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(19) **United States**(12) **Patent Application Publication**
Sugamata et al.(10) **Pub. No.: US 2025/0264745 A1**(43) **Pub. Date: Aug. 21, 2025**(54) **OPTICAL MODULATION DEVICE, OPTICAL MODULATOR, OPTICAL MODULATION MODULE, OPTICAL TRANSMISSION APPARATUS, AND OPTICAL TRANSMISSION SYSTEM**(52) **U.S. Cl.**CPC *G02F 1/035* (2013.01); *G02F 1/0316* (2013.01); *G02F 1/0344* (2013.01); *H04B 10/50* (2013.01); *G02F 2202/20* (2013.01)(71) Applicant: **SUMITOMO OSAKA CEMENT CO., LTD.**, Tokyo (JP)

(57)

ABSTRACT(72) Inventors: **Toru Sugamata**, Tokyo (JP); **Norikazu Miyazaki**, Tokyo (JP)

An optical modulation device includes a substrate including a multilayer portion, an optical waveguide layer on which an optical waveguide is formed in the multilayer portion, and a modulation electrode formed to be divided into a plurality of segments along a propagation direction of the optical waveguide to control a light wave propagating through the optical waveguide, in which in all sections of the electrode or a section excluding a part of the sections, 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, a first support layer, and a second support layer, and a refractive index n_0 of the optical waveguide layer, a refractive index n_1 of the first support layer, and a refractive index n_2 of the second support layer have a relationship of $n_0 > n_1$ and $n_2 > n_1$.

(21) Appl. No.: **18/900,053**(22) Filed: **Sep. 27, 2024**(30) **Foreign Application Priority Data**

Feb. 16, 2024 (JP) 2024-022427

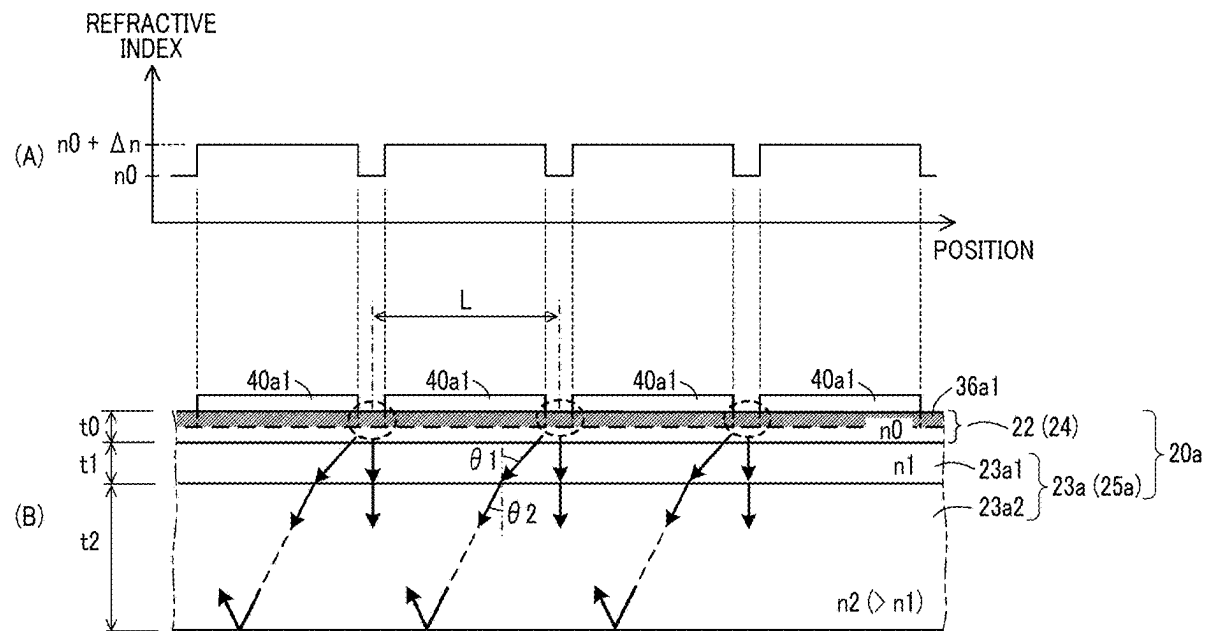
Publication Classification(51) **Int. Cl.***G02F 1/035* (2006.01)
G02F 1/03 (2006.01)
H04B 10/50 (2013.01)**CROSS-SECTIONAL VIEW TAKEN ALONG LINE V-V**

FIG. 1

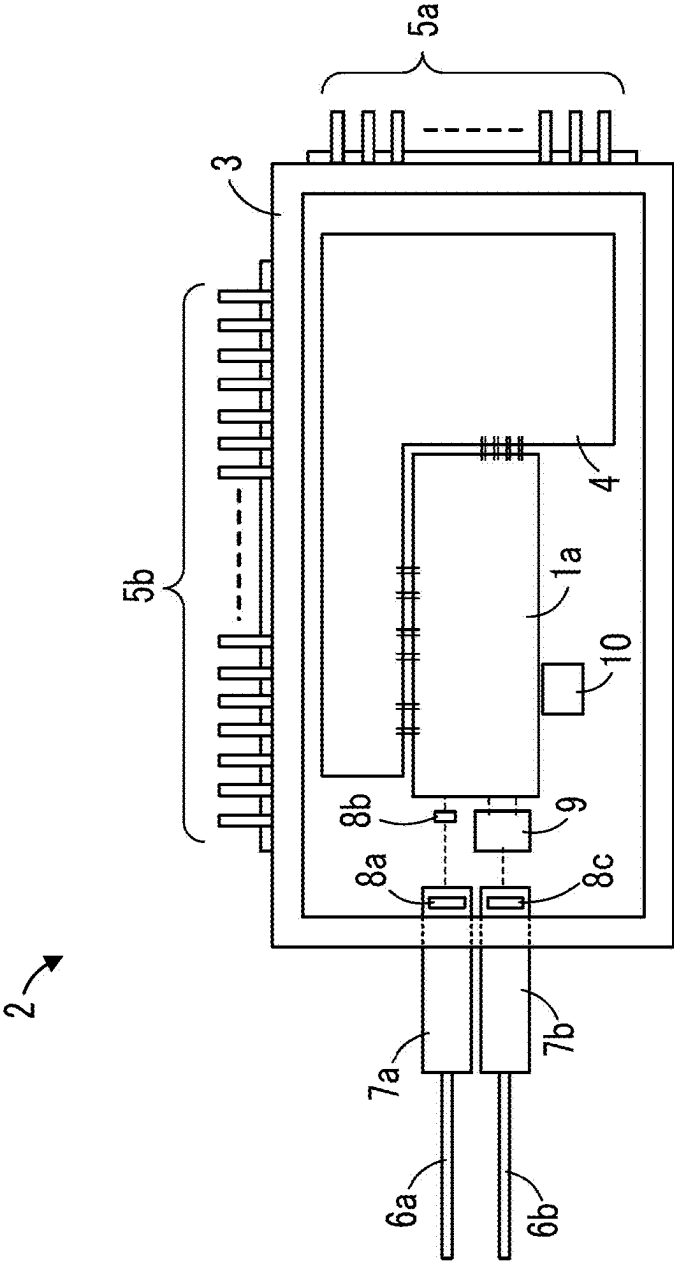


FIG. 2

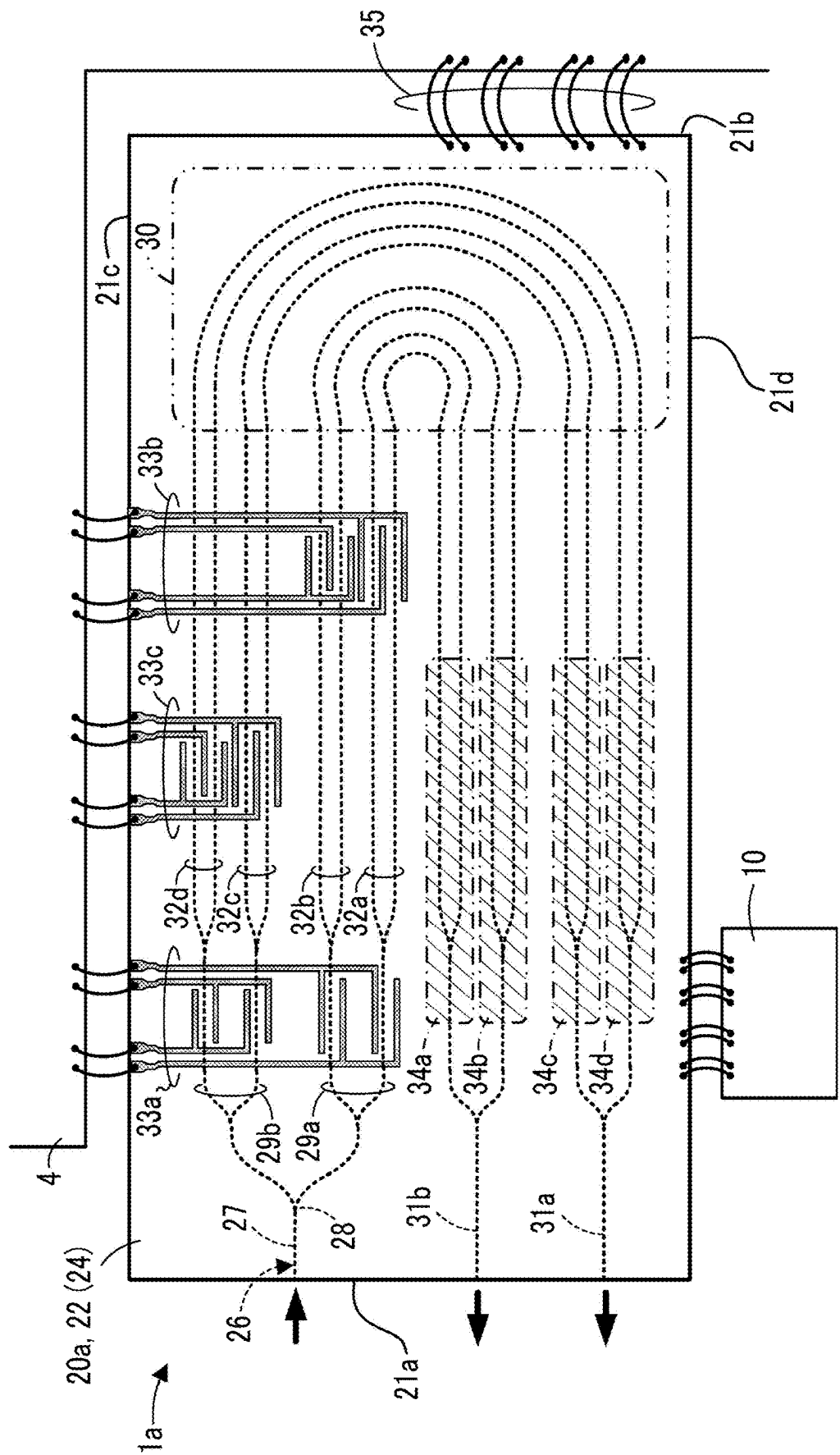


FIG. 3

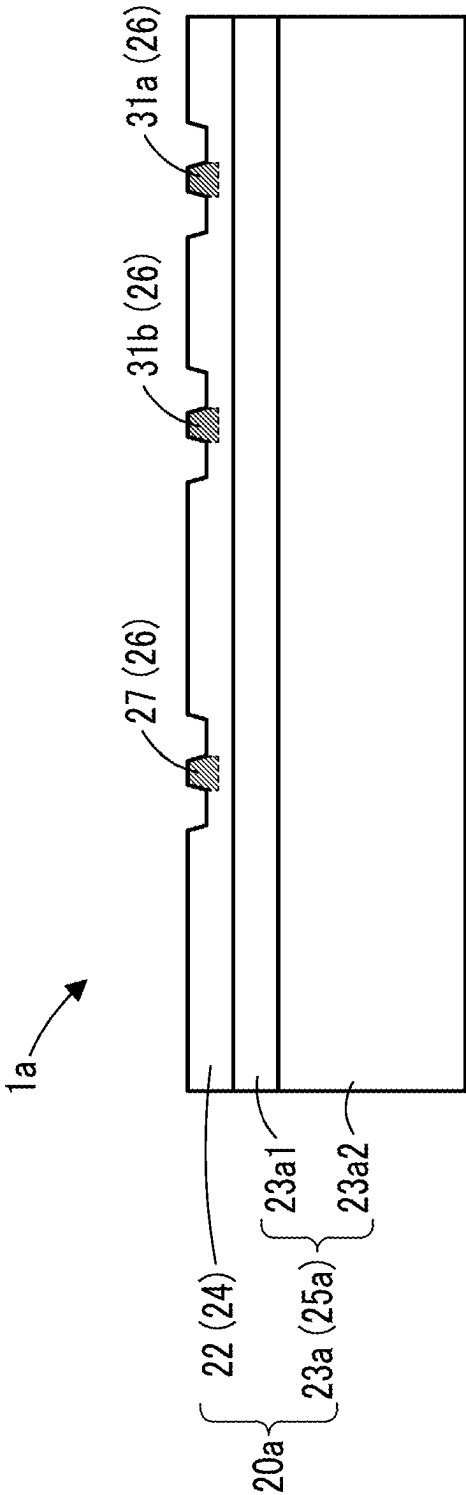


FIG. 4

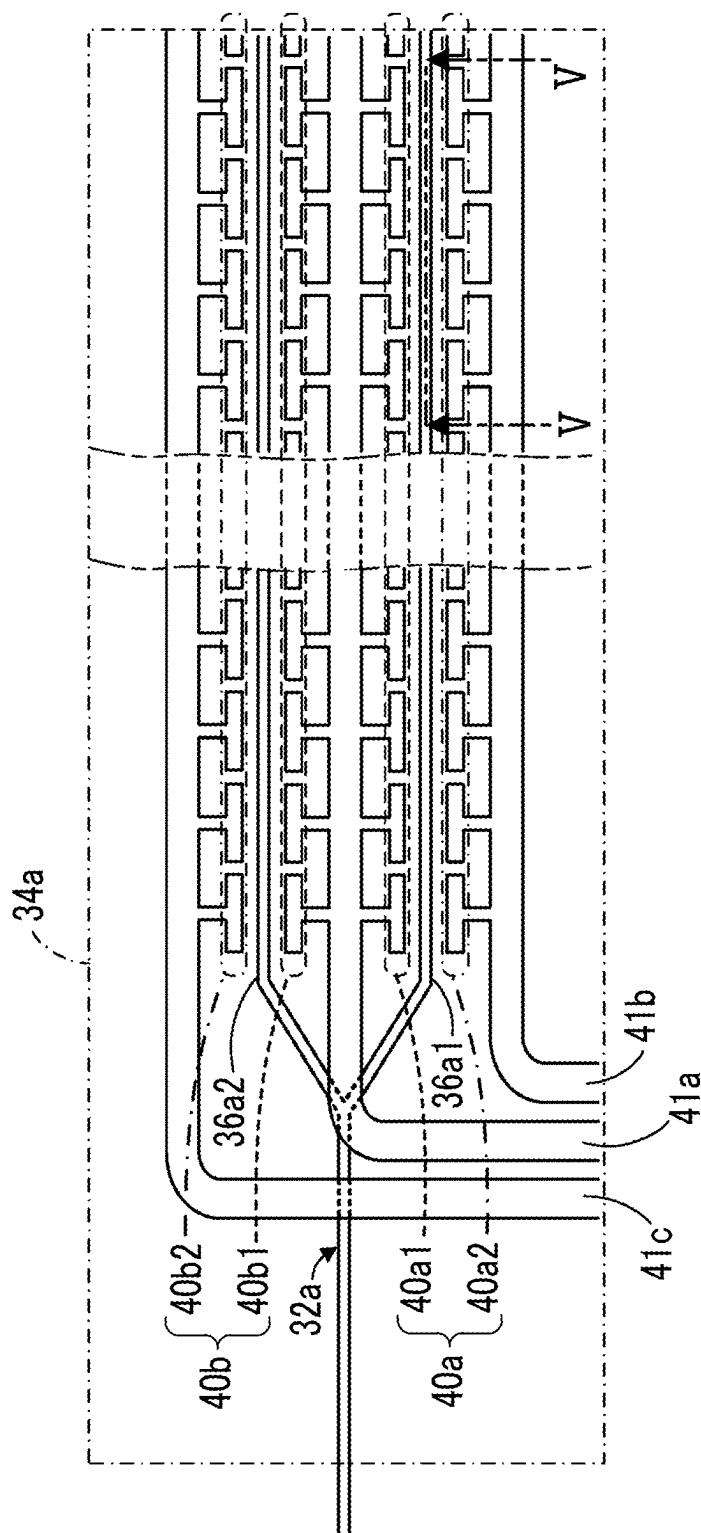
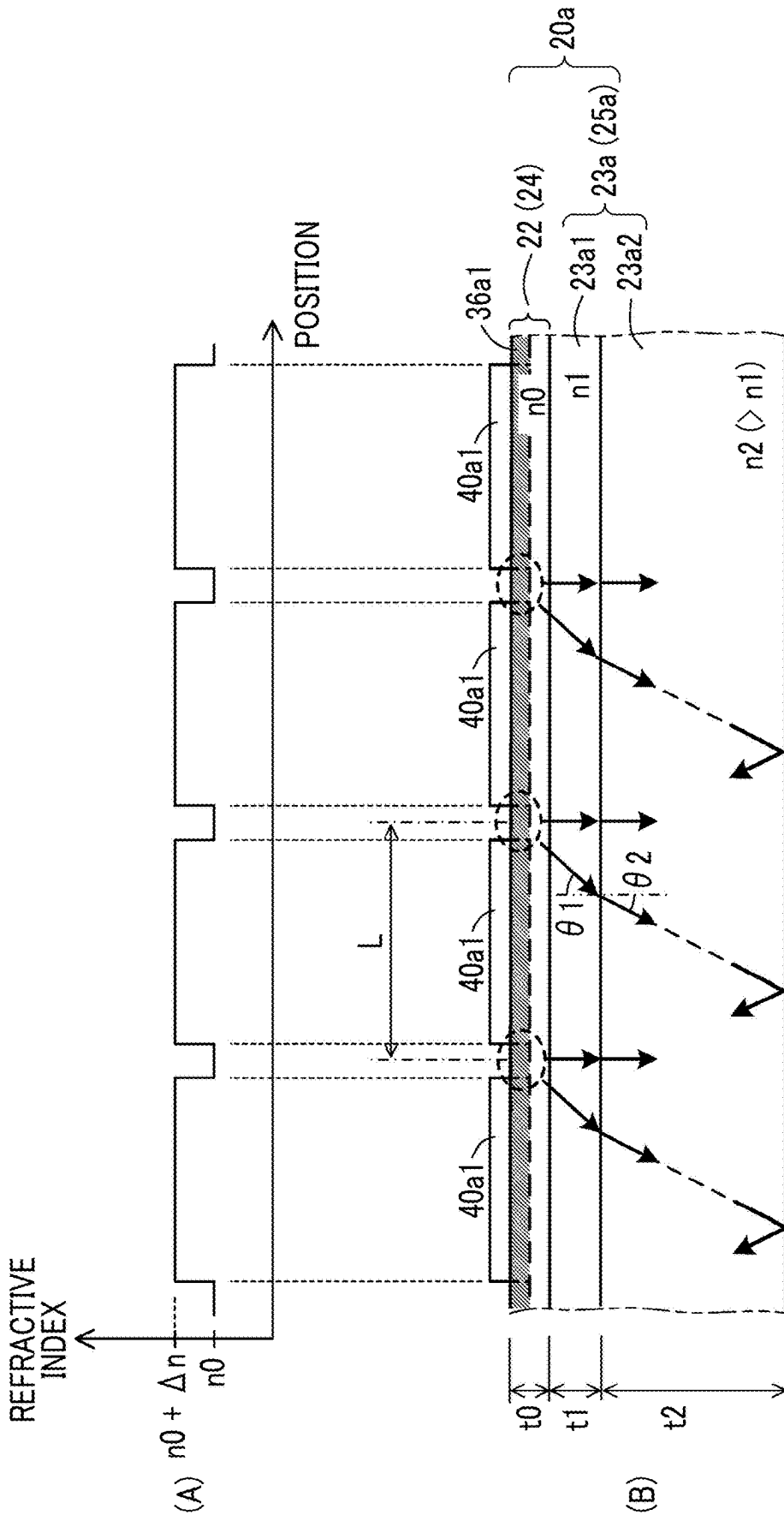


FIG. 5



CROSS-SECTIONAL VIEW TAKEN ALONG LINE V-V

FIG. 6

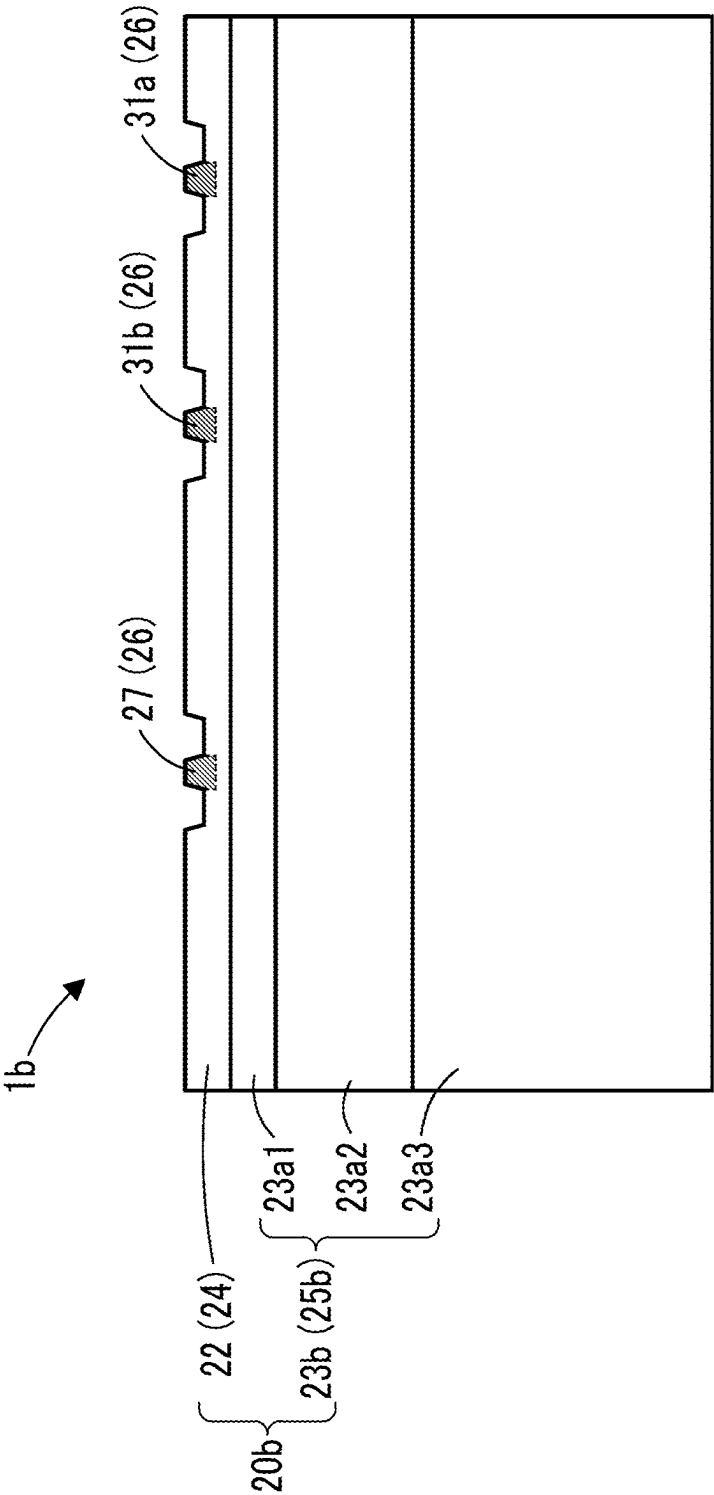


FIG. 7

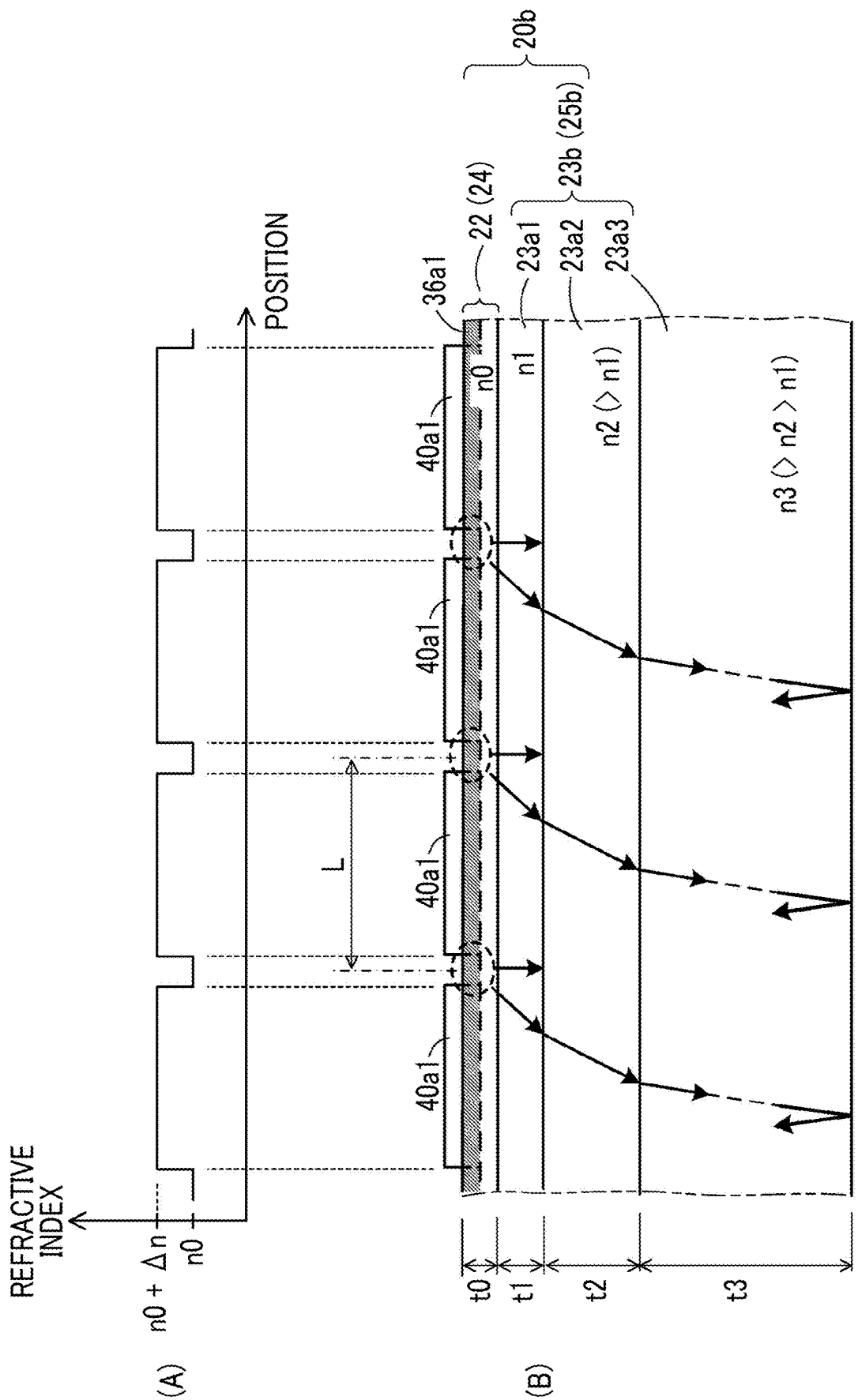


FIG. 8

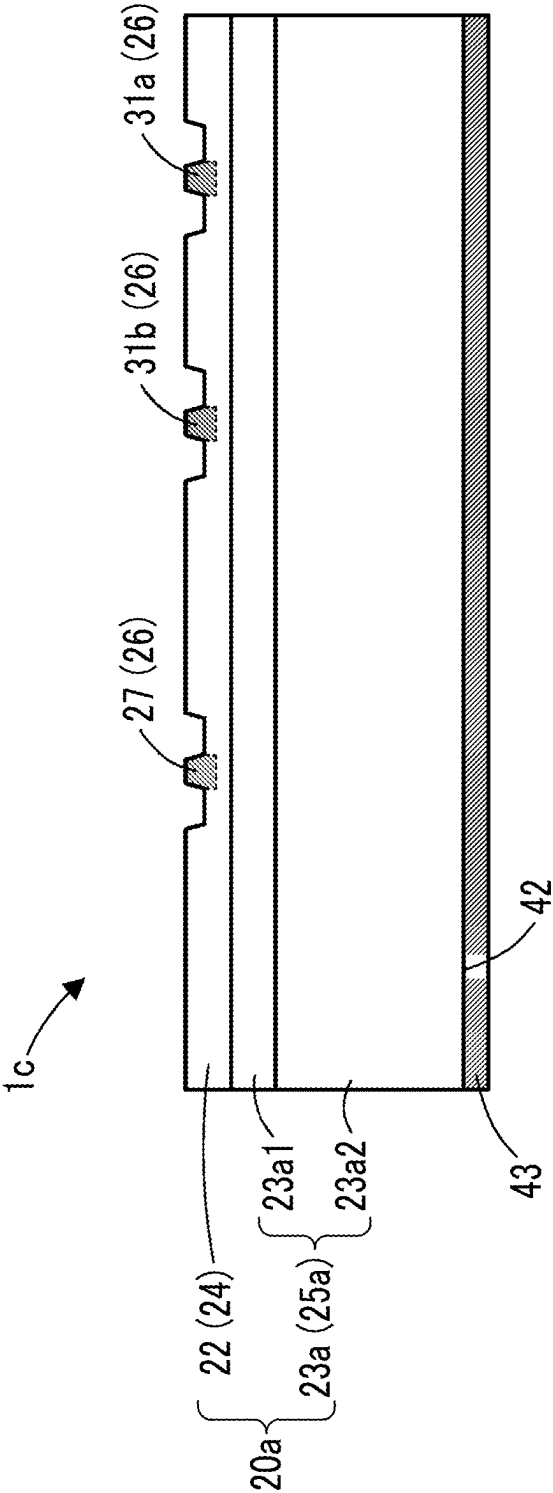


FIG. 9

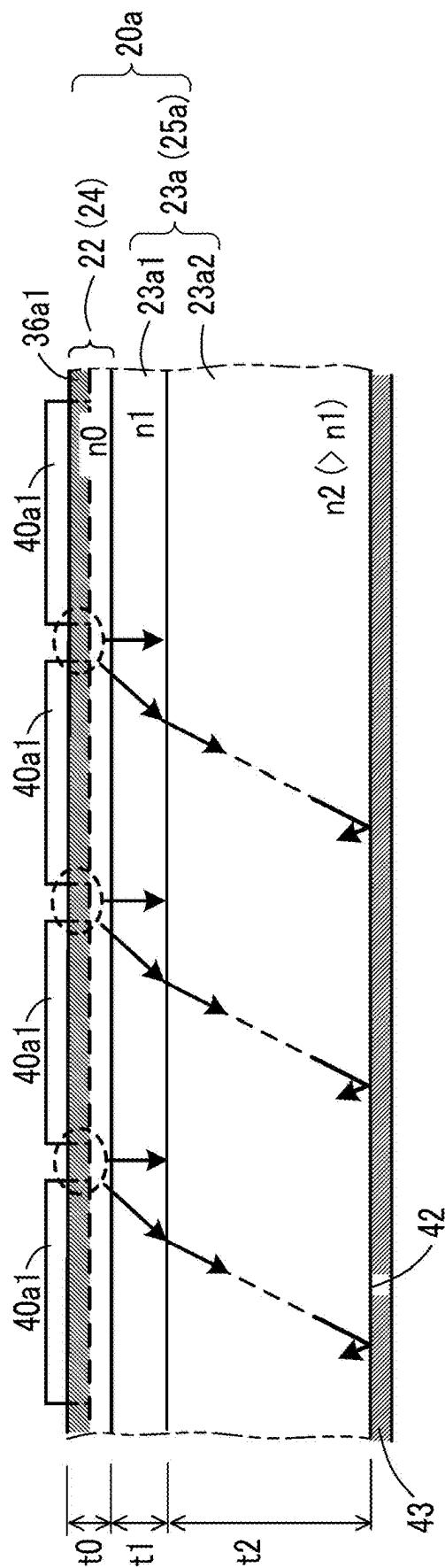


FIG. 10

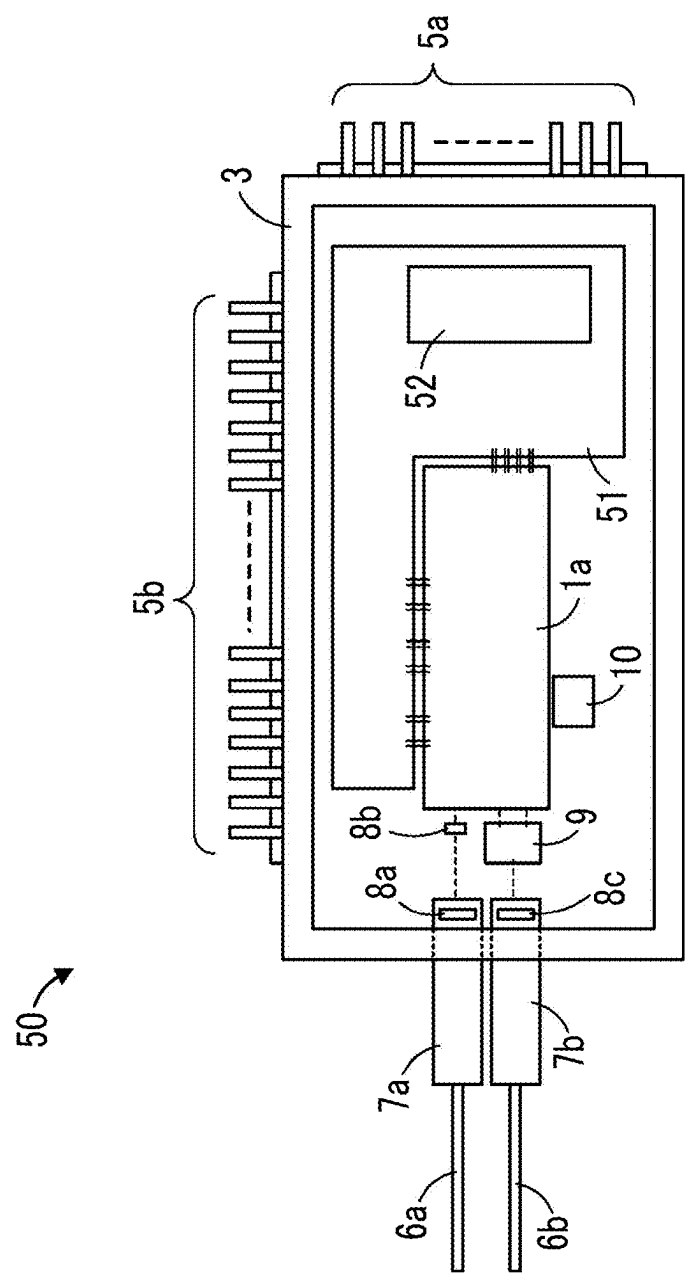


FIG. 11

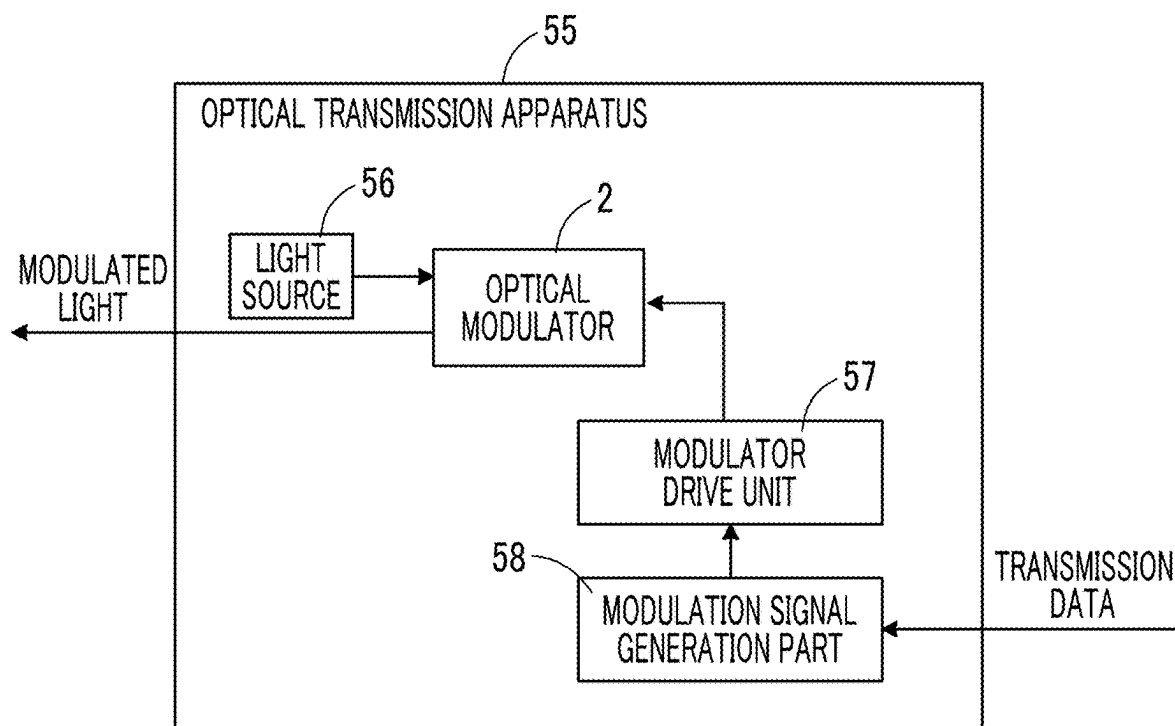


FIG. 12

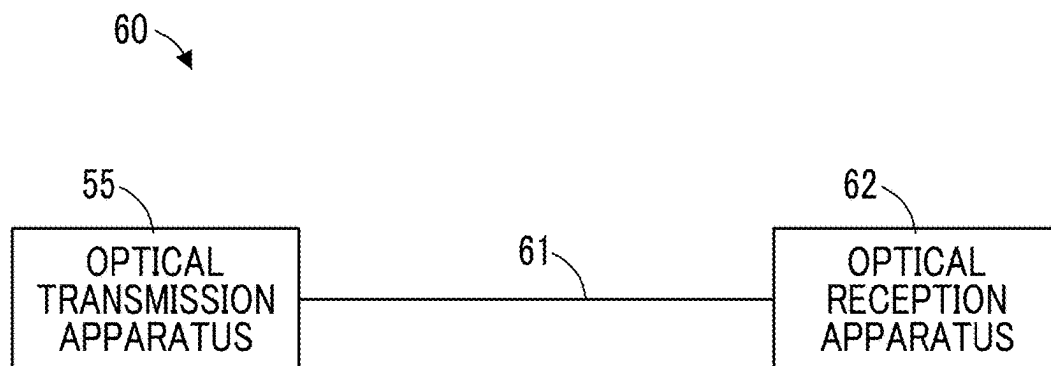


FIG. 13

[PRIOR ART]

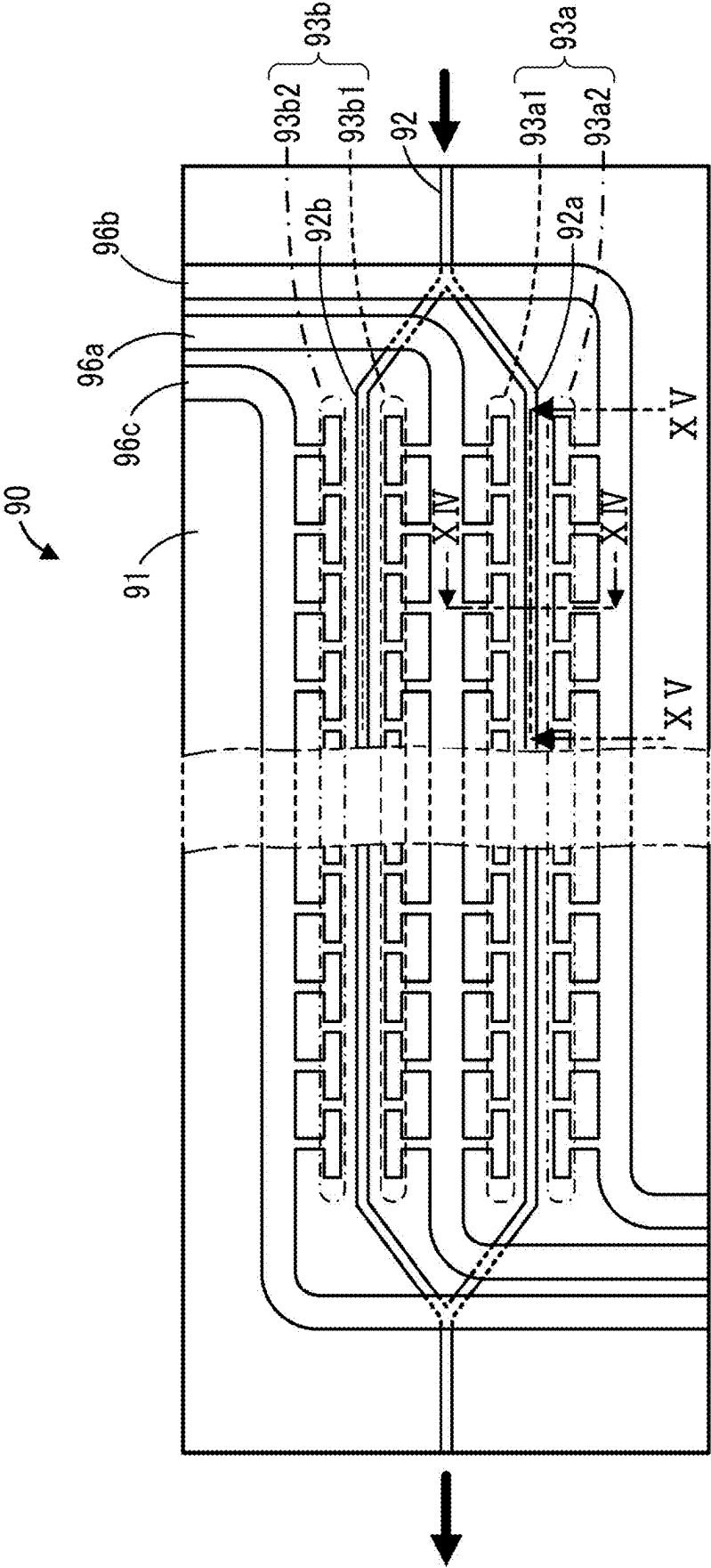


FIG. 14

[PRIOR ART]

CROSS-SECTIONAL VIEW TAKEN ALONG LINE XIV-XIV

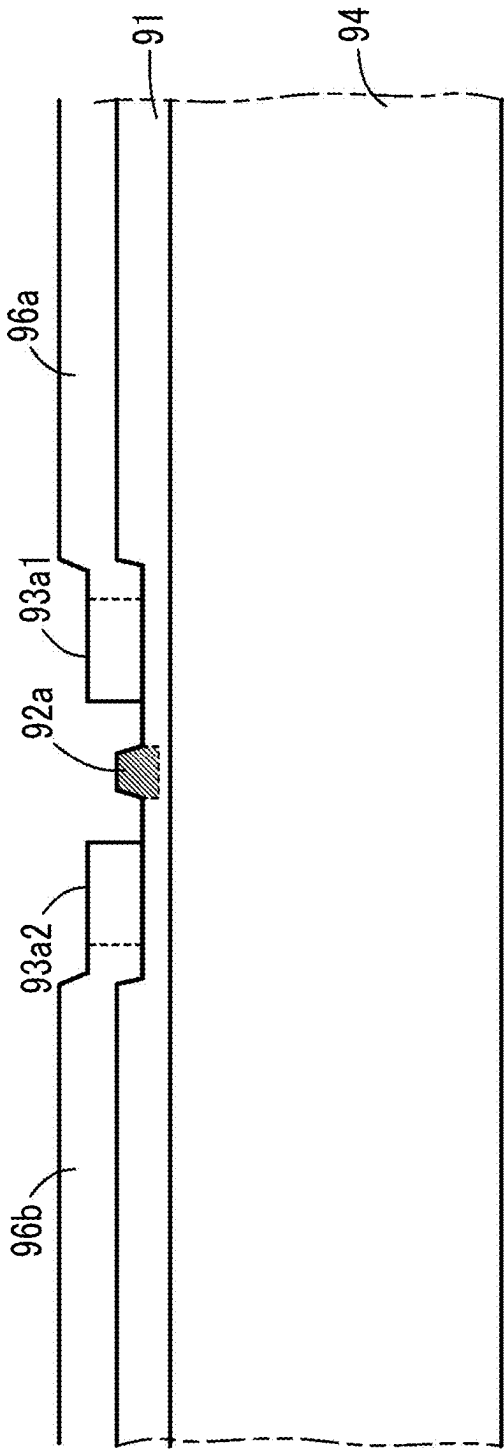
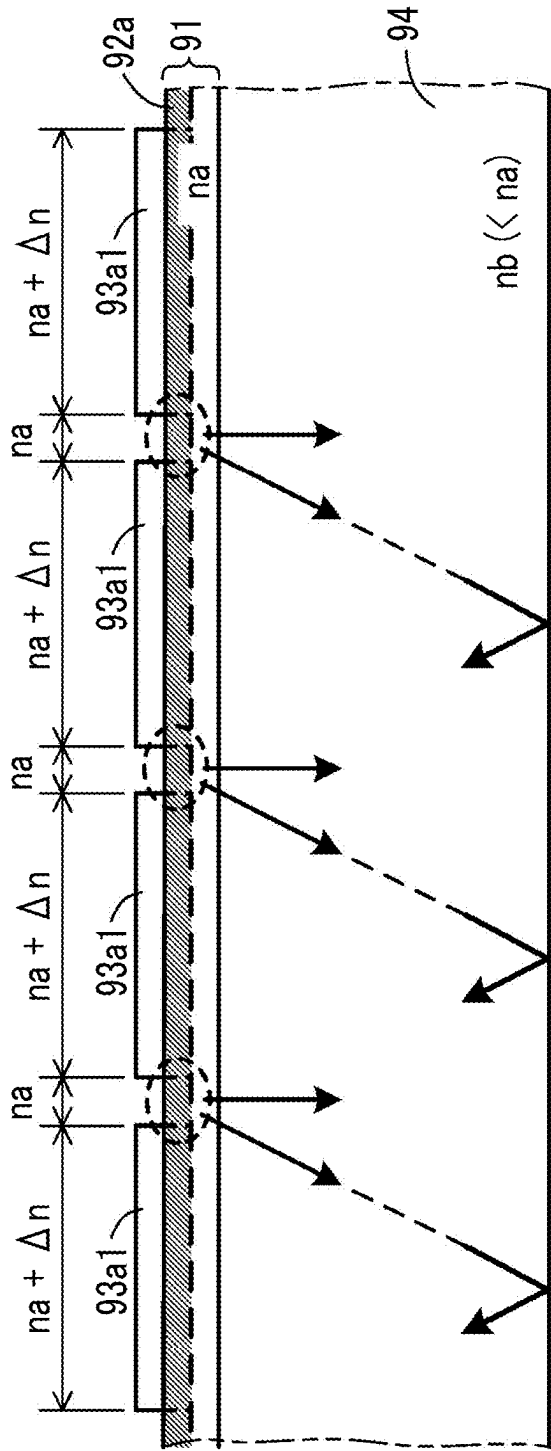


FIG. 15

[PRIOR ART]

CROSS-SECTIONAL VIEW TAKEN ALONG LINE X V - X V



**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. 2024-022427 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 LiNbO₃ (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 layer on which an optical waveguide is formed 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, a first support layer in contact with a lower surface of the optical waveguide layer, and a second support layer in contact with a lower surface of the first support layer, and a refractive index n₀ of the optical waveguide layer, a refractive index n₁ of the first support layer, and a refractive index n₂ of the second support layer have a relationship of n₀>n₁ and n₂>n₁.

[0009] According to another aspect of the present invention, with respect to a wavelength λ of the light wave propagating through the optical waveguide and the refractive index n₁ of the first support layer, the clearance L may have a relationship of $L > 4 \times \lambda / n_1$.

[0010] According to another aspect of the present invention, with respect to a wavelength λ of the light wave propagating through the optical waveguide and the refractive index n₁ of the first support layer, a thickness t₁ of the first support layer may have a relationship of $t_1 < 10 \times \lambda / n_1$.

[0011] According to another aspect of the present invention, the multilayer portion of the substrate may further include a third support layer in contact with a lower surface of the second support layer, and the refractive index n₀ of the optical waveguide layer, the refractive index n₁ of the first support layer, the refractive index n₂ of the second support layer, and a refractive index n₃ of the third support layer may have a relationship of n₀>n₁ and n₃>n₂>n₁.

[0012] 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.

[0013] According to another aspect of the present invention, the light absorbing material may be a carbon material, a black resin, or a metal filler.

[0014] 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 of any number among the optical waveguide layer and a plurality of support layers including the first support layer and the second support layer.

[0015] 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.

[0016] 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.

[0017] 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.

[0018] 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.

[0019] 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

[0020] 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.

[0021] FIG. 2 is a plan view of the optical modulation device according to the first embodiment.

[0022] FIG. 3 is a side view of the optical modulation device illustrated in FIG. 2.

[0023] FIG. 4 is a diagram illustrating a configuration of a modulation portion of the optical modulation device illustrated in FIG. 2.

[0024] FIG. 5 is a cross-sectional view taken along line V-V of the modulation portion illustrated in FIG. 4.

[0025] FIG. 6 is a side view of an optical modulation device according to a second embodiment.

[0026] FIG. 7 is a cross-sectional view of a modulation portion of the optical modulation device according to the second embodiment.

[0027] FIG. 8 is a side view of an optical modulation device according to a third embodiment.

[0028] FIG. 9 is a cross-sectional view of a modulation portion of the optical modulation device according to the third embodiment.

[0029] FIG. 10 is a diagram illustrating a configuration of an optical modulation module according to a fourth embodiment.

[0030] FIG. 11 is a diagram illustrating a configuration of an optical transmission apparatus according to a fifth embodiment.

[0031] FIG. 12 is a diagram illustrating a configuration of an optical transmission system according to a sixth embodiment.

[0032] FIG. 13 is a plan view illustrating an example of an optical modulation device of the prior art.

[0033] 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.

[0034] 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

[0035] 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.

[0036] 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.

[0037] 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 93a and 93b for controlling a light wave propagating through each of two arm waveguides 92a and 92b 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.

[0038] The modulation electrode 93a includes a hot electrode 93a1 and a ground electrode 93a2 that face each other with the arm waveguide 92a interposed therebetween in the principal surface of the optical substrate 91. Similarly, the modulation electrode 93b has a hot electrode 93b1 and a ground electrode 93b2 that face each other with the arm waveguide 92b interposed therebetween in the principal surface of the optical substrate 91.

[0039] Each of the modulation electrodes 93a and 93b is configured as a segmented electrode divided into a plurality of portions along optical propagation directions of the arm waveguides 92a and 92b. Specifically, each of the hot electrode 93a1 and the ground electrode 93a2 constituting the modulation electrode 93a is divided into a plurality of portions (segments) having the same length along the optical propagation direction of the arm waveguide 92a. Each of the hot electrode 93b1 and the ground electrode 93b2 constituting the modulation electrode 93b is also divided into a plurality of segments having the same length along the

optical propagation direction of the arm waveguide **92b**, and gaps between the segments are configured to be arranged at constant clearances.

[0040] Each segment of the hot electrodes **93a1** and **93b1** is electrically connected to each other by a hot transmission channel **96a**. In addition, each segment of the ground electrode **93a2** is electrically connected to each other by a ground transmission channel **96b**, and each segment of the ground electrode **93b2** is electrically connected to each other by a ground transmission channel **96c**. Accordingly, the hot electrodes **93a1** and **93b1** connected to each other by the hot transmission channel **96a**, the ground electrode **93a2** connected to the ground transmission channel **96b**, and the ground electrode **93b2** connected to the ground transmission channel **96c** constitute a coplanar electrode as a whole.

[0041] As illustrated in the cross-sectional view taken along line XV-XV in FIG. 15, in the arm waveguide **92a**, in a case where a high-frequency signal is transmitted to the modulation electrode **93a**, for example, an electric field is applied to the arm waveguide **92a** in a portion in which the segments of the hot electrode **93a1** and the segments of the ground electrode **93a2** face each other. Accordingly, a refractive index changes (for example, increases) by Δn from a refractive index n_a (substrate refractive index n_a) 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 **92a**. Thus, the refractive index remains as the substrate refractive index n_a .

[0042] Each of portions of the unchanging refractive index that are arranged along the arm waveguide **92a** and that occur at positions of the gap portions in which the segments of the modulation electrode **93a** 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 **92a** along the optical propagation direction, and is a factor that causes leaked light beam from the arm waveguide **92a**.

[0043] Leaked light beams generated from each of the portions of the unchanging refractive index arranged along the arm waveguide **92a** leak to the support substrate **94** having a refractive index n_b 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.

[0044] Particularly, each segmented electrode as the modulation electrode **93a** 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 **92a**, 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**.

[0045] The above phenomenon also occurs in the arm waveguide **92b** in which the modulation electrode **93b** is formed, and leaked light beams from the arm waveguide **92b** 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**.

[0046] 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 **92a** and **92b** 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.

[0047] 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.

[0048] Hereinafter, embodiments of the present invention will be described with reference to the drawings.

1. First Embodiment

[0049] 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 **1a** according to the first embodiment of the present invention. The optical modulator **2** includes the optical modulation device **1a** and a relay substrate **4** in a case **3**. For example, the optical modulation device **1a** 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**.

[0050] The optical modulator **2** also includes a signal pin **5a** for inputting a high-frequency electrical signal used for modulation of the optical modulation device **1a**, and a signal pin **5b** for inputting an electrical signal used for adjustment or the like of an operating point of the optical modulation device **1a**.

[0051] The optical modulator **2** further includes an input optical fiber **6a** for inputting light into the case **3** and an output optical fiber **6b** for guiding light modulated by the optical modulation device **1a** to an outside of the case **3**, on the same surface of the case **3**.

[0052] The input optical fiber **6a** and the output optical fiber **6b** are fixed to the case **3** through supports **7a** and **7b**, respectively, which are fixing members. The light input from the input optical fiber **6a** is collimated by a lens **8a** disposed in the support **7a** and is then input into the optical modulation device **1a** through a lens **8b**. However, this is only an example, and light may be input into the optical modulation device **1a** by, for example, introducing the input optical fiber **6a** into the case **3** through the support **7a** and connecting an end surface of the introduced input optical fiber **6a** to an end surface of a substrate **20a** (described later) of the optical modulation device **1a**, in accordance with the prior art.

[0053] The optical modulator **2** also includes an optical unit **9** that polarizes and combines two modulated light beams output from the optical modulation device **1a**. The light beam output from the optical unit **9** after being polarized and combined is condensed by a lens **8c** disposed in the support **7b** and is coupled to the output optical fiber **6b**.

[0054] The relay substrate 4 relays the high-frequency electrical signal input from the signal pin 5a and the electrical signal for adjustment or the like of the operating point input from the signal pin 5b to the optical modulation device 1a 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 1a by wire bonding. The optical modulator 2 also includes a terminator 10 having predetermined impedance in the case 3.

[0055] FIG. 2 is a plan view illustrating an example of a configuration of the optical modulation device 1a. The optical modulation device 1a includes the substrate 20a configured with multiple layers. For example, the substrate 20a is rectangular in plan view and has two sides 21a and 21b 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 21c and 21d 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.

[0056] FIG. 3 is a side view of the optical modulation device 1a illustrated in FIG. 2 from the side 21a. The substrate 20a includes an optical waveguide layer 22 and a support layer 23a. In the present embodiment, the support layer 23a includes a first support layer 23a1 and a second support layer 23a2. In the present embodiment, for example, the substrate 20a is formed by laminating a plurality of plate bodies. Specifically, the substrate 20a is configured by laminating an optical substrate 24 and a support substrate 25a. The optical substrate 24 includes the optical waveguide layer 22, and the support substrate 25a includes the support layer 23a formed with the first support layer 23a1 and the second support layer 23a2. 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 25a is a glass substrate including the first support layer 23a1 and the second support layer 23a2 that are configured with different substances or compositions of glass.

[0057] The substrate 20a is not necessarily configured with a plurality of plate bodies as described above. The substrate 20a may be configured with a film body formed to have a layer shape on an appropriate substrate. For example, the substrate 20a can be a substrate including the first support layer 23a1 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 23a2.

[0058] The optical modulation device 1a 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 20a. 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.

[0059] 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 6a on an upper side of the illustration of the side 21a

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 29a and 29b as two modulation portions for modulating each light beam caused to branch by the branched waveguide 28.

[0060] The nested Mach-Zehnder type optical waveguides 29a and 29b 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 21a of the optical waveguide layer 22 via output waveguides 31a and 31b.

[0061] The nested Mach-Zehnder type optical waveguides 29a and 29b include two Mach-Zehnder type optical waveguides 32a and 32b, and two Mach-Zehnder type optical waveguides 32c and 32d, respectively, provided in two waveguide portions forming a pair of arm waveguides. Hereinafter, the Mach-Zehnder type optical waveguides 32a, 32b, 32c, and 32d will be collectively referred to as Mach-Zehnder type optical waveguides 32. Each Mach-Zehnder type optical waveguide 32 includes two arm waveguides.

[0062] A bias electrode 33a for adjusting operating points of the nested Mach-Zehnder type optical waveguides 29a and 29b 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 32a, 32b and the Mach-Zehnder type optical waveguides 32c and 32d are also provided with bias electrodes 33b and 33c, respectively, for adjusting their operating points.

[0063] Modulation electrodes for causing each of the four Mach-Zehnder type optical waveguides 32a, 32b, 32c, and 32d to perform a modulation operation are also formed in modulation portions 34a, 34b, 34c, and 34d illustrated in a lower portion of the illustration of the nested Mach-Zehnder type optical waveguides 29a and 29b folded in the folded region 30. Hereinafter, the modulation portions 34a, 34b, 34c, and 34d will be collectively referred to as modulation portions 34.

[0064] 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.

[0065] 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 34a, 34b, 34c, and 34d. 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.

[0066] For example, FIG. 4 illustrates a configuration of the modulation electrode in the modulation portion 34a. The modulation electrodes of the other modulation portions 34b, 34c, and 34d are also configured as in FIG. 4.

[0067] In FIG. 4, modulation electrodes **40a** and **40b** control light waves propagating through arm waveguides **36a1** and **36a2** of the Mach-Zehnder type optical waveguide **32a**, respectively.

[0068] The modulation electrode **40a** includes a hot electrode **40a1** and a ground electrode **40a2** facing each other with one arm waveguide **36a1** interposed therebetween in a surface of the optical waveguide layer **22**. Similarly, the modulation electrode **40b** includes a hot electrode **40b1** and a ground electrode **40b2** facing each other with the other arm waveguide **36a2** interposed therebetween in the surface of the optical waveguide layer **22**.

[0069] The modulation electrodes **40a** and **40b** are configured as segmented electrodes divided into a plurality of portions along optical propagation directions of the arm waveguides **36a1** and **36a2**, respectively. Specifically, each of the hot electrode **40a1** and the ground electrode **40a2** constituting the modulation electrode **40a** is divided into a plurality of portions (segments) having the same length along the optical propagation direction of the arm waveguide **36a1**, and gaps between the segments are arranged at constant clearances. Each of the hot electrode **40b1** and the ground electrode **40b2** constituting the modulation electrode **40b** is also divided into a plurality of segments having the same length along the optical propagation direction of the arm waveguide **36a2**, and gaps between the segments are arranged at constant clearances. For example, the number of segments of each of the hot electrodes **40a1** and **40b1** and the ground electrodes **40a2** and **40b2** 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 **1a**.

[0070] Each segment of the hot electrodes **40a1** and **40b1** is electrically connected to each other by a hot transmission channel **41a**. In addition, each segment of the ground electrode **40a2** is electrically connected to each other by a ground transmission channel **41b**, and each segment of the ground electrode **40b2** is electrically connected to each other by a ground transmission channel **41c**. Accordingly, the hot electrodes **40a1** and **40b1** connected to each other by the hot transmission channel **41a**, the ground electrode **40a2** connected to the ground transmission channel **41b**, and the ground electrode **40b2** connected to the ground transmission channel **41c** constitute a coplanar electrode as a whole.

[0071] FIG. 5 is a cross-sectional view taken along line V-V along the arm waveguide **36a1** in the modulation portion **34a** illustrated in FIG. 4. In FIG. 5, lower part (B) illustrates a configuration of the optical modulation device **1a** in a V-V cross section, and upper part (A) is a graph illustrating a change in a refractive index of the arm waveguide **36a1** along the optical propagation direction in the V-V cross section.

[0072] As illustrated in (A) of FIG. 5, in the arm waveguide **36a1**, as in the arm waveguide **92a** 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 **40a**, an electric field is applied to the arm waveguide **36a1** in a portion in which the segments of the hot electrode **40a1** and the segments of the ground electrode **40a2** face each other. Accordingly, the refractive index changes (for example, increases) by Δn from a refractive index n_0 (substrate refractive index n_0) 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 **36a1**. Thus, the refractive index remains as the substrate refractive index n_0 .

[0073] Each of portions of the unchanging refractive index (that is, portions in which the refractive index does not change from the substrate refractive index n_0) that occur at positions of the gap portions in which the segments of the modulation electrode **40a** do not face each other in the arm waveguide **36a1** has disturbance in a change in the refractive index of the arm waveguide **36a1** 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 **36a1** formed on the optical waveguide layer **22**, as in the optical modulation device **90** according to the prior art.

[0074] However, in order not to cause the leaked light beams to interfere with each other, in the present embodiment, particularly, the support layer **23a** included in the substrate **20a** is configured with two layers including the first support layer **23a1** and the second support layer **23a2** that have different refractive indices. The refractive index n_0 of the optical waveguide layer **22** on which the optical waveguide **26** is formed, a refractive index n_1 of the first support layer **23a1**, and a refractive index n_2 of the second support layer **23a2** have the following relationship in Expression (1).

$$n_0 > n_1 \text{ and } n_2 > n_1 \quad (1)$$

[0075] Accordingly, the leaked light beams generated from the arm waveguide **36a1** formed on the optical waveguide layer **22** is input into the first support layer **23a1** having the refractive index n_1 lower than the refractive index n_0 of the optical waveguide layer **22** and is then input into the second support layer **23a2** having the refractive index n_2 higher than that of the first support layer **23a1**.

[0076] A refraction angle θ_2 of the leaked light beam in passing through a boundary surface between the first support layer **23a1** and the second support layer **23a2** is $n_1/n_2 (<1)$ times smaller than an input angle θ_1 . Accordingly, a spread angle of each leaked light beam input into the second support layer **23a2** is decreased below the spread angle of the leaked light beam in the first support layer **23a1**. Thus, overlapping between the leaked light beams in the second support layer **23a2** is suppressed, and occurrence of the interference between the leaked light beams is suppressed.

[0077] The modulation electrode **40b** of the arm waveguide **36a2** 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 **40a** of the arm waveguide **36a1**. Even for the leaked light beams generated in these arm waveguides, the overlapping between the leaked light beams is suppressed in the second support layer **23a2**, and the occurrence of the interference between the leaked light beams is suppressed, as described above.

[0078] Hereinafter, the arm waveguides of each Mach-Zehnder type optical waveguide **32** including the arm waveguides **36a1** and **36a2** of the Mach-Zehnder type optical waveguide **32a** 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 **40a** and **40b** provided in the arm waveguides **36a1** and **36a2** in the modulation portion **34a** will be collectively referred to as modulation electrodes **40**.

[0079] The above action suppresses the intensification caused by the interference between the leaked light beams generated from each arm waveguide **36** formed on the optical waveguide layer **22** while the leaked light beams propagate through the second support layer **23a2**. 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 **1a** is suppressed to be low compared to that in the optical modulation device **90** of the prior art.

[0080] In order to effectively suppress the interference between the leaked light beams generated in the arm waveguides **36** of the Mach-Zehnder type optical waveguides **32** formed on the optical waveguide layer **22** using the above action, it may be important to suppress the interference between the leaked light beams in the first support layer **23a1** before the leaked light beams reach the second support layer **23a2**. Specifically, the interference between the leaked light beams in the first support layer **23a1** 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 **23a1**. 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**.

[0081] More specifically, in order to suppress the interference between the leaked light beams in the first support layer **23a1**, the clearance **L** between the gaps of the segments constituting the modulation electrodes **40** preferably satisfies Expression (2) illustrated below and more preferably satisfies Expression (3) with respect to a wavelength λ of the light wave propagating through the optical waveguide **26** and the refractive index $n1$ of the first support layer **23a1**.

$$L > 4 \times \lambda / n1 \quad (2)$$

$$L > 10 \times \lambda / n1 \quad (3)$$

[0082] In order to suppress the interference between the leaked light beams in the first support layer **23a1**, the thickness **t1** of the first support layer **23a1** preferably satisfies Expression (4) illustrated below and more preferably satisfies Expression (5).

$$t1 < 10 \times \lambda / n1 \quad (4)$$

$$t1 < 4 \times \lambda / n1 \quad (5)$$

[0083] 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 λ . For example, the first support layer **23a1** 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 **23a2** is formed of alkali-free glass, has a thickness **t2** of 300 μm , and has the 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 **23a2**.

[0084] While the whole substrate **20a** is configured with multiple layers in the present embodiment, the whole substrate **20a** 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 **20a** 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.

[0085] That is, the substrate **20a** 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 **23a1** in contact with a lower surface of the optical waveguide layer **22**, and the second support layer **23a2** in contact with a lower surface of the first support layer **23a1**.

[0086] 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

[0087] Next, an optical modulation device **1b** according to a second embodiment of the present invention will be described. The optical modulation device **1b** has the same configuration as the optical modulation device **1a** except for including a substrate **20b** instead of the substrate **20a**. The optical modulation device **1b** may be used by mounting the optical modulation device **1b** on the optical modulator **2** instead of the optical modulation device **1a**.

[0088] A plan view of the optical modulation device **1b** is the same as the plan view of the optical modulation device **1a** illustrated in FIGS. 2 and 4. Thus, FIGS. 2 and 4 and the description for FIGS. 2 and 4 are incorporated herein.

[0089] FIG. 6 is a side view of the optical modulation device **1b** seen from the side **21a** and is a diagram corresponding to FIG. 3 for the optical modulation device **1a** according to the first embodiment. FIG. 7 is a cross-sectional view taken along the arm waveguide **36a1** in the modulation portion **34a** of the optical modulation device **1b** and is a

diagram corresponding to FIG. 5 for the optical modulation device **1a** according to the first embodiment.

[0090] 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.

[0091] With reference to FIGS. 6 and 7, the substrate **20b** constituting the optical modulation device **1b** has the same configuration as the substrate **20a** except for including a support layer **23b** instead of the support layer **23a**. The support layer **23b** has the same configuration as the support layer **23a** except for including a third support layer **23a3** in contact with a lower surface of the second support layer **23a2** in addition to the first support layer **23a1** and the second support layer **23a2**. For example, the substrate **20b** is configured by laminating a lower surface of the optical substrate **24** with a support substrate **25b** including the first support layer **23a1**, the second support layer **23a2**, and the third support layer **23a3**, instead of the support substrate **25a**.

[0092] The substrate **20b** is not necessarily configured with a plurality of plate bodies, like the substrate **20a**. The substrate **20b** may be configured with a film body formed to have a layer shape on an appropriate substrate. For example, the substrate **20b** can be a substrate including the second support layer **23a2**, the first support layer **23a1**, 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 **23a3**.

[0093] In FIG. 7, lower part (B) illustrates a configuration of the optical modulation device **1b** in a cross section along the arm waveguide **36a1**, and upper part (A) is a graph illustrating a change in a refractive index of the arm waveguide **36a1** along the optical propagation direction in the cross section, as in FIG. 5.

[0094] In the optical modulation device **1b**, the support layer **23b** included in the substrate **20b** is configured with three layers including the first support layer **23a1**, the second support layer **23a2**, and the third support layer **23a3** that have different refractive indices. The refractive index n_0 of the optical waveguide layer **22** on which the optical waveguide **26** is formed, the refractive index n_1 of the first support layer **23a1**, the refractive index n_2 of the second support layer **23a2**, and a refractive index n_3 of the third support layer **23a3** have the following relationship in Expression (6).

$$n_0 > n_1, n_2 > n_1, \text{ and } n_3 > n_2 > n_1 \quad (6)$$

[0095] Accordingly, the leaked light beams generated from the arm waveguide **36a1** formed on the optical waveguide layer **22** are refracted in a direction in which spread of the leaked light beams is narrowed, twice in passing through the boundary surface between the first support layer **23a1** and the second support layer **23a2** and passing through a boundary surface between the second support layer **23a2** and the third support layer **23a3**. Accordingly, the spread angle of each leaked light beam input into the third support layer **23a3** is further decreased below the spread angle in the second support layer **23a2** of the optical modulation device

1a according to the first embodiment. Thus, the overlapping between the leaked light beams is further suppressed, and the occurrence of the interference between the leaked light beams is more effectively suppressed.

[0096] The above action also occurs in the arm waveguide **36a2** and each arm waveguide **36** of the Mach-Zehnder type optical waveguides **32** in the other modulation portions **34**.

[0097] Compared to the action in the optical modulation device **1a** according to the first embodiment, the above action further suppresses an increase in the intensity of the leaked light beams caused by the interference between the leaked light beams generated from the arm waveguides **36** formed on the optical waveguide layer **22** while the leaked light beams propagate through the third support layer **23a3**. 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**, the effect of the leaked light beams on the optical characteristics of the optical modulation device **1b** is suppressed to be further low compared to that in the optical modulation device **90** of the prior art.

[0098] For the optical modulation device **1b**, preferable conditions related to the clearance L between the gaps between the segments constituting the modulation electrodes **40** along the corresponding arm waveguide **36** and the thickness t_1 of the first support layer **23a1** are the same as illustrated in Expressions (2) to (5).

[0099] In the present embodiment, for example, the wavelength λ of the light wave propagating through the optical waveguide **26** is $1.55 \mu\text{m}$, and the clearance L between the gaps of the segments constituting the modulation electrodes **40** is $50 \mu\text{m}$. For example, the optical waveguide layer **22** has the thickness t_0 of $1 \mu\text{m}$ in the optical waveguide **26** and has the refractive index n_0 of 2.2 in the wavelength λ . For example, the first support layer **23a1** is formed of SiO_2 , has the thickness t_1 of $3 \mu\text{m}$, and has the refractive index n_1 of 1.48 in the wavelength λ . For example, the second support layer **23a2** is formed of alkali-free glass, has the thickness t_2 of $200 \mu\text{m}$, and has the refractive index n_2 of 1.56 in the wavelength λ . The third support layer **23a3** is formed of Si, has a thickness t_3 of $300 \mu\text{m}$, and has the refractive index n_3 of 3.5 in the wavelength λ .

[0100] Even in the present embodiment, the action and the effect of suppressing the interference between the leaked light beams as in the substrate **20a** of the first embodiment can be achieved in a case where the substrate **20b** 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.

[0101] That is, the substrate **20b** 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 **23a1** in contact with the lower surface of the optical waveguide layer **22**, the second support layer **23a2** in contact with the lower surface of the first support layer **23a1**, and the third support layer **23a3** in contact with the lower surface of the second support layer **23a2**.

3. Third Embodiment

[0102] Next, an optical modulation device **1c** according to a third embodiment of the present invention will be described. The optical modulation device **1c** has the same configuration as the optical modulation device **1a** 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 **20a** facing the surface of the optical waveguide layer **22**. The optical modulation device **1c** may be used by mounting the optical modulation device **1c** on the optical modulator **2** instead of the optical modulation device **1a**.

[0103] A plan view of the optical modulation device **1c** is the same as the plan view of the optical modulation device **1a** illustrated in FIGS. **2** and **4**. Thus, FIGS. **2** and **4** and the description for FIGS. **2** and **4** are incorporated herein.

[0104] FIG. **8** is a side view of the optical modulation device **1c** seen from the side **21a** and is a diagram corresponding to FIG. **3** for the optical modulation device **1a** according to the first embodiment. FIG. **9** is a cross-sectional view taken along the arm waveguide **36a1** in the modulation portion **34a** of the optical modulation device **1c** and is a diagram corresponding to FIG. **5** for the optical modulation device **1a** according to the first embodiment. The graph of the refractive index in the arm waveguide **36a1** in FIG. **9** is the same as that in FIG. **5** and thus, will not be described.

[0105] 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.

[0106] With reference to FIGS. **8** and **9**, in the optical modulation device **1c**, a light absorbing material **43** 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 **20a** facing the surface of the optical waveguide layer **22**. Accordingly, in the optical modulation device **1c**, the leaked light beams generated from the arm waveguides **36** of the optical waveguide layer **22** are absorbed by the light absorbing material **43** to be attenuated in a case where the leaked light beams propagate through the second support layer **23a2** and reach the back surface **42**. Consequently, in the optical modulation device **1c**, 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 **1c** is further effectively suppressed compared to that in the optical modulation device **90** of the prior art.

[0107] For example, the light absorbing material **43** 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 **43** may be applied to the back surface **42** of the substrate **20a** and cured to be disposed on the back surface **42** using an appropriate resin as a binder.

[0108] While the light absorbing material **43** is disposed on the whole surface of the back surface **42** of the substrate **20a** in the present embodiment, the light absorbing material **43** 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 **43** 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.

[0109] In mounting the optical modulation device **1c** on the case **3**, the optical modulation device **1c** 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 **43** disposed on the back surface **42** of the substrate **20a** and a surface of the back surface **42** on which the light absorbing material **43** is not applied.

4. Fourth Embodiment

[0110] Next, a fourth embodiment of the present invention will be described. In the present embodiment, the optical modulation device **1a** 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.

[0111] 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 **1a** based on a modulation signal supplied from the outside through the signal pin **5a** and outputs the generated high-frequency electrical signal to the optical modulation device **1a**.

[0112] Since the optical modulation module **50** having the above configuration includes the optical modulation device **1a** 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 **1a**, like the optical modulator **2**.

[0113] While the optical modulation module **50** includes, for example, the optical modulation device **1a** in the present embodiment, the optical modulation module **50** may include the optical modulation device **1b** according to the second embodiment or the optical modulation device **1c** according to the third embodiment.

5. Fifth Embodiment

[0114] 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 **1b** or the optical modulation device **1c** instead of the optical modulation device **1a**.

[0115] 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.

[0116] 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 1a included in the optical modulator 2.

[0117] These high-frequency electrical signals are input into the signal pin 5a of the optical modulator 2 to drive the optical modulation device 1a. Accordingly, for example, the light output from the light source 56 is subjected to DPQPSK modulation by the optical modulator 2 and is output from the optical transmission apparatus 55 as modulated light.

[0118] In the optical transmission apparatus 55, since the optical modulator 2 or the optical modulation module 50 including the optical modulation device 1a, 1b, or 1c is used, favorable optical transmission can be performed by implementing favorable modulation characteristics.

6. Sixth Embodiment

[0119] 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 1a, 1b, or 1c. Thus, the optical transmission system 60 has favorable optical transmission performance.

7. Other Embodiments

[0120] 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.

[0121] In the embodiments, the substrates 20a and 20b configured with multiple layers are configured by laminating a plurality of plate bodies. However, this is only an example, and the substrates 20a and 20b may be configured with a film body formed to have a layer shape on an appropriate substrate, as described above.

[0122] In the embodiments, the optical substrate 24 as a plate body constituting the optical waveguide layer 22 and the support substrate 25a as a plate body constituting the first support layer 23a1 and the second support layer 23a2 are

laminated in the substrate 20a. However, the optical substrate 24 and the support substrate 25a are examples of plate bodies constituting the substrate 20a, 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 20a or 20b 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 23a1.

[0123] 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

[0124] The embodiments support the following configurations.

[0125] (Configuration 1) An optical modulation device including a substrate including a multilayer portion configured with multiple layers, an optical waveguide layer on which an optical waveguide is formed 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, a first support layer in contact with a lower surface of the optical waveguide layer, and a second support layer in contact with a lower surface of the first support layer, and a refractive index n0 of the optical waveguide layer, a refractive index n1 of the first support layer, and a refractive index n2 of the second support layer have a relationship of $n0 > n1$ and $n2 > n1$.

[0126] 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.

[0127] (Configuration 2) In the optical modulation device according to Configuration 1, with respect to a wavelength λ of the light wave propagating through the optical waveguide and the refractive index n1 of the first support layer, the clearance L has a relationship of $L > 4 \times \lambda / n1$.

[0128] According to the optical modulation device of Configuration 2, more favorable optical characteristics can be implemented by suppressing the intensification caused by the interference between the leaked light beams.

[0129] (Configuration 3) In the optical modulation device according to Configuration 1 or 2, with respect to a wavelength λ of the light wave propagating through the optical waveguide and the refractive index n1 of the first support layer, a thickness t1 of the first support layer has a relationship of $t1 < 10 \times \lambda / n1$.

[0130] According to the optical modulation device of Configuration 3, 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.

[0131] (Configuration 4) In the optical modulation device according to any one of Configurations 1 to 3, the multilayer portion of the substrate further includes a third support layer in contact with a lower surface of the second support layer, and the refractive index n_0 of the optical waveguide layer, the refractive index n_1 of the first support layer, the refractive index n_2 of the second support layer, and a refractive index n_3 of the third support layer have a relationship of $n_0 > n_1$ and $n_3 > n_2 > n_1$.

[0132] According to the optical modulation device of Configuration 4, further favorable optical characteristics can be implemented by further suppressing the intensification caused by the interference between the leaked light beams by configuring a support layer with three layers.

[0133] (Configuration 5) In the optical modulation device according to any one of Configurations 1 to 4, a light absorbing material that absorbs light in a wavelength range of the light wave propagating through the optical waveguide is disposed on a back surface of the substrate facing a surface of the optical waveguide layer.

[0134] According to the optical modulation device of Configuration 5, 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.

[0135] (Configuration 6) In the optical modulation device according to Configuration 5, the light absorbing material is a carbon material, a black resin, or a metal filler.

[0136] According to the optical modulation device of Configuration 6, 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.

[0137] (Configuration 7) In the optical modulation device according to any one of Configurations 1 to 6, the substrate is formed by laminating a plurality of plate bodies, and each plate body includes one layer or a plurality of layers of any number among the optical waveguide layer and a plurality of support layers including the first support layer and the second support layer.

[0138] According to the optical modulation device of Configuration 7, a substrate including a plurality of support layers and an optical waveguide layer in which an optical waveguide is formed can be easily configured.

[0139] (Configuration 8) An optical modulator includes the optical modulation device according to any one of Configurations 1 to 7, 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.

[0140] According to the optical modulator of Configuration 8, since the optical modulation device of any one of Configurations 1 to 7 is used, an optical modulator having favorable optical characteristics may be implemented.

[0141] (Configuration 9) An optical modulation module includes the optical modulation device according to any one

of Configurations 1 to 7, 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.

[0142] According to the optical modulation module of Configuration 9, since the optical modulation device of any one of Configurations 1 to 7 is used, an optical modulation module having favorable optical characteristics may be implemented.

[0143] (Configuration 10) An optical transmission apparatus includes the optical modulator according to Configuration 8 or the optical modulation module according to Configuration 9, and an electronic circuit for generating an electrical signal for causing the optical modulation device to perform a modulation operation.

[0144] According to the optical transmission apparatus of Configuration 10, since the optical modulator or the optical modulation module using the optical modulation device of any one of Configurations 1 to 7 is used, favorable optical transmission characteristics can be implemented.

[0145] (Configuration 11) An optical transmission system includes the optical transmission apparatus according to Configuration 10, and an optical fiber transmission channel through which output light of the optical modulation device is transmitted.

[0146] According to the optical transmission system of Configuration 11, since the optical transmission apparatus using the optical modulation device of any one of Configurations 1 to 7 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 layer on which an optical waveguide is formed 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, a first support layer in contact with a lower surface of the optical waveguide layer, and a second support layer in contact with a lower surface of the first support layer, and

a refractive index n_0 of the optical waveguide layer, a refractive index n_1 of the first support layer, and a refractive index n_2 of the second support layer have a relationship of

$$n_0 > n_1 \text{ and } n_2 > n_1.$$

2. The optical modulation device according to claim 1, wherein, with respect to a wavelength λ of the light wave propagating through the optical waveguide and the

refractive index n_1 of the first support layer, the clearance L has a relationship of

$$L > 4 \times \lambda / n_1.$$

- 3.** The optical modulation device according to claim **1**, wherein, with respect to a wavelength λ of the light wave propagating through the optical waveguide and the refractive index n_1 of the first support layer, a thickness t_1 of the first support layer has a relationship of

$$t_1 < 10 \times \lambda / n_1.$$

- 4.** The optical modulation device according to claim **1**, wherein the multilayer portion of the substrate further includes a third support layer in contact with a lower surface of the second support layer, and the refractive index n_0 of the optical waveguide layer, the refractive index n_1 of the first support layer, the refractive index n_2 of the second support layer, and a refractive index n_3 of the third support layer have a relationship of

$$n_0 > n_1 \text{ and } n_3 > n_2 > n_1.$$

- 5.** 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 a back surface of the substrate facing a surface of the optical waveguide layer.
- 6.** The optical modulation device according to claim **5**, wherein the light absorbing material is a carbon material, a black resin, or a metal filler.
- 7.** 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 of any number among the optical waveguide layer and a plurality of support layers including the first support layer and the second support layer.

- 8.** 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.

- 9.** An optical modulation module comprising:

the optical modulation device according to claim **1**;
a case for accommodating the optical modulation device;
an input optical fiber for inputting light into the optical modulation device;

an output 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.

- 10.** An optical transmission apparatus comprising:

the optical modulator according to claim **8**; and
an electronic circuit for generating an electrical signal for causing the optical modulation device to perform a modulation operation.

- 11.** An optical transmission system comprising:

the optical transmission apparatus according to claim **10**;
and
an optical fiber transmission channel through which output light of the optical modulation device is transmitted.

- 12.** An optical transmission apparatus comprising:
the optical modulation module according to claim **9**; 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.

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