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Noda et al.

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(45) **Date of Patent: Oct. 9, 2012**

(54) **PHOTONIC CRYSTAL LASER**

(75) Inventors: **Susumu Noda**, Uji (JP); **Yoshitaka Kurosaka**, Kyoto (JP); **Kyosuke Sakai**, Kyoto (JP); **Eiji Miyai**, Kyoto (JP); **Dai Ohnishi**, Otsu (JP); **Wataru Kunishi**, Kyoto (JP)

(73) Assignees: **Japan Science and Technology Agency**, Kawaguchi-Shi (JP); **Rohm Co., Ltd.**, Kyoto-Shi (JP)

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(22) Filed: **Aug. 29, 2008**

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(30) **Foreign Application Priority Data**

Aug. 31, 2007 (JP) 2007-226255

(51) **Int. Cl.**
H01S 3/08 (2006.01)

(52) **U.S. Cl.** **372/96**

(58) **Field of Classification Search** 372/96
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,876,842 A		4/1975	Bouwhuis	
6,154,480 A	*	11/2000	Magnusson et al.	372/96
6,829,281 B2	*	12/2004	Deng et al.	372/96
2001/0026857 A1	*	10/2001	Kinoshita	428/105
2005/0094956 A1	*	5/2005	Parker et al.	385/129
2007/0121694 A1	*	5/2007	Okamoto	372/50.124

FOREIGN PATENT DOCUMENTS

JP	A-2000-332351	11/2000
WO	WO03005513 A1 *	1/2003
WO	WO 2006117863 A1 *	11/2006

OTHER PUBLICATIONS

Fan et al., "Analysis of Guided Resonances in Photonic Crystal Slabs", 2002, Phys. Rev. B, 65, 235112, 1-8.*

Ito et al.; "Semiconductor Laser Basics and Applications;" Apr. 25, 1989; pp. 305-306; Baifukan Co., Ltd.; Tokyo.

Miyai et al.; "Possibility of lasing operation at non-Γ-point of photonic-crystal laser;" *Japan Society of Applied Physics*; 2006; pp. 968.

* cited by examiner

Primary Examiner — Tod T Van Roy
Assistant Examiner — Joshua King
(74) *Attorney, Agent, or Firm* — Oliff & Berridge, PLC

(57) **ABSTRACT**

A laser capable of emitting multiple laser beams is provided. A two-dimensional photonic crystal laser according to the present invention has a laminated structure including an active layer, a first photonic crystal layer having a periodic distribution of refractive index with a first period, and a second photonic crystal layer having a periodic distribution of refractive index with a second period that differs from the first period. This two-dimensional photonic crystal laser can emit a main beam traveling in a direction perpendicular to the two-dimensional photonic crystals and side beams each traveling in a direction inclined with respect to the main beam. These beams can be used, for example, in a recording/reproducing device by means of an optical disk, the main beam being used for recording/reproducing information and the side beams for following up the track.

14 Claims, 13 Drawing Sheets

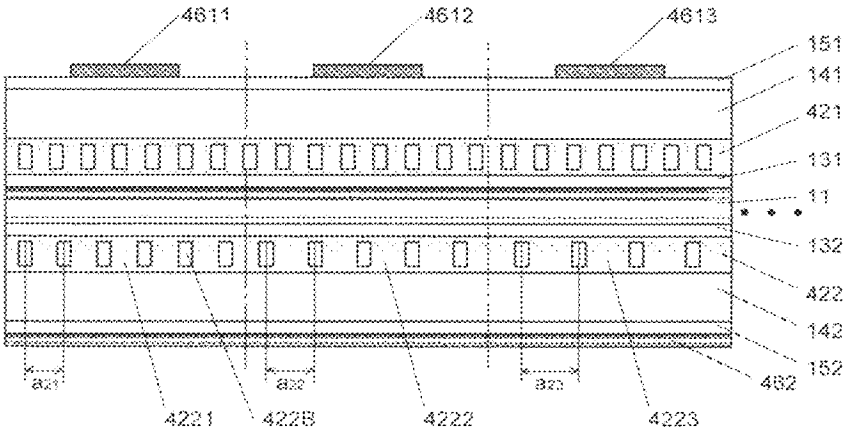


Fig. 1

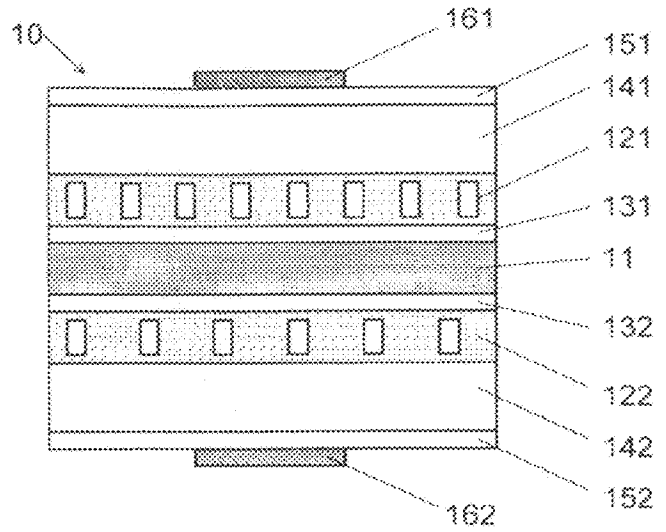
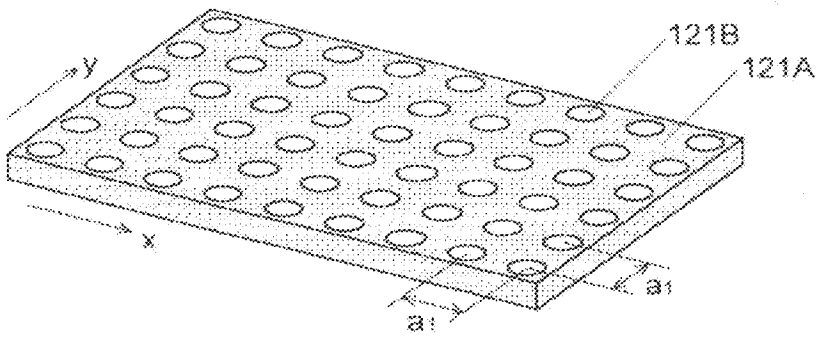


Fig. 2

(a) 1ST TWO-DIMENSIONAL PHOTONIC CRYSTAL LAYER 121



(b) 2ND TWO-DIMENSIONAL PHOTONIC CRYSTAL LAYER 122

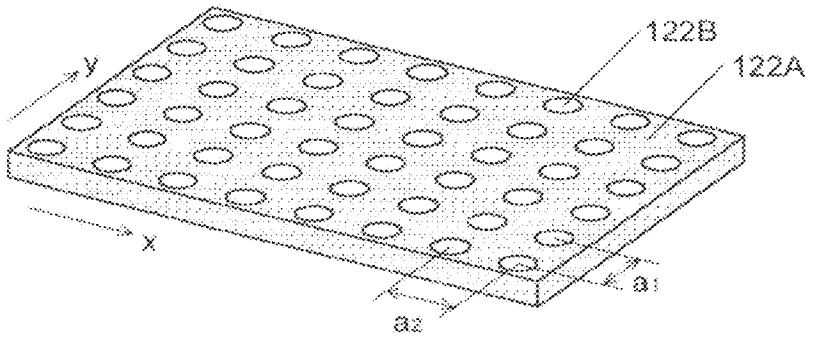


Fig. 3

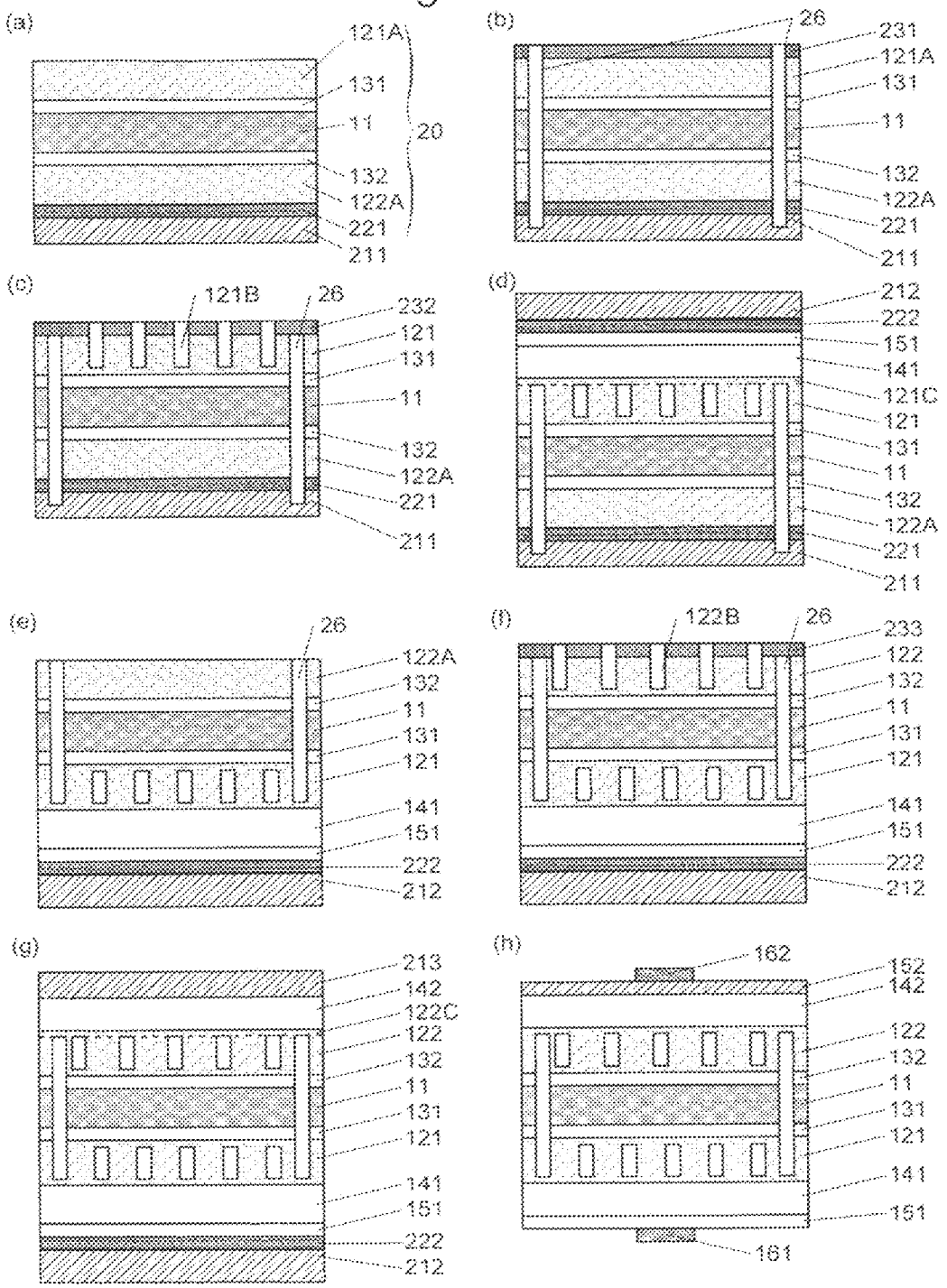

(a)
121A
131
11
20
132
122A
221
211
(b)
26
231
121A
131
11
132
122A
221
211
(c)
121B
26
232
121
131
11
132
122A
221
211
(d)
212
222
151
141
121C
121
131
11
132
122A
221
211
(e)
26
122A
132
11
131
121
141
151
222
212
(f)
122B
26
233
122
132
11
131
121
141
151
222
212
(g)
213
142
122C
122
132
11
131
121
141
151
222
212
(h)
162
152
142
122
132
11
131
121
141
151
161

Fig. 4

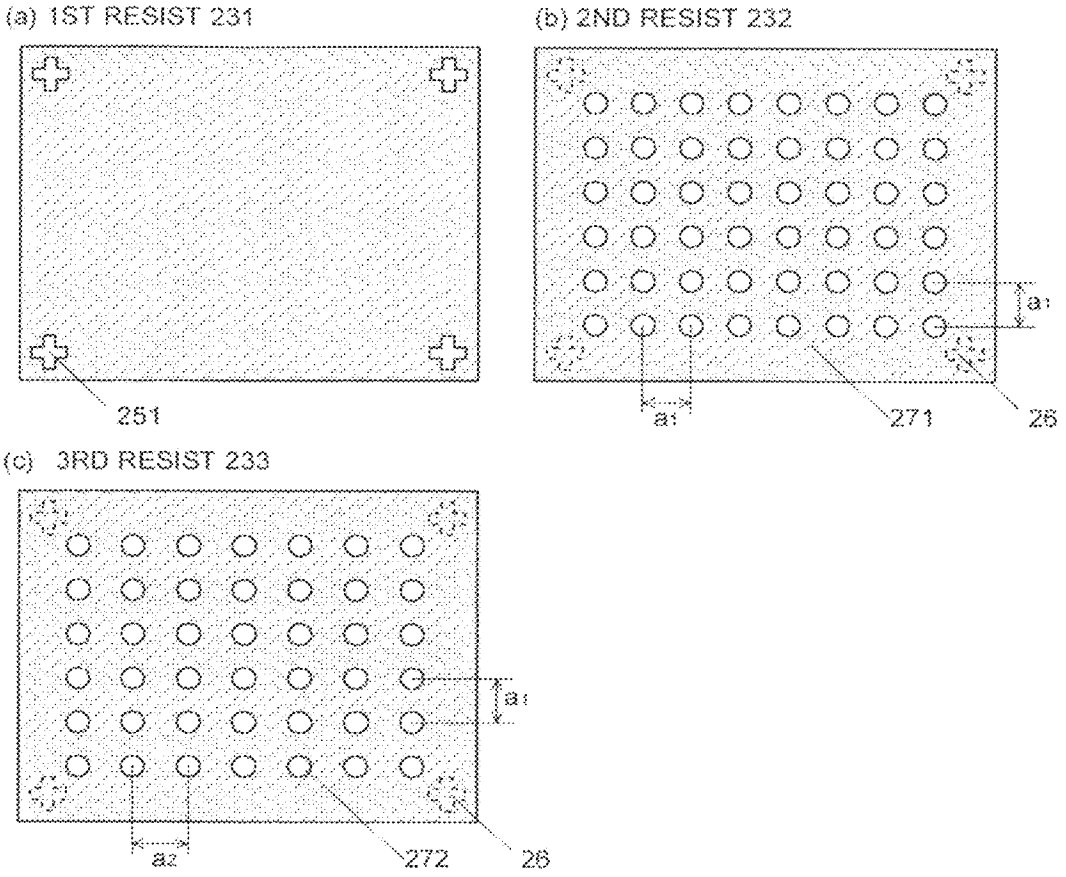

(a) 1ST RESIST 231
251
(b) 2ND RESIST 232
a1
a1
271
26
(c) 3RD RESIST 233
a1
a2
272
26

Fig. 5

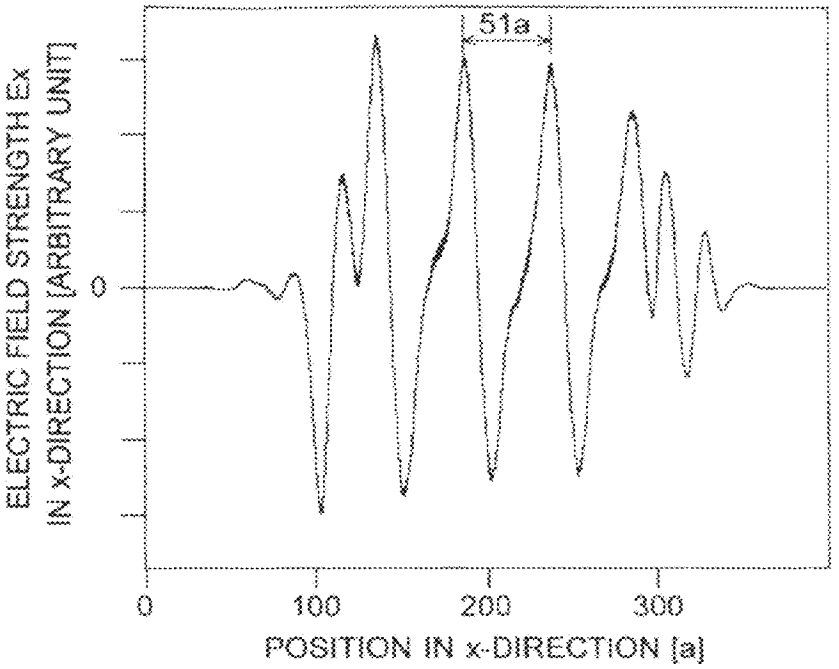

51a
ELECTRIC FIELD STRENGTH Ex
IN x-DIRECTION [ARBITRARY UNIT]
0
0
100
200
300
POSITION IN x-DIRECTION [a]

Fig. 6

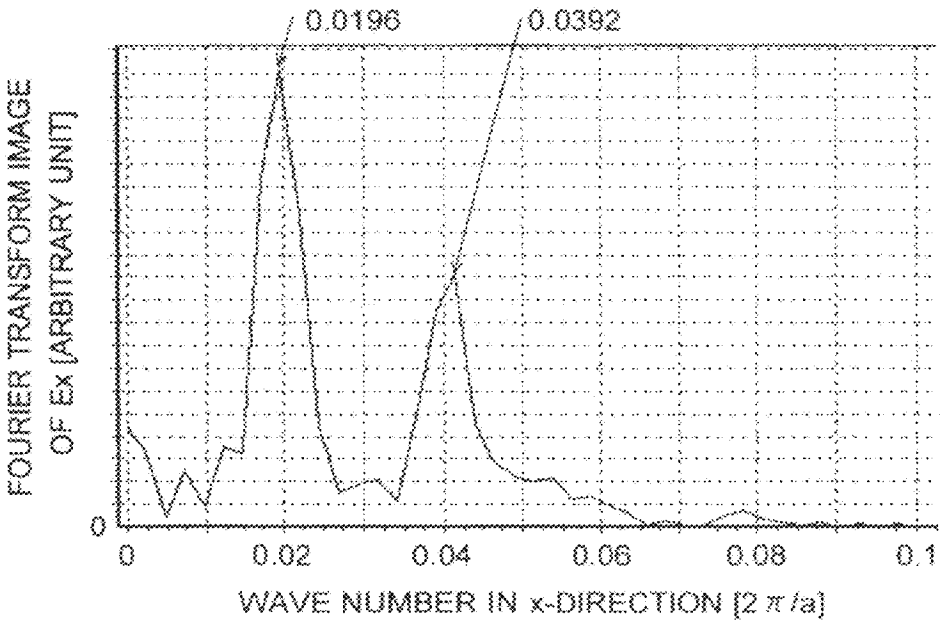

0.0196
0.0392
FOURIER TRANSFORM IMAGE
OF Ex [ARBITRARY UNIT]
0
0
0.02
0.04
0.06
0.08
0.1
WAVE NUMBER IN x-DIRECTION [2 π /a]

Fig. 7

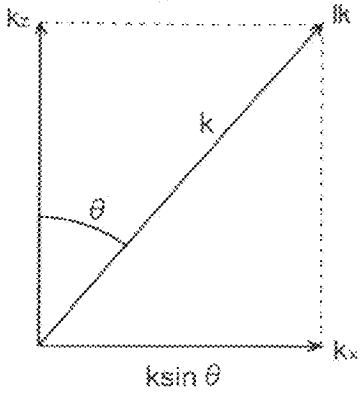

kz
k
θ
kx
ksin θ

Fig. 8

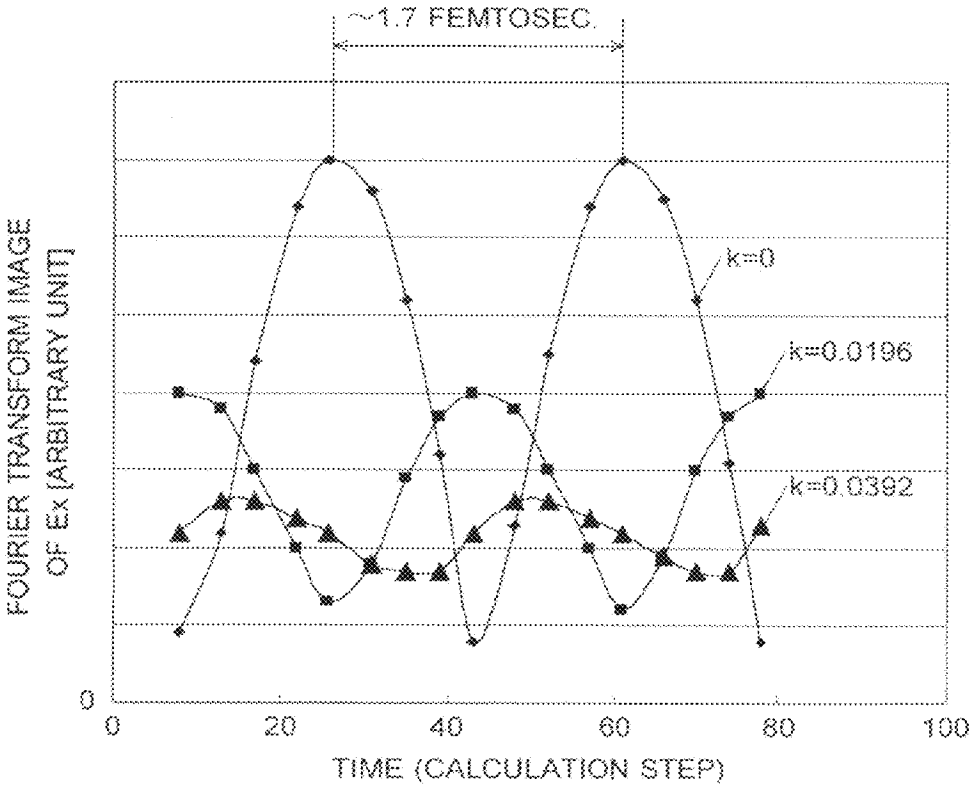

~1.7 FEMTOSEC.
k=0
k=0.0196
k=0.0392
FOURIER TRANSFORM IMAGE OF Ex [ARBITRARY UNIT]
0
0
20
40
60
80
100
TIME (CALCULATION STEP)

Fig. 9

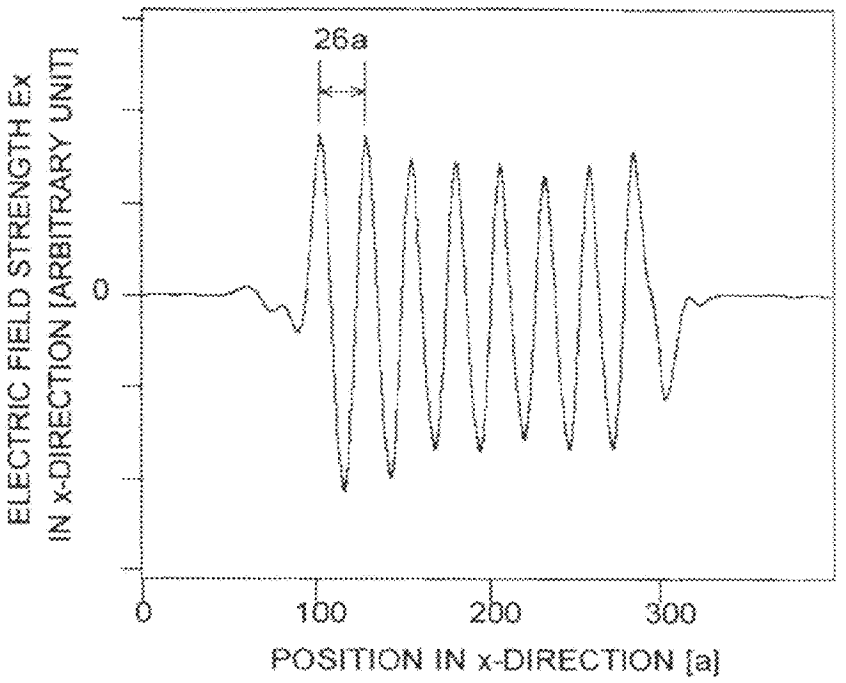

26a
ELECTRIC FIELD STRENGTH Ex
IN x-DIRECTION [ARBITRARY UNIT]
0
0
100
200
300
POSITION IN x-DIRECTION [a]

Fig. 10

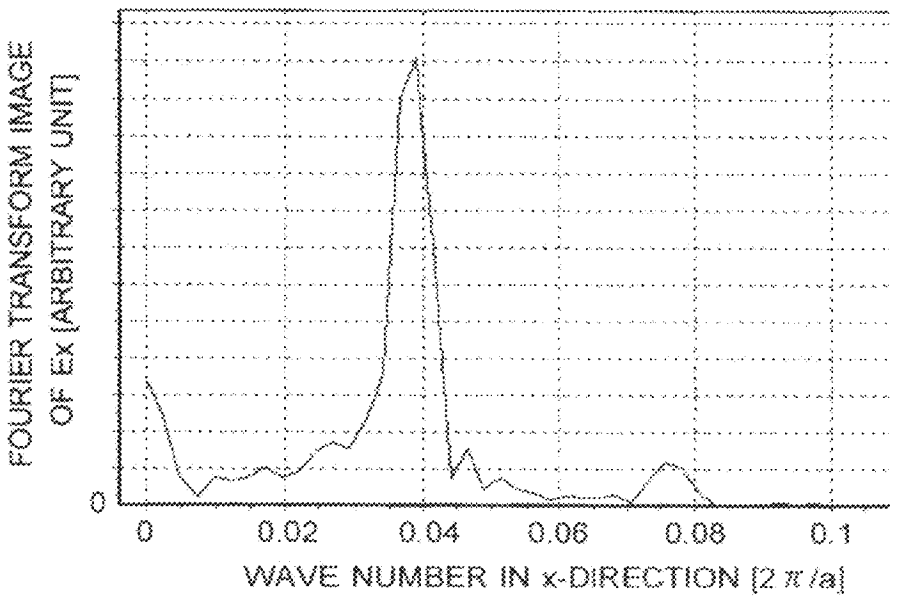

FOURIER TRANSFORM IMAGE
OF Ex [ARBITRARY UNIT]
0
0
0.02
0.04
0.06
0.08
0.1
WAVE NUMBER IN x-DIRECTION [2 π /a]

Fig. 11

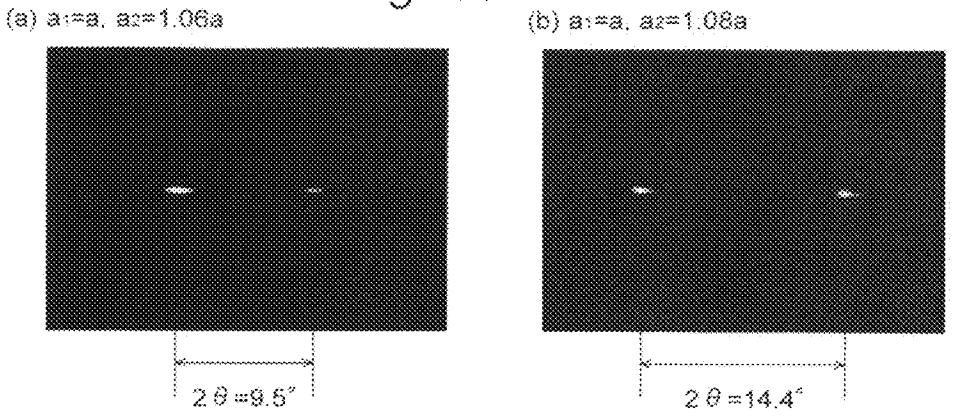

(a) a1=a, a2=1.06a
(b) a1=a, a2=1.08a
2θ=9.5°
2θ=14.4°

Fig. 12

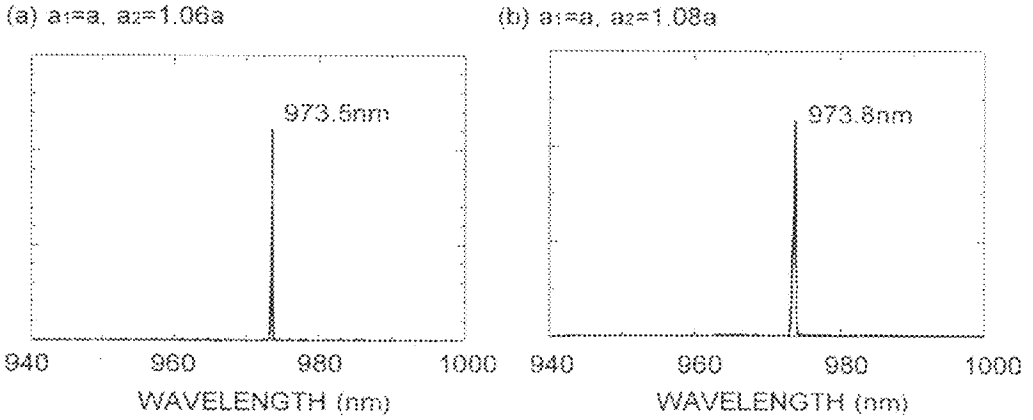

(a) a1=a, a2=1.06a
(b) a1=a, a2=1.08a
973.6nm
973.8nm
940
960
980
1000
WAVELENGTH (nm)

Fig. 13

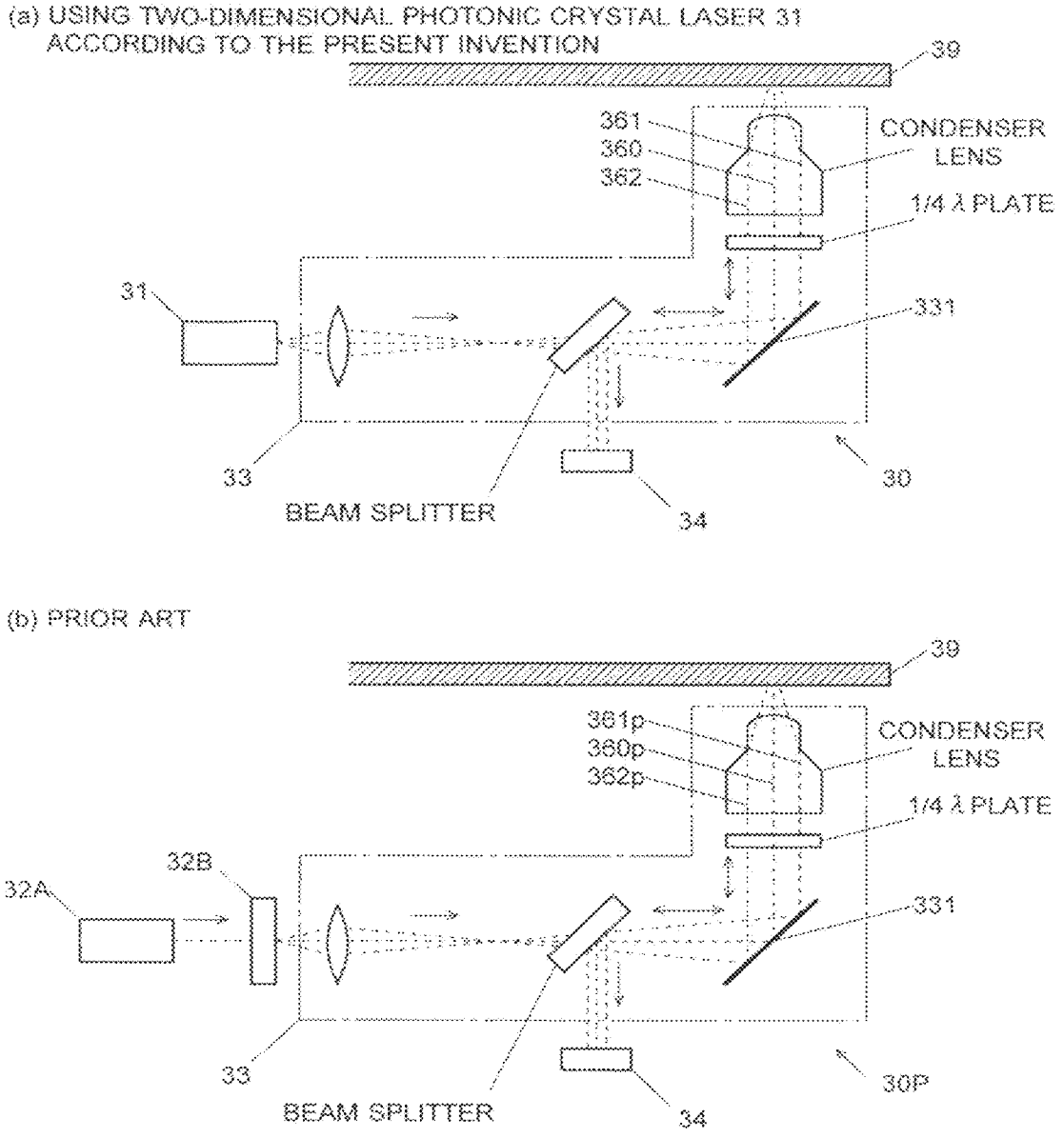

(a) USING TWO-DIMENSIONAL PHOTONIC CRYSTAL LASER 31 ACCORDING TO THE PRESENT INVENTION
39
361
360
362
CONDENSER LENS
1/4 λ PLATE
31
331
33
BEAM SPLITTER
34
30
(b) PRIOR ART
39
361p
360p
362p
CONDENSER LENS
1/4 λ PLATE
32B
32A
331
33
BEAM SPLITTER
34
30P

Fig. 14

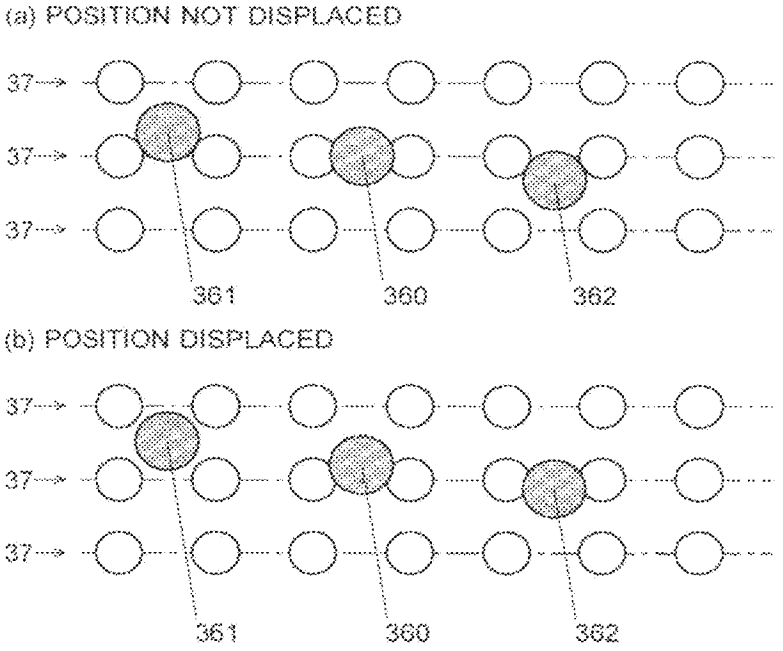

(a) POSITION NOT DISPLACED
37
37
37
361
360
362
(b) POSITION DISPLACED
37
37
37
361
360
362

Fig. 15

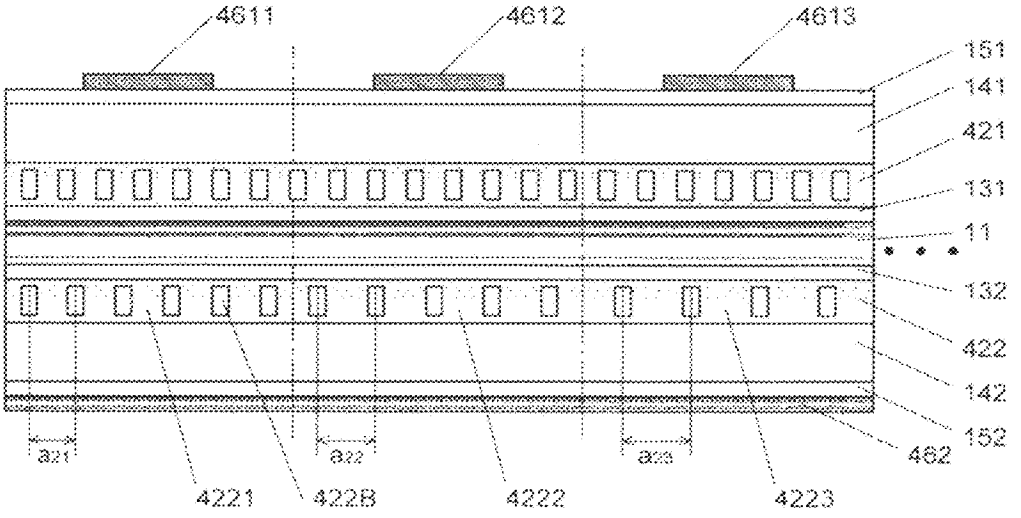

4611
4612
4613
151
141
421
131
11
132
422
142
152
462
a21
a22
a23
4221
422B
4222
4223

Fig. 16

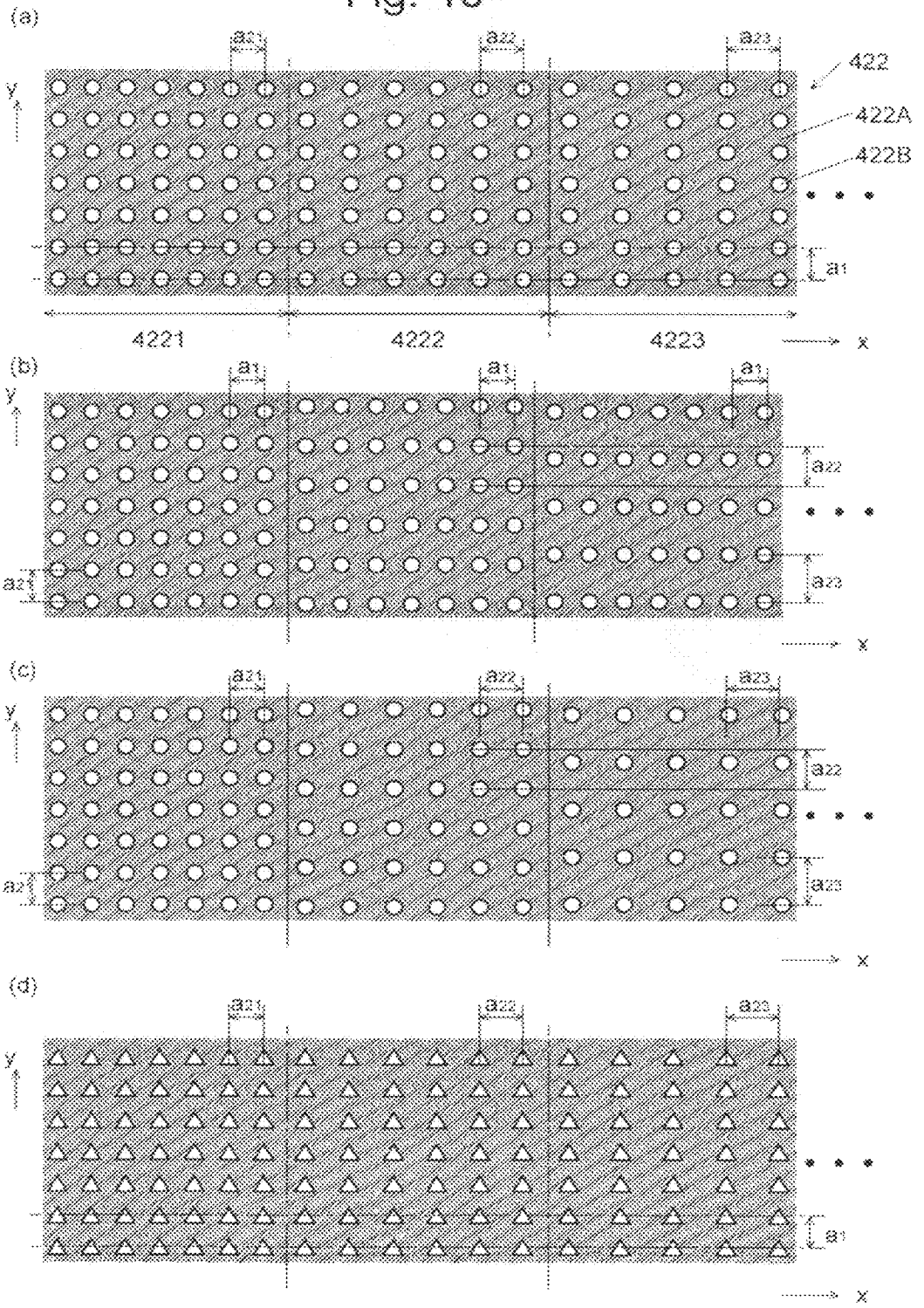

(a)
a_{21}
a_{22}
a_{23}
422
422A
422B
y
a_1
4221
4222
4223
x
(b)
a_1
a_{22}
a_{21}
a_{23}
(c)
(d)

Fig. 17

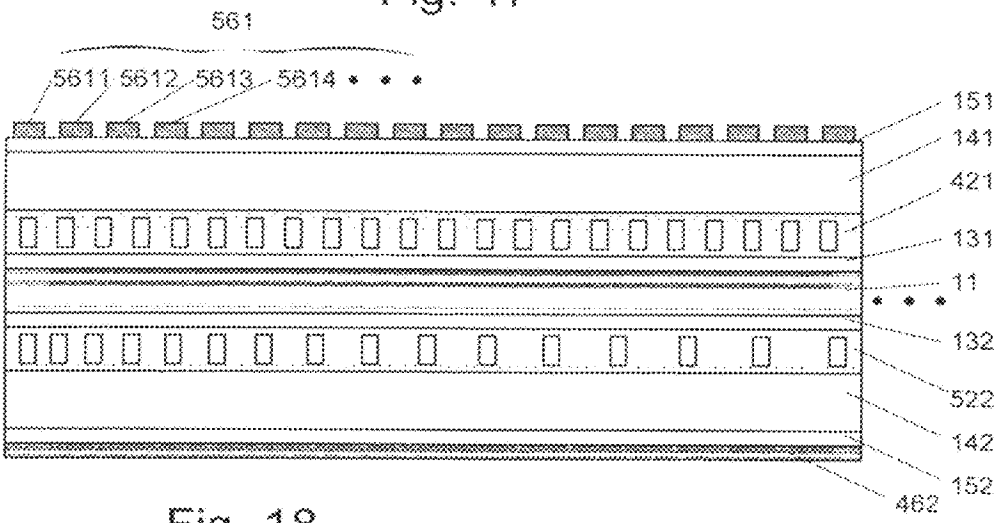


Fig. 18

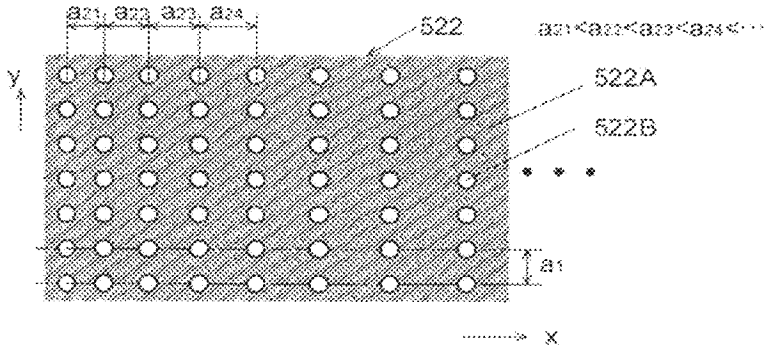


Fig. 19

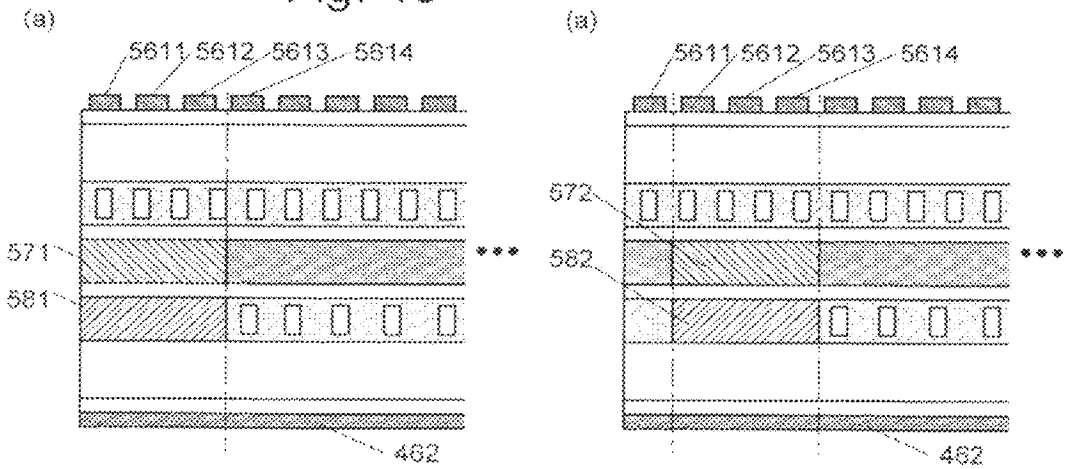


Fig. 20

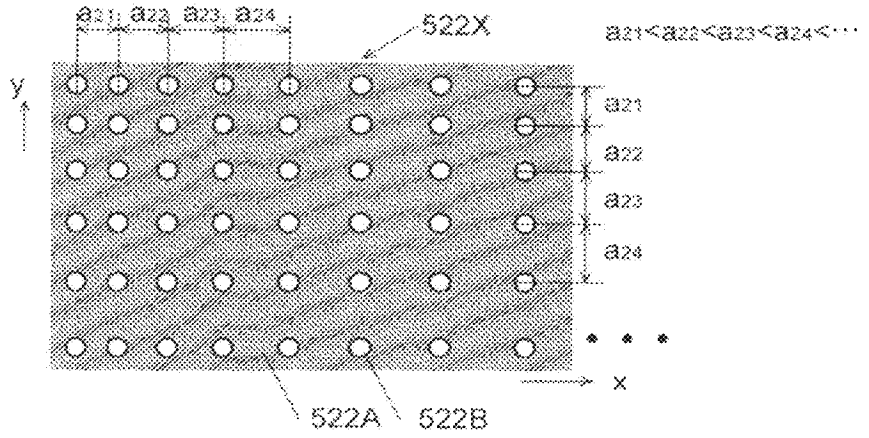


Fig. 21

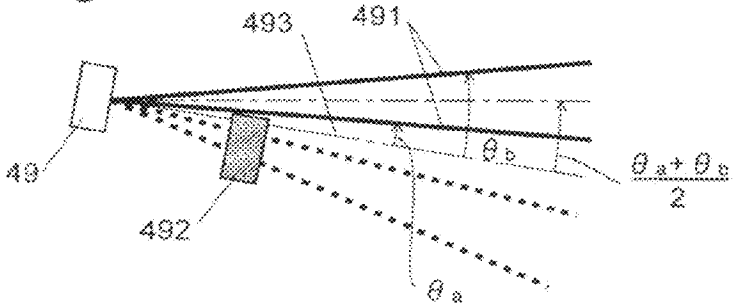


Fig. 22

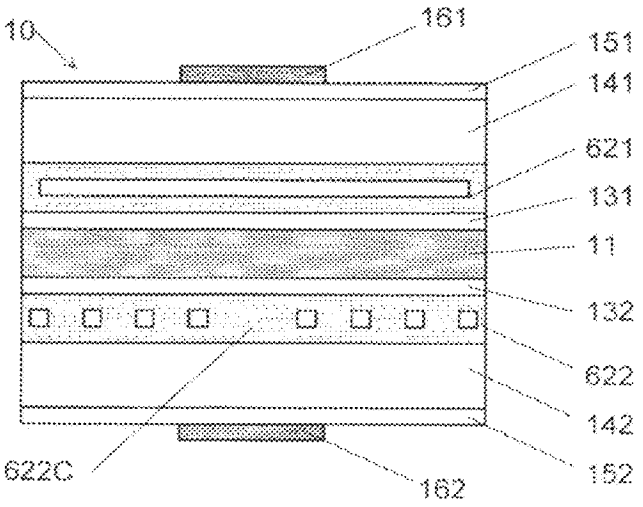


Fig. 23

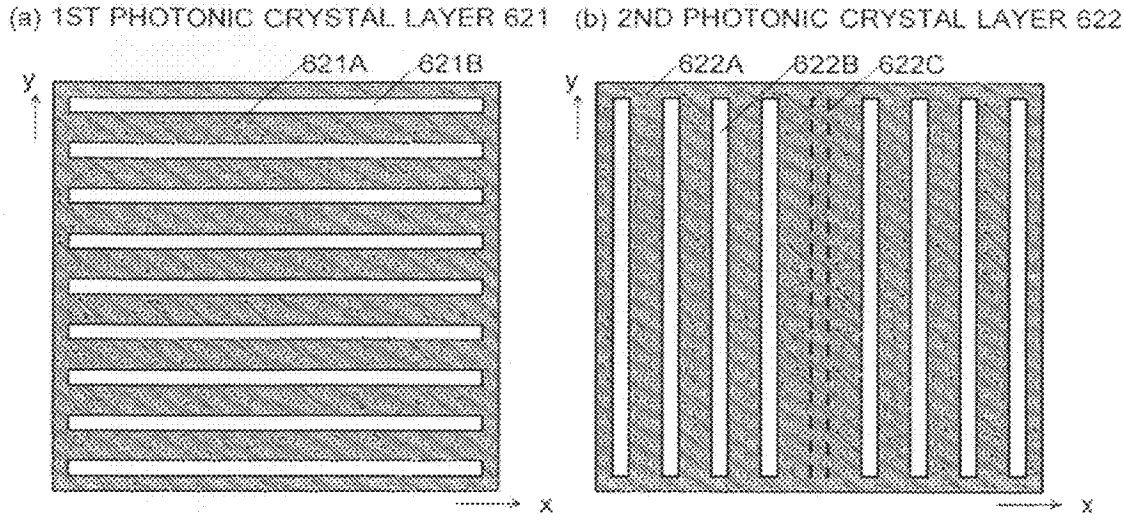
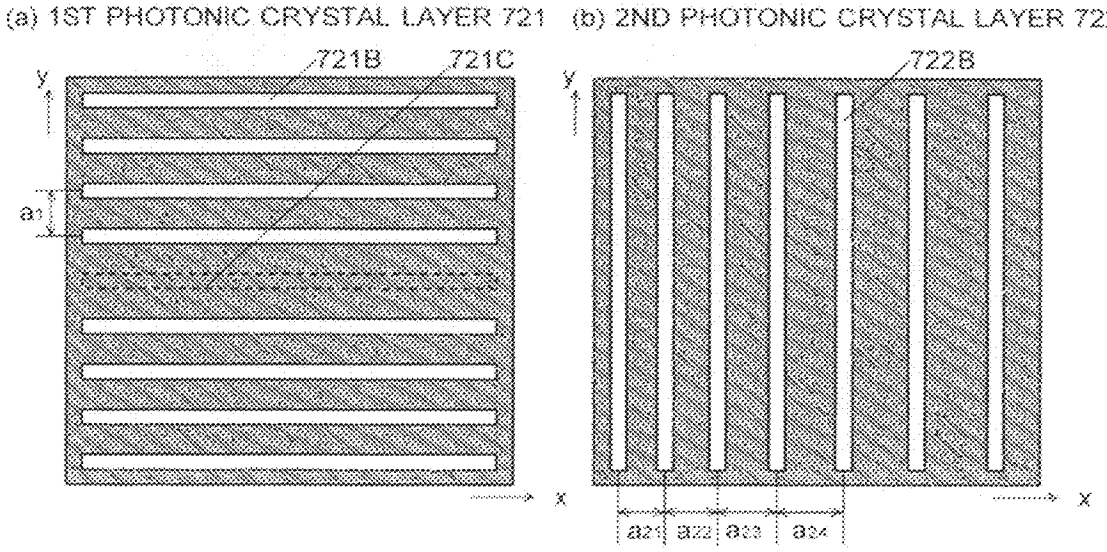

(a) 1ST PHOTONIC CRYSTAL LAYER 621
(b) 2ND PHOTONIC CRYSTAL LAYER 622
621A
621B
622A
622B
622C
y
x
y
x

Fig. 24


(a) 1ST PHOTONIC CRYSTAL LAYER 721
(b) 2ND PHOTONIC CRYSTAL LAYER 722
721B
721C
722B
y
x
y
x
a1
a21
a22
a23
a24

PHOTONIC CRYSTAL LASER

TECHNICAL FIELD

The present invention relates to a laser capable of emitting multiple beams. Such a laser can be used, for example, as a light source for recording or reproducing information by means of an optical disk.

BACKGROUND ART

In a device for recording information onto an optical disk or reproducing information from an optical disk, when a single recording/reproducing laser beam is delivered onto a track in which information is to be recorded or has been recorded, two position-detecting laser beams that are symmetrical with respect to the recording/reproducing laser beam are also delivered onto the same track. These beams are generated by splitting a single laser beam from one light source (i.e. a laser) with a diffraction grating (for example, refer to Patent Document 1 and Non-Patent Document 1).

A single laser light source generally emits a single laser beam in a specific direction. Therefore, if multiple laser beams are required, it is necessary to use a diffraction grating or similar dispersing element to split one laser beam emitted from the light source, or provide two or more light sources.

Accordingly, if multiple laser beams can be generated from a single element, the diffraction grating will no longer be necessary, so that the device will be downsized and its production cost will be decreased.

On the other hand, it is known that a laser using a two-dimensional photonic crystal normally emits a single laser beam in a direction perpendicular to the two-dimensional photonic crystal (for example, refer to Patent Document 2) yet allows the emitting direction of the laser beam to be controlled by appropriately shaping the holes created in the two-dimensional photonic crystal (refer to Non-Patent Document 2). This is because an appropriately shaped hole improves the light-confining property (which is represented by a $Q_{//}$ value) with respect to the direction parallel to the two-dimensional photonic crystal in a photonic band in which the group velocity becomes zero when the component $k_{//}$ of the wave number vector parallel to the two-dimensional photonic crystal is at a non-Γ point, i.e. when $k_{//}$ is not zero.

However, Non-Patent Document 2 makes no mention as to the number of laser beams emitted from the laser and thereby offers little help in the development of a device that requires multiple laser beams (e.g. the aforementioned optical disk recording/reproducing device).

Patent Document 1: U.S. Pat. No. 3,876,842

Patent Document 2: Japanese Unexamined Patent Application Publication No. 2000-332351

Non-Patent Document 1: Ryoichi Ito and Michiharu Nakamura, *Handoutai Rehza [Kiso To Ouyou]* (*Semiconductor Laser [Basics and Applications]*), pp. 305-306, published Apr. 25, 1989, Baifukan Co., Ltd, Tokyo

Non-Patent Document 2: Eiji Miyai et al., "Fotonikku Kesshou Men Hakkou Rehza No Gamma-Ten Igai Deno Hasshin No Kanousei No Kentou (Study on the Possibility of the Oscillation of a Photonic Crystal Surface Emitting Laser at a Point other than the Γ Point)", *Preprints of 67th Meeting of Japan Society of Applied Physics* (Issued Aug. 29, 2006), Part 3, p. 968, Japan Society of Applied Physics

DISCLOSURE OF THE INVENTION

Problem to be Solved by the Invention

A problem to be solved by the present invention is to provide a laser capable of emitting multiple laser beams.

The present invention also provides a laser in which the emitting direction of the laser beams is controllable.

Means for Solving the Problems

To solve the aforementioned problem, a photonic crystal laser characterized by comprising:

an active layer for generating light of a predetermined wave number range upon the injection of an electric current;

a first photonic crystal layer for forming a standing wave of light having a first wave number within the aforementioned wave number range, among the light generated in the active layer; and

a second photonic crystal layer for forming a standing wave of light having a second wave number within the aforementioned wave number range and different from the first wave number, among the light generated in the active layer.

The reason why the photonic crystal laser according to the present invention can emit multiple laser beams is hereinafter explained.

Conventional photonic crystal lasers have one active layer and one photonic crystal layer. Among the light generated within the active layer, light having a specific wave number, which depends on the periodic structure of the photonic crystal layer, forms a standing wave within the photonic crystal layer. Thus, only this light having the specific wave number is amplified and causes a laser oscillation. In the case of the photonic crystal laser according to the present invention, the wave number of the standing wave formed within the first photonic crystal layer (the first wave number) differs from that of the standing wave formed within the second photonic crystal layer (the second wave number). Therefore, a spatial beat results from the superposition of these two light. This causes a laser oscillation at a non-Γ point (where $k_{//}$ is not zero), whereby a beam that travels in a direction inclined with respect to a perpendicular to the photonic crystal layer is obtained. If the standing waves are formed in one direction within the photonic crystals, two beams that are respectively inclined forwards and backwards along that direction will result. If the standing waves are formed in two or more directions, two inclined beams will result in each of these directions. Thus, the photonic crystal laser according to the present invention can emit multiple laser beams. Increasing the difference between the first and second wave numbers increases the inclination angle from the perpendicular to the photonic crystal layer.

If a laser oscillation occurs at the Γ point (where the wave number component k// is zero), a beam that travels in the direction perpendicular to the photonic crystal layer is also obtained in addition to the inclined beams. In the following discussion, when both the perpendicular beam and inclined beams are present, the perpendicular beam and inclined beams will be referred to as the "main beam" and "side beams", respectively.

Both the first and second photonic crystal layers may be provided on one side (the same side) of the active layer. However, it is more preferable to provide the first photonic crystal layer on one side of the active layer and the second photonic crystal layer on the other side of the active layer, since a higher degree of structural symmetry leads to a higher efficiency of laser oscillation. In the case where both the first and second photonic crystal layers are provided on one side of the active layer, it is possible to create these two layers as a single component by, for example, providing the first photonic crystal layer on one side of a plate member and the second photonic crystal layer on the other side of the same plate member.

In the photonic crystal laser according to the present invention, the first and second photonic crystal layers may be configured so that the first photonic crystal layer has a periodic distribution of refractive index with a first period, while the second photonic crystal layer has a periodic distribution of refractive index with a second period that differs from the first period. With this configuration, a standing wave having a first wave number corresponding to the first period is formed within the first photonic crystal layer, while a standing wave having a second wave number, which corresponds to the second period and differs from the first wave number, is formed within the second photonic crystal layer.

Each of the first and second photonic crystal layers thus configured can be created by using a two-dimensional photonic crystal including a plate member in which modified refractive index portions whose refractive index differs from that of the plate member are periodically arranged. For example, the modified refractive index portions in the first photonic crystal layer may be arranged on the lattice points of an orthogonal (square or rectangular) lattice or triangular lattice, and the modified refractive index portions in the second photonic crystal layer may be arranged on the same type of lattice as the modified refractive index portions in the first photonic crystal layer.

The first and second photonic crystal layers may be configured so that one of these two layers has its modified refractive index portions arranged in a square lattice pattern while the other layer has its modified refractive index portions arranged in a rectangular lattice pattern, the period of this rectangular lattice in a first direction being equal to the period of the square lattice, and the period of the same rectangular lattice in a second direction perpendicular to the first direction being different from the period of the square lattice. With this configuration, no side beam is emitted in the first direction in which the first and second photonic crystal layers have the same period, while two side beams symmetrical with respect to the main beam are emitted in pairs in the second direction in which the two layers have different periods. The main beam and two side beams in this mode are suitable as a light source for the previously mentioned optical disk recording/reproducing device.

In the case where both the first and second photonic crystal layers have their modified refractive index portions arranged in a rectangular lattice pattern, it is possible to similarly obtain one main beam and two side beams by designing the two layers so that they have different periods in one direction and the same period in other directions. However, in order to achieve the highest possible degree of structural symmetry, it is preferable that, as in the previous case, one of the two photonic crystal layers has its modified refractive index portions arranged in a square lattice pattern.

If both the first and second photonic crystal layers have their modified refractive index portions arranged in a square lattice pattern, it is possible to obtain one main beam surrounded by a total of four side beams emitted at angular intervals of 90 degrees. If both the first and second photonic crystal layers have their modified refractive index portions arranged in a triangular lattice pattern, it is possible to obtain one main beam surrounded by a total of three side beams emitted at angular intervals of 120 degrees.

It is possible that: the first photonic crystal layer is a plate member having a first rod group formed by rods having a refractive index different from that of the plate member, the rods being embedded in the plate member in a pattern parallel to each other and parallel to the plate member; the second photonic crystal layer is a plate member having a second rod group formed by rods having a refractive index different from that of the plate member, the rods being embedded in the plate member in a pattern parallel to each other, parallel to the plate member and perpendicular to the rods of the first rod group; and at least either the first or second rod group has a defect created in the periodic structure thereof.

An operation of a laser using the photonic crystal layers having these rods is now explained. This explanation takes, as an example, the case where a defect is present in the second rod group. (The explanation also applies to the case where a defect is present in the first rod group.) Within the second photonic crystal layer, a standing wave is formed with a wave number component $k_{2\perp}$ in the direction perpendicular to the rods and a wave number component $k_{2//}$ in the direction parallel to the rods, $k_{2//}$ being adequately smaller than $k_{2\perp}$. The standing wave having this wave number component $k_{2//}$ and a standing wave having a wave number $k_{1\perp}(\neq k_{2//})$ formed in the direction perpendicular to the rods within the first photonic crystal layer produce a main beam and two side beams inclined with respect to the main beam.

A photonic crystal laser in which the emitting direction of multiple laser beams is controllable is hereinafter described. (This laser is hereinafter called the "emitting direction variable photonic crystal laser.") In the previously described photonic crystal laser according to the present invention, the emitting direction variable photonic crystal laser according to the present invention is characterized in that:

the second period changes according to the position in the second photonic crystal layer; and

the electric current is injected into only a portion of the active layer, the injection point being controllable.

An operation of the emitting direction variable photonic crystal laser according to the present invention is described next. Injecting an electric current into only a portion ("current injection portion") of the active layer causes a standing wave having a different wave number to be formed and amplified within each of the first and second photonic crystal layers at a portion facing the current injection portion. These light waves are superposed with each other, causing a spatial beat, so that oblique beams are generated as explained earlier. In this process, since the second period changes according to the position in the second photonic crystal layer, the second wave number can be changed by shifting the position of the current injection portion. As explained earlier, the emitting direction of the oblique beams changes depending on the difference between the first and second wave numbers. Therefore, it is possible to control the emitting direction of the oblique beams by changing the second wave number in the previously described manner.

In the emitting direction variable photonic crystal laser according to the present invention, the second photonic crystal layer may have a plurality of areas having different second periods (the modified period areas). In this case, the means for injecting an electric current into the active layer (the current injection means) may be a pair of electrodes between which the active layer, the first photonic crystal layer and the second photonic crystal layer are sandwiched, one of the two electrodes being divided into a plurality of electrode segments for each of the modified period areas. In this mode of the emitting direction variable photonic crystal laser, it is possible to select one of the electrode segments as an electrode for the injection of electric current so as to select a specific modified period area in which a standing wave is to be formed within the second photonic crystal layer, and thereby set the second wave number at a value specific to the selected area. Thus, the emitting direction of the oblique beams can be controlled.

In an example of the second photonic crystal layer having a plurality of modified period areas, the modified period areas

are arranged in a rectangular lattice pattern with lattice points arrayed in two directions intersecting each other in the rectangular lattice, in which (1) the lattice-point interval in one direction varies from one modified period area to another, or (2) the lattice-point intervals in both directions vary from one modified period area to another.

In the emitting direction variable photonic crystal laser according to the present invention, the second photonic crystal layer may have the second period continuously varying within the second photonic crystal layer. In this case, the current injection means may preferably include a pair of electrodes between which the active layer, the first photonic crystal layer and the second photonic crystal layer are sandwiched, one of the two electrodes being divided into a plurality of electrode segments. The use of these electrode segments enables the injection point of the current in the active layer to be controlled by selecting one electrode segment or a plurality of neighboring electrode segments as an electrode for injecting the current into the active layer. Controlling the current injection point in this manner makes it possible to select a specific modified period area in which a standing wave is to be formed within the second photonic crystal layer, and thereby set the second wave number at a value specific to the selected area. Thus, the emitting direction of the oblique beams can be controlled.

In an example of the second photonic crystal layer with a continuously varying second period, the modified period areas are arranged in a rectangular lattice pattern in which (1) the lattice-point interval in one direction of the rectangular lattice continuously varies, or (2) the lattice-point intervals in two directions of the rectangular lattice continuously vary.

Effects of the Invention

With the photonic crystal laser according to the present invention, a plurality of laser beams each traveling in a direction inclined with respect to a perpendicular to the photonic crystal layer can be obtained.

In the case where a laser oscillation occurs at the Γ point (where the wave number component kit is zero), it is possible to generate a main beam traveling in the direction perpendicular to the photonic crystal layers and side beams each traveling in a direction inclined with respect to the main beam by means of a single elemental device without using a diffraction grating or similar element. Such a laser is suitable, for example, for generating a recording/reproducing laser light (main beam) and position-detecting laser light (side beams) in recording information onto an optical disk or reproducing information from an optical disk.

The emitting direction variable photonic crystal laser according to the present invention allows the emitting direction of the side beams to be controlled by changing the injection point of an electric current into the active layer. This emitting direction control can be achieved by only a single laser element without using any mechanical scanning system. Therefore, the emitting direction variable photonic crystal laser according to the present invention is suitable for micro-sized devices that require a laser-beam scan. Examples of such micro-sized devices include a capsulated medical laser knife (i.e. a laser knife enclosed in a capsule to be swallowed by a patient for the purpose of performing medical treatment by scanning the inside of the digestive system with a laser light emitted from the capsule) and a micro-sized display device.

BEST MODES FOR CARRYING OUT THE INVENTION

(1) Configuration of an Embodiment of the Photonic Crystal Laser According to the Present Invention

An embodiment of the photonic crystal laser according to the present invention (a two-dimensional photonic crystal laser) is described using FIGS. **1** to **14**. FIG. **1** is a vertical sectional view of the two-dimensional photonic crystal laser **10** in the present embodiment. This two-dimensional photonic crystal laser **10** has an active layer **11**, which emits light of a predetermined wavelength range when electrons and positive holes are injected into it. On one side (the upper side in the figure) of the active layer **11**, a first photonic crystal layer **121** is provided, with a first carrier-blocking layer **131** in between. On the other side (the lower side in FIG. **1**) of the active layer **11**, a second photonic crystal layer **122** is provided, with a second carrier-blocking layer **132** in between. The configurations of these photonic crystal layers will be described later. Located on the upper side of the first photonic crystal layer **121** is a first cladding layer **141** made of a p-type semiconductor, and located beneath the lower side of the second photonic crystal layer **122** is a second cladding layer **142** made of an n-type semiconductor. The upper side of the first cladding layer **141** is covered by a first contact layer **151**, and the lower side of the second cladding layer **142** is covered by a second contact layer **152**. The first contact layer **151** and second contact layer **152** have a first electrode **161** and second electrode **162** on their surfaces, respectively.

FIG. **2** shows perspective views of the first photonic crystal layer **121** and second photonic crystal layer **122**. The first photonic crystal layer **121** comprises a first plate member **121**A made of a dielectric material in which first air holes **121**B are arrayed in a square lattice pattern. The period of this square lattice is a_1. The second photonic crystal layer **122** comprises a second plate member **122**A made of the same material as that of the first plate member **121**A, in which second air holes **122**B identical in shape to the first air hole **121**B are arrayed in a rectangular lattice pattern. The period of this rectangular lattice in one direction (y-axis direction) is a_1, which equals that of the aforementioned square lattice, whereas the period in the perpendicular direction (i.e. the x-axis direction) is $a_2(\neq a_1)$. The period a_2 may be larger or smaller than a_1. The square lattice and rectangular lattice have their x-axes and y-axes oriented in the same directions.

An example of the material for the active layer **11** is InGaAs. The material for the plate member of both the first photonic crystal layer **121** and second photonic crystal **122** may be GaAs. As the modified refractive index portion, a modified refractive index member whose refractive index differs from that of the plate member may be used instead of the air hole. The air hole is advantageous in that it can be easily manufactured, whereas the modified refractive index member is favorable in the case where the plate member may be deformed due to heat or other factors during the manufacturing process.

(2) Method for Manufacturing the Two-Dimensional Photonic Crystal Laser of the Present Embodiment

A method for manufacturing the two-dimensional photonic crystal laser **10** is described using FIGS. **3** and **4**. FIG. **3** is a vertical sectional view illustrating the manufacturing method according to the present embodiment, and FIG. **4** is a top view of various patterns drawn in a resist used in the manufacturing method of the present embodiment.

Initially, a first substrate **211** is prepared, on which a laminated body **20** is created by layering, in this order, the first etch-stop layer **221**, second plate member **122**A, second carrier-blocking layer **132**, active layer **11**, first carrier-blocking layer **131** and first plate member **121**A (FIG. **3**(*a*)). The laminated body **20** can be created by sequentially forming each layer by MO-CVD (metal organic chemical vapor deposition) or other methods. No air hole is bored in the first plate member **121**A or the second plate member **122**A at this stage.

Next, a first resist **231** is applied to the first plate member **121**A, and a cross mark **251** is drawn at each of the four corners of the first resist **231** (FIG. **4**(*a*)). Then, the laminated body **20** is etched through the cross marks **251** by an inductively coupled plasma (ICP) or the like to create positioning marks **26** penetrating through the laminated body **20** (FIG. **3**(*b*)). After the first resist **231** is removed, a second resist **232** is freshly applied. With positioning marks **26**, which are visible through the second resist **232**, as the reference points, circular holes **271** are drawn at the positions corresponding to the air holes **121**B (FIG. **4**(*b*)). Through these circular holes **271**, the first plate member **121**A is etched by an ICP or the like to create air holes **121**B in the first plate member **121**A. Thus, the first photonic crystal layer **121** is completed (FIG. **3**(*c*)). After that, the second resist **232** is removed.

Separately, the second etch-stop layer **222**, first contact layer **151**, first cladding layer **141** and first fusion layer **121**C, which is made of the same material as that of the plate member **121**A, are formed in this order on a second substrate **212**, and then the first plate member **121**A and the first fusion layer **121**C are fused together (FIG. **3**(*d*)). Then, the first substrate **211** is removed by abrading and wet-etching processes, and further, the first etch-stop layer **221** is removed with a different etching agent (FIG. **3**(*e*)). Subsequently, a third resist **233** is applied to the surface of the second plate member **122**A, which has been exposed as a result of removing the first substrate **211** and first etch-stop layer **221**. With positioning marks **26**, which are visible through the third resist **233**, as the reference points, circular holes **272** are drawn at the positions corresponding to the air holes **122**B (FIG. **4**(*c*)) so that the positions of the columns of the air holes **121**B in the x-axis direction (FIG. **2**) coincide with those of the air holes **122**B. Through these circular holes **272**, the second plate member **122**A is etched by an ICP or the like to create air holes **122**B in the second plate member **122**A. Thus, the second photonic crystal layer **122** is completed (FIG. **3**(*f*)). After that, the third resist **233** is removed.

Separately, the second cladding layer **142** and the second fusion layer **122**C, which is made of the same material as that of the second plate member **122**A, are formed in this order on a third substrate **213** made of the same material as that of the second contact layer **152**, and then the second plate member **122**A and the second fusion layer **122**C are fused together (FIG. **3**(*g*)). Then, the second substrate **212** is removed by abrading and wet-etching processes, and further, the second etch-stop layer **222** is removed with a different etching agent. Subsequently, the third substrate **213** is mirror polished until its thickness is reduced to a predetermined thickness. The third substrate **213** with its thickness thus reduced becomes the second contact layer **152**. Furthermore, a first electrode **161** is created on the surface of the first contact layer **151**, and a second electrode **162** on the surface of the second contact layer **152**. Thus, the two-dimensional photonic crystal laser **10** is completed (FIG. **3**(*h*)).

(3) Operation of the Two-Dimensional Photonic Crystal Laser of the Present Embodiment

In the two-dimensional photonic crystal laser of the present embodiment, when a voltage is applied between the first electrode **161** and the second electrode **162**, electrons and positive holes are supplied into the active layer **11**. These electrons and positive holes recombine together, emitting light with a predetermined wavelength range. This light is introduced into both the first photonic crystal layer **121** and the second photonic crystal layer **122**. In these layers, light having a wave number k_1 corresponding to the period of the modified refractive index portions in the first photonic crystal layer **121** is amplified within the first photonic crystal layer **121**, while another light having a wave number k_2, which corresponds to the period of the modified refractive index portions in the second photonic crystal layer **122** and differs from the wave number k_1, is amplified within the second photonic crystal layer **122**. These light having the wave numbers k_1 and k_2 generate a spatial beat of light. As a result, a laser oscillation occurs at a non-Γ point ($k_{//}\neq 0$) and oblique side beams are produced.

The process of generating oblique side beams is hereinafter described using a specific example. The following description deals with the case where $a_1=a$ and $a_2=1.02a$ in the two-dimensional photonic crystal laser **10**. In this case, since the period a_1 of the first photonic crystal layer **121** differs from the period a_2 of the second photonic crystal layer **122**, a standing wave having a different wave number is formed in each of these two-dimensional photonic layers. These standing waves are superposed with each other, causing a spatial beat in the x-directional component E_x of the electric field strength. FIG. **5** shows E_x at a specific point in time, calculated by a finite difference time domain (FDTD) method. The calculated result demonstrates that E_x has a spatial beat with a period $a_b\sim 51a$. The calculated period a_b of the spatial beat satisfies the relationship expressed as $1/a_1-1/a_2=1/a_b$. Fourier transformation of the calculated value E_x yields a spectrum of k_x, i.e. the x-component of the wave number. The result of the Fourier transformation of E_x obtained in FIG. **5** is shown in FIG. **6**. This figure shows the result only for positive values of k_x; a similar result will also be obtained for negative values of k_x. This graph shows a peak located at $k_x=\pm 0.0196\times(2\pi/a)$ and a weaker peak located at $k_x=\pm 0.0392\times(2\pi/a)$. In regard to the y-component k_y of the wave number, the peak appears only when $k_y=0$ since there is no difference in the y-directional period between the two-dimensional photonic crystal layers.

Letting θ denote the angle between a line perpendicular to the two-dimensional photonic crystal layer and the wave vector, θ and k_x satisfy the following relationship (FIG. **7**):

$$k_x=k\sin\theta=(a/\lambda)\sin\theta \quad (1).$$

In the present case, λ=980 nm (the wavelength of light generated by the active layer **11** made of InGaAs), a=296 nm (the period of a two-dimensional photonic crystal that can amplify light having the aforementioned wavelength λ in the case where the plate member is made of GaAs), and k_x is the wave number at which a peak is located in FIG. **6**. Substituting these values into equation (1) shows that side beams are produced in the directions θ=3.8° ($k_x=0.0196\times(2\pi/a)$) and θ=7.6° ($k_x=0.0392\times(2\pi/a)$).

In FIG. **6**, the peak corresponding to the main beam, i.e. a laser beam that is emitted in the direction perpendicular to the two-dimensional photonic crystal (θ=0, k=0), is hardly recognizable. This is because FIG. **6** shows a spectrum at a specific point in time where the peak at $k_x=0.0196\times(2\pi/a)$ is maximized. However, a clear peak actually also appears at k=0 at other points in time. FIG. **8** shows a temporal change of peak value calculated for a Fourier transform image of E_x at $k_x=0$, $0.0196\times(2\pi/a)$ and $0.0392\times(2\pi/a)$. The strength of actually emitted laser light corresponds to the magnitude of

the time-averaged value of this calculated result. This result shows that the strongest laser beam is $k_x=0$, i.e. the main beam, and the second strongest laser beam is the side beam generated at $k_x=0.0196\times(2\pi/a)$.

FIG. **9** shows the spatial distribution of E_x calculated for $a_1=a$ and $a_2=1.04a$ in the two-dimensional photonic crystal laser **10**, and FIG. **10** shows a Fourier transform image of the spatial distribution of E_x. In this example, a peak is observed at $k_x=0.0392\times(2\pi/a)$. Accordingly, from equation (1) it can be demonstrated that a side beam is generated in the direction of $\theta=7.6°$.

(4) Experimental Example of the Two-Dimensional Photonic Crystal Laser **10**

Two types of the two-dimensional photonic crystal laser **10** were manufactured with (a) $a_2=1.06a_1$ (0.305 μm) and (b) $a_2=1.08a_1$ (0.311 μm), where $a_1=0.288$ μm, and an experiment was conducted to take a photograph of the far-field pattern of the laser beams. The far-field patterns obtained in this experiment are shown in FIG. **11**. Two oblique beams were observed in either of (a) and (b). An estimation of 2θ from the distance between the two oblique beams resulted in $2\theta=9.5°$ for (a) and $2\theta=14.4°$ for (b). In addition, the spectrums of the laser lights thereby obtained are shown in FIG. **12**. In either of (a) $a_2=1.06a_1$ and (b) $a_2=1.08a_1$, the resultant laser light was a single-wavelength light with the central wavelength at (a) 973.5 nm or (b) 973.8 nm.

(5) Example of Embodiments Other than the Two-Dimensional Photonic Crystal Laser **10**

The configuration of the two-dimensional photonic crystal laser according to the present invention is not limited to the previously described embodiment (i.e. the two-dimensional photonic crystal laser **10**). For example, the two-dimensional photonic crystal layer **122** having a rectangular lattice may be replaced by a two-dimensional photonic crystal layer having a square lattice with a period a_2. This configuration provides a two-dimensional photonic crystal laser in which a spatial beat is generated in both the x and y directions so that a side beam inclined in the x-direction and a side beam inclined in the y-direction are emitted. It is also possible to set the x-directional period at a_2 and y-directional period at $a_3(\neq a_1, a_2)$ to obtain a two-dimensional photonic crystal laser that emits a side beam inclined in the x-direction and a side beam inclined in the y-direction by an angle different from that of the side beam in the x-direction. It is also possible to provide both the first and second photonic crystal layers on the upper (or lower) side of the active layer.

(6) Application Example of the Two-Dimensional Photonic Crystal Laser According to the Present Invention

As an application example of the two-dimensional photonic crystal laser according to the present invention, an optical disk recording/reproducing device **30** is described using FIGS. **13** and **14**. FIG. **13**(*a*) is a schematic configuration diagram of the optical disk recording/reproducing device **30** using a two-dimensional photonic crystal laser **31** according to the present invention. FIG. **13**(*b*) is a schematic configuration diagram of a conventional optical disk recording/reproducing device **30**P. This conventional optical disk recording/reproducing device **30**P is the one disclosed in Patent Document 2 and Non-Patent Document 2.

The optical disk recording/reproducing device **30** includes a two-dimensional photonic crystal laser **31** according to the present invention, which emits a main beam **360** with a first side beam **361** and second side beam **362** that are symmetrical with respect to the axis of the main beam **360**. For example, the two-dimensional photonic crystal laser **10** in the previous embodiment can be used as the two-dimensional photonic crystal laser **31**. The optical disk recording/reproducing device **30** also includes an optical system **33**, which consists of a lens and other components for delivering the main beam **360**, first side beam **361** and second side beam **362** from the two-dimensional photonic crystal laser **31** onto an optical disk **39**, and a detector **34** for detecting a laser light reflected by the optical disk **39**. The optical system **33** includes a track follow-up mirror **331** that can be moved for adjusting the spot position of the laser beam focused on the optical disk **39**.

An operation of this optical disk recording/reproducing device **30** is described. The description mainly focuses on the operation for making the main beam **360** follow up the track of the optical disk. The main beam **360**, first side beam **361** and second side beam **362**, all being emitted from the two-dimensional photonic crystal laser **31**, are focused onto the record surface of the optical disk **39** by the optical system **33**, then reflected by the record surface, and ultimately detected by the detector **34**. Since the shape of the information track **37** on the record surface is bilaterally symmetrical, the strengths of the first and second side beams **361** and **362** thereby detected will be equal to each other when the main beam **360** is correctly focused on the center of the information track **37** (FIG. **14**(*a*)) or different from each other when the main beam **360** is displaced from the center (FIG. **14**(*b*)). When a displacement is detected, it is possible to correct the focusing position of the main beam **360** by moving the track follow-up mirror **331** so that the detected strengths of the first and second side beams **361** and **362** will be equal to each other.

On the other hand, the conventional optical disk recording/reproducing device **30**P includes a laser **32**A emitting only a single beam, and a diffraction grating **32**B for diffracting the single beam into three beams. The other components are identical to those of the previously described optical disk recording/reproducing device **30**. Thus, the optical disk recording/reproducing device **30** in the present embodiment, which does not require the diffraction grating, is more suited for the miniaturization and cost reduction of the device.

(7) First Embodiment of the Emitting Direction Variable Photonic Crystal Laser According to the Present Invention

An emitting direction variable photonic crystal laser **40** as the first embodiment is described using FIGS. **15** and **16**. FIG. **15** is a vertical sectional view of the emitting direction variable photonic crystal laser **40**. This emitting direction variable photonic crystal laser **40** includes an active layer **11**, first carrier-blocking layer **131**, second carrier-blocking layer **132**, first cladding layer **141**, second cladding layer **142**, first contact layer **151** and second contact layer **152**. These layers are identical to those of the previous two-dimensional photonic crystal laser **10**. Furthermore, the present laser has a first photonic crystal layer **421** on one side (upper side) of the active layer **11**, with the first carrier-blocking layer **131** in between, and a second photonic crystal layer **422** on the other side (lower side) of the active layer **11**, with the second carrier-blocking layer **132** in between. The first photonic crystal layer **421** is structurally identical to that of the previous two-dimensional photonic crystal **10**, whereas, as will be described later, the second photonic crystal layer **422** is struc-

turally different from the second photonic crystal layer **122** in the previous two-dimensional photonic crystal **10**.

The second photonic crystal layer **422** has a first modified period area **4221**, second modified period area **4222**, third modified period area **4223**, and so on in a plate member **422**A. In each modified period area, air holes (modified refractive index portions) **422**B are arranged with a period that differs from those of the other modified period areas. In the present embodiment, the air holes **422**B have a circular horizontal shape and are arranged in a rectangular lattice pattern in the plate member **422**A, as shown by the top view in FIG. **16**(*a*). The period of the rectangular lattice in one direction (y-axis direction) is a_1, which equals that of the first photonic crystal layer **421**, whereas the period in the perpendicular direction (x-axis direction) is a_{21} in the first modified period area **4221**, a_{22} in the second modified period area **4222**, a_{23} in the third modified period area **4223**, and so on.

A first upper electrode **4611**, second upper electrode **4612**, third upper electrode **4612**, and so on are provided on the upper surface of the first contact layer **151** and directly above the first modified period area **4221**, second modified period area **4222**, third modified period area **4223**, and so on. One lower electrode **462** is provided on the lower surface of the second contact layer **152**.

An operation of the emitting direction variable photonic crystal laser **40** in the first embodiment is now described. Firstly, a voltage is applied between one of the upper electrodes (the first upper electrode **4611**, second upper electrode **4612**, third upper electrode **4613**, and so on) and the lower electrode **462**. The following explanation assumes that the voltage is initially applied between the first upper electrode **4611** and the lower electrode **462**. Due to this voltage application, electrons and positive holes are supplied into the portion of the active layer **11** located directly below the first upper electrode **4611**, and an emission of light with a predetermined wavelength range occurs within that portion. This light is introduced into the first photonic crystal layer **421** and also the first modified period area **4221** of the second photonic crystal layer **422** located directly below the first upper electrode **4611**. Then, light having a wave number k_1 corresponding to the period a_1 is amplified within the first photonic crystal layer **421**, and simultaneously another light having a wave number $k_{21}(\neq k_1)$ corresponding to the x-directional period a_{21} is also amplified in the x-direction within the first modified period area **4221**. As a result, a spatial beat of light is generated, and side beams each being inclined in the x-direction by an angle corresponding to the difference in the wave number are emitted, as in the case of the two-dimensional photonic crystal laser **10**.

Secondly, the upper electrode to which the voltage is applied is switched from the first upper electrode **4611** to another upper electrode (which is the second upper electrode **4612** in the present case). Then, as in the case of the first upper electrode **4611**, light having a wave number $k_{22}(\neq k_1, k_{21})$ corresponding to the x-directional period $a_{22}(\neq a_{21})$ is amplified in the x-direction within the second modified period area **4222** located directly below the second upper electrode **4612**. Since the light thus amplified has a wave number that differs from that of the light generated in the case where the first upper electrode **4611** was used, the inclination angle of the resultant side beams in the x-direction will be different from the angle observed in the case where the first upper electrode **4611** was used. Applying the voltage between the lower electrode **462** and the third upper electrode **4613** or any other electrode will similarly produce side beams each being inclined in the x-direction by an angle that corresponds to the period of the modified period area located directly below the newly selected upper electrode and therefore differs from the angle observed in the case where any other upper electrode was used.

Other examples of the configuration of the second photonic crystal layer **422** are shown by the plan views in FIGS. **16**(*b*) to **16**(*d*). In case (b), all the modified period areas have the period a_1 in the x-direction, which equals the period of the first photonic crystal layer **421**, whereas the period in the y-direction varies from one modified period area to another, such as a_{21}, a_{22}, a_{23} and so on. In this case, when the upper electrode to which the voltage is applied is switched, side beams that are inclined in the y-direction by an angle corresponding to the period of the modified period area located directly below the newly selected upper electrode are produced. In case (c), the period in the x-direction equals the period in the y-direction in every modified period area (i.e. the square lattice), and this period varies from one modified period area to another. In this case, when the upper electrode to which the voltage is applied is switched, side beams are produced in both the x and y directions, each side beam being inclined in the x or y direction by an angle corresponding to the period of the modified period area located directly below the newly selected upper electrode. In case (d), the air holes having a circular horizontal shape in case (a) have been changed to air holes having an equilaterally triangular horizontal shape. This change in the shape of the air holes does not affect the emitting direction of the side beams.

In the previous examples, only the upper electrodes were separately provided for each modified period area. However, it is possible to separately provide only the lower electrodes for each modified period area, or both the upper and lower electrodes for each modified period area.

(8) Second Embodiment of the Emitting Direction Variable Photonic Crystal Laser According to the Present Invention

An emitting direction variable photonic crystal laser **50** as the second embodiment is described using FIGS. **17** to **20**. FIG. **17** is a vertical sectional view of the emitting direction variable photonic crystal laser **50**. This emitting direction variable photonic crystal laser **50** is structurally identical to the emitting direction variable photonic crystal laser **40** of the first embodiment except that it includes a second photonic crystal layer **522** and upper electrodes (which will be described later) in place of the photonic crystal layer **422** and upper electrodes used in the emitting direction variable photonic crystal laser **40**.

As shown by the top view in FIG. **18**, the second photonic crystal layer **522** comprises a plate member **522**A in which circular air holes **522**B are arranged in an orthogonal lattice pattern. The arrangement period of the air holes **522**B in the y-direction is a_1, which equals that of the air holes in the first photonic crystal layer **421**, whereas their arrangement period in the x-direction continuously changes; the distances a_{21}, a_{22}, a_{23} . . . between the neighboring air holes in the x-direction gradually increase in the positive direction ($a_{21}<a_{22}<a_{23}<\ldots$). For example, if the distance between the neighboring air holes is increased in steps of 0.1% in the positive direction, the distance values at two points intervened by 100 air holes will have a 10% difference.

The upper electrode **561** is divided into a large number of electrodes (the first upper electrode **5611**, second upper electrode **5612** and so on) arrayed in the x-direction on the first contact layer **151** (FIG. **17**).

An operation of the emitting direction variable photonic crystal laser **50** is described using FIG. **19**. Firstly, a voltage is

applied between two or more neighboring upper electrodes **561** and the lower electrode **462**. For example, suppose that the voltage is applied between three electrodes (the first upper electrode **5611**, second upper electrode **5612** and third upper electrode **5613**) and the lower electrode **462** (FIG. **19**(*a*)). Due to this voltage application, electrons and positive holes are supplied into the portion directly below the first, second and third upper electrodes **5611** to **5613** (this portion is called the first current supply area **571**), and an emission of light with a predetermined wavelength range occurs within that portion. This light is introduced into the first photonic crystal layer **421** and also the portion of the second photonic crystal layer **522** located directly below the first, second and third upper electrodes **5611** to **5613** (this portion is called the first light-amplifying area **581**). Then, light having a wave number k_1 corresponding to the period a_1 is amplified within the first photonic crystal layer **421**, and simultaneously light having a wave number corresponding to the average period in the first light-amplifying area **581** is also amplified within the second photonic crystal layer **522**. Due to a difference in the period in the x-direction, the wave number of the light amplified within the second photonic crystal layer **522** in the x-direction differs from the wave number k_1 in the first photonic crystal layer **421**. As a result, a spatial beat of light is generated, and side beams each being inclined in the x-direction by an angle corresponding to the difference in the wave number are produced.

Secondly, the upper electrodes being used for applying the voltage are changed to the second upper electrode **5612**, third upper electrode **5613** and fourth upper electrode **5614** (FIG. **19**(*b*)). As a result, the current supply area and light-amplifying area are shifted in the x-direction (the second current supply area **572** and second light-amplifying area **582**). The average period of the second photonic crystal layer **522** in the second light-amplifying area **582** differs from the period in the first light-amplifying area **581**. Therefore, the shift of the light-amplifying area changes the wave number of the light amplified within the second photonic crystal layer **522** and further the inclination angle of the side beam, which depends on the wave number. It is possible to continuously change the inclination angle of the side beam in a similar manner by changing the upper electrodes being used for the voltage application so as to sequentially shift the light-amplifying area.

FIG. **20** shows another example of the second photonic crystal layer **522** (the second photonic crystal layer **522**X) in the emitting direction variable photonic crystal laser **50** of the second embodiment. The second photonic crystal layer **522**X is designed so that the distance of the neighboring air holes gradually increases in the positive direction of the y-direction ($a_{21}<a_{22}<a_{23}<\ldots$) as well as in the positive direction of the x-direction ($a_2<a_{22}<a_{23}<\ldots$). As a result, oblique side beams are generated in each of the x and y directions. In the case of using this second photonic crystal layer **522**X, it is necessary to use an upper electrode that is divided in both x and y directions. In addition, the shape of the air holes, which was circular in the second photonic crystal layer **522** or **522**X, may be an equilateral triangle or any other shape.

As described thus far, the emitting direction variable photonic crystal laser according to the present invention emits multiple laser beams. If only a portion **491** of these multiple beams needs to be used, the other beams **493** can be blocked with a blocking member **492** (FIG. **21**). For example, if an angular range from θ_a to θ_b is to be scanned with a single side beam (the first side beam **491**) as shown in FIG. **21**, the objective can be achieved by orienting the emitting direction variable photonic crystal laser **49** so that the perpendicular **493** to the photonic crystal layer is inclined from the center of the scan range by $(\theta_a+\theta_b)/2$ and setting a blocking plate **492** in the direction in which unnecessary beams are emitted.

(9) Example of a Photonic Crystal Laser Using a Photonic Crystal Comprising a Plate Member in Which Rods Are Arranged in One Direction

FIG. **22** is a vertical sectional view of a photonic crystal laser **60** using a photonic crystal comprising a plate member in which rods are arrayed in one direction. FIG. **23** is a cross sectional view of the first photonic crystal layer **621** and second photonic crystal layer **622** in the photonic crystal laser **60**. The first photonic crystal layer **621** comprises a first plate member **621**A in which a large number of rod-shaped air holes **621**B extending in the x-direction are periodically arranged along the y-direction. On the other hand, the second photonic crystal layer **622** comprises a second plate member **622**A in which a large number of rod-shaped air holes **622**B extending in the y-direction are periodically arranged along the x-direction. Furthermore, a defect **622**C is created in the rods of the second plate member **622**A by omitting one rod corresponding to one period. The other configurations are identical to those of the previously described photonic crystal laser **10**.

The photonic crystal laser **60** in the present embodiment is identical to the photonic crystal lasers in the other embodiments in that an injection of an electric current from the first electrode **161** and second electrode **162** into the active layer **11** generates light and this light is introduced into the first photonic crystal layer **621** and second photonic crystal layer **622**. The light introduced into the first photonic crystal layer **621** forms a y-directional standing wave due to the periodicity of the rod-shaped air holes **621**B in the y-direction. By contrast, the light introduced into the second photonic crystal layer **622** form a standing wave not only in the x-direction, in which the rod-shaped air holes **622**B has a periodicity, but also in the y-direction due to the presence of the defect **622**C of the rods. As a result, a beat is generated from the y-directional standing wave within the first photonic crystal layer **621** and the y-directional component of the standing wave within the second photonic crystal layer **622**, so that a main beam and two side beams that are inclined in the y-direction with respect to the main beam are produced.

The photonic crystal comprising a plate member in which rods are arrayed in one direction can also be used in the emitting direction variable photonic crystal laser. For example, as show in FIG. **24**, it is possible to use a first photonic crystal layer **721** in which rod-shaped air holes **721**B extending in the x-direction are arranged at equal intervals a_1 along the y-direction, with a defect **721**C of the rods, and a second photonic crystal layer **722** in which rod-shaped air holes **722**B extending in the y-direction are arranged along the x-direction with their intervals gradually increasing in the positive direction ($a_{21}<a_{22}<a_{23}<\ldots$). Use of these layers enables the emitting direction of the side beams to be controlled as in case of the emitting direction variable photonic crystal laser in the second embodiment.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a vertical sectional view of a two-dimensional photonic crystal laser **10** according to one embodiment of the present invention.

FIGS. **2**(*a*) and **2**(*b*) are perspective views of a first photonic crystal layer **121** and second photonic crystal layer **122** in the two-dimensional photonic crystal laser **10**.

FIG. **3** is a vertical sectional view illustrating a method of manufacturing the two-dimensional photonic crystal laser **10**.

FIG. **4** is a top view of various patterns each drawn in a resist used in the manufacturing method of the present embodiment.

FIG. **5** is a graph showing the result of a calculation of the x-directional component E_x of an electric field strength in the case of a_1=a and a_2=1.02a.

FIG. **6** is a graph showing the result of a calculation of a Fourier transformation image of E_x in the case of a_1=a and a_2=1.02a.

FIG. **7** is a diagram showing the relationship between an emission angle θ and the x-directional component k_x of a wave number.

FIG. **8** is a graph showing a temporal change of each peak value calculated in the case of a Fourier transform image of E_x in the case of a_1=a and a_2=1.02a.

FIG. **9** is a graph showing the spatial distribution of E_x calculated in the case of a_1=a and a_2=1.04a.

FIG. **10** is a graph showing a Fourier transform image of the spatial distribution of E_x calculated in the case of a_1=a and a_2=1.04a.

FIGS. **11**(*a*) and **11**(*b*) are photographs of side beams obtained in an experiment for the two-dimensional photonic crystal laser **10** with a_1=a and a_2=1.06a and 1.08a.

FIGS. **12**(*a*) and **12**(*b*) are spectrums of side beams obtained in an experiment for the two-dimensional photonic crystal laser **10** with a_1=a and a_2=1.06a and 1.08a.

FIG. **13**(*a*) is a schematic configuration diagram of an example of the optical disk recording/reproducing device using a two-dimensional photonic crystal laser according to the present invention, and FIG. **13**(*b*) is a schematic configuration diagram of an example of conventional optical disk recording/reproducing devices.

FIG. **14** is a schematic diagram for explaining an operation of an optical disk recording/reproducing device.

FIG. **15** is a vertical sectional view of the emitting direction variable photonic crystal laser **40** as a first embodiment.

FIG. **16** is a plan view of the second photonic crystal layer **422** in the emitting direction variable photonic crystal laser **40**.

FIG. **17** is a vertical sectional view of the emitting direction variable photonic crystal laser **50** as a second embodiment.

FIG. **18** a plan view of the second photonic crystal layer **522** in the emitting direction variable photonic crystal laser **50**.

FIG. **19** is a vertical sectional view for explaining an operation of the emitting direction variable photonic crystal laser **50**.

FIG. **20** is a plan view showing another example of the second photonic crystal layer **522**.

FIG. **21** is a schematic diagram showing an example of a method for blocking a portion of the laser beams.

FIG. **22** is a vertical sectional view of a photonic crystal laser **60** using a photonic crystal comprising a plate member in which rods are arrayed in one direction.

FIG. **23** a cross sectional view of the photonic crystal layers in the photonic crystal laser **60**.

FIG. **24** is a cross sectional view showing an example of photonic crystals for use in a emitting direction variable photonic crystal laser, each photonic crystal comprising a plate member in which rods are arranged in one direction.

EXPLANATION OF NUMERALS

10, **31**, **60** . . . Photonic Crystal Laser
11 . . . Active Layer
121, **421**, **521**, **621**, **721** . . . First Photonic Crystal Layer
121A . . . First Plate Member
121B . . . First Air Hole
121C. First Fusion Layer
122, **422**, **522**, **522**X, **622**, **722** . . . Second Photonic Crystal Layer
122A . . . Second Plate Member
122B . . . Second Air Hole
122C . . . Second Fusion Layer
131 . . . First Carrier-Blocking Layer
132 . . . Second Carrier-Blocking Layer
141 . . . First Cladding Layer
142 . . . Second Cladding Layer
151 . . . First Contact Layer
152 . . . Second Contact Layer
161 . . . First Electrode
162 . . . Second Electrode
20 . . . Laminated Body
211 . . . First Substrate
212 . . . Second Substrate
213 . . . Third Substrate
221 . . . First Etch-Stop Layer
222 . . . Second Etch-Stop Layer
231 . . . First Resist
232 . . . Second Resist
233 . . . Third Resist
251 . . . Cross Mark
26 . . . Positioning Mark
271, **272** . . . Circular Hole
30 . . . Optical Disk Recording/Reproducing Device
30P . . . Conventional Optical Disk Recording/Reproducing Device
32A . . . Laser
32B . . . Diffraction Grating
33 . . . Optical System
331 . . . Track Follow-Up Mirror
34 . . . Detector
360 . . . Main Beam
361 . . . First Side Beam
362 . . . Second Side Beam
37 . . . Information Track
39 . . . Optical Disk
40, **50** . . . Emitting Direction Variable Photonic Crystal Laser
422A, **522**A . . . Plate Member
422B, **522**B . . . Air Hole
4221 . . . First Modified Period Area
4222 . . . Second Modified Period Area
4223 . . . Third Modified Period Area
4611 . . . First Upper Electrode
4612 . . . Second Upper Electrode
4613 . . . Third Upper Electrode
462 . . . Lower Electrode
561 . . . Upper Electrode
5611 . . . First Upper Electrode
5612 . . . Second Upper Electrode
5613 . . . Third Upper Electrode
5614 . . . Fourth Upper Electrode
571 . . . First Current Supply Area
572 . . . Second Current Supply Area
581 . . . First Light-Amplifying Area
582 . . . Second Light-Amplifying Area
621A . . . First Plate Member
622A . . . Second Plate Member
621B, **622**B, **721**B, **722**B . . . Rod-Shaped Air Hole
622C, **721**C . . . Defect of Rod-Shaped Air Hole

The invention claimed is:

1. A photonic crystal laser comprising:

an active layer for generating light of a predetermined wave number range upon an injection of an electric current;

a first photonic crystal layer for forming a standing wave of light within the first photonic crystal layer having a first wave number within the predetermined wave number range, among the light generated in the active layer; and

a second photonic crystal layer for forming a standing wave of light within the second photonic crystal layer having a second wave number within the predetermined wave number range and different from the first wave number, among the light generated in the active layer, wherein

the first photonic crystal layer is provided on one side of the active layer, and the second photonic crystal layer is provided on the other side of the active layer, and

a spatial beat results from a superposition of the standing wave of light formed by the first photonic crystal layer and the standing wave of light formed by the second photonic crystal layer.

2. The photonic crystal laser according to claim **1**, wherein the first photonic crystal layer has a periodic distribution of refractive index with a first period, while the second photonic crystal layer has a periodic distribution of refractive index with a second period that differs from the first period.

3. The photonic crystal laser according to claim **2**, wherein each of the first and second photonic crystal layers is a two-dimensional photonic crystal including a plate member in which modified refractive index portions whose refractive index differs from that of the plate member are periodically arranged.

4. The photonic crystal laser according to claim **3**, wherein:

the modified refractive index portions in the first photonic crystal layer are arranged on lattice points of an orthogonal lattice or triangular lattice; and

the modified refractive index portions in the second photonic crystal layer are arranged on a same type of lattice as the modified refractive index portions in the first photonic crystal layer.

5. The photonic crystal laser according to claim **4**, wherein the first and second photonic crystal layers are configured so that one of these two layers has its modified refractive index portions arranged in a square lattice pattern while the other layer has its modified refractive index portions arranged in a rectangular lattice pattern, the period of this rectangular lattice in a first direction being equal to the period of the square lattice, and the period of the same rectangular lattice in a second direction perpendicular to the first direction being different from the period of the square lattice.

6. The photonic crystal laser according to claim **2**, wherein:

the first photonic crystal layer is a first plate member defined by an X-Y plane and having a first rod group formed by rods having a refractive index different from that of the first plate member, the rods being embedded in the first plate member in a pattern parallel to each other in a first direction and parallel to the X-Y plane;

the second photonic crystal layer is a second plate member defined by the X-Y plane and having a second rod group formed by rods having a refractive index different from that of the second plate member, the rods being embedded in the second plate member in a pattern parallel to each other in a second direction and parallel to the X-Y plane, and perpendicular to the rods of the first rod group; and

at least either the first or second rod group has a defect created in a periodic structure thereof.

7. The photonic crystal laser according to claim **2** wherein:

a current injection means for injecting the electric current into only a portion of the active layer is provided, an injection point thereof being controllable; and

the second period of the second photonic crystal layer changes according to a position within the same layer.

8. The photonic crystal laser according to claim **7**, wherein:

the second photonic crystal layer has a plurality of modified period areas having different second periods; and

the current injection means includes a pair of electrodes between which the active layer, the first photonic crystal layer and the second photonic crystal layer are sandwiched, one of the two electrodes being divided into a plurality of electrode segments for each of the modified period areas.

9. The photonic crystal laser according to claim **8**, wherein the modified period areas are arranged in a rectangular lattice pattern with lattice points arrayed in two directions intersecting each other in the rectangular lattice, in which a lattice-point interval in one direction varies from one modified period area to another.

10. The photonic crystal laser according to claim **8**, wherein the modified period areas are arranged in a rectangular lattice pattern with lattice points arrayed in two directions intersecting each other in the rectangular lattice, in which lattice-point intervals in both directions vary from one modified period area to another.

11. The photonic crystal laser according to claim **7**, wherein the second period continuously varies within the second photonic crystal layer.

12. The photonic crystal laser according to claim **11**, wherein the current injection means includes a pair of electrodes between which the active layer, the first photonic crystal layer and the second photonic crystal layer are sandwiched, one of the two electrodes being divided into a plurality of electrode segments.

13. The photonic crystal laser according to claim **11**, wherein the modified period areas are arranged in a rectangular lattice pattern with lattice points arrayed in two directions intersecting each other in the rectangular lattice, in which a lattice-point interval in one direction varies from one modified period area to another.

14. The photonic crystal laser according to claim **11**, wherein the modified period areas are arranged in a rectangular lattice pattern with lattice points arrayed in two directions intersecting each other in the rectangular lattice, in which lattice-point intervals in both directions vary from one modified period area to another.

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