(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
20 July 2017 (20.07.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/123493 A1

(51) International Patent Classification:
H01S 5/042 (2006.01) *H01S 5/00* (2006.01)
H01S 5/183 (2006.01) *H01S 5/026* (2006.01)
H01S 5/062 (2006.01)

(21) International Application Number:
PCT/US2017/012688

(22) International Filing Date:
9 January 2017 (09.01.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
14/992,760 11 January 2016 (11.01.2016) US

(71) Applicant: **ALCATEL-LUCENT USA INC.** [US/US]; 600-700 Mountain Avenue, Murray Hill, NJ 07974-0636 (US).

(72) Inventors: **CHEN, Haoshuo**; 791 Holmdel-keyport Road, Holmedel, NJ 07733-1661 (US). **FONTAINE, Nicolas**; 791 Holmdel-keyport Road, Holmedel, NJ 07733-1661 (US). **RYF, Roland**; 791 Holmedel-keyport Road, Holmdel, NJ 07733-1661 (US).

(74) Agent: **MCCABE, John, F.**; Alcatel-Lucent Usa Inc., Attention: Docket Administrator-Room 3B-212F, 600-700 Mountain Avenue, Murray Hill, NJ 07974-0636 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

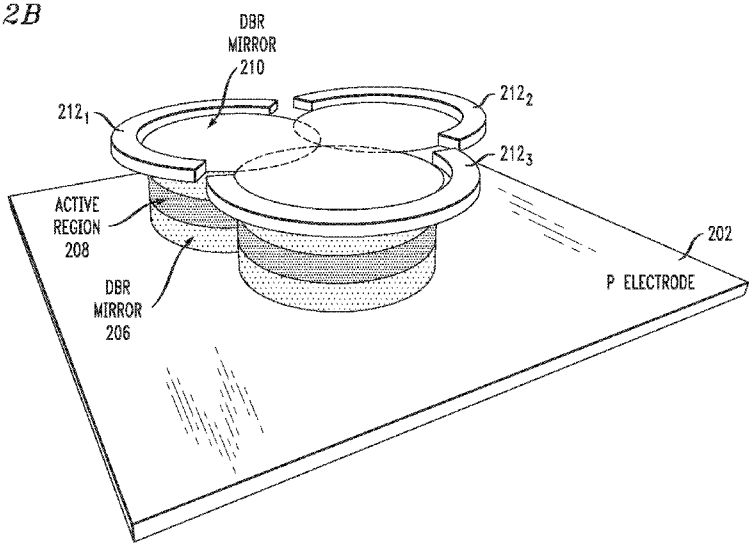
(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

(54) Title: MULTIMODE VERTICAL-CAVITY SURFACE-EMITTING LASER

FIG. 2B



(57) Abstract: We disclose a vertical-cavity surface-emitting laser (VCSEL) whose optical resonator can support multiple transverse resonator modes. The VCSEL has a plurality of electrodes (212) that can apply individually controllable electrical currents to the active semiconductor region of the optical resonator and be configured to excite, e.g., a single selected transverse resonator mode or a desired linear combination of transverse resonator modes. In some embodiments, the VCSEL's optical resonator may have an effective lateral geometric shape that causes the excitable transverse resonator modes to correspond to the waveguide modes of a cylindrical optical fiber.

WO 2017/123493 A1

MULTIMODE VERTICAL-CAVITY SURFACE-EMITTING LASER

BACKGROUND

Field

The present disclosure relates to optical communication equipment and, more specifically but not exclusively, to a multimode vertical-cavity surface-emitting laser (VCSEL).

Description of the Related Art

This section introduces aspects that may help facilitate a better understanding of the disclosure. Accordingly, the statements of this section are to be read in this light and are not to be understood as admissions about what is in the prior art or what is not in the prior art.

A vertical-cavity surface-emitting laser (VCSEL) is a semiconductor-based laser that emits a light beam in a direction that is substantially orthogonal to the substrate on which the layered structure of the laser is formed. Due to this geometry, thousands of VCSELs can be manufactured on a single semiconductor wafer. An additional benefit of the VCSEL technology is that each VCSEL can be tested at various stages of the manufacturing process while still in wafer form, which helps to achieve a better-controlled and more-predictable yield and enables lower production costs compared to those of other semiconductor-laser technologies. For at least some of these reasons, the VCSEL technology is being currently actively developed.

SUMMARY OF SOME SPECIFIC EMBODIMENTS

Disclosed herein are various embodiments of a vertical-cavity surface-emitting laser (VCSEL) whose optical resonator can support multiple transverse resonator modes. The VCSEL has a plurality of electrodes that can apply individually controllable electrical currents to the active semiconductor region of the optical resonator and be configured to excite, e.g., a single selected transverse resonator mode or a desired linear combination of transverse resonator modes. In some embodiments, the VCSEL's optical resonator may have an effective lateral geometric shape that causes the excitable transverse resonator modes to correspond to the waveguide modes of a cylindrical optical fiber that may be butt-coupled to the VCSEL.

According to an example embodiment, provided is an apparatus comprising: a substrate; a first distributed Bragg reflector (DBR) mirror supported on the substrate at a first offset distance; a second DBR mirror supported on the substrate at a second offset distance that is greater than the first offset distance; an active semiconductor region located between the first DBR mirror and the second DBR mirror; and a first plurality of electrodes, each configured to inject a respective individually controllable electrical current into the active semiconductor region to cause light generation therein at a lasing wavelength; and wherein an optical resonator bounded by the first DBR mirror and the second DBR mirror is configured to support a plurality of transverse resonator modes corresponding to the lasing wavelength.

BRIEF DESCRIPTION OF THE DRAWINGS

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

Other aspects, features, and benefits of various disclosed embodiments will become more fully apparent, by way of example, from the following detailed description and the accompanying drawings, in which:

FIGs. 1A-1B show top and cross-sectional side views of a vertical-cavity surface-emitting laser (VCSEL) according to an embodiment;

FIGs. 2A-2B show top and three-dimensional perspective views of a VCSEL according to another embodiment;

FIG. 3 pictorially illustrates example transverse electric-field profiles that can be generated in the optical resonator of the VCSEL shown in FIGs. 2A-2B according to an embodiment;

FIG. 4 shows a top view of a VCSEL according to an alternative embodiment;

FIG. 5 shows a top view of a VCSEL according to another alternative embodiment;

FIG. 6 shows a block diagram of a light source according to an embodiment;

FIG. 7 shows a block diagram of a light source according to another embodiment;

FIG. 8 shows a block diagram of a light source according to yet another embodiment;

FIG. 9 shows a cross-sectional side view of a VCSEL according to yet another alternative embodiment; and

FIG. 10 shows a cross-sectional side view of a VCSEL according to yet another alternative embodiment.

DETAILED DESCRIPTION

Some embodiments disclosed herein may benefit from the subject matter disclosed in U.S. Patent Application No. 14/992,981, by Aref Chowdhury and Roland Ryf, attorney docket reference 818527-US-NP, filed on the same date as the present application, and entitled "OPTICAL SPATIAL DIVISION MULTIPLEXING USABLE AT SHORT REACH," which is incorporated herein by reference in its entirety.

FIGs. 1A-1B show top and cross-sectional side views of a vertical-cavity surface-emitting laser (VCSEL) **100** according to an embodiment. More specifically, FIG. 1A shows a top view of VCSEL **100**. FIG. 1B shows a cross-sectional side view of VCSEL **100** along the cross-section plane labeled **AA** in FIG. 1A.

VCSEL **100** includes a plurality of layers formed on a substrate **104**. Some of the layers may include two or more sub-layers (not explicitly shown in FIG. 1A) that differ from each other in chemical composition and/or the concentration and type of the introduced dopant(s). VCSEL **100** further includes metal electrodes **102** and $\mathbf{112_1}$-$\mathbf{112_3}$. The direction orthogonal to substrate **104** is hereafter referred to as the vertical or axial direction. The directions parallel to substrate **104** are hereafter referred to as the horizontal or lateral directions. In an example embodiment, the vertical size (or thickness) of VCSEL **100** is significantly smaller than its lateral size (or width).

VCSEL **100** has an optical resonator defined by distributed Bragg reflector (DBR) mirrors **106** and **110**. This optical resonator also includes an active region **108** sandwiched between DBR mirrors **106** and **110**. DBR mirror **106** comprises a plurality of p-doped semiconductor layers **107**, only four of which (labeled $\mathbf{107_1}$-$\mathbf{107_4}$) are shown in FIG. 1B for illustration purposes. Each layer **107** has a thickness that is approximately one quarter of the nominal lasing wavelength. Adjacent layers **107** have alternating (e.g., high/low) refractive indices, which causes DBR mirror **106** to have relatively high reflectivity (e.g., >99%) at the nominal lasing wavelength. In an example embodiment, DBR mirror **106** may have sixty-nine alternating layers of p-doped $Al_{0.9}Ga_{0.1}As$ and p-doped $Al_{0.12}Ga_{0.88}As$.

DBR mirror **110** comprises a plurality of n-doped semiconductor layers **111**, only four of which (labeled $\mathbf{111_1}$-$\mathbf{111_4}$) are shown in FIG. 1B for illustration purposes. Each layer **111** has a quarter-wavelength thickness. Adjacent layers **111** have alternating refractive

indices, which causes DBR mirror **110** to also have relatively high reflectivity at the nominal lasing wavelength. In an example embodiment, DBR mirror **110** may have forty-five alternating layers of n-doped $Al_{0.9}Ga_{0.1}As$ and n-doped $Al_{0.12}Ga_{0.88}As$.

Active region **108** includes a quantum-well structure having one or more quantum wells (not explicitly shown in FIG. 1A) designed for generating light at the nominal lasing wavelength. In an example embodiment, the quantum wells of active region **108** are made using doped GaAs. In operation, the relatively high reflectivity of DBR mirrors **106** and **110** causes the generated light to oscillate multiple times between the DBR mirrors before escaping from the optical resonator. These multiple round trips through the optical resonator compensate for the relatively small thickness of active region **108** and enables VCSEL **100** to generate sufficient optical output power for various applications, e.g., in the telecommunications industry. In different embodiments, the pertinent characteristics of DBR mirrors **106** and **110** and active region **108** can be tailored to cause VCSEL **100** to emit light at different desirable wavelengths. For example, different telecommunications applications may use embodiments of VCSEL **100** designed for emitting light in the respective spectral bands located near 850 nm, 1300 nm, or 1550 nm.

DBR mirrors **106** and **110** and active region **108** form an n/p diode junction that can be electrically biased using electrodes **102** and $\mathbf{112}_1$-$\mathbf{112}_3$. When appropriately biased, active region **108** generates light that is amplified due to the multiple passes through the active region caused by light oscillation in the optical resonator between DBR mirrors **106** and **110**. In the shown embodiment, the generated light escapes from the optical resonator of VCSEL **100** through DBR mirror **110**. A person of ordinary skill in the art will understand that embodiments in which the generated light escapes from the optical resonator through DBR mirror **106** are also possible.

Some embodiments of VCSEL **100** may benefit from the use of structural features and/or chemical compositions of the various layers disclosed in U.S. Patent Application Publications 2008/0279229 and 2011/0280269 and International Patent Application Publication WO 2014/056508, all of which are incorporated herein by reference in their entirety.

The lateral dimensions of the optical resonator in VCSEL **100** are defined using an aperture **109** and/or ion-implanted regions **114**. Ion-implanted regions **114** are formed by implanting suitable ions (e.g., hydrogen ions, H^+) into DBR mirror **110** around the mirror periphery, e.g., as indicated in FIG. 1B. The ion-implantation process disrupts, perturbs,

and/or destroys the semiconductor lattice in regions **114**, thereby inhibiting the flow of the injection current therethrough. Aperture **109** is typically made of an oxide material that is a poor electrical conductor. As such, aperture **109** also inhibits the flow of the injection current through the peripheral portions of VCSEL **100**. Since light generation in active region **108** primarily occurs where the injection current physically flows, the optical output of VCSEL **100** is laterally confined to a middle portion **120** thereof. As already indicated above, middle portion **120** is laterally bounded by aperture **109** and/or ion-implanted regions **114**.

As indicated in FIG. 1A, middle portion **120** has an approximately circular shape. In alternative embodiments, other transverse geometric shapes of the VCSEL's optical resonator are also possible, e.g., as further illustrated by FIGs. 2A and 5. Typically, the lasing wavelength of VCSEL **100** and the lateral dimensions of middle portion **120** are selected such that the optical resonator of VCSEL **100** can support multiple transverse resonator modes. For example, in a possible embodiment, the optical resonator of VCSEL **100** can be designed to support three or more transverse resonator modes.

A person of ordinary skill in the art will understand that different transverse resonator modes or different combinations of transverse resonator modes can be excited in the optical resonator of VCSEL **100** by applying different individually controlled injection currents to electrodes $\mathbf{112}_1$-$\mathbf{112}_3$. For example, a fundamental transverse resonator mode can be excited in the optical resonator of VCSEL **100** by applying nominally identical injection currents to all three electrodes $\mathbf{112}_1$-$\mathbf{112}_3$. A linear combination of transverse resonator modes can be excited in the optical resonator of VCSEL **100** by applying a relatively large injection current to electrode $\mathbf{112}_1$ while applying substantially no injection current to electrodes $\mathbf{112}_2$-$\mathbf{112}_3$. Another linear combination of transverse resonator modes can be excited in the optical resonator of VCSEL **100** by applying a relatively large injection current to electrode $\mathbf{112}_2$ while applying substantially no injection current to electrodes $\mathbf{112}_1$ and $\mathbf{112}_3$, etc.

In some embodiments, optional ion-implanted regions **116** can be formed within DBR mirrors **106** and **110** to enable more-selective excitation of the individual transverse resonator modes using electrodes $\mathbf{112}_1$-$\mathbf{112}_3$ and/or to cause at least some of the transverse resonator modes of VCSEL **100** to have a more-desirable electric-field profile. In particular, ion-implanted regions **116** can be configured to have a geometric shape and position that cause a better match between the transverse resonator modes of VCSEL **100** and the transverse waveguide modes of an optical fiber configured to receive light from the VCSEL

(also see FIGs. 3 and 6). For example, ion-implanted regions **116** can have a geometric shape and position that cause:

(i) a first combination of individual injection currents applied to electrodes $\mathbf{112_1}$-$\mathbf{112_3}$ to produce, across middle portion **120**, an electric-field profile that is similar to the electric-field profile of an LP01 waveguide mode of a cylindrical optical fiber;

(ii) a second combination of individual injection currents applied to electrodes $\mathbf{112_1}$-$\mathbf{112_3}$ to produce across middle portion **120** an electric-field profile that is similar to the electric-field profile of an LP11a waveguide mode of the cylindrical optical fiber; and

(iii) a third combination of individual injection currents applied to electrodes $\mathbf{112_1}$-$\mathbf{112_3}$ to produce across middle portion **120** an electric-field profile that is similar to the electric-field profile of an LP11b waveguide mode of the cylindrical optical fiber.

A person of ordinary skill in the art will understand that the LP11a and LP11b waveguide modes are degenerate waveguide modes of a cylindrical optical fiber that differ from one another in the relative orientation of the two corresponding light-intensity peaks. More specifically, for the LP11a and LP11b waveguide modes, the two corresponding light-intensity peaks may be aligned along the X- and Y-coordinate axes, respectively (also see FIG. 3).

FIGs. 2A-2B show top and three-dimensional perspective views of a VCSEL **200** according to an alternative embodiment. More specifically, FIG. 2A shows a top view of VCSEL **200**. FIG. 2B shows a three-dimensional perspective view of VCSEL **200** in which some peripheral structures of the VCSEL are not shown for clarity of depiction.

The semiconductor layer stack used in VCSEL **200** may be generally similar to the semiconductor layer stack used in VCSEL **100** (see FIG. 1B). For example, similar to VCSEL **100**, VCSEL **200** has an optical resonator formed by DBR mirrors **206** and **210**, with an active region **208** sandwiched between these two DBR mirrors. In an example embodiment, the layer structure of DBR mirrors **206** and **210** and active region **208** may be substantially similar to the layer structure of DBR mirrors **106** and **110** and active region **108**, respectively. VCSEL **200** also has metal electrodes **202** and $\mathbf{212_1}$-$\mathbf{212_3}$ that are functionally analogous to metal electrodes **102** and $\mathbf{112_1}$-$\mathbf{112_3}$, respectively, of VCSEL **100** (also see FIGs. 1A-1B).

However, VCSEL **200** and VCSEL **100** differ from one another in the geometric shape of their respective optical resonators. For example, the lateral shape of the optical resonator of VCSEL **200** can be approximated using three overlapping circles indicated by the dashed lines in FIG. 2A and labeled $\mathbf{220_1}$-$\mathbf{220_3}$, respectively. Each of metal electrodes $\mathbf{212_1}$-$\mathbf{212_3}$ has an approximately semi-circular shape and is located at the outer periphery of the corresponding one of circles $\mathbf{220_1}$-$\mathbf{220_3}$. When an injection current is applied to active region **208** using a single one of metal electrodes $\mathbf{212_1}$-$\mathbf{212_3}$, the light emitted by VCSEL **200** exits the optical resonator thereof primarily through the corresponding one of circles $\mathbf{220_1}$-$\mathbf{220_3}$, with substantially no light being emitted from the other two circles. Different individual injection currents can be applied to metal electrodes $\mathbf{212_1}$-$\mathbf{212_3}$ to individually control the light-intensity distributions emitted from circles $\mathbf{220_1}$-$\mathbf{220_3}$. In some embodiments, the relative phase of the electric field of the light emitted from different circles **220** can be controlled, e.g., using appropriate current-injection techniques or by adding one or more extra layers (not explicitly shown in FIG. 2B) to the layer stack of VCSEL **200**. In an example embodiment, such extra layers may be specifically designed and configured to controllably vary the phase of the emitted light (also see FIGs. 9-10).

FIG. 3 pictorially illustrates example transverse electric-field profiles that can be generated in the optical resonator of VCSEL **200** according to an embodiment. Three example configurations are shown for illustration purposes. A person of ordinary skill in the art will understand that other configurations are also possible.

In a first configuration illustrated in FIG. 3, nominally identical injection currents are applied to each of electrodes $\mathbf{212_1}$-$\mathbf{212_3}$ (also see FIGs. 2A-2B). In this configuration, the electric-field profile of the light beam emitted by VCSEL **200** has three peaks of approximately equal amplitude, each approximately centered in the respective one of circles $\mathbf{220_1}$-$\mathbf{220_3}$. The electric fields in these three peaks have substantially the same phase. A person of ordinary skill in the art will understand that this particular light distribution may be suitable for exciting, with relatively high efficiency, the fundamental mode (e.g., LP10) of a cylindrical optical fiber. The electric-field profile of the LP10 fiber mode is also shown in FIG. 3 for illustration purposes. The optical fiber configured to receive light from VCSEL **200** may be directly butt-coupled to the VCSEL (also see FIG. 6) or, alternatively, optically coupled to the VCSEL using appropriate imaging optics.

In a second configuration illustrated in FIG. 3, nominally identical smaller injection currents are applied to each of electrodes $\mathbf{212_1}$ and $\mathbf{212_3}$ and a larger injection current is

applied to electrode **212**$_2$. In addition, VCSEL **200** is configured to cause (i) the light of the peaks located in circles **220**$_1$ and **220**$_3$ to have the same relative phase and (ii) the light of the peak located in circle **220**$_2$ to be phase-shifted by about 180 degrees with respect to the light of the peaks located in circles **220**$_1$ and **220**$_3$. A person of ordinary skill in the art will understand that this particular light distribution may be suitable for exciting the LP11a mode of a cylindrical optical fiber. The electric-field profile of the LP11a fiber mode is also shown in FIG. 3 for illustration purposes.

In a third configuration illustrated in FIG. 3, nominally identical injection currents are applied to each of electrodes **212**$_1$ and **212**$_3$ and no injection current is applied to electrode **212**$_2$. In addition, VCSEL **200** is configured to cause the light of the peaks located in circles **220**$_1$ and **220**$_3$ to have a relative phase shift of about 180 degrees. A person of ordinary skill in the art will understand that this particular light distribution may be suitable for exciting the LP11b mode of a cylindrical optical fiber. The electric-field profile of the LP11b fiber mode is also shown in FIG. 3 for illustration purposes.

FIG. 4 shows a top view of a VCSEL **400** according to another alternative embodiment. The layer stack used in VCSEL **400** may be generally similar to the layer stack used in VCSEL **100** (see FIG. 1B). However, VCSEL **400** and VCSEL **100** (FIGs. 1A-1B) differ from one another in the number of the metal electrodes that are used for injecting electrical current into the active region of the optical resonator. Also, the lasing wavelength of VCSEL **400** and the lateral dimensions of the optical resonator of VCSEL **400** are selected such that the optical resonator can support six (or more) transverse resonator modes. Recall that the optical resonator of VCSEL **100** is designed to support three (or more) transverse resonator modes.

Different transverse resonator modes or different linear combinations of transverse resonator modes can be excited in the optical resonator of VCSEL **400** by applying different individually controlled injection currents to electrodes **412**$_1$-**412**$_6$. As shown in FIG. 4, electrodes **412**$_1$-**412**$_5$ have an arched shape and are placed at the edge of the circle that approximately marks the lateral boundary of the optical resonator of VCSEL **400**. Electrode **412**$_6$ has a circular shape and is located closer to the central axis of the optical resonator. A person of ordinary skill in the art will understand that the shape and position of electrode **412**$_6$ help to provide more-selective excitation of an optical-resonator mode that is similar to the LP02 mode of a cylindrical optical fiber.

FIG. 5 shows a top view of a VCSEL **500** according to yet another alternative embodiment. The layer stack used in VCSEL **500** may be generally similar to the layer stack used in VCSEL **100** (see FIG. 1B). VCSEL **500** is similar to VCSEL **400** in that its optical resonator can support six or more transverse resonator modes. However, VCSEL **500** and VCSEL **400** differ from one another in the geometric shape of their respective optical resonators. More specifically, the transverse shape of the optical resonator of VCSEL **200** can be approximated using six overlapping circles indicated by the dashed lines in FIG. 5. Each of metal electrodes **512**$_1$-**512**$_5$ has an approximately semi-circular shape and is located at the outer periphery of the corresponding outer circle. Electrode **512**$_6$ has a circular shape and is located closer to the central axis, encircling the inner circle. In operation, different individual injection currents can be applied to electrodes **512**$_1$-**512**$_6$ to control the modal distribution of the light emitted from the optical resonator of VCSEL **500**.

From the examples described in reference to FIGs. 1-5, a person of ordinary skill in the art will be able to make and use other embodiments having other geometric shapes of the VCSEL's optical resonator and/or other numbers and shapes of the electrodes for exciting different individual transverse resonator modes or different linear combinations of transverse resonator modes.

FIG. 6 shows a block diagram of a light source **600** according to an embodiment. Light source **600** comprises a VCSEL **610** configured to generate a light beam **614** having a carrier wavelength, λ_0. VCSEL **610** includes VCSEL **200** (FIGs. 2A-2B) outfitted with a polarization-tailoring layer **612**. In operation, polarization-tailoring layer **612** filters the output of VCSEL **200** in a manner that causes light beam **614** to be linearly polarized. Depending on the orientation of polarization-tailoring layer **612**, light beam **614** can have an X-polarization or a Y-polarization. The orientation of VCSEL **610** with respect to the X- and Y-coordinate axes is indicated in FIG. 6 by the corresponding coordinate-axis triad. Example polarization-tailoring layers that can be used as polarization-tailoring layer **612** are disclosed, e.g., in the above-cited U.S. Patent Application Publication 2011/0280269.

Light source **600** further comprises an optical fiber **620** that is butt-coupled to VCSEL **610** to receive light beam **614** for guiding the received light beam to an external circuit or device (not explicitly shown in FIG. 6). Optical fiber **620** has an optical core **622** and a cladding **624**. The refractive indices of optical core **622** and cladding **624** and the diameter of the optical core are such that, for wavelength λ_0, optical fiber **620** is a multimode fiber. In some embodiments, optical fiber **620** can be a few-mode fiber. VCSEL **610** can be

operated to selectively excite the LP01 mode or an LP11 mode of optical fiber **620**, e.g., as already explained above in reference to FIG. 3.

FIG. 7 shows a block diagram of a light source **700** according to another embodiment. Light source **700** operates to generate a light beam **714** having two orthogonal polarization components suitable for polarization-division-multiplexing (PDM) applications. Light source **700** comprises two instances (nominal copies) of VCSEL **610** (FIG. 6), one of which is rotated with respect to the other by 90 degrees. As a result, the first instance of VCSEL **610** operates to generate an X-polarized light beam **704**, while the second instance of VCSEL **610** operates to generate a Y-polarized light beam **706**. A mirror **708** and a polarization combiner **710** are configured to spatially and directionally combine light beams **704** and **706**, thereby generating light beam **714**. In some embodiments, the two instances of VCSEL **610** used in light source **700** can be fabricated using a common semiconductor substrate **702**.

FIG. 8 shows a block diagram of a light source **800** according to yet another embodiment. Light source **800** is functionally similar to light source **700** (FIG. 7) and operates to generate a light beam **814** having two orthogonal polarization components suitable for PDM applications. However, light source **800** differs from light source **700** in that the two instances of VCSEL **610** (labeled $\mathbf{610}_1$ and $\mathbf{610}_2$) have the same orientation of their polarization-tailoring layers **612**, which causes each of them to output X-polarized light. A half-wavelength waveplate **802** rotates the polarization of the light beam generated by VCSEL $\mathbf{610}_2$, thereby generating a Y-polarized light beam **806**. Mirror **708** and polarization combiner **710** then generate light beam **814** by spatially and directionally combining light beams **704** and **806**, as indicated in FIG. 8.

FIG. 9 shows a cross-sectional side view of a VCSEL **900** according to yet another alternative embodiment. VCSEL **900** is a modification of VCSEL **100** (FIG. 1) that includes an added fixed two-dimensional phase mask **910**. Phase mask **910** has a plurality of segments **912**, each having a respective fixed thickness that differs from the thickness of at least one other segment **912**. In operation, different segments **912** impose phase shifts corresponding to their thickness, thereby spatially phase-filtering the optical output beam generated by VCSEL **100**. In various embodiments, phase mask **910** can be fabricated using, e.g., quartz, photoresist, silicon nitride, or other suitable optically transparent material.

FIG. 10 shows a cross-sectional side view of a VCSEL **1000** according to yet another alternative embodiment. VCSEL **1000** is a modification of VCSEL **100** (FIG. 1) that

includes an added configurable two-dimensional phase mask **1010**. Phase mask **1010** comprises a configurable phase-modulation layer **1004** disposed on an electrode **1002**. Phase mask **1010** further comprises a plurality of electrodes **1006** disposed on phase-modulation layer **1004**. Each electrode **1006** can be individually electrically biased with respect to electrode **1002**. Phase-modulation layer **1004** comprises a material (e.g., a liquid crystal) whose refractive index depends on the applied electric field. In operation, different desired voltages can be applied to different electrodes **1006** to cause the respective portions of phase-modulation layer **1004** to impose phase shifts corresponding to their local refractive indices. The applied voltages can be changed as appropriate or necessary to change the two-dimensional phase profile imposed by phase mask **1010** onto the optical output beam generated by VCSEL **100**. In an example embodiment, electrodes **1002** and **1006** may be fabricated using a suitable optically transparent material, such as an electrically conducting metal oxide.

According to an example embodiment disclosed above in reference to FIGs. 1-10, provided is an apparatus comprising: a substrate (e.g., **104**, FIG. 1B); a first DBR mirror (e.g., **106**, FIG. 1B) supported on the substrate at a first offset distance; a second DBR mirror (e.g., **110**, FIG. 1B) supported on the substrate at a second offset distance that is greater than the first offset distance; an active semiconductor region (e.g., **108**, FIG. 1B) located between the first DBR mirror and the second DBR mirror; and a first plurality of electrodes (e.g., $\mathbf{112}_1$-$\mathbf{112}_3$, FIG. 1A), each configured to inject a respective individually controllable electrical current into the active semiconductor region to cause light generation therein at a lasing wavelength (e.g., λ_0). An optical resonator bounded by the first DBR mirror and the second DBR mirror is configured to support a plurality of transverse resonator modes corresponding to the lasing wavelength (e.g., as indicated in FIG. 3).

In some embodiments of the above apparatus, the apparatus is operable to: excite a first linear combination of the transverse resonator modes (e.g., configuration 1, FIG. 3) using a first set of the respective individually controllable electrical currents applied to the first plurality of electrodes; and excite a second linear combination of the transverse resonator modes (e.g., configuration 3, FIG. 3) using a second set of the respective individually controllable electrical currents applied to the first plurality of electrodes, the second linear combination being different from the first linear combination.

In some embodiments of any of the above apparatus, the first plurality of electrodes includes at least three electrodes (e.g., $\mathbf{112}_1$-$\mathbf{112}_3$, FIG. 1A).

In some embodiments of any of the above apparatus, the first plurality of electrodes includes at least six electrodes (e.g., $\mathbf{412_1}$-$\mathbf{412_6}$, FIG. 4).

In some embodiments of any of the above apparatus, each of the first plurality of electrodes is supported on the substrate at a third offset distance different from each of the first and second offset distances.

In some embodiments of any of the above apparatus, the third offset distance is greater than the second offset distance.

In some embodiments of any of the above apparatus, the apparatus further comprises an additional electrode (e.g., **102**, FIG. 1B) configured to receive the electrical currents from the first plurality of electrodes by way of the active semiconductor region.

In some embodiments of any of the above apparatus, the additional electrode is adjacent to the first DBR mirror.

In some embodiments of any of the above apparatus, each of the first plurality of electrodes is adjacent to the second DBR mirror.

In some embodiments of any of the above apparatus, the first DBR mirror comprises a first plurality of layers (e.g., $\mathbf{107_1}$-$\mathbf{107_4}$, FIG. 1B) including a respective first subset of layers having a first refractive index and a respective second subset of layers having a second refractive index different from the first refractive index.

In some embodiments of any of the above apparatus, the second DBR mirror comprises a second plurality of layers (e.g., $\mathbf{111_1}$-$\mathbf{111_4}$, FIG. 1B) including a respective first subset of layers having a third refractive index and a respective second subset of layers having a fourth refractive index different from the third refractive index.

In some embodiments of any of the above apparatus, the first DBR mirror comprises a p-type semiconductor.

In some embodiments of any of the above apparatus, the second DBR mirror comprises an n-type semiconductor.

In some embodiments of any of the above apparatus, the active semiconductor region includes one or more quantum wells configured to generate light at the lasing wavelength in response to an electrical current received by way of the first plurality of electrodes.

In some embodiments of any of the above apparatus, the first DBR mirror or the second DBR mirror, or both the first and second DBR mirrors comprise one or more ion-implanted regions (e.g., **116**, FIG. 1B) located in an optical path of light emitted from the optical resonator.

In some embodiments of any of the above apparatus, the apparatus further comprises a polarization-tailoring layer (e.g., **612**, FIG. 6) configured to cause a light beam (e.g., **614**, FIG. 6) emitted by the apparatus to be linearly polarized.

In some embodiments of any of the above apparatus, the first DBR mirror, the second DBR mirror, the active semiconductor region, and the first plurality of electrodes are parts of a first VCSEL (e.g., $\mathbf{610}_1$, FIG. 8); and wherein the apparatus further comprises a second VCSEL (e.g., $\mathbf{610}_2$, FIG. 8) fabricated on the substrate (e.g., **702**, FIG. 8).

In some embodiments of any of the above apparatus, the first VCSEL is configured to emit a first light beam (e.g., **704**, FIG. 7) having a first linear polarization (e.g., X-polarization); and the second VCSEL is configured to emit a second light beam (e.g., **706**, FIG. 7) having a second linear polarization (e.g., Y-polarization) orthogonal to the first linear polarization.

In some embodiments of any of the above apparatus, the apparatus further comprises a beam combiner (e.g., **708** and **710**, FIG. 7) configured to spatially and directionally combine the first light beam and the second light beam.

In some embodiments of any of the above apparatus, the optical resonator has a transverse geometric shape approximated by three or more partially overlapping circles (e.g., $\mathbf{220}_1$-$\mathbf{220}_3$, FIG. 2A).

In some embodiments of any of the above apparatus, the first plurality of electrodes includes at least three electrodes (e.g., $\mathbf{212}_1$-$\mathbf{212}_3$, FIG. 2A; $\mathbf{512}_1$-$\mathbf{512}_5$, FIG. 5), each having an approximately semicircular shape (e.g., corresponding to an arch angle between 90 degrees and 270 degrees) and located at an edge of a respective one of the three or more partially overlapping circles.

In some embodiments of any of the above apparatus, the first plurality of electrodes includes: a circular electrode (e.g., $\mathbf{412}_6$, FIG. 4; e.g., $\mathbf{512}_6$, FIG. 5) that is approximately centered (e.g., within 25% of the electrode's diameter) on an optical axis of the optical resonator; and two or more arch-shaped electrodes (e.g., $\mathbf{412}_1$-$\mathbf{412}_5$, FIG. 4; e.g., $\mathbf{512}_1$-$\mathbf{512}_5$, FIG. 5) that laterally surround the circular electrode.

In some embodiments of any of the above apparatus, the apparatus further comprises an optical fiber (e.g., **620**, FIG. 6) configured to receive a light beam (e.g., **614**, FIG. 6) emitted from the optical resonator.

In some embodiments of any of the above apparatus, the apparatus further comprises a fixed or configurable phase mask (e.g., **910**, FIG. 9; **1010**, FIG. 10) configured to spatially filter light emitted from the optical resonator.

While this disclosure includes references to illustrative embodiments, this specification is not intended to be construed in a limiting sense.

For example, as used herein, the term "linear combination of transverse resonator modes" should be construed to cover a single transverse resonator mode of the optical resonator of a disclosed VCSEL. Under this interpretation, a single transverse resonator mode is a linear combination of transverse resonator modes having only one non-zero coefficient, with all other coefficients being zero.

Various modifications of the described embodiments, as well as other embodiments within the scope of the disclosure, which are apparent to persons skilled in the art to which the disclosure pertains are deemed to lie within the principle and scope of the disclosure, e.g., as expressed in the following claims.

Unless explicitly stated otherwise, each numerical value and range should be interpreted as being approximate as if the word "about" or "approximately" preceded the value or range.

Reference herein to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the disclosure. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments necessarily mutually exclusive of other embodiments. The same applies to the term "implementation."

Throughout the detailed description, the drawings, which are not to scale, are illustrative only and are used in order to explain, rather than limit the disclosure. The use of terms such as height, length, width, top, bottom, is strictly to facilitate the description of the embodiments and is not intended to limit the embodiments to a specific orientation. For example, height does not imply only a vertical rise limitation, but is used to identify one of the three dimensions of a three dimensional structure as shown in the figures. Such "height" would be vertical where the layers and electrodes are horizontal but would be horizontal where the layers and electrodes are vertical, and so on. Similarly, while all figures show the different layers as horizontal layers such orientation is for descriptive purpose only and not to be construed as a limitation.

Also for purposes of this description, the terms "couple," "coupling," "coupled," "connect," "connecting," or "connected" refer to any manner known in the art or later developed in which energy is allowed to be transferred between two or more elements, and the interposition of one or more additional elements is contemplated, although not required. Conversely, the terms "directly coupled," "directly connected," etc., imply the absence of such additional elements.

The described embodiments are to be considered in all respects as only illustrative and not restrictive. In particular, the scope of the disclosure is indicated by the appended claims rather than by the description and figures herein. All changes that come within the meaning and range of equivalency of the claims are to be embraced within their scope.

The description and drawings merely illustrate the principles of the disclosure. It will thus be appreciated that those of ordinary skill in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the disclosure and are included within its spirit and scope. Furthermore, all statements herein reciting principles, aspects, and embodiments of the disclosure, as well as specific examples thereof, are intended to encompass equivalents thereof.

It should be appreciated by those of ordinary skill in the art that any block diagrams herein represent conceptual views of illustrative circuitry embodying the principles of the disclosure.

CLAIMS

What is claimed is:

1. An apparatus comprising:

a substrate;

a first distributed Bragg reflector (DBR) mirror supported on the substrate at a first offset distance;

a second DBR mirror supported on the substrate at a second offset distance that is greater than the first offset distance;

an active semiconductor region located between the first DBR mirror and the second DBR mirror; and

a first plurality of electrodes, each configured to inject a respective individually controllable electrical current into the active semiconductor region to cause light generation therein at a lasing wavelength; and

wherein an optical resonator bounded by the first DBR mirror and the second DBR mirror is configured to support a plurality of transverse resonator modes corresponding to the lasing wavelength.

2. The apparatus of claim 1, wherein the apparatus is operable to:

excite a first linear combination of the transverse resonator modes using a first set of the respective individually controllable electrical currents applied to the first plurality of electrodes; and

excite a second linear combination of the transverse resonator modes using a second set of the respective individually controllable electrical currents applied to the first plurality of electrodes, the second linear combination being different from the first linear combination.

3. The apparatus of claim 1, further comprising an additional electrode configured to receive the electrical currents from the first plurality of electrodes by way of the active semiconductor region;

wherein the additional electrode is adjacent to the first DBR mirror; and

wherein each of the first plurality of electrodes is adjacent to the second DBR mirror.

4. The apparatus of claim 1, wherein the first DBR mirror or the second DBR mirror, or both the first and second DBR mirrors comprise one or more ion-implanted regions located in an optical path of light emitted from the optical resonator.

5. The apparatus of claim 1,

wherein the first DBR mirror, the second DBR mirror, the active semiconductor region, and the first plurality of electrodes are parts of a first vertical-cavity surface-emitting laser (VCSEL); and

wherein the apparatus further comprises a second VCSEL fabricated on the substrate.

6. The apparatus of claim 5, wherein:

the first VCSEL is configured to emit a first light beam having a first linear polarization; and

the second VCSEL is configured to emit a second light beam having a second linear polarization orthogonal to the first linear polarization.

7. The apparatus of claim 1,

wherein the optical resonator has a transverse geometric shape approximated by three or more partially overlapping circles; and

wherein the first plurality of electrodes includes at least three electrodes, each having an approximately semicircular shape and located at an edge of a respective one of the three or more partially overlapping circles.

8. The apparatus of claim 1, wherein the first plurality of electrodes includes:

a circular electrode that is approximately centered on an optical axis of the optical resonator; and

two or more arch-shaped electrodes that laterally surround the circular electrode.

9. The apparatus of claim 1, further comprising an optical fiber configured to receive a light beam emitted from the optical resonator.

10. The apparatus of claim 1, further comprising a fixed or configurable phase mask configured to spatially filter light emitted from the optical resonator.

FIG. 1A

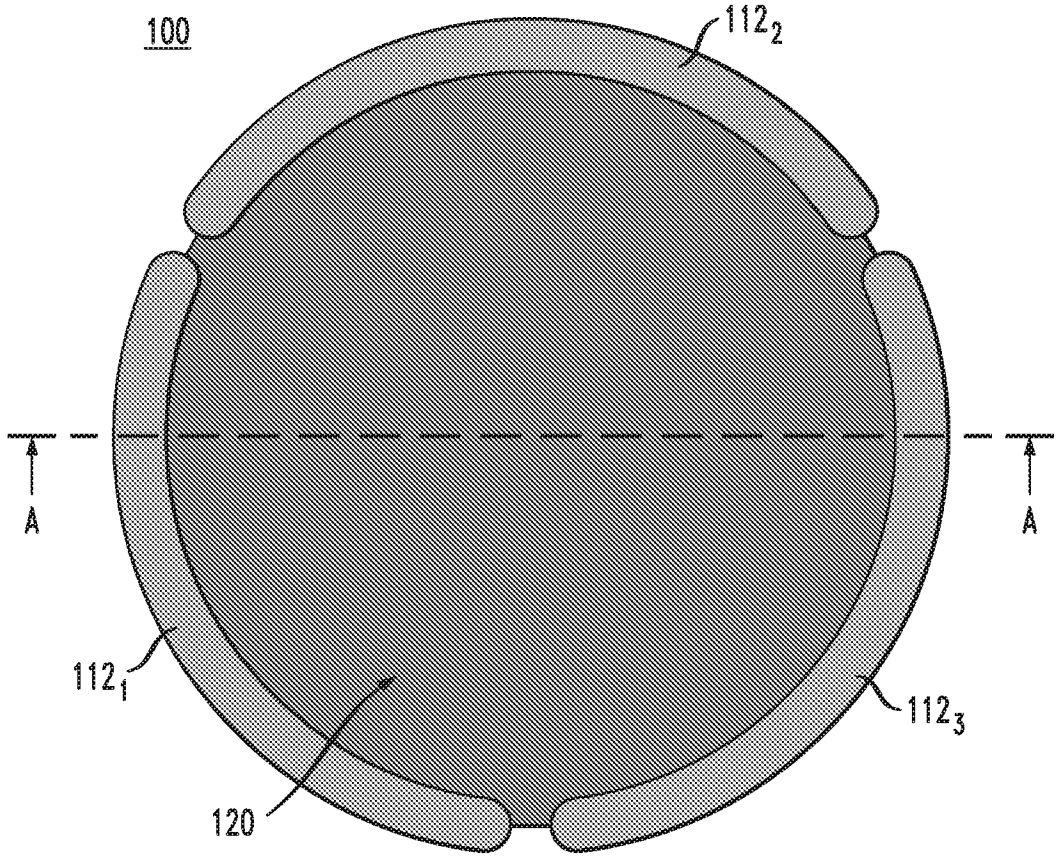
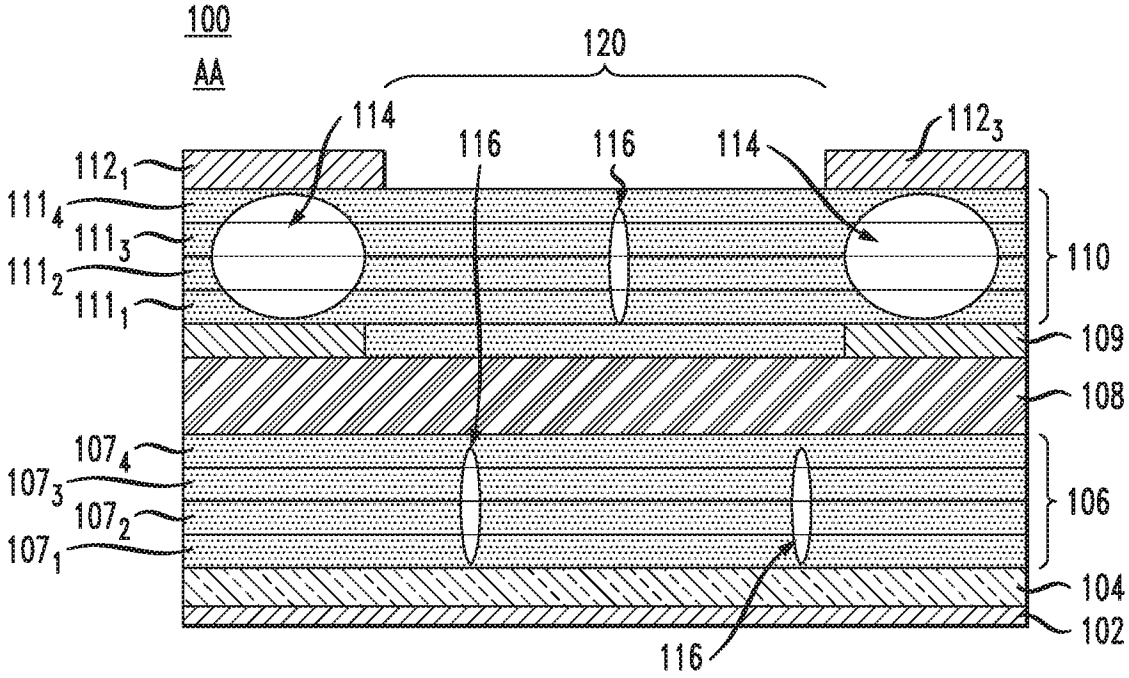

100
112_2
A
A
112_1
112_3
120

FIG. 1B


100
AA
120
114
116
116
114
112_3
112_1
111_4
111_3
111_2
111_1
110
109
108
107_4
107_3
107_2
107_1
106
104
102
116

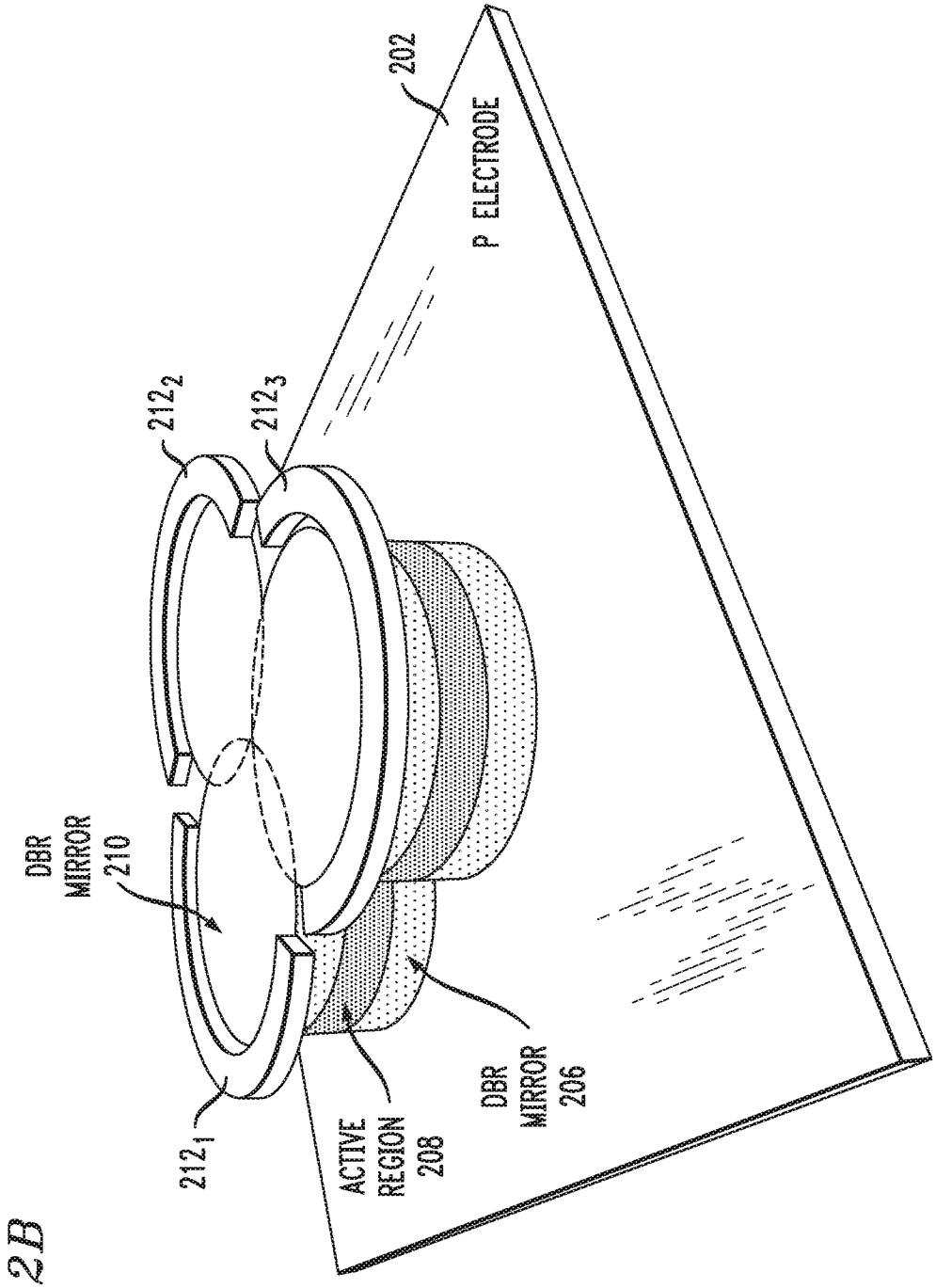

202
P ELECTRODE
212_2
212_3
DBR MIRROR 210
212_1
ACTIVE REGION 208
DBR MIRROR 206

FIG. 2B

200

FIG. 2A

200

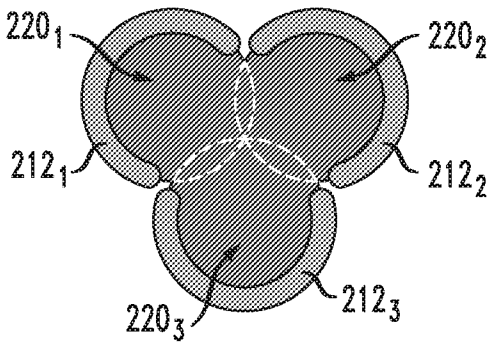


FIG. 4

400

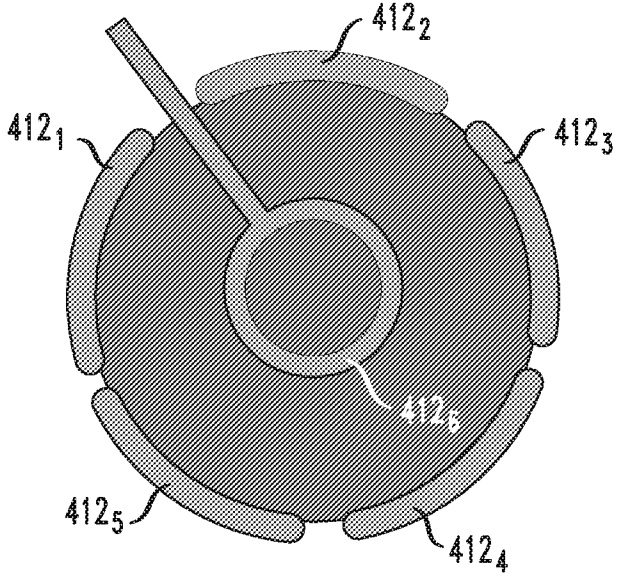


FIG. 5

500

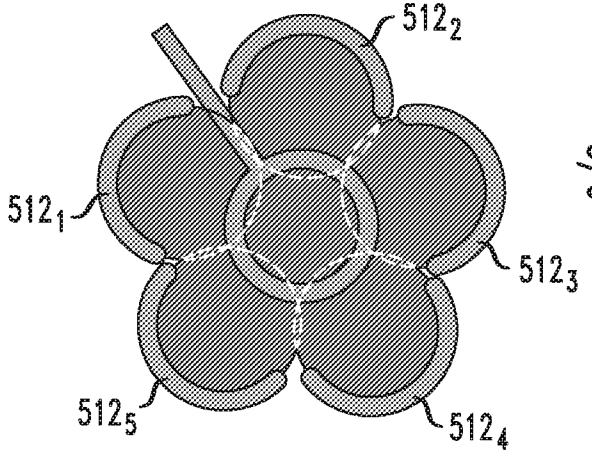


FIG. 3

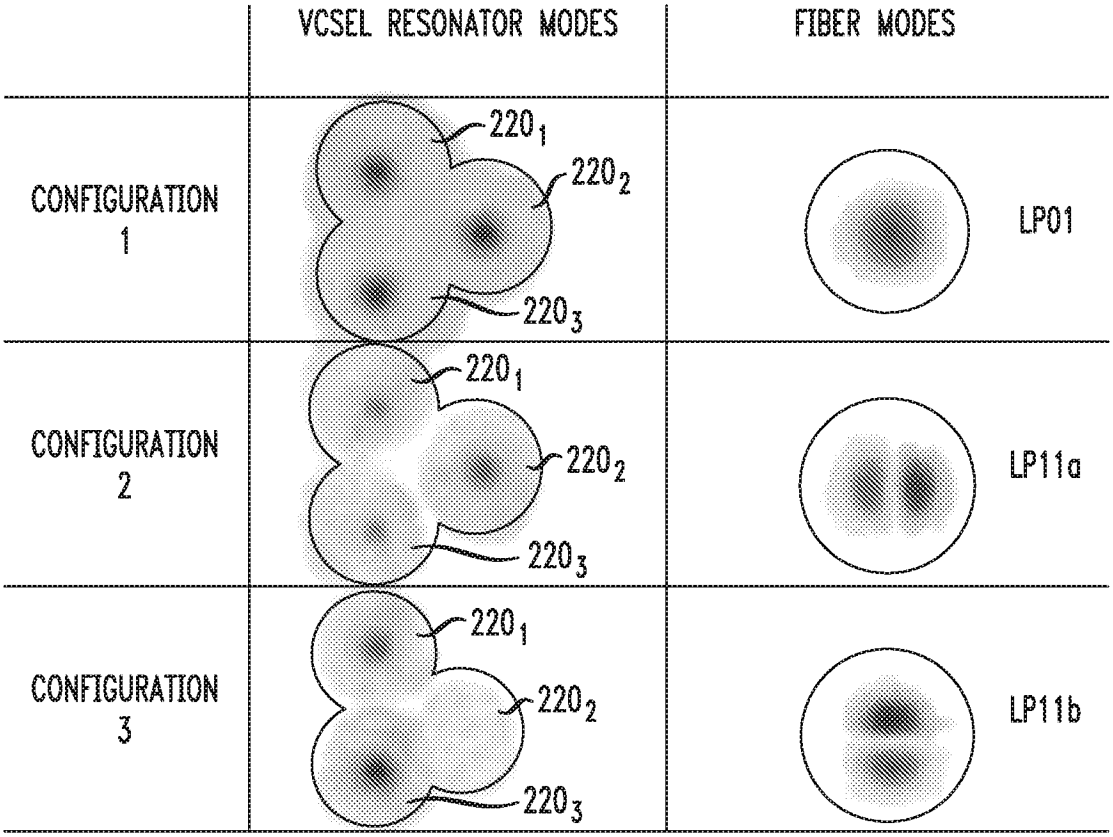

VCSEL RESONATOR MODES
FIBER MODES
CONFIGURATION 1
CONFIGURATION 2
CONFIGURATION 3
220_1
220_2
220_3
LP01
LP11a
LP11b

FIG. 8

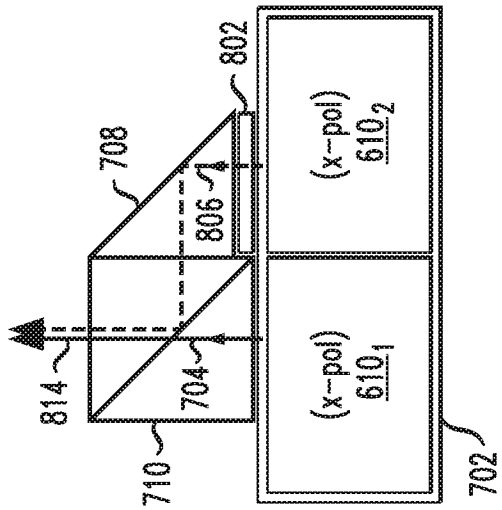


FIG. 7

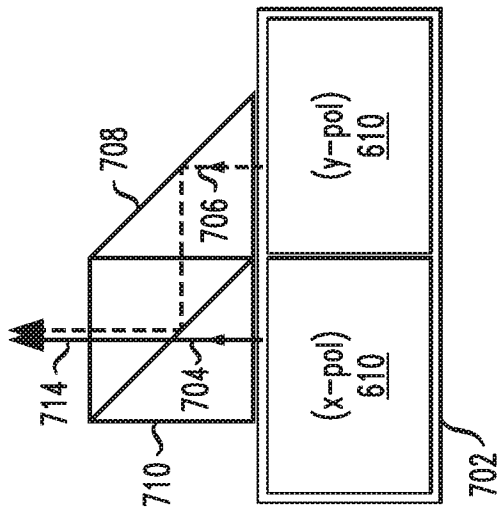


FIG. 6

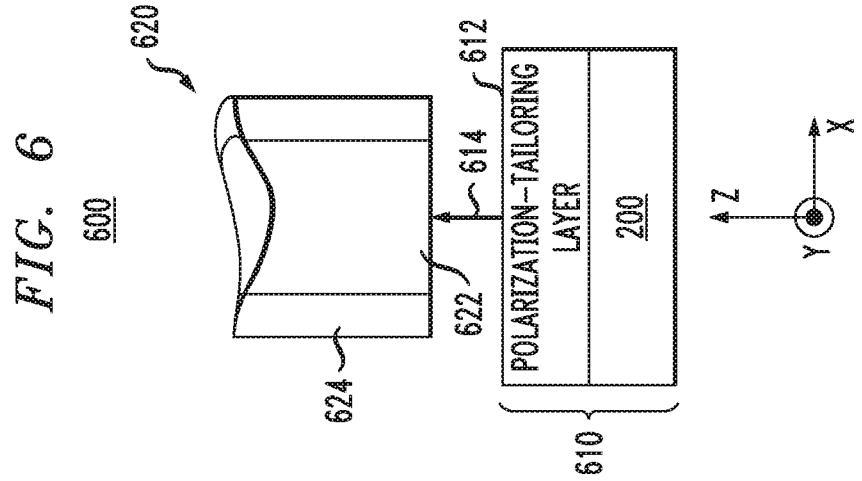


FIG. 9

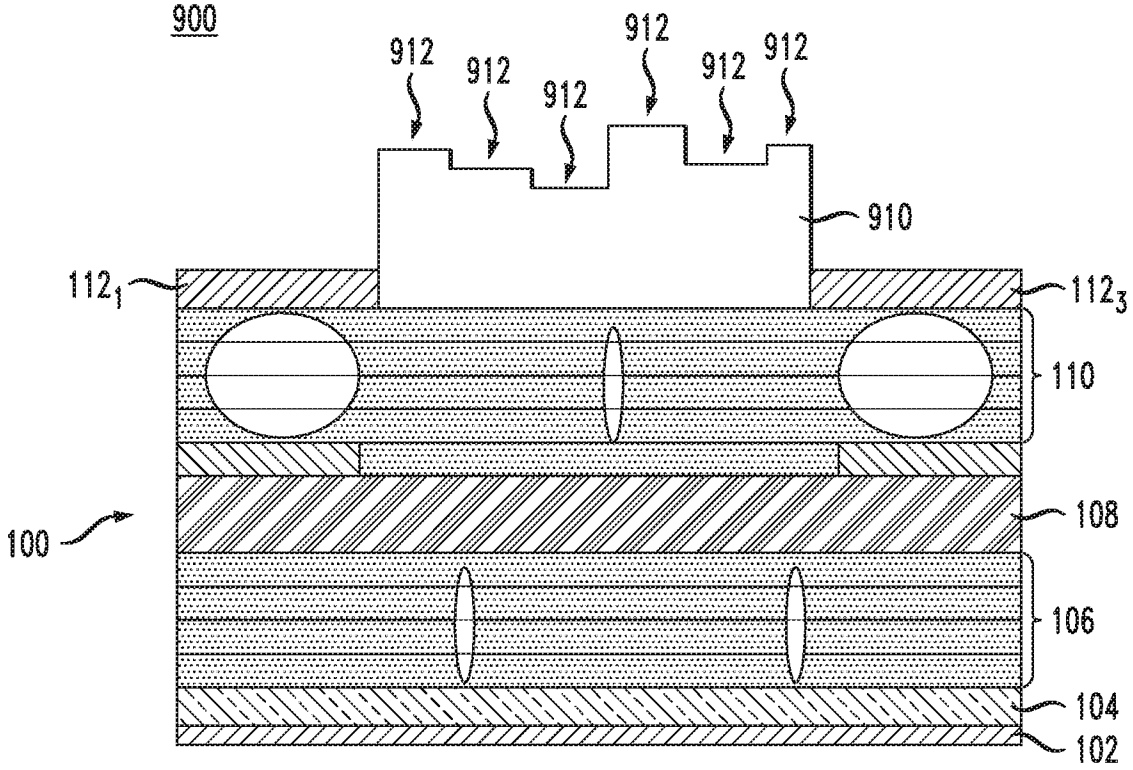
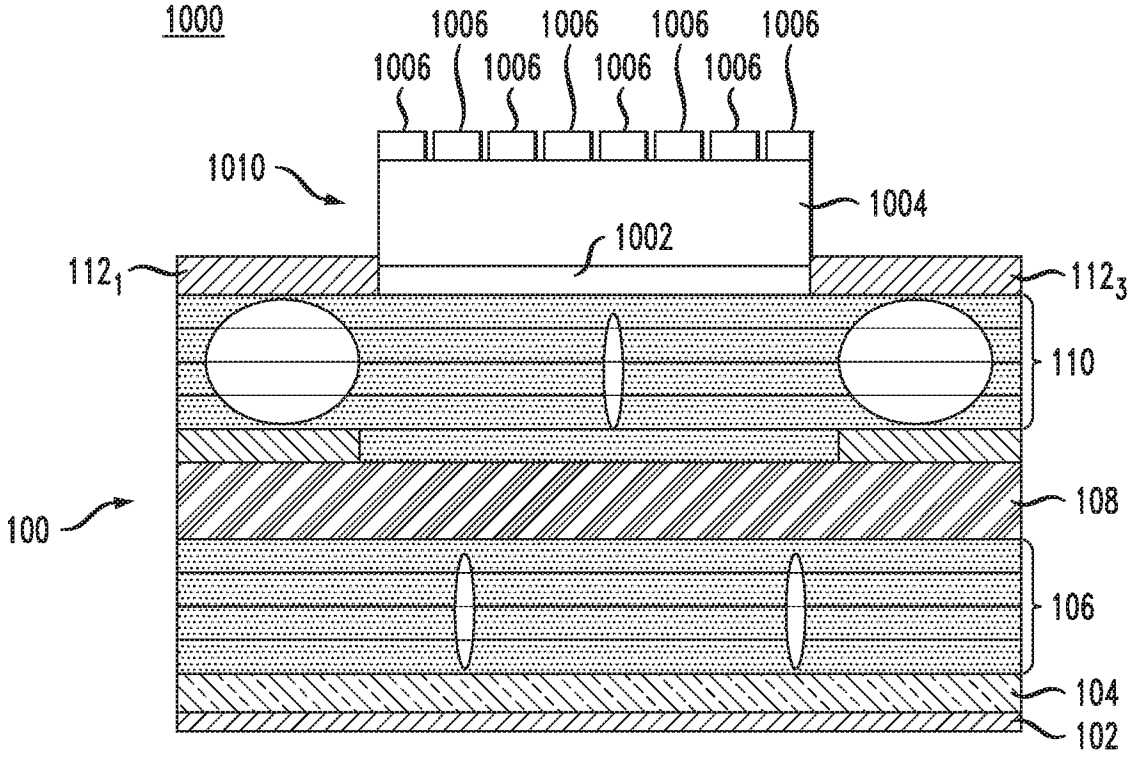

900
912
912
912
912
912
910
112_1
112_3
110
100
108
106
104
102

FIG. 10


1000
1006
1006
1006
1006
1006
1006
1006
1006
1010
1004
1002
112_1
112_3
110
100
108
106
104
102

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/012688

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01S5/042 H01S5/183 H01S5/062
ADD. H01S5/00 H01S5/026

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)
H01S

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	UCHIDA T ET AL: "Transverse mode control in long-monolithic-cavity VCSELs with temperature-profile control", ELECTRONICS LETTERS, IEE STEVENAGE, GB, vol. 42, no. 2, 19 January 2006 (2006-01-19), pages 94-96, XP006025979, ISSN: 0013-5194, DOI: 10.1049/EL:20063465 the whole document	1-5
X	US 5 903 590 A (HADLEY G RONALD [US] ET AL) 11 May 1999 (1999-05-11) column 10, line 56 - column 11, line 14; figure 10 column 3, line 38 - column 9, line 20; figure 1	1-5,9,10

-/--

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

[X] See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 March 2017	29/03/2017

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Riechel, Stefan

1

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/012688

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP H07 321405 A (GIJUTSU KENKYU KUMIAI SHINJIYO; FUJITSU LTD) 8 December 1995 (1995-12-08) abstract; figures 1A-1E,2	1-6,8-10
X	EP 0 618 652 A2 (AT & T CORP [US]) 5 October 1994 (1994-10-05) abstract column 3, line 36 - column 4, line 58; figure 3 figure 2	1-7,9,10
X	EP 0 765 015 A1 (HITACHI LTD [JP]) 26 March 1997 (1997-03-26)	1-5,9
A	page 5, line 40 - page 6, line 34; figures 10-12	6
A	US 2005/100070 A1 (NAKAYAMA HITOSHI [JP] ET AL) 12 May 2005 (2005-05-12) abstract; figures 1-6	7

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2017/012688

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5903590 A	11-05-1999	NONE	
JP H07321405 A	08-12-1995	NONE	
EP 0618652 A2	05-10-1994	CA 2118992 A1	30-09-1994
		EP 0618652 A2	05-10-1994
		JP H06302911 A	28-10-1994
		US 5345462 A	06-09-1994
EP 0765015 A1	26-03-1997	DE 69619047 D1	21-03-2002
		DE 69619047 T2	18-07-2002
		EP 0765015 A1	26-03-1997
		JP H0983082 A	28-03-1997
		US 5781576 A	14-07-1998
US 2005100070 A1	12-05-2005	JP 4058635 B2	12-03-2008
		JP 2005093798 A	07-04-2005
		US 2005100070 A1	12-05-2005
		US 2009279580 A1	12-11-2009