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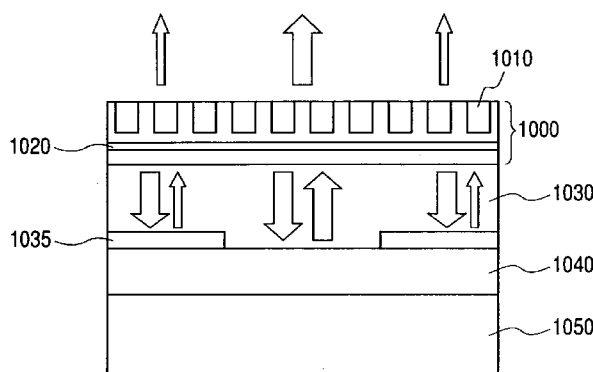
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(54) Title: PHOTONIC CRYSTAL SURFACE EMITTING LASER

FIG. 1



(57) Abstract: The present invention provides a photonic crystal surface emitting laser with which an arbitrary beam shape can be obtained and which enables design with a high degree of freedom. The surface emitting laser including a photonic crystal (1010) having a resonance mode in an in-plane direction parallel to a substrate (1050) includes a reflecting mirror (1040) for reflecting light emitted from the photonic crystal (1010) in a normal direction of the substrate (1050) and a spacer layer (1030) interposed between the reflecting mirror (1040) and the photonic crystal (1010), wherein a nonuniform in-plane distribution is provided to the characteristics of one of the reflecting mirror (1040) and the spacer layer (1030), so that a Q-value, which is a resonator characteristic in the normal direction of the substrate in the surface emitting laser, has a nonuniform in-plane distribution.

DESCRIPTION

PHOTONIC CRYSTAL SURFACE EMITTING LASER

5 TECHNICAL FIELD

The present invention relates to a photonic crystal surface emitting laser.

BACKGROUND ART

10 In recent years, there have been reported many examples in which a photonic crystal is applied to a semiconductor laser. Japanese Patent Application Laid-Open No. 2000-332351 (Patent Document 1) describes a surface emitting laser in which an active layer containing a
15 luminescence material is provided and a two-dimensional photonic crystal is formed in the vicinity of the active layer. This is a type of distributed-feedback (DFB) laser. In this two-dimensional photonic crystal, columnar holes are periodically provided in a semiconductor layer and the
20 refractive index distribution of the photonic crystal has two-dimensional periodicity. This periodicity causes light produced in the active layer to resonate, thereby forming a standing wave and allowing laser oscillation to take place. This laser-oscillated laser light is extracted in a surface
25 normal direction due to primary diffraction caused by the photonic crystal, and the laser operates as a surface emitting laser.

The above-described two-dimensional photonic crystal surface emitting laser is known to have an annular beam shape in which light intensity is low at the central portion of an emitting region and high in the peripheral portion thereof.

However, a unimodal beam shape in which light intensity is high at the central portion is more desirable in some cases for the case of, for example, coupling with a single-mode optical fiber. In order to obtain such a unimodal beam shape, Japanese Patent Application Laid-Open No. 2004-296538 (Patent Document 2) discusses a surface emitting laser light source in which the symmetry of the lattice structure of a two-dimensional photonic crystal is broken by shaping each hole of the two-dimensional photonic crystal into, for example, an equilateral triangle, thereby obtaining a beam shape close to a unimodal beam shape.

DISCLOSURE OF THE INVENTION

In the above-described Patent Document 2, beam shape control is made possible by changing the shape of a hole. However, changing the shape of a hole breaks the symmetry of the lattice structure of the photonic crystal. This affects the efficiency of light extraction in a surface normal direction, thus exerting an effect on, for example, oscillation threshold. That is, in Patent Document 2, changing the shape of a hole in an attempt to obtain an arbitrary beam shape also changes other characteristics of

the photonic crystal, causing the problem that the degree of design freedom is low.

In view of the foregoing problem, it is an object of the present invention to provide a photonic crystal surface emitting laser which is higher in the degree of design
5 freedom than the laser light source discussed in Patent Document 2 and in which an arbitrary beam shape can be obtained.

In an embodiment of the invention, there is provided
10 a photonic crystal surface emitting laser comprising: a photonic crystal having a resonance mode in an in-plane direction of a substrate; an active layer located in the vicinity of the photonic crystal and caused to emit light by carrier injection; a reflecting mirror for reflecting
15 light emitted from the photonic crystal in a normal direction of the substrate; and a spacer layer interposed between the reflecting mirror and the photonic crystal, wherein one of the reflecting mirror and the spacer layer is composed so that a Q-value, which is a resonator
20 characteristic in the normal direction of the substrate, has a nonuniform in-plane distribution.

According to the present invention, it is possible to realize a photonic crystal surface emitting laser which is higher in the degree of design freedom than in the case of
25 Patent Document 2 and in which an arbitrary beam shape can be obtained.

Further features of the present invention will become

apparent from the following description of exemplary embodiments with reference to the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

5 FIG. 1 is a schematic view to describe a photonic crystal surface emitting laser in an embodiment of the present invention.

 FIG. 2A, 2B and 2C are graphs to describe the variation of a Q-value in an embodiment of the present
10 invention.

 FIG. 3 is a schematic view used to describe a photonic crystal surface emitting laser in Embodiment 1 of the present invention.

 FIG. 4 is a schematic view to describe a photonic
15 crystal surface emitting laser in Embodiment 2 of the present invention.

 FIG. 5 is a schematic view to describe a photonic crystal surface emitting laser in Embodiment 3 of the present invention.

20 FIG. 6 is a schematic view to describe a photonic crystal surface emitting laser in Embodiment 4 of the present invention.

BEST MODES FOR CARRYING OUT THE INVENTION

25 Now, a structure of a photonic crystal surface emitting laser in an embodiment of the present invention will be described using FIG. 1. Note that in the present

specification, a description will be given assuming that the substrate side of a laser element is a lower side and a side opposite to the substrate side is an upper side. The photonic crystal surface emitting laser in the present

5 embodiment includes a two-dimensional photonic crystal 1010 having a resonance mode in the in-plane direction of a substrate 1050. In addition, an optical waveguide layer 1000 includes an active layer 1020 and is designed so that a peak of a light intensity distribution generally lies in

10 the active layer. In the optical waveguide layer 1000, the two-dimensional photonic crystal is provided on at least one side of the active layer 1020. This two-dimensional photonic crystal is formed by periodically disposing, in a plate-like base material, regions having a different

15 refractive index from that of the base material. For example, holes are periodically formed in the plate-like base material. The active layer 1020 and the two-dimensional photonic crystal 1010 may be in contact with each other or another layer may be interposed therebetween.

20 That is, it is enough that the active layer 1020 is located in the vicinity of the two-dimensional photonic crystal 1010. Consequently, light emitted from the active layer due to carrier injection is resonated by the two-dimensional photonic crystal 1010.

25 As the lattice shape of the photonic crystal, a rectangular lattice, a triangular lattice, a honeycomb lattice, or the like can be used. The lattice constant of

the photonic crystal is determined by taking into consideration a wavelength at which laser oscillation is desired to take place and the refractive index of a material. The shape of each lattice point is, for example,
5 circular, triangular, rectangular or hexagonal. Alternatively, one-dimensional photonic crystal may be used.

The photonic crystal functions as a laser resonator. As a parameter representative of the performance of a resonator, a Q-value is commonly used. The Q-value is a
10 parameter related to the dissipation of energy from the resonator. In general, oscillation can be caused at a lower threshold with the increase of the Q-value. Now, let the Q-value of a photonic crystal slab as a resonator be Q_{total} . Also let a Q-value in a direction vertical to a
15 substrate surface be $Q_{\perp}$ and a Q-value in a direction horizontal to the substrate surface be $Q_{\parallel}$. Then, the following relationship is known to hold:

$$1/Q_{\text{total}} = 1/Q_{\perp} + 1/Q_{\parallel}$$

This means that if either $Q_{\perp}$ or $1/Q_{\parallel}$ or both thereof can be
20 controlled, then the resonance characteristic Q_{total} can be controlled as well.

Adding a reflecting mirror to a photonic crystal laser enables the control of $Q_{\perp}$. For example, Q-value control can be realized by providing a DBR as a reflecting
25 mirror on the lower side of a two-dimensional photonic crystal surface emitting laser. The principles of such control are considered to be based on interference between

light directly emitted from the photonic crystal to the upper side and light reflecting upon and returning from the reflecting mirror. If the abovementioned directly emitted light and reflected and returned light are opposite in phase to each other (with a phase shift of π) and the same in light intensity with each other, then the light to be emitted to the upper side is completely cancelled and, therefore, cannot be emitted. Consequently, $Q_{\perp}$, which is a Q-value in a surface normal direction, can be increased.

FIG. 2 illustrates the results of Q-value calculations. FIG. 2 illustrates the variations of a Q-value when the optical path length (one-way) between the photonic crystal and the reflecting mirror is varied for three types of reflecting mirrors different in reflectance. FIG. 2A corresponds to a reflectance of 0%, FIG. 2B corresponds to a reflectance of 50%, and FIG. 2C corresponds to a reflectance of 100%. The wavelength of light used in the calculations is 400 nm. The axis of ordinates denotes Q-value normalized by the Q-value when no reflecting mirrors are provided (Q_0). Needless to say, the Q-value does not vary if the reflectance of a reflecting mirror is 0%. If the reflecting mirror has a reflectance value other than zero, then the Q-value varies depending on the optical path length. From FIGS. 2B and 2C, it is understood that the range of Q-value variation widens as the reflectance increases, and the Q-value varies over a range of 1/2 to the infinite at a reflectance of 100%. In

addition, the variation is repeated with a period of a length corresponding to a half-wave length in the optical path length. From the abovementioned calculation results, it has been confirmed that the Q-value can be controlled by
5 the intensity and phase (which are referred to as a complex amplitude) of reflected light.

The present invention has been accomplished by realizing arbitrary beam shapes by providing an arbitrary in-plane distribution to the intensity and phase of
10 reflected light based on such knowledge and findings as described above, thereby providing an arbitrary in-plane distribution to the Q-value. That is, the laser of the present invention has an in-plane nonuniform structure in the spacer layer or the reflecting mirror.

15 FIG. 1, which represents a structure of the present embodiment, illustrates an example of providing an in-plane distribution to the intensity of reflected light. Arrows in the figure denote flows of light emitted in a surface normal direction from the two-dimensional photonic crystal
20 1010. A structure 1035 for reducing reflectance is provided on part of a reflecting mirror 1040 and, thereby, a nonuniform in-plane distribution is formed in the intensity of reflected light. As means for providing an arbitrary in-plane distribution to the intensity of
25 reflected light other than modulating reflectance, light absorption at pathways of light before and after reflection, i.e., at the spacer layer, may be modulated. In order to

modulate a coefficient of light absorption in the spacer layer, an impurity of some sort may be implanted by means of ion implantation or the like. Consequently, the amount of light absorption can be increased. On the other hand, 5 in order to modulate the phase of reflected light in an in-plane direction, an optical path length may be modulated and, therefore, modulation may applied to one of the thickness and average refractive index of the spacer layer. Application of modulation to the refractive index of the 10 spacer layer can be achieved by means of ion implantation, oxidization, modulation of a compound composition, temperature distribution, stress-induced density distribution, or the like. In the case of means, among the abovementioned means, which takes advantage of reversible 15 change, the beam shape can be made variable. For example, in a configuration in which a heater is provided to form an in-plane temperature distribution or an in-plane stress distribution is formed using a piezoelectric element, the beam shape can be controlled in a reversible manner.

20 In a structure of the photonic crystal surface emitting laser of the present embodiment, the reflecting mirror or the spacer layer is an auxiliary element for applying modulation to the characteristics of the photonic crystal. That is, the photonic crystal surface emitting 25 laser is structured so that laser oscillation is possible with a photonic crystal having no reflecting mirrors alone. In other words, the photonic crystal itself constitutes a

laser resonator and laser oscillation is possible only with the photonic crystal. The abovementioned reflecting mirror or spacer layer is provided supplementarily, so that a Q-value, which is a resonator characteristic in a direction
5 vertical to a substrate in a laser resonator based on the photonic crystal, has a nonuniform in-plane distribution. Accordingly, the photonic crystal and the reflecting mirror or the spacer layer can be designed independently of each other, thereby enabling design with a higher degree of
10 freedom, compared with the laser light source of Patent Document 2.

As described above, the reflecting mirror or the spacer layer in the present embodiment is supplementarily provided in the laser resonator and is substantially
15 different from a surface relief structure used in a vertical cavity surface emitting laser (VCSEL) described below. That is, as an example of controlling a laser beam shape by providing an in-plane distribution of some sort to the reflectance of a reflecting mirror, there is known a
20 surface-relief structure used in a vertical cavity surface emitting laser (VCSEL). This example is such that an in-plane reflectance distribution is formed by forming an unlevel structure on a mirror surface provided by an emitting-side DBR of a vertical resonator comprised of a
25 pair of DBRs. In the surface relief structure, unnecessary modes, among some inherently existent lateral modes, are cut off to leave only necessary modes (lowest-order mode

referred to generally as a fundamental mode). Thus, the surface relief structure is able to obtain a beam shape having a specific mode. In contrast, in the present embodiment, the beam shape is controlled by modulating the in-plane resonator characteristic of a laser, which originally oscillates in a single mode, using one of the abovementioned supplementarily-provided reflecting mirror and spacer layer. Accordingly, the structure of the above-described present embodiment is substantially different in operating principles from the above-described surface relief structure of the VCSEL.

In the photonic crystal surface emitting laser of the present embodiment, an active layer similar to one used in a common semiconductor laser can be used for the active layer 1020. For example, the active layer is a multiquantum well structure formed using a material selected from the group consisting of GaAs/AlGaAs, GaInP/AlGaInP, GaN/InGaN, and the like. In addition, the spacer layer 1030 can be composed using one of a semiconductor and a dielectric material. The reflecting mirror 1040 can be composed using, for example, a DBR, a low-refractive index dielectric material, or a metal film. The substrate 1050 can be composed using, for example, a material selected from the group consisting of GaAs, GaN, Si, SiC, and sapphire.

In the photonic crystal surface emitting laser of the present embodiment, a plurality of laser elements can also

be two-dimensionally disposed in an array within a plane. The size of each photonic crystal and the pitch at which these photonic crystals are disposed can be determined according to the purpose of use of the laser elements. For
5 example, the size of each photonic crystal is 5 μm to 500 μm square and the pitch at which these photonic crystals are disposed is within a range of 10 μm to 1 mm. The laser may be composed so that the shapes of all beams emitted from the respective laser elements are the same or each
10 laser element has a different beam shape. In addition, the photonic crystal surface emitting laser of the present embodiment can be driven by one of a light excitation method and a current injection method. Note that in FIG. 1, electrodes are omitted.

15 Embodiments

Hereinafter, embodiments of the present invention will be described.

<Embodiment 1>

A photonic crystal surface emitting laser according
20 to the present embodiment will be described using FIG. 3. The laser illustrated in FIG. 3 includes an optical waveguide layer 3000, a two-dimensional photonic crystal 3010, an active layer 3020, a spacer layer 3030, and a semiconductor DBR 3040. The two-dimensional photonic
25 crystal 3010 is so structured that columnar holes are arranged in a square grid-like manner in p-type GaN which is a base material. The two-dimensional photonic crystal

has a lattice constant of 160 nm, a hole diameter of 70 nm, and a hole depth of 200 nm. The active layer 3020 is made of an $\text{In}_{0.09}\text{Ga}_{0.91}\text{N}/\text{In}_{0.02}\text{Ga}_{0.98}\text{N}$ multiquantum well, the n-type spacer layer 3030 is made of $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$, and the

5 semiconductor DBR 3040 is made of GaN/AlN. Electrodes are omitted in the figure. This laser structure is designed so that laser oscillation takes place at a wavelength near 400 nm. As illustrated in FIG. 3, a projected portion 3035 is formed so that only the central portion of the laser has

10 one more pair of DBRs, thus causing the spacer layer 3030 to be thinner at the central portion. As the result of providing the projected portion 3035 only in the central portion, the thickness of the spacer layer changes and the reflectance of DBRs, which are reflecting mirrors, also

15 changes.

In the present embodiment, the height of the projected portion 3035 is approximately 80 nm, which is then multiplied by the refractive index of the spacer layer to give a product of approximately 200 nm. Since a round-

20 trip optical path difference basically agrees with a wavelength, a phase difference of reflected light between the projected portion and the other portions need not be considered. As described above, reflectance varies as the number of DBR pairs varies. Our calculations show that a

25 reflectance of approximately 24% is obtained for 10 pairs of DBRs, and a reflectance of approximately 28% is obtained for 11 pairs of DBRs. If the number of DBR pairs is set to

11 at the projected portion 3035 and to 10 at a peripheral portion around the central portion, then there is obtained a Q-value difference of approximately 5% between the central portion and the peripheral portion. This
5 difference causes a difference in oscillation threshold between the central portion and the peripheral portion. Consequently, if the laser is driven using a proper current value, there can be obtained a beam shape close to a unimodal one in which the light intensity is high at the
10 central portion. On the other hand, if a projected portion is formed so that only the central portion has one less pair of DBRs, there can be obtained an annular beam shape the light intensity of which is high at the peripheral portion. This means that, in addition to a beam shape
15 close to a unimodal one, arbitrary beam shapes can be realized by varying the structure of a reflecting mirror in the in-plane direction thereof.

<Embodiment 2>

A photonic crystal surface emitting laser according
20 to the present embodiment will be described using FIG. 4. The laser illustrated in FIG. 4 includes an optical waveguide layer 4000, a two-dimensional photonic crystal 4010, an active layer 4020, spacer layers 4030 and 4035, and a semiconductor DBR 4040. The photonic crystal surface
25 emitting laser of the present embodiment is designed so that laser oscillation takes place at a wavelength near 400 nm. In FIG. 4, the in-plane structure of each reflecting

mirror is uniform but that of the spacer layers are not uniform. Specifically, ion implantation is selectively performed so as to decrease the refractive index of only the spacer layer 4035 in the peripheral portion of a laser
5 element. The source of ions to be implanted is, for example, Al.

If the refractive index differs, the optical path length also differs, even if the thickness of the spacer layers is uniform. Hence, the structure of the spacer
10 layer is designed such that the Q-value is large at the central portion and then is shifted therefrom at the peripheral portion (desirably, by shifting the optical path length by a half-wave length). Consequently, laser oscillation less easily takes place at the peripheral
15 portion than at the central portion. There is therefore obtained a beam shape close to a unimodal one in which the light intensity is high at the central portion. Also in the present embodiment, arbitrary beam shapes can be obtained. For example, the laser can be caused to emit
20 beams in an annular shape by setting the refractive index distribution opposite to the abovementioned distribution.

<Embodiment 3>

A photonic crystal surface emitting laser according to the present embodiment will be described using FIG. 5.
25 The laser illustrated in FIG. 5 includes an optical waveguide layer 5000, a two-dimensional photonic crystal 5010, an active layer 5020, spacer layers 5030 and 5035,

and a semiconductor DBR 5040. The photonic crystal surface emitting laser of the present embodiment is designed so that laser oscillation takes place at a wavelength near 400 nm. In FIG. 5, part of the spacer layer is oxidized to
5 form an oxidized region 5035. In general, the refractive index of the oxidized part decreases and therefore the optical path length shortens. As a result, as with Embodiment 2, a nonuniform in-plane distribution can be formed in the optical path length, thereby enabling an
10 arbitrary beam shape to be formed.

<Embodiment 4>

A photonic crystal surface emitting laser according to the present embodiment will be described using FIG. 6. The laser illustrated in FIG. 6 includes an optical
15 waveguide layer 6000, a two-dimensional photonic crystal 6010, an active layer 6020, spacer layers 6030 and 6035, and a semiconductor DBR 6040. The photonic crystal surface emitting laser of the present embodiment is designed so that laser oscillation takes place at a wavelength near 400
20 nm. In FIG. 6, a compositionally-heterogeneous region 6035 is formed in the spacer layer 6030. For example, the spacer layer 6030 is formed of $\text{Al}_{0.07}\text{GaN}$ and the compositionally-heterogeneous region 6035 is formed of $\text{Al}_{0.20}\text{GaN}$. In an AlGaIn-based compound semiconductor, a
25 refractive index generally decreases as an Al composition becomes larger at longer wavelengths with respect to the absorption edge. That is, in the above-described structure,

the spacer layer 6035 is lower in refractive index than the spacer layer 6030. As a result, as in Embodiments 2 and 3, a beam shape is controllable. Such a compositionally-heterogeneous region as mentioned above can be formed by
5 means of patterning based on lithography or etching and embedded regrowth.

While embodiments of the present invention have been described heretofore, a surface emitting laser of the present invention is not limited to these embodiments. The
10 shape, material and size of a photonic crystal, and materials constituting the active layer, clad layer and electrodes can be changed as appropriate within the scope of the present invention. In addition, while in the above-described embodiments, lasers having a laser oscillation
15 wavelength of 400 nm have been shown, laser oscillation at an arbitrary wavelength is also possible by selecting an appropriate material and structure. Furthermore, in addition to the Gaussian unimodal and annular beam shapes discussed in the embodiments, arbitrary beam shapes can be
20 obtained, including triangular, rectangular, semicircular, fan-shaped, and heart-shaped beam shapes. The above-described surface emitting lasers of the present invention can be used also as light sources for drawing images on a photosensitive drum included in an image forming apparatus,
25 such as a copying machine or a laser printer.

While the present invention has been described with reference to exemplary embodiments, it is to be understood

that the invention is not limited to the disclosed
exemplary embodiments. The scope of the following claims
is to be accorded the broadest interpretation so as to
encompass all such modifications and equivalent structures
5 and functions.

This application claims the benefit of Japanese
Patent Application No. 2009-112479, filed May 7, 2009,
which is hereby incorporated by reference herein in its
entirety.

CLAIMS

1. A photonic crystal surface emitting laser comprising:

5 a photonic crystal having a resonance mode in an in-plane direction of a substrate;

an active layer located in the vicinity of the photonic crystal and caused to emit light by carrier injection;

10 a reflecting mirror for reflecting light emitted from the photonic crystal in a normal direction of the substrate; and

a spacer layer interposed between the reflecting mirror and the photonic crystal,

15 wherein one of the reflecting mirror and the spacer layer is composed so that a Q-value, which is a resonator characteristic in the normal direction of the substrate, has a nonuniform in-plane distribution.

2. The photonic crystal surface emitting laser
20 according to claim 1, wherein a complex amplitude of reflected light reflected by the reflecting mirror to make a round trip in the spacer layer has a nonuniform in-plane distribution.

3. The photonic crystal surface emitting laser
25 according to claim 2, wherein an intensity of the reflected light has a nonuniform in-plane distribution.

4. The photonic crystal surface emitting laser

according to claim 3, wherein a reflectance of the reflecting mirror has a nonuniform in-plane distribution.

5 5. The photonic crystal surface emitting laser according to claim 3, wherein a light absorption coefficient of the spacer layer has a nonuniform in-plane distribution.

6. The photonic crystal surface emitting laser according to claim 2, wherein a phase of the reflected light has a nonuniform in-plane distribution.

10 7. The photonic crystal surface emitting laser according to claim 6, wherein a thickness of the spacer layer has a nonuniform in-plane distribution.

8. The photonic crystal surface emitting laser according to claim 6, wherein an average refractive index
15 of the spacer layer has a nonuniform in-plane distribution.

9. The photonic crystal surface emitting laser according to any one of claims 1 to 8, wherein a nonuniform in-plane distribution of characteristics of one of the reflecting mirror and the spacer layer is variable.

20 10. The photonic crystal surface emitting laser according to any one of claims 1 to 9, wherein the photonic crystal is two-dimensionally disposed in an array within a plane.

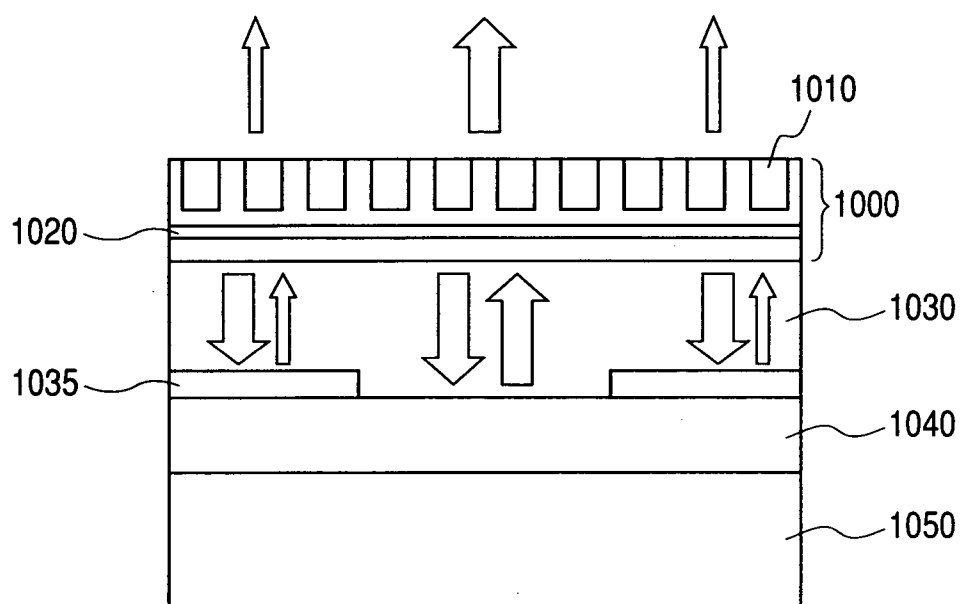
FIG. 1

FIG. 2A

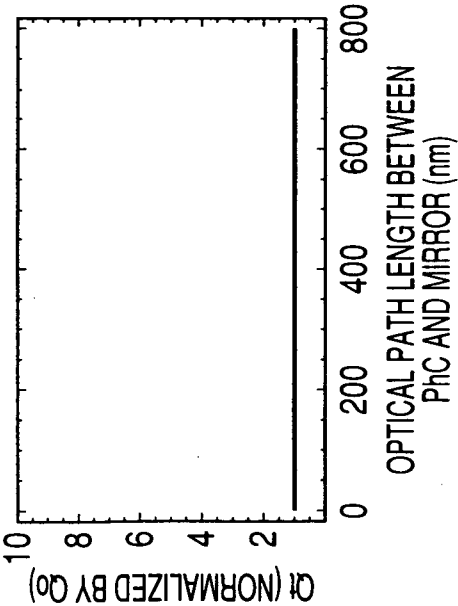


FIG. 2B

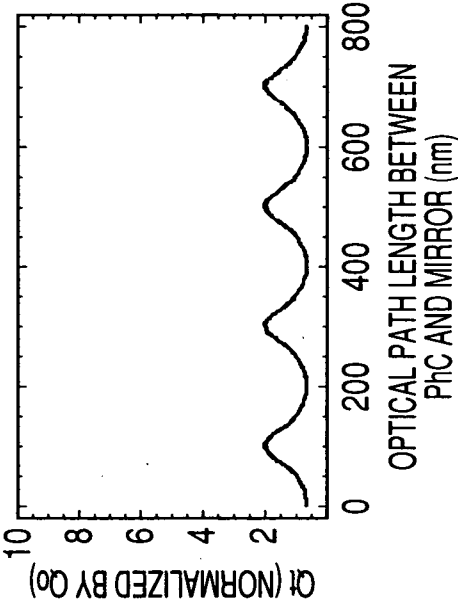


FIG. 2C

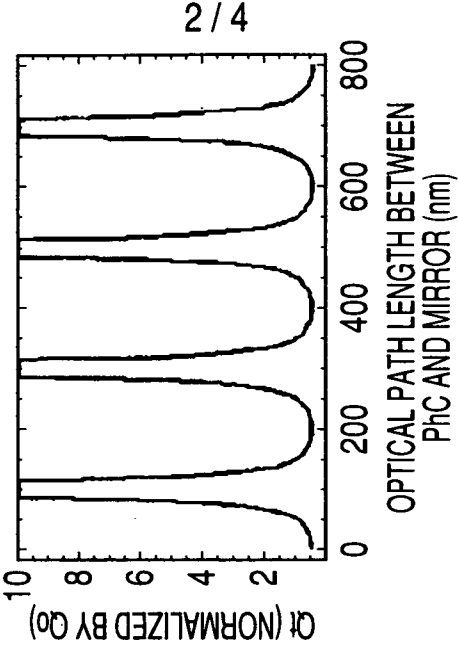


FIG. 3

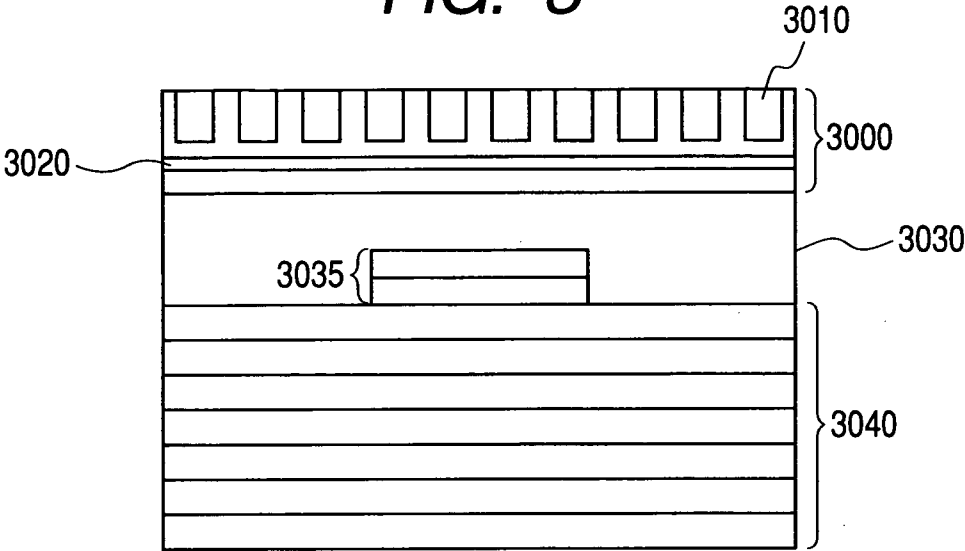


FIG. 4

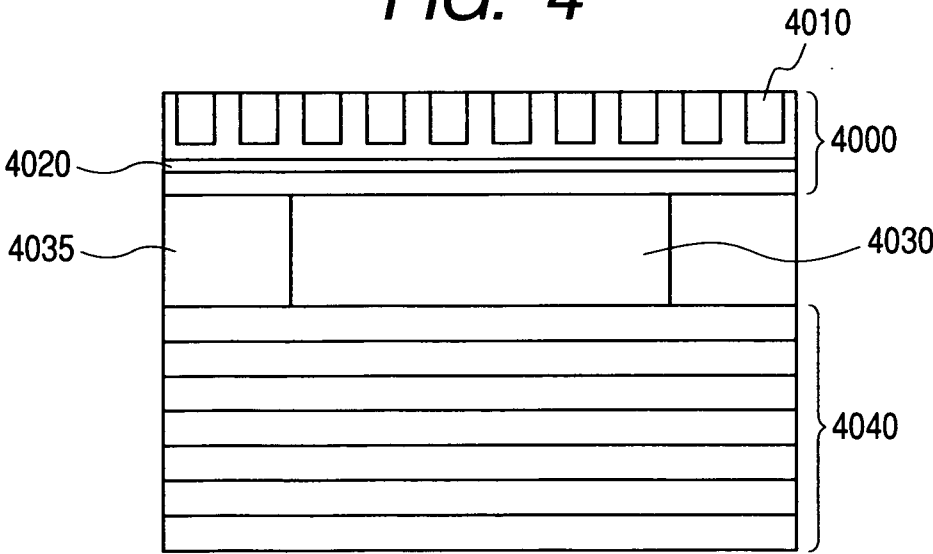


FIG. 5

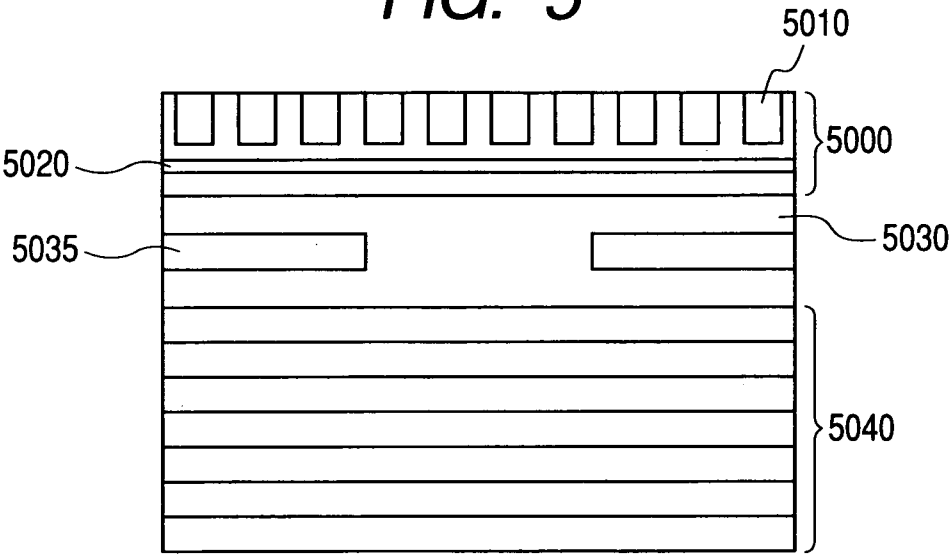
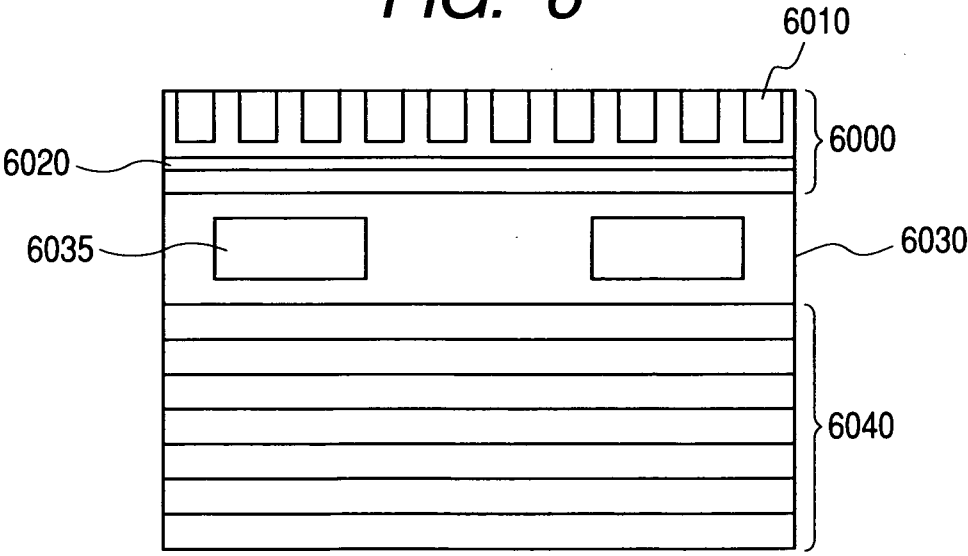


FIG. 6



INTERNATIONAL SEARCH REPORT

International application No

PCT/JP2010/056725

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01S5/183

ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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 practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2007/201527 A1 (HORI YUICHIRO [JP] ET AL) 30 August 2007 (2007-08-30) paragraphs [0070], [0082]; figures 5a,6a,7,9a,10	1-3,5,6,8-10
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X	US 2008/285608 A1 (HORI YUICHIRO [JP]) 20 November 2008 (2008-11-20) paragraphs [0020], [0037] - [0039]; figures 7a-7c,10,11	1-3,5,6,8,10
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Further documents are listed in the continuation of Box C.



See patent family annex.

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