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(54) OPTICAL MODULATION DEVICE, OPTICAL MODULATOR, OPTICAL MODULATION MODULE, OPTICAL TRANSMISSION APPARATUS, AND OPTICAL TRANSMISSION SYSTEM

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(52) **U.S. Cl.**

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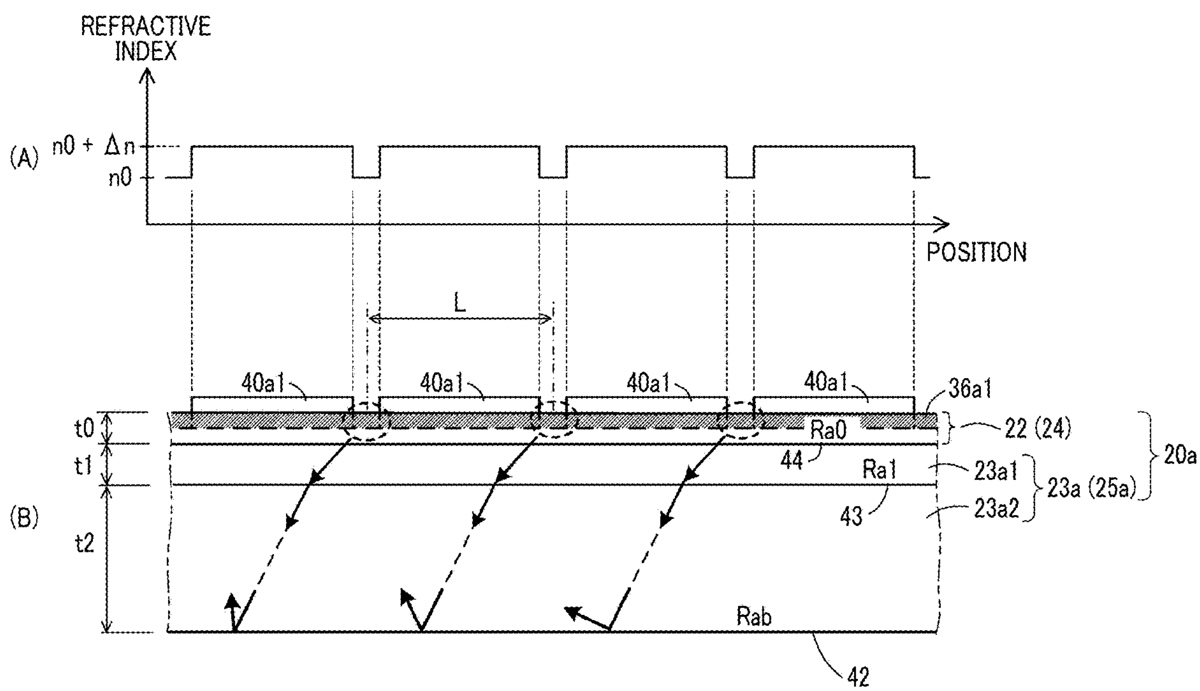
(57) **ABSTRACT**

An optical modulation device includes a substrate including a multilayer portion, an optical waveguide configured with a protruding portion extending on an optical waveguide layer in the multilayer portion, and a modulation electrode formed on the optical waveguide layer to control a light wave propagating through the optical waveguide and formed to be divided into a plurality of segments along a propagation direction of light of the optical waveguide, in which in all sections of the electrode or a section excluding a part of the sections of the electrode, a clearance, measured in an extending direction of the optical waveguide, between gaps between adjacent segments is constant, the multilayer portion includes the optical waveguide layer and a plurality of support layers, and surface roughness Rab of a back surface of the substrate has a relationship of Rab>λ with respect to a wavelength λ of the light wave.



CROSS-SECTIONAL VIEW TAKEN ALONG LINE V-V

FIG. 1

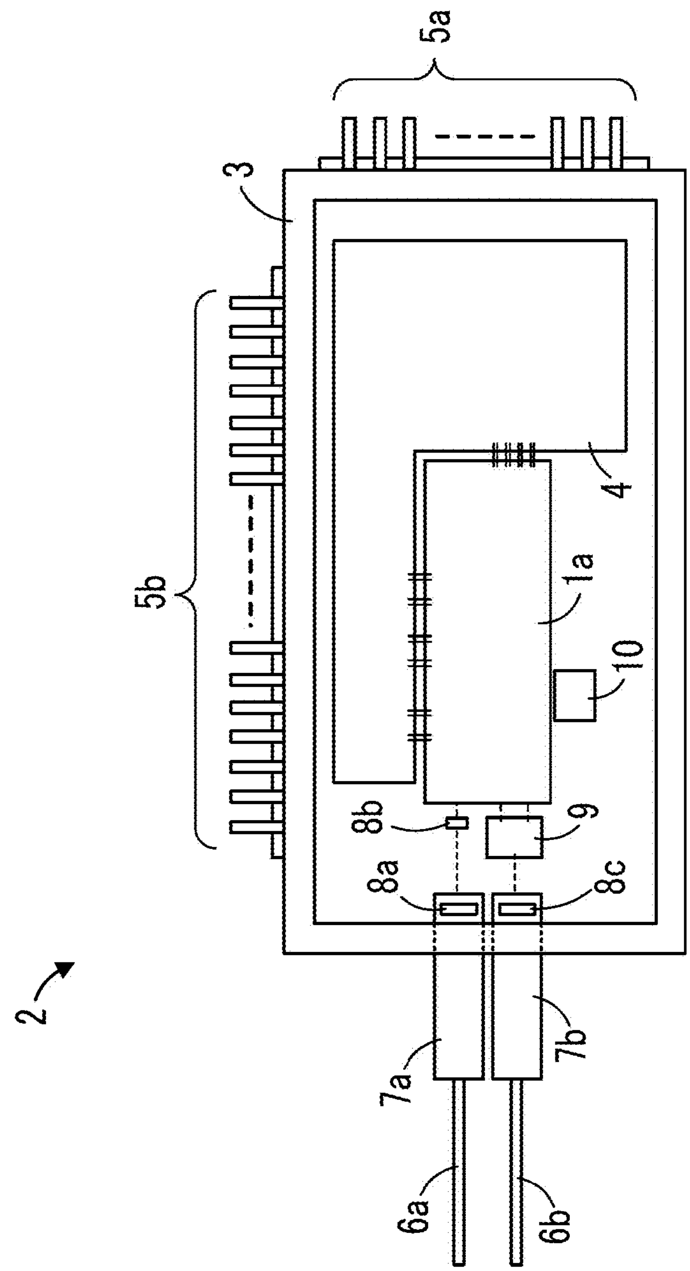


FIG. 2

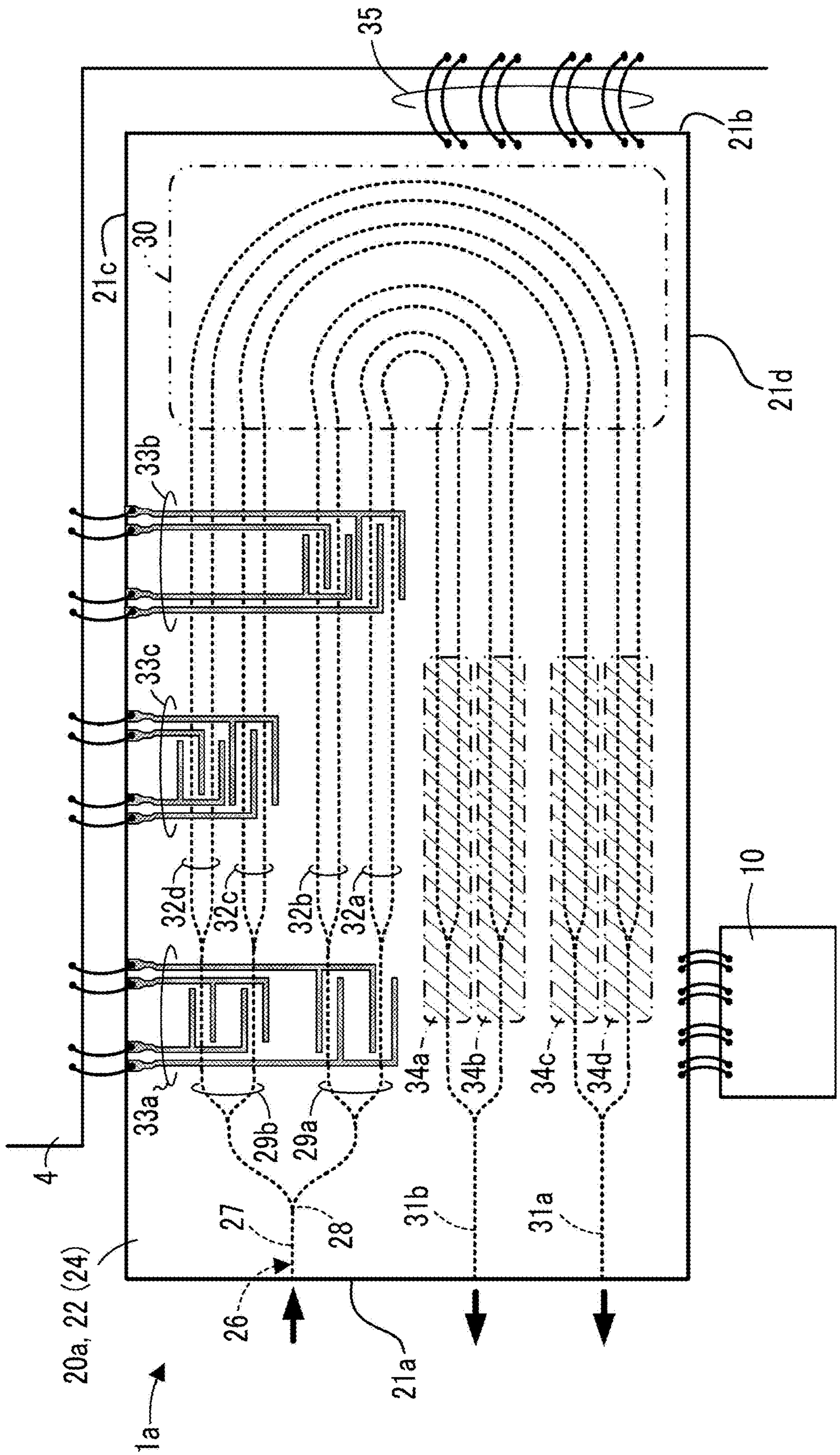

35
21b
21c
30
21d
33b
33c
10
32d
32c
32b
32a
33a
29b
29a
34a
34b
34c
34d
4
27
28
31b
31a
20a, 22 (24)
26
21a
1a

FIG. 3

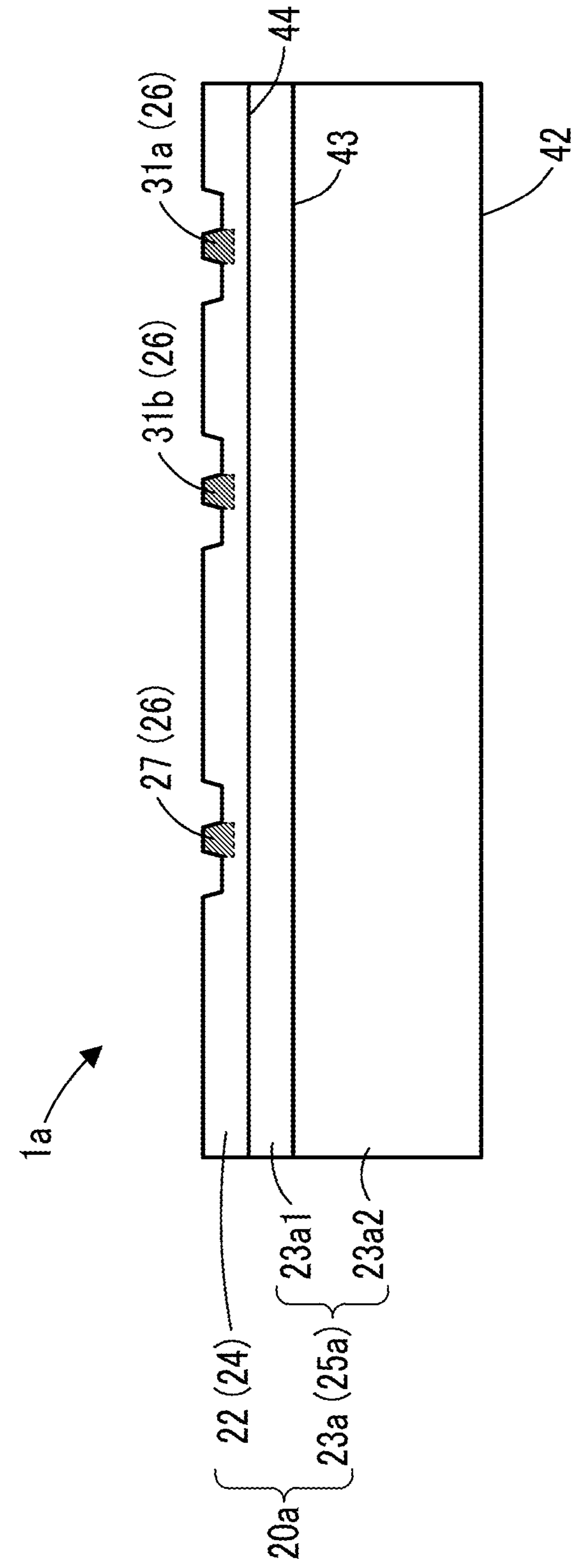


FIG. 4

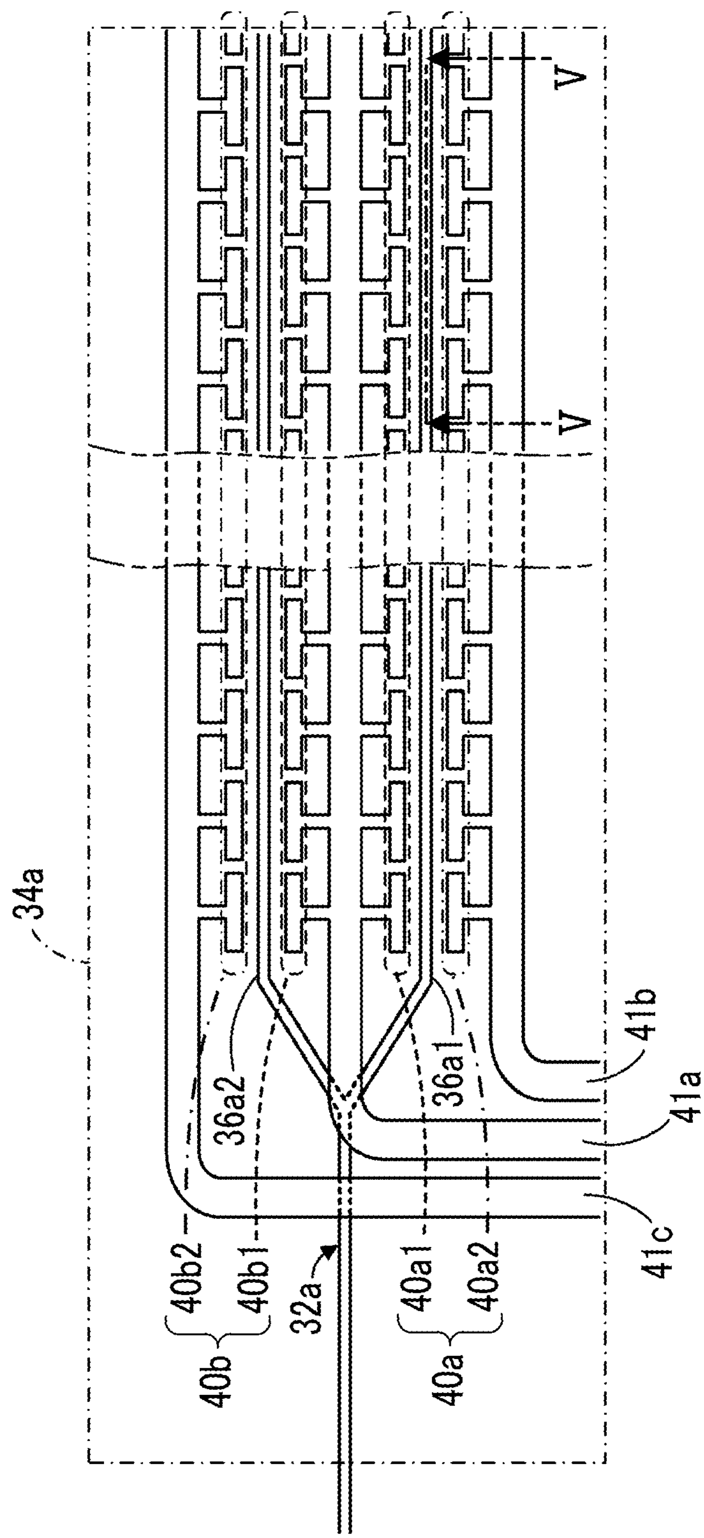
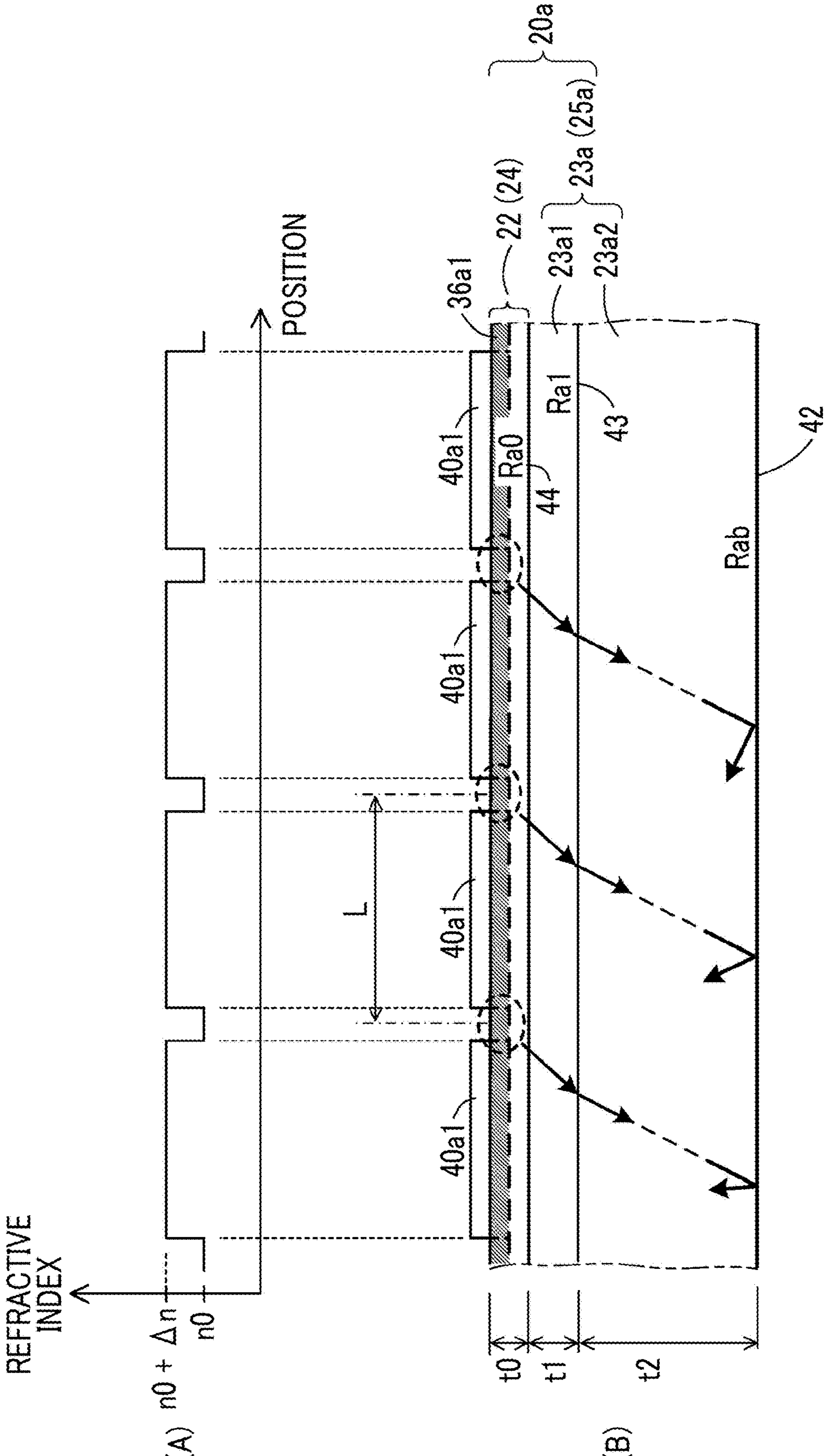


FIG. 5



CROSS-SECTIONAL VIEW TAKEN ALONG LINE V–V

FIG. 6

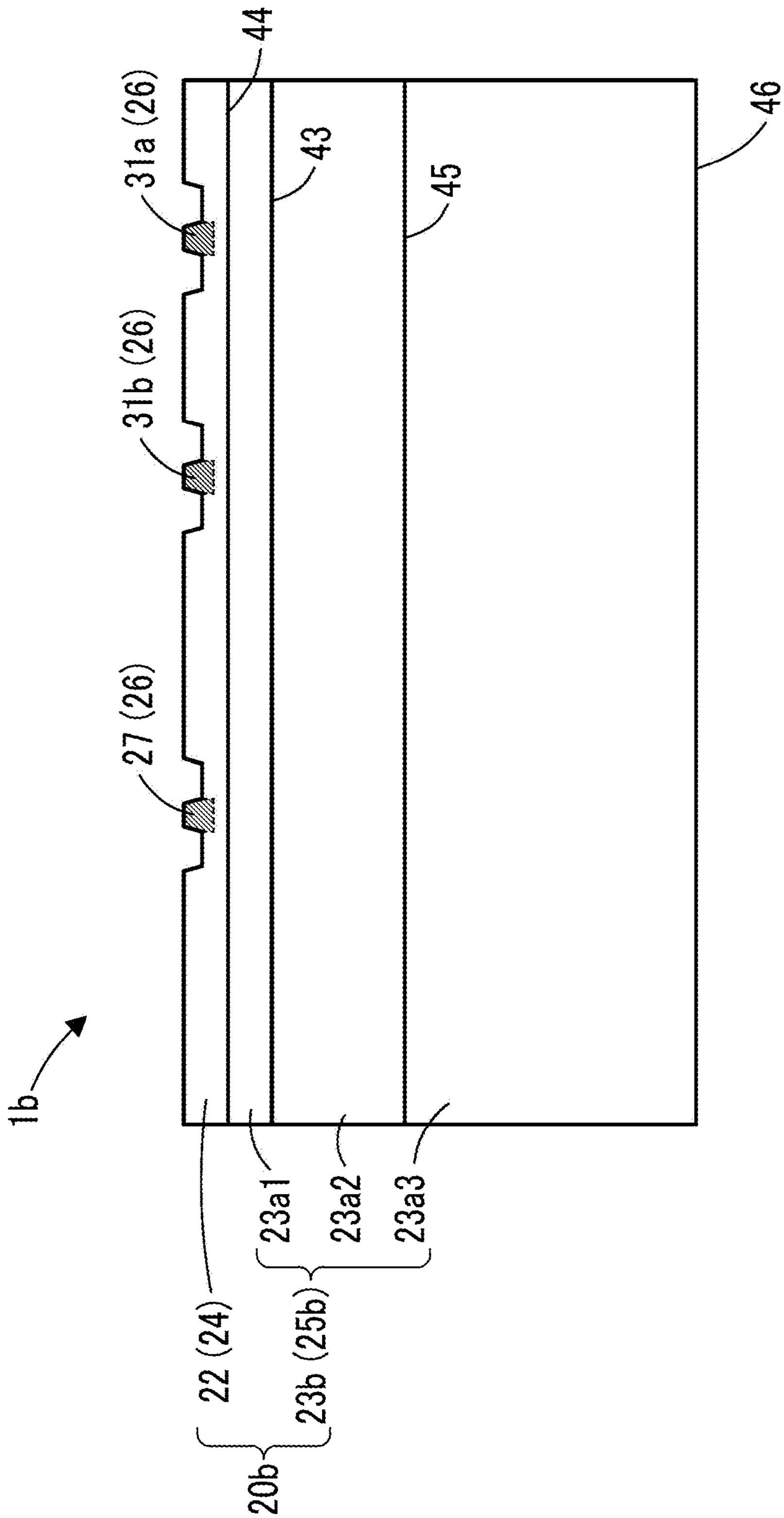


FIG. 7

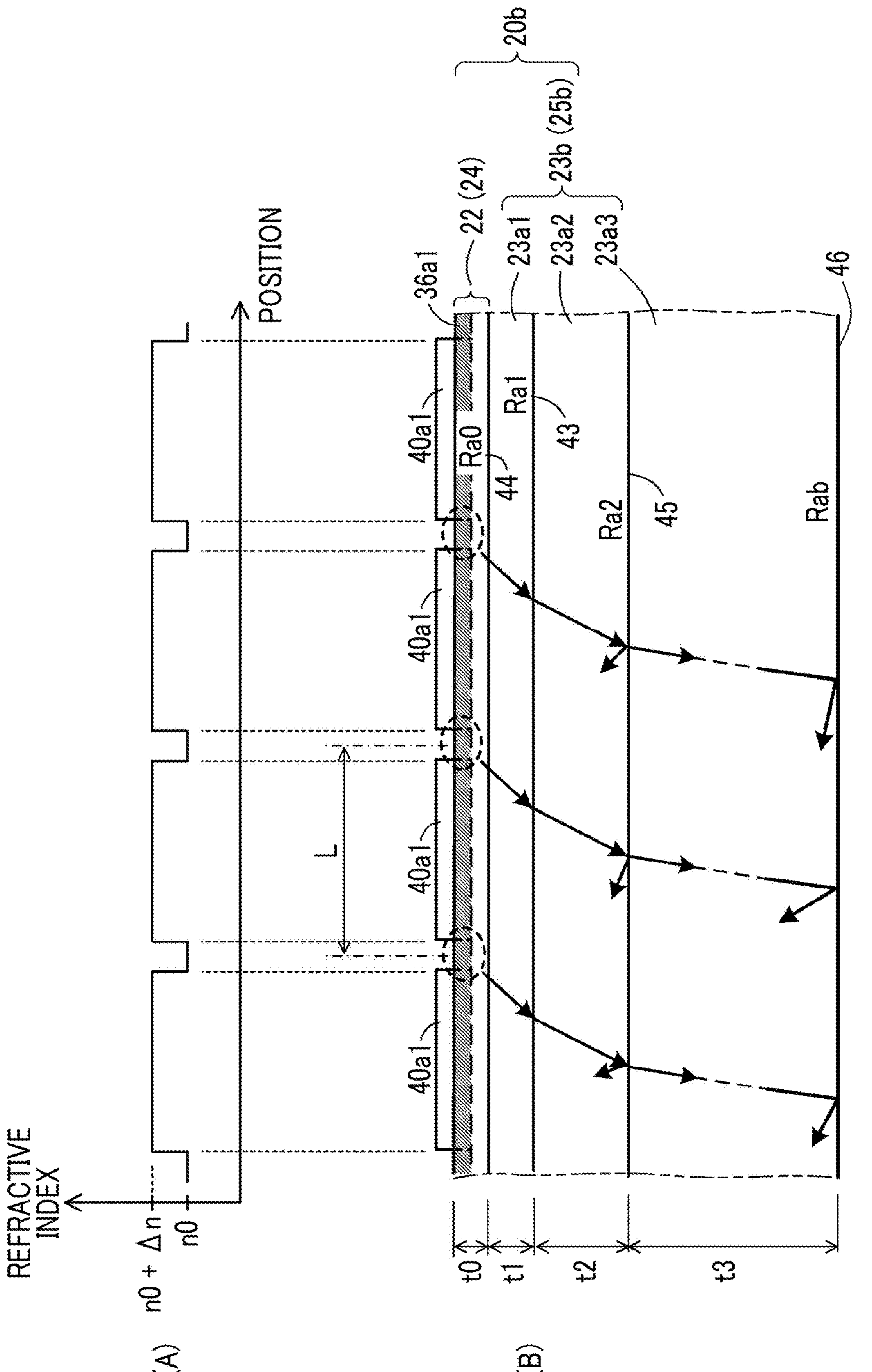

(A)
(B)
REFRACTIVE INDEX
POSITION
n0 + Δn
n0
L
20b
22 (24)
23b (25b)
36a1
23a1
23a2
23a3
46
40a1
Ra0
Ra1
Ra2
Rab
43
44
45
t0
t1
t2
t3

FIG. 8

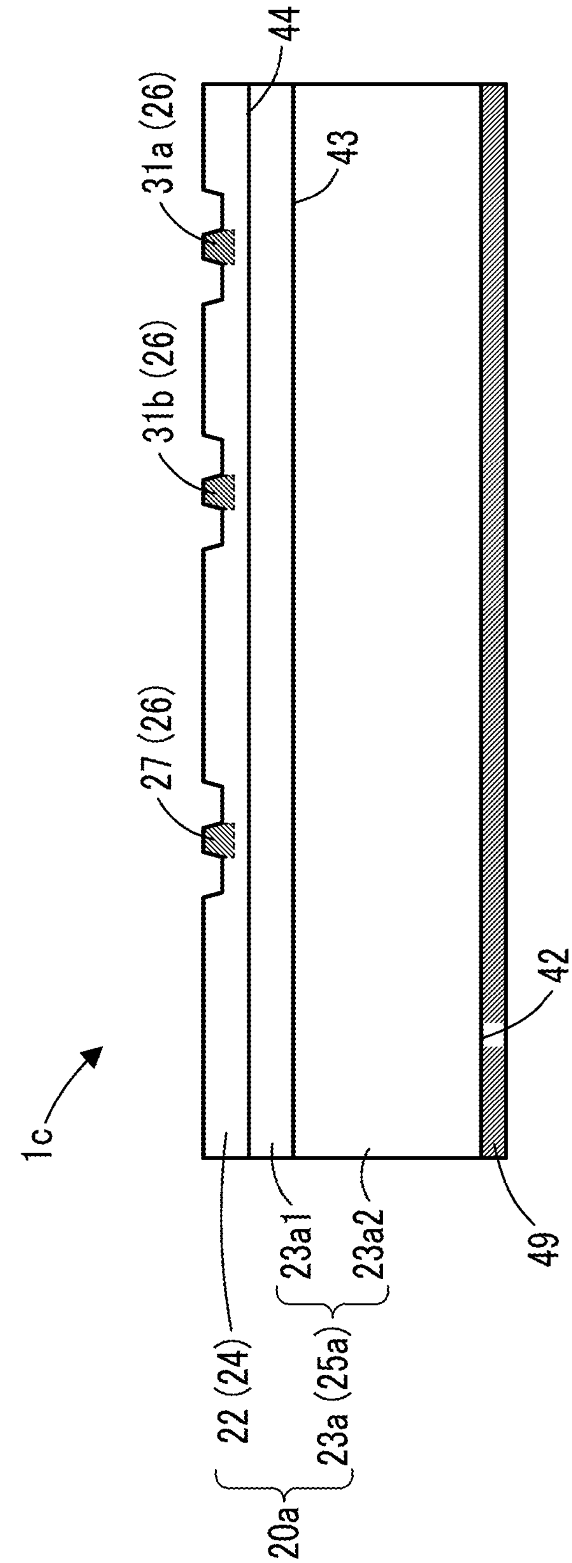


FIG. 9

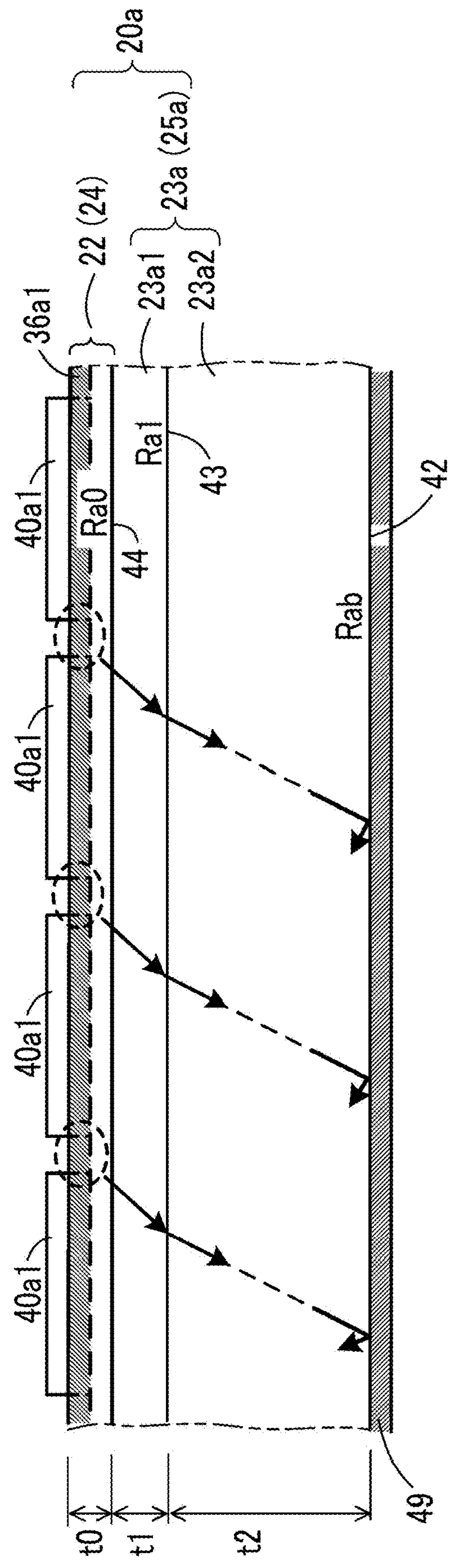

20a
23a (25a)
22 (24)
23a1
23a2
36a1
40a1
40a1
40a1
40a1
Ra0
Ra1
43
44
42
Rab
49
t0
t1
t2

FIG. 10

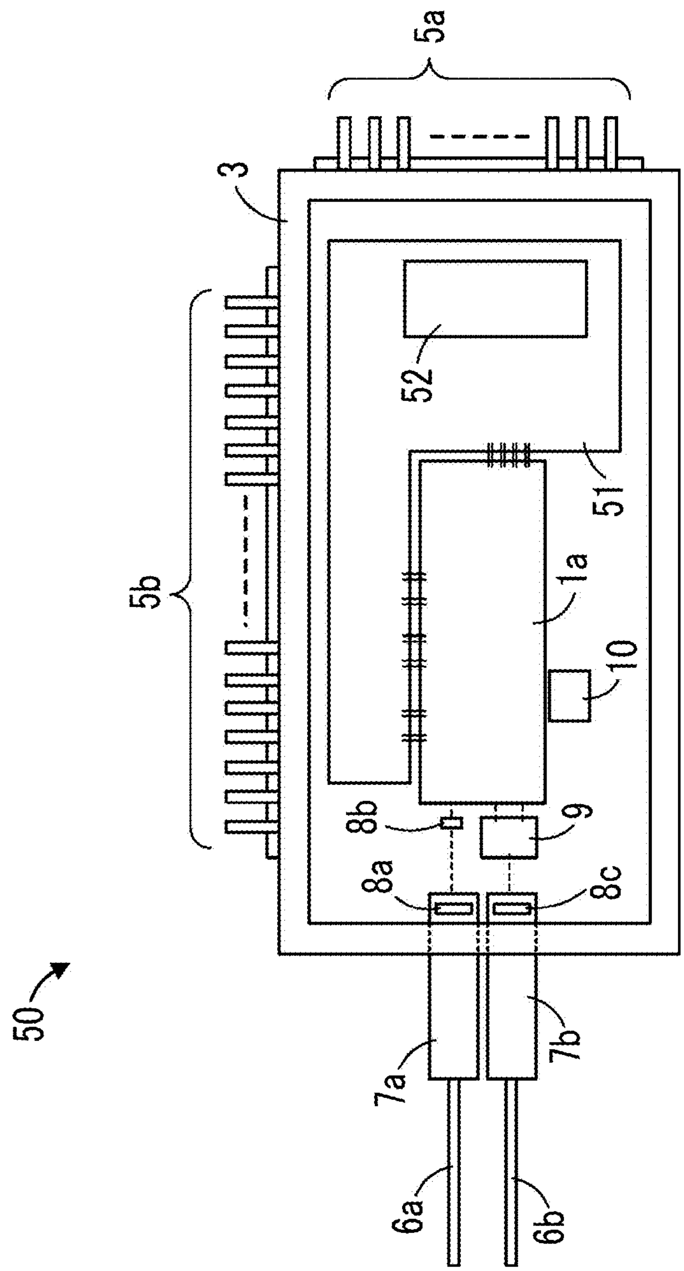


FIG. 11

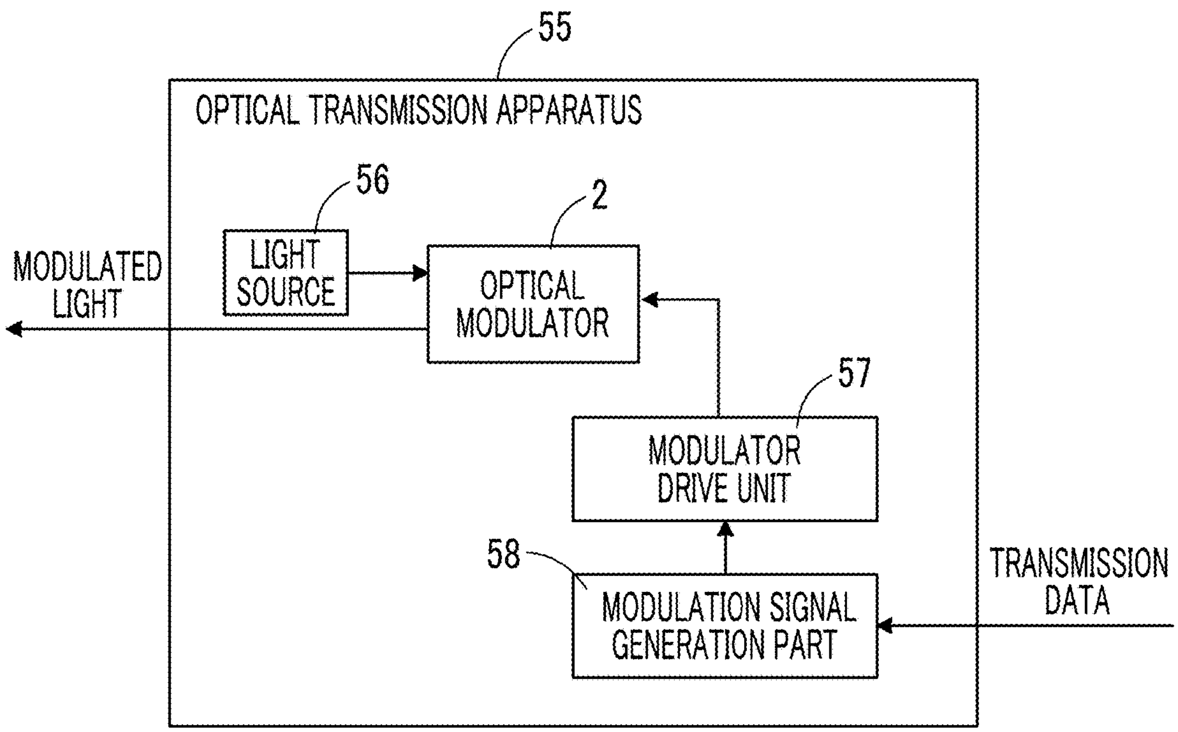

55
OPTICAL TRANSMISSION APPARATUS
56
2
MODULATED LIGHT
LIGHT SOURCE
OPTICAL MODULATOR
57
MODULATOR DRIVE UNIT
58
MODULATION SIGNAL GENERATION PART
TRANSMISSION DATA

FIG. 12

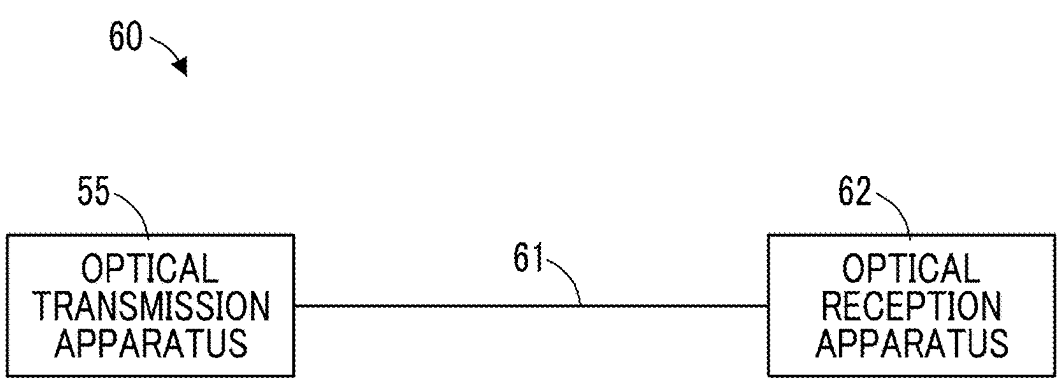

60
55
62
OPTICAL TRANSMISSION APPARATUS
61
OPTICAL RECEPTION APPARATUS

FIG. 13

[PRIOR ART]

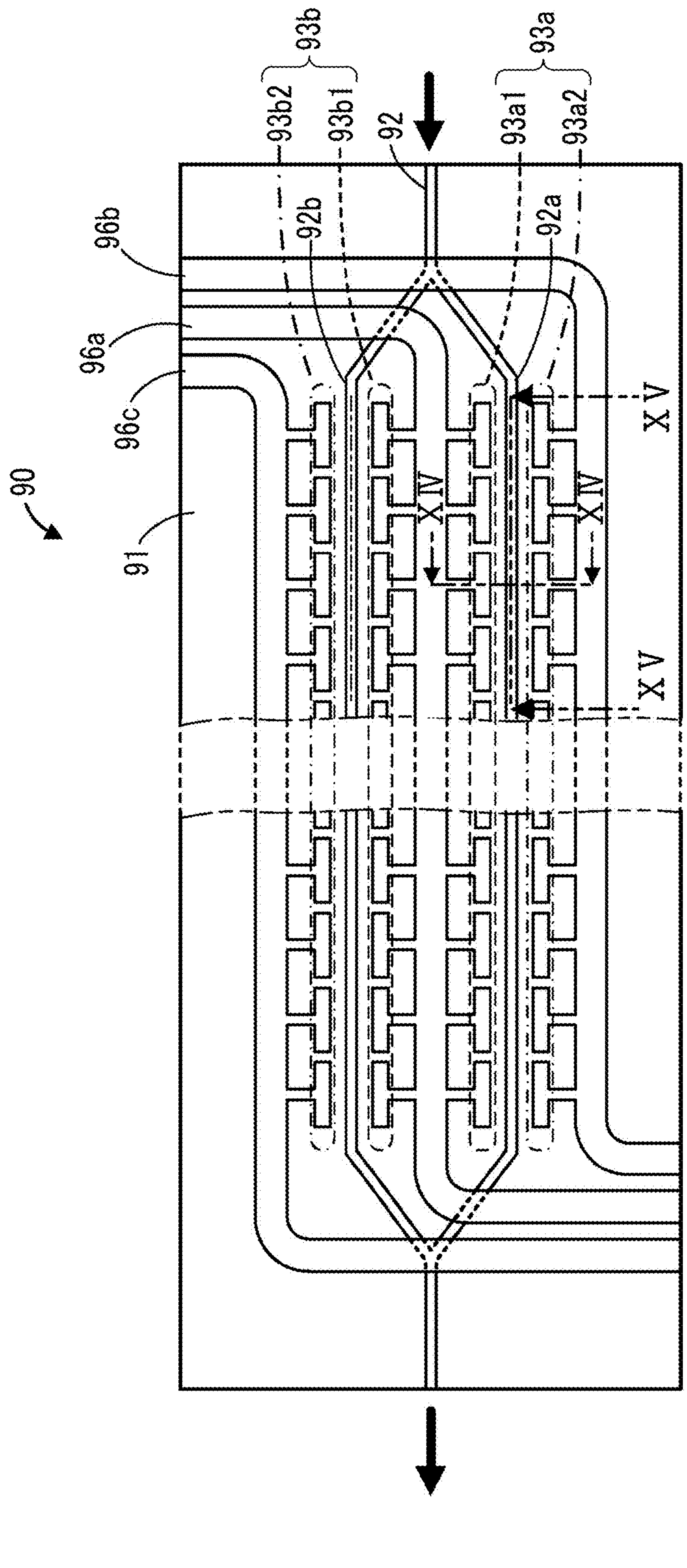


FIG. 14

[PRIOR ART]

CROSS-SECTIONAL VIEW TAKEN ALONG LINE XIV-XIV

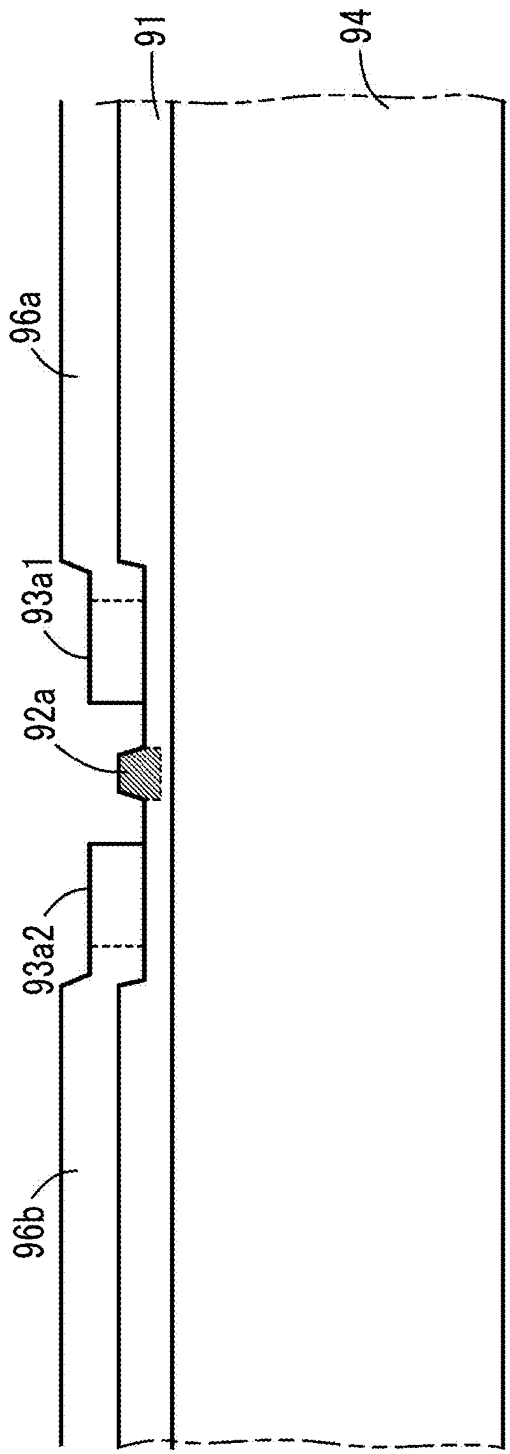
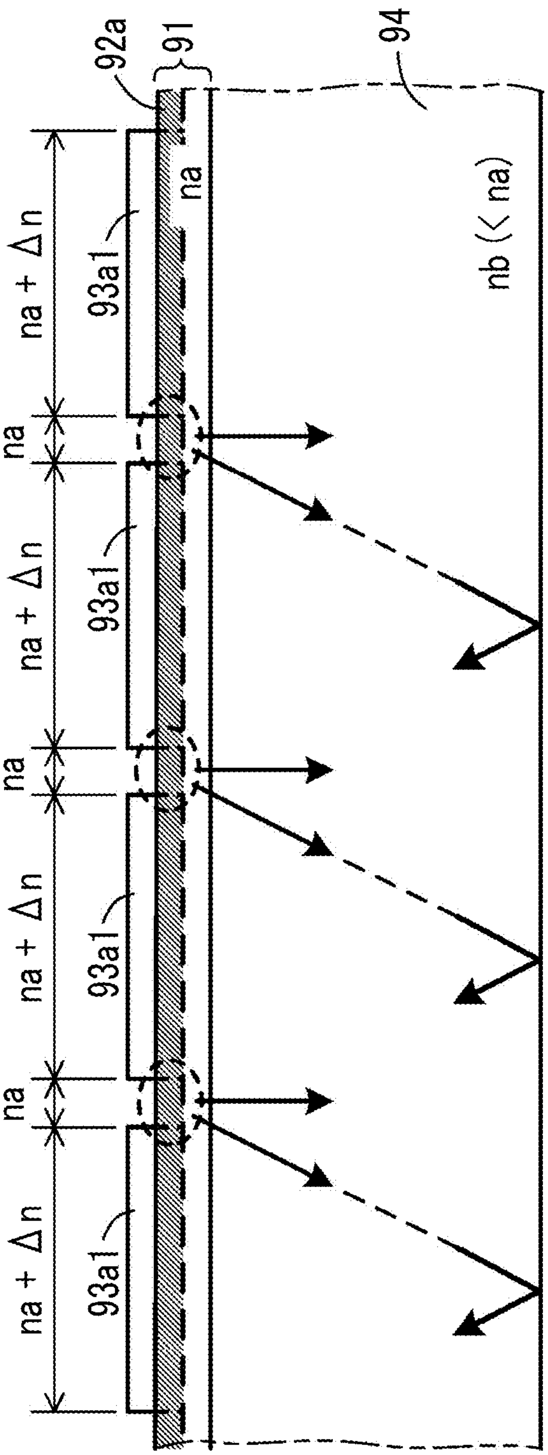


FIG. 15

[PRIOR ART]

CROSS-SECTIONAL VIEW TAKEN ALONG LINE XV-XV



OPTICAL MODULATION DEVICE, OPTICAL MODULATOR, OPTICAL MODULATION MODULE, OPTICAL TRANSMISSION APPARATUS, AND OPTICAL TRANSMISSION SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of Japanese Patent Application No. 2024-022426 filed Feb. 16, 2024, the disclosure of which is herein incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention relates to an optical modulation device, an optical modulator, an optical modulation module, an optical transmission apparatus, and an optical transmission system.

Description of Related Art

[0003] In a high-frequency/high-capacity optical fiber communication system, an optical modulator incorporating an optical modulation device as an optical waveguide device including an optical waveguide formed on a semiconductor substrate of InP or the like or on a substrate of $LiNbO_3$ (hereinafter, referred to as LN) or the like having an electro-optic effect, and a control electrode for controlling a light wave propagating through the optical waveguide has been widely used. Particularly, the optical modulation device using the LN substrate may implement optical modulation characteristics of a small optical loss and a wide bandwidth and thus, has been widely used in the high-frequency/high-capacity optical fiber communication system.

[0004] In recent years, in order to implement further low-voltage driving and high-frequency modulation while reducing a size of the optical modulator, an optical modulator using a rib optical waveguide or a ridge optical waveguide (hereinafter collectively referred to as a protruding optical waveguide) configured by forming a strip-shaped protruding portion on a surface of an LN substrate formed as a thin film (or a thin plate) (for example, having a thickness of 20 μm or lower) to further strengthen interaction between a signal electric field and guided light in the substrate has also been used in practice.

[0005] In addition, in recent years, it has been suggested to use a so-called segmented electrode in which an electrode is divided into a plurality of segments along an optical propagation direction of the optical waveguide as a coplanar modulation electrode, in order to achieve impedance matching between the modulation electrode and a drive circuit and velocity matching between a high-frequency propagation velocity in the modulation electrode and an optical propagation velocity in the optical waveguide (Japanese Laid-open Patent Publication No. 2022-148652, Japanese Laid-open Patent Publication No. 2016-194544, and Japanese Laid-open Patent Publication No. 2020-181173).

SUMMARY OF THE INVENTION

[0006] The inventors of the present invention have found that in the protruding optical waveguide provided with the segmented electrode as the modulation electrode, forming the protruding portion (that is, a rib or a ridge) constituting the optical waveguide with high accuracy in a wafer process still poses an issue of variation in optical characteristics such as a modulation extinction ratio. A factor or a solution of the issue has not been found for a long time.

[0007] An object of the present invention is to implement favorable optical characteristics in an optical modulation device using a protruding optical waveguide and a segmented electrode as a modulation electrode.

[0008] According to an aspect of the present invention, there is provided an optical modulation device including a substrate including a multilayer portion configured with multiple layers, an optical waveguide configured with a protruding portion extending on an optical waveguide layer in the multilayer portion of the substrate, and a modulation electrode that is an electrode formed on the optical waveguide layer to control a light wave propagating through the optical waveguide and that is formed to be divided into a plurality of segments along a propagation direction of light of the optical waveguide, in which in all sections of the electrode or a section excluding a part of the sections of the electrode, a clearance L, measured in an extending direction of the optical waveguide, between gaps between adjacent segments is constant, the multilayer portion of the substrate includes the optical waveguide layer and a plurality of support layers disposed in multiple layers below the optical waveguide layer, and surface roughness Rab of a back surface of the substrate facing a surface of the optical waveguide layer has a relationship of Rab>λ with respect to a wavelength λ of the light wave propagating through the optical waveguide.

[0009] According to another aspect of the present invention, surface roughness Ra1 of a boundary surface between a first support layer that is the support layer in contact with a lower surface of the optical waveguide layer and a second support layer that is the support layer in contact with a lower surface of the first support layer, and the surface roughness Rab of the back surface of the substrate may have a relationship of Rab>Ra1.

[0010] According to another aspect of the present invention, the surface roughness Ra1 of the boundary surface between the first support layer and the second support layer may have a relationship of Ra1>Ra0 with respect to surface roughness Ra0 of a boundary surface between the lower surface of the optical waveguide layer and the first support layer.

[0011] According to another aspect of the present invention, surface roughness Ran of each support layer boundary surface that is an interlayer boundary surface of the plurality of support layers may be higher than surface roughness Ra0 of a boundary surface between the optical waveguide layer and the first support layer and lower than the surface roughness Rab of the back surface of the substrate, and a value of the surface roughness Ran may be higher as the support layer boundary surface is closer to the back surface.

[0012] According to another aspect of the present invention, the modulation electrode may be formed to be divided into a plurality of segments having the same length, and the clearance L, measured in the extending direction of the optical waveguide, between the gaps between the adjacent segments may have a relationship of L>4×λ/n1 with respect to the wavelength λ of the light wave propagating through the optical waveguide and a refractive index n1 of a first support layer that is the support layer in contact with a lower surface of the optical waveguide layer.

[0013] According to another aspect of the present invention, a thickness t1 of a first support layer that is the support layer in contact with a lower surface of the optical waveguide layer may have a relationship of $t1<10\times\lambda/n1$ with respect to the wavelength λ of the light wave propagating through the optical waveguide and a refractive index n1 of the first support layer.

[0014] According to another aspect of the present invention, a light absorbing material that absorbs light in a wavelength range of the light wave propagating through the optical waveguide may be disposed on the back surface of the substrate facing the surface of the optical waveguide layer.

[0015] According to another aspect of the present invention, the light absorbing material may be a carbon material, a black resin, or a metal filler.

[0016] According to another aspect of the present invention, the substrate may be formed by laminating a plurality of plate bodies, and each plate body may include one layer or a plurality of layers among the optical waveguide layer and the plurality of support layers.

[0017] According to another aspect of the present invention, there is provided an optical modulator including any of the optical modulation devices, a case for accommodating the optical modulation device, an optical fiber for inputting light into the optical modulation device, and an optical fiber for guiding light output from the optical modulation device to an outside of the case.

[0018] According to another aspect of the present invention, there is provided an optical modulation module including any of the optical modulation devices, a case for accommodating the optical modulation device, an optical fiber for inputting light into the optical modulation device, an optical fiber for guiding light output from the optical modulation device to an outside of the case, and a drive circuit for driving the optical modulation device.

[0019] According to another aspect of the present invention, there is provided an optical transmission apparatus including the optical modulator or the optical modulation module, and an electronic circuit for generating an electrical signal for causing the optical modulation device to perform a modulation operation.

[0020] According to another aspect of the present invention, there is provided an optical transmission system including the optical transmission apparatus, and an optical fiber transmission channel through which output light of the optical modulation device is transmitted.

[0021] According to the present invention, favorable optical characteristics can be implemented in an optical modulation device using a protruding optical waveguide and a segmented electrode as a modulation electrode.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] FIG. **1** is a diagram illustrating a configuration of an optical modulator using an optical modulation device according to a first embodiment of the present invention.

[0023] FIG. **2** is a plan view of the optical modulation device according to the first embodiment.

[0024] FIG. **3** is a side view of the optical modulation device illustrated in FIG. **2**.

[0025] FIG. **4** is a diagram illustrating a configuration of a modulation portion of the optical modulation device illustrated in FIG. **2**.

[0026] FIG. **5** is a cross-sectional view taken along line V-V of the modulation portion illustrated in FIG. **4**.

[0027] FIG. **6** is a side view of an optical modulation device according to a second embodiment.

[0028] FIG. **7** is a cross-sectional view of a modulation portion of the optical modulation device according to the second embodiment.

[0029] FIG. **8** is a side view of an optical modulation device according to a third embodiment.

[0030] FIG. **9** is a cross-sectional view of a modulation portion of the optical modulation device according to the third embodiment.

[0031] FIG. **10** is a diagram illustrating a configuration of an optical modulation module according to a fourth embodiment.

[0032] FIG. **11** is a diagram illustrating a configuration of an optical transmission apparatus according to a fifth embodiment.

[0033] FIG. **12** is a diagram illustrating a configuration of an optical transmission system according to a sixth embodiment.

[0034] FIG. **13** is a plan view illustrating an example of an optical modulation device of the prior art.

[0035] FIG. **14** is a cross-sectional view taken along line XIV-XIV of the optical modulation device of the prior art illustrated in FIG. **13**.

[0036] FIG. **15** is a cross-sectional view taken along line XV-XV of the optical modulation device of the prior art illustrated in FIG. **13**.

DETAILED DESCRIPTION OF THE INVENTION

[0037] The inventors of the present invention have intensively studied variation in optical characteristics of a protruding optical waveguide provided with a segmented electrode as a modulation electrode, and have found that a factor of the variation is interference of a leaked light beam generated from the protruding optical waveguide at a position of each gap portion between segments (each portion of the electrode divided at constant clearances) constituting the segmented electrode.

[0038] FIGS. **13**, **14**, and **15** are descriptive diagrams for describing the factor of the variation in the optical characteristics in an optical modulation device of the prior art. FIG. **13** is a plan view of an optical modulation device including a protruding optical waveguide provided with a segmented electrode as a modulation electrode, and FIG. **14** is a cross-sectional view taken along line XIV-XIV of the optical modulation device illustrated in FIG. **13**. FIG. **15** is a cross-sectional view taken along line XV-XV in the optical modulation device illustrated in FIG. **13**.

[0039] With reference to FIGS. **13**, **14**, and **15**, an optical modulation device **90** of the prior art illustrated as an example includes a Mach-Zehnder type optical waveguide **92** that is formed on one principal surface (upper surface) of an optical substrate **91** which is an LN substrate having a thickness of several μm to several tens of μm and that includes a protruding optical waveguide, and modulation electrodes **93*a*** and **93*b*** for controlling a light wave propagating through each of two arm waveguides **92*a*** and **92*b*** of the Mach-Zehnder type optical waveguide **92**. Another principal surface (lower surface) of the optical substrate **91** is bonded to a support substrate **94** (refer to FIGS. **14** and **15**). For example, the support substrate **94** is generally a glass plate having a lower refractive index than the optical substrate **91**.

[0040] The modulation electrode **93***a* includes a hot electrode **93***a***1** and a ground electrode **93***a***2** that face each other with the arm waveguide **92***a* interposed therebetween in the principal surface of the optical substrate **91**. Similarly, the modulation electrode **93***b* has a hot electrode **93***b***1** and a ground electrode **93***b***2** that face each other with the arm waveguide **92***b* interposed therebetween in the principal surface of the optical substrate **91**.

[0041] Each of the modulation electrodes **93***a* and **93***b* is configured as a segmented electrode divided into a plurality of portions along optical propagation directions of the arm waveguides **92***a* and **92***b*. Specifically, each of the hot electrode **93***a***1** and the ground electrode **93***a***2** constituting the modulation electrode **93***a* is divided into a plurality of portions (segments) having the same length along the optical propagation direction of the arm waveguide **92***a*. Each of the hot electrode **93***b***1** and the ground electrode **93***b***2** constituting the modulation electrode **93***b* is also divided into a plurality of segments having the same length along the optical propagation direction of the arm waveguide **92***b*, and gaps between the segments are configured to be arranged at constant clearances.

[0042] Each segment of the hot electrodes **93***a***1** and **93***b***1** is electrically connected to each other by a hot transmission channel **96***a*. In addition, each segment of the ground electrode **93***a***2** is electrically connected to each other by a ground transmission channel **96***b*, and each segment of the ground electrode **93***b***2** is electrically connected to each other by a ground transmission channel **96***c*. Accordingly, the hot electrodes **93***a***1** and **93***b***1** connected to each other by the hot transmission channel **96***a*, the ground electrode **93***a***2** connected to the ground transmission channel **96***b*, and the ground electrode **93***b***2** connected to the ground transmission channel **96***c* constitute a coplanar electrode as a whole.

[0043] As illustrated in the cross-sectional view taken along line XV-XV in FIG. **15**, in the arm waveguide **92***a*, in a case where a high-frequency signal is transmitted to the modulation electrode **93***a*, for example, an electric field is applied to the arm waveguide **92***a* in a portion in which the segments of the hot electrode **93***a***1** and the segments of the ground electrode **93***a***2** face each other. Accordingly, a refractive index changes (for example, increases) by Δn from a refractive index na (substrate refractive index na) of the optical substrate **91**. In gap portions in which the segments do not face each other, an electric field is not applied to the arm waveguide **92***a*. Thus, the refractive index remains as the substrate refractive index na.

[0044] Each of portions of the unchanging refractive index that are arranged along the arm waveguide **92***a* and that occur at positions of the gap portions in which the segments of the modulation electrode **93***a* do not face each other has a point of discontinuity of the refractive index (disturbance in a change in the refractive index) of the arm waveguide **92***a* along the optical propagation direction, and is a factor that causes leaked lights beam from the arm waveguide **92***a*.

[0045] Leaked light beams generated from each of the portions of the unchanging refractive index arranged along the arm waveguide **92***a* leak to the support substrate **94** having a refractive index nb lower than that of the optical substrate **91** and are repeatedly reflected between the principal surfaces of the support substrate **94** to be intensified while interfering with each other in the support substrate **94** and propagate in a left-right direction of the illustration.

[0046] Particularly, each segmented electrode as the modulation electrode **93***a* is generally divided into several hundred to several thousand segments. Thus, the number of gaps between the segments is also several hundreds to several thousands. Consequently, in the arm waveguide **92***a*, the number of leaked light beams generated from each gap arranged at equal clearances between the segments is several hundreds to several thousands, and these leaked light beams interfere with each other to be intensified in the support substrate **94**. Accordingly, leaked light beams having considerable intensity may be generated in the support substrate **94**.

[0047] The above phenomenon also occurs in the arm waveguide **92***b* in which the modulation electrode **93***b* is formed, and leaked light beams from the arm waveguide **92***b* interfere with each other to be intensified in the support substrate **94**. Accordingly, the leaked light beams having considerable intensity are further increased in the support substrate **94**.

[0048] A part of the high-intensity leaked light beams generated by the interference may enter a part of the Mach-Zehnder type optical waveguide **92** other than the arm waveguides **92***a* and **92***b* to be coupled with signal light (or modulated light) propagating through the Mach-Zehnder type optical waveguide **92**. Such leaked light beams coupled with the signal light (or the modulated light) propagating through the Mach-Zehnder type optical waveguide **92** are noise light and deteriorate the optical characteristics such as an extinction ratio of an optical modulation operation in the Mach-Zehnder type optical waveguide **92**, thereby causing the variation in the optical characteristics.

[0049] The present invention is conceived based on the knowledge about the factor of the variation in the optical characteristics and particularly, reduces the variation in the optical characteristics in the optical modulation operation by suppressing the interference between the leaked light beams in the support substrate to suppress an increase in the intensity of the leaked light beams caused by the interference.

[0050] Hereinafter, embodiments of the present invention will be described with reference to the drawings.

1. First Embodiment

[0051] First, a first embodiment of the present invention will be described. FIG. **1** is a diagram illustrating a configuration of an optical modulator **2** using an optical modulation device **1***a* according to the first embodiment of the present invention. The optical modulator **2** includes the optical modulation device **1***a* and a relay substrate **4** in a case **3**. For example, the optical modulation device **1***a* has a DPQPSK modulator configuration. The case **3** is finally sealed airtight by fixing a cover (not illustrated) that is a plate body to an opening portion of the case **3**.

[0052] The optical modulator **2** also includes a signal pin **5***a* for inputting a high-frequency electrical signal used for modulation of the optical modulation device **1***a*, and a signal pin **5***b* for inputting an electrical signal used for adjustment or the like of an operating point of the optical modulation device **1***a*.

[0053] The optical modulator **2** further includes an input optical fiber **6***a* for inputting light into the case **3** and an output optical fiber **6***b* for guiding light modulated by the optical modulation device **1***a* to an outside of the case **3**, on the same surface of the case **3**.

[0054] The input optical fiber **6***a* and the output optical fiber **6***b* are fixed to the case **3** through supports **7***a* and **7***b*, respectively, which are fixing members. The light input from the input optical fiber **6***a* is collimated by a lens **8***a* disposed in the support **7***a* and is then input into the optical modulation device **1***a* through a lens **8***b*. However, this is only an example, and light may be input into the optical modulation device **1***a* by, for example, introducing the input optical fiber **6***a* into the case **3** through the support **7***a* and connecting an end surface of the introduced input optical fiber **6***a* to an end surface of a substrate **20***a* (described later) of the optical modulation device **1***a*, in accordance with the prior art.

[0055] The optical modulator **2** also includes an optical unit **9** that polarizes and combines two modulated light beams output from the optical modulation device **1***a*. The light beam output from the optical unit **9** after being polarized and combined is condensed by a lens **8***c* disposed in the support **7***b* and is coupled to the output optical fiber **6***b*.

[0056] The relay substrate **4** relays the high-frequency electrical signal input from the signal pin **5***a* and the electrical signal for adjustment or the like of the operating point input from the signal pin **5***b* to the optical modulation device **1***a* based on a conductor pattern (not illustrated) formed on the relay substrate **4**. For example, the conductor pattern on the relay substrate **4** is connected to each of the electrodes of the optical modulation device **1***a* by wire bonding. The optical modulator **2** also includes a terminator **10** having predetermined impedance in the case **3**.

[0057] FIG. **2** is a plan view illustrating an example of a configuration of the optical modulation device **1***a*. The optical modulation device **1***a* includes the substrate **20***a* configured with multiple layers. For example, the substrate **20***a* is rectangular in plan view and has two sides **21***a* and **21***b* on the left and the right of the illustration that extend in an up-down direction of the illustration to face each other, and two sides **21***c* and **21***d* at the top and the bottom of the illustration that extend in the left-right direction of the illustration to face each other in FIG. **2**.

[0058] FIG. **3** is a side view of the optical modulation device **1***a* illustrated in FIG. **2** from the side **21***a*. The substrate **20***a* includes an optical waveguide layer **22** and a support layer **23***a*. In the present embodiment, the support layer **23***a* includes a first support layer **23***a***1** and a second support layer **23***a***2**. In the present embodiment, for example, the substrate **20***a* is formed by laminating a plurality of plate bodies. Specifically, the substrate **20***a* is configured by laminating an optical substrate **24** and a support substrate **25***a*. The optical substrate **24** includes the optical waveguide layer **22**, and the support substrate **25***a* includes the support layer **23***a* formed with the first support layer **23***a***1** and the second support layer **23***a***2**. For example, the optical substrate **24** is an X-cut LN substrate that has an electro-optic effect and that is processed to have a thickness of 20 μm or lower (for example, 2 μm) to be formed as a thin film. For example, the support substrate **25***a* is a glass substrate including the first support layer **23***a***1** and the second support layer **23***a***2** that are configured with different substances or compositions of glass.

[0059] The substrate **20***a* is not necessarily configured with a plurality of plate bodies as described above. The substrate **20***a* may be configured with a film body formed to have a layer shape on an appropriate substrate. For example, the substrate **20***a* can be a substrate including the first support layer **23***a***1** and the optical waveguide layer **22** that are formed to have a layer shape through a film forming process such as sputtering, vapor deposition, and/or crystal growth on an appropriate plate body constituting the second support layer **23***a***2**.

[0060] The optical modulation device **1***a* includes an optical waveguide **26** (the whole thick dotted line illustrated in FIG. **2**) formed on the optical waveguide layer **22** (in the present embodiment, on the optical substrate **24**) of the substrate **20***a*. The optical waveguide **26** is a protruding optical waveguide (for example, a rib optical waveguide or a ridge optical waveguide) configured with a protruding portion extending on the optical waveguide layer **22** and, for example, performs coherent multi-level modulation exceeding 100 GBaud.

[0061] With reference to FIG. **2**, the optical waveguide **26** includes an input waveguide **27** that receives input light (an arrow to the right of the illustration) from the input optical fiber **6***a* on an upper side of the illustration of the side **21***a* on the left of the illustration of the optical waveguide layer **22**, and a branched waveguide **28** that causes the input light to branch into two light beams having the same light quantity. The optical waveguide **26** also includes so-called nested Mach-Zehnder type optical waveguides **29***a* and **29***b* as two modulation portions for modulating each light beam caused to branch by the branched waveguide **28**.

[0062] The nested Mach-Zehnder type optical waveguides **29***a* and **29***b* have a propagation direction of light that is folded by 180 degrees in a folded region **30** of the optical waveguide layer **22** in a right portion of the illustration, and output light to the left of the illustration from the side **21***a* of the optical waveguide layer **22** via output waveguides **31***a* and **31***b*.

[0063] The nested Mach-Zehnder type optical waveguides **29***a* and **29***b* include two Mach-Zehnder type optical waveguides **32***a* and **32***b*, and two Mach-Zehnder type optical waveguides **32***c* and **32***d*, respectively, provided in two waveguide portions forming a pair of arm waveguides. Hereinafter, the Mach-Zehnder type optical waveguides **32***a*, **32***b*, **32***c*, and **32***d* will be collectively referred to as Mach-Zehnder type optical waveguides **32**. Each Mach-Zehnder type optical waveguide **32** includes two arm waveguides.

[0064] A bias electrode **33***a* for adjusting operating points of the nested Mach-Zehnder type optical waveguides **29***a* and **29***b* is formed in an upper portion of the illustration of the optical waveguide layer **22** upstream of the folded region **30** along a propagation direction of a light wave of the optical waveguide **26**. The Mach-Zehnder type optical waveguides **32***a*, **32***b* and the Mach-Zehnder type optical waveguides **32***c* and **32***d* are also provided with bias electrodes **33***b* and **33***c*, respectively, for adjusting their operating points.

[0065] Modulation electrodes for causing each of the four Mach-Zehnder type optical waveguides **32***a*, **32***b*, **32***c*, and **32***d* to perform a modulation operation are also formed in modulation portions **34***a*, **34***b*, **34***c*, and **34***d* illustrated in a lower portion of the illustration of the nested Mach-Zehnder type optical waveguides **29***a* and **29***b* folded in the folded region **30**. Hereinafter, the modulation portions **34***a*, **34***b*, **34***c*, and **34***d* will be collectively referred to as modulation portions **34**.

[0066] The high-frequency electrical signal for causing each Mach-Zehnder type optical waveguide **32** to perform the modulation operation is input from the relay substrate **4** through wire bonding **35** on the right of the illustration. The high-frequency electrical signal propagates through the modulation electrode formed in each modulation portion **34** and is terminated by a termination resistor (not illustrated) provided in the terminator **10** illustrated at the bottom of the illustration.

[0067] In order to avoid complication of the illustration to facilitate understanding, FIG. **2** does not illustrate details of the electrodes formed in the modulation portions **34***a*, **34***b*, **34***c*, and **34***d*. A segmented electrode formed to be divided into a plurality of segments along the propagation direction of light in the optical waveguide, as in the prior art illustrated in FIG. **13**, is formed in each modulation portion **34** as the modulation electrode.

[0068] For example, FIG. **4** illustrates a configuration of the modulation electrode in the modulation portion **34***a*. The modulation electrodes of the other modulation portions **34***b*, **34***c*, and **34***d* are also configured as in FIG. **4**.

[0069] In FIG. **4**, modulation electrodes **40***a* and **40***b* control light waves propagating through arm waveguides **36***a***1** and **36***a***2** of the Mach-Zehnder type optical waveguide **32***a*, respectively.

[0070] The modulation electrode **40***a* includes a hot electrode **40***a***1** and a ground electrode **40***a***2** facing each other with one arm waveguide **36***a***1** interposed therebetween in a surface of the optical waveguide layer **22**. Similarly, the modulation electrode **40***b* includes a hot electrode **40***b***1** and a ground electrode **40***b***2** facing each other with the other arm waveguide **36***a***2** interposed therebetween in the surface of the optical waveguide layer **22**.

[0071] The modulation electrodes **40***a* and **40***b* are configured as segmented electrodes divided into a plurality of portions along optical propagation directions of the arm waveguides **36***a***1** and **36***a***2**, respectively. Specifically, each of the hot electrode **40***a***1** and the ground electrode **40***a***2** constituting the modulation electrode **40***a* is divided into a plurality of portions (segments) having the same length along the optical propagation direction of the arm waveguide **36***al*, and gaps between the segments are arranged at constant clearances. Each of the hot electrode **40***b***1** and the ground electrode **40***b***2** constituting the modulation electrode **40***b* is also divided into a plurality of segments having the same length along the optical propagation direction of the arm waveguide **36***a***2**, and gaps between the segments are arranged at constant clearances. For example, the number of segments of each of the hot electrodes **40***a***1** and **40***b***1** and the ground electrodes **40***a***2** and **40***b***2** is in the order of several thousands. However, the number of segments may be any number in accordance with optical modulation characteristics required for the optical modulation device **1***a*.

[0072] Each segment of the hot electrodes **40***a***1** and **40***b***1** is electrically connected to each other by a hot transmission channel **41***a*. In addition, each segment of the ground electrode **40***a***2** is electrically connected to each other by a ground transmission channel **41***b*, and each segment of the ground electrode **40***b***2** is electrically connected to each other by a ground transmission channel **41***c*. Accordingly, the hot electrodes **40***a***1** and **40***b***1** connected to each other by the hot transmission channel **41***a*, the ground electrode **40***a***2** connected to the ground transmission channel **41***b*, and the ground electrode **40***b***2** connected to the ground transmission channel **41***c* constitute a coplanar electrode as a whole.

[0073] FIG. **5** is a cross-sectional view taken along line V-V along the arm waveguide **36***a***1** in the modulation portion **34***a* illustrated in FIG. **4**. In FIG. **5**, lower part (B) illustrates a configuration of the optical modulation device **1***a* in a V-V cross section, and upper part (A) is a graph illustrating a change in a refractive index of the arm waveguide **36***a***1** along the optical propagation direction in the V-V cross section.

[0074] As illustrated in (A) of FIG. **5**, in the arm waveguide **36***al*, as in the arm waveguide **92***a* of the optical modulation device **90** according to the prior art illustrated in FIG. **15**, in a case where a high-frequency signal is transmitted to the modulation electrode **40***a*, an electric field is applied to the arm waveguide **36***a***1** in a portion in which the segments of the hot electrode **40***a***1** and the segments of the ground electrode **40***a***2** face each other. Accordingly, the refractive index changes (for example, increases) by Δn from a refractive index n0 (substrate refractive index n0) of the optical waveguide layer **22** (that is, the optical substrate **24**). In gap portions in which the segments do not face each other, an electric field is not applied to the arm waveguide **36***a***1**. Thus, the refractive index remains as the substrate refractive index n0.

[0075] Each of portions of the unchanging refractive index (that is, portions in which the refractive index does not change from the substrate refractive index n0) that occur at positions of the gap portions in which the segments of the modulation electrode **40***a* do not face each other in the arm waveguide **36***a***1** has disturbance in a change in the refractive index of the arm waveguide **36***a***1** along the optical propagation direction. In each of the portions having disturbance in the refractive index, leaked light beams may occur from the arm waveguide **36***a***1** formed in the optical waveguide layer **22**, as in the optical modulation device **90** according to the prior art.

[0076] In order not to cause the leaked light beams to interfere with each other, in the present embodiment, particularly, surface roughness Rab of a back surface **42** of the substrate **20***a* facing the surface of the optical waveguide layer **22** has the following relationship in Expression (1) with respect to a wavelength λ of the light wave propagating through the optical waveguide **26**.

$$Rab > \lambda \tag{1}$$

[0077] For example, the surface roughness may be measured as arithmetic mean roughness Ra that is generally used. The same applies to surface roughness of other boundary surfaces and the like illustrated below.

[0078] The leaked light beams of the wavelength λ that have leaked to the first support layer **23***a***1** from the arm waveguide **36***a***1** formed in the optical waveguide layer **22** pass through a boundary surface **43** between the first support layer **23***a***1** and the second support layer **23***a***2** and then reach a lower surface of the second support layer **23***a***2**, that is, the back surface **42** of the substrate **20***a*. In the present embodiment, the back surface **42** of the substrate **20***a* is roughened such that the surface roughness Rab satisfies Expression (1).

Thus, the leaked light beams of the wavelength λ that have reached the back surface **42** are effectively scattered, and the interference between the leaked light beams is suppressed.

[0079] The modulation electrode **40***b* of the arm waveguide **36***a***2** and the modulation electrodes of the arm waveguides of the Mach-Zehnder type optical waveguides **32** in other modulation portions **34** are also configured in the same manner as the modulation electrode **40***a* of the arm waveguide **36***a***1**. Even the leaked light beams generated in these arm waveguides are scattered on the back surface **42** of the substrate **20***a*, and the interference between the leaked light beams is suppressed, as described above.

[0080] Hereinafter, the arm waveguides of each Mach-Zehnder type optical waveguide **32** including the arm waveguides **36***a***1** and **36***a***2** of the Mach-Zehnder type optical waveguide **32***a* will be collectively referred to as arm waveguides **36**. The modification electrodes provided in the arm waveguides **36** in each modulation portion **34** including the modulation electrodes **40***a* and **40***b* provided in the arm waveguides **36***a***1** and **36***a***2** in the modulation portion **34***a* will be collectively referred to as modulation electrodes **40**.

[0081] The above action suppresses the intensification caused by the interference between the leaked light beams generated from the arm waveguides **36** formed in the optical waveguide layer **22**, in the substrate **20***a*. Consequently, even in a case where the leaked light beams reach the optical waveguide layer **22** again to be combined with the signal light propagating through the optical waveguide **26**, an effect of the leaked light beams on the optical characteristics of the optical modulation device **1***a* is suppressed to be low compared to that in the optical modulation device **90** of the prior art.

[0082] The scattering of the leaked light beams generated from the arm waveguides **36** preferably occurs at a position as far as possible from the arm waveguides **36** so that the leaked light beams after being scattered are not recombined with the signal light propagating through the arm waveguides **36**.

[0083] Accordingly, surface roughness Ra1 of the boundary surface **43** between the first support layer **23***a***1** in contact with a lower surface of the optical waveguide layer **22** and the second support layer **23***a***2** in contact with a lower surface of the first support layer **23***a***1**, and the surface roughness Rab of the back surface **42** of the substrate **20***a* preferably have the following relationship in Expression (2).

$$Rab > Ra1 \tag{2}$$

[0084] In addition to the relationship in Expression (2), the surface roughness Ra1 of the boundary surface **43** between the first support layer **23***a***1** and the second support layer **23***a***2** further preferably has the following relationship in Expression (3) with respect to surface roughness Ra0 of a boundary surface **44** between the lower surface of the optical waveguide layer **22** and the first support layer **23***a***1**.

$$Ra1 > Ra0 \tag{3}$$

[0085] In the present embodiment, for example, the wavelength λ of the light wave propagating through the optical waveguide **26** is 1.55 μm, Ra0 is 0.1 μm, Ra1 is 0.5 μm, and Ra2 is 2 μm.

[0086] In order to obtain an effect of suppressing the interference between the leaked light beams based on the scattering of the leaked light beams on the back surface **42** of the substrate **20***a*, it may be important to suppress the interference between the leaked light beams generated in the arm waveguides **36** in the first support layer **23***a***1** before the leaked light beams reach the substrate **20***a*. Specifically, the interference depends on a clearance L between the gaps arranged at constant clearances between each segment constituting the modulation electrodes **40** and/or a thickness t1 of the first support layer **23***a***1**. The clearance L between the gaps refers to a distance between centers of each gap in a length direction along the corresponding arm waveguide **36**.

[0087] More specifically, in order to suppress the interference between the leaked light beams in the first support layer **23***a***1**, the clearance L between the gaps of the segments constituting the modulation electrodes **40** preferably satisfies Expression (4) illustrated below and more preferably satisfies Expression (5) with respect to the wavelength λ of the light wave propagating through the optical waveguide **26** and a refractive index n1 of the first support layer **23***a***1**.

$$L > 4\times\lambda/n1 \tag{4}$$

$$L > 10\times\lambda/n1 \tag{5}$$

[0088] In order to suppress the interference between the leaked light beams in the first support layer **23***a***1**, the thickness t1 of the first support layer **23***a***1** preferably satisfies Expression (6) illustrated below and more preferably satisfies Expression (7).

$$t1 < 10\times\lambda/n1 \tag{6}$$

$$t1 < 4\times\lambda/n1 \tag{7}$$

[0089] In the present embodiment, for example, the wavelength λ of the light wave propagating through the optical waveguide **26** is 1.55 μm, and the clearance L between the gaps of the segments constituting the modulation electrodes **40** is 50 μm. For example, the optical waveguide layer **22** has a thickness t0 of 1 μm in the optical waveguide **26** and has the refractive index n0 of 2.2 in the wavelength A. For example, the first support layer **23***a***1** is formed of SiO_2, has the thickness t1 of 3 μm, and has the refractive index n1 of 1.48 in the wavelength λ. For example, the second support layer **23***a***2** is formed of alkali-free glass, has a thickness t2 of 300 μm, and has a refractive index n2 of 1.56 in the wavelength λ. Instead of alkali-free glass, a semiconductor material such as Si (having a refractive index of 3.5 in the wavelength λ) can also be used in the second support layer **23***a***2**.

[0090] While the whole substrate **20***a* is configured with multiple layers in the present embodiment, the whole substrate **20***a* is not necessarily configured with multiple layers. For example, the action and the effect of suppressing the interference between the leaked light beams can be achieved in a case where the substrate **20***a* is configured with multiple layers in at least a lower portion of the modulation portions **34** in which the modulation electrodes **40** which are the segmented electrodes are formed.

[0091] That is, the substrate **20***a* may include at least a multilayer portion configured with multiple layers, and the multilayer portion may include the optical waveguide layer **22**, the first support layer **23***a***1** in contact with the lower surface of the optical waveguide layer **22**, and the second support layer **23***a***2** in contact with the lower surface of the first support layer **23***al*.

[0092] In the present embodiment and each embodiment described below, the clearance L between the gaps between the adjacent segments is not necessarily constant in all sections (that is, the whole) of each modulation electrode **40**. The clearance L between the gaps between the adjacent segments may be constant in all sections of the modulation electrode **40** or a section excluding a part of the sections of the modulation electrode **40**. Similarly, each segment does not necessarily have the same length in all sections of each modulation electrode **40**. Each segment may have a constant length in all sections of the modulation electrode **40** or a section excluding a part of the sections of the modulation electrode **40**. For example, in a case where the modulation electrode **40** is divided into several hundred to several thousand segments, the lengths of the segments and/or the clearance between the gaps between the adjacent segments in one section or a plurality of sections of the modulation electrode **40** may be different from the lengths of the segments and/or the clearance between the gaps between the adjacent segments in other sections.

2. Second Embodiment

[0093] Next, an optical modulation device **1***b* according to a second embodiment of the present invention will be described.

[0094] As described above, the scattering of the leaked light beams generated from the arm waveguides **36** preferably occurs at a position as far as possible from the arm waveguides **36** so that the leaked light beams after being scattered are not recombined with the signal light propagating through the arm waveguides **36**.

[0095] Accordingly, for example, in a case where a substrate further including one or more additional support layers below the second support layer **23***a***2** is used instead of the substrate **20***a* including the first support layer **23***a***1** and the second support layer **23***a***2**, surface roughness Ran of each support layer boundary surface that is an interlayer boundary surface of each support layer is preferably higher than the surface roughness Ra0 of the boundary surface **44** between the optical waveguide layer **22** and the first support layer **23***a***1** and lower than the surface roughness Rab of the back surface of the substrate, and a value of the surface roughness is preferably higher as the support layer boundary surface is closer to the back surface of the substrate.

[0096] The optical modulation device **1***b* according to the present embodiment has the same configuration as the optical modulation device **1***a* according to the first embodiment except for including a substrate **20***b* including three support layers instead of the substrate **20***a*. The optical modulation device **1***b* may be used by mounting the optical modulation device **1***b* on the optical modulator **2** instead of the optical modulation device **1***a*.

[0097] A plan view of the optical modulation device **1***b* is the same as the plan view of the optical modulation device **1***a* illustrated in FIGS. **2** and **4**. Thus, FIGS. **2** and **4** and the description for FIGS. **2** and **4** are incorporated herein.

[0098] FIG. **6** is a side view of the optical modulation device **1***b* seen from the side **21***a* and is a diagram corresponding to FIG. **3** for the optical modulation device **1***a* according to the first embodiment. FIG. **7** is a cross-sectional view taken along the arm waveguide **36***a***1** in the modulation portion **34***a* of the optical modulation device **1***b* and is a diagram corresponding to FIG. **5** for the optical modulation device **1***a* according to the first embodiment.

[0099] In FIGS. **6** and **7**, the same constituents as the constituents illustrated in FIGS. **3** and **5** are designated using the same reference numerals as the reference numerals illustrated in FIGS. **3** and **5**, and the description for FIGS. **3** and **5** is incorporated herein.

[0100] With reference to FIGS. **6** and **7**, the substrate **20***b* constituting the optical modulation device **1***b* has the same configuration as the substrate **20***a* except for including a support layer **23***b* instead of the support layer **23***a*. The support layer **23***b* has the same configuration as the support layer **23***a* except for including a third support layer **23***a***3** in contact with the lower surface of the second support layer **23***a***2** in addition to the first support layer **23***a***1** and the second support layer **23***a***2**. For example, the substrate **20***b* is configured by laminating a lower surface of the optical substrate **24** with a support substrate **25***b* including the first support layer **23***a***1**, the second support layer **23***a***2**, and the third support layer **23***a***3**, instead of the support substrate **25***a*.

[0101] The substrate **20***b* is not necessarily configured with a plurality of plate bodies, like the substrate **20***a*. The substrate **20***b* may be configured with a film body formed to have a layer shape on an appropriate substrate. For example, the substrate **20***b* can be a substrate including the second support layer **23***a***2**, the first support layer **23***a***1**, and the optical waveguide layer **22** that are formed to have a layer shape through a film forming process such as sputtering, vapor deposition, and/or crystal growth on an appropriate plate body constituting the third support layer **23***a***3**.

[0102] In FIG. **7**, lower part (B) illustrates a configuration of the optical modulation device **1***b* in a cross section along the arm waveguide **36***al*, and upper part (A) is a graph illustrating a change in a refractive index of the arm waveguide **36***a***1** along the optical propagation direction in the cross section, as in FIG. **5**.

[0103] In the optical modulation device **1***b*, two support layer boundary surfaces are present in the substrate **20***b*. That is, the boundary surface **43** between the first support layer **23***a***1** and the second support layer **23***a***2**, and a boundary surface **45** between the second support layer **23***a***2** and the third support layer **23***a***3** are present. For these support layer boundary surfaces, the boundary surface **45** has a shorter distance from the back surface **46** of the substrate **20***b* than the boundary surface **43**. The surface roughness Ra2 of the boundary surface **45**, the surface roughness Ra1 of the boundary surface **43**, the surface roughness Ra0 of the boundary surface **44** between the optical waveguide layer **22** and the first support layer **23***a***1**, and the surface roughness Rab of the back surface **46** of the substrate **20***b* have the following relationship in Expression (8).

$$Rab>Ra2>Ra1>Ra0 \quad (8)$$

[0104] That is, the surface roughness Ran (in the present embodiment, n=1 and 2) of each support layer boundary surface is higher than the surface roughness Ra0 of the boundary surface **44** between the optical waveguide layer **22** and the first support layer **23**a**1** and lower than the surface roughness Rab of the back surface **46** of the substrate **20**b, and the value of the surface roughness is higher as the support layer boundary surface is closer to the back surface **46** of the substrate **20**b.

[0105] Accordingly, a degree of the scattering of the leaked light beams generated from the arm waveguides **36** is lower as the boundary surface is closer to the arm waveguides **36**. Consequently, recombining of the leaked light beams after being scattered with the signal light propagating through the arm waveguides **36** is effectively suppressed while the intensification caused by the interference between the leaked light beams in the substrate **20**b is suppressed based on the scattering.

3. Third Embodiment

[0106] Next, an optical modulation device **1**c according to a third embodiment of the present invention will be described. The optical modulation device **1**c has the same configuration as the optical modulation device **1**a except that a light absorbing material that absorbs light in a wavelength range of the light wave propagating through the optical waveguide **26** is disposed on the back surface of the substrate **20**a facing the surface of the optical waveguide layer **22**. The optical modulation device **1**c may be used by mounting the optical modulation device **1**c on the optical modulator **2** instead of the optical modulation device **1**a.

[0107] A plan view of the optical modulation device **1**c is the same as the plan view of the optical modulation device **1**a illustrated in FIGS. **2** and **4**. Thus, FIGS. **2** and **4** and the description for FIGS. **2** and **4** are incorporated herein.

[0108] FIG. **8** is a side view of the optical modulation device **1**c seen from the side **21**a and is a diagram corresponding to FIG. **3** for the optical modulation device **1**a according to the first embodiment. FIG. **9** is a cross-sectional view taken along the arm waveguide **36**a**1** in the modulation portion **34**a of the optical modulation device **1**c and is a diagram corresponding to FIG. **5** for the optical modulation device **1**a according to the first embodiment. The graph of the refractive index in the arm waveguide **36**a**1** in FIG. **9** is the same as that in FIG. **5** and thus, will not be described.

[0109] In FIGS. **8** and **9**, the same constituents as the constituents illustrated in FIGS. **3** and **5** are designated using the same reference numerals as the reference numerals illustrated in FIGS. **3** and **5**, and the description for FIGS. **3** and **5** is incorporated herein.

[0110] With reference to FIGS. **8** and **9**, in the optical modulation device **1**c, a light absorbing material **49** that absorbs light in the wavelength range of the light wave propagating through the optical waveguide **26** is disposed on the whole back surface **42** of the substrate **20**a facing the surface of the optical waveguide layer **22**. Accordingly, in the optical modulation device **1**c, the leaked light beams generated from the arm waveguides **36** of the optical waveguide layer **22** are absorbed by the light absorbing material **49** to be attenuated in a case where the leaked light beams propagate through the second support layer **23**a**2** and reach the back surface **42**. Consequently, in the optical modulation device **1**c, the intensity of the leaked light beams reaching the optical waveguide layer **22** again is reduced, and the effect of the leaked light beams on the optical characteristics of the optical modulation device **1**c is further effectively suppressed compared to that in the optical modulation device **90** of the prior art.

[0111] For example, the light absorbing material **49** may be a carbon material such as carbon black, a black resin such as a cashew oil, or a metal filler such as Ag. For example, these types of the light absorbing material **49** may be applied to the back surface **42** of the substrate **20**a and cured to be disposed on the back surface **42** using an appropriate resin as a binder.

[0112] While the light absorbing material **49** is disposed on the whole surface of the back surface **42** of the substrate **20**a in the present embodiment, the light absorbing material **49** may be applied to a part of the back surface **42**. For example, the effect of attenuating the leaked light beams can be achieved in a case where the light absorbing material **49** is disposed in at least a range of the back surface **42** corresponding to the lower portion of the modulation portions **34** in which the modulation electrodes **40** which are the segmented electrodes are formed.

[0113] In mounting the optical modulation device **1**c on the case **3**, the optical modulation device **1**c may be fixed to the case **3** by, for example, providing an adhesive layer between the case **3** and a surface of the light absorbing material **49** disposed on the back surface **42** of the substrate **20**a and a surface of the back surface **42** on which the light absorbing material **49** is not applied.

4. Fourth Embodiment

[0114] Next, a fourth embodiment of the present invention will be described. In the present embodiment, the optical modulation device **1**a according to the first embodiment is included in an optical modulation module **50**. FIG. **10** is a diagram illustrating a configuration of the optical modulation module **50** according to the present embodiment. In FIG. **10**, the same constituents as those of the optical modulator **2** according to the first embodiment illustrated in FIG. **1** are designated using the same reference numerals as the reference numerals illustrated in FIG. **1**, and the description for FIG. **1** is incorporated herein.

[0115] The optical modulation module **50** has the same configuration as the optical modulator **2** illustrated in FIG. **1** except for including a circuit substrate **51** instead of the relay substrate **4**. The circuit substrate **51** includes a drive circuit **52**. For example, the drive circuit **52** generates a high-frequency electrical signal for driving the optical modulation device **1**a based on a modulation signal supplied from the outside through the signal pin **5**a and outputs the generated high-frequency electrical signal to the optical modulation device **1**a.

[0116] Since the optical modulation module **50** having the above configuration includes the optical modulation device **1**a like the optical modulator **2** according to the first embodiment, the optical modulation module **50** can implement a favorable optical modulation operation by reducing the effect of the leaked light beams from the arm waveguides **36** provided with the modulation electrodes **40**, which are the segmented electrodes, on the optical characteristics of the optical modulation device **1**a, like the optical modulator **2**.

[0117] While the optical modulation module **50** includes, for example, the optical modulation device **1**a in the present embodiment, the optical modulation module **50** may include the optical modulation device **1***b* according to the second embodiment or the optical modulation device **1***c* according to the third embodiment.

5. Fifth Embodiment

[0118] Next, a fifth embodiment of the present invention will be described. In the present embodiment, the optical modulator **2** according to the first embodiment is mounted on an optical transmission apparatus **55**. FIG. **11** is a diagram illustrating a configuration of the optical transmission apparatus **55** according to the present embodiment. The optical transmission apparatus **55** includes the optical modulator **2**, a light source **56** that inputs light into the optical modulator **2**, a modulator drive unit **57**, and a modulation signal generation part **58**. The optical modulation module **50** according to the fourth embodiment can be used instead of the optical modulator **2** and the modulator drive unit **57**. The optical modulator **2** may include the optical modulation device **1***b* or the optical modulation device **1***c* instead of the optical modulation device **1***a*.

[0119] The modulation signal generation part **58** is an electronic circuit for generating an electrical signal for causing the optical modulator **2** to perform the modulation operation, and generates a modulation signal that is a high-frequency signal for causing the optical modulator **2** to perform an optical modulation operation in accordance with corresponding modulation data, based on transmission data provided from the outside and outputs the modulation signal to the modulator drive unit **57**.

[0120] The modulator drive unit **57** amplifies the modulation signal input from the modulation signal generation part **58** to output four sets of high-frequency electrical signals for driving each modulation electrode **40** provided in the four Mach-Zehnder type optical waveguides **32** of the optical modulation device **1***a* included in the optical modulator **2**.

[0121] These high-frequency electrical signals are input into the signal pin **5***a* of the optical modulator **2** to drive the optical modulation device **1***a*. Accordingly, for example, the light output from the light source **56** is subjected to DP-QPSK modulation by the optical modulator **2** and is output from the optical transmission apparatus **55** as modulated light.

[0122] In the optical transmission apparatus **55**, since the optical modulator **2** or the optical modulation module **50** including the optical modulation device **1***a*, **1***b*, or **1***c* is used, favorable optical transmission can be performed by implementing favorable modulation characteristics.

6. Sixth Embodiment

[0123] Next, a sixth embodiment of the present invention will be described. In the present embodiment, the optical transmission apparatus **55** according to the fifth embodiment is used in an optical transmission system **60**. FIG. **12** is a diagram illustrating a configuration of the optical transmission system **60** according to the present embodiment. The optical transmission system **60** includes the optical transmission apparatus **55** according to the fifth embodiment, an optical fiber transmission channel **61** for transmitting a modulated optical signal that is output light of the optical transmission apparatus **55**, and an optical reception apparatus **62** that receives the optical signal transmitted by the optical fiber transmission channel **61**. The optical transmission system **60** transmits the optical signal via the optical transmission apparatus **55** using the optical modulator **2** or the optical modulation module **50** including the optical modulation device **1***a*, **1***b*, or **1***c*. Thus, the optical transmission system **60** has favorable optical transmission performance.

7. Other Embodiments

[0124] While the optical waveguide layer **22** on which the optical waveguide **26** is formed is included in the optical substrate **24** which is the LN substrate in the first to third embodiments, the optical waveguide layer **22** is not necessarily formed of LN. The optical waveguide layer **22** may be formed of a semiconductor material such as InP.

[0125] In the embodiments, the substrates **20***a* and **20***b* configured with multiple layers are configured by laminating a plurality of plate bodies. However, this is only an example, and the substrates **20***a* and **20***b* may be configured with a film body formed to have a layer shape on an appropriate substrate, as described above.

[0126] In the embodiments, the optical substrate **24** as a plate body constituting the optical waveguide layer **22** and the support substrate **25***a* as a plate body constituting the first support layer **23***a***1** and the second support layer **23***a***2** are laminated in the substrate **20***a*. However, the optical substrate **24** and the support substrate **25***a* are examples of plate bodies constituting the substrate **20***a*, and any distribution of the layers included in each of the plurality of plate bodies may be used. That is, in a case where a substrate such as the substrate **20***a* or **20***b* is formed by laminating a plurality of plate bodies, each plate body may include one layer or a plurality of layers of any number among the optical waveguide layer **22** and a plurality of support layers such as the first support layer **23***a***1**.

[0127] The present invention is not limited to the configurations of the embodiments and can be embodied in various aspects without departing from its gist.

8. Configurations Supported by Embodiments

[0128] The embodiments support the following configurations.

[0129] (Configuration 1) An optical modulation device includes a substrate including a multilayer portion configured with multiple layers, an optical waveguide configured with a protruding portion extending on an optical waveguide layer in the multilayer portion of the substrate, and a modulation electrode that is an electrode formed on the optical waveguide layer to control a light wave propagating through the optical waveguide and that is formed to be divided into a plurality of segments along a propagation direction of light of the optical waveguide, in all sections of the electrode or a section excluding a part of the sections of the electrode, a clearance L, measured in an extending direction of the optical waveguide, between gaps between adjacent segments is constant, the multilayer portion of the substrate includes the optical waveguide layer and a plurality of support layers disposed in multiple layers below the optical waveguide layer, and surface roughness Rab of a back surface of the substrate facing a surface of the optical waveguide layer has a relationship of $Rab>\lambda$ with respect to a wavelength λ of the light wave propagating through the optical waveguide.

[0130] According to the optical modulation device of Configuration 1, intensification caused by interference between leaked light beams from the optical waveguide caused by the gaps between the segments of the optical modulation electrode which is a segmented electrode formed to be divided into a plurality of segments along the propagation direction of the light of the optical waveguide can be suppressed. Accordingly, in the optical modulation device of Configuration 1, favorable optical characteristics can be implemented by reducing an effect of the leaked light beams on optical characteristics of the optical modulation device.

[0131] (Configuration 2) In the optical modulation device according to Configuration 1, surface roughness Ra1 of a boundary surface between a first support layer that is the support layer in contact with a lower surface of the optical waveguide layer and a second support layer that is the support layer in contact with a lower surface of the first support layer, and the surface roughness Rab of the back surface of the substrate have a relationship of Rab>Ra1.

[0132] According to the optical modulation device of Configuration 2, more significant scattering of the leaked light beams occurs on the back surface of the substrate farther from an interlayer boundary surface closer to the optical waveguide layer on which the optical waveguide is formed, and a degree of the scattering is lower on the boundary surface closer to the optical waveguide. Thus, recombining of the leaked light beams after being scattered with signal light propagating through the optical waveguide can be suppressed.

[0133] (Configuration 3) In the optical modulation device according to Configuration 2, the surface roughness Ra1 of the boundary surface between the first support layer and the second support layer has a relationship of Ra1>Ra0 with respect to surface roughness Ra0 of a boundary surface between the lower surface of the optical waveguide layer and the first support layer.

[0134] According to the optical modulation device of Configuration 3, in a case where two interlayer boundary surfaces are present in the substrate, more significant scattering of the leaked light beams occurs on the back surface of the substrate farther from the interlayer boundary surface closer to the optical waveguide layer on which the optical waveguide is formed, and the degree of the scattering is lower on the boundary surface closer to the optical waveguide. Thus, recombining of the leaked light beams after being scattered with the signal light propagating through the optical waveguide can be suppressed.

[0135] (Configuration 4) In the optical modulation device according to Configuration 2 or 3, surface roughness Ran of each support layer boundary surface that is an interlayer boundary surface of the plurality of support layers is higher than surface roughness Ra0 of a boundary surface between the optical waveguide layer and the first support layer and lower than the surface roughness Rab of the back surface of the substrate, and a value of the surface roughness Ran is higher as the support layer boundary surface is closer to the back surface.

[0136] According to the optical modulation device of Configuration 4, in a case where a plurality of interlayer boundary surfaces of any number are present in the substrate, more significant scattering of the leaked light beams occurs on the back surface of the substrate farther from the interlayer boundary surface closer to the optical waveguide layer on which the optical waveguide is formed, and the degree of the scattering is lower on the boundary surface closer to the optical waveguide. Thus, recombining of the leaked light beams after being scattered with the signal light propagating through the optical waveguide can be suppressed.

[0137] (Configuration 5) In the optical modulation device according to any one of Configurations 1 to 4, the modulation electrode is formed to be divided into a plurality of segments having the same length, and the clearance L, measured in the extending direction of the optical waveguide, between the gaps between the adjacent segments has a relationship of $L>4\times\lambda/n1$ with respect to the wavelength λ of the light wave propagating through the optical waveguide and a refractive index n1 of a first support layer that is the support layer in contact with a lower surface of the optical waveguide layer.

[0138] According to the optical modulation device of Configuration 5, more favorable optical characteristics can be implemented by suppressing the intensification caused by the interference between the leaked light beams.

[0139] (Configuration 6) In the optical modulation device according to any one of Configurations 1 to 5, a thickness t1 of a first support layer that is the support layer in contact with a lower surface of the optical waveguide layer has a relationship of $t1<10\times\lambda/n1$ with respect to the wavelength λ of the light wave propagating through the optical waveguide and a refractive index n1 of the first support layer.

[0140] According to the optical modulation device of Configuration 6, more favorable optical characteristics can be implemented by suppressing the intensification caused by the interference between the leaked light beams in the first support layer.

[0141] (Configuration 7) In the optical modulation device according to any one of Configurations 1 to 6, a light absorbing material that absorbs light in a wavelength range of the light wave propagating through the optical waveguide is disposed on the back surface of the substrate facing the surface of the optical waveguide layer.

[0142] According to the optical modulation device of Configuration 7, further favorable optical characteristics can be implemented by reducing intensity of the leaked light beams that have reached the back surface of the substrate via the light absorbing material disposed on the back surface to effectively reduce the effect of the leaked light beams on the optical characteristics of the optical modulation device.

[0143] (Configuration 8) In the optical modulation device according to Configuration 7, the light absorbing material is a carbon material, a black resin, or a metal filler.

[0144] According to the optical modulation device of Configuration 8, further favorable optical characteristics of the optical modulation device can be implemented by effectively reducing the intensity of the leaked light beams that have reached the back surface of the substrate.

[0145] (Configuration 9) In the optical modulation device according to any one of Configurations 1 to 8, the substrate is formed by laminating a plurality of plate bodies, and each plate body includes one layer or a plurality of layers among the optical waveguide layer and the plurality of support layers.

[0146] According to the optical modulation device of Configuration 9, a substrate including a plurality of support layers and an optical waveguide layer on which an optical waveguide is formed can be easily configured.

[0147] (Configuration 10) An optical modulator includes the optical modulation device according to any one of Configurations 1 to 9, a case for accommodating the optical modulation device, an optical fiber for inputting light into the optical modulation device, and an optical fiber for guiding light output from the optical modulation device to an outside of the case.

[0148] According to the optical modulator of Configuration 10, since the optical modulation device of any one of Configurations 1 to 9 is used, an optical modulator having favorable optical characteristics may be implemented.

[0149] (Configuration 11) An optical modulation module includes the optical modulation device according to any one of Configurations 1 to 9, a case for accommodating the optical modulation device, an optical fiber for inputting light into the optical modulation device, an optical fiber for guiding light output from the optical modulation device to an outside of the case, and a drive circuit for driving the optical modulation device.

[0150] According to the optical modulation module of Configuration 11, since the optical modulation device of any one of Configurations 1 to 9 is used, an optical modulation module having favorable optical characteristics may be implemented.

[0151] (Configuration 12) An optical transmission apparatus includes the optical modulator according to Configuration 10 or the optical modulation module according to Configuration 11, and an electronic circuit for generating an electrical signal for causing the optical modulation device to perform a modulation operation.

[0152] According to the optical transmission apparatus of Configuration 12, since the optical modulator or the optical modulation module using the optical modulation device of any one of Configurations 1 to 9 is used, favorable optical transmission characteristics can be implemented.

[0153] (Configuration 13) An optical transmission system includes the optical transmission apparatus according to Configuration 12, and an optical fiber transmission channel through which output light of the optical modulation device is transmitted.

[0154] According to the optical transmission system of Configuration 13, since the optical transmission apparatus using the optical modulation device of any one of Configurations 1 to 9 is used, favorable optical transmission characteristics can be implemented.

What is claimed is:

1. An optical modulation device comprising:

a substrate including a multilayer portion configured with multiple layers;

an optical waveguide configured with a protruding portion extending on an optical waveguide layer in the multilayer portion of the substrate; and

a modulation electrode that is an electrode formed on the optical waveguide layer to control a light wave propagating through the optical waveguide and that is formed to be divided into a plurality of segments along a propagation direction of light of the optical waveguide,

wherein in all sections of the electrode or a section excluding a part of the sections of the electrode, a clearance L, measured in an extending direction of the optical waveguide, between gaps between adjacent segments is constant,

the multilayer portion of the substrate includes the optical waveguide layer and a plurality of support layers disposed in multiple layers below the optical waveguide layer, and

surface roughness Rab of a back surface of the substrate facing a surface of the optical waveguide layer has a relationship of

$$Rab>\lambda$$

with respect to a wavelength λ of the light wave propagating through the optical waveguide.

2. The optical modulation device according to claim **1**, wherein surface roughness Ra1 of a boundary surface between a first support layer that is the support layer in contact with a lower surface of the optical waveguide layer and a second support layer that is the support layer in contact with a lower surface of the first support layer, and the surface roughness Rab of the back surface of the substrate have a relationship of

$$Rab>Ra1.$$

3. The optical modulation device according to claim **2**, wherein the surface roughness Ra1 of the boundary surface between the first support layer and the second support layer has a relationship of

$$Ra1>Ra0$$

with respect to surface roughness Ra0 of a boundary surface between the lower surface of the optical waveguide layer and the first support layer.

4. The optical modulation device according to claim **2**, wherein surface roughness Ran of each support layer boundary surface that is an interlayer boundary surface of the plurality of support layers is

higher than surface roughness Ra0 of a boundary surface between the optical waveguide layer and the first support layer and lower than the surface roughness Rab of the back surface of the substrate, and

a value of the surface roughness Ran is higher as the support layer boundary surface is closer to the back surface.

5. The optical modulation device according to claim **1**, wherein the modulation electrode is formed to be divided into a plurality of segments having the same length, and

the clearance L, measured in the extending direction of the optical waveguide, between the gaps between the adjacent segments has a relationship of

$$L > 4\times\lambda/n1$$

with respect to the wavelength λ of the light wave propagating through the optical waveguide and a refractive index n1 of a first support layer that is the support layer in contact with a lower surface of the optical waveguide layer.

6. The optical modulation device according to claim **1**, wherein a thickness t1 of a first support layer that is the support layer in contact with a lower surface of the optical waveguide layer has a relationship of

$$t1 < 10\times\lambda/n1$$

with respect to the wavelength λ of the light wave propagating through the optical waveguide and a refractive index n1 of the first support layer.

7. The optical modulation device according to claim **1**, wherein a light absorbing material that absorbs light in a wavelength range of the light wave propagating through the optical waveguide is disposed on the back surface of the substrate facing the surface of the optical waveguide layer.

8. The optical modulation device according to claim **7**, wherein the light absorbing material is a carbon material, a black resin, or a metal filler.

9. The optical modulation device according to claim **1**, wherein the substrate is formed by laminating a plurality of plate bodies, and

each plate body includes one layer or a plurality of layers among the optical waveguide layer and the plurality of support layers.

10. An optical modulator comprising:

the optical modulation device according to claim **1**;

a case for accommodating the optical modulation device;

an optical fiber for inputting light into the optical modulation device; and

an optical fiber for guiding light output from the optical modulation device to an outside of the case.

11. An optical modulation module comprising:

the optical modulation device according to claim **1**;

a case for accommodating the optical modulation device;

an optical fiber for inputting light into the optical modulation device;

an optical fiber for guiding light output from the optical modulation device to an outside of the case; and

a drive circuit for driving the optical modulation device.

12. An optical transmission apparatus comprising:

the optical modulator according to claim **10**; and

an electronic circuit for generating an electrical signal for causing the optical modulation device to perform a modulation operation.

13. An optical transmission system comprising:

the optical transmission apparatus according to claim **12**; and

an optical fiber transmission channel through which output light of the optical modulation device is transmitted.

14. An optical transmission apparatus comprising:

the optical modulation module according to claim **11**; and

an electronic circuit for generating an electrical signal for causing the optical modulation device to perform a modulation operation.

15. An optical transmission system comprising:

the optical transmission apparatus according to claim **14**; and

an optical fiber transmission channel through which output light of the optical modulation device is transmitted.

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