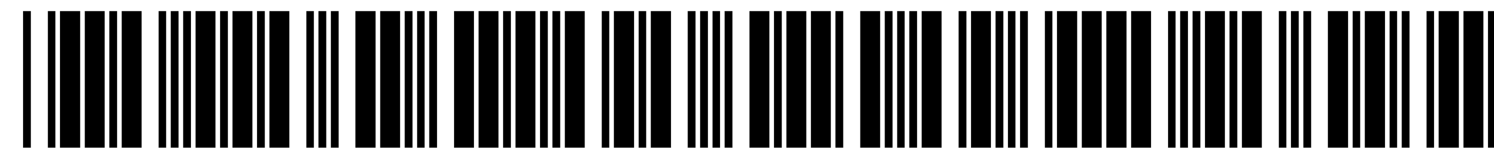

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(12) **Reissued Patent**
Kuramoto et al.

(10) **Patent Number: US RE45,973 E**
(45) **Date of Reissued Patent: Apr. 12, 2016**

(54) **SEMICONDUCTOR OPTICAL AMPLIFIER**

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(73) Assignees: **SONY CORPORATION**, Tokyo (JP); **TOHOKU UNIVERSITY**, Miyagi (JP)

(21) Appl. No.: **14/614,652**

(22) Filed: **Feb. 5, 2015**

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(64) Patent No.: **8,786,941**
Issued: **Jul. 22, 2014**
Appl. No.: **13/166,900**
Filed: **Jun. 23, 2011**

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Jun. 30, 2010 (JP) P2010-149345

(51) **Int. Cl.**
H01S 5/00 (2006.01)
H01S 5/10 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H01S 5/1064*** (2013.01); ***H01S 5/16*** (2013.01); ***H01S 5/32341*** (2013.01); ***H01S 5/50*** (2013.01)

(58) **Field of Classification Search**
CPC H01S 5/1064; H01S 5/16; H01S 5/32341; H01S 5/50
USPC 359/344
See application file for complete search history.

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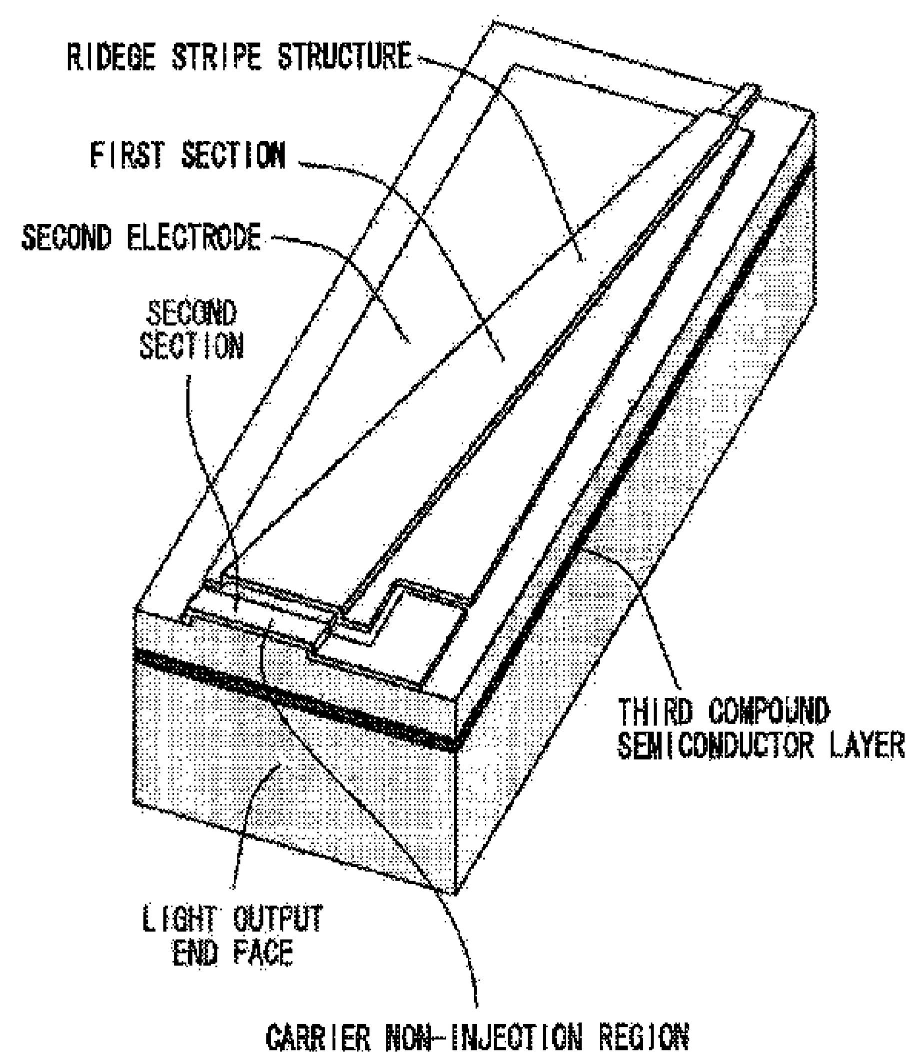
Primary Examiner — William Doerrler
(74) *Attorney, Agent, or Firm* — Dentons US LLP

(57) **ABSTRACT**

A semiconductor optical amplifier includes: a laminated structure sequentially including a first compound semiconductor layer composed of GaN compound semiconductor and having a first conductivity type, a third compound semiconductor layer having a light amplification region composed of GaN compound semiconductor, and a second compound semiconductor layer composed of GaN compound semiconductor and having a second conductivity type; a second electrode formed on the second compound semiconductor layer; and a first electrode electrically connected to the first compound semiconductor layer. The laminated structure has a ridge stripe structure. When widths of the ridge stripe structure in a light output end face and the ridge stripe structure in a light incident end face are respectively W_{out}, and W_{in}, $W_{out}>W_{in}$ is satisfied. A carrier non-injection region is provided in an internal region of the laminated structure from the light output end face along an axis line of the semiconductor optical amplifier.

23 Claims, 30 Drawing Sheets



(51) **Int. Cl.**

H01S 5/16	(2006.01)
H01S 5/323	(2006.01)
H01S 5/50	(2006.01)

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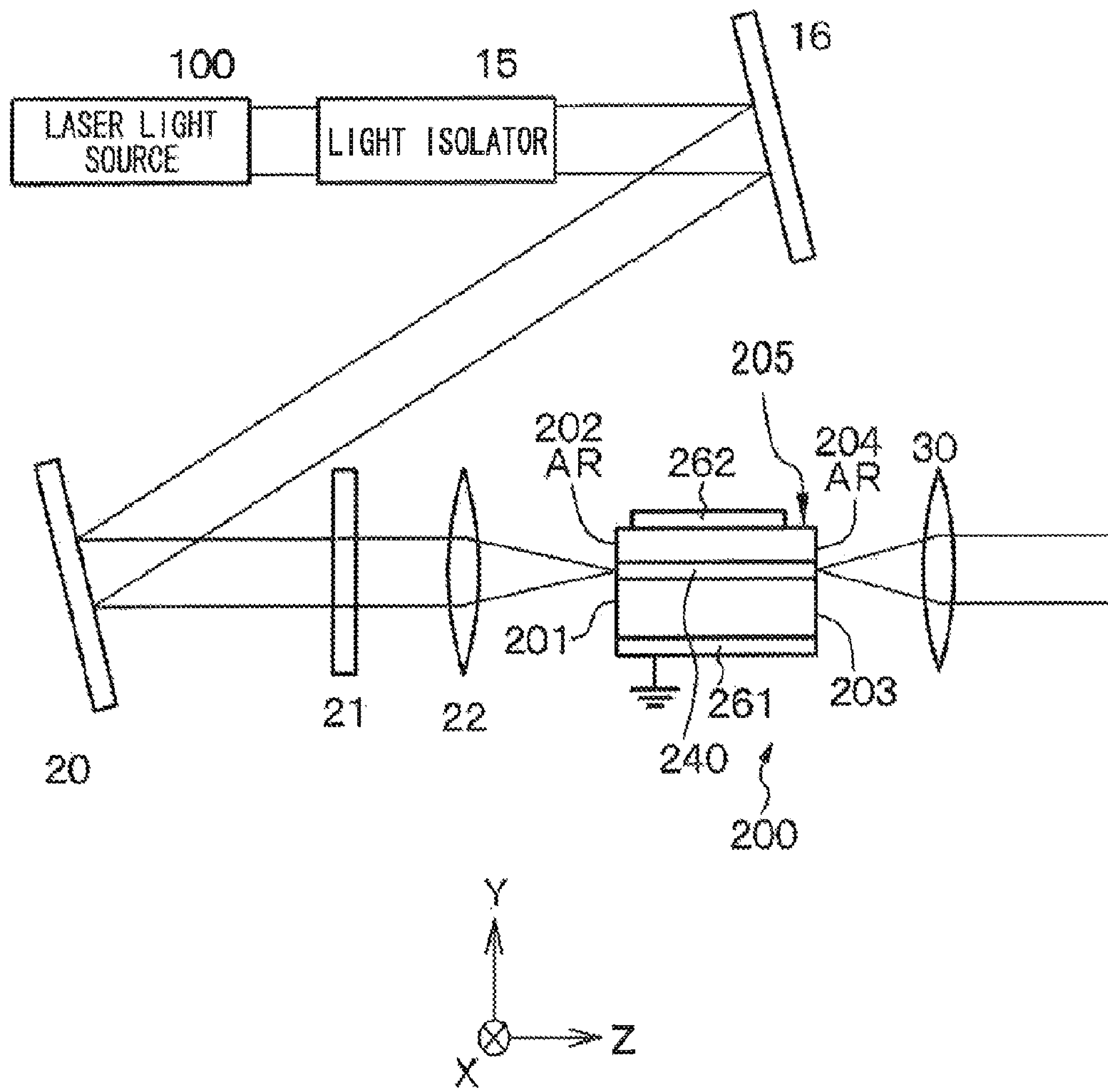


FIG. 1

FIG. 2

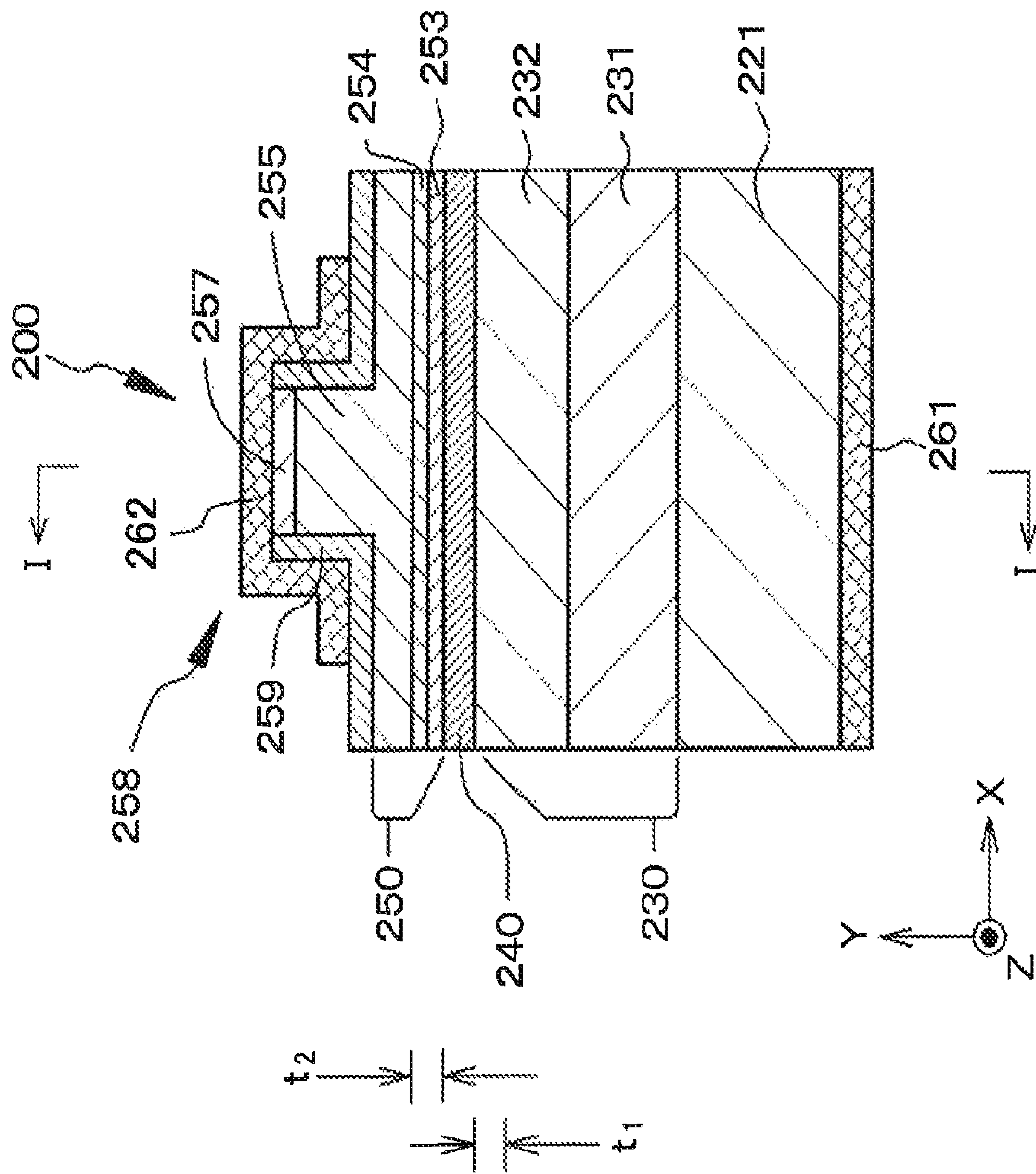


FIG. 3

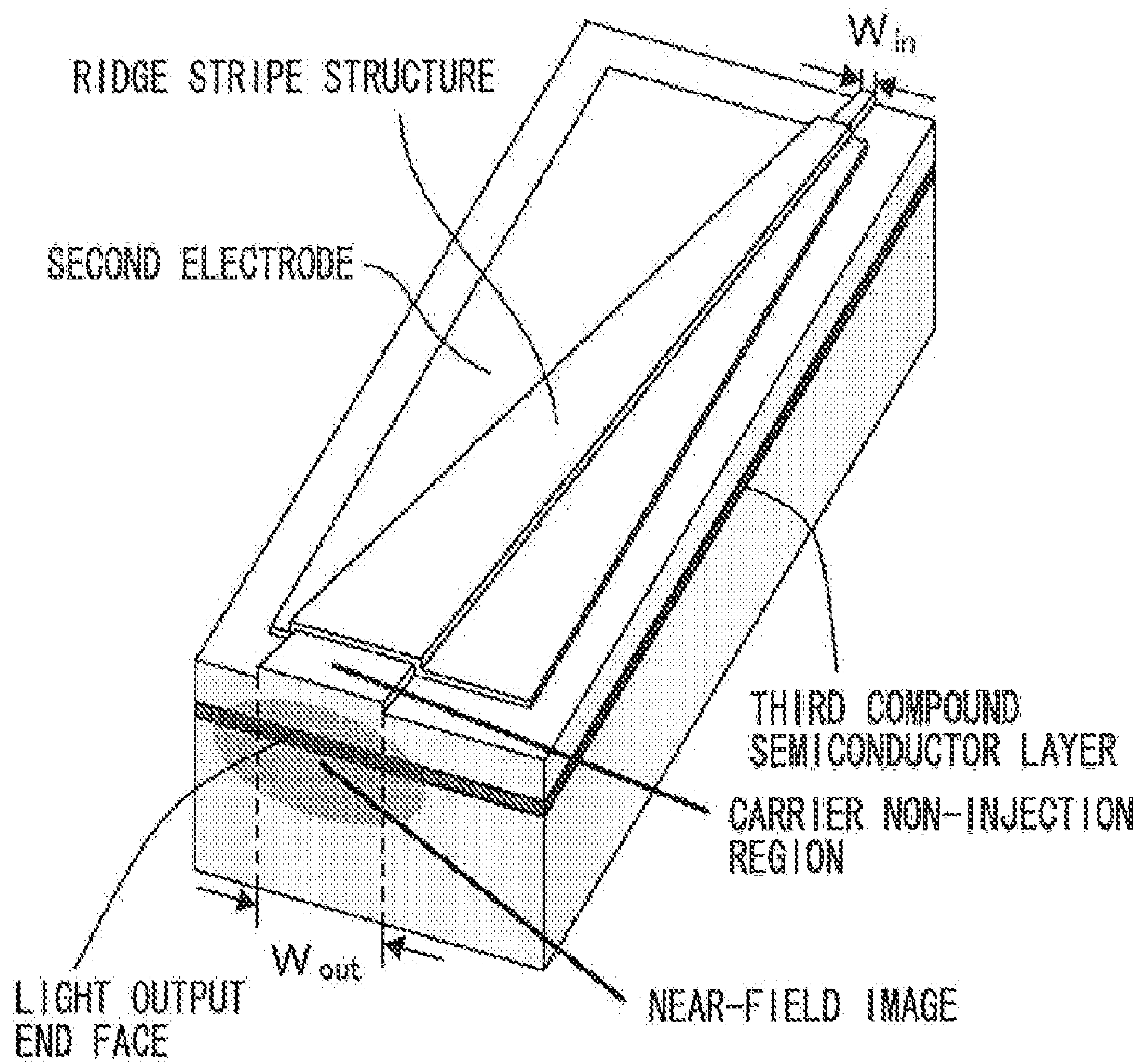


FIG. 4

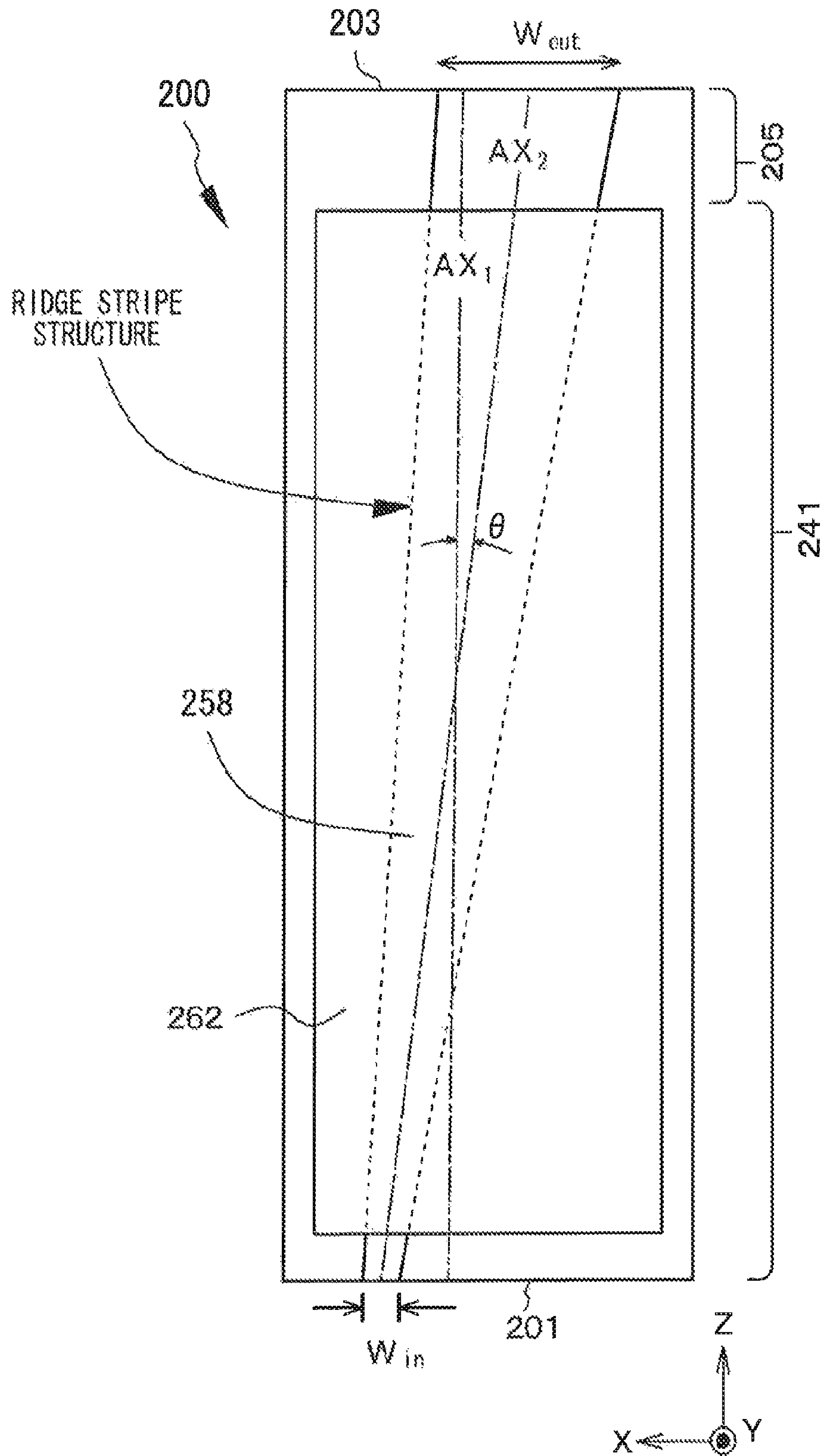
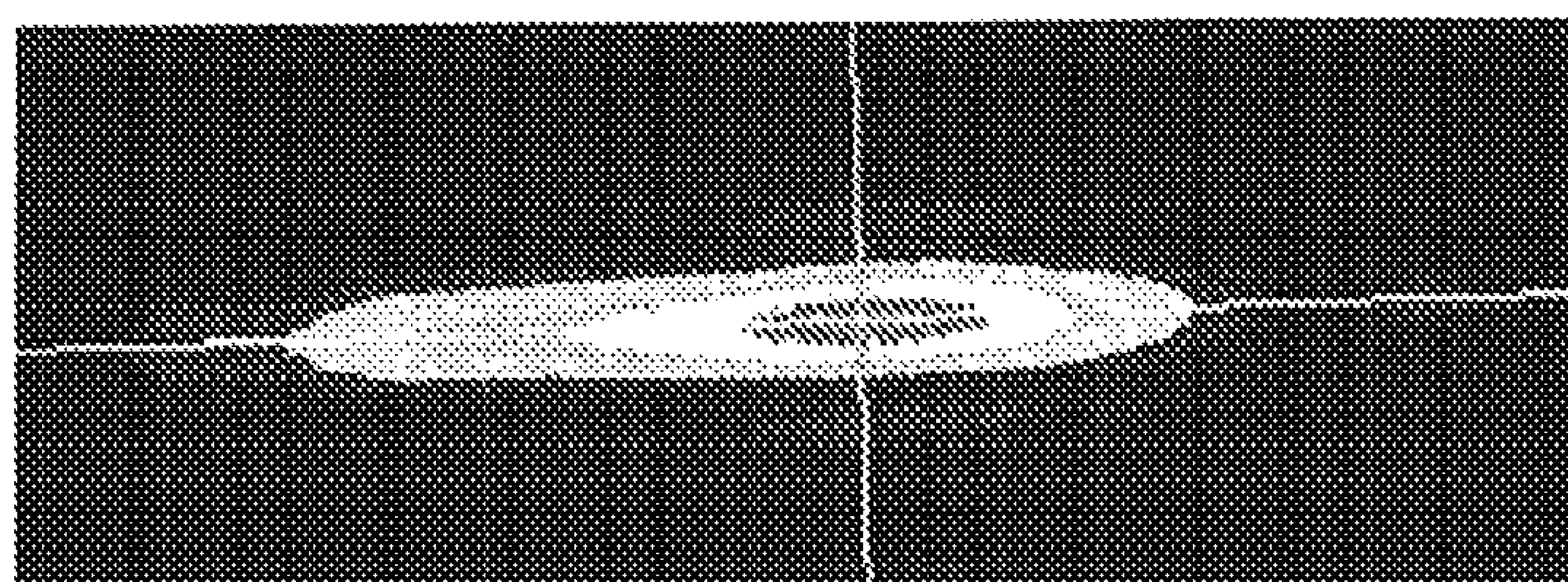


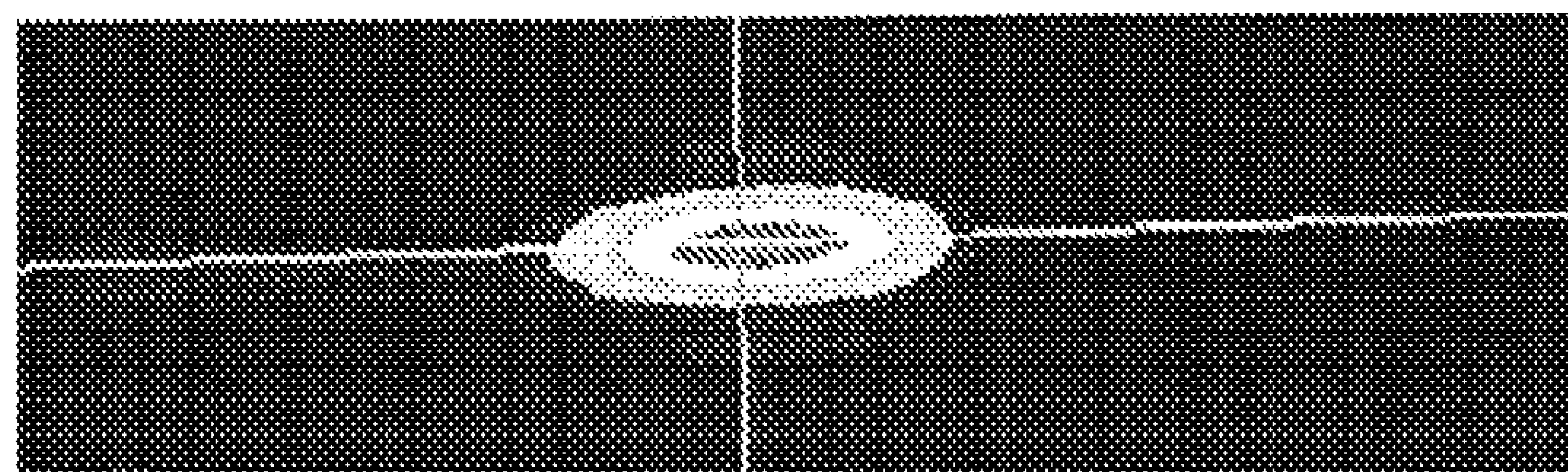
FIG. 5

FIG. 6A



15 μm

FIG. 6B



15 μm

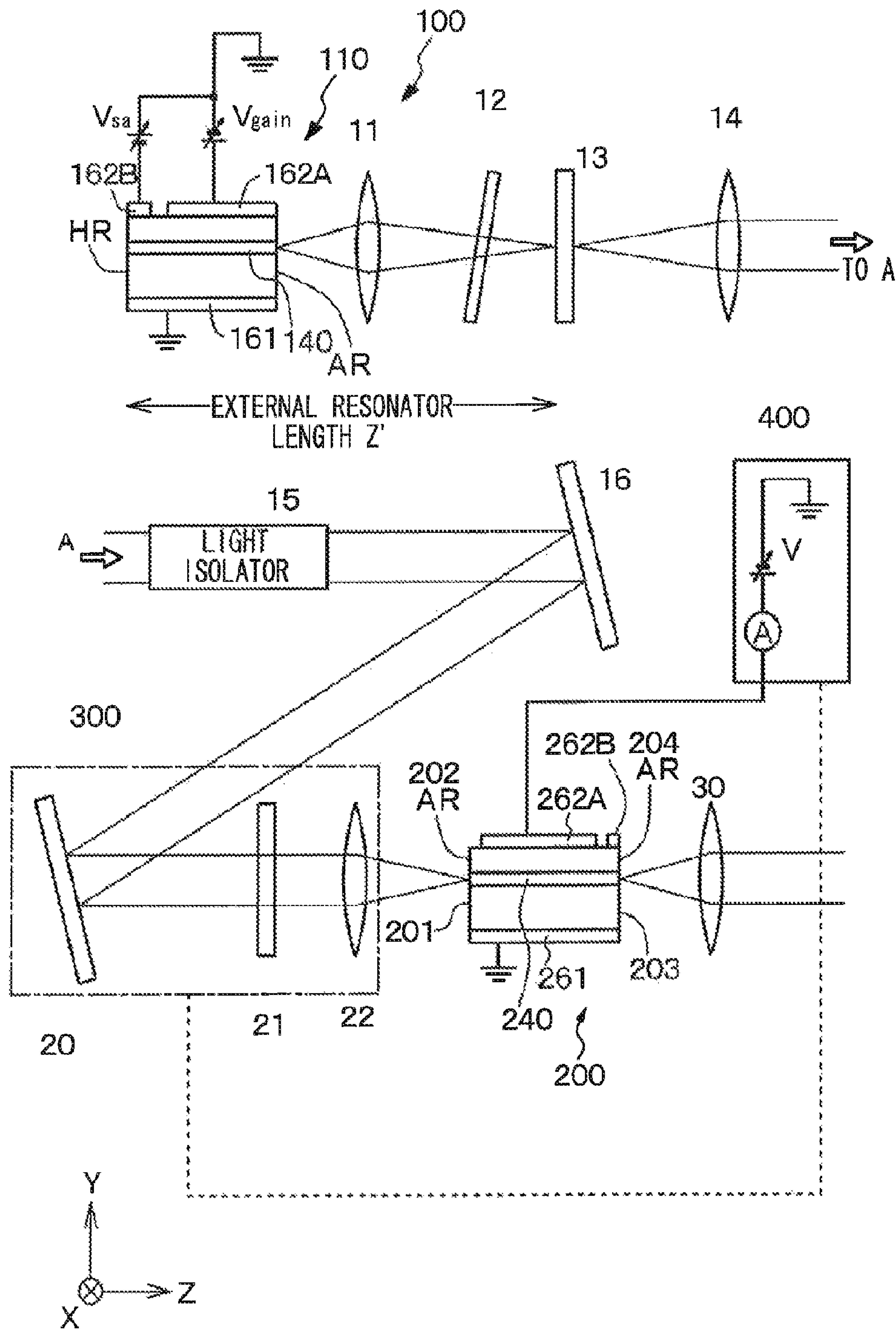


FIG. 7

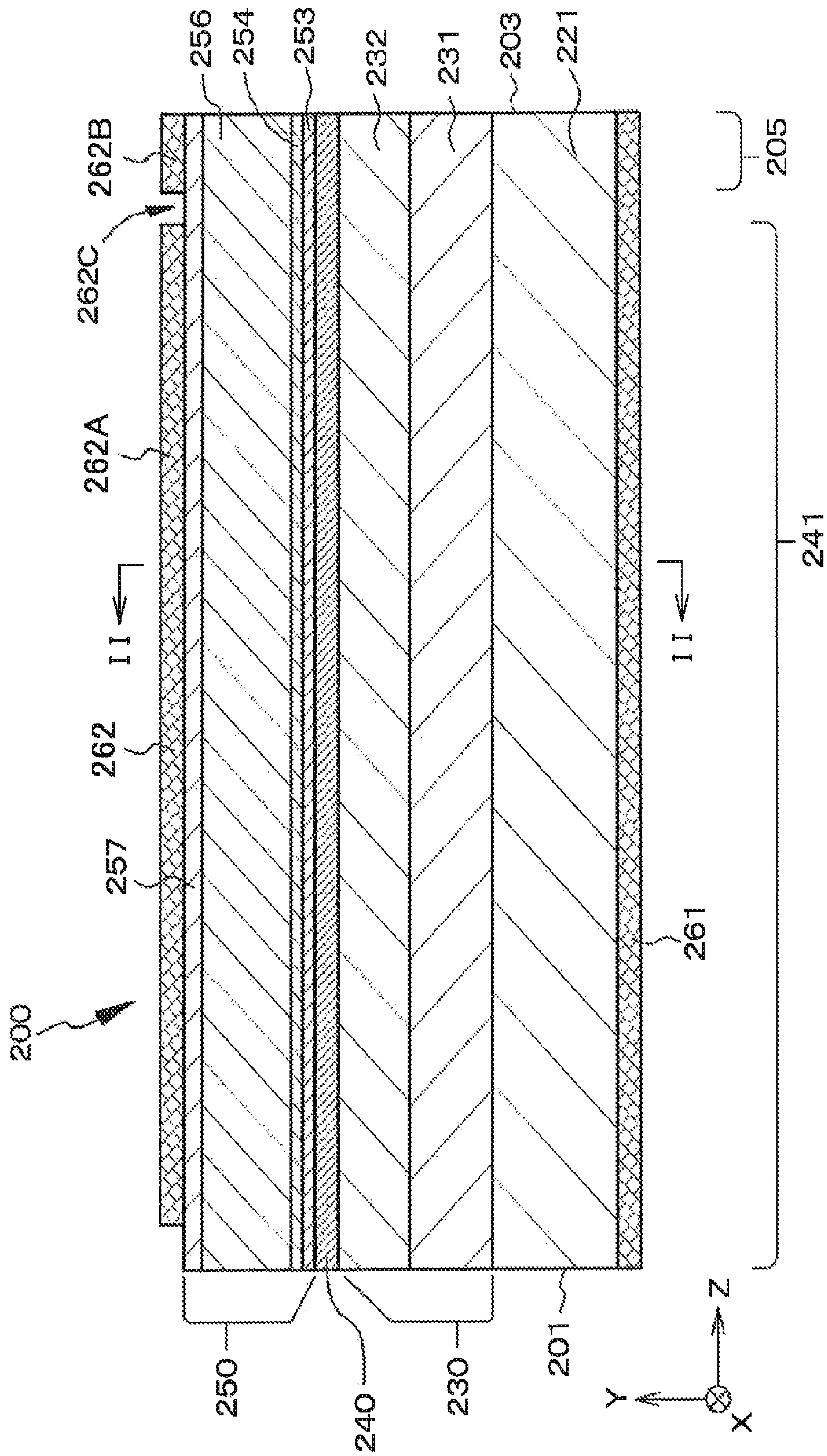


FIG. 8

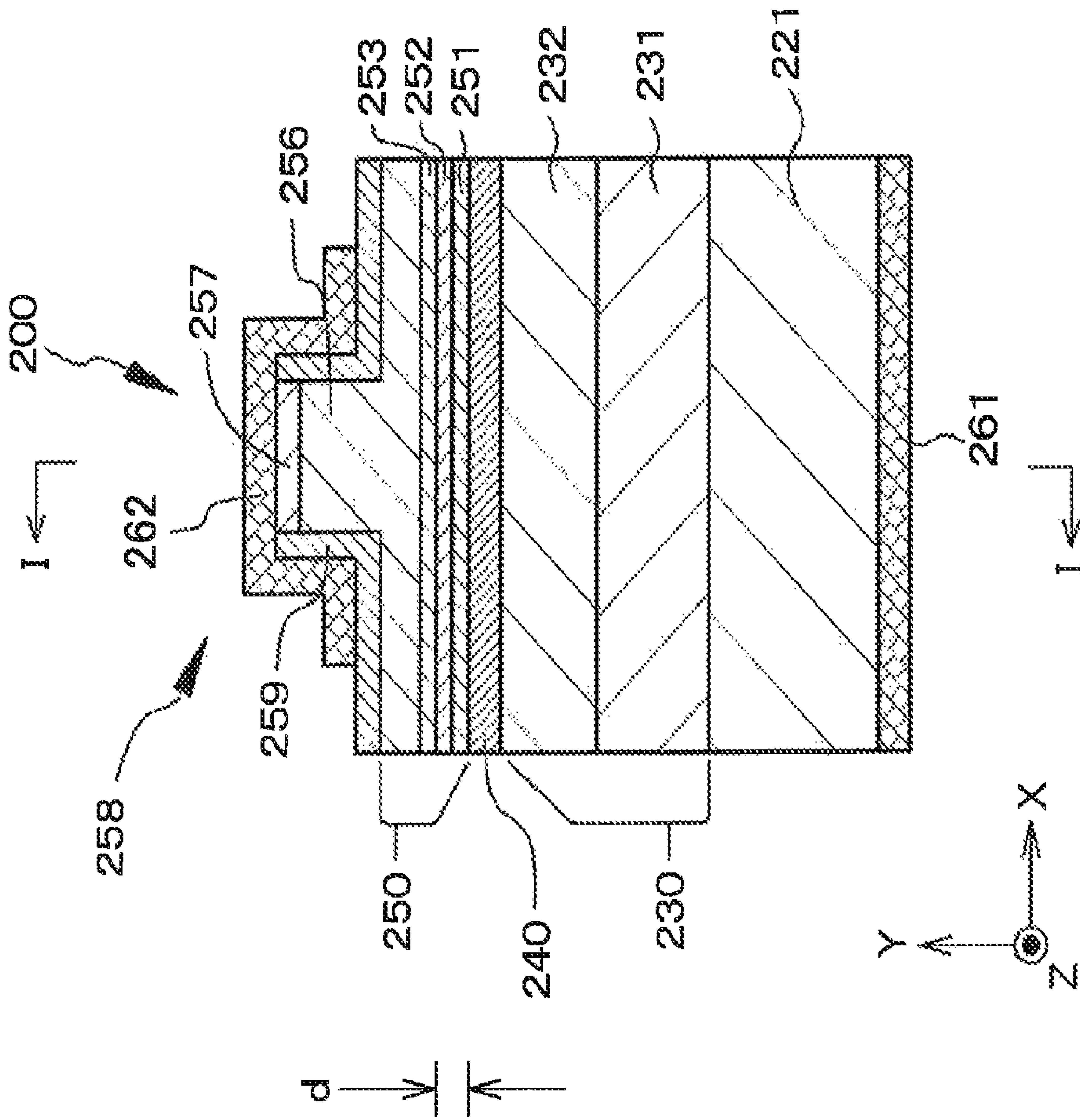


FIG. 9

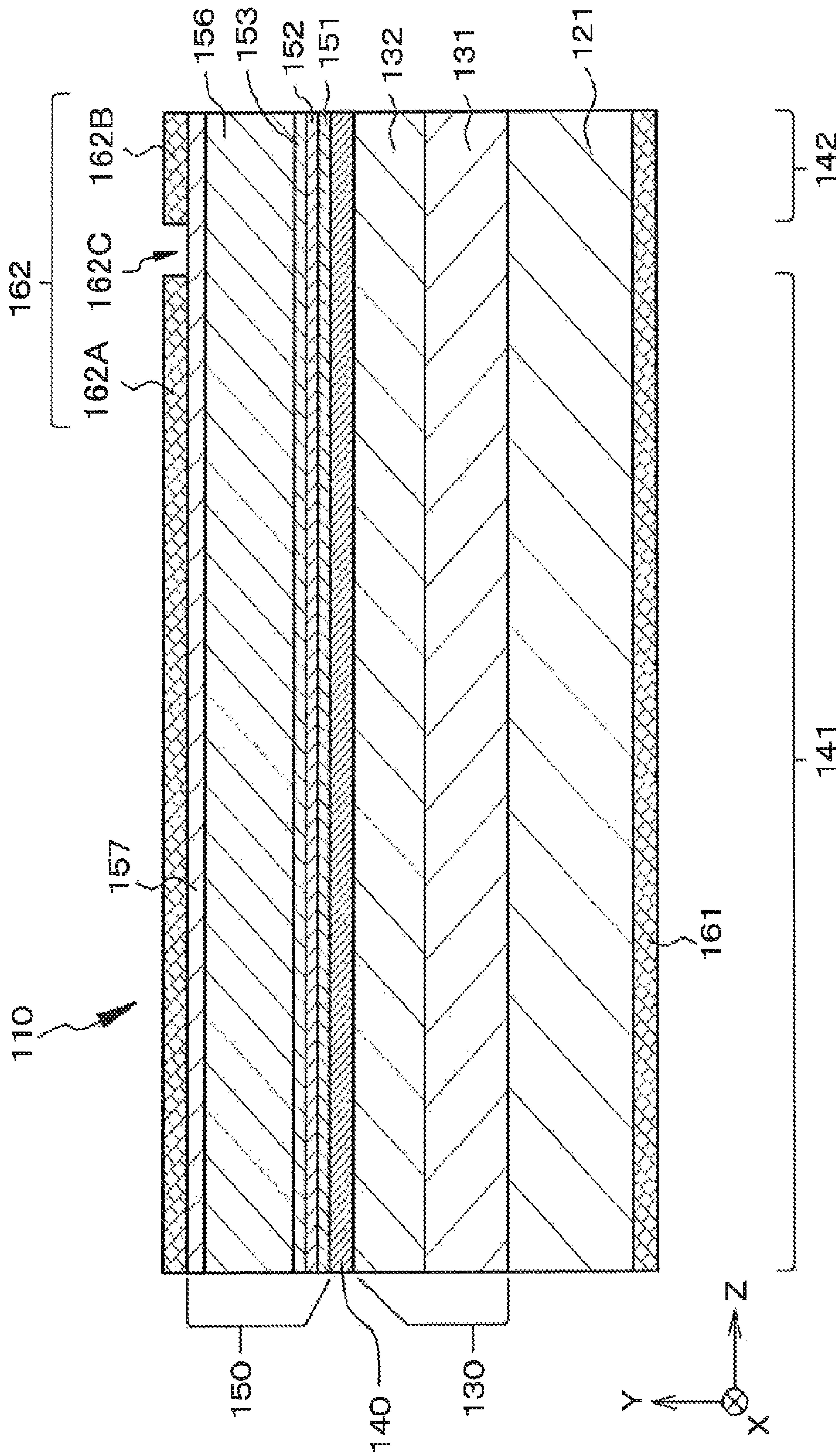


FIG. 10

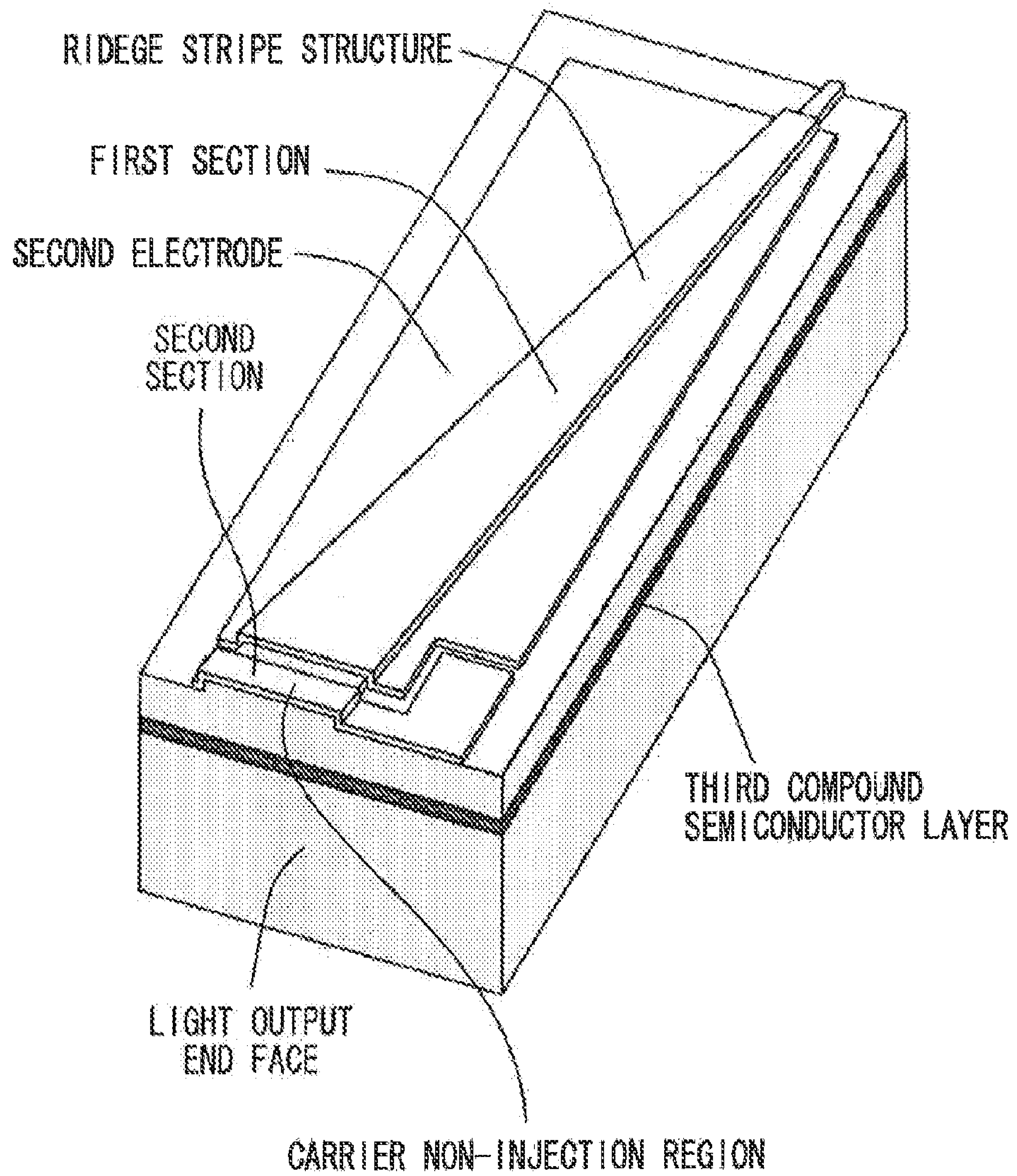


FIG. 11

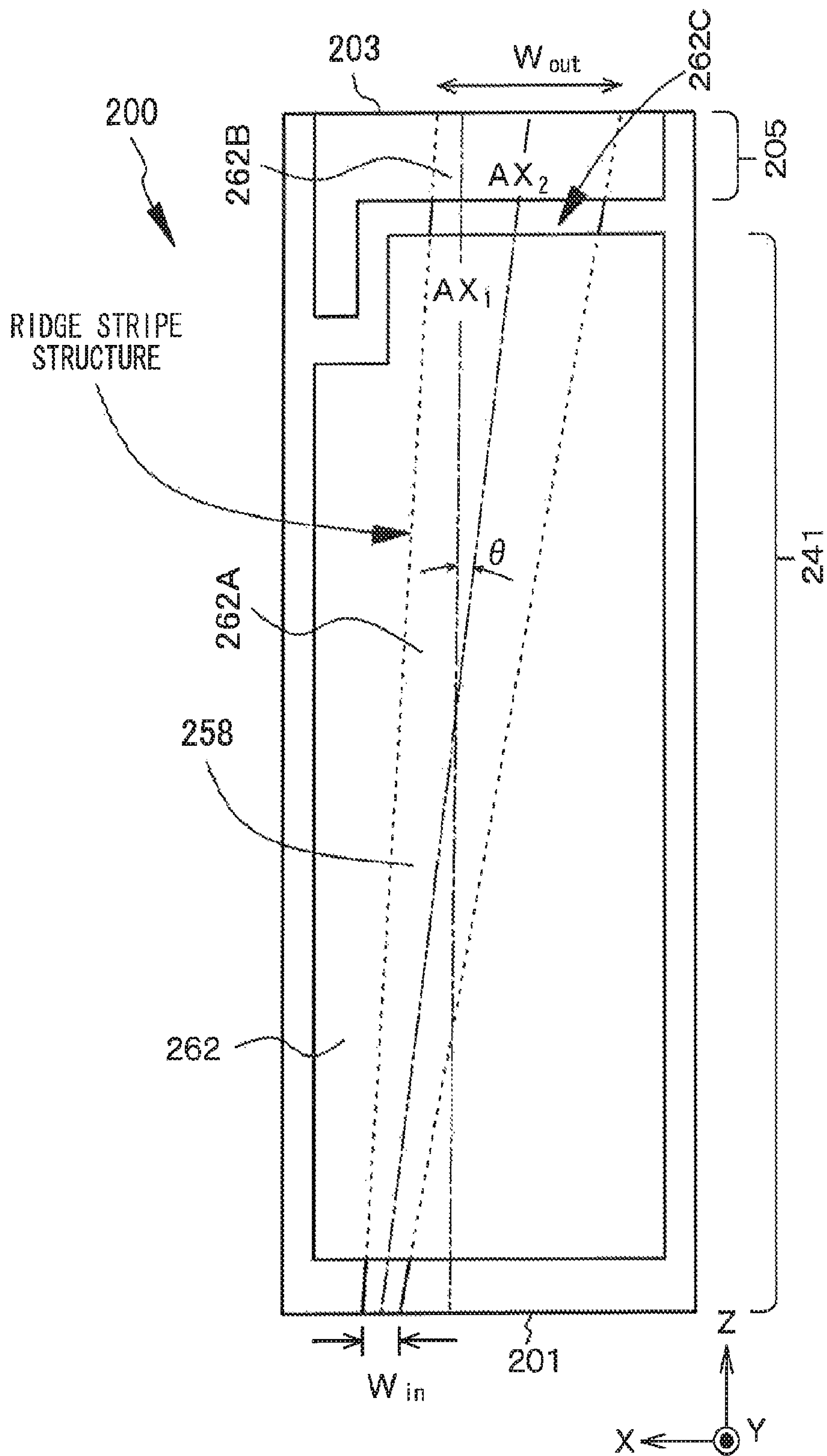


FIG. 12

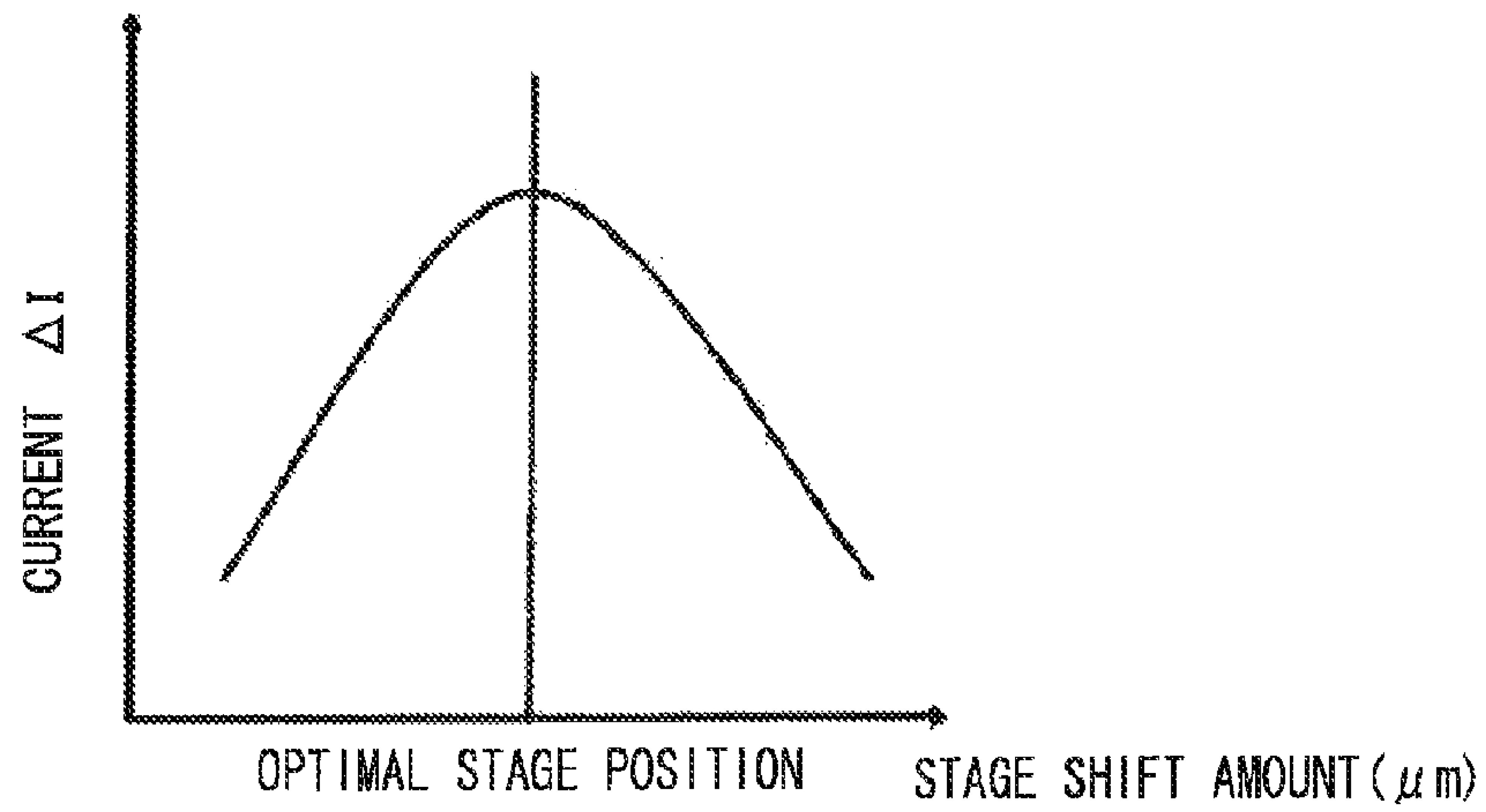


FIG. 13

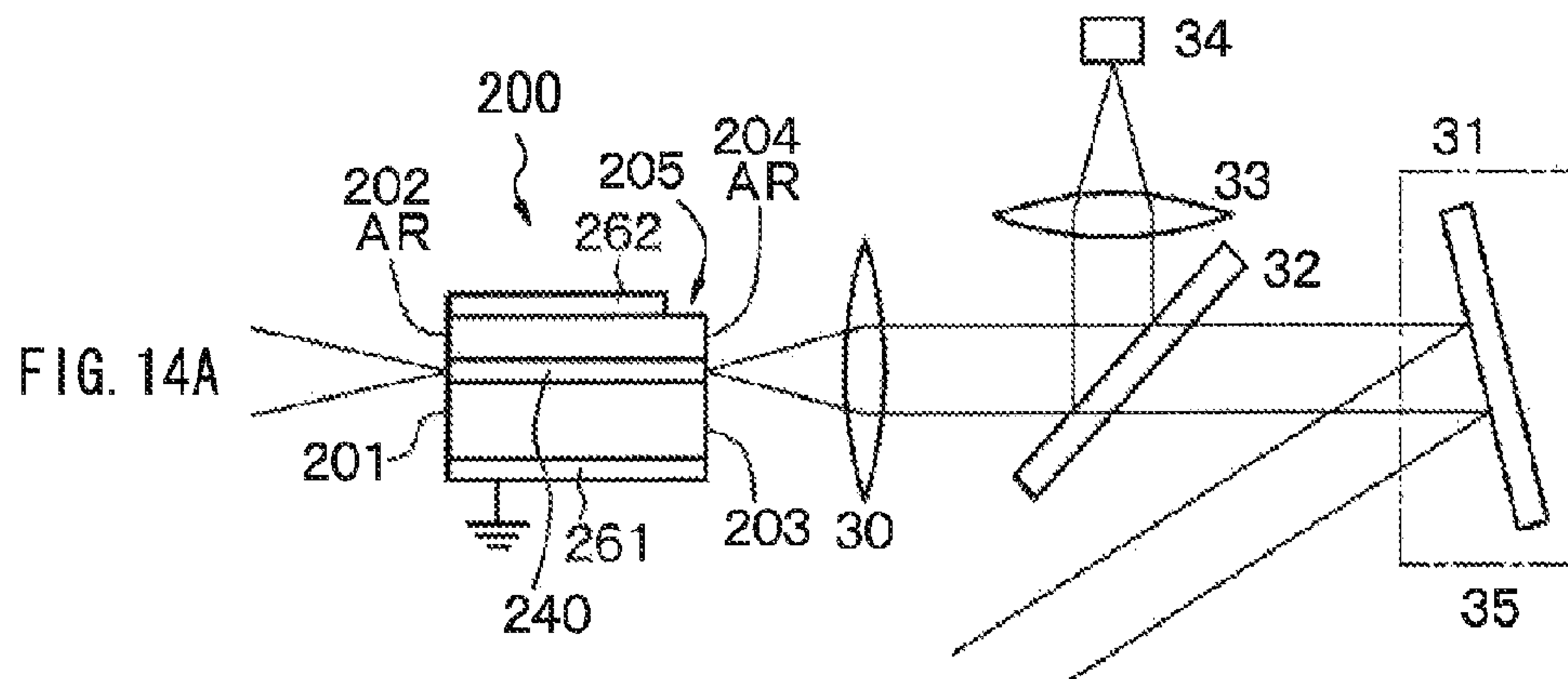


FIG. 14A

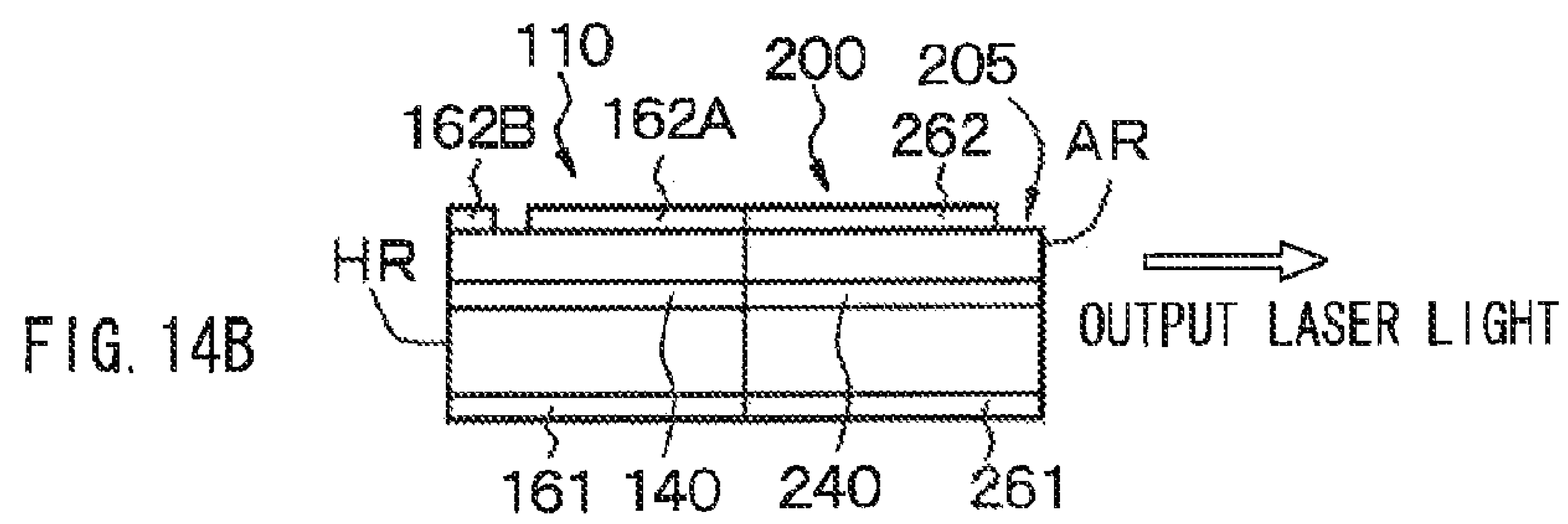
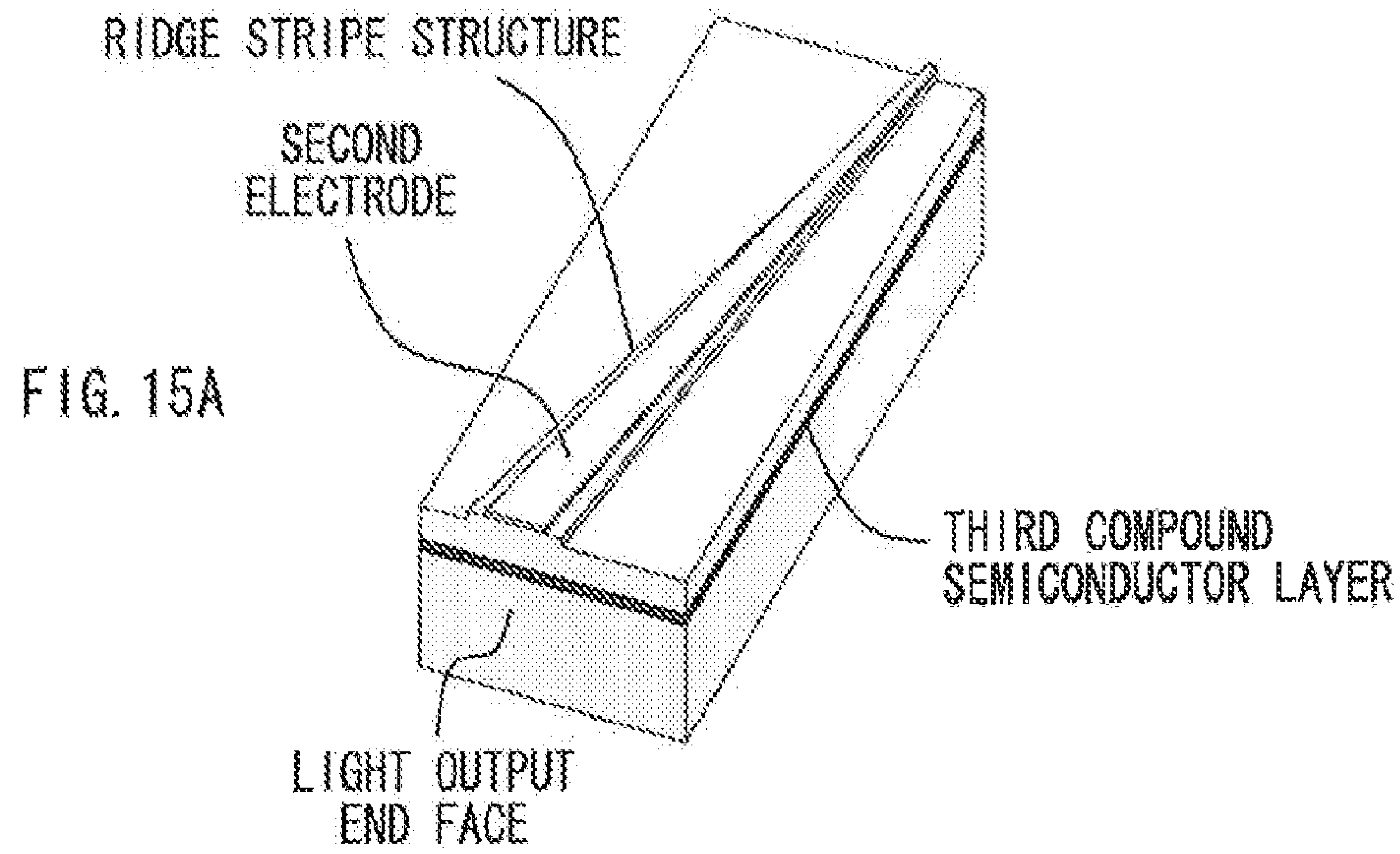
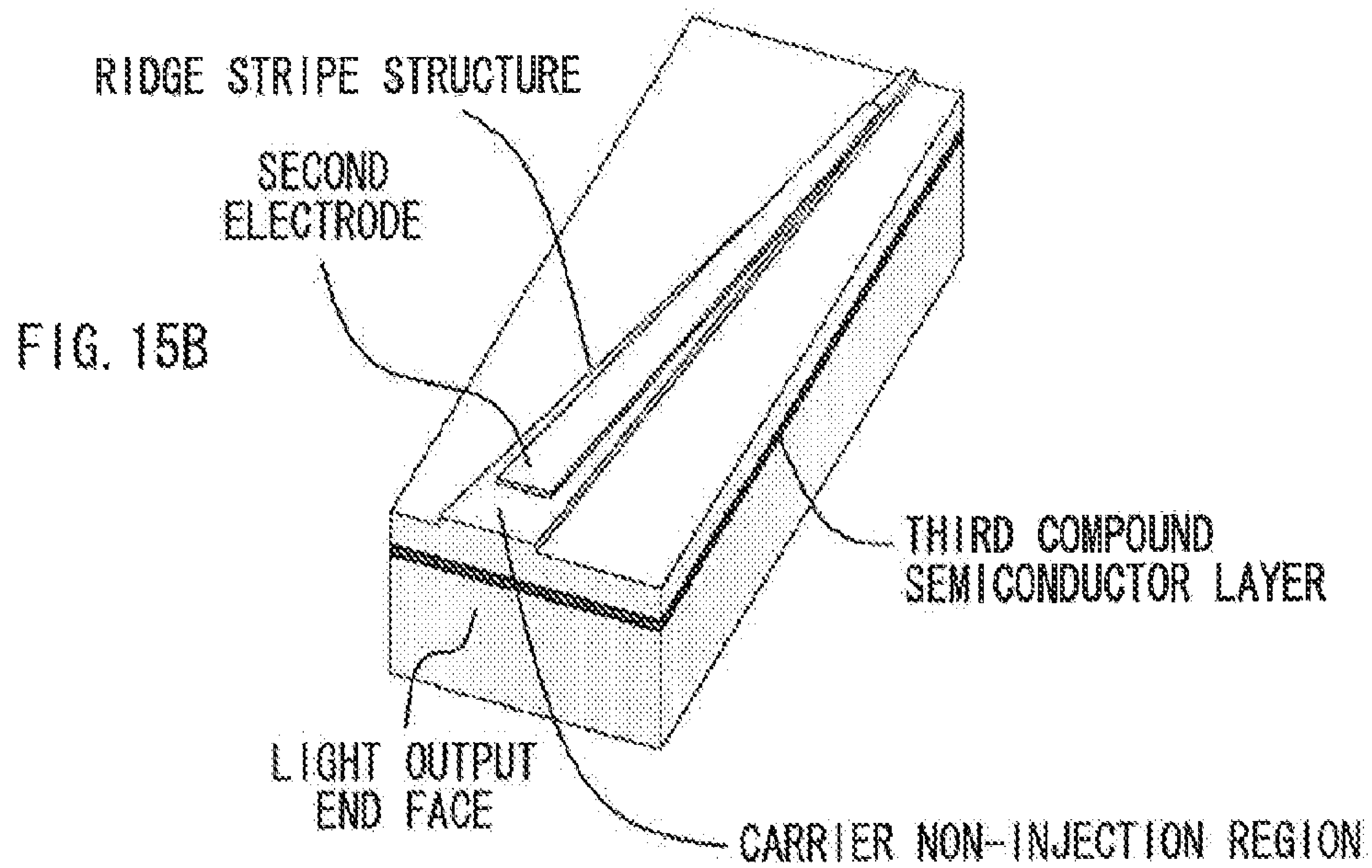


FIG. 14B


RIDGE STRIPE STRUCTURE
SECOND ELECTRODE
FIG. 15A
THIRD COMPOUND SEMICONDUCTOR LAYER
LIGHT OUTPUT END FACE


RIDGE STRIPE STRUCTURE
SECOND ELECTRODE
FIG. 15B
THIRD COMPOUND SEMICONDUCTOR LAYER
LIGHT OUTPUT END FACE
CARRIER NON-INJECTION REGION

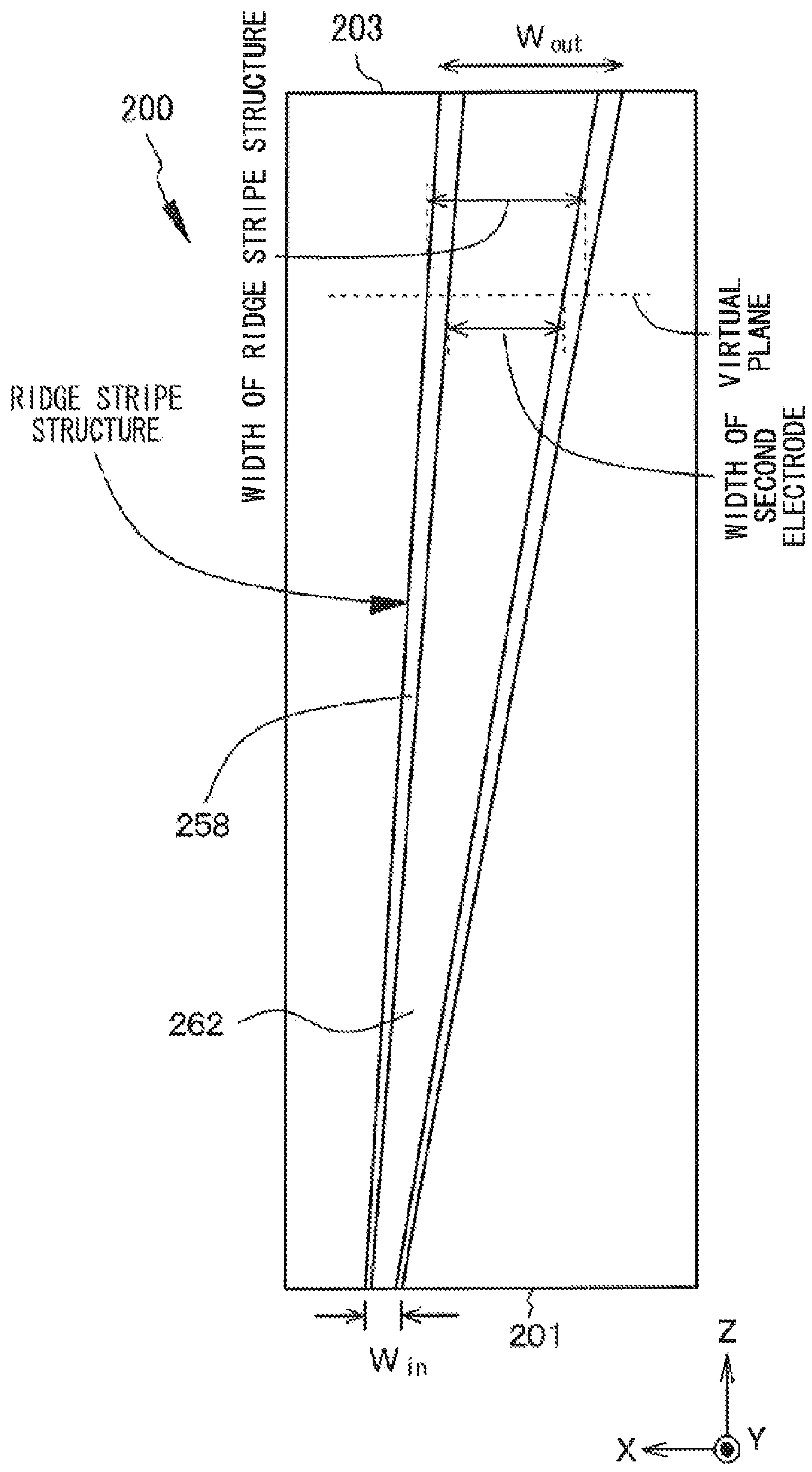


FIG. 16

FIG. 17A

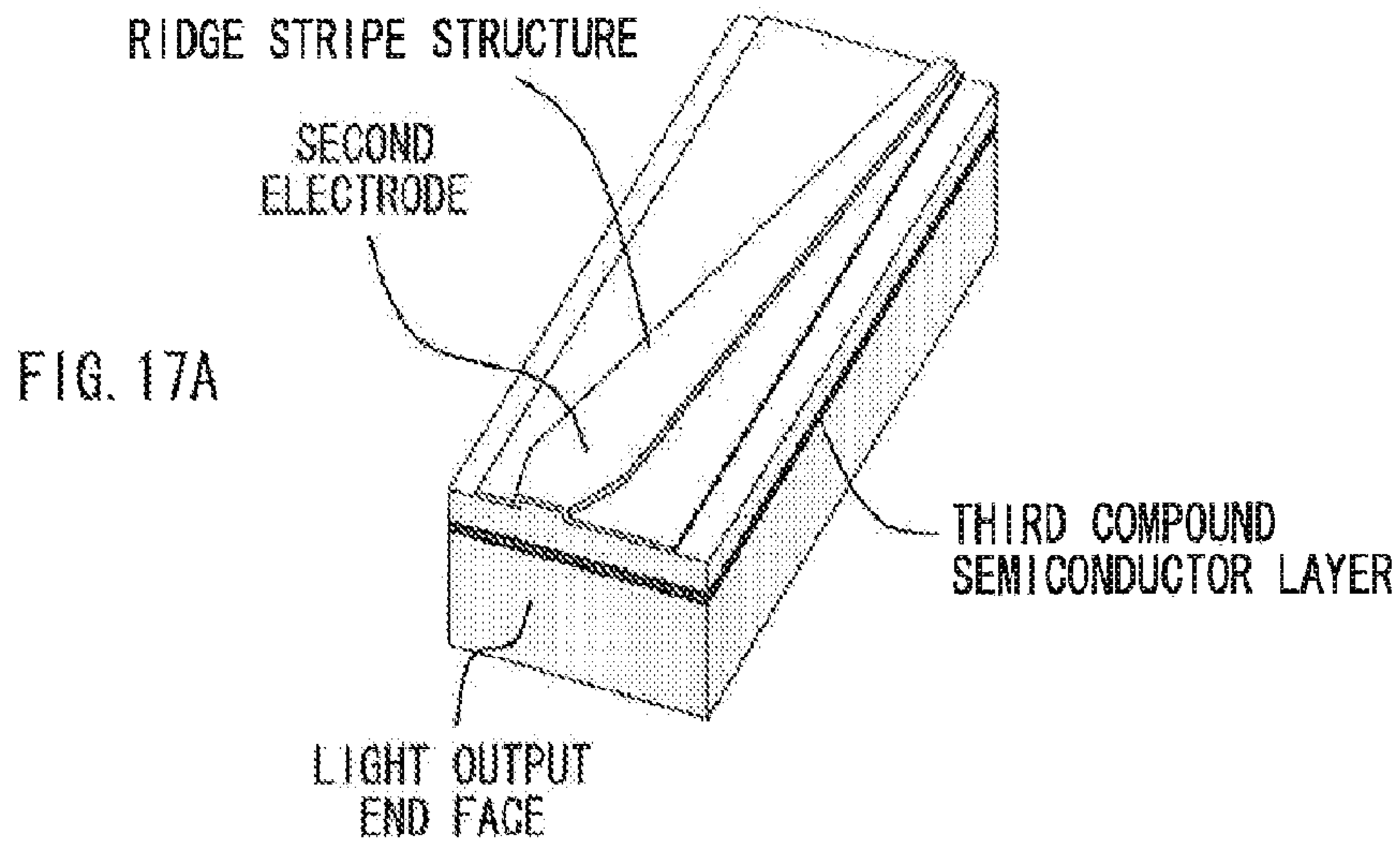
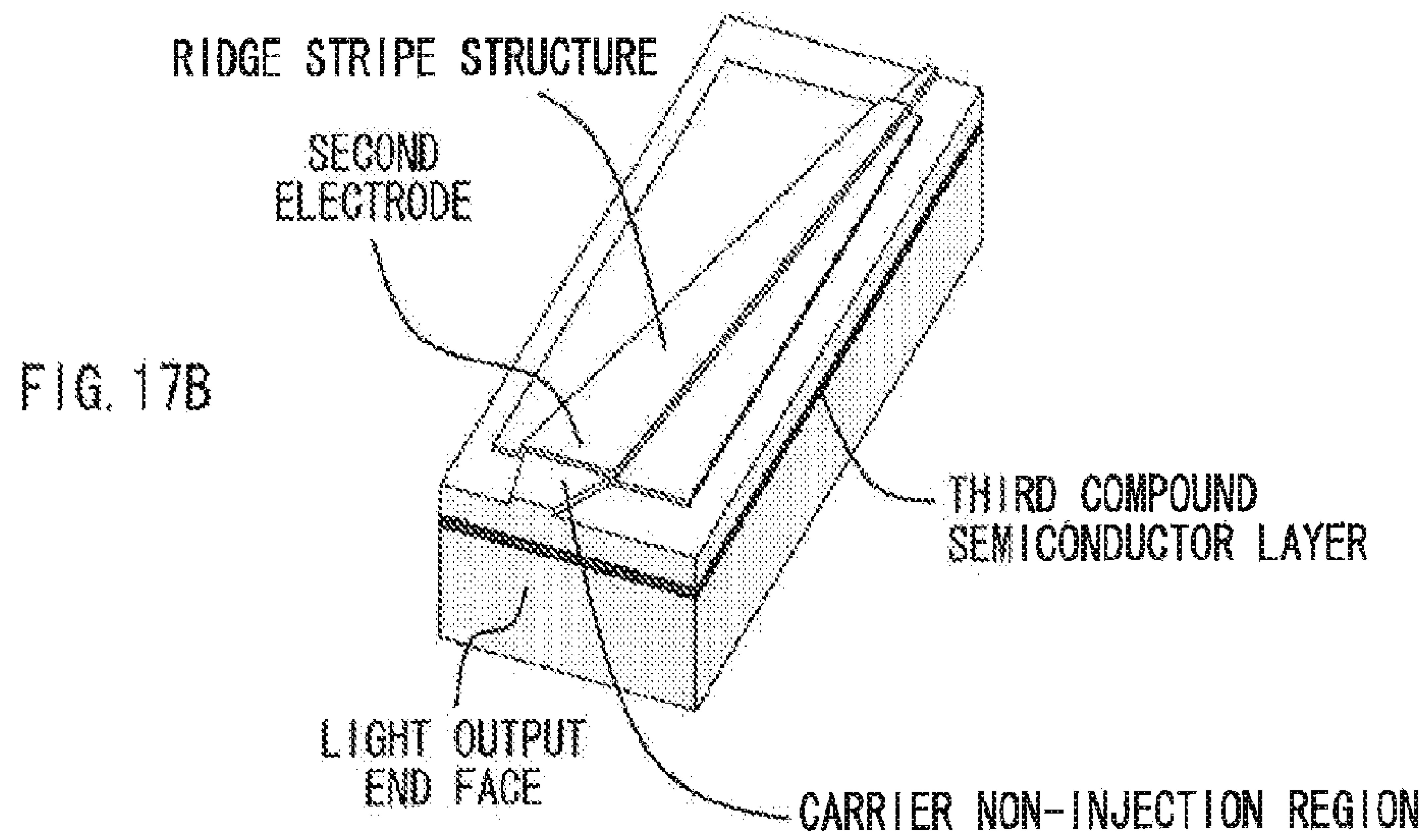


FIG. 17B



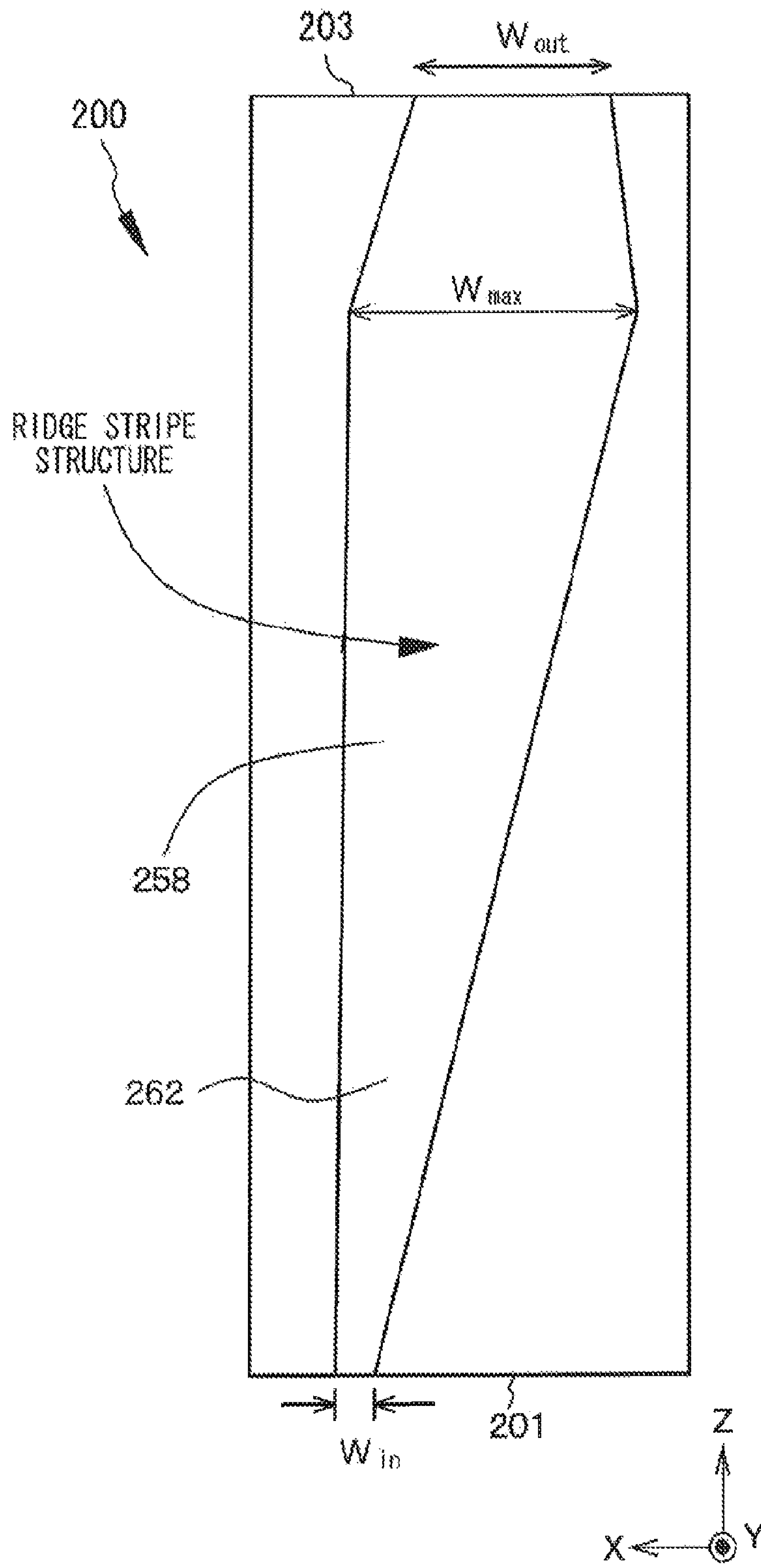


FIG. 18

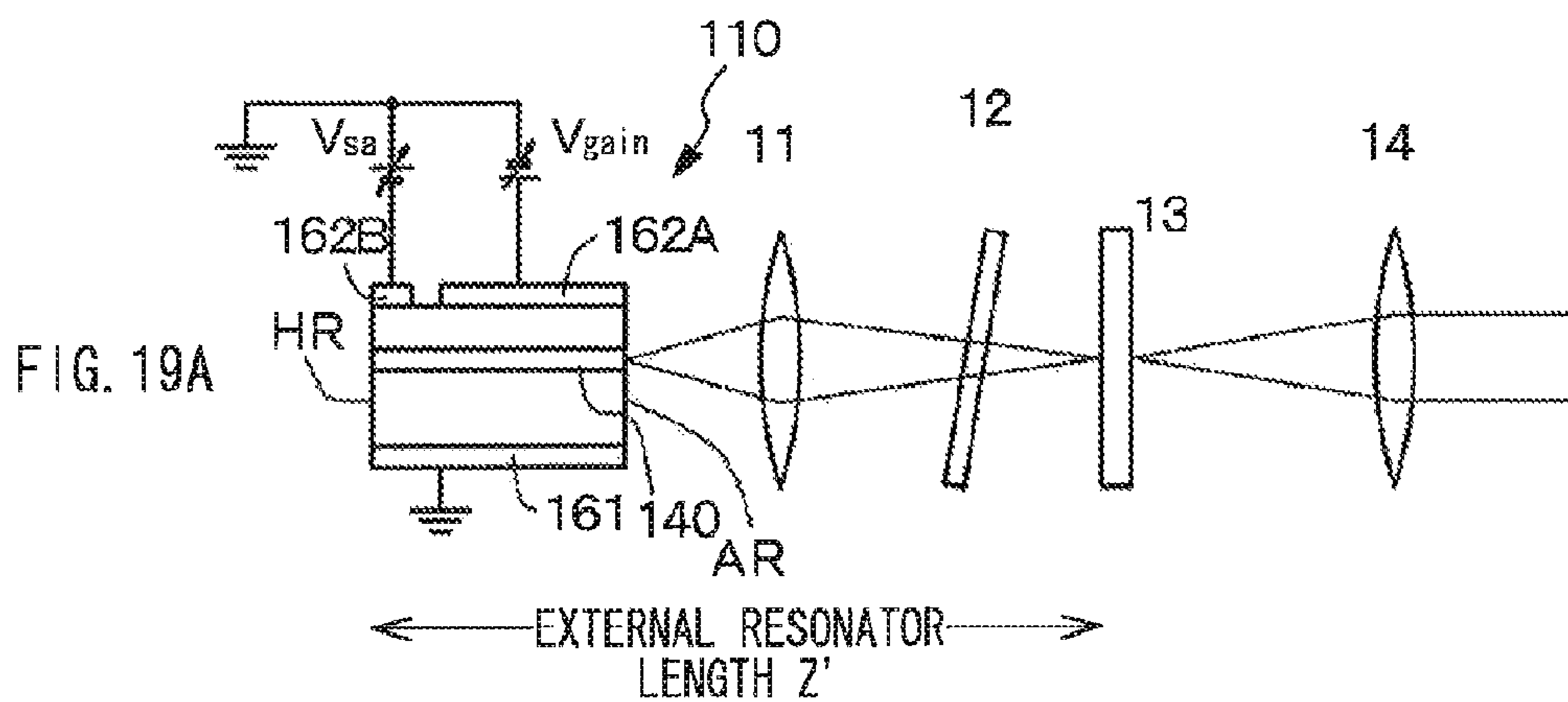


FIG. 19A

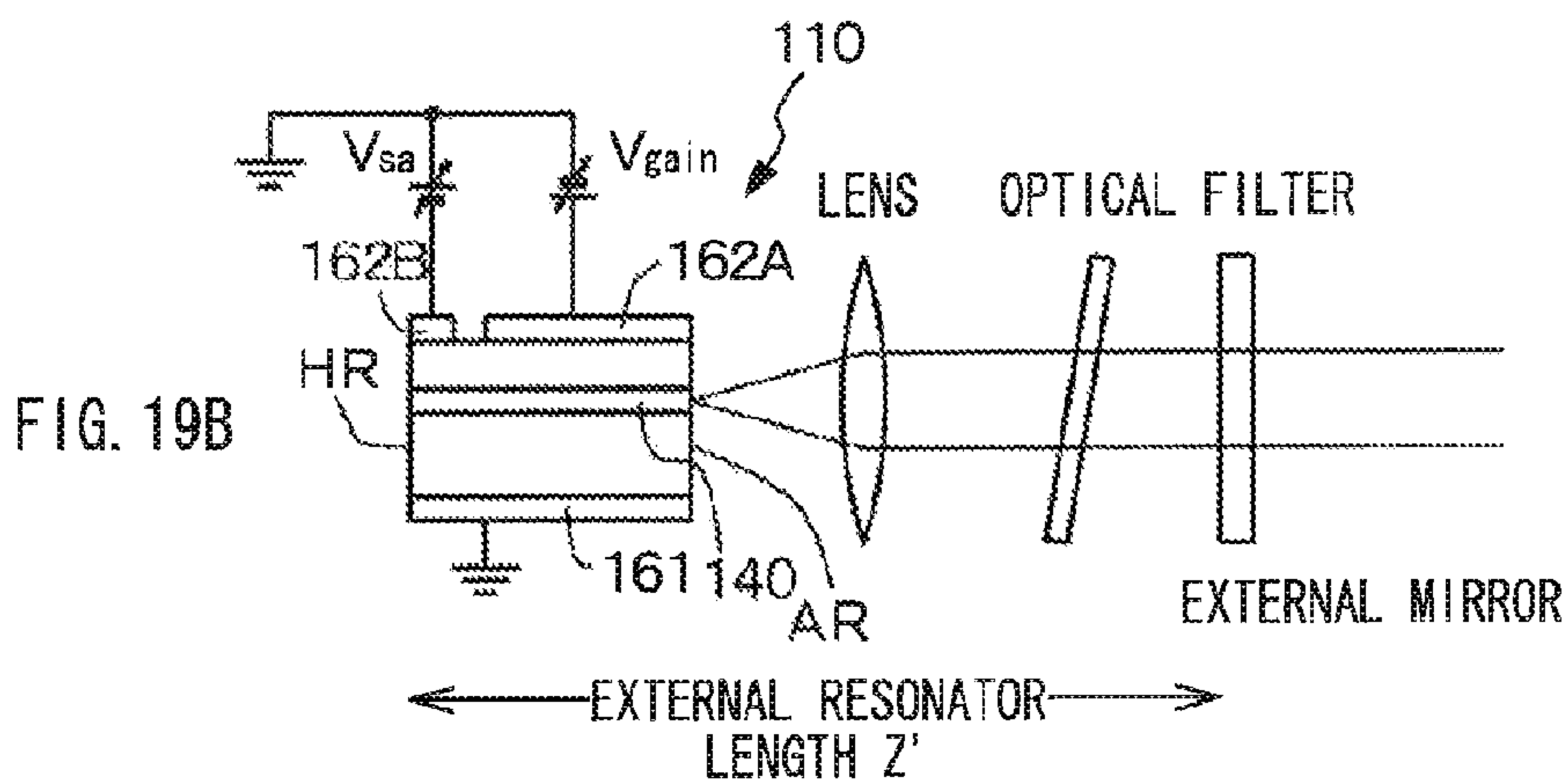


FIG. 19B

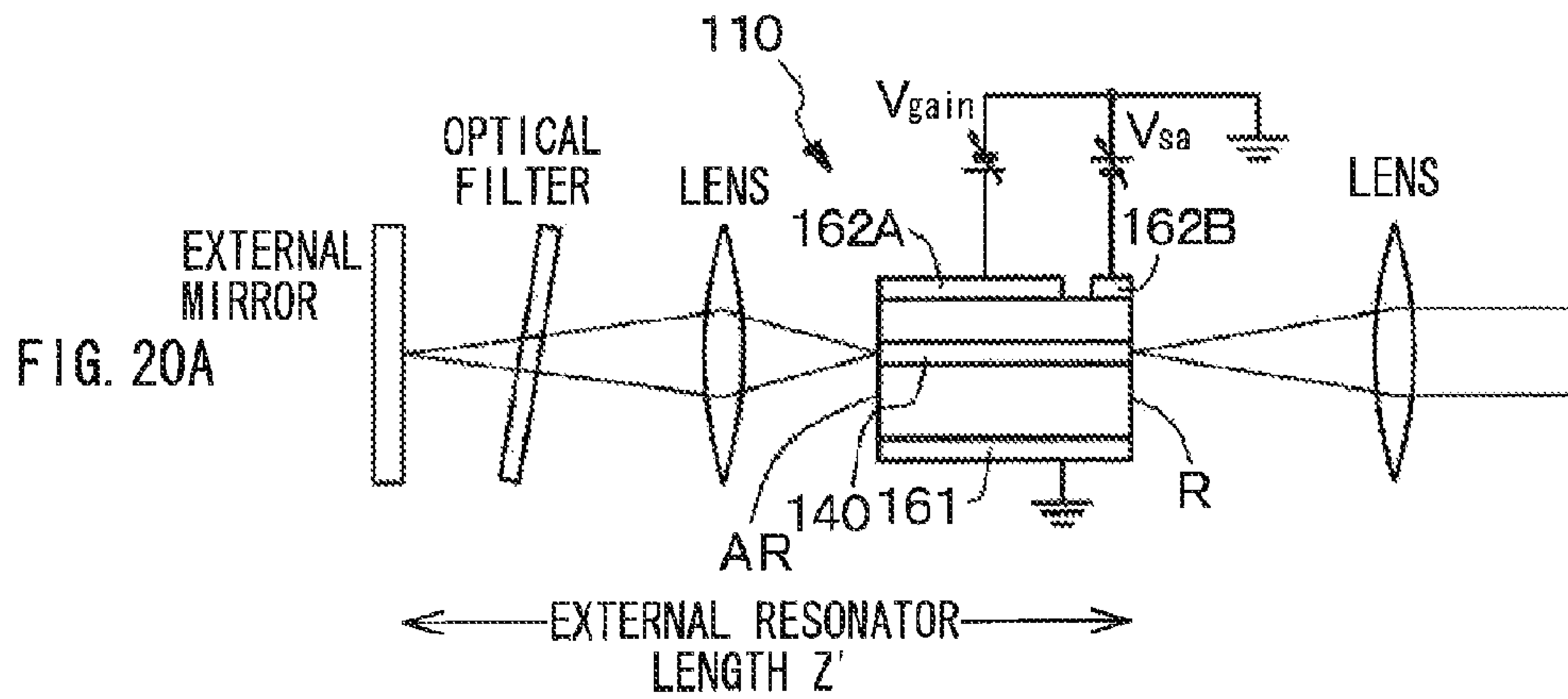


FIG. 20A

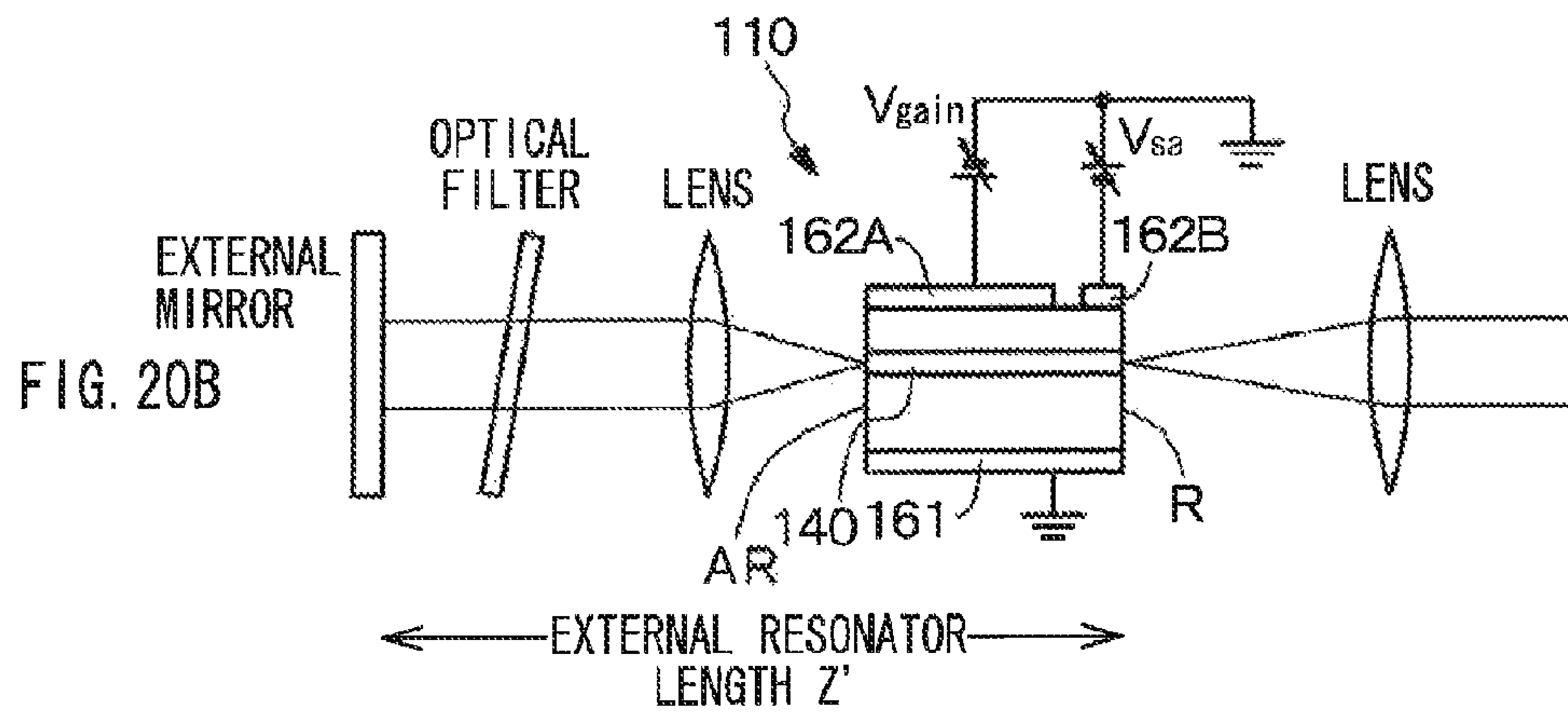


FIG. 20B

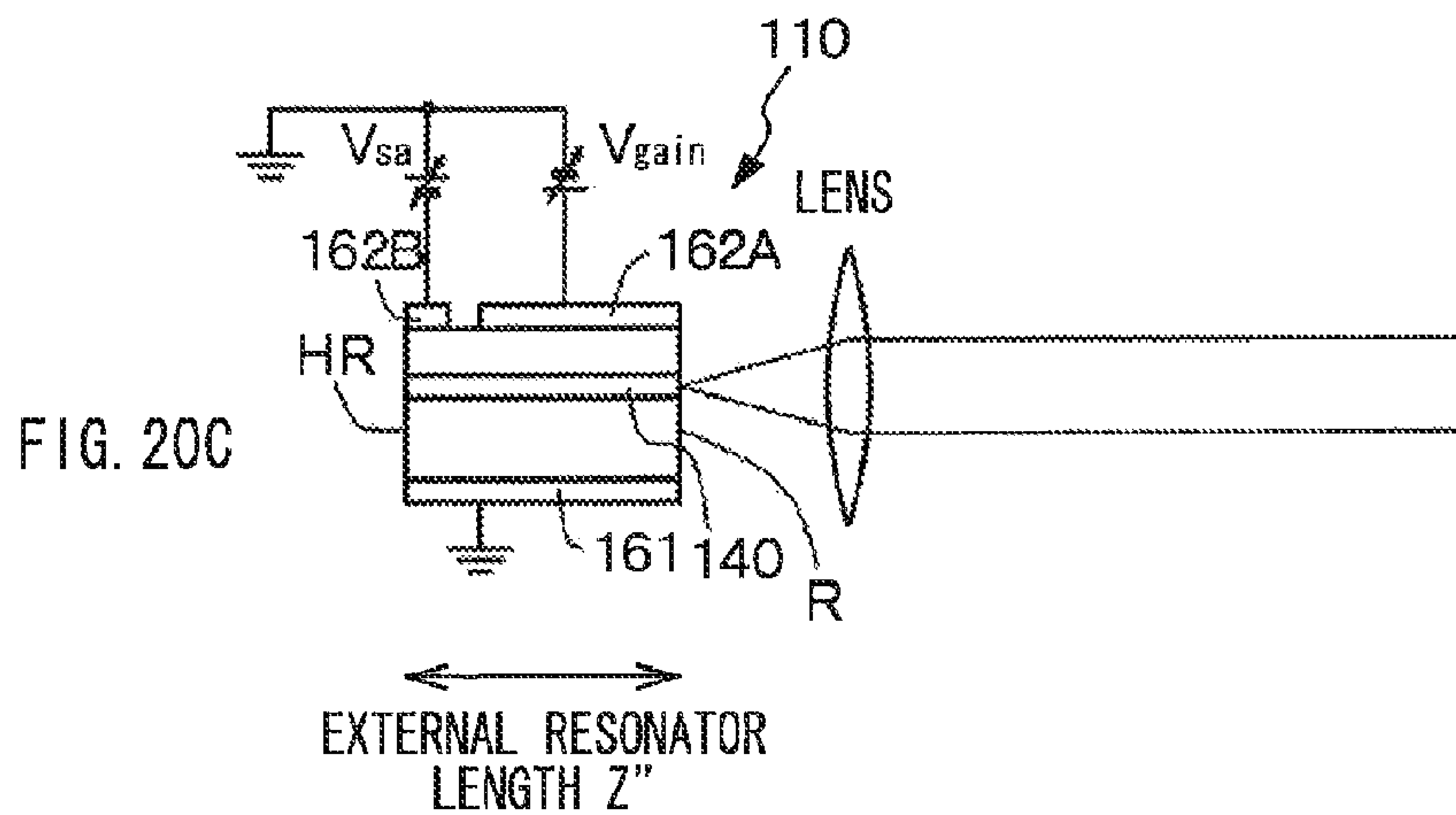


FIG. 20C

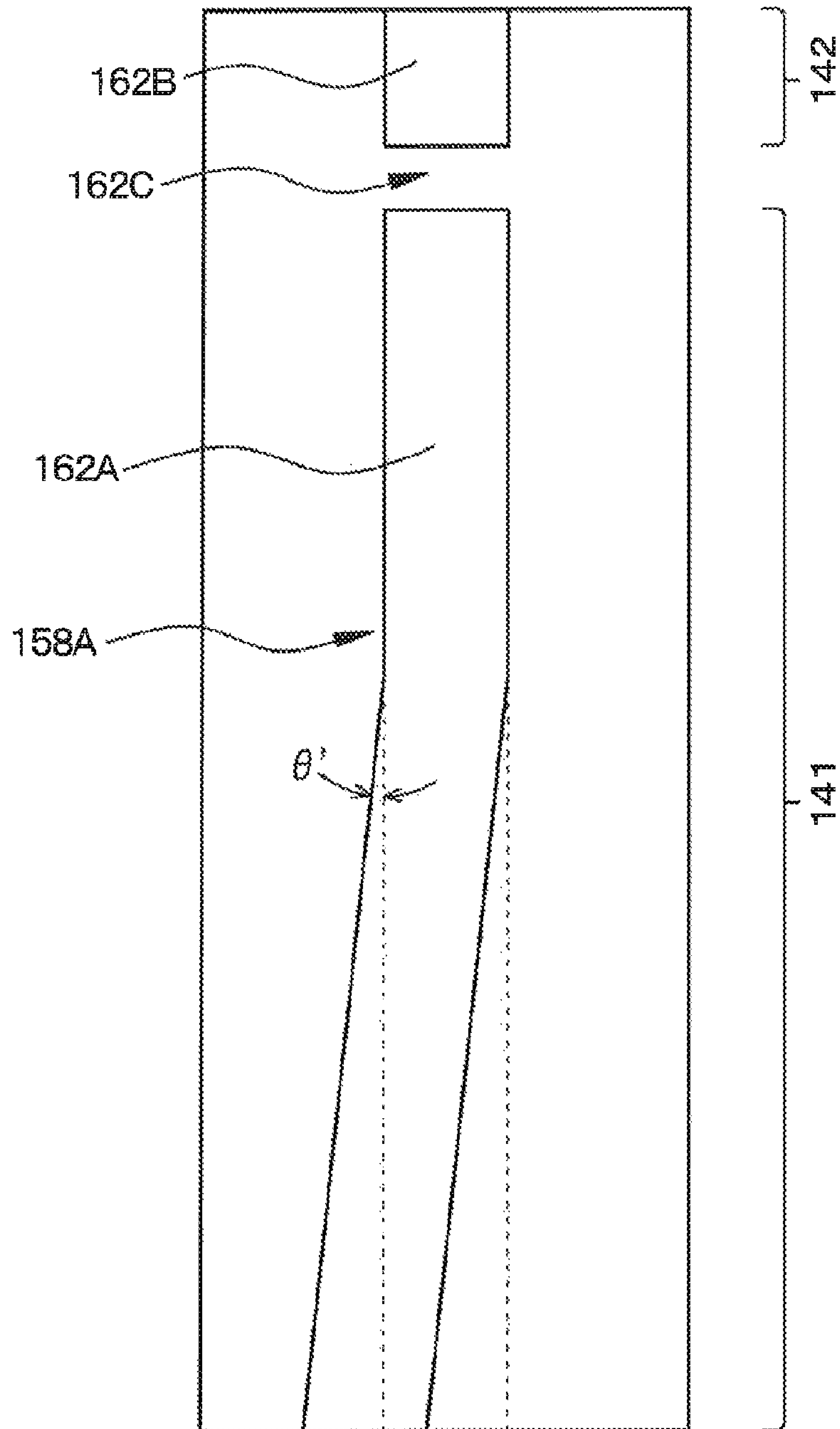
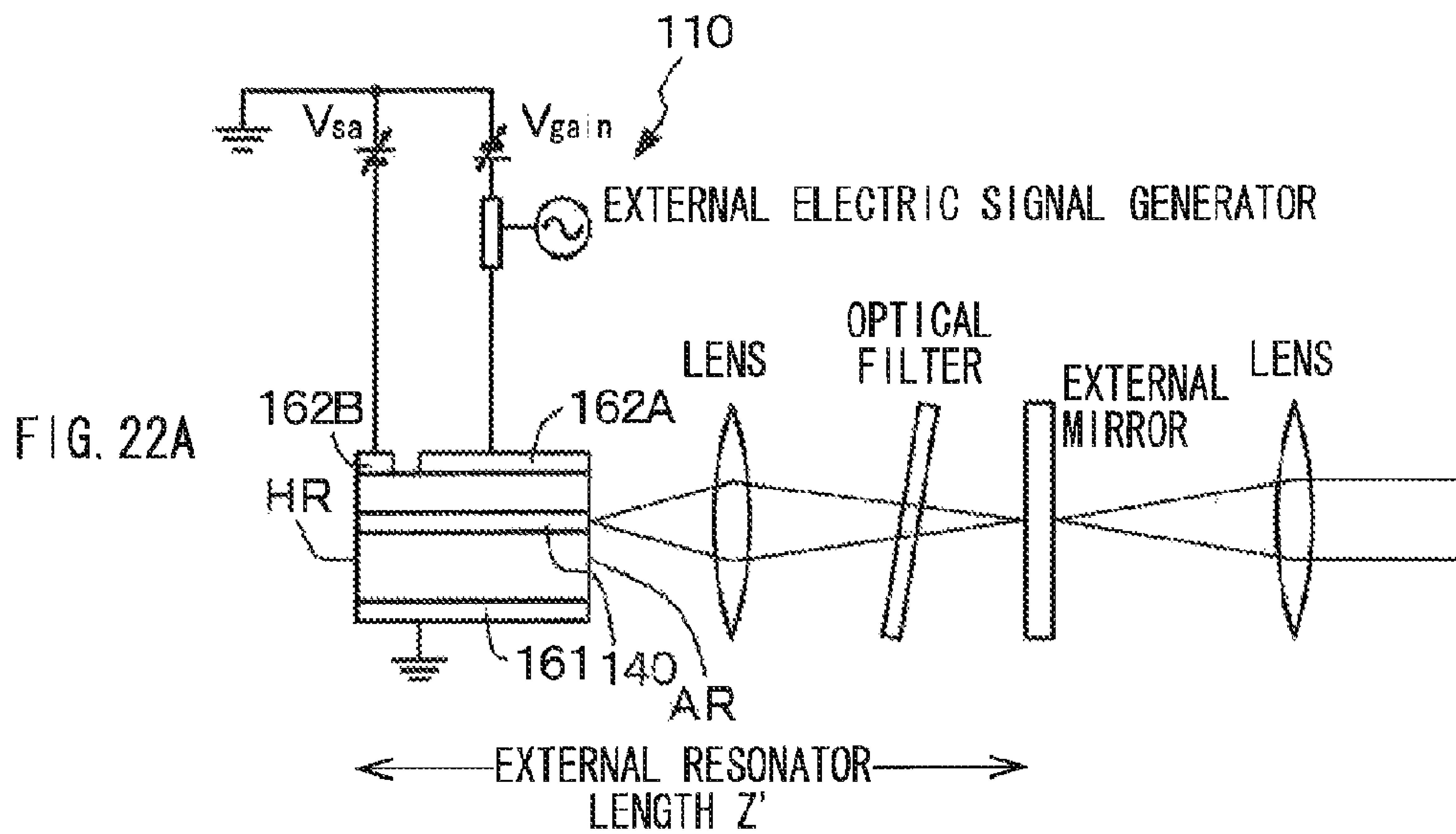
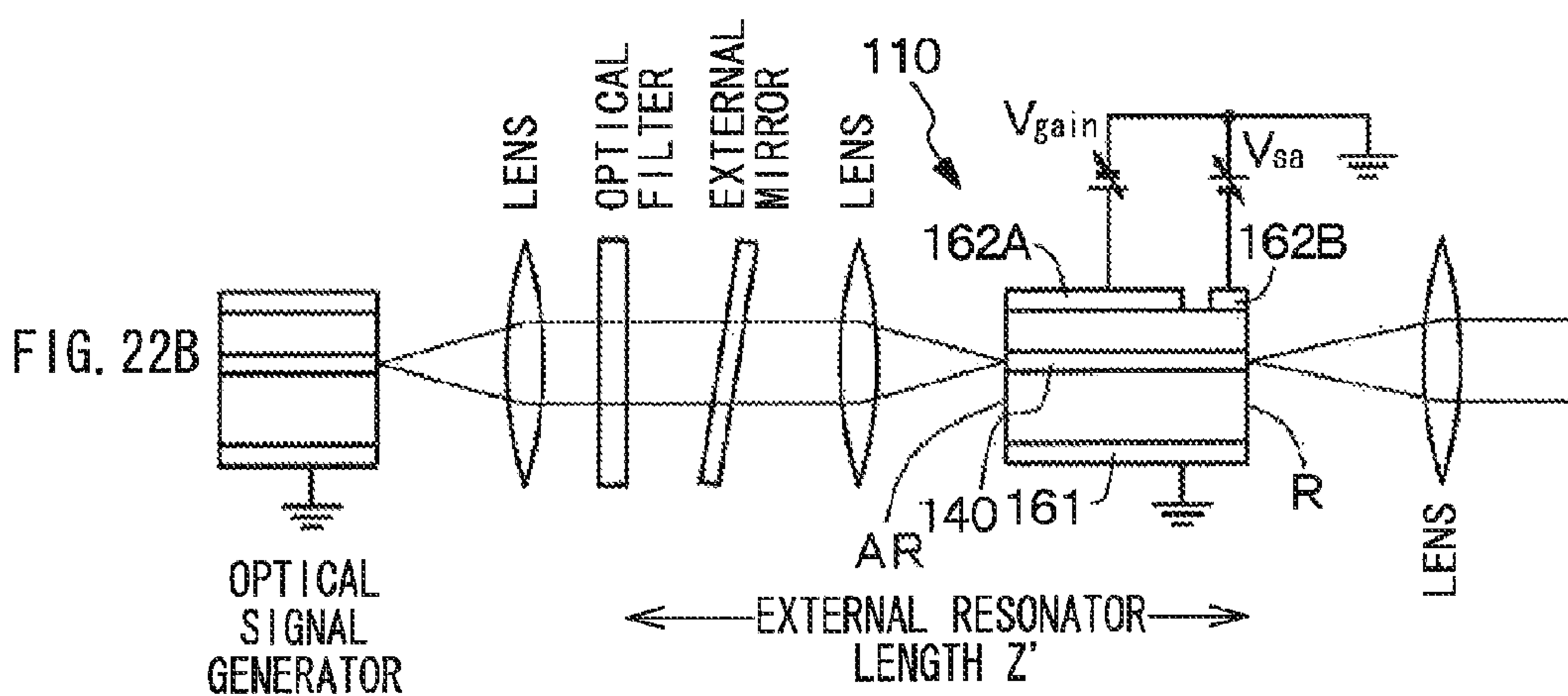


FIG. 21


110
V_{sa}
V_{gain}
EXTERNAL ELECTRIC SIGNAL GENERATOR
LENS
OPTICAL FILTER
EXTERNAL MIRROR
LENS
FIG. 22A
162B
162A
HR
161
140
AR
EXTERNAL RESONATOR LENGTH Z'


LENS
OPTICAL FILTER
EXTERNAL MIRROR
LENS
110
V_{gain}
V_{sa}
162A
162B
FIG. 22B
AR
140
161
R
LENS
OPTICAL SIGNAL GENERATOR
EXTERNAL RESONATOR LENGTH Z'

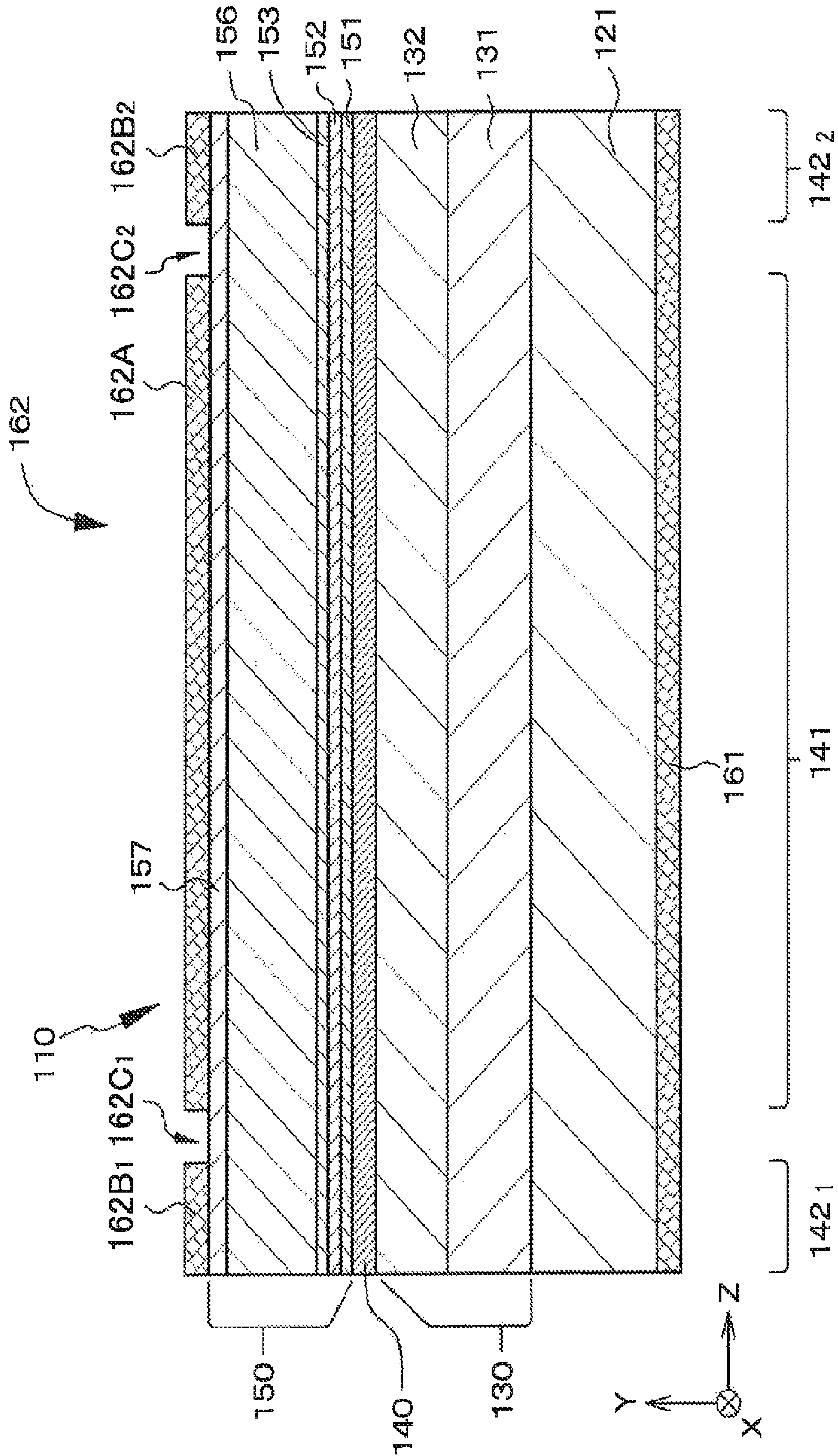


FIG. 23

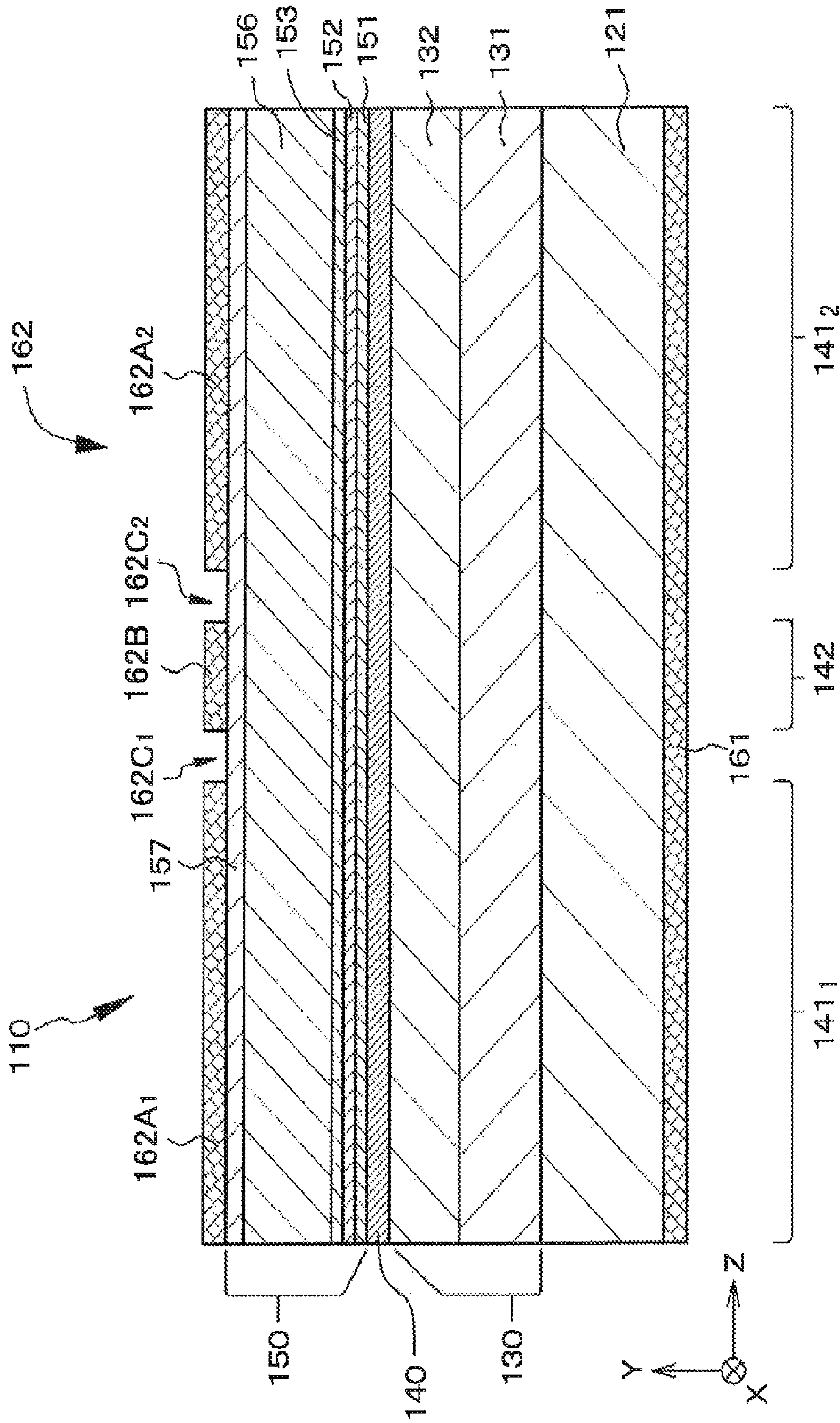


FIG. 24

FIG. 25A

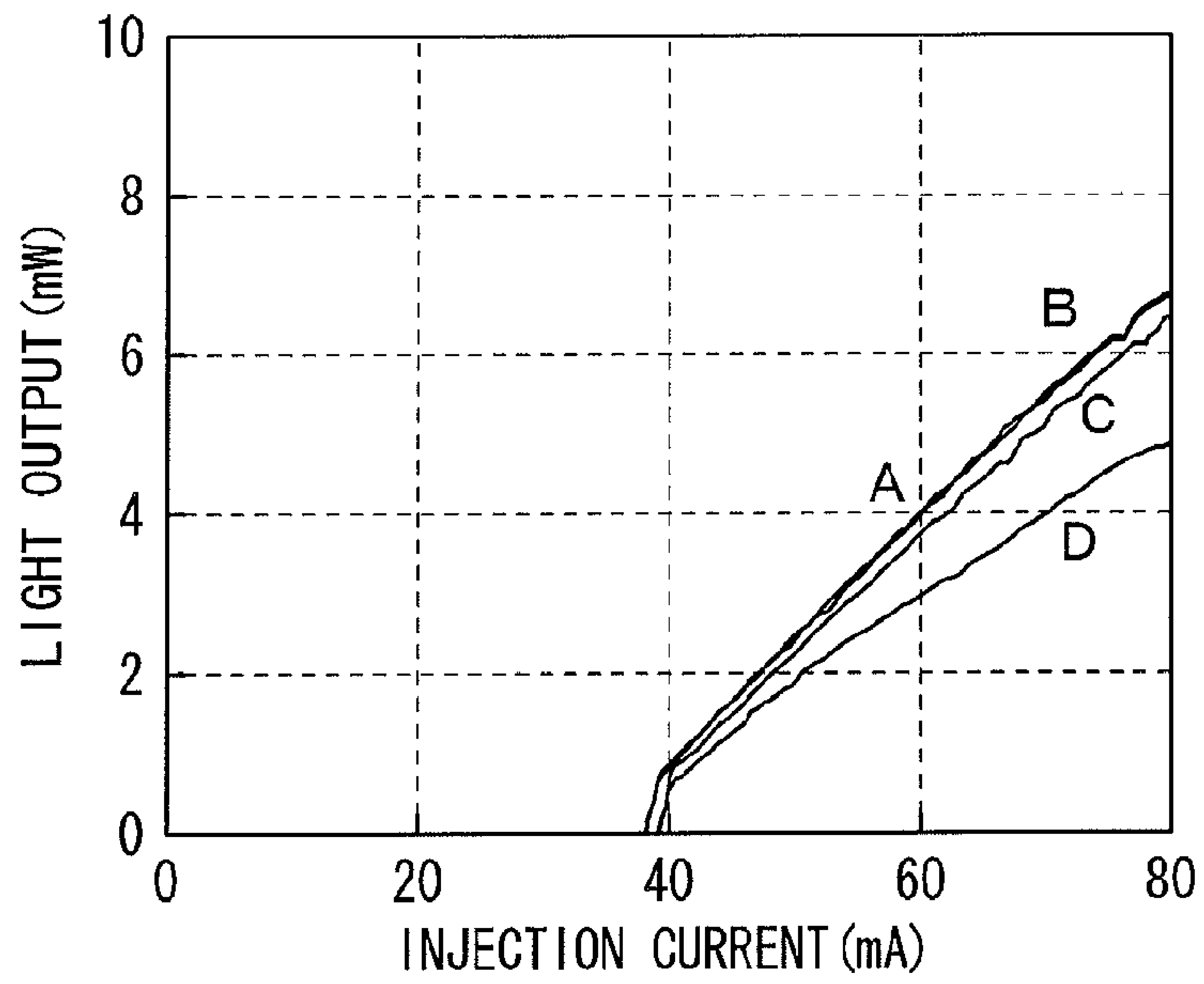


FIG. 25B

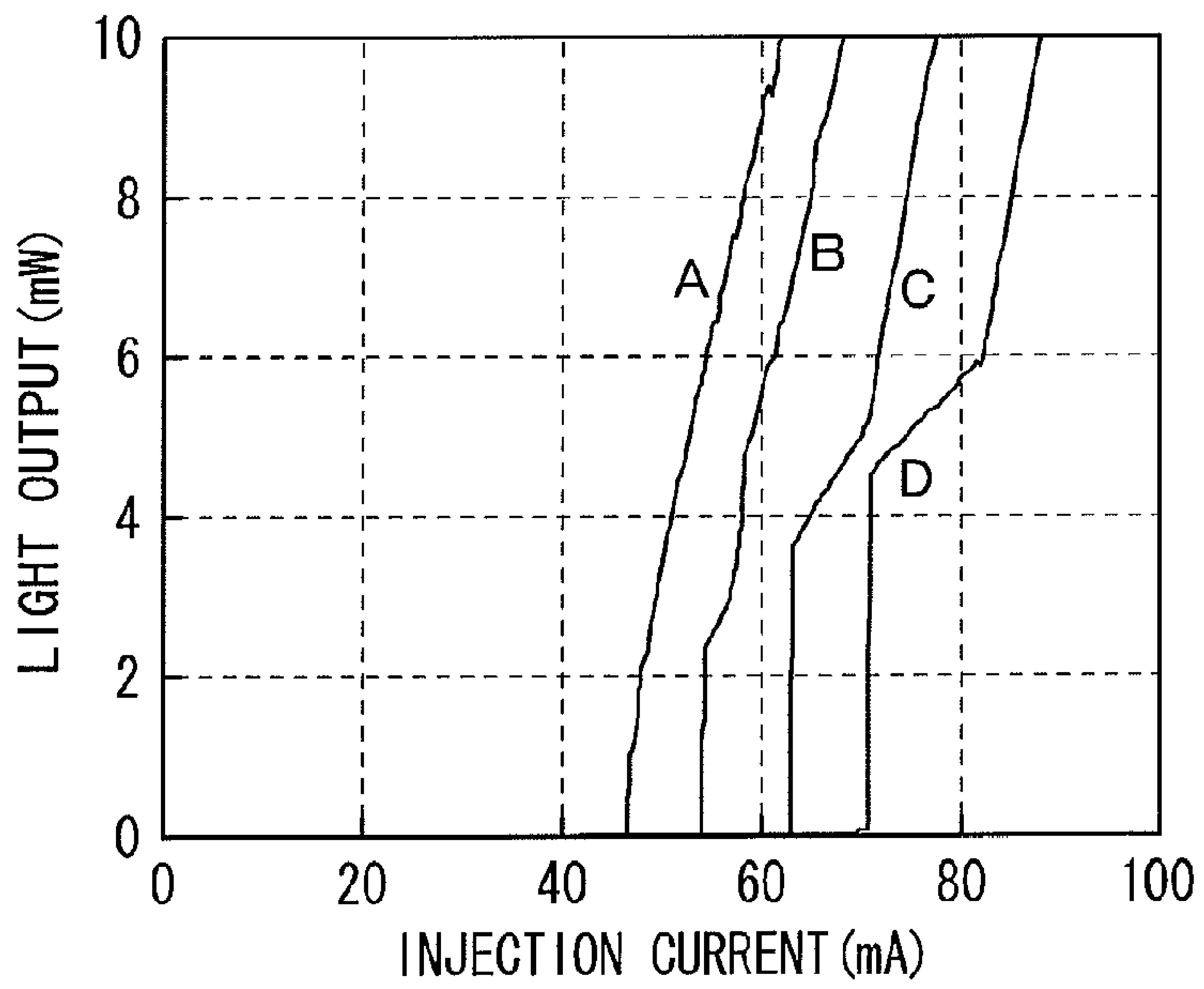


FIG. 26A

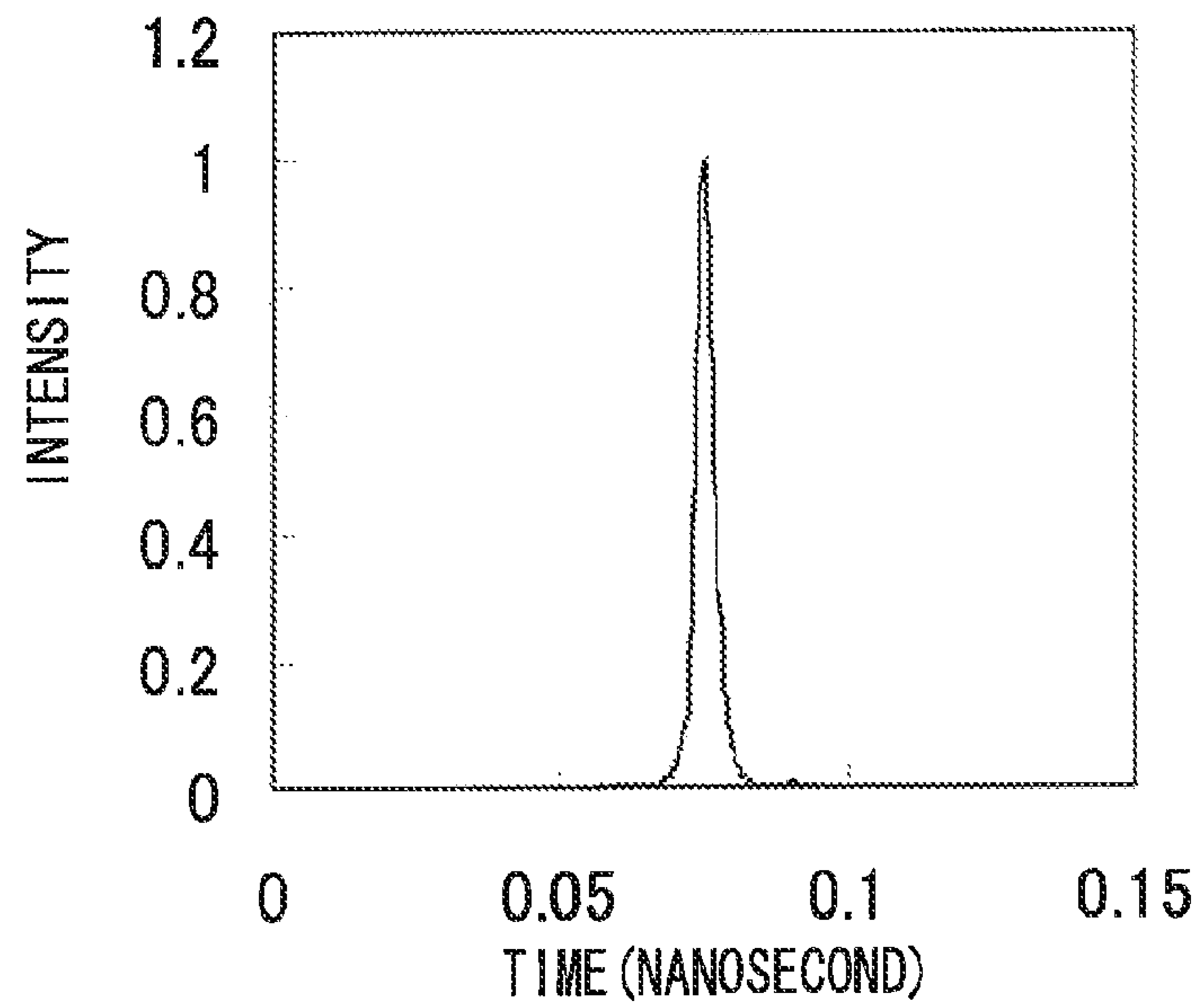
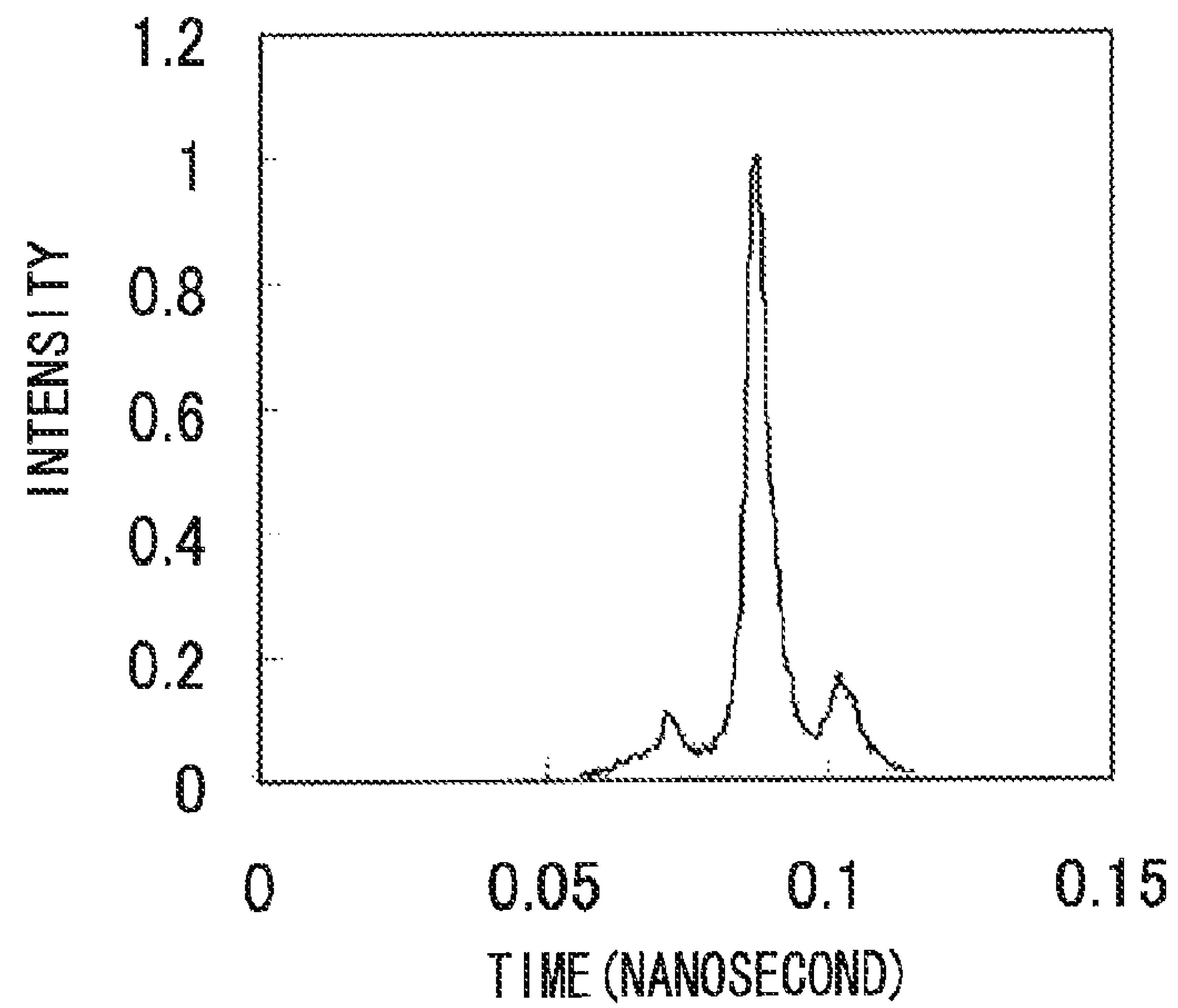


FIG. 26B



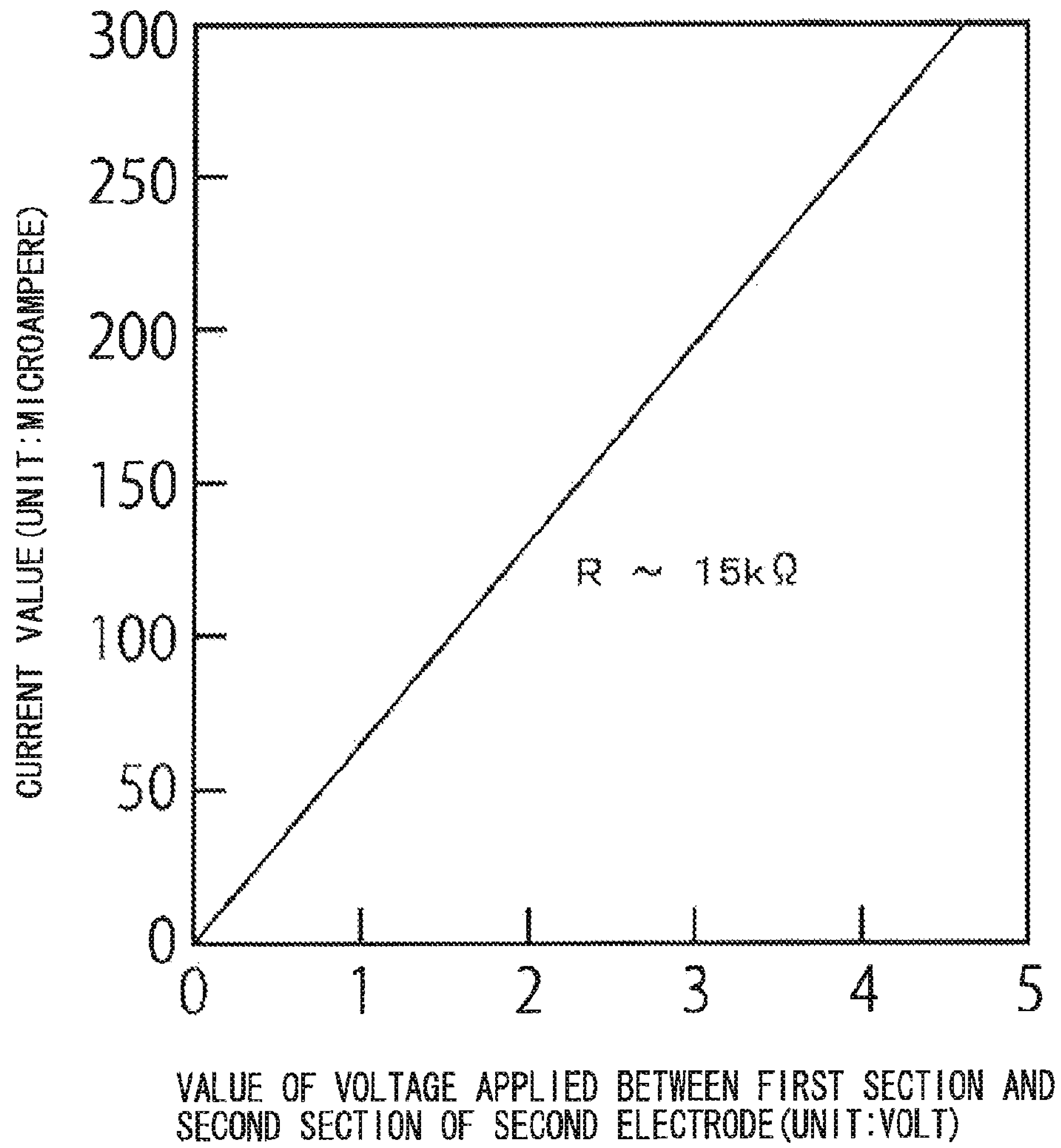


FIG. 27

FIG. 28A

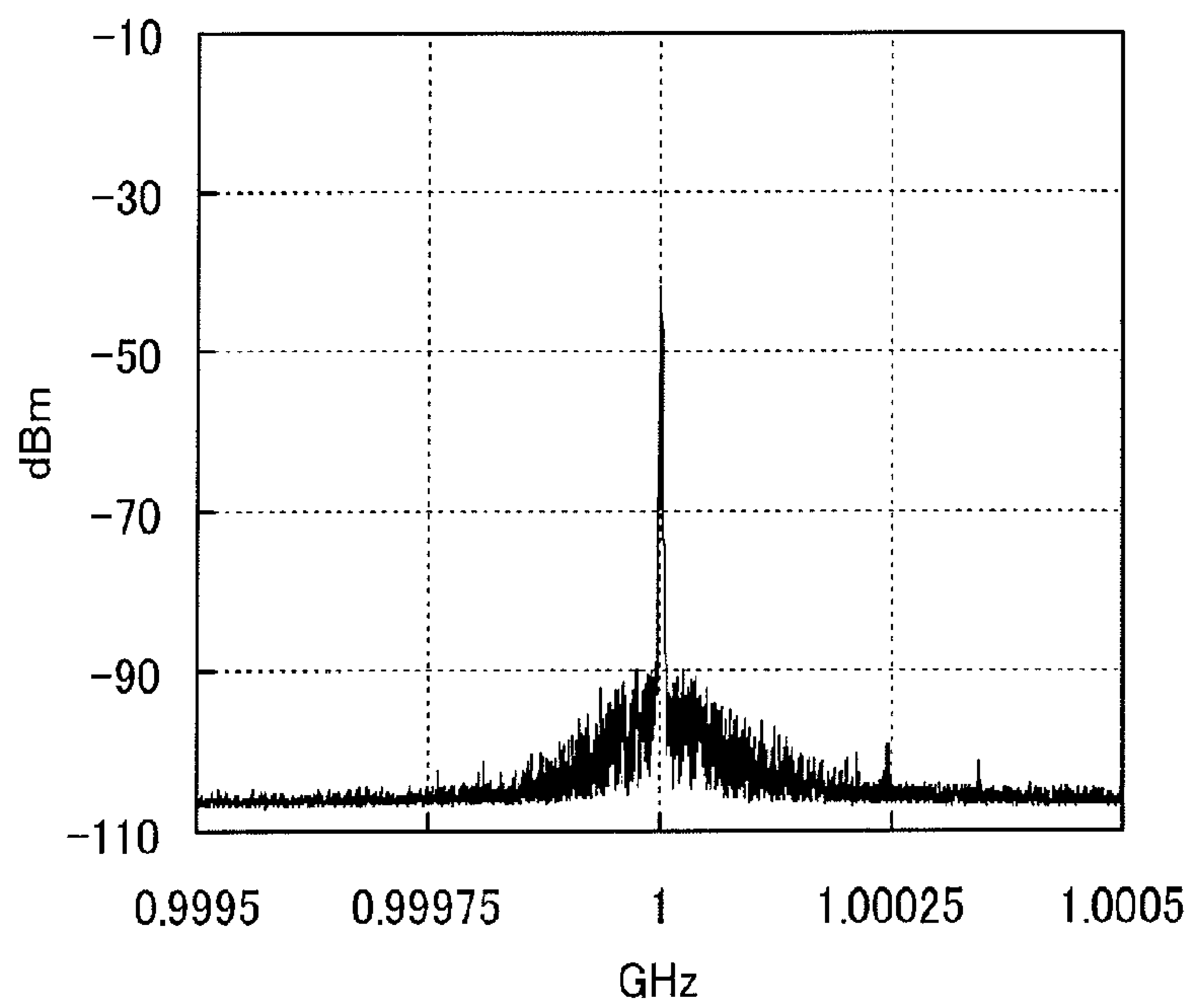
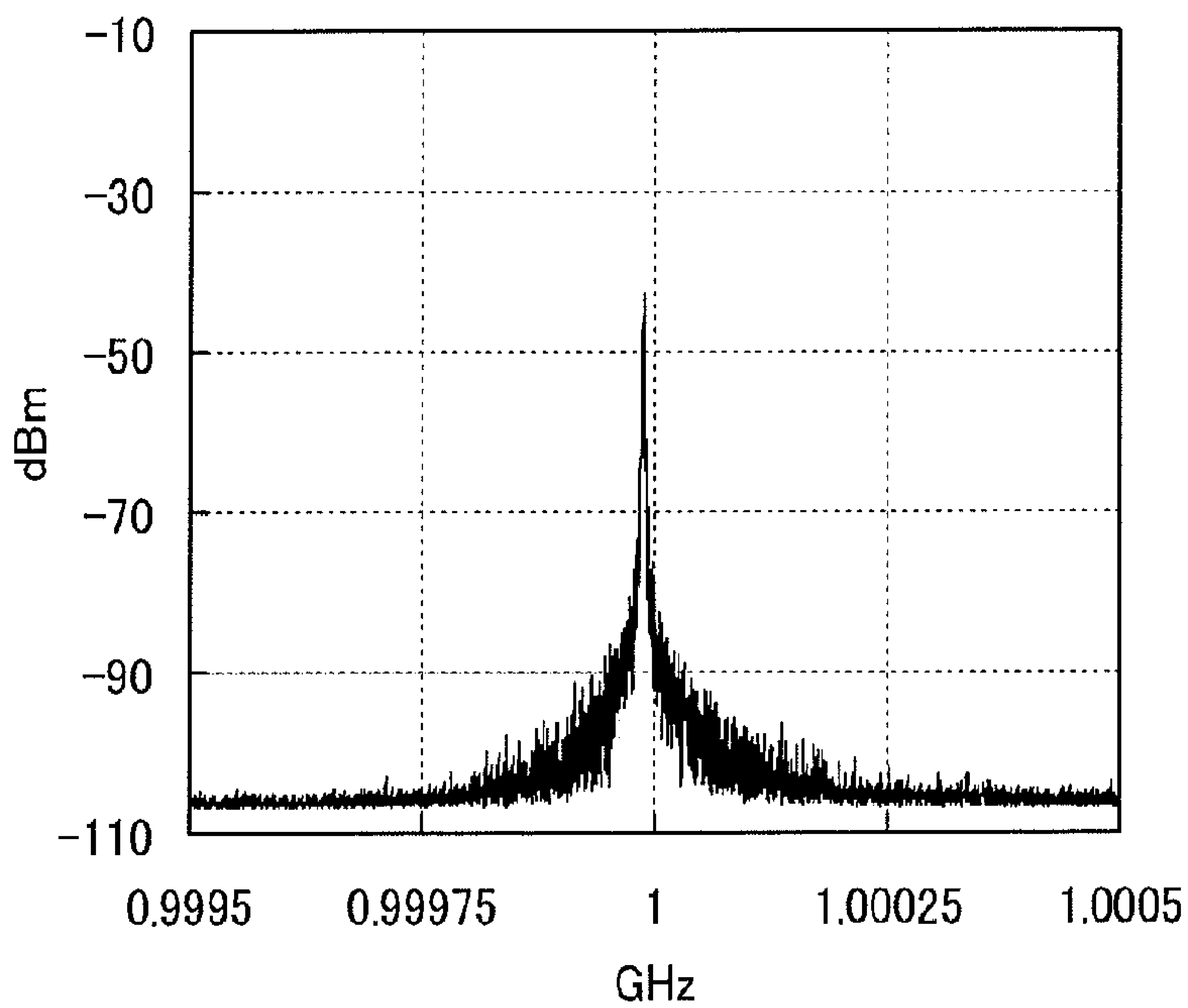


FIG. 28B



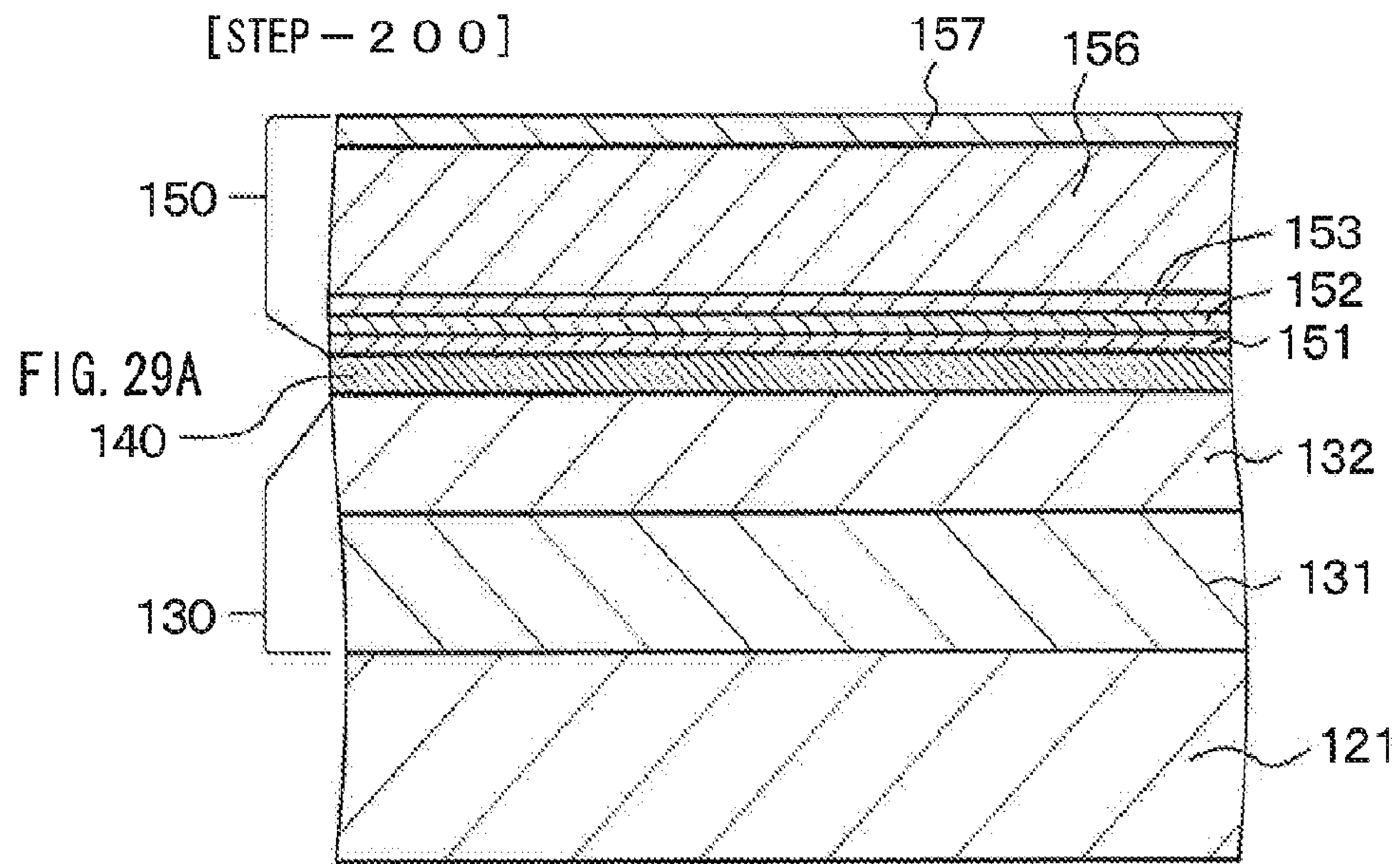


FIG. 29A

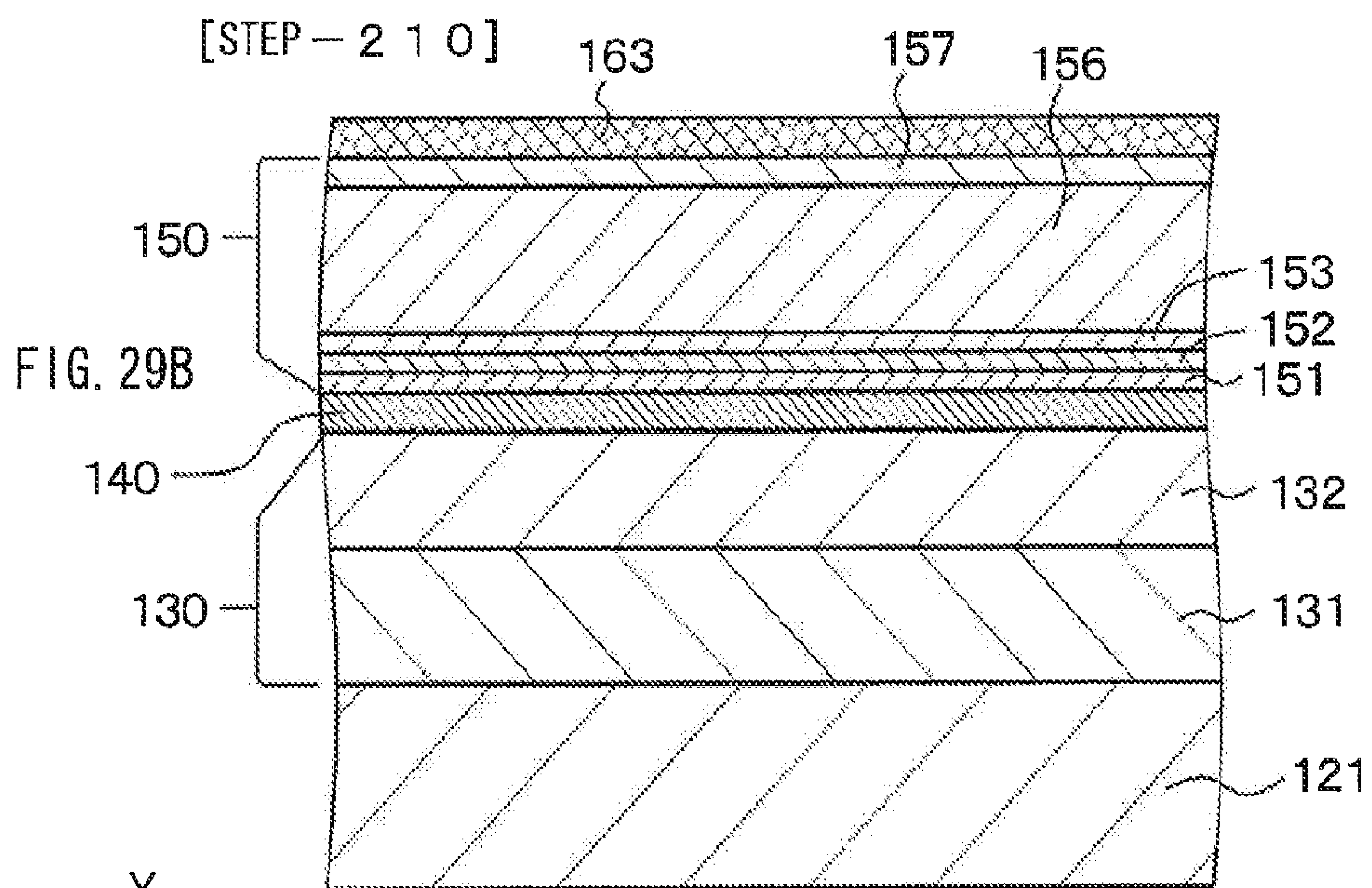
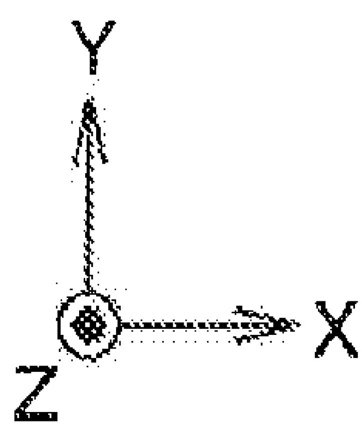


FIG. 29B



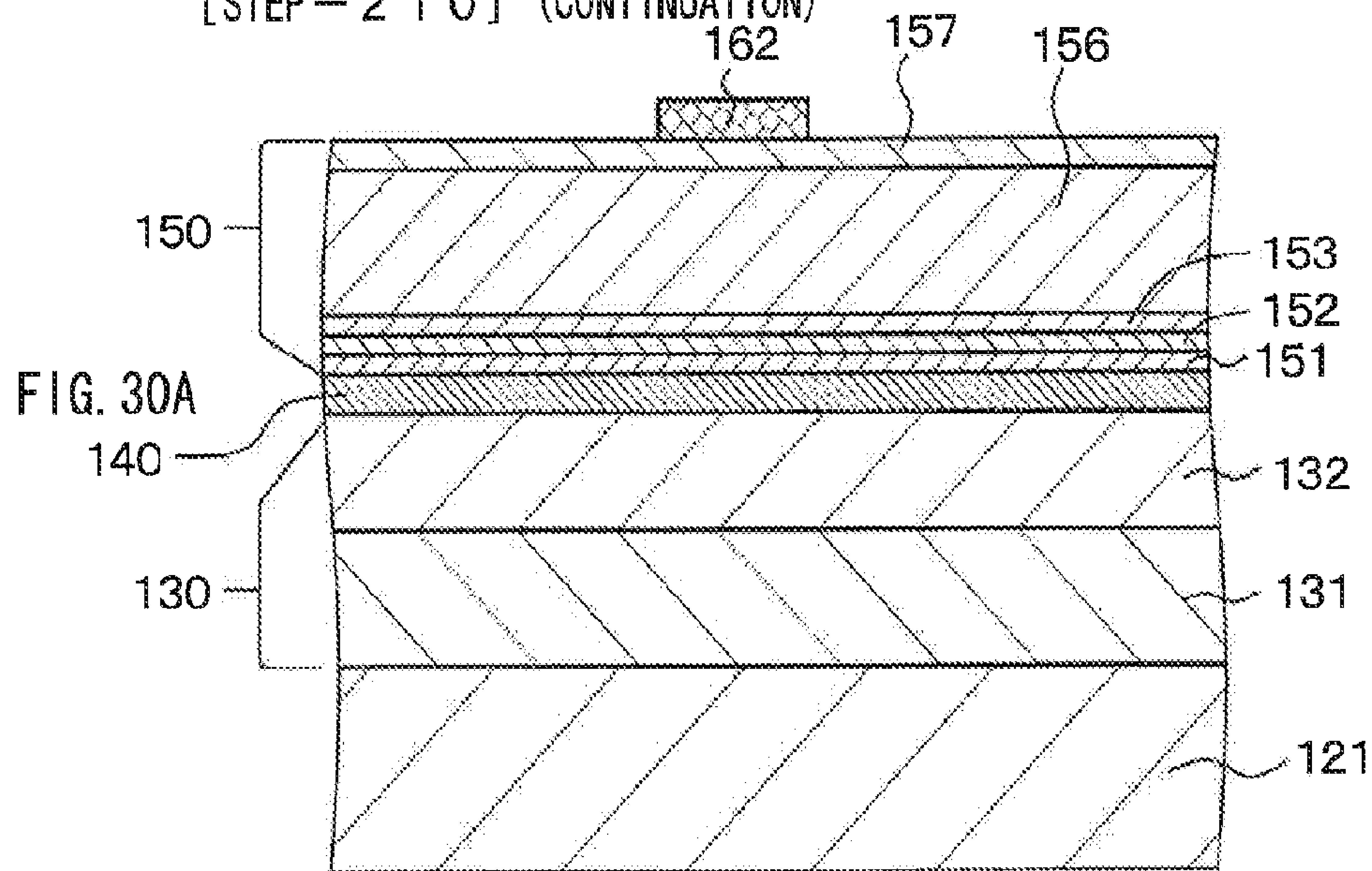


FIG. 30A

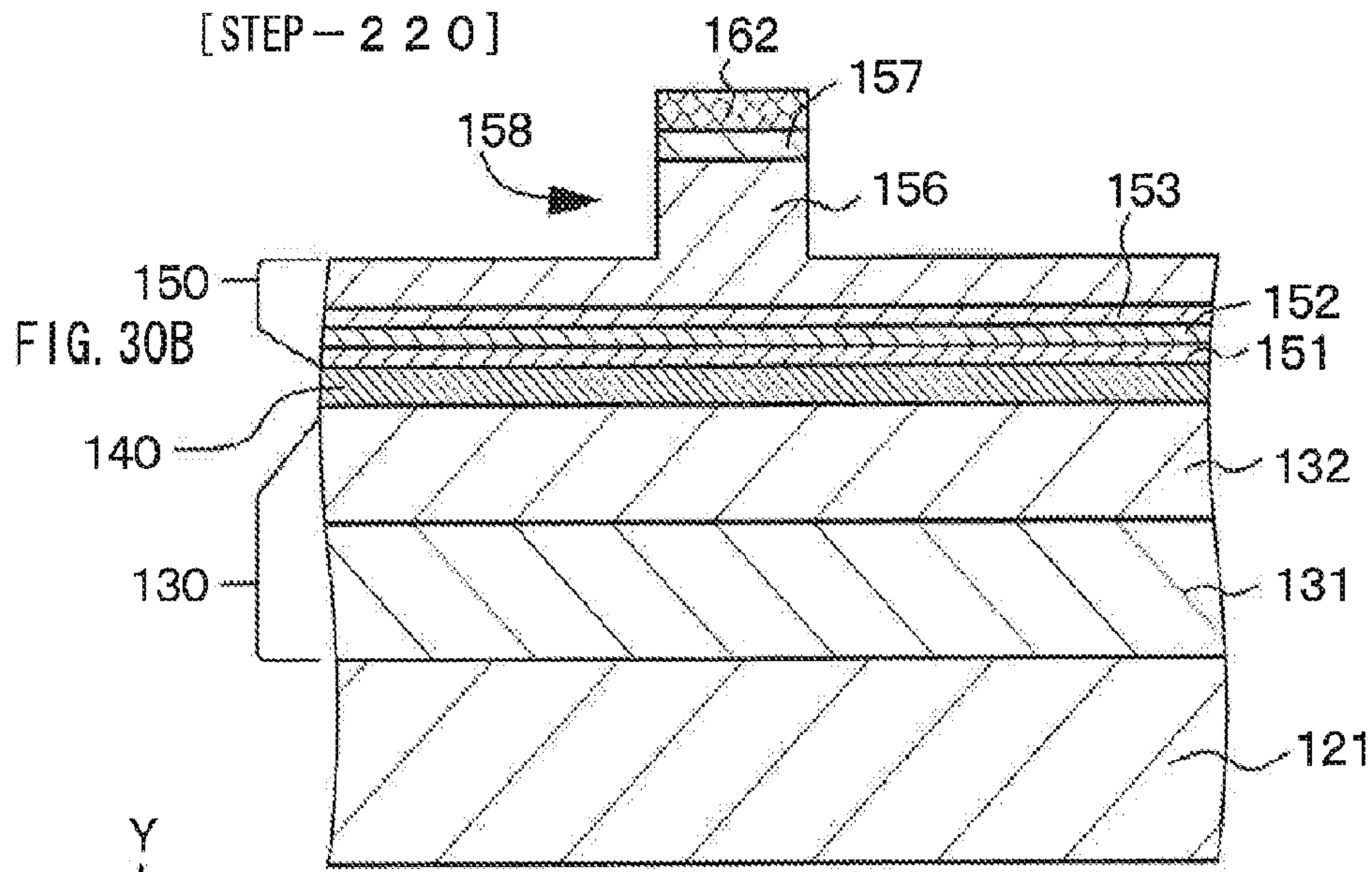
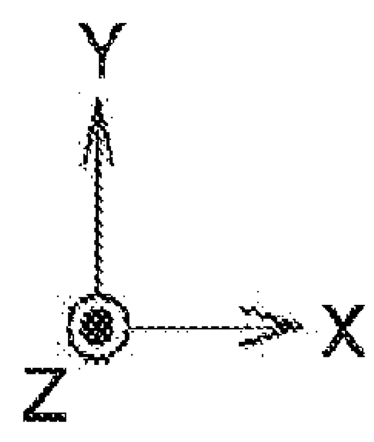


FIG. 30B



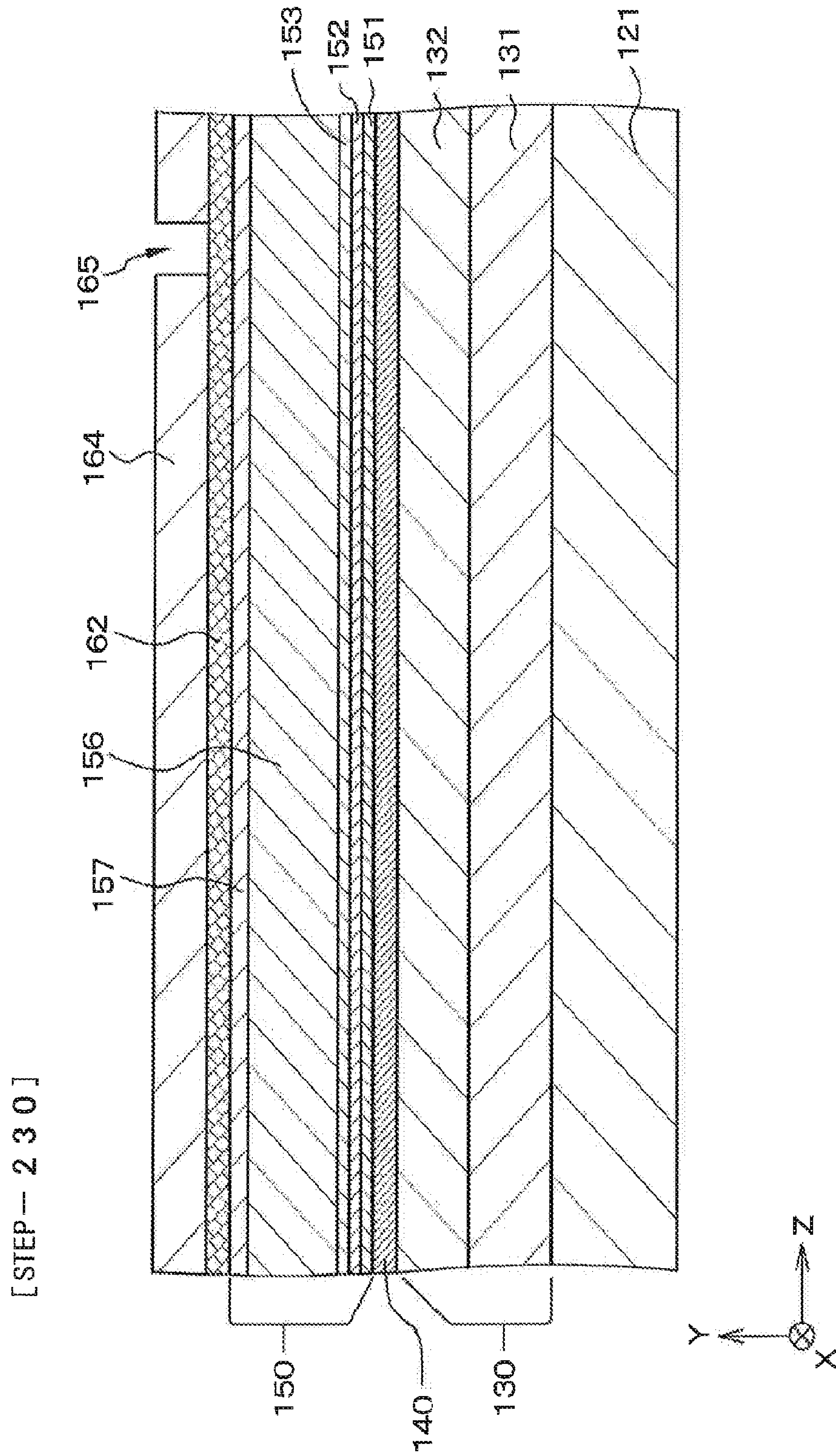


FIG. 31

SEMICONDUCTOR OPTICAL AMPLIFIER

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue; a claim printed with strikethrough indicates that the claim was canceled, disclaimed, or held invalid by a prior post-patent action or proceeding.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a semiconductor optical amplifier.

2. Description of the Related Art

In these days, in the advanced scientific region researches using laser light with the pulse time on the attosecond time scale or on the femtosecond time scale, the ultrashort pulse and ultrahigh power laser is actively used. Further, the high power and ultrashort pulse laser diode device that is composed of GaN compound semiconductor and that has light emitting wavelength of 405 nm band has been expected to be a light source for a volumetric optical disc system expected as a next generation optical disc system displacing the blu-ray optical disc system or has been expected to be a light source demanded in the medical field, the bio imaging field and the like.

As the ultrashort pulse and ultrahigh power laser, for example, titanium/sapphire laser is known. Such a titanium/sapphire laser is an expensive and large solid laser light source, which is a main factor to inhibit spread of the technology. If the ultrashort pulse and ultrahigh power laser is realized with the use of a laser diode or a laser diode device, significant miniaturization, price reduction, and high stability are able to be realized, which is expected to become a breakthrough for promoting its wide usage in these fields.

Meanwhile, short pulsation of the laser diode device has been actively researched since 1960s in the communication system field. As a method of generating short pulses in the laser diode device, gain switching method, loss switching method (Q switching method), and mode locking method are known. In these methods, high output is pursued by combining the laser diode device with a semiconductor amplifier, a nonlinear optical device, an optical fiber and the like. The mode locking is further categorized into active mode locking and passive mode locking. To generate light pulses based on the active mode locking, an external oscillator is configured by using a mirror or a lens, and further high frequency (RF) modulation is added to the laser diode device. Meanwhile, in the passive mode locking, light pulses are able to be generated by simple direct current drive by using a laser diode device having a multiple electrode structure.

In the laser light source, obtaining high power is a big challenge. As a means for amplifying light from the laser light source, the semiconductor optical amplifier (SOA) has been keenly examined. The optical amplifier is an amplifier that directly amplifies an optical signal in a state of light without converting the optical signal to an electric signal. The optical amplifier has a laser structure without resonator, and amplifies incident light by light gain of the amplifier.

In the past, the optical amplifier has been mainly developed for optical communication. Thus, for practical application of the semiconductor optical amplifier in 405 nm band, very few precedent cases exist. For example, based on Japanese Unexamined Patent Application Publication No. 5-067845, the semiconductor optical amplifier in 1.5 μm band that uses GaInAsP compound semiconductor and that has a tapered ridge stripe structure has been known. In the technique disclosed in the foregoing Japanese Unexamined Patent Application Publication No. 5-067845, in the semiconductor optical amplifier, a light guide width is gently extended in tapered shape from the narrow input-side-light guide satisfying single mode conditions to output-side-light guide. Thereby, mode field is expanded along the light guide width to improve maximum output of the semiconductor optical amplifier.

SUMMARY OF THE INVENTION

However, it becomes clear by studies by the inventors of the invention as follows. That is, in the semiconductor optical amplifier composed of GaN compound semiconductor, even if the light guide width on the output side is widened, the width of an outputted near-field image is not expanded and is narrower than the light guide width. The foregoing fact may lead to inhibition of increase of the maximum output of the semiconductor optical amplifier, and instability of laser light outputted from the semiconductor optical amplifier.

Accordingly, in the invention, it is firstly desirable to provide a semiconductor optical amplifier composed of GaN compound semiconductor that is able to retain higher light output. Further, it is secondly desirable to provide a semiconductor optical amplifier with which there is no possibility that laser light outputted from the semiconductor optical amplifier is unstable.

According to a first embodiment to a third embodiment of the invention to attain the foregoing first and the second objects, there is provided a semiconductor optical amplifier including: a laminated structure in which a first compound semiconductor layer that has a first conductivity type and is composed of GaN compound semiconductor, a third compound semiconductor layer that has a light amplification region (carrier non-injection region, gain region) composed of GaN compound semiconductor, and a second compound semiconductor layer that has a second conductivity type different from the first conductivity type and is composed of GaN compound semiconductor are sequentially layered; a second electrode formed on the second compound semiconductor layer; and a first electrode electrically connected to the first compound semiconductor layer, wherein the laminated structure has a ridge stripe structure. When a width of the ridge stripe structure in a light output end face is W_{out}, and a width of the ridge stripe structure in a light incident end face is W_{in}, $W_{out} > W_{in}$ is satisfied.

In the semiconductor optical amplifier according to the first embodiment of the invention to attain the foregoing first object, a carrier non-injection region is provided in an internal region of the laminated structure from the light output end face along an axis line of the semiconductor optical amplifier.

In the semiconductor optical amplifier according to the second embodiment of the invention to attain the foregoing second object, a width of the second electrode is narrower than the width of the ridge stripe structure.

In the semiconductor optical amplifier according to the third embodiment of the invention to attain the foregoing second object, when a maximum width of the ridge stripe structure is W_{max}, $W_{max} > W_{out}$ is satisfied.

In the semiconductor optical amplifiers according to the first embodiment to the third embodiment of the invention, where the width of the ridge stripe structure in the light output end face is W_{out}, and the width of the ridge stripe structure in the light incident end face is W_{in}, $W_{out} > W_{in}$ is satisfied. That is, the light guide width is broadened from the light guide on the light output side having a narrow width satisfying single

mode conditions to the light guide on the light output side having a wide width. Thus, mode field is able to be expanded according to the light guide width, high light output of the semiconductor optical amplifier is able to be attained, and laser light is able to be optically amplified while single lateral mode is maintained.

Further, in the semiconductor optical amplifier according to the first embodiment of the invention, the carrier non-injection region is provided in the internal region of the laminated structure from the light output end face along the axis line of the semiconductor optical amplifier. Thus, the width of laser light outputted from the light output end face is able to be broadened. Therefore, higher light output is able to be attained, and reliability is able to be improved. Meanwhile, in the semiconductor optical amplifier according to the second embodiment of the invention, the width of the second electrode is narrower than the width of the ridge stripe structure. In the semiconductor optical amplifier according to the third embodiment of the invention, when the maximum width of the ridge stripe structure is W_{max}, $W_{max}>W_{out}$ is satisfied. Thereby, stable lateral mode amplified light is obtained, and there is no possibility that laser light outputted from the semiconductor optical amplifier becomes unstable.

Other and further objects, features and advantages of the invention will appear more fully from the following description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a conceptual view of a light output device of a first example including a semiconductor optical amplifier.

FIG. **2** is a schematic cross sectional view of the semiconductor optical amplifier where the semiconductor optical amplifier is cut along a virtual vertical plane (YZ plane) including an axis line (Z direction) of the semiconductor optical amplifier of the first example.

FIG. **3** is a schematic cross sectional view of the semiconductor optical amplifier where the semiconductor optical amplifier is cut along a virtual vertical plane (XY plane) orthogonal to the axis line of the semiconductor optical amplifier of the first example.

FIG. **4** is a schematic perspective view of the semiconductor optical amplifier of the first example.

FIG. **5** is a schematic plan view of a ridge stripe structure in the semiconductor optical amplifier of the first example.

FIGS. **6**A and **6**B are respectively near-field images of laser light outputted from the semiconductor optical amplifier of the first example and a semiconductor optical amplifier of Comparative example 1.

FIG. **7** is a conceptual view of a light output device of a second example including the semiconductor optical amplifier.

FIG. **8** is a schematic cross sectional view of the semiconductor optical amplifier where the semiconductor optical amplifier is cut along a virtual vertical plane (YZ plane) including an axis line (Z direction) of the semiconductor optical amplifier of the second example.

FIG. **9** is a schematic cross sectional view of the semiconductor optical amplifier where the semiconductor optical amplifier is cut along a virtual vertical plane (XY plane) orthogonal to the axis line of the semiconductor optical amplifier of the second example.

FIG. **10** is a schematic end view taken along the direction in which a resonator of a mode locking laser diode device in the second example extends.

FIG. **11** is a schematic perspective view of the semiconductor optical amplifier of the second example.

FIG. **12** is a schematic plan view of a ridge stripe structure in the semiconductor optical amplifier of the second example.

FIG. **13** is a graph schematically illustrating change of a current flown in the semiconductor optical amplifier in the case where a given value of voltage is applied to the semiconductor optical amplifier while making laser light enter the semiconductor optical amplifier of the second example from the laser light source and XYZ stage is moved in the X direction.

FIG. **14**A is a conceptual view of a modification of the light output device of the second example, and FIG. **14**B is a conceptual view of a monolithic semiconductor optical amplifier.

FIGS. **15**A and **15**B are schematic perspective views of semiconductor optical amplifiers according to a third example and a fourth example.

FIG. **16** is a schematic plan view of a ridge stripe structure of the semiconductor optical amplifier of the third example illustrated in FIG. **15**A.

FIGS. **17**A and **17**B are schematic perspective views of semiconductor optical amplifiers of modifications of the third example and the fourth example.

FIG. **18** is a schematic plan view of a ridge stripe structure of the semiconductor optical amplifier of the modification of the third example illustrated in FIG. **17**A.

FIGS. **19**A and **19**B are views respectively and schematically illustrating a system of performing mode locking drive by configuring an external resonator from the mode locking laser diode device in the second example and a mode locking laser diode device in a sixth example.

FIGS. **20**A and **20**B are views respectively and schematically illustrating a system of performing mode locking drive by configuring an external resonator from a mode locking laser diode device in a fifth example, and FIG. **20**C is a view schematically illustrating a system of performing mode locking drive by using the mode locking laser diode device in the sixth example.

FIG. **21** is a schematic view viewed from above of a ridge section in a mode locking laser diode device of a seventh example.

FIGS. **22**A and **22**B are views respectively and schematically illustrating a system of performing mode locking drive by using a mode locking laser diode device in an eighth example and a mode locking laser diode device in a ninth example.

FIG. **23** is a schematic end view taken along a direction in which a resonator of a modification of the mode locking laser diode device in the second example is extended.

FIG. **24** is a schematic end view taken along a direction in which a resonator of another modification of the mode locking laser diode device in the second example is extended.

FIGS. **25**A and **25**B are graphs illustrating reverse bias voltage dependence measurement results of relation between an injection current and light output (L-I characteristics) in the second example and a second referential example.

FIGS. **26**A and **26**B are views illustrating results obtained by measuring light pulse generated in the second example and the second referential example by a streak camera.

FIG. **27** is a graph illustrating result obtained by measuring an electric resistance value between a first section and a second section of a second electrode of the mode locking laser diode device obtained in the second example by four terminal method.

FIGS. **28**A and **28**B are graphs respectively illustrating results of measuring RF spectrum of the eighth example and an eighth referential example.

FIGS. **29**A and **29**B are schematic partial cross sectional views of a substrate and the like for explaining a method of manufacturing the mode locking laser diode device in the second example.

FIGS. **30**A and **30**B are schematic partial cross sectional views of a substrate and the like for explaining a method of manufacturing the mode locking laser diode device in the second example following FIG. **29**B.

FIG. **31** is a schematic partial end view of a substrate and the like for explaining a method of manufacturing the mode locking laser diode device in the second example following FIG. **30**B.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

While the invention will be hereinafter described based on examples with reference to the drawings, the invention is not limited to the examples, and various numerical values and materials in the examples are exemplification. The description will be given in the following order:

1. Semiconductor optical amplifiers according to a first embodiment to a third embodiment of the invention and overall description
2. First example (the semiconductor optical amplifier according to the first embodiment of the invention)
3. Second example (modification of the first example)
4. Third example (the semiconductor optical amplifiers according to the second embodiment and the third embodiment of the invention)
5. Fourth example (modification of the third example)
6. Fifth example (modification of the mode locking laser diode device in the second example)
7. Sixth example (another modification of the mode locking laser diode device in the second example)
8. Seventh example (another modification of the mode locking laser diode device in the second example)
9. Eighth example (another modification of the mode locking laser diode device in the second example)
10. Ninth example (another modification of the mode locking laser diode device in the second example) and others

Semiconductor Optical Amplifiers According to a First Embodiment to a Third Embodiment of the Invention and Overall Description

In the semiconductor optical amplifier according to the first embodiment of the invention, W_{out} may be 5 μm or more. Though the upper limit of W_{out} is not limited, for example, 4×10^2 μm can be exemplified as the upper limit of W_{out}. Further, in the semiconductor optical amplifier according to the first embodiment of the invention, W_{in} may be from 1.4 μm to 2.0 μm both inclusive. The foregoing preferred embodiments may be applied to the semiconductor optical amplifiers according to the second embodiment and the third embodiment of the invention.

In the semiconductor optical amplifier according to the second embodiment of the invention, the value of (width of a second electrode)/(width of a ridge stripe structure) is desirably from 0.2 to 0.9 both inclusive, and is preferably from 0.6 to 0.9 both inclusive. The width of the second electrode and the width of the ridge stripe structure mean the width of the second electrode and the width of the ridge stripe structure obtained where the semiconductor optical amplifier is cut in a certain virtual plane orthogonal to the axis line of the semiconductor optical amplifier.

Further, in the semiconductor optical amplifier according to the third embodiment of the invention, $0.2\leq W_{out}/W_{max}\leq0.9$ is desirably satisfied, and $0.5\leq W_{out}/W_{max}\leq0.9$ is preferably satisfied.

In the semiconductor optical amplifiers according to the second embodiment and the third embodiment of the invention, as in the semiconductor optical amplifier according to the first embodiment of the invention, a carrier non-injection region may be provided in an internal region of a laminated structure from a light output end face along the axis line of the semiconductor optical amplifier. In the semiconductor optical amplifiers according to the first embodiment to the third embodiment of the invention, further, the carrier non-injection region may be also provided in an internal region of the laminated structure from a light incident end face along the axis line of the semiconductor optical amplifier.

Further, in the semiconductor optical amplifiers according to the first embodiment to the third embodiment of the invention, it is possible that the second electrode is not provided in the carrier non-injection region, or it is possible that the second electrode is composed of a first section and a second section that are separated by an isolation trench, and the second section of the second electrode is provided in the carrier non-injection region. In the latter case, a voltage equal to or less than a built-in voltage is desirably applied to the second section of the second electrode. Specifically, a voltage equal to or less than (1.2398/λ) is desirably applied to the second section of the second electrode. λ represents wavelength of incident laser light to the semiconductor optical amplifier (unit: μm), and "1.2398" represents constant number. For example, in the case where 0.4 μm wavelength laser light enters the semiconductor optical amplifier, a voltage equal to or less than 3.0995 volt is desirably applied. Though not limited, as the lower limit value of voltage applied to the second section of the second electrode, −20 volt can be exemplified. Light amplification as an inherent function of the semiconductor optical amplifier is able to be performed by applying a voltage to the first section of the second electrode, while monitoring light intensity and measurement for position adjustment and the like are able to be performed by applying a voltage to the second section of the second electrode. For such a point, a description will be given in detail later. Further, near-field image is able to be controlled.

Further, in the semiconductor optical amplifiers according to the first embodiment to the third embodiment of the invention, the axis line of the semiconductor optical amplifier may intersect with the axis line of the ridge stripe structure at a given angle. As given angle θ, 0.1 deg≤θ≤10 deg can be exemplified. The axis line of the ridge stripe structure is a straight line that connects the point obtained by equally dividing the line between both ends of the ridge stripe structure in the light output end face with the point obtained by equally dividing the line between both ends of the ridge stripe structure in the light incident end face.

Further, in the semiconductor optical amplifiers according to the first embodiment to the third embodiment of the invention, a low reflective coating layer formed from a laminated structure composed of at least two types of layers selected from the group consisting of a titanium oxide layer, a tantalum oxide layer, a zirconia oxide layer, a silicon oxide layer, and an aluminum oxide layer may be formed in the light incident end face and the light output end face.

Further, in the semiconductor optical amplifiers according to the first embodiment to the third embodiment of the invention, though not limited, the light intensity density of laser light outputted from the semiconductor optical amplifier may be 60 kilowatt or more per 1 cm^2 of a third compound semi-

conductor structuring the light output end face, and may be preferably 600 kilowatt or more.

Further, in the semiconductor optical amplifiers according to the first embodiment to the third embodiment of the invention, the value of (width of the ridge stripe structure in the light output end face)/(width of laser light outputted from the semiconductor optical amplifier) may be from 1.1 to 10 both inclusive, and may be preferably from 1.1 to 5 both inclusive.

Further, in the semiconductor optical amplifiers according to the first embodiment to the third embodiment of the invention (hereinafter, in some cases, such semiconductor optical amplifiers will be generically and simply referred to as "semiconductor optical amplifier of the embodiment of the invention,") the semiconductor optical amplifier may be composed of a transmissive semiconductor optical amplifier. However, the semiconductor optical amplifier is not limited to the transmissive semiconductor optical amplifier. For example, the semiconductor optical amplifier may be composed of a monolithic semiconductor optical amplifier.

In the semiconductor optical amplifier of the embodiment of the invention, $W_{out}>W_{in}$ is satisfied where the width of the ridge stripe structure in the light output end face is W_{out}, and the width of the ridge stripe structure in the light incident end face is W_{in}. In this case, each end section of the ridge stripe structure may be composed of one line segment (the semiconductor optical amplifiers according to the first embodiment and the second embodiment of the invention), or may be composed of two or more line segments (the semiconductor optical amplifiers according to the first embodiment to the third embodiment of the invention). In the former case, for example, the width of the ridge stripe structure is gently and flatly extended in tapered shape from the light incident end face to the light output end face. Meanwhile, in the latter case and in the semiconductor optical amplifiers according to the first embodiment and the second embodiment of the invention, for example, the width of the ridge stripe structure is firstly the same, and is next gently and flatly extended in tapered shape from the light incident end face to the light output end face. Further, in the latter case and in the semiconductor optical amplifier according to the second embodiment of the invention, for example, the width of the ridge stripe structure is firstly widened, and is next narrowed after the width exceeds the maximum width from the light incident end face to the light output end face.

In the semiconductor optical amplifier according to the first embodiment of the invention or the semiconductor optical amplifiers according to the second embodiment to the third embodiment of the invention, the carrier non-injection region is provided in the internal region of the laminated structure from the light output end face along the axis line of the semiconductor optical amplifier. As length of the carrier non-injection region along the axis line of the semiconductor optical amplifier (width of the carrier non-injection region) L_{NC}, a value from 0.1 μm to 100 μm both inclusive can be exemplified.

Further, in the semiconductor optical amplifier according to the first embodiment of the invention or the semiconductor optical amplifiers according to the second embodiment to the third embodiment of the invention, the second electrode is composed of the first section and the second section that are separated by the isolation trench, and the second section of the second electrode is provided in the carrier non-injection region. When the length of the first section is L_{Amp-1} and the length of the second section is L_{Amp-2}, $0.001 \leq L_{Amp-2}/L_{Amp-1} \leq 0.01$ is desirably satisfied, and $0.0025 \leq L_{Amp-2}/L_{Amp-1} \leq 0.01$ is preferably satisfied. The electric resistance value between the first section and the second section of the second electrode in the semiconductor optical amplifier is $1\times10^2\Omega$ or more, is preferably $1\times10^3\Omega$ or more, and is more preferably $1\times10^4\Omega$ or more. Further, the electric resistance value between the first section and the second section of the second electrode is 1×10 times or more the electric resistance value between the second electrode and the first electrode, is preferably 1×10^2 times or more the electric resistance value between the second electrode and the first electrode, and is more preferably 1×10^3 times or more the electric resistance value between the second electrode and the first electrode. Further, the width of the isolation trench that separates the second electrode into the first section and the second section is desirably 1 μm or more and 50% or less the length of the semiconductor optical amplifier, and is preferably 10 μm or more and 10% or less as much as the length of the semiconductor optical amplifier. Further, as the width of the isolation trench, a value from 3 μm to 20 μm both inclusive can be exemplified. As the length of the second section of the second electrode L_{Amp-2}, a value from 3 μm to 100 μm both inclusive can be exemplified.

In the semiconductor optical amplifier of the embodiment of the invention, a laser light source may be composed of a mode locking laser diode device, and pulse laser light outputted from the mode locking laser diode device may enter the semiconductor optical amplifier. In this case, the laser light source may output pulse laser light based on mode locking operation. However, the laser light source is not limited thereto. A known continuous oscillation laser light source, known various types of pulse oscillation laser light sources such as a gain switching laser light source and a loss switching laser light source (Q switching laser light source), and a laser light source such as a titanium sapphire laser are able to be used. The semiconductor optical amplifier of the embodiment of the invention is an amplifier that directly amplifies an optical signal in a state of light without converting the optical signal to an electric signal. The semiconductor optical amplifier of the embodiment of the invention has a laser structure excluding resonator effect as much as possible, and amplifies incident light by light gain of the semiconductor optical amplifier. That is, the semiconductor optical amplifier of the embodiment of the invention may substantially have the same composition and the same configuration as those of the laser diode device structuring the laser light source of the embodiment of the invention, and may have a composition and a configuration different from those of the laser diode device structuring the laser light source of the embodiment of the invention.

In the semiconductor optical amplifier of the embodiment of the invention, in the case where the laser light source is composed of the mode locking laser diode device as described above, the mode locking laser diode device (hereinafter referred to as "mode locking laser diode device of the embodiment of the invention") may include: a laminated structure in which a first compound semiconductor layer that has a first conductivity type and is composed of GaN compound semiconductor, a third compound semiconductor layer that has a light emitting region composed of GaN compound semiconductor, and a second compound semiconductor layer that has a second conductivity type different from the first conductivity type and is composed of GaN compound semiconductor are sequentially layered; the second electrode formed on the second compound semiconductor layer; and a first electrode electrically connected to the first compound semiconductor layer. The laminated structure may be formed on a compound semiconductor substrate having polarity. The third compound semiconductor layer may have a quantum well structure including a well layer and a barrier layer. In addition, though not limited, the thickness of the well layer is

from 1 nm to 10 nm both inclusive, and is preferably from 1 nm to 8 nm both inclusive. The impurity doping concentration of the barrier layer is from 2×10^{18} cm^{-3} to 1×10^{20} cm^{-3} both inclusive, and is preferably from 1×10^{19} cm^{-3} to 1×10^{20} cm^{-3} both inclusive.

In driving the mode locking laser diode device of the embodiment of the invention, light pulse may be generated in the light emitting region by flowing a current from the second electrode to the first electrode through the laminated structure. Further, in the mode locking laser diode device of the embodiment of the invention, light pulse may be generated in the light emitting region by flowing a current from the second electrode to the first electrode through the laminated structure.

To enable mode locking operation of the laser diode device, the light emitting region and a saturable absorption region should be provided for the laser diode device. Based on arrangement state of the light emitting region and the saturable absorption region, the laser diode device is able to be generally categorized into SAL (saturable absorber layer) type or WI (weakly index guide) type in which the light emitting region and the saturable absorption region are arranged in vertical direction, and multielectrode type including bisection type in which the light emitting region and the saturable absorption region are arranged in line in the resonator direction. In the mode locking method, in a cubic (mainly GaAs) laser diode device, it has been confirmed that light pulse with time width of 0.6 psec is able to be generated (see "Appl. Phys. Lett. 39 (1981) 525," [H. Yokoyama] *J. P. van Der Ziel*, et al.). Further, in the hexagonal (mainly GaAs) laser diode device, S. Gee et al. firstly reported generation of light pulse by using mode locking method in 2001 (see "Appl. Phys. Lett. 79 (2001) 1951," S. Gee and J. E. Bowers). However, according to "Appl. Phys. Lett. 79 (2001) 1951," the time width of light pulse is 30 psec, which is still long. Further, in the case where the multielectrode laser diode device is fabricated by using a substrate having polarity, specifically, for example, in the case where a multielectrode GaN laser diode device is provided on {0001} plane (C plane) of a GaN substrate, in some cases, saturable absorption is difficult to be controlled electrically due to QCSE effect (quantum confinement Stark effect) by internal electric field resulting from piezoelectric polarization or intrinsic polarization. That is, it has been found that in some cases, it is necessary to increase direct current value flown to the first electrode for obtaining mode locking operation and reverse bias voltage value applied to the saturable absorption region, subpulse component associated with main pulse is generated, or synchronization is difficult to be obtained between an external signal and light pulse.

In the mode locking laser diode device of the embodiment of the invention, it is preferable that the thickness of the well layer composing the third compound semiconductor layer is defined as a value from 1 nm to 10 nm both inclusive, and the impurity doping concentration of the barrier layer composing the third compound semiconductor layer is defined as a value from 2×10^{18} cm^{-3} to 1×10^{20} cm^{-3} both inclusive. That is, the thickness of the well layer is decreased, and carrier of the third compound semiconductor layer is increased. In the result, influence of piezoelectric polarization is able to be decreased, and a laser light source capable of generating single-peaked light pulse that has a short time width and small subpulse component is able to be obtained. Further, mode locking drive is able to be retained with low reverse bias voltage, and light pulse train in synchronization with an external signal (electric signal and optical signal) is able to be generated. Accordingly, the mode locking laser diode device of the embodiment of the invention is able to be applied as an oscillator that generates light pulse in a volumetric optical disc system, for example.

In the mode locking laser diode device of the embodiment of the invention, the third compound semiconductor layer may further include the saturable absorption region, the second electrode may be separated into the first section for obtaining forward bias state by flowing a current to the first electrode through the light emitting region and the second section for adding electric field to the saturable absorption region by an isolation trench. The forward bias state may be obtained by flowing a current from the first section of the second electrode to the first electrode through the light emitting region, and electric field may be added to the saturable absorption region by applying a voltage between the first electrode and the second section of the second electrode.

It is desirable that a reverse bias voltage is applied between the first electrode and the second section (that is, the first electrode is a cathode and the second section is an anode). A pulse current or a pulse voltage in synchronization with a pulse current or a pulse voltage applied to the first section of the second electrode, or direct current bias may be applied to the second section of the second electrode.

Further, in the mode locking laser diode device of the embodiment of the invention, the electric resistance value between the first section and the second section of the second electrode is $1\times10^2\Omega$ or more, is preferably $1\times10^3\Omega$ or more, and is more preferably $1\times10^4\Omega$ or more. Further, the electric resistance value between the first section and the second section of the second electrode is desirably 1×10 times or more as much as the electric resistance value between the second electrode and the first electrode, is preferably 1×10^2 times or more the electric resistance value between the second electrode and the first electrode, and is more preferably 1×10^3 times or more the electric resistance value between the second electrode and the first electrode.

In the case where the electric resistance value between the first section and the second section of the second electrode is $1\times10^2\Omega$ or more, or the electric resistance value between the first section and the second section of the second electrode is 10 times or more the electric resistance value between the second electrode and the first electrode, flow of leakage current from the first section to the second section of the second electrode is able to be inhibited securely. That is, a current injected to the light emitting region (carrier injection region, gain region) is able to be increased. At the same time, reverse bias voltage V_{sa} applied to the saturable absorption region (carrier non-injection region) is able to be increased. In addition, such a high electric resistance value between the first section and the second section of the second electrode is able to be attained only by separating the second electrode into the first section and the second section by the isolation trench. That is, generation of light pulse by mode locking is able to be realized more easily.

Further, in the mode locking laser diode device of the embodiment of the invention, the width of the isolation trench that separates the second electrode into the first section and the second section is desirably 1 μm or more and 50% or less the resonator length, and is preferably 10 μm or more and 10% or less the resonator length. As the resonator length, though 0.3 mm can be exemplified. However, the value is not limited thereto. In the following description, the resonator direction is regarded as Z direction and the thickness direction of the laminated structure is regarded as Y direction. Further, the length of the saturable absorption region may be shorter than the length of the light emitting region. Further, the length of the second electrode (total length of the first section and the second section) may be shorter than the length of the third

compound semiconductor layer. Examples of arrangement state of the first section and the second section of the second electrode include the following:

(1) State in which two first sections of the second electrode and one second section of the second electrode are provided, an end of the second section is opposed to one first section with one isolation trench in between, and the other end of the second section is opposed to the other first section with the other isolation trench in between (that is, the second electrode has a structure in which the second section is sandwiched between the first sections);

(2) State in which one first section of the second electrode and one second section of the second electrode are provided, and the first section of the second electrode and the second section of the second electrode are arranged with an isolation trench in between; and

(3) State in which one first sections of the second electrode and two second sections of the second electrode are provided, an end of the first section is opposed to one second section with one isolation trench in between, and the other end of the first section is opposed to the other second section with the other isolation trench in between. Specially, the structures (1) and (2) are desirable. Further, more generally, examples of arrangement state of the first section and the second section of the second electrode include the following:

(4) State that N pieces of the first sections of the second electrode and (N−1) pieces of the second sections of the second electrode are provided, and the second section of the second electrode is sandwiched between the first sections of the second electrode; and

(5) State that N pieces of the second sections of the second electrode and (N−1) pieces of the first sections of the second electrode are provided, and the first section of the second electrode is sandwiched between the second sections of the second electrode. In other words, the States 4 and 5 are described as follows:

(4') State that N pieces of light emitting regions [carrier injection region, gain region] and (N−1) pieces of saturable absorption regions [carrier non-injection region] are provided, and the saturable absorption region is sandwiched between the light emitting regions; and

(5') State that N pieces of saturable absorption regions [carrier non-injection region] and (N−1) pieces of light emitting regions [carrier injection region, gain region] are provided, and the light emitting region is sandwiched between the saturable absorption regions.

Further, in the driving method of the mode locking laser diode device of the embodiment of the invention, it is possible that a current is flown from the second electrode to the first electrode through the light emitting region, and an external electric signal is superimposed on the first electrode from the second electrode through the light emitting region. Thereby, light pulse is able to be sync with the external electric signal. Alternatively, an optical signal may enter from one end face of the laminated structure. Again, thereby light pulse is able to be sync with the optical signal.

Further, in the semiconductor optical amplifier of the embodiment of the invention or the mode locking laser diode device of the embodiment of the invention, doping impurity for the barrier layer may be silicon (Si). However, doping impurity is not limited thereto. As other doping impurity, oxygen (O) may be adopted.

Further, the mode locking laser diode device of the embodiment of the invention may be a laser diode device having a ridge stripe type separate confinement heterostructure (SCH structure). Alternatively, the mode locking laser diode device of the embodiment of the invention may be a laser diode device having an oblique ridge stripe type separate confinement heterostructure. The height of the ridge stripe structure is desirably from 0.1 μm to 10 μm both inclusive, and is preferably from 0.2 μm to 1 μm both inclusive. However, the value thereof is not limited thereto. Further, as the width of the ridge stripe structure, 2 μm or less is able to be exemplified, and as the lower limit of the width of the ridge stripe structure, for example, 0.8 μm is able to be exemplified. However, the value thereof is not limited thereto. Definition of the height of the ridge stripe structure is also able to be applied to the semiconductor optical amplifier of the embodiment of the invention.

The mode locking laser diode device of the embodiment of the invention is, for example, able to be manufactured by the following method. That is, the mode locking laser diode device of the embodiment of the invention is, for example, able to be manufactured by the following manufacturing method including the following respective steps:

(A) step of forming the laminated structure in which the first compound semiconductor layer that has the first conductivity type and is composed of GaN compound semiconductor, the third compound semiconductor layer that has the light emitting region composed of GaN compound semiconductor and the saturable absorption region, and the second compound semiconductor layer that has the second conductivity type different from the first conductivity type and is composed of GaN compound semiconductor are sequentially layered is formed;

(B) subsequent step of forming the strip-shaped second electrode on the second compound semiconductor layer;

(C) subsequent step of etching at least part of the second compound semiconductor layer with the use of the second electrode as an etching mask, and thereby forming the ridge stripe structure; and

(D) subsequent step of forming a resist layer for forming the isolation trench in the second electrode, and subsequently forming the isolation trench in the second electrode by wet etching method with the use of the resist layer as a wet etching mask, and thereby separating the second electrode into the first section and the second section by the isolation trench.

The ridge stripe structure is formed by adopting the foregoing manufacturing method, that is, by etching at least part of the second compound semiconductor layer with the use of the strip-shaped second electrode as an etching mask. That is, the ridge stripe structure is formed by self alignment method by using the patterned second electrode as an etching mask. Thus, there is no joint misalignment between the second electrode and the ridge stripe structure. Further, the isolation trench is formed in the second electrode by wet etching method. By adopting wet etching method as described above, deterioration of the optical and electric characteristics of the second compound semiconductor layer is able to be inhibited differently from dry etching method. Accordingly, deterioration of light emitting characteristics is able to be securely prevented.

In the step (C), part of the second compound semiconductor layer may be etched in the thickness direction, all of the second compound semiconductor layer may be etched in the thickness direction, the second compound semiconductor layer and the third compound semiconductor layer may be etched in the thickness direction, or part of the second compound semiconductor layer, the third compound semiconductor layer, and the first compound semiconductor layer may be etched in the thickness direction.

Further, when etching rate of the second electrode is ER_1 and etching rate of the laminated structure is ER_1 in forming the isolation trench in the second electrode in the foregoing

step D, $ER_0/ER_1 \geq 1\times10$ is desirably satisfied, and $ERr_0/ER_1 \geq 1\times10^2$ is preferably satisfied. In the case where ER_0/ER_1 satisfies the foregoing relation, the second electrode is able to be securely etched without etching the laminated structure (or if the laminated structure is etched, the etching portion is little.)

The semiconductor optical amplifier of the embodiment of the invention is able to be substantially manufactured by a manufacturing method similar to the manufacturing method of the foregoing mode locking laser diode device of the embodiment of the invention though depending on the form thereof. However, the manufacturing method thereof is not limited thereto.

In the mode locking laser diode device of the embodiment of the invention, the second electrode may be composed of a palladium (Pd) single layer, a nickel (Ni) single layer, a platinum (Pt) single layer, or a laminated structure of a palladium layer and a platinum layer in which the palladium layer is in contact with the second compound semiconductor layer, or a laminated structure of a palladium layer and a nickel layer in which the palladium layer is in contact with the second compound semiconductor layer. In the case where the lower metal layer is composed of palladium, and the upper metal layer is composed of nickel, the thickness of the upper metal layer is desirably 0.1 μm or more, and is preferably 0.2 μm or more. Further, the second electrode is preferably composed of the palladium (Pd) single layer. In this case, the thickness thereof is desirably 20 nm or more, and is preferably 50 nm or more. Further, the second electrode is preferably composed of a palladium (Pd) single layer, a nickel (Ni) single layer, a platinum (Pt) single layer, or a laminated structure of a lower metal layer and an upper metal layer in which the lower metal layer is in contact with the second compound semiconductor layer (however, the lower metal layer is composed of one metal selected from the group consisting of palladium, nickel, and platinum; and the upper metal layer is composed of a metal having etching rate in forming the isolation trench in the second electrode in the foregoing step (D) equal to, similar to, or higher than etching rate of the lower metal layer). Further, an etching liquid used in forming the isolation trench in the second electrode in the foregoing step (D) is desirably aqua regia, nitric acid, vitriolic acid, muriatic acid, or a mixed liquid composed of at least two types out of these acids (specifically, a mixed liquid composed of nitric acid and vitriolic acid, or a mixed liquid composed of nitric acid and muriatic acid). The width of the second electrode is desirably from 0.5 μm to 50 μm both inclusive, and is preferably from 1 μm to 5 μm both inclusive. The structure of the second electrode in the foregoing mode locking laser diode device of the embodiment of the invention is able to be also applied to the semiconductor optical amplifier of the embodiment of the invention though depending on the form thereof.

In the semiconductor optical amplifier of the embodiment of the invention or the mode locking laser diode device of the embodiment of the invention, the laminated structure may be composed of AlGaInN compound semiconductor. Specific examples of AlGaInN compound semiconductor include GaN, AlGaN, GaInN, and AlGaInN. Further, such a compound semiconductor may include boron (B) atom, thallium (Tl) atom, arsenic (As) atom, phosphorus (P) atom, or antimony (Sb) atom according to needs. Further, the third compound semiconductor layer structuring a light amplification region or the light emitting region (gain region) and the saturable absorption region (in some cases, the third compound semiconductor layer is referred to as "active layer") has the quantum well structure. Specifically, the third compound semiconductor layer may have single quantum well structure [QW structure], or multiquantum well structure [MQW structure]. The third compound semiconductor layer having the quantum well structure has a structure in which at least one well layer and at least one barrier layer are layered. As a combination of compound semiconductor composing the well layer and compound semiconductor composing the barrier layer, ($In_yGa_{(1-y)}N$, GaN), ($In_yGa_{(1-y)}N$, $In_zGa_{(1-z)}N$) (y>z), and ($In_yGa_{(1-y)}N$, AlGaN) can be exemplified.

Further, in the mode locking laser diode device of the embodiment of the invention, the second compound semiconductor layer may have a superlattice structure in which a p-type GaN layer and a p-type AlGaN layer are alternately layered. The thickness of the superlattice structure may be 0.7 μm or less. By adopting such a superlattice structure, while a refractive index necessary as a cladding layer is maintained, a series resistance component of the laser diode device is able to be decreased, leading to realizing a low operation voltage of the laser diode device. Though the lower limit value of the thickness of the superlattice structure is not limited, the lower limit value is, for example, 0.3 μm. As the thickness of the p-type GaN layer composing the superlattice structure, a thickness from 1 nm to 5 nm both inclusive can be exemplified. As the thickness of the p-type AlGaN layer composing the superlattice structure, a thickness from 1 nm to 5 nm both inclusive can be exemplified. As the total number of layers of the p-type GaN layer and the p-type AlGaN layer, the number from 60 layers to 300 layers both inclusive can be exemplified. Further, the distance from the third compound semiconductor layer to the second electrode may be 1 μm or less, and preferably 0.6 μm or less. By defining the distance from the third compound semiconductor layer to the second electrode, the thickness of the p-type second compound semiconductor layer having high resistance is able to be decreased, and the operation voltage of the laser diode device is able to be decreased. Though the lower limit value of the distance from the third compound semiconductor layer to the second electrode is not limited, for example, the lower limit value of the distance from the third compound semiconductor layer to the second electrode is 0.3 μm. Further, the second compound semiconductor layer may be doped with Mg at the level of 1×10^{19} cm^{-3} or more. The absorption coefficient of the second compound semiconductor layer to light in 405 nm wavelength from third compound semiconductor layer may be at least 50 cm^{-1}. The atom concentration of Mg comes from material property that the maximum hole concentration is shown at the value of 2×10^{19} cm^{-3}, and is a result of design that the maximum hole concentration, that is, the specific resistance of the second compound semiconductor layer becomes the minimum. The absorption coefficient of the second compound semiconductor layer is defined in viewpoint of decreasing resistance of the laser diode device as much as possible. In the result, in general, the absorption coefficient of light of the third compound semiconductor layer becomes 50 cm^{-1}. However, it is possible that the Mg dope amount is intentionally set to the concentration of 2×10^{19} cm^{-3} or more in order to increase the absorption coefficient. In this case, the upper limit Mg dope amount for obtaining a practical hole concentration is, for example, 8×10^{19} cm^{-3}. Further, the second compound semiconductor layer may have a non-doped compound semiconductor layer and a p-type compound semiconductor layer from the third compound semiconductor layer side. The distance from the third compound semiconductor layer to the p-type compound semiconductor layer may be 1.2×10^{-7} m or less. By defining the distance from the third compound semiconductor layer to the p-type compound semiconductor layer as above, internal loss is able to be suppressed in a range in which the internal

quantum efficiency is not lowered. Thereby, threshold current I_{th} at which laser oscillation is started is able to be decreased. Though the lower limit value of the distance from the third compound semiconductor layer to the p-type compound semiconductor layer is not limited, for example, the lower limit value is 5×10^{-8} m. Further, on both side faces of the ridge section, a laminated insulating film composed of SiO_2/Si laminated structure may be formed. The difference between the effective refractive index of the ridge section and the effective refractive index of the laminated insulating film may be from 5×10^{-3} to 1×10^{-2} both inclusive. By using such a laminated insulating film, even in the case of high output operation exceeding 100 mW, single fundamental lateral mode is able to be maintained. Further, the second compound semiconductor layer may have a structure in which a non-doped GaInN layer (p-side light guide layer), a non-doped AlGaN layer (p-side cladding layer), a Mg doped AlGaN layer (electron barrier layer), a superlattice structure (superlattice cladding layer) composed of a GaN layer (Mg doped)/AlGaN layer, and a Mg doped GaN layer (p-side contact layer) are layered from the third compound semiconductor layer side. The bandgap of compound semiconductor composing the well layer in the third compound semiconductor layer is desirably 2.4 eV or more. Further, the wavelength of laser light outputted from the third compound semiconductor layer is desirably from 360 nm to 500 nm both inclusive, and is preferably from 400 nm to 410 nm both inclusive. It is needless to say that the foregoing various structures are able to be combined as appropriate. The above-mentioned structure in the foregoing mode locking laser diode device of the embodiment of the invention is also applicable to the semiconductor optical amplifier of the embodiment of the invention substantially though depending on the form thereof.

As described above, in the second compound semiconductor layer, a non-doped compound semiconductor layer (for example, a non-doped GaInN layer or a non-doped AlGaN layer) may be formed between the third compound semiconductor layer and the electron barrier layer. Further, a non-doped GaInN layer as a light guide layer may be formed between the third compound semiconductor layer and the non-doped compound semiconductor layer. The uppermost layer of the second compound semiconductor layer may have a structure occupied by a Mg doped GaN layer (p-side contact layer).

Various GaN compound semiconductor layers composing the semiconductor optical amplifier of the embodiment of the invention or the mode locking laser diode device of the embodiment of the invention are sequentially formed over a substrate. Examples of the substrate include a GaAs substrate, a GaN substrate, an SiC substrate, an alumina substrate, a ZnS substrate, a ZnO substrate, an MN substrate, a LiMgO substrate, a $LiGaO_2$ substrate, a $MgAl_2O_4$ substrate, an InP substrate, an Si substrate, and a laminated body in which a foundation layer and a buffer layer are formed on the surface (main face) of the foregoing substrate in addition to a sapphire substrate. Mainly, in the case where the GaN compound semiconductor layer is formed on the substrate, the GaN substrate has the preference due to its small defect density. However, it is known that in the GaN substrate, its characteristics are changed from/to polarity, non-polarity, and semi-polarity according to the growth plane. Further, examples of methods of forming the various GaN compound semiconductor layers composing the semiconductor optical amplifier of the embodiment of the invention or the mode locking laser diode device of the embodiment of the invention include metal organic chemical vapor deposition method (MOCVD method and MOVPE method), molecular beam epitaxy method (MBE method), and hydride vapor growth method in which halogen contributes to transfer or reaction and the like.

Examples of organic gallium source gas in MOCVD method include trimethyl gallium (TMG) gas and triethyl gallium (TEG) gas. Examples of nitrogen source gas include ammonia gas and hydrazine gas. In forming the GaN compound semiconductor layer having n-type conductivity type, for example, silicon (Si) may be added as n-type impurity (n-type dopant). In forming the GaN compound semiconductor layer having p-type conductivity type, for example, magnesium (Mg) may be added as p-type impurity (p-type dopant). Further, in the case where aluminum (Al) or indium (In) is contained as a component atom of the GaN compound semiconductor layer, trimethyl aluminum (TMA) gas may be used as an Al source, and trimethyl indium (TMI) gas may be used as an In source. Further, monosilane gas (SiH_4 gas) may be used as a Si source, and ciclopentadienyl magnesium gas, methylciclopentadienyl magnesium, or bisciclopentadienyl magnesium (Cp_2Mg) may be used as a Mg source. Examples of n-type impurity (n-type dopant) include Ge, Se, Sn, C, Te, SO, Pd, and Po in addition to Si. Examples of p-type impurity (p-type dopant) include Zn, Cd, Be, Ca, Ba, C, Hg, and Sr in addition to Mg.

When the first conductive type is n type, the first electrode electrically connected to the first compound semiconductor layer having n-type conductivity type desirably has a single layer structure or a multilayer structure containing at least one metal selected from the group consisting of gold (Au), silver (Ag), palladium (Pd), Al (aluminum), Ti (titanium), tungsten (W), Cu (copper), Zn (zinc), tin (Sn) and indium (In), and for example, Ti/Au, Ti/Al, and Ti/Pt/Au are able to be exemplified. The first electrode is electrically connected to the first compound semiconductor layer. The first electrode may be formed on the first compound semiconductor layer, and the first electrode may be connected to the first compound semiconductor layer with a conductive material layer or a conducive substrate in between. The first electrode and the second electrode are able to be formed by PVD method such as vacuum evaporation method and sputtering method.

A pad electrode may be provided on the first electrode and the second electrode in order to obtain electrical connection to an external electrode or a circuit. The pad electrode desirably has a single layer structure or a multilayer structure containing at least one metal selected from the group consisting of Ti (titanium), aluminum (Al), Pt (platinum), Au (gold), and Ni (nickel). Otherwise, the pad electrode may have a multilayer structure exemplified as a Ti/Pt/Au multilayer structure and a Ti/Au multilayer structure.

The mode locking laser diode device of the embodiment of the invention may further include an external reflecting mirror. That is, the mode locking laser diode device of the embodiment of the invention may be an external resonator type mode locking laser diode device. Alternatively, the mode locking laser diode device of the embodiment of the invention may be a monolithic mode locking laser diode device. The external resonator type mode locking laser diode device may be light condensing type, or collimation type. In the external resonator type mode locking laser diode device, light reflectance on one end face of a laminated structure from which light pulse is outputted is preferably 0.5% or less. The light reflectance value is significantly lower than the light reflectance on one end face of a laminated structure from which light pulse is outputted in existing laser diode devices (in general, from 5% to 10% both inclusive). In the external resonator mode locking laser diode device, the value of the

external resonator (Z', unit mm) desirably satisfies $0<Z'<1500$, and is preferably satisfies $30 \leq Z' \leq 150$.

The embodiment of the invention is applicable to various fields such as the optical disc system, the communication field, the optical information field, the photoelectronic integration circuit, the field applying nonlinear optical phenomenon, the optical switch, the laser measurement field and various analysis fields, the ultrafast spectroscopy field, the multiphoton excitation spectroscopy field, the mass analysis field, the microspectroscopic field using multiphoton absorption, quantum control of chemical reaction, the nano three-dimensional processing field, various processing fields applying multiphoton absorption, the medical field, and the bio imaging field.

First Example

The first example relates to the semiconductor optical amplifier according to the first embodiment of the invention. FIG. **1** illustrates a conceptual view of a light output device of the first example including the semiconductor optical amplifier. FIG. **2** illustrates a schematic cross sectional view of the semiconductor optical amplifier where the semiconductor optical amplifier is cut along a virtual vertical plane (YZ plane) including an axis line of the semiconductor optical amplifier (direction in which a light guide extends, and is referred to as "Z direction" for convenience sake). FIG. **3** illustrates a schematic cross sectional view of the semiconductor optical amplifier where the semiconductor optical amplifier is cut along a virtual vertical plane (XY plane) orthogonal to the axis line of the semiconductor optical amplifier. FIG. **2** is a schematic cross sectional view taken along line I-I of FIG. **3**. FIG. **3** is a schematic cross sectional view taken along line II-II of FIG. **2**. FIG. **4** illustrates a schematic perspective view of the semiconductor optical amplifier. FIG. **5** illustrates a schematic plan view of a ridge stripe structure.

The light output device of the first example includes a laser light source **100** and a semiconductor optical amplifier **200** that optically amplifies laser light from the laser light source **100** and outputs amplified light.

As illustrated in FIG. **1**, the semiconductor optical amplifier **200** is composed of a transmissive semiconductor optical amplifier. Low reflective coating layers (AR) **202** and **204** are formed on a light incident end face **201** of the semiconductor optical amplifier **200** and a light output end face **203** opposed to the light incident end face **201**. The low reflecting coating layers **202** and **204** have a structure in which a titanium oxide layer and an aluminum oxide layer are layered. The laser light entering from the light incident end face **201** side is optically amplified inside the semiconductor optical amplifier **200**, and is outputted from the light output end face **203** on the opposite side of the light incident end face **201** side. The laser light is fundamentally guided in only one direction. Further, in the first example, the laser light source **100** is composed of a known continuous oscillation laser equipment. Laser light outputted from the laser equipment enters the semiconductor optical amplifier **200**.

In the light output device of the first example illustrated in FIG. **1**, laser light outputted from the laser light source **100** enters a reflecting mirror **20** through a light isolator **15** and a reflecting mirror **16**. Laser light reflected by the reflecting mirror **20** passes through a half-wave plate ($\lambda/2$ wave plate) **21** and a lens **22**, and enters the semiconductor optical amplifier **200**. The light isolator **15** is arranged to prevent returned light from the semiconductor optical amplifier **200** from heading for the laser light source **100**. The laser light is optically amplified in the semiconductor optical amplifier **200**, and is outputted outside the system through a lens **30**.

The semiconductor optical amplifier **200** includes: a laminated structure in which a first compound semiconductor layer **230** that has a first conductivity type (in the first example, specifically, n-type conductivity type) and is composed of GaN compound semiconductor, a third compound semiconductor layer (active layer) **240** that has a light amplification region (carrier injection region, gain region) **241** composed of GaN compound semiconductor, and a second compound semiconductor layer **250** that has a second conductivity type different from the first conductivity type (in the first example, specifically, p-type conductivity type) and is composed of GaN compound semiconductor are sequentially layered; a second electrode **262** formed on the second compound semiconductor layer **250**; and a first electrode **261** electrically connected to the first compound semiconductor layer **230**.

In the semiconductor optical amplifier **200** of the first example, the laminated structure has the ridge stripe structure. When the width of the ridge stripe structure in the light output end face **203** is W_{out}, and the width of the ridge stripe structure in the light incident end face **201** is W_{in}, $W_{out}>W_{in}$ is satisfied. Specifically, W_{out} is 15 **82** m and W_{in} is 1.4 μm. A carrier non-injection region **205** is provided in an internal region of the laminated structure from the light output end face **203** along axis line AX_1 of the semiconductor optical amplifier **200**. When length of the carrier non-injection region **205** along the axis line AX_1 of the semiconductor optical amplifier **200** (width of the carrier non-injection region **205**) is L_{NC}, $L_{NC}=5$ μm is satisfied. The second electrode **262** is not provided in the carrier non-injection region **205**. The length of the entire semiconductor optical amplifier is 2.0 mm. The carrier non-injection region is also provided in an internal region of the laminated structure from the light incident end face **201** along the axis line of the semiconductor optical amplifier **200**.

More specifically, the semiconductor optical amplifier **200** of the first example has a ridge stripe type separate confinement heterostructure (SCH structure). In addition, the semiconductor optical amplifier **200** of the first example has a structure similar to a GaN laser diode structure composed of an index guide type AlGaInN. The width of the ridge stripe structure is gently and flatly extended in tapered shape from the light incident end face **201** to the light output end face **203**. Further, the axis line AX_1 of the semiconductor optical amplifier **200** intersects with axis line AX_2 of the ridge stripe structure at a given angle, specifically at $\theta=5.0$ deg. The axis line AX_1 and the axis line AX_2 are indicated by dotted lines in FIG. **5**.

The laminated structure is formed on a compound semiconductor substrate **221**. Specifically, the semiconductor optical amplifier **200** is provided on (0001) plane of the n-type GaN substrate **221**. The (0001) plane of the n-type GaN substrate **221** is also called "C plane," and is a crystal plane having polarity. The first compound semiconductor layer **230**, the third compound semiconductor layer **240**, and the second compound semiconductor layer **250** are specifically composed of AlGaInN compound semiconductor. More specifically, the first compound semiconductor layer **230**, the third compound semiconductor layer **240**, and the second compound semiconductor layer **250** have a layer structure illustrated in the following Table 1. In Table 1, the listed items are shown in the order from the layer farthest from the n-type GaN substrate **221** to the layer closest to the n-type GaN substrate **221**. The bandgap of compound semiconductor composing the well layer in the third compound semiconduc-

tor layer **240** is 3.06 eV. The third compound semiconductor layer **240** has a quantum well structure including a well layer and a barrier layer. The doping concentration of impurity (specifically, silicon (Si)) of the barrier layer is from 2×10^{17} cm^{-3} to 1×10^{20} cm^{-3} both inclusive.

TABLE 1

Second compound semiconductor layer 250
p-type GaN contact layer (Mg doped) 257
p-type AlGaN (Mg doped) cladding layer 255
p-type GaN (Mg doped) layer 254
p-type AlGaN electron barrier layer (Mg doped) 253
Third compound semiconductor layer 240
GaInN quantum well active layer
(well layer: $Ga_{0.92}In_{0.08}N$/barrier layer: $Ga_{0.95}In_{0.02}N$)
First compound semiconductor layer 230
n-type GaN layer 232
n-type AlGaN cladding layer 231
well layer (two layers): 10 nm [non-doped]
barrier layer (three layers): 12 nm [doping concentration (Si): 2×10^{15} cm^{-3}]

Further, part of the p-type GaN contact layer **257** and part of the p-type AlGaN cladding layer **255** are removed by RIE method, and a ridge stripe structure (ridge section **258**) is formed. On both sides of the ridge section **258**, a laminated insulating film **259** composed of SiO_2/Si is formed. The SiO_2 layer is the lower layer and the Si layer is the upper layer. The difference between the effective refractive index of the ridge section **258** and the effective refractive index of the laminated insulating film **259** is from 5×10^{-3} to 1×10^{-2} both inclusive, and specifically 7×10^{-3}. On the p-type GaN contact layer **257** corresponding to the top face of the ridge section **258** to part of the top face of the p-type AlGaN cladding layer **255**, the second electrode (p-type ohmic electrode) **262** is formed. Meanwhile, on the rear face of the n-type GaN substrate **221**, the first electrode (n-type ohmic electrode) **261** composed of Ti/Pt/Au is formed. In the first example, the second electrode **262** is formed from a Pd single layer having a thickness of 0.1 μm.

The thickness of the p-type AlGaN cladding layer **255** is 400 nm. The thickness of the p-type GaN layer **254** is 100 nm. The thickness of the p-type GaN electron barrier layer **253** is 20 nm. The thickness of the p-type GaN contact layer **257** is 100 nm. Further, the p-type AlGaN electron barrier layer **253**, the p-type GaN layer **254**, and the p-type AlGaN cladding layer **255**, and the p-type GaN contact layer **257** composing the second compound semiconductor layer **250** are doped with Mg at the level of 1×10^{19} cm^{-3} or more (specifically at the level of 2×10^{19} cm^{-3}). Meanwhile, the thickness of the n-type AlGaN cladding layer **231** is 2.5 μm, and the thickness of the n-type GaN layer **232** is 200 nm. When the thickness of the n-type compound semiconductor layer sandwiched between the n-type AlGaN cladding layer **231** and the third compound semiconductor layer **240** (thickness of the n-type GaN layer **232**) is t_1, and the thickness of the p-type compound semiconductor layer sandwiched between the p-type AlGaN cladding layer **255** and the third compound semiconductor layer **240** (total thickness of the p-type GaN layer **254** and the p-type AlGaN electron barrier layer **253**) is t_2, t_1=200 nm, t_2=120 nm, and $0.1\leq t_2/t_1<1$ are satisfied.

In the first example, single mode continuous oscillation laser light in wavelength of 405 nm (light output: 15 milliwatt) entered the semiconductor optical amplifier **200**. A direct current of 600 milliampere was flown from the second electrode **262** to the first electrode **261**. In the case where the value of the direct current is converted to a value per 1 cm^2 of the third compound semiconductor layer **240** structuring the light incident end face **201**, the value is 3.7×10^3 ampere/cm^2. A near-field image of laser light outputted from the semiconductor optical amplifier **200** at this time is illustrated in FIG. **6**A. As Comparative example 1, a semiconductor optical amplifier having the same composition and the same structure as those of first example was fabricated, except that the carrier non-injection region **205** was not provided. A near-field image of laser light outputted from a semiconductor optical amplifier of Comparative example 1 in the case where a direct current of 600 milliampere was flown from the second electrode to the first electrode is illustrated in FIG. **6**B. As evidenced by FIG. **6**B, in the semiconductor optical amplifier of Comparative example 1, the width of the near-field image was narrower than W_{out} (15 μm), and its $1/e^2$ width was 5 μm (half bandwidth: 3.1 μm). The inventors of the invention firstly found that such a phenomenon is a phenomenon unique to nitride semiconductor system semiconductor optical amplifiers. Such a narrow near-field image adversely affects saturation and reliability of amplified light output. The light intensity density of laser light outputted from the semiconductor optical amplifier of Comparative example 1 was 47 milliwatt. Meanwhile, as evidenced by FIG. **6**A, in the semiconductor optical amplifier **200** of the first example, the mode field was broadened, the width of the near-field image was wide and its $1/e^2$ width was 11.5 μm (half bandwidth: 5.8 μm). Further, the light intensity density of laser light outputted from the semiconductor optical amplifier **200** of the first example was 122 milliwatt. The amplified light output was higher than that of the semiconductor optical amplifier of Comparative example 1. As described above, it was confirmed that the amplified light output was significantly increased by providing the carrier non-injection region **205**. Further, the value of (width of the ridge stripe structure in the light output end face)/(width of the laser light outputted from the semiconductor optical amplifier) was 1.3. The width of the laser light outputted from the semiconductor optical amplifier means $1/e^2$ width in a near-field image, that is, width of a near-field image having $1/e^2$ intensity to the peak intensity.

It is presumed that the width of the near-field image of outputted laser light is broadened by providing the carrier non-injection region **205** for the following reason. That is, carrier distribution in the laminated structure in XY plane is in the shape of a mountain having one peak if the light intensity of the incident laser light is low. However, if the light intensity of the incident laser light is increased, carrier injection/diffusion in the laminated structure of the semiconductor optical amplifier are not performed sufficiently, and thus the carrier distribution in the laminated structure in XY plane becomes in the shape of a mountain having two peaks (mountain/valley/mountain-like light intensity pattern). It is known that in the case where the number of carriers is decreased in the compound semiconductor layer, relative refractive index of the compound semiconductor layer is increased. Thus, laser light outputted from the light output end face of the semiconductor optical amplifier is difficult to be broadened in the width direction, and the width of the near-field image was narrower than W_{out}. In addition, since the area occupying the light output end face of the region from which laser light is outputted from the semiconductor optical amplifier is small, high output of the semiconductor optical amplifier is difficult to be realized.

Meanwhile, in the semiconductor optical amplifier of the first example, the carrier non-injection region **205** not contributing to light amplification is provided. Thus, even if the light intensity of incident laser light is increased, the phenomenon that relative refractive index is increased due to carrier distribution is able to be suppressed from being generated. Thus, laser light outputted from the light output end face of

the semiconductor optical amplifier is easily broadened in the width direction. In addition, since the area occupying the light output end face of the region from which laser light is outputted from the semiconductor optical amplifier is large, high output of the semiconductor optical amplifier is able to be realized.

Second Example

The second example is a modification of the first example. FIG. **7** illustrates a conceptual view of a light output device of the second example including the semiconductor optical amplifier. FIG. **8** illustrates a schematic cross sectional view of the semiconductor optical amplifier where the semiconductor optical amplifier is cut along a virtual vertical plane (YZ plane) including an axis line (Z direction) of the semiconductor optical amplifier. FIG. **9** illustrates a schematic cross sectional view of the semiconductor optical amplifier where the semiconductor optical amplifier is cut along a virtual vertical plane (XY plane) orthogonal to the axis line of the semiconductor optical amplifier. FIG. **8** is a schematic cross sectional view taken along line I-I of FIG. **9**. FIG. **9** is a schematic cross sectional view taken along line II-II of FIG. **8**. Further, FIG. **11** illustrates a schematic perspective view of the semiconductor optical amplifier, and FIG. **12** illustrates a schematic plan view of a ridge stripe structure.

Further, FIG. **10** illustrates a schematic end view along the direction in which a resonator of a mode locking laser diode device configuring a laser light source extends (a schematic end view where the mode locking laser diode device is cut along the YZ plane). A schematic cross sectional view taken along the direction perpendicular to the direction in which the resonator extends (schematic cross sectional view where the mode locking laser diode device is cut along the XY plane) is the same as FIG. **9** except for referential numbers. That is, the **200**s referential numbers in FIG. **9** correspond to **100**s referential numbers of the schematic cross sectional view taken along the direction perpendicular to the direction in which the resonator extends. FIG. **10** is a schematic end view similar to the view taken along line I-I of FIG. **9**. Further, FIG. **19**A schematically illustrates a system of performing mode locking drive by configuring an external resonator from the mode locking laser diode device of the second example.

In the second example, a second electrode **262** is composed of a first section **262**A and a second section **262**B that are separated by an isolation trench **262**C, and the second section **262**B of the second electrode is provided in a carrier non-injection region **205**. A voltage equal to or less than a built-in voltage is applied to the second section **262**B of the second electrode. Specifically, 0 volt is applied to the second section **262**B of the second electrode. Light amplification as an inherent function of the semiconductor optical amplifier **200** is able to be performed by applying a voltage to the first section **262**A of the second electrode, while measurement for position adjustment and the like is able to be performed by applying a voltage to the second section **262**B of the second electrode.

In the second example, when the length of the first section **262**A is L_{Amp-1}, and the length of the second section **262**B is L_{Amp-2}, L_{Amp-1}=1.97 mm, L_{Amp-2}=0.01 mm, and $0.001 \leq L_{Amp-2}/L_{Amp-1} \leq 0.01$ are satisfied. Further, the width of the isolation trench is 0.02 mm.

In the second example, a voltage applied to the second section of the second electrode is lower the voltage applied to the first section of the second electrode. Thereby, since the carrier non-injection region including the second section exists, even if the light intensity of incident laser light is increased, the phenomenon that relative refractive index of the compound semiconductor layer is increased is able to be inhibited from being generated. In addition, laser light outputted from the light output end face of the semiconductor optical amplifier is easily broadened in the width direction. Further, since the area occupying the light output end face of the region from which laser light is outputted from the semiconductor optical amplifier is large, high output of the semiconductor optical amplifier is able to be realized.

The light output device of the second example includes: the laser light source **100**; the semiconductor optical amplifier **200** that optically amplifies laser light from the laser light source **100** and outputs amplified light; an alignment device **300** that adjusts relative position of the semiconductor optical amplifier with respect to laser light entering the semiconductor optical amplifier **200**; and a semiconductor optical amplifier control device **400** that controls operation of the semiconductor optical amplifier **200**.

The semiconductor optical amplifier control device **400** is specifically composed of a combination of a known direct current electric power source, a voltage measurement device, and a current measurement device. Further, resolution capability of a voltage monitor in the semiconductor optical amplifier control device **400** is 1 millivolt or less, and is more specifically 0.1 millivolt or less. Further, resolution capability of a current monitor in the semiconductor optical amplifier control device **400** is 100 microampere or less, and is more specifically 10 microampere or less.

In the second example, the laser light source **100** is composed of a mode locking laser diode device, and pulse laser light outputted from the mode locking laser diode device enters the semiconductor optical amplifier **200**. In this case, the laser light source **100** outputs pulse laser light based on mode locking operation. For details of the mode locking laser diode device, a description will be given later. The semiconductor optical amplifier **200** in the second example substantially has the same composition and the same configuration as those of a mode locking laser diode device **110** configuring the laser light source **100** in the second example, except for the composition and the structure of the second electrode.

In the light output device of the second example illustrated in FIG. **7**, the laser light source **100** is composed of the mode locking laser diode device **110**, a lens **11**, an optical filter **12**, an external mirror **13**, and a lens **14**. Laser light outputted from the laser light source **100** enters a reflecting mirror **20** through the light isolator **15** and the reflecting mirror **16**. Laser light reflected by the reflecting mirror **20** passes through the half-wave plate (λ/2 wave plate) **21** and the lens **22**, and enters the semiconductor optical amplifier **200**. Light is amplified in the semiconductor optical amplifier **200**, and is outputted outside the system through the lens **30**. The reflecting mirror **20**, the half-wave plate **21**, and the lens **22** are laid on the alignment device **300**. The alignment device **300** is specifically composed of XYZ stage. When the thickness direction of the laminated structure in the semiconductor optical amplifier **200** described later is Y direction and the axis line direction of the semiconductor optical amplifier **200** is Z direction, the reflecting mirror **20** and the lens **22** are moved in the X direction, the Y direction, and the Z direction by the alignment device **300**.

The mode locking laser diode device **110** of the second example that configures the laser light source **100** and has light emitting wavelength band of 405 nm includes: a laminated structure in which a first compound semiconductor layer **130** that has a first conductivity type (in the second example, specifically, n-type conductivity type) and is composed of GaN compound semiconductor, a third compound

semiconductor layer (active layer) **140** that has a light emitting region (gain region) **141** composed of GaN compound semiconductor, and a second compound semiconductor layer **150** that has a second conductivity type different from the first conductivity type (in the second example, specifically, p-type conductivity type) and is composed of GaN compound semiconductor are sequentially layered; b. a strip-shaped second electrode **162** formed on the second compound semiconductor layer **150**; and a first electrode **161** electrically connected to the first compound semiconductor layer **130**.

The laminated structure is formed on compound semiconductor substrates **121** and **221** having polarity. The third compound semiconductor layers **140** and **240** have a quantum well structure including a well layer and a barrier layer. The thickness of the well layer is from 1 nm to 10 nm both inclusive. The doping concentration of impurity (specifically, silicon (Si)) of the barrier layer is from 2×10^{18} cm^{-3} to 1×10^{20} cm^{-3} both inclusive.

Specifically, the mode locking laser diode device **110** and the semiconductor optical amplifier **200** of the second example have a ridge stripe type separate confinement heterostructure (SCH structure). More specifically, the mode locking laser diode device **110** and the semiconductor optical amplifier **200** of the second example have a GaN laser diode structure composed of an index guide type AlGaInN, and a straight line-like ridge section (ridge stripe structure). In addition, the mode locking laser diode device **110** and the semiconductor optical amplifier **200** are provided on (0001) plane of an n-type GaN substrate **121** and the n-type GaN substrate **221**. The third compound semiconductor layers **140** and **240** have a quantum well structure. The (0001) plane of the n-type GaN substrates **121** and **221** is also called "C plane," and is a crystal plane having polarity. The first compound semiconductor layers **130** and **230**, the third compound semiconductor layers **140** and **240**, and the second compound semiconductor layers **150** and **250** are specifically composed of AlGaInN compound semiconductor. More specifically, the first compound semiconductor layers **130** and **230**, the third compound semiconductor layers **140** and **240**, and the second compound semiconductor layers **150** and **250** have a layer structure illustrated in the following Table 2. In Table 2, the listed items are shown in the order from the layer farthest from the n-type GaN substrates **121** and **221** to the layer closest to the n-type GaN substrates **121** and **221**.

TABLE 2

Second compound semiconductor layers 150 and 250
p-type GaN contact layer (Mg doped) 157 and 257
p-type GaN (Mg doped)/AlGaN superlattice cladding layers 156 and 256
p-typeAlGaN electron barrier layer (Mg doped) 153 and 253
Non-doped AlGaN cladding layer 152 and 252
Non-doped GaInN light guide layers 151 and 251
Third compound semiconductor layers 140 and 240
GaInN quantum well active layer
(well layer: $Ga_{0.92}$ $In_{0.08}N$/barrier layer: $Ga_{0.98}$ $In_{0.02}N$)
First compound semiconductor layers 130 and 230
n-type GaN layers 132 and 232
n-type AlGaN cladding layers 131 and 231
well layer (two layers): 8 nm [non-doped]
barrier layer (three layers): 10 nm [doping concentration (Si): 2×10^{18} cm^{-3}]

Further, part of the p-type GaN contact layers **157** and **257** and part of the p-type GaN/AlGaN superlattice cladding layers **156** and **256** are removed by RIE method, and ridge stripe structures (a ridge section **158** and the ridge section **258**) are formed. On both sides of the ridge sections **158** and **258**, a laminated insulating film **159** and the laminated insulating film **259** composed of SiO_2/Si is formed. The SiO_2 layer is the lower layer and the Si layer is the upper layer. The difference between the effective refractive index of the ridge sections **158** and **258** and the effective refractive index of the laminated insulating films **159** and **259** is from 5×10^{-3} to 1×10^{-2} both inclusive, and is specifically 7×10^{-3}. On the p-type GaN contact layers **157** and **257** corresponding to the top face of the ridge sections **158** and **258**, the second electrodes (p-side ohmic electrodes) **162** and **262** are formed. Meanwhile, on the rear face of the n-type GaN substrates **121** and **221**, a first electrode (n-side ohmic electrode) **161** and the first electrode (n-side ohmic electrode) **261** composed of Ti/Pt/Au are formed. Specifically, the laminated insulating films **159** and **259** have SiO_2/Si laminated structure.

In the mode locking laser diode device **110** of the second example, the p-type AlGaN electron barrier layer **153**, the p-type GaN/AlGaN superlattice cladding layer **156**, and the p-type GaN contact layer **157** that are Mg-doped compound semiconductor layers are arranged not to overlap with each other as much as possible in the light density distribution generated from the third compound semiconductor layer **140** and regions in the vicinity thereof. Theref, internal loss is inhibited in a range in which internal quantum efficiency is not lowered. Therefore, threshold current I_{th} at which laser oscillation is started is decreased. Further, it was found that internal loss α_i is lowered by increasing a value of distance d from the third compound semiconductor layers **140** to the p-type AlGaN electron barrier layer **153**. It was also found that if the value d becomes a certain value or more, efficiency of hole injection into the well layer is lowered, and as a result, electron-hole recombination ratio in the third compound semiconductor layer **140** is lowered, and internal quantum efficiency η_i is decreased. Thus, the distance d from the third compound semiconductor layer **140** to the p-type AlGaN electron barrier layer **153** was set to 0.10 μm, the height of the ridge section (ridge stripe structure) was set to 0.30 μm, the thickness of the second compound semiconductor layer **150** located between the second electrode **162** and the third compound semiconductor layer **140** was set to 0.50 μm, and the thickness of a portion of the p-type GaN/AlGaN superlattice cladding layer **156** located below the second electrode **162** was set to 0.40 μm. "The distance d between the electron barrier layer **153** and the third compound semiconductor layers **140**" means a distance between a portion of the electron barrier layer **153** facing the third compound semiconductor layer **140** (interface) and a portion of the third compound semiconductor layer **140** facing the electron barrier layer **153** (interface). A composition and a configuration of the semiconductor optical amplifier **200** are similar to the foregoing composition and the foregoing configuration of the mode locking laser diode device **110**.

In the second example, the second electrodes **162** and **262** are formed from a Pd single layer having a thickness of 0.1 μm. Further, in the second example, the width of an isolation trench **162**C that separates the second electrode **162** composing the mode locking laser diode device **110** into a first section **162**A and a second section **162**B is 1 μm or more and 50% or less the resonator length. Further, the length of a saturable absorption region **142** is shorter than the length of the light emitting region **141**. Further, the length of the second electrode **162** (total length of the first section and the second section) is shorter than the length of the third compound semiconductor layer **140**. Specifically, resonator length Z" was set to 0.60 mm, the length of the first section **162**A of the second electrode **162** was set to 0.52 mm, the length of the second section **162**B was set to 0.06 mm, and the width of the isolation trench **162**C (length in the resonator length direction) was set to 0.02 mm.

The thickness of the p-type GaN/AlGaN superlattice cladding layers **156** and **256** having a superlattice structure in which a p-type GaN layer and a p-type AlGaN layer are alternately layered is 0.7 μm or less, and specifically 0.4 μm. The thickness of the p-type GaN layer composing the superlattice structure is 2.5 nm. The thickness of the p-type AlGaN layer composing the superlattice structure is 2.5 nm. The total number of layers of the p-type GaN layer and the p-type AlGaN layer is 160. Further, the distance from the third compound semiconductor layers **140** and **240** to the second electrodes **162** and **262** is 1 μm or less, and specifically 0.5 μm. Further, the p-type AlGaN electron barrier layers **153** and **253**, the p-type GaN/AlGaN superlattice cladding layers **156** and **256**, and the p-type GaN contact layers **157** and **257** composing the second compound semiconductor layers **150** and **250** are doped with Mg at the level of 1×10^{19} cm^{-3} or more (specifically at the level of 2×10^{19} cm^{-3}). Further, the second compound semiconductor layers **150** and **250** are provided with the non-doped compound semiconductor layer (the non-doped GaInN light guide layers **151** and **251** and the non-doped AlGaN cladding layer **152** and **252**) and the p-type compound semiconductor layer from the third compound semiconductor layer side. The distance d from the third compound semiconductor layer **140** to the p-type compound semiconductor layer (specifically, the p-type AlGaN electron barrier layers **153** and **253**) is 1.2×10^{-7} m or less, and specifically 100 nm.

Further, in the second example, a given value of voltage (voltage equal to or less than built-in voltage) is applied to the second section **262**B of the semiconductor optical amplifier **200** while laser light enters the semiconductor optical amplifier **200** from the laser light source **100**. The relative position of the semiconductor optical amplifier **200** with respect to laser light entering the semiconductor optical amplifier **200** is adjusted so that the current flown in the semiconductor optical amplifier **200** becomes the maximum.

Specifically, in the second example, when a current flown in the second section **262**B of the semiconductor optical amplifier **200** in the case where a given value of voltage V_0 is applied to the semiconductor optical amplifier **200** while laser light does not enter the semiconductor optical amplifier **200** from the laser light source **100** is I_1, and a current flown in the second section **262**B of the semiconductor optical amplifier **200** in the case where a given value of voltage V_0 is applied to the semiconductor optical amplifier **200** while laser light enters the semiconductor optical amplifier **200** from the laser light source **100** is I_2, the relative position of the semiconductor optical amplifier **200** with respect to laser light entering the semiconductor optical amplifier **200** is adjusted so that value of $\Delta I=(I_2-I_1)$ becomes the maximum.

FIG. **13** schematically illustrates change of the current ΔI flown in the semiconductor optical amplifier **200** in the case where a given value of voltage is applied to the semiconductor optical amplifier **200** while laser light enters the semiconductor optical amplifier **200** from the laser light source **100** and the XYZ stage is moved in the X direction. Along with movement of the XYZ stage in the X direction, the current ΔI flown in the semiconductor optical amplifier **200** is flatly increased until the ΔI exceeds the maximum value, and is flatly decreased. Change of light output of laser light emitted from the semiconductor optical amplifier **200** at this time shows the totally same behavior as that of change of current. Thus, light output of laser light emitted from the semiconductor optical amplifier **200** is able to be the maximum by adjusting the relative position of the semiconductor optical amplifier **200** with respect to laser light entering the semiconductor optical amplifier **200** so that the current flown in the semiconductor optical amplifier **200** becomes the maximum.

In the semiconductor optical amplifier **200** of the second example, in the case where a given value of voltage V_0 is applied to the semiconductor optical amplifier **200** while laser light enters the semiconductor optical amplifier **200** from the laser light source **100** and the XYZ stage is moved in the X direction, as illustrated in FIG. **13**, a voltage applied to (added to) the semiconductor optical amplifier **200** is increased. In the case where the XYZ stage is moved, light output from the semiconductor optical amplifier **200** is increased, and when such a phenomenon is generated, the number of carriers in the light amplification region (carrier injection region, gain region) **241** is decreased. Thus, a current flown in the semiconductor optical amplifier **200** is increased to compensate such decrease of the number of carriers. Positioning method of the semiconductor optical amplifier and the light output device in the second example are based on the foregoing phenomenon. A positioning equipment (XYZ stage) **300** may be moved by an operator. Otherwise, the positioning equipment (XYZ stage) **300** is able to be automatically moved by direction of a semiconductor optical amplifier control device **400** based on voltage measurement result.

In the second example, a current applied to the semiconductor optical amplifier **200** is measured to adjust the relative position of the semiconductor optical amplifier **200** with respect to laser light entering the semiconductor optical amplifier **200**. Thus, measurement for position adjustment is able to be performed without depending an external monitoring equipment. Thus, the relative position of the semiconductor optical amplifier **200** with respect to laser light entering the semiconductor optical amplifier **200** is able to be adjusted accurately.

Further, by monitoring the currents I_1 and I_2 flown in the second section **262**B of the semiconductor optical amplifier **200**, operation state of the semiconductor optical amplifier **200** and the mode locking laser diode device **110** is able to be monitored.

In the mode locking laser diode device **110** of the second example, the third compound semiconductor layer **140** includes the saturable absorption region **142**. Further, the second electrode **162** is separated into the first section **162**A for obtaining forward bias state by flowing a current to the first electrode **161** through the light emitting region **141**, and the second section **162**B for applying an electric field to the saturable absorption region **142** by the isolation trench **162**C. Forward bias state is obtained by flowing a current to the first electrode **161** from the first section **162**A of the second electrode **162** through the light emitting region **141**, and an electric field is added to the saturable absorption region **142** by applying a voltage between the first electrode **161** and the second section **162**B of the second electrode **162**. In addition, in the mode locking laser diode device of the second example, light pulse is generated in the light emitting region **141** by flowing a current from the second electrode **162** to the first electrode **161** through the laminated structure.

Specifically, in the mode locking laser diode device **110** of the second example, as described above, the second electrode **162** is separated into the first section **162**A for obtaining forward bias state by flowing a direct current (forward bias current I_{gain}) to the first electrode **161** through the light emitting region (gain region) **141**, and the second section **162**B for applying an electric field to the saturable absorption region **142** (the second section **162**B for adding reverse bias voltage V_{sa} to the saturable absorption region **142**) by the isolation trench **162**C. The electric resistance value (also referred to as "separating resistance value") between the first section **162**A

and the second section **162**B of the second electrode **162** is 1×10 times or more the electric resistance value between the second electrode **162** and the first electrode **161**, is specifically 1.5×10^3 times the electric resistance value between the second electrode **162** and the first electrode **161**. Further, the electric resistance value (separating resistance value) between the first section **162**A and the second section **162**B of the second section **162** is $1\times10^2\Omega$ or more, and is specifically $1.5\times10^4\Omega$.

Further, in the mode locking laser diode device **110** of the second example, the second electrode **162** having a separating resistance value of $1\times10^2\Omega$ or more should be formed on the second compound semiconductor layer **150**. In the case of the GaN laser diode device, mobility in the compound semiconductor having p-type conductivity type is small differently in the existing GaAs laser diode device. Thus, it is possible that the electric resistance value between the first section **162**A and the second section **162**B of the second electrode **162** becomes 10 times or more the electric resistance value between the second electrode **162** and the first electrode **161**, or the electric resistance value between the first section **162**A and the second section **162**B of the second section **162** becomes $1\times10^2\Omega$ or more without setting high resistance of the second compound semiconductor layer **150** having p-type conductivity type by ion injection or the like but separating the second electrode **162** formed thereon by the isolation trench **162**C.

A description will be given of a method of manufacturing the mode locking laser diode device of the second example with reference to FIGS. **29**A, **29**B, **30**A, **30**B, and **31**. FIGS. **29**A, **29**B, **30**A, and **30**B are schematic partial cross sectional views where the substrate and the like are cut in XY plane. FIG. **31** is a schematic partial end view where the substrate and the like are cut in YZ plane.

Requested characteristics of the second electrode **162** are as follows:

(1) a function as an etching mask in etching the second compound semiconductor layer **150** is included;

(2) the second electrode **162** is able to be wet-etched without deteriorating optical and electric characteristics of the second compound semiconductor layer **150**;

(3) contact specific resistance value of $10^{-2}\Omega\cdot cm^2$ or less is shown in the case where the second electrode **162** is formed on the second compound semiconductor layer **150**;

(4) in the case of a laminated structure, a material composing the lower metal layer has large work function, shows low contact specific resistance value to the second compound semiconductor layer **150**, and is able to be wet-etched; and

(5) in the case of a laminated structure, a material composing the upper metal layer has resistance to etching in forming the ridge stripe structure (for example, Cl_2 gas used in RIE method), and is able to be wet-etched.

Step-**200**

First, a laminated structure in which the first compound semiconductor layer **130** that has first conductivity type (n-type conductivity type) and is composed of GaN compound semiconductor, the third compound semiconductor layer (active layer) **140** including the light emitting region (gain region) **141** composed of GaN compound semiconductor and the saturable absorption region **142**, and the second compound semiconductor layer **150** that has second conductivity type (p-type conductivity type) different from the first conductivity type and is composed of GaN compound semiconductor are sequentially layered is formed on a substrate, specifically on (0001) plane of the n-type GaN substrate **121** based on known MOCVD method (refer to FIG. **29**A).

Step-**210**

After that, the strip-shaped second electrode **162** is formed on the second compound semiconductor layer **150**. Specifically, after a Pd layer **163** is formed over the entire face of the second compound semiconductor layer **150** based on vacuum evaporation method (refer to FIG. **29**B), a strip-shaped etching-use resist layer is formed on the Pd layer **163** based on photolithography technique. After the Pd layer **163** not covered with the etching-use resist layer is removed by using aqua regia, the etching-use resist layer is removed. Thereby, the structure illustrated in FIG. **30**A is able to be obtained. It is possible that the strip-shaped second electrode **162** is formed on the second compound semiconductor layer **150** based on liftoff method.

Step-**220**

Next, at least part of the second compound semiconductor layer **150** is etched (in the second example, part of the second compound semiconductor layer **150** is etched) with the use of the second electrode **162** as an etching-use mask to form the ridge stripe structure. Specifically, part of the second compound semiconductor layer **150** is etched with the use of the second electrode **162** as an etching-use mask based on RIE method using Cl_2 gas. Thereby, the structure illustrated in FIG. **30**B is able to be obtained. As described above, the ridge stripe structure is formed by self alignment method by using the second electrode **162** patterned in the shape of a strip as an etching-use mask. Thus, misalignment is not generated between the second electrode **162** and the ridge stripe structure.

Step-**230**

After that, a resist layer **164** for forming the isolation trench in the second electrode **162** is formed (refer to FIG. **31**). Referential number **165** represents an aperture provided in the resist layer **164** for forming the isolation trench. Next, the isolation trench **162**C is formed in the second electrode **162** by wet etching method with the use of the resist layer **164** as a wet etching-use mask, and thereby the second electrode **162** is separated into the first section **162**A and the second section **162**B by the isolation trench **162**C. Specifically, aqua regia is used as an etching liquid, and the entire body is dipped into the aqua regia for about 10 seconds, and thereby the isolation trench **162**C is formed in the second electrode **162**. After that, the resist layer **164** is removed. Accordingly, the structure illustrated in FIG. **10** is able to be obtained. As described above, differently from dry etching method, by adopting wet etching method, optical characteristics and electric characteristics of the second compound semiconductor layer **150** are not deteriorated. Thus, light emitting characteristics of the mode locking laser diode device are not deteriorated. If dry etching method is adopted, there is a possibility that internal loss α_i of the second compound semiconductor layer **150** is increased, the threshold voltage is increased, and light output is lowered. In this case, when an etching rate of the second electrode **162** is ER_0, and an etching rate of the laminated body is ER_1, the following formula is established:

$$ER_0/ER_1 \approx 1\times10^2$$

As described above, since the high etching selection ratio exists between the second electrode **162** and the second compound semiconductor layer **150**, the second electrode **162** is able to be surely etched without etching the laminated structure (or even if the laminated structure is etched, the etching amount is slight).

Step-**240**

After that, the n-side electrode **161** is formed, the substrate is cleaved, and further packaging is made. Accordingly, the mode locking laser diode device **110** is able to be fabricated.

In general, resistance R (Ω) of a semiconductor layer is expressed as follows by using specific resistance value ρ (Ω·m) of a material composing a semiconductor layer, length of the semiconductor layer X_0 (m), cross section area S of the semiconductor layer (m^2), carrier density n (cm^{-3}), electric charge amount e (C), and mobility μ (m^2/V sec).

$$R=(\rho\cdot X_0)/S=X_0/(n\cdot e\cdot \mu\cdot S)$$

Since mobility of the p-type GaN semiconductor is two-digit or more smaller than that of the p-type GaAs semiconductor, the electric resistance value gets high easily. Thus, it is found that the electric resistance value of the laser diode device having a ridge stripe structure with small cross section area being 1.5 μm wide and 0.35 μm high becomes a large value based on the foregoing formula.

FIG. **27** illustrates a result obtained by measuring an electric resistance value between the first section **162**A and the second section **162**B of the second electrode **162** of the fabricated mode locking laser diode device **110** of the second example by four terminal method. When the width of the isolation trench **162**C was 20 μm, the electric resistance value between the first section **162**A and the second section **162**B of the second electrode **162** was 15 kΩ.

In the fabricated mode locking laser diode device **110** of the second example, forward bias state was obtained by flowing a direct current from the first section **162**A of the second electrode **162** to the first electrode **161** through the light emitting region **141**, and electric field was applied to the saturable absorption region **142** by applying reverse bias voltage V_{sa} between the first electrode **161** and the second section **162**B of the second electrode **162**, and thereby mode locking drive was performed.

Further, the electric resistance value between the first section **162**A and the second section **162**B of the second electrode **162** is ten times or more the electric resistance value between the second electrode **162** and the first electrode **161**, or 1×10^2Ω or more. Thus, flow of leakage current from the first section **162**A of the second electrode **162** to the second section **162**B of the second electrode **162** is able to be inhibited securely. In the result, the light emitting region **141** is able to be in forward bias state, the saturable absorption region **142** is securely able to be in reverse bias state, and mode locking operation is able to be securely performed.

Further, the semiconductor optical amplifier **200** is able to be manufactured by the same manufacturing method as that of the mode locking laser diode device **110**, except that the structure of the second electrode is different. Thus, detailed description thereof will be omitted.

To promote better understanding of the mode locking laser diode device of the second example, a mode locking laser diode device of a second referential example was fabricated. In the mode locking laser diode device of the second referential example, the structure of the third compound semiconductor layer **140** in the layer structure illustrated in Table 2 was as illustrated in the following Table 3.

TABLE 3

	Second example	Second referential example
Well layer	8 nm	10.5 nm
Barrier layer	12 nm	14 nm
Impurity doping concentration of well layer	Non-doped	Non-doped
Impurity doping concentration of barrier layer	Si: 2×10^{18} cm^{-3}	Non-doped

In the second example, the thickness of the well layer is 8 nm, the barrier layer is doped with Si at a concentration of Si: 2×10^{18} cm^{-3}, and QCSE effect in the third compound semiconductor layer is modified. Meanwhile, in the second referential example, the thickness of the well layer is 10.5 nm, and the barrier layer is not doped with impurity.

A light condensing external resonator was formed from the mode locking laser diode devices of the second example and the second referential example, and mode locking driving was performed (refer to FIG. **19**A). In the light condensing external resonator illustrated in FIG. **19**A, the external resonator is configured of the end face of the mode locking laser diode device in which a high reflective coating layer (HR) is formed on the saturable absorption region side and the external mirror **13**, and light pulse is extracted from the external mirror **13**. A low reflective coating layer (AR) is formed on the end face (light output end face) of the mode locking laser diode device on the light emitting region (gain region) side. As the optical filter **12**, a bandpass filter is mainly used, which is inserted for controlling laser oscillation wavelength. Repetition frequency f of light pulse train is determined by the external resonator length Z' as expressed by the following formula, where c represents light velocity and n represents reflective index of waveguide.

$$f=c/(2n\cdot Z')$$

Mode locking is determined by a direct current applied to the light emitting region **141** and the reverse bias voltage V_{sa} applied to the saturable absorption region **142**. FIGS. **25**A and **25**B illustrate reverse bias voltage dependence measurement results of relation between an injection current and light output (L-I characteristics) of the second example and the second referential example. In FIGS. **25**A and **25**B, measurement results affixed with referential symbol "A" are results in the case of the reverse bias voltage V_{sa}=0 volt, measurement results affixed with referential symbol "B" are results in the case of the reverse bias voltage V_{sa}=−3 volt, measurement results affixed with referential symbol "C" are results in the case of the reverse bias voltage V_{sa}=−6 volt, and measurement results affixed with referential symbol "D" are results in the case of the reverse bias voltage V_{sa}=−9 volt. In FIG. **25**A, the measurement result in the case of the reverse bias voltage V_{sa}=0 volt almost overlaps the measurement result in the case of the reverse bias voltage V_{sa}=−3 volt.

Based on comparison between FIGS. **25**A and **25**B, it is found that in the second referential example, as the reverse bias voltage V_{sa} is increased, the threshold current I_{th} at which laser oscillation is started is gradually increased, and change is shown at lower reverse bias voltage V_{sa} compared to in the second example. It indicates that in the third compound semiconductor layer **140** of the second example, effect of saturable absorption is electrically controlled more by the reverse bias voltage V_{sa}.

FIGS. **26**A and **26**B illustrate results obtained by measuring light pulse generated in the second example and the second referential example by a streak camera. In FIG. **26**B obtained in the second referential example, subpulse component is generated before and after main pulse. Meanwhile, in FIG. **26**A obtained in the second example, subpulse component is inhibited from being generated. The results may be all caused by increased effect of saturable absorption since QCSE effect is moderated by the structure of the third compound semiconductor layer **140**.

Drive conditions and the like of the mode locking laser diode device of the second example illustrated in FIG. **19**A are exemplified in the following Table 4. I_{th} represents a threshold current.

TABLE 4

Mode locking drive conditions: $0 < 1_{gain}/I_{th} \leq 5$
$-20 \leq V_{sa}$ (volt) ≤ 0
High reflective coating layer (HR): $85 \leq$ reflectance R_{HR} (%) < 100
Low reflective coating layer (AR): $0 <$ reflectance R_{AR} (%) ≤ 0.5
Optical filter: $85 \leq$ transmittance T_{BPF} (%) < 100
$0 <$ half bandwidth τ_{BPF} (nm) ≤ 2.0
$400 <$ peak wavelength λ_{bpf} (nm) < 450
External mirror: $0 <$ reflectance Roc (%) < 100
External resonator length Z'
$0 < Z'$ (mm) < 1500

More specifically, in the second example, the following conditions were adopted as an example:

I_{gain}: 120 mA
I_{th}: 45 mA
Reverse bias voltage V_{sa}: −11 (volt)
Reflectance R_{HR}: 95%
Reflectance R_{AR}: 0.3%
Transmittance T_{BPF}: 90%
Half bandwidth τ_{BPF}: 1 nm
Peak wavelength λ_{BPF}: 410 nm
Reflectance R_{OC}: 20%
External resonator length Z': 150 mm

Meanwhile, in the second referential example, the same conditions as those of the second example were adopted except for the following conditions:

I_{gain}: 95 mA
I_{th}: 50 mA
Reverse bias voltage V_{sa}: −12.5 (volt)
Reflectance R_{OC}: 50%

As illustrated in the conceptual view of FIG. **14**A, part of light output of laser light outputted from the semiconductor optical amplifier **200** is extracted by using a beam splitter **32**, and extracted light enters a photodiode **34** through a lens **33**. Thereby, the light output of laser light outputted from the semiconductor optical amplifier **200** may be measured. In the case where light output is changed from a desired value, alignment method of the semiconductor optical amplifier of the second example is executed again. That is, a given value of voltage V_0 is applied to the semiconductor optical amplifier **200** while laser light enters the semiconductor optical amplifier **200** from the laser light source **100**, and thereby the relative position of the semiconductor optical amplifier **200** with respect to laser light entering the semiconductor optical amplifier **200** is adjusted again so that a current flown in the semiconductor optical amplifier **200** becomes the maximum. In the case where result of readjustment of the relative position of the semiconductor optical amplifier **200** with respect to laser light entering the semiconductor optical amplifier **200** is the same as the relative position of the semiconductor optical amplifier with respect to laser light entering the semiconductor optical amplifier **200** before readjustment, light path through which the laser light outputted from the semiconductor optical amplifier **200** passes is adjusted. Such adjustment may be performed by, for example, laying a reflective mirror **31** on an XYZ stage **35**. The XYZ stage **35** may be moved by an operator. Otherwise, the XYZ stage **35** is able to be automatically moved by direction of the semiconductor optical amplifier control device **400** based on the voltage and measurement result of the photodiode **34**. In FIG. **14**A, elements of the light output device located in the upstream of the semiconductor optical amplifier **200** are the same as the elements of the light output device of the second example, and thus the elements of the light output device located in the upstream of the semiconductor optical amplifier **200** are not illustrated in the figure. By adopting such a method, in the case where change occurs in the light output monitor, it is possible to easily determine whether or not such change is caused by relative position change of the semiconductor optical amplifier **200** with respect to laser light entering the semiconductor optical amplifier **200** (that is, change of efficiency of coupling of the entrance laser light and the light guide of the semiconductor optical amplifier).

Third Example

The third example relates to the semiconductor optical amplifiers according to the second embodiment and the third embodiment of the invention. FIGS. **15**A and **16** illustrate a schematic perspective view of the semiconductor optical amplifier and a schematic plan view of a ridge stripe structure according to the second embodiment of the invention of the third example. The width of the second electrode **262** is narrower than the width of the ridge stripe structure. In this case, (width of the second electrode)/(width of the ridge stripe structure) satisfies a value from 0.2 to 0.9 both inclusive. Further, FIGS. **17**A and **18** illustrate a schematic perspective view of the semiconductor optical amplifier and a schematic plan view of a ridge stripe structure according to the third embodiment of the invention of the third example. Where the maximum width of the ridge stripe structure is W_{max}, W_{max}/W_{out} is satisfied, and $0.2 \leq W_{out}/W_{max} \leq 0.9$ is satisfied. In FIG. **18**, though the second electrode **262** is not illustrated, the second electrode **262** is formed from the p-type GaN contact layer corresponding to the top face of the ridge section to part of the top face of the p-type AlGaN cladding layer as in the first example.

A composition and a structure of the semiconductor optical amplifier of the third example are the same as the composition and the structure of the semiconductor optical amplifier described in the first example except for the foregoing points or except that the carrier non-injection region is not provided, and thus detailed description thereof will be omitted.

As illustrated in FIG. **6**B, in the case where the width of the near-field image is narrower than W_{out}, there is a possibility that light field becomes unstable depending on drive conditions and light output conditions such as the light density, the carrier diffusion length, and device temperature. Thus, in the third example, by adopting the foregoing composition and the foregoing structure, mode instability is modified.

Fourth Example

The fourth example is a modification of the third example. FIG. **15**B illustrates a schematic perspective view of a modified example of the semiconductor optical amplifier illustrated in FIGS. **15**A and **16**, and FIG. **17**B illustrates a schematic perspective view of a modified example of the semiconductor optical amplifier illustrated in FIGS. **17**A and **18**. As illustrated in FIG. **15**B and FIG. **17**B, in the fourth example, differently from the third example, a carrier non-injection region is provided in the internal region of the laminated structure from the light output end face along the axis line of the semiconductor optical amplifier. A composition and a structure of the semiconductor optical amplifier of the fourth example are the same as the composition and the structure of the semiconductor optical amplifier described in the third example except for the foregoing points, and thus detailed description thereof will be omitted. In the forth example, the second electrode may be separated into the first section and the second section by the isolation trench as in the second example.

Fifth Example

The fifth example is a modification of the mode locking laser diode device in the second example. FIGS. **19**B, FIG. **20**A, and FIG. **20**B illustrate an example in which an external resonator is structured by the mode locking laser diode device of the fifth example.

In the collimation type external resonator illustrated in FIG. **19**B, the external resonator is formed from the end face of the mode locking laser diode device in which a high reflective coating layer (HR) is formed on the saturable absorption region side and the external mirror, and light pulse is extracted from the external mirror. A low reflective coating layer (AR) is formed on the end face (light output end face) of the mode locking laser diode device on the light emitting region (gain region) side. The drive conditions and the like of the mode locking laser diode device of the fifth example illustrated in FIG. **19**B are similar to those of the foregoing Table 4.

Meanwhile, in the external resonator illustrated in FIGS. **20**A and **20**B, the external resonator is formed from the end face of the mode locking laser diode device in which a reflective coating layer (R) is formed on the saturable absorption region side (light output end face) and the external mirror, and light pulse is extracted from the saturable absorption region **142**. A low reflective coating layer (AR) is formed on the end face of the mode locking laser diode device on the light emitting region (gain region) side. The example illustrated in FIG. **20**A is light condensing type, and the example illustrated in FIG. **20**B is collimation type. The drive conditions and the like of the mode locking laser diode device of the fifth example illustrated in FIGS. **20**A and **20**B are similar to those of the foregoing Table 4. However, the reflective coating layer (R) may be as illustrated in the following Table 5.

TABLE 5

Reflective coating layer (R)
$0 < \text{reflectance } R_R\ (\%) < 100$

Specifically, reflectance R_R was set to 20%. A composition and a structure of the mode locking laser diode device in the fifth example are the same as the composition and the structure of the mode locking laser diode device described in the second example, and thus detailed description thereof will be omitted.

Sixth Example

The sixth example is also a modification of the mode locking laser diode device of the second example. In the sixth example, as illustrated in FIG. **20**C, the mode locking laser diode device is monolithic type. The drive conditions and the like of the mode locking laser diode device of the sixth example are similar to those of the foregoing Table 4. Other composition and other structure of the mode locking laser diode device of the sixth example are similar to the composition and the structure of the mode locking laser diode device described in the second example, and thus detailed description thereof will be omitted.

Seventh Example

The seventh example is also a modification of the mode locking laser diode device in the second example. The mode locking laser diode device of the seventh example is a laser diode device having a ridge stripe type separate confinement heterostructure with oblique light guide. FIG. **21** illustrates a schematic view viewed from above of a ridge section **158**A in the mode locking laser diode device of the seventh example. The mode locking laser diode device of the seventh example has a structure in which two straight line-like ridge sections. A value of angle θ' of intersection of the two ridge sections desirably satisfies, for example, $0<\theta'\leq 10$ (deg), and preferably satisfies $0<\theta'\leq 6$ (deg). By adopting the oblique ridge stripe type, reflectance of the end face provided with low reflective coating is able to be closer to 0% as the ideal value. In the result, generation of light pulse that would revolve in the laser diode device is able to be prevented, and generation of sub-light pulse associated with main light pulse is able to be inhibited. The oblique ridge stripe type mode locking laser diode device of the seventh example is applicable to the second example, the fifth example, and the sixth example. Other composition and other structure of the mode locking laser diode device in the seventh example are similar to the composition and the structure of the mode locking laser diode device described in the second example, and thus detailed description thereof will be omitted.

Eighth Example

The eighth example is also a modification of the mode locking laser diode device in the second example. In the eighth example, a current is flown from the second electrode **162** to the first electrode **161** through the light emitting region **141**, and an external electric signal (RMS jitter Δ_{signal}) is superimposed on the first electrode **161** from the second electrode **162** through the light emitting region **141**. FIG. **22**A schematically illustrates a system of performing mode locking drive by using the mode locking laser diode device of the eighth example. The external electric signal is sent from a known external electric signal generator to the second electrode **162**. Thereby, light pulse is able to be sync with the external electric signal. That is, RMS timing jitter Δt_{MILD} is able to be kept down as the following formula: $\Delta_{signal}\leq\Delta t_{MILD}$.

The drive conditions and the like of the mode locking laser diode device of the eighth example illustrated in FIG. **22**A are similar to those of the foregoing Table 4. Voltage maximum value V_{p-p} (unit: volt) of the external electric signal desirably satisfies $0<V_{p-p}\leq 10$, and preferably satisfies $0<V_{p-p}\leq 3$. Further, frequency f_{signal} of the external electric signal and repetition frequency f_{MILD} of a light pulse train desirably satisfy $0.99\leq f_{signal}/f_{MILD}\leq 1.01$.

More specifically, in the eighth example, the following conditions were adopted as an example:

I_{gain}: 120 mA
I_{th}: 45 mA
Reverse bias voltage V_{sa}: −11 (volt)
Reflectance R_{HR}: 95%
Reflectance R_{AR}: 0.3%
Transmittance T_{BPF}: 90%
Half bandwidth τ_{BPF}: 1 nm
Peak wavelength λ_{BPF}: 410 nm
Reflectance R_{OC}: 20%
External resonator length Z': 150 mm
V_{p-p}: 2.8 volt
f_{signal}: 1 GHz
f_{MILD}: 1 GHz
Δ_{signal}: 1 picosecond
Δt_{MILD}: 1.5 picosecond

Meanwhile, in the eighth referential example, a current was flown from the second electrode **162** to the first electrode **161** through the light emitting region **141** without superimposing an external electric signal on the first electrode **161** from the

second electrode **162** through the light emitting region **141**. RF spectrum was measured. FIGS. **28**A and **28**B illustrate measurement results in the eighth example and the eighth referential example. In the eighth referential example, the same conditions as those of the eighth example were adopted except for the following conditions:

Reflectance R_{OC}: 50%

FIGS. **28**A and **28**B show that in the eighth example, the area of bottom component of RF spectrum is decreased more than in the eighth referential example. Such a fact shows that the eighth example is a drive method in which the phase noise and the timing jitter are smaller compared to those of the eighth referential example.

Other composition and other structure of the mode locking laser diode device in the eighth example are similar to the composition and the structure of the mode locking laser diode device described in the second example, the fifth example, the sixth example, and the seventh example, and thus detailed description thereof will be omitted.

Ninth Example

The ninth example is also a modification of the mode locking laser diode device in the second example. In the ninth example, an optical signal enters from one end face of the laminated structure. FIG. **22**B schematically illustrates a system of performing mode locking drive by using the mode locking laser diode device of the ninth example. The optical signal (RMS jitter: Δ_{opto}) is outputted from an optical signal generator composed of the laser diode device, and enters one end face of the laminated structure through a lens, an external mirror, an optical filter, and a lens. Thereby, light pulse is able to be sync with the optical signal. That is, the RMS timing jitter Δt_{MILD} is able to be kept down as the following formula. $\Delta_{opto} \leq \Delta t_{MILD}$.

Other composition and other structure of the mode locking laser diode device in the ninth example are similar to the composition and the structure of the mode locking laser diode device described in the second example, the fifth example, the sixth example, and the seventh example, and thus detailed description thereof will be omitted.

Descriptions have been hereinbefore given of the invention with reference to the preferred embodiments. However, the invention is not limited to the foregoing embodiments. The compositions and the structures of the semiconductor optical amplifier, the light output device, the laser light source, and the laser diode device described in the embodiments are just exemplified, and modifications may be made as appropriate. Further, in the embodiments, though various values have been shown, such various values are just exemplified as well, and thus it is needless to say that, for example, if specifications of the semiconductor optical amplifier, the light output device, and the laser diode device to be used are changed, values are also changed. For example, the second electrode **162** may have a laminated structure including a lower metal layer composed of palladium (Pd) having a thickness of 20 nm and an upper metal layer composed of nickel (Ni) having a thickness of 200 nm. In performing wet etching with the use of aqua regia, the etching rate of nickel is about 1.25 times the etching rate of palladium.

In the embodiments, the semiconductor optical amplifier is composed of a transmissive semiconductor optical amplifier. However, the semiconductor optical amplifier is not limited thereto. As illustrated in a conceptual view of FIG. **14**B, the semiconductor optical amplifier may be composed of a monolithic semiconductor optical amplifier. The monolithic semiconductor optical amplifier is an integrated body composed of a laser diode device and a semiconductor optical amplifier.

In the embodiments, the mode locking laser diode device **110** is provided on the {0001} plane, which is the C plane as the polarity plane of the n-type GaN substrate **121**. Alternately, the mode locking laser diode device **110** may be provided on A plane as {11-20} plane, M plane as {1-100} plane, non-polarity plane such as {1-102} plane, {11-2n} plane including {11-24} plane and {11-22} plane, or a semi-polarity plane such as {10-11} plane and {10-12} plane. Even if piezoelectric polarization or intrinsic polarization is thereby generated in the third compound semiconductor layer of the mode locking laser diode device **110**, piezoelectric polarization is not generated in the thickness direction of the third compound semiconductor layer and piezoelectric polarization is generated in the direction approximately perpendicular to the thickness direction of the third compound semiconductor layer. Thus, adverse effect resulting from piezoelectric polarization and intrinsic polarization is able to be excluded. {11-2n} plane means a non-polarity plane making 40 deg approximately with respect to the C plane. In the case where the mode locking laser diode device **110** is provided on a non-polarity plane or on a semi-polarity plane, limitation of the thickness of the well layer (from 1 nm to 10 nm both inclusive) and limitation of the impurity doping concentration of the barrier layer (from 2×10^{18} cm^{-3} to 1×10^{20} cm^{-3} both inclusive) are able to be eliminated.

The number of the light emitting regions **141** and the saturable absorption regions **142** is not limited to 1. FIG. **23** illustrates a schematic end view of a mode locking laser diode device in which one first section **162**A of the second electrode and two second sections **162**B_1, and **162**B_2 of the second electrode are provided. In the mode locking laser diode device, one end of the first section **162**A is opposed to one second section **162**B_1 with one isolation trench **162** C_1 in between, and the other end of the first section **162**A is opposed to the other second section **162**B_2 with the other isolation trench **162**C_2 in between. Further, one light emitting region **141** is sandwiched between saturable absorption regions **142**$_1$, and **142**$_2$. Further, FIG. **24** illustrates a schematic end view of a mode locking laser diode device in which two first sections **162**A_1, and **162**A_2 of the second electrode and one second section **162**B of the second electrode are provided. In the mode locking laser diode device, an end section of the second section **162**B is opposed to one first section **162**A_1 with one isolation trench **162** C_1 in between, and the other end of the second section **162**B is opposed to the other first section **162**A_2 with the other isolation trench **162** C_2 in between. Further, one saturable absorption region **142** is sandwiched between two light emitting regions **141**$_1$, and **141**$_2$.

Further, as a modification of the second embodiment, it is possible that a given value of current is applied to the semiconductor optical amplifier while laser light enters the semiconductor optical amplifier from the laser light source, and thereby the relative position of the semiconductor optical amplifier with respect to laser light entering the semiconductor optical amplifier is adjusted so that voltage applied to (added to) the semiconductor optical amplifier becomes the maximum. In this case, in the case where light output of laser light outputted from the semiconductor optical amplifier is measured and the light output is changed from a desired value, it is possible that a given value of current is applied to the semiconductor optical amplifier while laser light enters the semiconductor optical amplifier from the laser light source, and thereby the relative position of the semiconductor

optical amplifier with respect to laser light entering the semiconductor optical amplifier is adjusted again so that voltage applied to (added to) the semiconductor optical amplifier becomes the maximum. Further, in the case where result of readjustment of the relative position of the semiconductor optical amplifier with respect to laser light entering the semiconductor optical amplifier is the same as the relative position of the semiconductor optical amplifier with respect to laser light entering the semiconductor optical amplifier before readjustment, light path through which the laser light outputted from the semiconductor optical amplifier passes is able to be adjusted. Specifically, where a voltage applied to (added to) the semiconductor optical amplifier in the case where a given value of current I_0 is flown to the semiconductor optical amplifier while laser light does not enter the semiconductor optical amplifier from the laser light source is V_1, and a voltage applied to (added to) the semiconductor optical amplifier in the case where a given value of current I_0 is flown to the semiconductor optical amplifier while laser light enters the semiconductor optical amplifier from the laser light source is V_2, the relative position of the semiconductor optical amplifier with respect to laser light entering the semiconductor optical amplifier may be adjusted so that value of $\Delta V=(V_2-V_1)$ becomes the maximum. As a given value of current, 0 milliampere$<\Delta I\leq 20$ milliampere is able to be exemplified.

Further, as a modification of the second embodiment, it is possible that a given value of voltage is applied to the semiconductor optical amplifier while laser light enters the semiconductor optical amplifier from the laser light source, and thereby the relative position of the semiconductor optical amplifier with respect to laser light entering the semiconductor optical amplifier is adjusted so that a current flown to the semiconductor optical amplifier becomes the maximum. In this case, when light output of laser light outputted from the semiconductor optical amplifier is measured and the light output is changed from a desired value, it is possible that a given value of voltage is applied to the semiconductor optical amplifier while laser light enters the semiconductor optical amplifier from the laser light source, and thereby the relative position of the semiconductor optical amplifier with respect to laser light entering the semiconductor optical amplifier is adjusted again so that current flown in the semiconductor optical amplifier becomes the maximum. Further, in the case where result of readjustment of the relative position of the semiconductor optical amplifier with respect to laser light entering the semiconductor optical amplifier is the same as the relative position of the semiconductor optical amplifier with respect to laser light entering the semiconductor optical amplifier before readjustment, light path through which the laser light outputted from the semiconductor optical amplifier passes is able to be adjusted. Specifically, when a current flown in the semiconductor optical amplifier in the case where a given value of voltage V_0 is applied to the semiconductor optical amplifier while laser light does not enter the semiconductor optical amplifier from the laser light source is I_1, and a current flown in the semiconductor optical amplifier in the case where a given value of voltage V_0 is applied to the semiconductor optical amplifier while laser light enters the semiconductor optical amplifier from the laser light source is I_2, the relative position of the semiconductor optical amplifier with respect to laser light entering the semiconductor optical amplifier may be adjusted so that value of $\Delta I=(I_2-I_1)$ becomes the maximum. As a given value of voltage, 0 volt$\leq\Delta V\leq 5$ volt is able to be exemplified.

The present application contains subject matter related to that disclosed in Japanese Priority Patent Application JP 2010-149345 filed in the Japanese Patent Office on Jun. 30, 2010, the entire contents of which is hereby incorporated by reference.

It should be understood by those skilled in the art that various modifications, combinations, sub combinations and alternations may occur depending on design requirements and other factors insofar as they are within the scope of the appended claims or the equivalents thereof.

What is claimed is:

1. A semiconductor optical amplifier comprising:

a laminated structure including (i) a first compound semiconductor layer that has a first conductivity type and is composed of GaN compound semiconductor, (ii) a second compound semiconductor layer that has a second conductivity type different from the first conductivity type and is composed of GaN compound semiconductor, and (iii) a third compound semiconductor layer that has a light amplification region composed of GaN compound semiconductor, the first compound semiconductor layer, the third compound semiconductor layer, and the second compound semiconductor layer being sequentially layered;

a second electrode on the second compound semiconductor layer; and

a first electrode electrically connected to the first compound semiconductor layer,

wherein,

the laminated structure has a ridge stripe structure,

when a width of the ridge stripe structure in a light output end face is W_{out}, and a width of the ridge stripe structure in a light incident end face is W_{in}, $W_{out}>W_{in}$ is satisfied, and

a carrier non-injection region is provided in the laminated structure, the carrier non-injection region extending from the light output end face of the ridge stripe structure and towards the light incident end face of the ridge stripe structure along an axis line of the semiconductor optical amplifier, the first, second, and third compound semiconductor layers being present in the carrier non-injection region, and the second electrode not being present in the carrier non-injection region.

2. The semiconductor optical amplifier according to claim **1**, wherein W_{out} is greater or equal to 5 μm.

3. The semiconductor optical amplifier according to claim **1**, wherein W_{in} is from 1.4 μm to 2.0 μm, both inclusive.

4. The semiconductor optical amplifier according to claim **1**,

wherein the second electrode is composed of a first section and a second section separated by an isolation trench, and

the second section of the second electrode is provided in the carrier non-injection region.

5. The semiconductor optical amplifier according to claim **4**, wherein a voltage equal to or less than a built-in voltage is applied to the second section of the second electrode.

6. The semiconductor optical amplifier according to claim **1**, wherein the axis line of the semiconductor optical amplifier intersects with an axis line of the ridge stripe structure at a given angle that ranges from 0.1 to 10 degrees.

7. The semiconductor optical amplifier according to claim **1**, wherein a value of (width of the ridge stripe structure in the light output end face)/(width of laser light outputted from the semiconductor optical amplifier) is from 1.1 to 10, both inclusive.

8. A light output device comprising:

a laser light source; and

a semiconductor optical amplifier according claim 1 that optically amplifies laser light from the laser light source and outputs amplified light.

9. The light output device according to claim 8, further comprising a mirror and a light isolator positioned such that laser light output from the laser light source passes through the light isolator and then is reflected by the mirror.

10. The light output device according to claim 9, further comprising a half-wave plate and a lens positioned such that laser light reflected by the mirror passes through the half-wave plate and lens and then enters the semiconductor optical amplifier.

11. The light output device according to claim 10, wherein the light isolator is positioned to prevent light returned from the semiconductor optical amplifier from returning to the laser light source.

12. The light output device according to claim 11, further comprising an output lens, wherein the laser light is optically amplified in the semiconductor optical amplifier, and is output outside the system through the output lens.

13. The light output device according to claim 8, wherein the laser light source is a mode locking laser diode device, and pulse laser light output from the mode locking laser diode device enters the semiconductor optical amplifier.

14. A light output device comprising:

a laser light source;

a semiconductor optical amplifier according claim 1;

an alignment device that adjusts a relative position of the semiconductor optical amplifier with respect to laser light entering the semiconductor optical amplifier; and

a semiconductor optical amplifier control device that controls operation of the semiconductor optical amplifier.

15. The light output device according to claim 14, further comprising a mirror and a light isolator positioned such that laser light output from the laser light source passes through the light isolator and then is reflected by the mirror.

16. The light output device according to claim 15, further comprising a half-wave plate and a lens positioned such that laser light reflected by the mirror passes through the half-wave plate and lens and then enters the semiconductor optical amplifier.

17. The light output device according to claim 16, wherein the light isolator is positioned to prevent light returned from the semiconductor optical amplifier from returning to the laser light source.

18. The light output device according to claim 17, further comprising an output lens, wherein the laser light is optically amplified in the semiconductor optical amplifier, and is output outside the system through the output lens.

19. The light output device according to claim 14, wherein the laser light source is a mode locking laser diode device, and pulse laser light output from the mode locking laser diode device enters the semiconductor optical amplifier.

20. The light output device according to claim 14, wherein the reflecting mirror, the half-wave plate, and the lens are on the alignment device.

21. The light output device according to claim 20, wherein the alignment device comprises an XYZ stage and when the thickness direction of the laminated structure in the semiconductor optical amplifier is the Y direction and an axis line direction of the semiconductor optical amplifier is the Z direction, the reflecting mirror and the lens are moved in the X direction, the Y direction, and the Z direction by the alignment device.

22. A light output device comprising:

a laser;

a semiconductor optical amplifier that amplifies light output by the laser;

a light isolator between the laser and the semiconductor optical amplifier;

a mirror between the light isolator and the semiconductor optical amplifier;

a half-wave plate between the mirror and the semiconductor optical amplifier; and

a lens between the half-wave plate and the semiconductor optical amplifier,

wherein,

(1) the semiconductor optical amplifier comprises

(a) a laminated structure including (i) a first compound semiconductor layer that has a first conductivity type and is composed of GaN compound semiconductor, (ii) a second compound semiconductor layer that has a second conductivity type different from the first conductivity type and is composed of GaN compound semiconductor, and (iii) a third compound semiconductor layer that has a light amplification region composed of GaN compound semiconductor, the first compound semiconductor layer, the third compound semiconductor layer, and the second compound semiconductor layer are sequentially layered,

(b) a second electrode on the second compound semiconductor layer, and

(c) a first electrode electrically connected to the first compound semiconductor layer,

(2) the laminated structure has a ridge stripe structure, and

(3) a carrier non-injection region is provided in the laminated structure, the carrier non-injection region extending from the light output end face of the ridge stripe structure and towards the light incident end face of the ridge stripe structure along an axis line of the semiconductor optical amplifier, the first, second, and third compound semiconductor layers being present in the carrier non-injection region, and the second electrode not being present in the carrier non-injection region.

23. The light output device of claim 22, wherein, for the semiconductor optical amplifier, when a width of the ridge stripe structure in a light output end face is W_{out} and a width of the ridge stripe structure in a light incident end face is W_{in}, $W_{out} > W_{in}$ is satisfied.

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