may be demonstrated using the commercially available Finite Difference Time Domain software FDTD Solutions (Lumerical Solutions Inc., Canada).

[0115] FIG. 3A shows a plot 300 illustrating the dependence of the calculated Q factor of a resonator, which includes a chain of identical high-refractive index cylinders, on the number of cylinders in the chain. The simulation may be based on the design 200 shown in FIG. 2A. The cylinders may be described in the context of the nanoparticles 204 of FIG. 2A. Dielectric function corresponding to that of InP may be used in the calculations. Each of the cylinders may have a diameter of about 230 nm and a height of about 230 nm. The cylinders may be located in the same plane in air (as indicated by squares 302) or on a dielectric substrate with refractive index of 1.5 (as indicated by crosses 304) with side to side separation of about 50 nm (centre to centre separation of about 280 nm).

[0116] The Q factor may be calculated by exciting the cavity (e.g. chain 202 of FIG. 2A) with a short pulse and then calculating the spectral response of the laser system by applying a Fast Fourier Transform to the temporal response of the fields. The simulations may be allowed to run for a sufficiently long amount of time (> 14.5 ps) in order to ensure an approximately 0.25 nm wavelength resolution around the wavelengths of interest.

Error bars on the plot of FIG. 3A may indicate the uncertainty due to a finite frequency resolution. The cavity may be excited by multiple randomly oriented and phased dipoles within the nanoparticles with a pulse spectral content covering the emission bandwidth of InP to mimic spontaneous emission. Consequently, the simulation may have excited all the modes that may be excited by spontaneous emission within the cavity. A coarse mesh with size of about 10 nm, which may account for the actual roughness of lithographically

fabricated structures, may be used. Convergence testing on the finite size of the shows that results obtained with an approximately 10 nm mesh may be acceptable.

[0117] The calculations show that the Q factor of such resonators may rapidly and significantly grow with increasing number of nanoparticles in the chain. This may be in agreement with results obtained for similar conventional systems. As seen in FIG. 3A, the Q factor values obtained for chains of 8 and 16 nanoparticles in air are 70 and 410, respectively.

[0118] As an example, FIG. 3B shows a plot 320 illustrating a normalized spectrum with respect to wavelength for a chain of 16 nanoparticles (as indicated by a dotted circle 306 of FIG. 3A), while FIG. 3C shows a plot 340 illustrating a normalized spectrum with respect to wavelength for a chain located on the substrate (as indicated by a dotted circle 308 of FIG. 3A). The substrate may be described in the context of the substrate 282 of FIG. 2E.

[0119] When the cylinders are placed on the substrate, the Q factor may be degraded for the same number of cylinders (when not placed on the substrate). Nevertheless, for a relatively low refractive index substrate like glass, a guiding mode may still form as evidenced by the increase in Q factor with increasing number of cylinders (as seen in FIG. 3A).

[0120] The Q factor values (as seen in FIG. 3A) may be higher than those of plasmonic nanolasers and may approach those of disk lasers. In the presence of a dielectric substrate, the Q factor of the laser system may decrease. In this case, the same high values of the Q factor may be achieved with higher number of nanoparticles in the chain.

[0121] For comparison, the Q factor calculations of the nanoparticle chain with 8 nanoparticles and one reflector particle in air may be performed based on the design shown in FIG. 2B. FIG. 3D shows a plot 360 illustrating the dependence of the calculated Q factor of a resonator (e.g. as in FIG. 2B) on the reflector particle's radius. The calculations may be performed for different gaps (about 50 nm gap 362, about 400 nm gap 364, and about 500 nm gap 366) between the reflector particle and the nanoparticle chain as well as with different reflector radii. The cylinders (of the nanoparticle chain) may be made of InP with both height and diameter at about 230 nm and side-to-side separation of about 50 nm. The height of the reflector particle (in a

cylinder form) may also be at about 230 nm. The reflector particle may also be n InP. It may be observed that the addition of the reflector particle may increase the Q factor by more than twice (e.g. from 70 as seen in the case for certain configurations shown in FIG. 3A).

5 [0122] FIG. 4A shows a plot 400 illustrating the dependence of the emitted laser power on the pumping light intensity for chains with 1 cylinder 402, 8 cylinders 404, 16 cylinders 406, and 8 rectangular nanoparticles 408. The nanoparticles may be located in air and their parameters may be similar to those as in FIG. 3A.

[0123] The lasing simulations may be modelled using a four level two electron model
10 that may be implemented with Lumerical's plugin taking into account significant non-radiative decay channels present in InP.

[0124] The dielectric function may be InP and the bandgap of InP may be about 1.34 eV. The additional material parameters used in the four level two electron model may be shown in Table 1, as follows:

15 [0125] Table 1

Parameter	Value
Density of states at the edge of the conduction band	$5.2 \times 10^{17} \text{ cm}^{-3}$
Intra-band (Conduction) Lifetime	1.7 ps
Intra-band (Valence) Lifetime	100 fs
Total Inter-Band (Radiative and Non-Radiative) Lifetime	100 ps
Radiative Lifetime	1.5 ns
Dipole Dephasing Time	100 fs

[0126] All laser simulations may be run for 12 ps time, which may correspond to picosecond laser pumping in an actual physical experiment. The pumping wavelength may be about 735 nm and the emission wavelength may be about 935 nm. The
20 configurations of the nanoparticle chains may be similar to those in FIG. 3A. For example, the nanoparticle may have a diameter of about 230 nm, a height of about 230 nm, and a side to side separation with respect to a neighbouring nanoparticle of about 50 nm.

[0127] The pumping intensity (which may be interchangeably referred to as intensity) corresponding to the lasing threshold may significantly decrease with increasing number of nanoparticles in the chain (as seen in FIG. 4A). In this example, the nanoparticle may be interchangeably referred to as the cylinder. For a single nanoparticle 402, it may be above 10^7 W/cm². This may be considered a high value which may make it difficult to obtain lasing in an actual experimental situation because of extensive heating. However, for a chain of 8 nanoparticles 404, the threshold intensity may drop more than 10 times (below 7×10^5 W/cm²), which may make it comparatively easier to realize in actual practice. For a chain of 16 nanoparticles 406, the lasing threshold may decrease further. However, the difference in average output power between the 8-nanoparticle chain 404 and the 16-nanoparticle chain 406 may not be significant. This may be explained by a short pumping time (12 ps), which may be not enough to fully pump the high-Q laser resonator at low pumping intensities. With increase of the pumping time, the threshold pumping intensity required for lasing of designs with high number of nanoparticles may be expected to decrease further.

[0128] FIG. 4B shows a mode structure 420 inside the cavity (8-nanoparticle chain) at the emission wavelength of about 936 nm. Larger E^2 values may be observed for nanoparticles positioned in the middle of the nanoparticle chain as compared to nanoparticles positioned in at the ends of the nanoparticle chain.

[0129] FIG. 4C shows a plot 440 illustrating the normalized spectrum for the 16-nanoparticle chain at different pump intensities of 5.0×10^2 kW/cm² (as shown by plotline 442) and 2.1×10^3 kW/cm² (as shown by plotline 444). FIG. 4D shows the respective energy density plots 460 inside a cylinder with respect to pumping time at the pump intensities described in FIG. 4C.

[0130] Narrowing of emission linewidth above the lasing threshold may be observed. Further, fraction of spectrum due to emission at bandgap may increase by about 5 orders of magnitude. Spike in temporal dependence of energy density at a point inside a cylinder may also be observed above the lasing threshold.

[0131] FIG. 4E shows a plot 480 illustrating the dependence of the output emission power on pumping intensity for 16 nanoparticles in the cavity with the same parameters as in FIG. 4A, located in air (denoted by plotline with squares 482), and on a dielectric

substrate with refractive index of 1.5 (denoted by plotline with diamonds 484).

presence of the substrate, the threshold pumping intensity required for lasing (lasing threshold) may increase. However, it may still be significantly lower than that for a single cylinder. By increasing the number of nanoparticles, it may be possible to further
5 decrease the threshold pumping intensity. In any actual experimental situation (where heating and cooling conditions of the device may be taken into account), the number of nanoparticles may be sufficiently high such that the threshold pumping intensity may be low enough to achieve lasing in the device without causing substantial heating and damage. The foot print of the design in accordance with various embodiments may be
10 defined by the particle diameter in lateral direction (about 230 nm for the realization) and the number of nanoparticles in the chain (about 2190 nm for 8 nanoparticles and about 4430 nm for 16 nanoparticles in the realization), which may be significantly lower than the micro-disk lasers.

[0132] FIG. 4F shows a plot 490 illustrating the dependence of the output emission
15 power on pumping intensity for 8 nanoparticles in the cavity with the same parameters as in FIG. 4A, located in air (denoted by plotline with squares 492), and with introduced random variations of nanoparticle diameter (1%) and side to side separation (10%) (denoted by plotline with diamonds 494). FIG. 4F may demonstrate the robustness of the design in accordance with various embodiments to variations of nanoparticle parameters,
20 which may appear due to fabrication imperfections. Plotline 492 corresponds to the case of 8 cylinders in air with diameter and height of 230 nm and side to side separation of 50 nm (similar to FIG. 4A). Plotline 494 correspond to the similar case of 8 cylinders in air but with diameters randomly varied in the range of 1% around 230 nm, and the side to side separation also randomly varied in the range of 10% around 50 nm. Such random
25 variations of nanoparticles diameters and side to side separations may not affect the threshold pumping intensity required for lasing significantly, reflecting that robustness of the design in accordance with various embodiments considered for actual experimental imperfections.

[0133] All the above calculations may be done for the case of optical pumping. However,
30 the same design may also be realized for electrical pumping. In order to do this, the shape of the nanoparticles may be changed to cuboidal or similar, which may be more suitable

for fabrication. Electrical contacts may be put from any side of the nanoparticle chain using conventional lithography steps.

[0134] The emission diagrams of the laser designs in accordance with various embodiments may be observed as shown in FIGs. 5A to 5C. The material and nanoparticle parameter may be the same or similar to those of FIGs. 3A, 3D, 4A, 4E and 4F. However, in this case, the number of cylinders in the chain may be 8. When the pumping intensity is lower than the lasing threshold, the device may emit light out of plane (as shown in the emission diagram 500 of FIG. 5A, with insert 502 illustrating a continuous wave CW pump used to excite the nanoparticle chain). At the pump intensity of about $2.1 \times 10^3 \text{ kW/cm}^2$, no lasing may be observed. However, when the lasing threshold is exceeded, the emission diagram may change abruptly and significantly, and the device may start to emit in certain preferred directions defined by the device geometry.

[0135] For a simple chain of coupled nanoparticles (device of 8 cylinders shown in FIG. 2A), there may be two preferred emission directions from both sides of the chain when the pumping intensity is higher than the lasing threshold (as shown in the emission diagram 520 of FIG. 5B, with insert 522 illustrating a CW pump used to excite the nanoparticle chain). Nanoparticle parameters may be similar to FIG. 3A. At the pump intensity of about $6.5 \times 10^3 \text{ kW/cm}^2$, lasing may be observed. Generally, for similar examples, when the lasing starts the emission may go into preferred directions defined by the cavity geometry.

[0136] When an additional reflector with a diameter of about 355 nm is placed about 450 nm from one side of the chain (e.g. as shown in FIG. 2B), the emission diagram may change and more light may be emitted from the other side of the chain (as shown in the emission diagram 540 of FIG. 5C, with insert 542 illustrating a CW pump used to excite the nanoparticle chain). Nanoparticle parameters may be similar to FIG. 3D. At the pump intensity of about $6.5 \times 10^3 \text{ kW/cm}^2$, lasing may be observed with the reflector particle suppressing emission from one side of the chain making it aligned along single preferred direction. By carefully optimizing the number, size and distances of the reflector particles, the directivity may be expected to further improve.

[0137] FIG. 5D shows an angular line plot 560 illustrating the emissions of a nanoparticle chain with a reflector particle 562 and the nanoparticle chain without any reflector particle 564, as seen from the x-z plane.

[0138] The simulations show that efficient laser emission in preferred directions inside the device plane may be realized. This may be advantageous as compared to disk lasers and coaxial lasers, which require additional outcoupling scheme. This emission may be further coupled directly to on-chip optical elements, e.g. waveguides. This way, the designs in accordance with various embodiments may be compact in lateral directions as compared to disk lasers (as an example). On the other hand, flexibility in design may also be possible, for example, if emission in the vertical direction is desired (for example in a 3-dimensional chip assembly), devices similar to the one shown in FIG. 2C may be realized, which may provide preferential emission of light perpendicular to the device plane. The Q factor may increase and the threshold pumping power may decrease with increase of the number of nanoparticles. Q factor may be tuned from a few tens to several hundreds of units and higher. These parameters may be adjusted in each particular case to obtain lasing. This may be advantageous as compared to plasmonic nanolasers with low Q factor. Further, the design in accordance with various embodiments may be based on semiconductor materials transparent at emission wavelength and thus almost loss-free. This may be advantageous as compared to metal-based plasmonic nanolasers.

[0139] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A light source comprising a nanoparticle,
wherein the nanoparticle is made of a gain material with a refractive index of at
5 least 2.
2. The light source of claim 1, wherein the gain material comprises a III-V semiconductor material.
- 10 3. The light source of claim 1, wherein the gain material is selected from the group consisting of gallium nitride, aluminum indium nitride, aluminum gallium nitride, gallium phosphide, indium nitride, gallium arsenide, indium phosphide, indium gallium arsenide, indium gallium arsenide phosphide, and any combination thereof.
- 15 4. The light source of claim 1, wherein the nanoparticle comprises a cylindrical nanoparticle, a spherical nanoparticle, a cuboidal nanoparticle, or a prism-shaped nanoparticle.
5. The light source of claim 1,
20 wherein the light source has an emission wavelength at least substantially corresponding to a spectral position of a first Mie resonance exhibited by the nanoparticle.
6. The light source of claim 5,
25 wherein the emission wavelength is within $\pm 25\%$ from the spectral position of the first Mie resonance.
7. The light source of claim 1, further comprising a plurality of nanoparticles, wherein each of the plurality of nanoparticles is made of a gain material with a refractive
30 index of at least 2.

8. The light source of claim 7, wherein the plurality of nanoparticles are arranged laterally to form a chain of nanoparticles.

9. The light source of claim 8, wherein the chain of nanoparticles comprises a linear chain of nanoparticles.

10. The light source of claim 8, wherein the chain of nanoparticles comprises a non-linear chain of nanoparticles.

11. The light source of claim 8, further comprising a reflector particle arranged to at least minimize transmission of light emitted from the plurality of nanoparticles in a predetermined direction.

12. The light source of claim 11, wherein the reflector particle has a size associated with a directivity of the light source.

13. The light source of claim 11, wherein the reflector particle is arranged at one end of the chain of nanoparticles.

14. The light source of claim 8, further comprising a substrate having a surface on which the plurality of nanoparticles are disposed.

15. The light source of claim 14, wherein the chain of nanoparticles is arranged to extend along a plane substantially parallel to the surface of the substrate.

16. The light source of claim 14, wherein the chain of nanoparticles is arranged to extend along a direction substantially perpendicular to the surface of the substrate.

17. The light source of claim 7, wherein the plurality of nanoparticles are spaced apart from one another.

18. The light source of claim 17, further comprising a dielectric material disposed between the spaced apart nanoparticles.

19. The light source of claim 18, wherein the dielectric material has a refractive index of less than 2.

20. The light source of claim 1, wherein the light source comprises a laser.

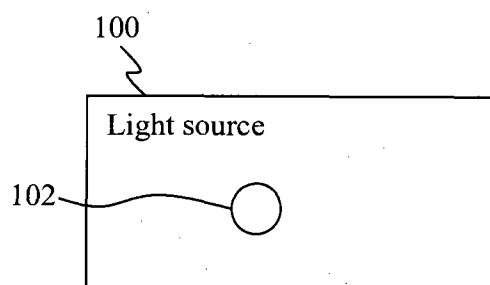


FIG. 1

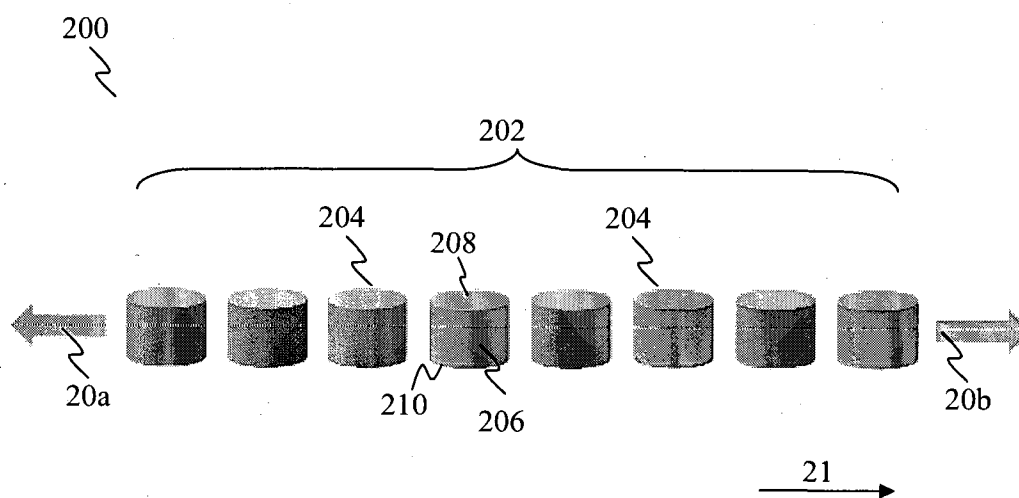


FIG. 2A

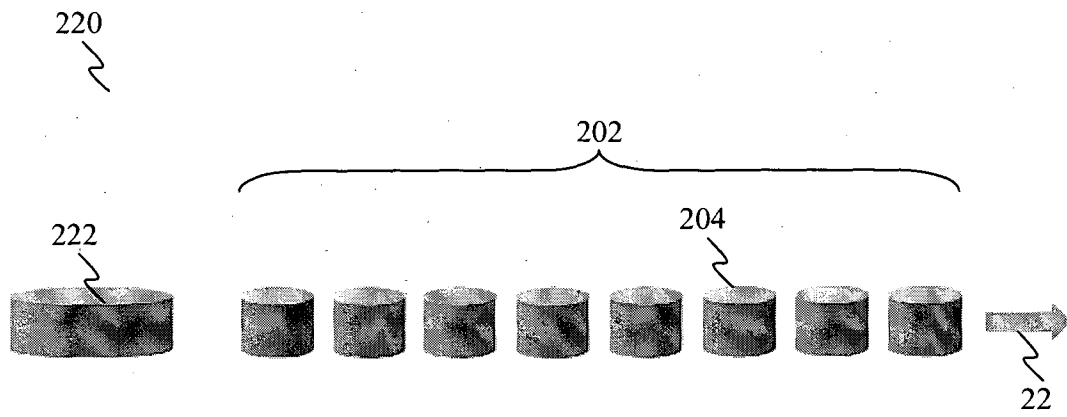


FIG. 2B

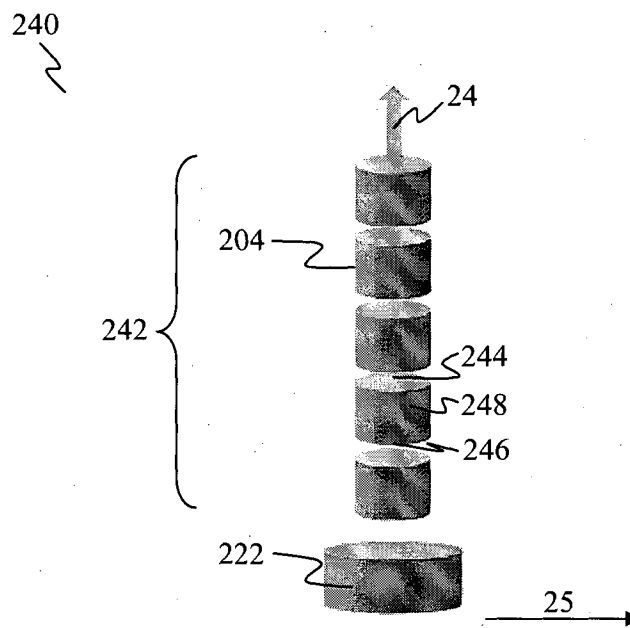


FIG. 2C

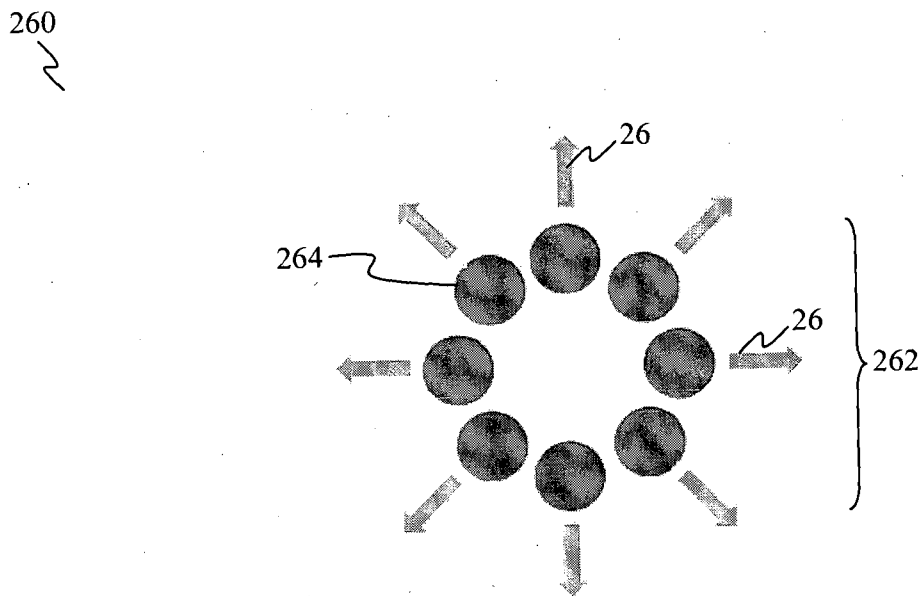


FIG. 2D

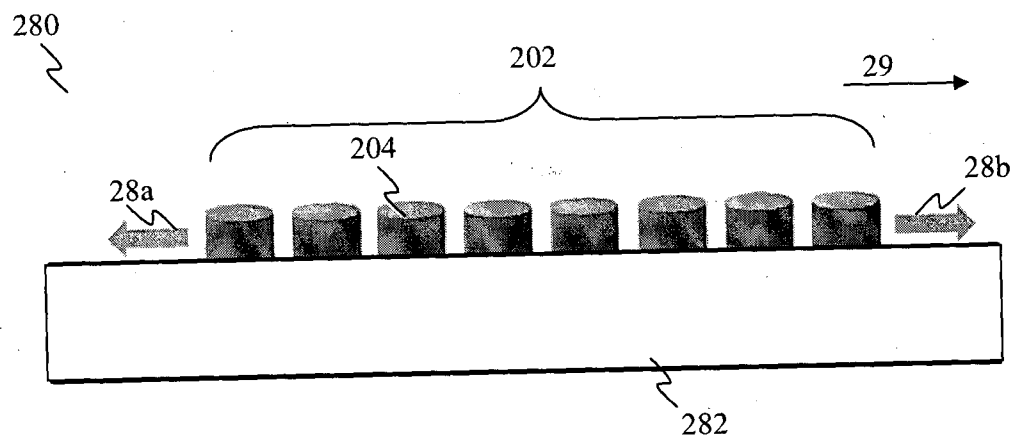


FIG. 2E

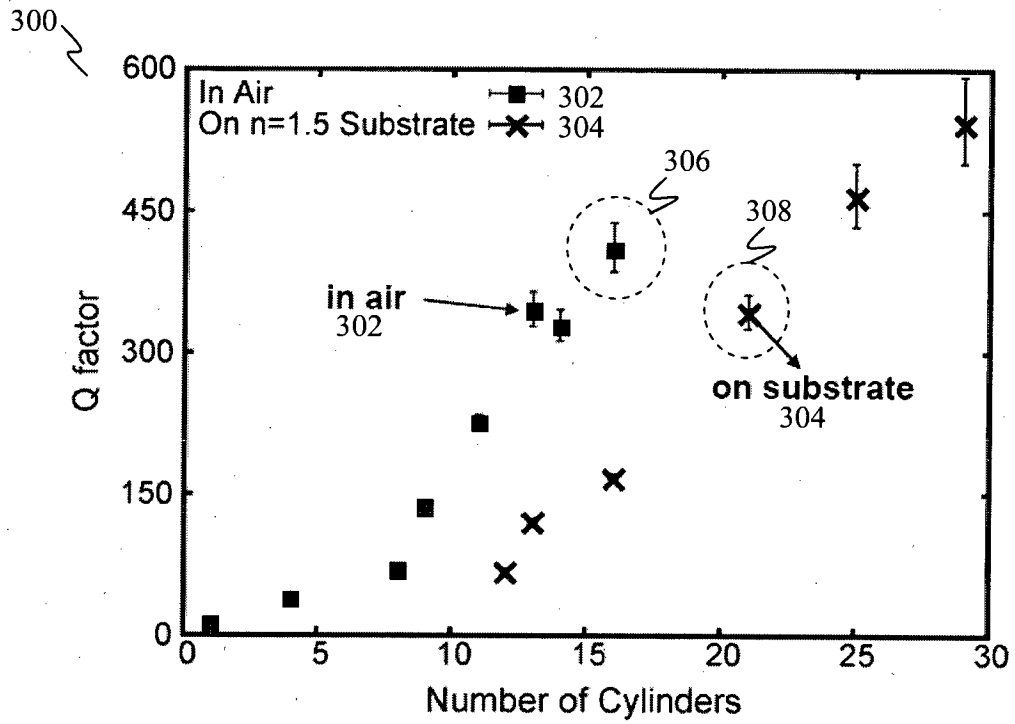


FIG. 3A

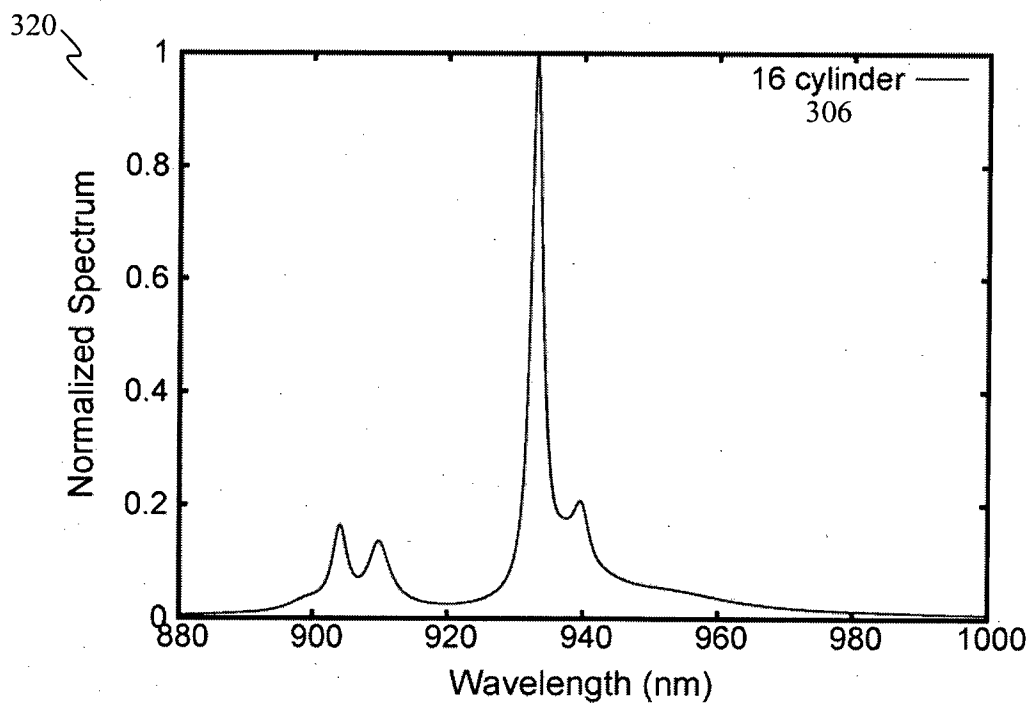


FIG. 3B

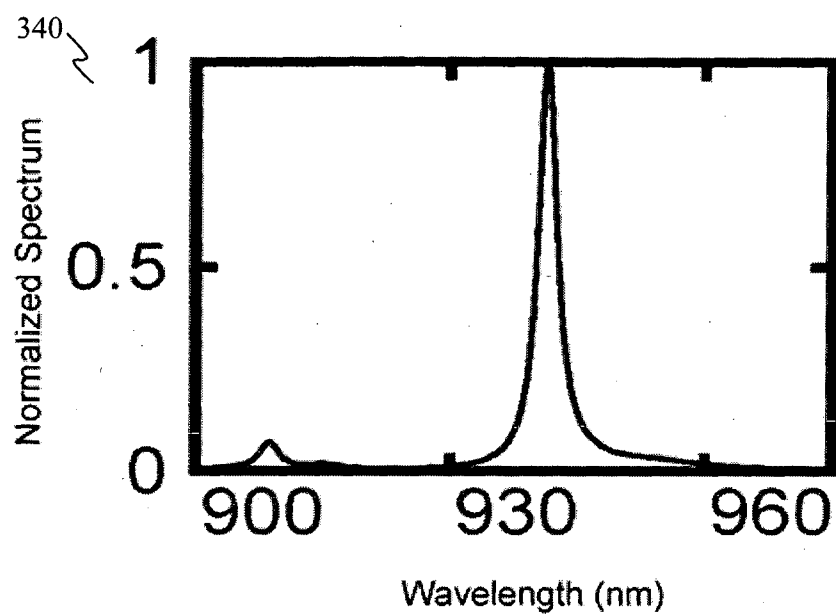


FIG. 3C

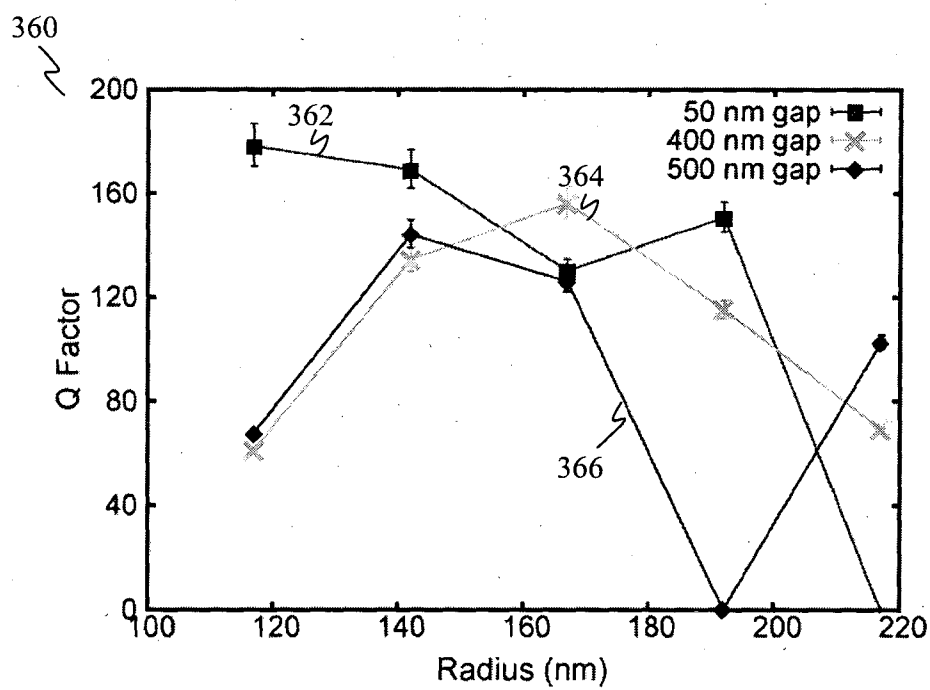


FIG. 3D

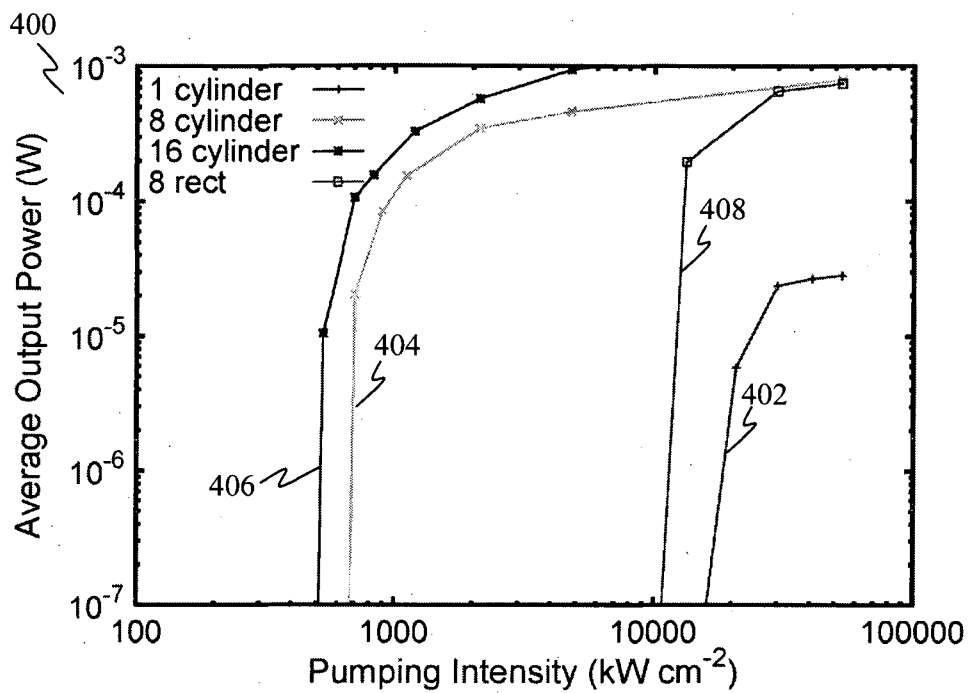


FIG. 4A

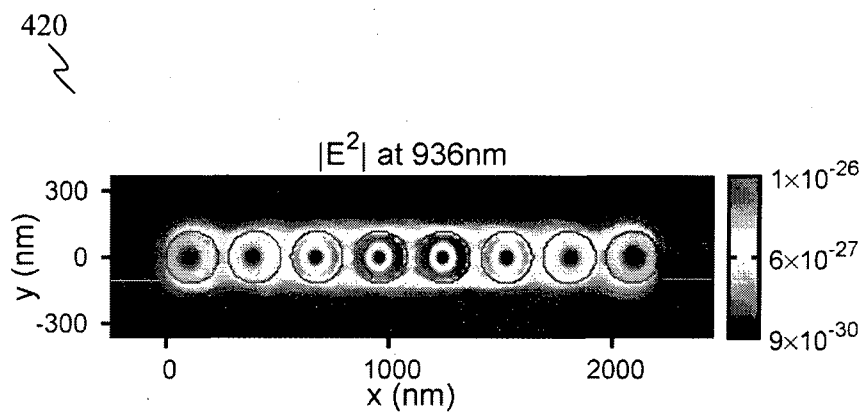


FIG. 4B

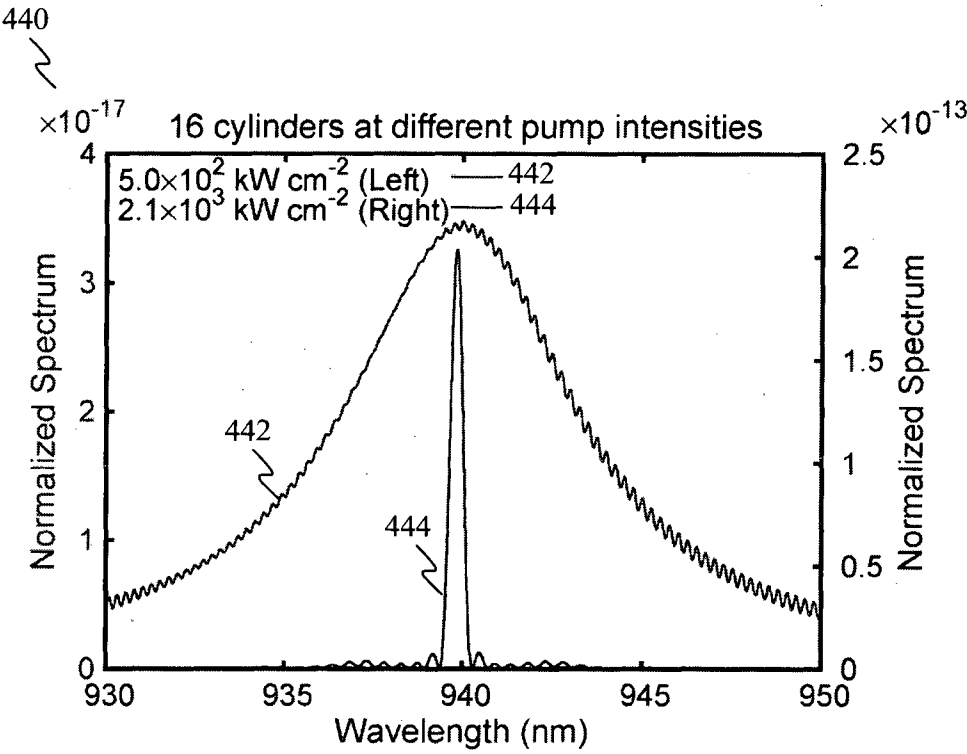


FIG. 4C

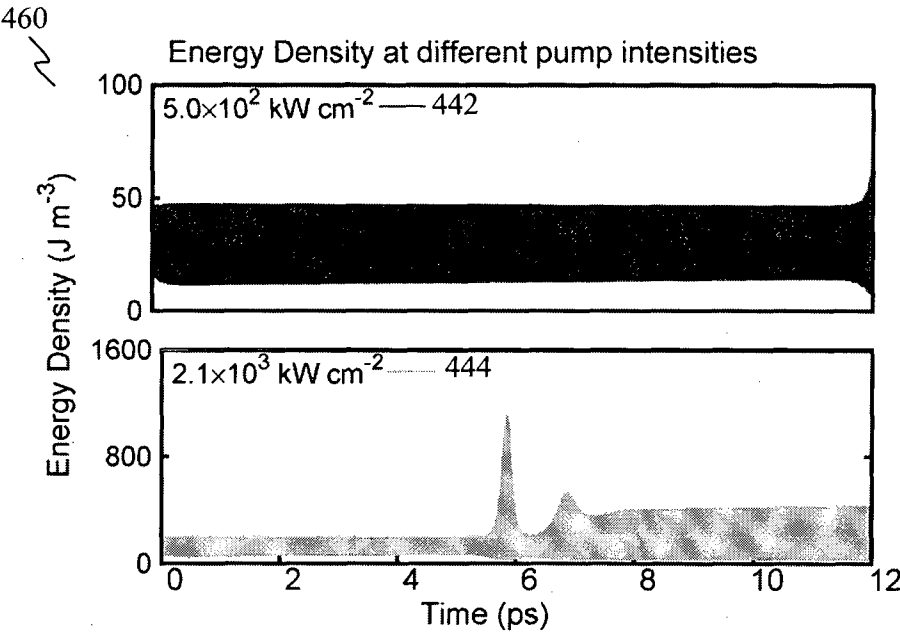


FIG. 4D

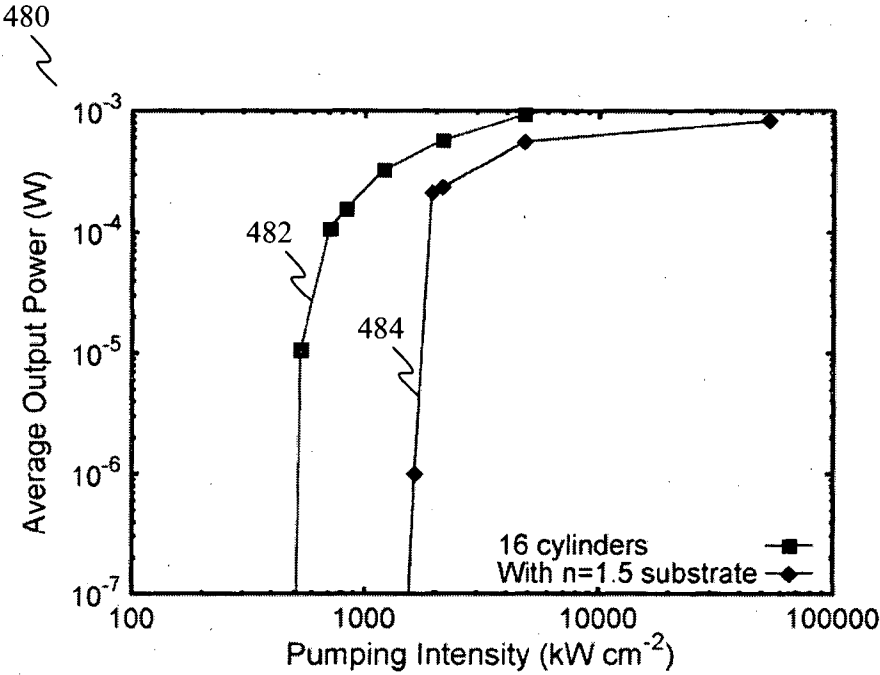


FIG. 4E

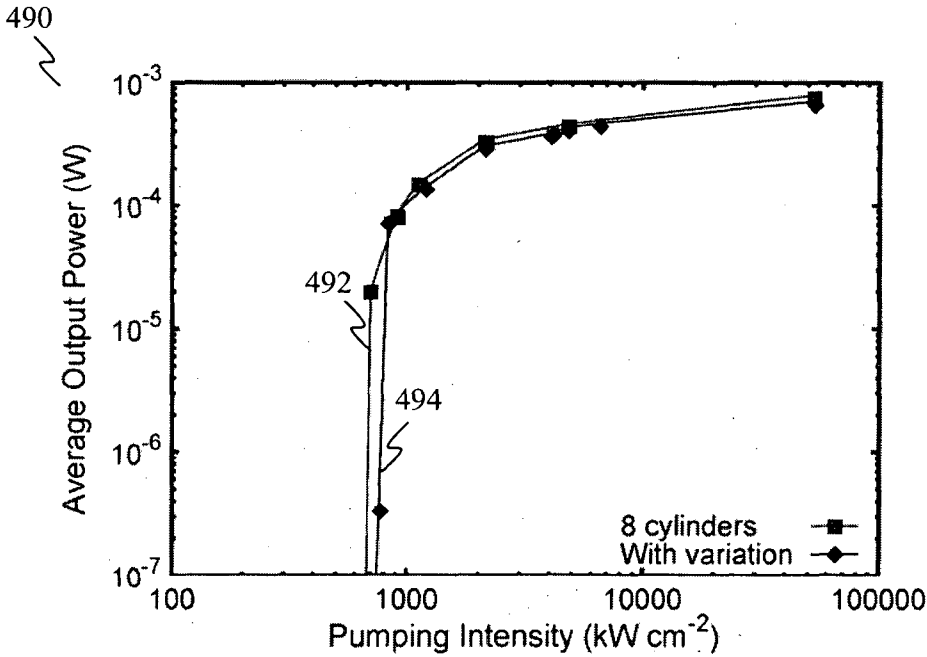


FIG. 4F

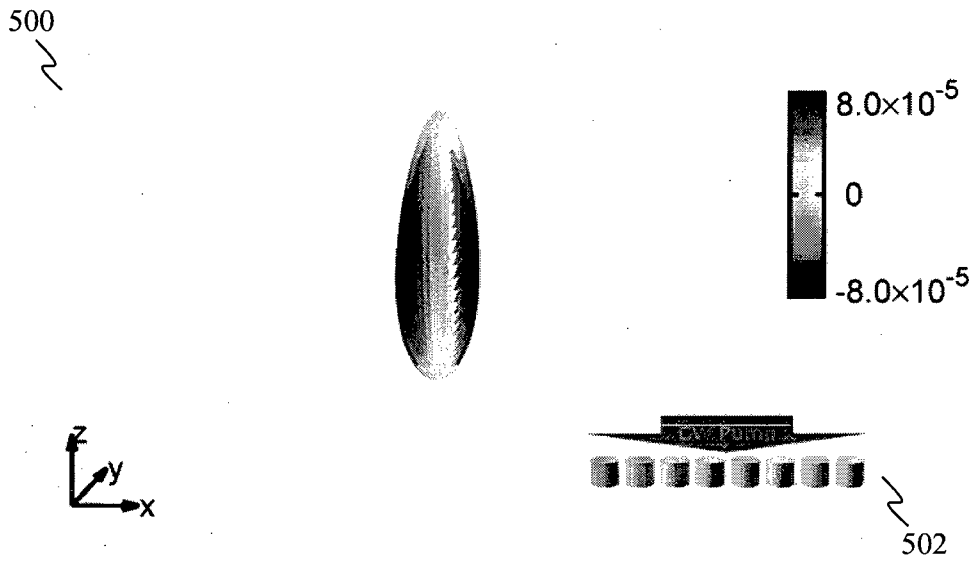


FIG. 5A

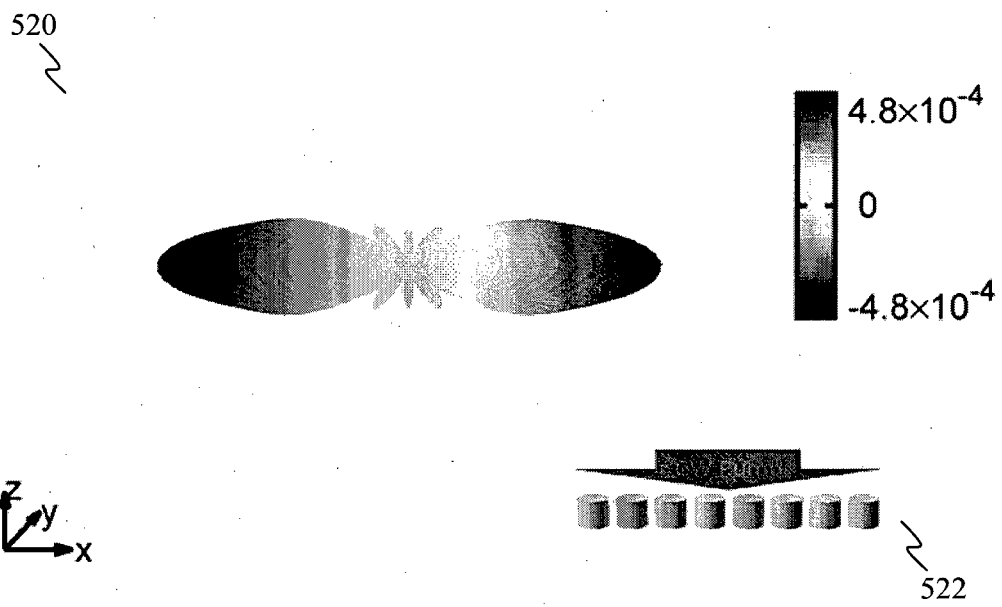


FIG. 5B

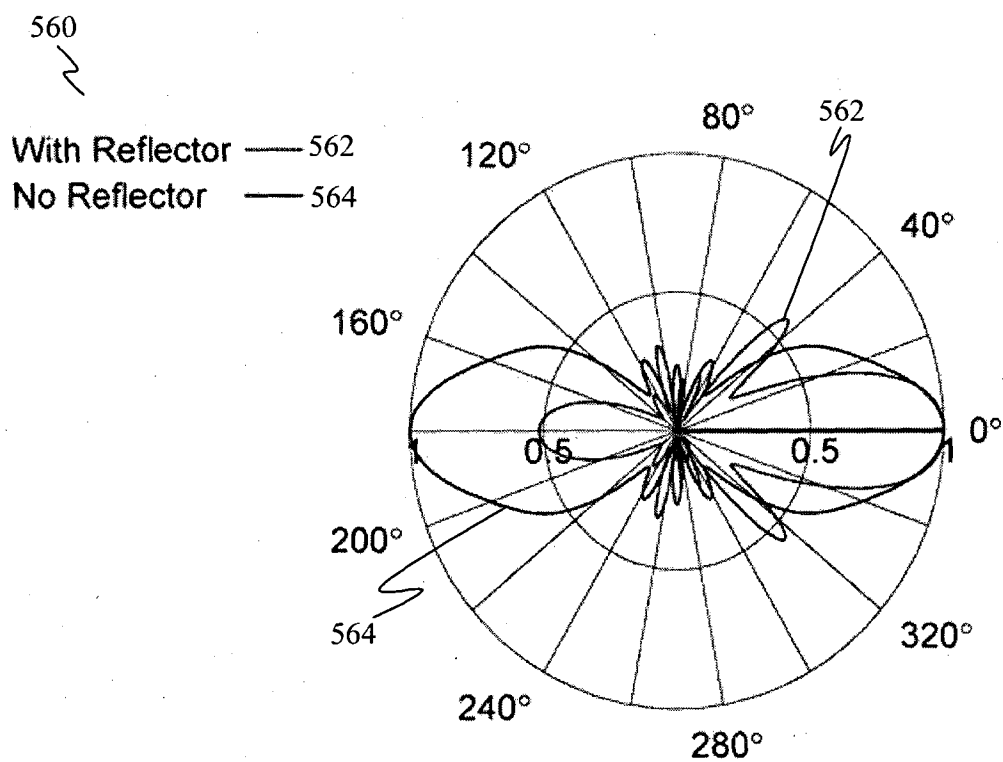
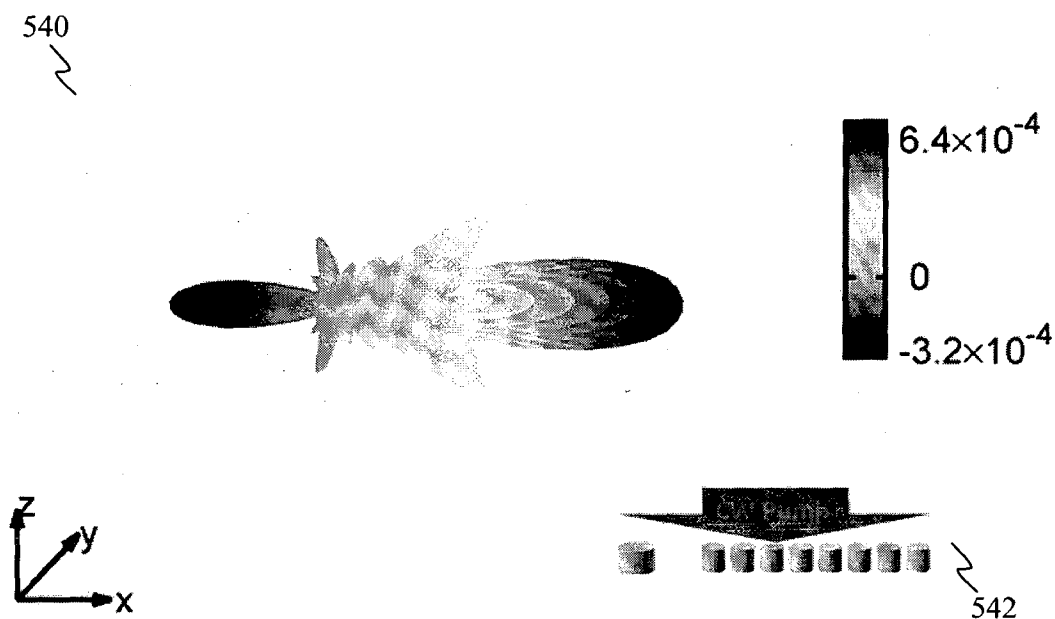


FIG. 5D

INTERNATIONAL SEARCH REPORT

 International application No.
PCT/SG2014/000559

A. CLASSIFICATION OF SUBJECT MATTER

H01S 5/20 (2006.01) H01L 33/26 (2010.01) H01S 3/0933 (2006.01) B82Y 20/00 (2011.01)

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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

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

EPODOC, WPIAP, INSPEC, Google Scholar, Espacenet.

IPC/CPC: H01L33; H01S3/00; H01S5/00; B82Y20.

Keywords: Mie scattering, refractive index, GaN, nanolaser, nanophotonic, semiconductor laser and the like terms.

Applicant: Agency for Science, Technology and Research. Inventor: Kuznetsov Arseniy; Lee Yun Yi.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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



Further documents are listed in the continuation of Box C



See patent family annex

* "A"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
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Date of the actual completion of the international search 13 April 2015	Date of mailing of the international search report 13 April 2015
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustalia.gov.au	Authorised officer Olga Shcherbakova AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 0262832634

INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/SG2014/000559
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1804350 A1 (INTERUNIVERSITAIR MICROELEKTRONICA CENTRUM) 04 July 2007 Abstract; Figs. 1, 5; [0008], [0011], [0012], [0013], [0055]	1-4, 7-20
X	KUZNETSOV, A. et al., 'Magnetic light', Scientific Reports, 2012, Vol. 2, No. 492, pages 1-6; DOI:10.1038/srep00492 Abstract, first paragraph of 'Results' section; Figs. 2, 3, 4	1-7, 17
X	INOSE, Y. et al., 'Anderson localization of light in a random configuration of nanocolumns', Journal of Physics: Conference Series. 2009, Vol. 193, pages 012055-1 - 012055-4 Abstract, 'Introduction' section, Figs. 1, 2	1-4, 7, 17
X	JOHNSON, J. C. et al., 'Single gallium nitride nanowire lasers', Nature Materials. 2002, Vol. 1, pages 106-110 Abstract, Figs. 1a, 2a, 2c	1-4, 7, 17, 20
A	US 2002/0028526 A1 (KURAHASHI et al.) 07 March 2002 Abstract	11-13

INTERNATIONAL SEARCH REPORT Information on patent family members		International application No. PCT/SG2014/000559	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
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Publication Number	Publication Date	Publication Number	Publication Date
EP 1804350 A1	04 July 2007		
US 2002/0028526 A1	07 March 2002	US 6617614 B2	09 Sep 2003
		JP 2002076433 A	15 Mar 2002
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		TW 548688 B	21 Aug 2003
End of Annex			
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001. Form PCT/ISA/210 (Family Annex)(July 2009)			