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Utsunomiya et al.

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(54) **OPTICAL MODULATOR AND DRIVING METHOD OF OPTICAL MODULATION ELEMENT**

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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,334,004 B1 12/2001 Ohkuma et al.
8,849,071 B2 * 9/2014 Kissa G02F 1/225 385/50

(Continued)

FOREIGN PATENT DOCUMENTS

JP H09-211400 A 8/1997
JP 2000-180804 A 6/2000

(Continued)

OTHER PUBLICATIONS

Sep. 7, 2021 International Search Report issued in Patent Application No. PCT/JP2021/023145.

(Continued)

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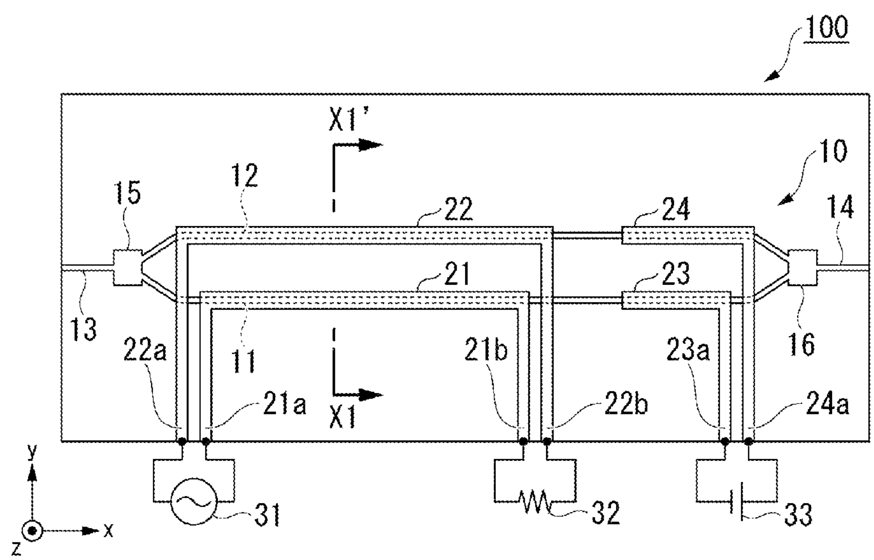
(57) **ABSTRACT**

The optical modulator includes an optical modulation element having a first optical waveguide, a second optical waveguide, a first electrode which applies an electric field to the first optical waveguide, and a second electrode which applies an electric field to the second optical waveguide, and a control unit configured to control an applied voltage between the first electrode and the second electrode. When a half-wave voltage of the optical modulation element is $V\pi$ and a null point voltage of the optical modulation element is Vn, the control unit sets an operating point Vd in a range of $Vn+0.50V\pi \leq Vd \leq Vn+0.75V\pi$ or $Vn-0.75V\pi \leq Vd \leq Vn-0.50V\pi$ and sets an applied voltage width Vpp, which is an amplitude of an applied voltage applied to the optical modulation element, in a range of $0.22V\pi \leq Vpp \leq 0.50V\pi$.

4 Claims, 5 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

10,243,667	B2 *	3/2019	Iwata	H04B 10/50575
12,242,143	B2 *	3/2025	Yoshida	G02F 1/035
12,248,205	B2 *	3/2025	Utsunomiya	G02F 1/0316
2002/0146190	A1 *	10/2002	Doi	G02F 1/2255 385/40
2015/0138619	A1	5/2015	Iwatsuka et al.	
2018/0294888	A1	10/2018	Iwata et al.	
2022/0276513	A1 *	9/2022	Utsunomiya	G02F 1/212
2023/0213791	A1 *	7/2023	Utsunomiya	G02F 1/2255 385/2
2023/0229030	A1 *	7/2023	Utsunomiya	G02F 1/035 385/2

FOREIGN PATENT DOCUMENTS

JP	2004-037695	A	2/2004
JP	4164179	B2	10/2008
JP	2015-102686	A	6/2015
JP	2018-182465	A	11/2018
JP	2019-045880	A	3/2019

OTHER PUBLICATIONS

Translation of Jun. 6, 2023 Office Action issued in Japanese Patent Application No. 2020-135861.

Translation of Jan. 4, 2023 Office Action issued in Japanese Patent Application No. 2020-135861.

* cited by examiner

FIG. 1

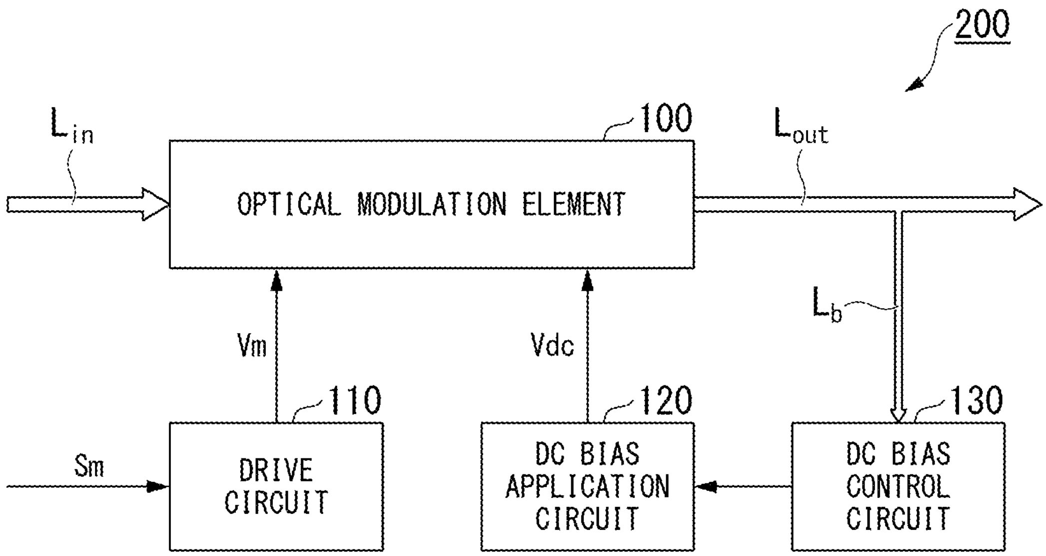

200
L_{in}
100
L_{out}
OPTICAL MODULATION ELEMENT
L_b
Vm
Vdc
110
120
130
Sm
DRIVE CIRCUIT
DC BIAS APPLICATION CIRCUIT
DC BIAS CONTROL CIRCUIT

FIG. 2

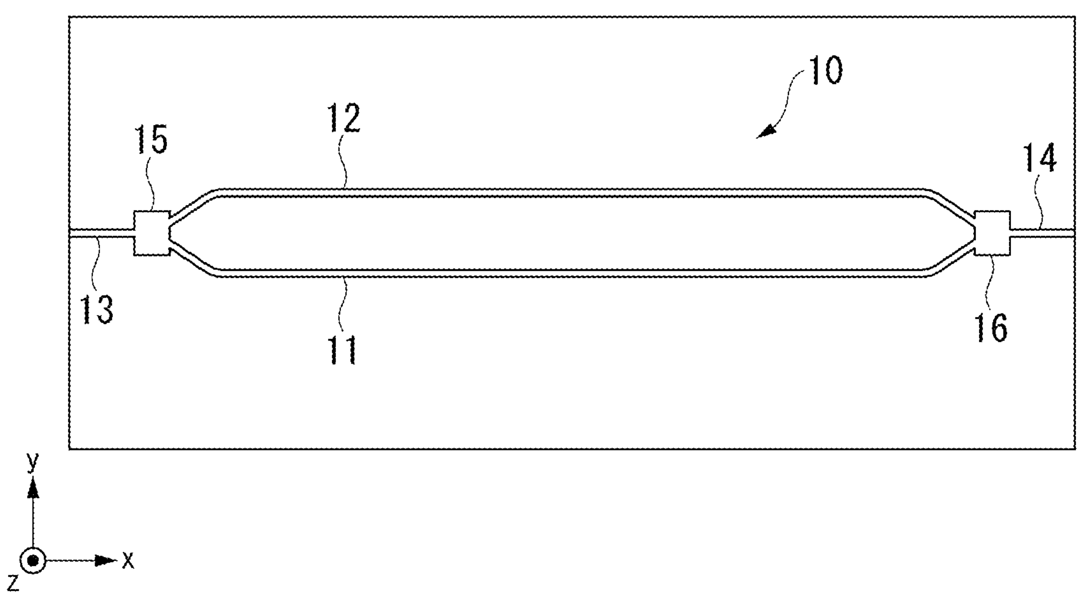

10
12
15
14
13
16
11
y
x
z

FIG. 3

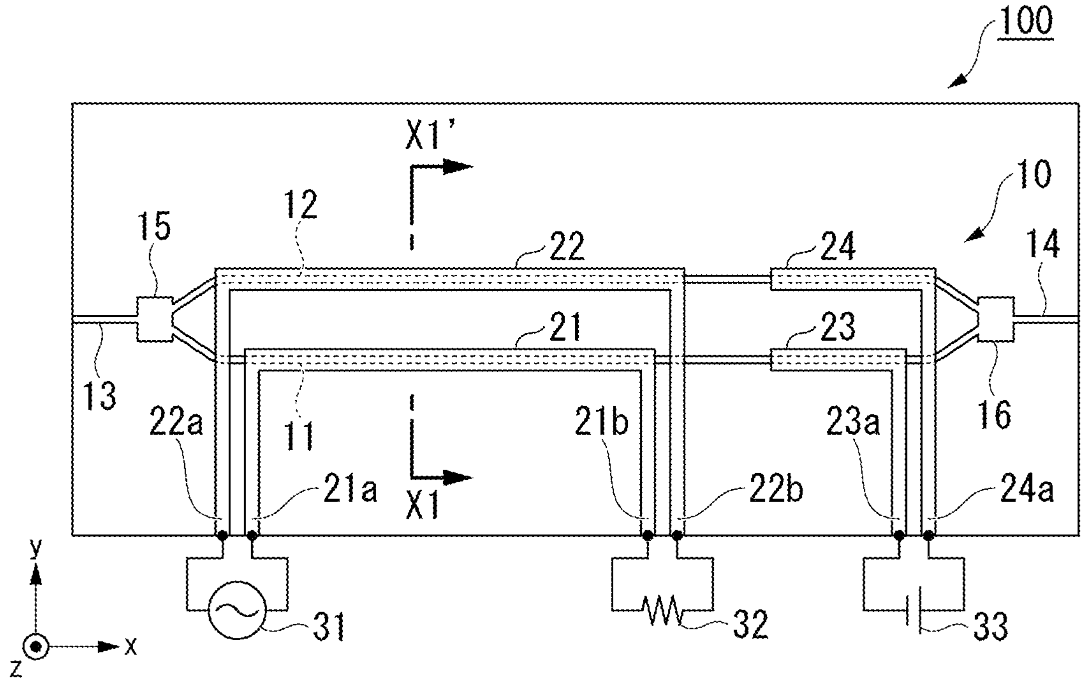

100
X1'
10
15
12
22
24
14
21
23
13
16
22a
11
21b
23a
21a
22b
24a
X1
y
z
x
31
32
33

FIG. 4

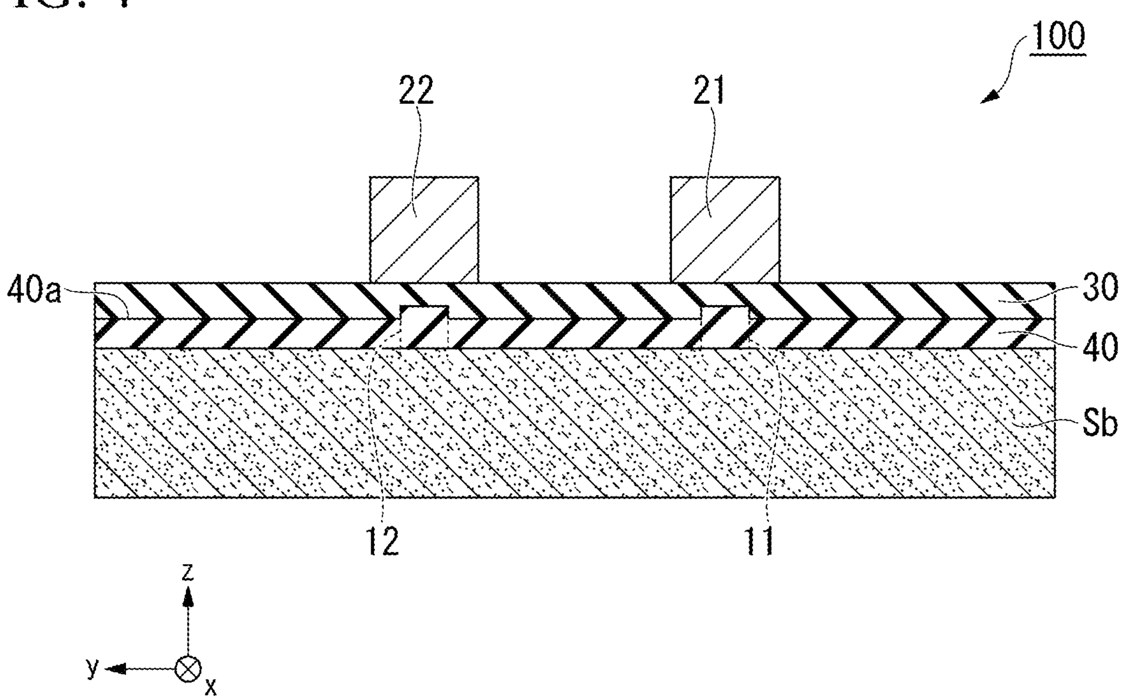

100
22
21
40a
30
40
Sb
12
11
z
y
x

FIG. 5

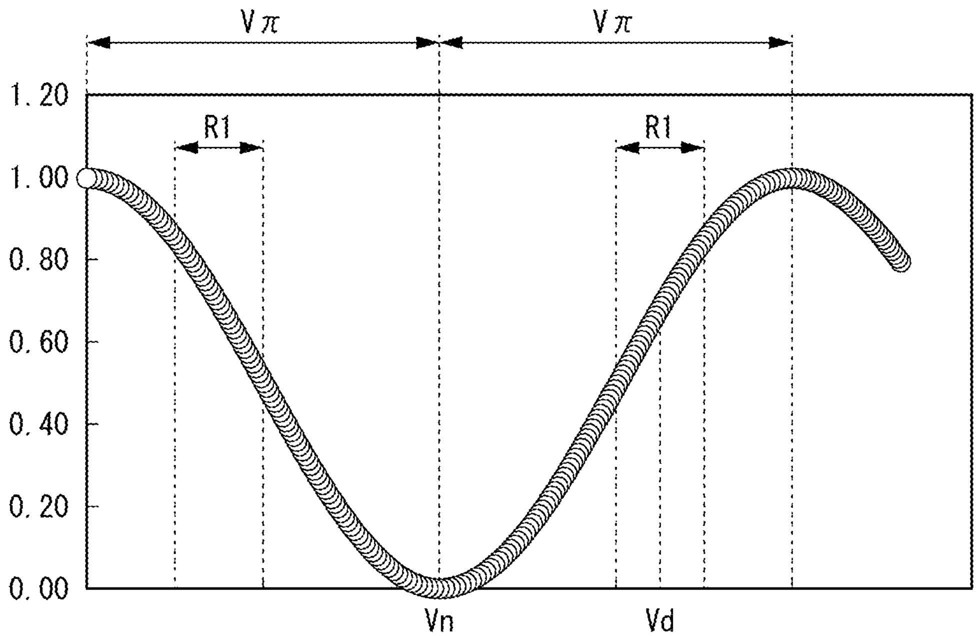

Vπ
Vπ
R1
R1
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Vn
Vd

FIG. 6

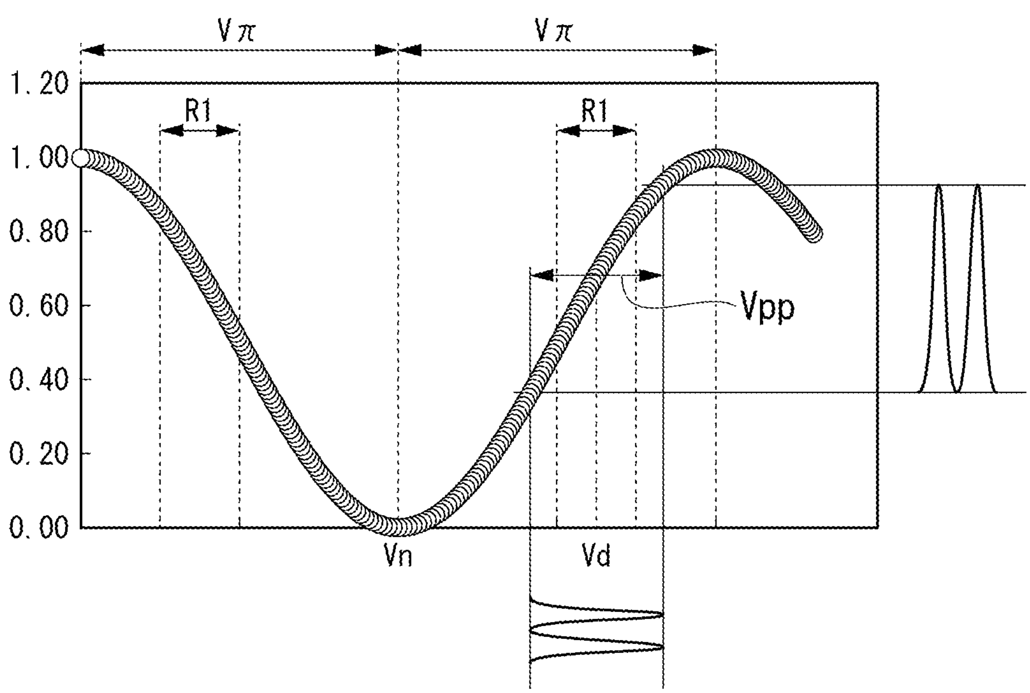

Vπ
Vπ
R1
R1
Vpp
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Vn
Vd

FIG. 7

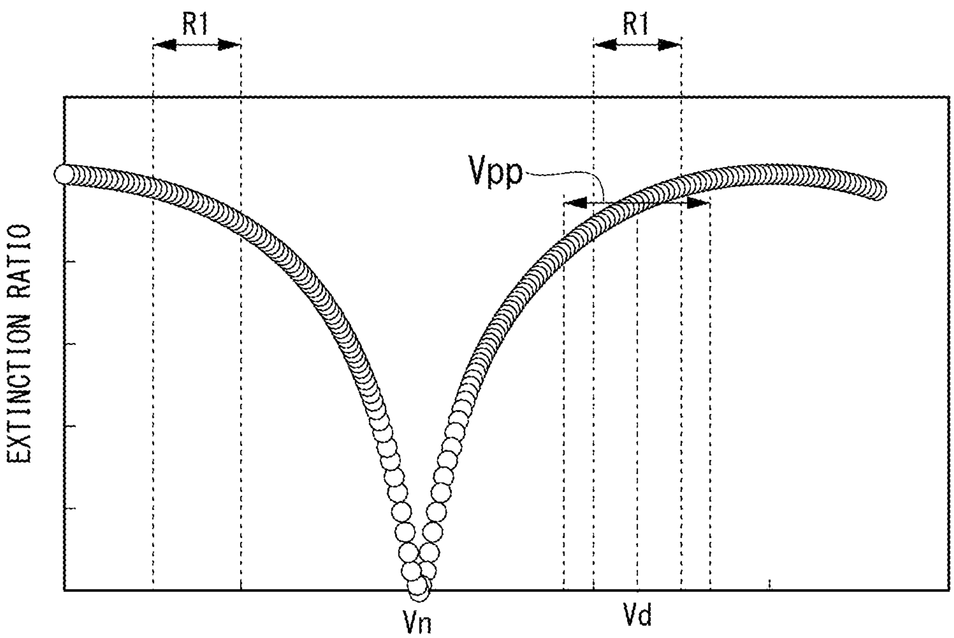
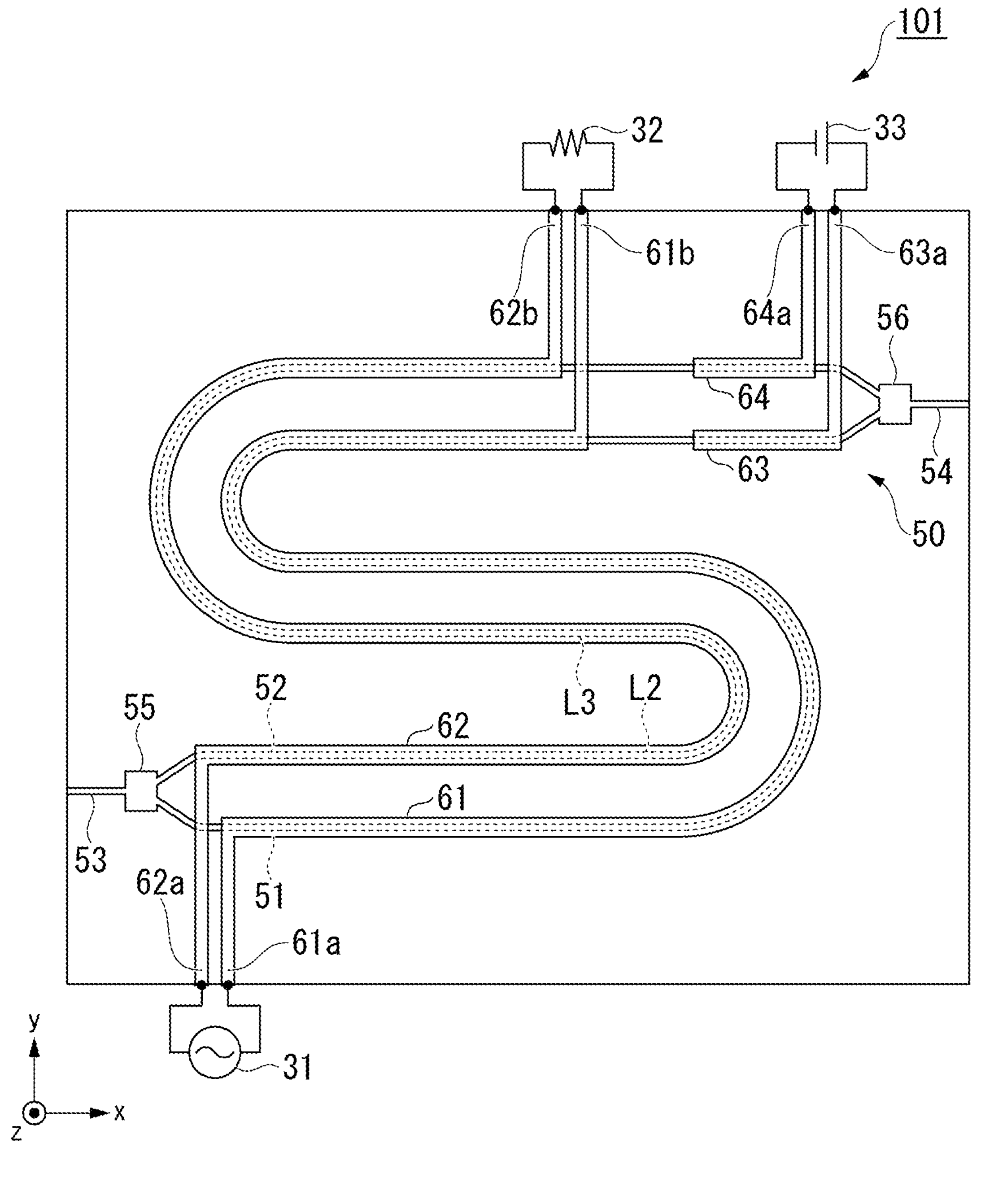


FIG. 8


101
32
33
61b
63a
62b
64a
56
64
63
54
50
52
L3
L2
55
62
61
53
62a
51
61a
31
y
x
z

OPTICAL MODULATOR AND DRIVING METHOD OF OPTICAL MODULATION ELEMENT

TECHNICAL FIELD

The present disclosure relates to an optical modulator and a driving method of an optical modulation element.

Priority is claimed on Japanese Patent Application No. 2020-135861, filed Aug. 11, 2020, the content of which is incorporated herein by reference.

BACKGROUND ART

With spread of the Internet, the amount of communication traffic thereon has increased dramatically, and the importance of optical fiber communication has increased significantly. Optical fiber communication transmits an optical signal by optical fiber by converting an electrical signal into an optical signal, and has features of having a wide band, a low loss, and resistance to noise.

An optical modulator converts an electrical signal into an optical signal. For example, Patent Document 1 and 2 describe a Mach-Zehnder type optical modulator in which an optical waveguide is formed by Ti (titanium) diffusion in the vicinity of a surface of a lithium niobate single crystal substrate. Also, Patent Document 2 describes that a drift of an operating point of the optical modulator is corrected. The optical modulators described in Patent Document 1 and 2 operate at a high speed of 40 Gb/s or more, but have a long total length of about 10 cm.

In contrast, Patent Document 3 describes a Mach-Zehnder type optical modulator using a c-axis-oriented lithium niobate film. The optical modulator using a lithium niobate film is smaller in size and has a lower drive voltage compared to an optical modulator using a lithium niobate single crystal substrate.

CITATION LIST

Patent Document

[Patent Document 1]
Japanese Unexamined Patent Application, First Publication No. 2004-37695
[Patent Document 2]
Japanese Patent No. 4164179
[Patent Document 3]
Japanese Unexamined Patent Application, First Publication No. 2019-45880

SUMMARY OF INVENTION

Technical Problem

Since an optical modulator using lithium niobate have a large extinction ratio and can operate in a high-frequency band, the optical modulator is used for long-distance communication such as between cities. Also, since an optical modulator using indium phosphide (InP) can also operate in a high-frequency band, this optical modulator is expected to be used for long-distance communication. On the other hand, in recent years, short-distance and medium-distance communication within and between data centers also have increased, and in such applications, there are cases in which an optical modulator using silicon is used and cases in which emitted light is directly modulated by a drive circuit of a laser diode without using an optical modulator. Modulation by an optical modulator using silicon or direct modulation cannot support frequencies becoming even higher.

On the other hand, in order to apply an optical modulator that can operate in a high-frequency band, such as an optical modulator using a lithium niobate thin film or an optical modulator using indium phosphide, to communication within or between data centers, a drive voltage is required to be lowered.

The present disclosure has been made in view of the above-described problems and an objective thereof is to provide an optical modulator that can be driven at a low voltage and furthermore has little modulation loss, and a driving method of an optical modulation element that can be driven at a low voltage and in which a modulation loss can be reduced to a low level.

Solution to Problem

(1) An optical modulator according to a first aspect includes an optical modulation element having a first optical waveguide, a second optical waveguide, a first electrode which applies an electric field to the first optical waveguide, and a second electrode which applies an electric field to the second optical waveguide, and a control unit configured to control an applied voltage between the first electrode and the second electrode, in which when a half-wave voltage of the optical modulation element is $V\pi$ and a null point voltage of the optical modulation element is Vn, the control unit sets an operating point Vd in a range of $Vn+0.50V\pi \leq Vd \leq Vn+0.75V\pi$ or $Vn-0.75V\pi \leq Vd \leq Vn-0.50V\pi$ and sets an applied voltage width Vpp, which is an amplitude of an applied voltage applied to the optical modulation element, in a range of $0.22V\pi \leq Vpp \leq 0.50V\pi$.

(2) In the optical modulator according to the above-describe aspect, the first optical waveguide and the second optical waveguide may each include a ridge-shaped portion protruding from a first surface of a lithium niobate film.

(3) A driving method of an optical modulation element according to a second aspect is a driving method of an optical modulation element including a first optical waveguide, a second optical waveguide, a first electrode which is at a position overlapping the first optical waveguide in a plan view, and a second electrode which is at a position overlapping the second optical waveguide in a plan view, the driving method includes setting an operating point Vd in a range of $Vn+0.50V\pi \leq Vd \leq Vn+0.75V\pi$ or $Vn-0.75V\pi \leq Vd \leq Vn-0.50V\pi$, when a half-wave voltage of the optical modulation element is $V\pi$ and a null point voltage of the optical modulation element is Vn; and setting an applied voltage width Vpp, which is an amplitude of an applied voltage applied to the optical modulation element, in a range of $0.22V\pi \leq Vpp \leq 0.50V\pi$.

(4) In the driving method of an optical modulation element according to the above-describe aspect, the first optical waveguide and the second optical waveguide may each include a ridge-shaped portion protruding from a first surface of a lithium niobate film.

Advantageous Effects of Invention

The optical modulator and the driving method of an optical modulation element according to the above-described aspects provide an optical modulator that can be driven at a low voltage and has little modulation loss.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a block diagram of an optical modulator according to a first embodiment.

FIG. **2** is a plan view of an optical waveguide of an optical modulation element according to the first embodiment.

FIG. **3** is a plan view of the optical modulation element according to the first embodiment.

FIG. **4** is a cross-sectional view of the optical modulation element according to the first embodiment.

FIG. **5** is a diagram showing a relationship between an applied voltage and an output of the optical modulator according to the first embodiment.

FIG. **6** is a diagram for explaining an applied voltage width of the optical modulator according to the first embodiment.

FIG. **7** is a diagram showing a relationship between an applied voltage and an extinction ratio of the optical modulator according to the first embodiment.

FIG. **8** is a plan view of an optical modulation element according to a first modified example.

DESCRIPTION OF EMBODIMENTS

Hereinafter, the present embodiment will be described in detail with reference to the drawings as appropriate. In the drawings used in the following description, there are cases in which characteristic portions are enlarged for convenience of illustration so that characteristics can be easily understood, and dimensional proportions or the like of respective constituent elements may be different from actual ones. Materials, dimensions, and the like illustrated in the following description are merely examples, and the present disclosure is not limited thereto and can be implemented with appropriate modifications within a range in which the effects of the present disclosure are achieved.

First, directions will be defined. One direction of one surface of a substrate Sb is defined as an x direction, and a direction perpendicular to the x direction is defined as a y direction. The x direction is, for example, a direction in which a first optical waveguide **11** extends. A z direction is a direction perpendicular to the substrate Sb. The z direction is a direction perpendicular to the x direction and the y direction. Hereinafter, the positive z direction may be expressed as "upward" and the negative z direction may be expressed as "downward." "Upward" and "downward" do not necessarily have to coincide with a direction in which gravity is applied.

FIG. **1** is a block diagram of an optical modulator **200** according to a first embodiment. The optical modulator **200** includes an optical modulation element **100**, a drive circuit **110**, a direct current (DC) bias application circuit **120**, and a DC bias control circuit **130**. The drive circuit **110**, the DC bias application circuit **120**, and the DC bias control circuit **130** form a control unit.

The optical modulation element **100** converts an electrical signal into an optical signal. The optical modulation element **100** converts input light L_{in} that has been input into an output light L_{out} according to a modulation signal Sm.

The drive circuit **110** applies a modulation voltage Vm according to the modulation signal Sm to the optical modulation element **100**. The DC bias application circuit **120** applies a DC bias voltage Vdc to the optical modulation element **100**. The DC bias control circuit **130** monitors the output light L_{out} and controls the DC bias voltage Vdc output from the DC bias application circuit **120**. When the DC bias voltage Vdc is adjusted, an operating point Vd to be described later is controlled.

FIG. **2** is a plan view of an optical waveguide **10** of the optical modulation element **100** from the z direction. FIG. **3** is a plan view of the optical modulation element **100** from the z direction. FIG. **4** is a cross section taken along line X1-X1' in FIG. **3**. The optical modulation element **100** includes the optical waveguide **10** and electrodes **21**, **22**, **23**, and **24**.

The optical modulation element **100** includes the substrate Sb. The substrate Sb may be any substrate on which an oxide film **40** such as a lithium niobate film can be formed as an epitaxial film, and a sapphire single crystal substrate or a silicon single crystal substrate is preferable. A crystal orientation of the substrate Sb is not particularly limited. Further, a lithium niobate film has a property of being easily formed as a c-axis-oriented epitaxial film with respect to the substrate Sb having various crystal orientations. Since crystals forming the c-axis-oriented lithium niobate film have three-fold symmetry, it is desirable that the underlying substrate Sb also have the same symmetry, a c-plane substrate is preferable in a case of a sapphire single crystal substrate, and a (111) plane substrate is preferable in a case of a silicon single crystal substrate.

The optical waveguide **10** is a light passage through which light propagates inside. The optical waveguide **10** includes, for example, the first optical waveguide **11**, a second optical waveguide **12**, an input path **13**, an output path **14**, a branch portion **15**, and a coupling portion **16**. The first optical waveguide **11** and the second optical waveguide **12** extend, for example, in the x direction. Lengths of the first optical waveguide **11** and the second optical waveguide **12** in the x direction are substantially the same. The branch portion **15** is between the input path **13**, and the first optical waveguide **11** and the second optical waveguide **12**. The input path **13** is connected to the first optical waveguide **11** and the second optical waveguide **12** via the branch portion **15**. The coupling portion **16** is between the first optical waveguide **11** and the second optical waveguide **12**, and the output path **14**. The first optical waveguide **11** and the second optical waveguide **12** are connected to the output path **14** via the coupling portion **16**.

The optical waveguide **10** includes the first optical waveguide **11** and the second optical waveguide **12** which are ridge-shaped portions protruding from a first surface **40***a* of the oxide film **40**. The first surface **40***a* is an upper surface of the oxide film **40** other than the ridge-shaped portions. The ridge-shaped portions protrude in the z direction from the first surface **40***a* and extend along the optical waveguide **10**. A shape of the X1-X1' cross section (cross section perpendicular to a traveling direction of light) of the ridge-shaped portion may be any shape as long as it can guide light, and may be, for example, a dome-shaped, a triangular, or a rectangular. A width of the ridge-shaped portion in the y direction is, for example, 0.3 μm or more and 5.0 μm or less, and a height of the ridge-shaped portion (protrusion height from the first surface **40***a*) is, for example, 0.1 μm or more and 1.0 μm or less.

The oxide film **40** is, for example, a c-axis-oriented lithium niobate film. The oxide film **40** is, for example, an epitaxial film epitaxially grown on the substrate Sb. An epitaxial film refers to a single crystal film whose crystal orientation is aligned by an underlying substrate. An epitaxial film is a film having a single crystal orientation in the z direction and an xy in-plane direction, and in which crystals are aligned in the x-axis, y-axis, and z-axis directions. Whether or not it is an epitaxial film can be proved, for example, by ascertaining a peak intensity and a pole at an orientation position in 2θ−θ X-ray diffraction. Also, the oxide film **40** may be a lithium niobate film provided on a Si substrate via SiO_2.

A composition of the lithium niobate is $Li_xNbA_yO_z$. A denotes an element other than Li, Nb, and O. x is 0.5 or more and 1.2 or less, and preferably 0.9 or more and 1.05 or less. y is 0 or more and 0.5 or less. z is 1.5 or more and 4.0 or less, and preferably 2.5 or more and 3.5 or less. An element for A may be, for example, K, Na, Rb, Cs, Be, Mg, Ca, Sr, Ba, Ti, Zr, Hf, V, Cr, Mo, W, Fe, Co, Ni, Zn, Sc, or Ce, or a combination of two or more types of these elements may be used.

The electrodes **21** and **22** are electrodes that apply the modulation voltage Vm to the optical waveguide **10**. The electrode **21** is an example of a first electrode, and the electrode **22** is an example of a second electrode. A first end **21***a* of the electrode **21** is connected to a power supply **31**, and a second end **21***b* thereof is connected to a terminating resistor **32**. A first end **22***a* of the electrode **22** is connected to the power supply **31**, and a second end **22***b* is connected to the terminating resistor **32**. The power supply **31** is a part of the drive circuit **110** that applies the modulation voltage Vm to the optical modulation element **100**.

The electrodes **23** and **24** are electrodes that apply the DC bias voltage Vdc to the optical waveguide **10**. A first end **23***a* of the electrode **23** and a first end **24***a* of the electrode **24** are connected to a power supply **33**. The power supply **33** is a part of the DC bias application circuit **120** that applies the DC bias voltage Vdc to the optical modulation element **100**.

In FIG. **3**, line widths of and a distance between the electrodes **21** and **22** disposed in parallel are made larger than they actually are for easy viewing. Therefore, a length of a portion in which the electrode **21** and the first optical waveguide **11** overlap and a length of a portion in which the electrode **22** and the second optical waveguide **12** overlap appear to be different, but these lengths are substantially the same. Similarly, a length of a portion in which the electrode **23** and the first optical waveguide **11** overlap and a length of a portion in which the electrode **24** and the second optical waveguide **12** overlap are substantially the same.

Also, when the DC bias voltage Vdc is additionally applied to the electrodes **21** and **22**, the electrodes **23** and **24** may not be provided. Also, ground electrodes may be provided around the electrodes **21**, **22**, **23**, and **24**.

The electrodes **21**, **22**, **23**, and **24** are above the oxide film **40** with the buffer layer **30** interposed therebetween. The electrodes **21** and **23** each can apply an electric field to the first optical waveguide **11**. The electrodes **21** and **23** are positioned at positions at which, for example, they each overlap the first optical waveguide **11** in a plan view from the z direction. The electrodes **21** and **23** are each above the first optical waveguide **11**. The electrodes **22** and **24** each can apply an electric field to the second optical waveguide **12**. The electrodes **22** and **24** are positioned at positions at which they each overlap the second optical waveguide **12** in a plan view from the z direction. The electrodes **22** and **24** are each above the second optical waveguide **12**.

The buffer layer **30** is between the optical waveguide **10** and an electrode **20**. The buffer layer **30** covers and protects the ridge-shaped portion. Also, the buffer layer **30** prevents light propagating through the optical waveguide **10** from being absorbed by the electrode **20**. The buffer layer **30** has a lower refractive index than the oxide film **40**. The buffer layer **30** is made of, for example, SiO_2, Al_2O_3, MgF_2, La_2O_3, ZnO, HfO_2, MgO, Y_2O_3, CaF_2, In_2O_3, or the like, or a mixture thereof.

The optical modulation element **100** can be manufactured by a known method. The optical modulation element **100** is manufactured using semiconductor processes such as, for example, epitaxial growth, photolithography, etching, vapor phase epitaxy, and metallization.

The optical modulation element **100** converts an electrical signal into an optical signal. The optical modulation element **100** modulates the input light L_{in} into the output light L_{out}. First, a modulation operation of the optical modulation element **100** will be described.

The input light L_{in} input from the input path **13** branches to the first optical waveguide **11** and the second optical waveguide **12** and propagates. A phase difference between light propagating through the first optical waveguide **11** and light propagating through the second optical waveguide **12** is zero at the time of branching.

Next, an applied voltage is applied between the electrode **21** and the electrode **22**. For example, differential signals that have the same absolute value, have opposite polarities, and are not out of phase with each other may be applied to the electrode **21** and the electrode **22**. Refractive indexes of the first optical waveguide **11** and the second optical waveguide **12** change due to an electro-optical effect. For example, the refractive index of the first optical waveguide **11** changes by +Δn from a reference refractive index n, and the refractive index of the second optical waveguide **12** changes by −Δn from the reference refractive index n.

A difference in refractive index between the first optical waveguide **11** and the second optical waveguide **12** generates the phase difference between the light propagating through the first optical waveguide **11** and the light propagating through the second optical waveguide **12**. The light propagating through the first optical waveguide **11** and the second optical waveguide **12** is combined in the output path **14** and is output as the output light L_{out}. The output light L_{out} is superposition of the light propagating in the first optical waveguide **11** and the light propagating in the second optical waveguide **12**. An intensity of the output light L_{out} changes according to the phase difference between the light propagating in the first optical waveguide **11** and the light propagating in the second optical waveguide **12**. For example, when the phase difference is an even multiple of π, the light intensifies each other, and when the phase difference is an odd multiple of π, the light weakens each other. With such a procedure, the optical modulation element **100** modulates the input light L_{in} into the output light L_{out} according to the electrical signal.

The modulation voltage Vm according to the modulation signal is applied to the electrodes **21** and **22** which are for applying a modulation voltage to the optical modulation element **100**. The voltage applied to the electrodes **23** and **24** which are for applying a DC bias voltage, that is, the DC bias voltage Vdc output from the DC bias application circuit **120** is controlled by the DC bias control circuit **130**. The DC bias control circuit **130** adjusts the operating point Vd of the optical modulation element **100** by controlling the DC bias voltage Vdc. The operating point Vd refers to a voltage that is a center of a modulation voltage amplitude.

The DC bias control circuit **130** is configured to set the operating point Vd of the optical modulation element **100** within a voltage width R1. The voltage width R1 is defined by a half-wave voltage Vπ and a null point voltage Vn.

An optical modulation due to the optical modulation element **100** will be described with reference to FIG. **5**. FIG. **5** is a diagram showing a relationship between an applied voltage and an output of the optical modulator **200** according to the first embodiment. The horizontal axis of FIG. **5** represents a voltage applied to the optical modulation element **100**, and the vertical axis represents one in which an output from the optical modulation element **100** is standardized. The output is standardized as "1" when the phase difference between the light propagating through the first optical waveguide **11** and the light propagating through the second optical waveguide **12** is zero.

Next, the null point voltage Vn and the half-wave voltage Vπ will be described.

An output of the optical modulation element **100** is maximum when the applied voltage is zero. This is because when the applied voltage is zero, the phase difference between the light propagating through the first optical waveguide **11** and the light propagating through the second optical waveguide **12** is zero.

The output from the optical modulation element **100** gradually decreases as the applied voltage increases, and is minimized at a certain point. A voltage at which the output from the optical modulation element **100** is minimized is the null point voltage Vn. The null point voltage Vn can be ascertained by measuring a voltage when a light output from the optical modulation element **100** is minimized. Specifically, the null point voltage Vn can be ascertained by applying a voltage to the electrodes **21** and **22** used for applying a modulation voltage and measuring a voltage (potential difference between the electrodes **21** and **22**) when the light output from the optical modulation element **100** is minimized.

The half-wave voltage (half-wave phase modulation voltage) is a voltage for making a phase difference of light 180° in a Mach-Zehnder type optical modulator, and a voltage width in which the light output from the optical modulation element **100** reaches the minimum from the maximum corresponds to the half-wave voltage Vπ. When a voltage exceeding the null point voltage Vn is applied, the output from the optical modulation element **100** changes periodically. The output from the optical modulation element **100** repeats the maximum and the minimum alternately for each half-wave voltage Vπ. The half-wave voltage Vπ can be ascertained by measuring a voltage at which the light output from the optical modulation element **100** is minimized and a voltage at which the light is maximized. Specifically, the half-wave voltage Vπ can be ascertained by applying a voltage to the electrodes **21** and **22** used for applying a modulation voltage and measuring a voltage (potential difference between the electrodes **21** and **22**) at which the light output from the optical modulation element **100** is maximized and a voltage (potential difference between the electrodes **21** and **22**) at which the light is minimized.

The half-wave voltage Vπ of the optical modulation element **100** changes according to a configuration of the optical modulation element **100**. The half-wave voltage Vπ changes according to, for example, a length of the electrode **21** on the first optical waveguide **11**, a length of the electrode **22** on the second optical waveguide **12**, and the like. The length refers to a length in a propagation direction of light. In a case of the optical modulation element **100** of FIG. **3**, the length refers to a length of a portion of the electrode **21** that overlaps the first optical waveguide **11** or a length of a portion of the electrode **22** that overlaps the second optical waveguide **12**. The length is called an interaction length. When the interaction length becomes large, the half-wave voltage Vπ reduces, and when the interaction length becomes small, the half-wave voltage Vπ increases.

Since the optical modulation element using a lithium niobate thin film can efficiently apply an electric field to the optical waveguide compared to an optical modulation element using bulk lithium niobate, the half-wave voltage Vπ can be reduced. However, in order to be incorporated into a transceiver for a data center, the optical modulation element **100** needs to be further miniaturized, and the interaction length of the optical modulation element **100** needs to be made small. Also, in order to extend a modulation frequency band of the optical modulation element **100**, the interaction length needs to be made small. Therefore, the half-wave voltage Vπ of the optical modulation element **100** becomes, for example, as large as 4.9 V or more. Therefore, the optical modulator **200** according to the present embodiment is configured to set the operating point Vd within the voltage width R**1** and controls an applied voltage width Vpp to be described later.

The voltage width R**1** is in a range of Vn+0.50Vπ or more and Vn+0.75Vπ or less, or Vn−0.75Vπ or more and Vn−0.50Vπ or less. That is, the operating point Vd is designed to satisfy the following relational expression.

$$Vn+0.50V\pi \leq Vd \leq Vn+0.75V\pi \text{ or } Vn-0.75V\pi \leq Vd \leq Vn-0.50V\pi$$

The operating point Vd may fluctuate due to a temperature of a usage environment or the like. If the operating point Vd fluctuates during use, it is corrected by the DC bias control circuit **130**. The DC bias control circuit **130** corrects a fluctuation of the operating point Vd based on, for example, branched light L_b branched off from the output light L_{out}.

The drive circuit **110** controls the applied voltage width Vpp applied to the optical modulation element **100**. The drive circuit **110** controls a high-frequency voltage applied to the optical modulation element **100**. The drive circuit **110** inputs an electrical signal converted into an optical signal to the optical modulation element **100**. The drive circuit **110** includes, for example, a power supply, a driver, and the like.

FIG. **6** is a diagram for explaining the applied voltage width Vpp of the optical modulator **200** according to the first embodiment. FIG. **6** is a diagram in which a description of the applied voltage width Vpp is added to FIG. **5**.

The applied voltage width Vpp refers to a range of a voltage utilized when the optical modulation element **100** is operated. A voltage in a range of a predetermined voltage width with the operating point Vd as a center is applied to the optical modulation element **100**. A high-frequency voltage, whose difference between a maximum value and a minimum value is the applied voltage width Vpp with the operating point Vd as a center, is applied to the optical modulation element **100**. The output from the optical modulation element **100** changes in a range corresponding to the applied voltage width Vpp.

For example, when the operating point Vd is Vn+0.5π and the applied voltage width Vpp is a half-wave voltage Vπ, a voltage in a range of Vn to Vn+Vπ is applied to the optical modulation element **100**. The output from the optical modulation element **100** is minimum when an applied voltage is Vn and is maximum when the applied voltage is Vn+Vπ. That is, when the applied voltage width Vpp is set in the above-described range, a change width of the output of the optical modulation element **100** becomes a maximum. On the other hand, a drive voltage required to drive the optical modulation element **100** increases.

The drive circuit **110** is configured to set the applied voltage width Vpp applied to the optical modulation element **100** in a range of 0.22Vπ≤Vpp≤0.50Vπ.

The applied voltage width Vpp can be ascertained by measuring a minimum voltage (potential difference between the electrodes **21** and **22**) and a maximum voltage (potential difference between the electrodes **21** and **22**) applied to the electrodes **21** and **22** used for applying a modulation voltage.

FIG. **7** is a diagram showing a relationship between an applied voltage and an extinction ratio of the optical modulator **200** according to the first embodiment. The horizontal axis of FIG. **7** represents a voltage applied to the optical modulation element **100**, and the vertical axis represents a ratio of the output light L_{out} at an applied voltage and the output light L_{out} at a null point voltage. The extinction ratio is a ratio of a maximum value and a minimum value of the output light L_{out}.

As shown in FIGS. **5** and **7**, when the operating point Vd is set within the voltage width **R1** and the applied voltage width Vpp is set within a predetermined range, the optical modulation element **100** operates in a region in which an amount of light of the output light L_{out} is relatively large.

If the optical modulation element **100** is driven in a region (region in the vicinity of the null point voltage Vn) in which the amount of light of the output light L_{out} is relatively small, a modulation loss in the optical modulation element **100** may increase, and the output light L_{out} may not be sufficiently detected. That is, there is a likelihood that a signal component is buried in noise and cannot be detected.

On the other hand, if the optical modulation element **100** is driven in a region in which the amount of light of the output light L_{out} of the optical modulation element **100** is sufficiently large, sufficient sensitivity can be obtained. For example, if the operating point Vd is set within the voltage width **R1** and the applied voltage width Vpp is set within a predetermined range, the optical modulation element **100** can be used in a range in which a modulation loss is 3 dB or less.

Here, as shown in FIG. **7**, an extinction ratio is small in a region in which the amount of light of the output light L_{out} of the optical modulation element **100** is sufficiently large. For example, under the condition that the applied voltage width Vpp is the same, when the operating point Vd is set at a position away from the null point voltage Vn, an amount of light increases compared to a case in which the operating point Vd is set in the vicinity of the null point voltage Vn, but an extinction ratio decreases. However, an extinction ratio required for an optical modulator for a data center is smaller than that for an optical modulator for long-distance communication, and is about 3 dB to 9 dB. Therefore, if the operating point Vd is set within the voltage width **R1** and the applied voltage width Vpp is set within a predetermined range, the optical modulator can have the extinction ratio of 3 dB or more and can be used for a data center.

Also, in the optical modulation element **100** using a lithium niobate film, the drive voltage increases when an attempt is made to maximize the extinction ratio, but when the applied voltage width Vpp is set within a predetermined range, the optical modulator **200** can be driven at a low voltage.

As described above, the optical modulator **200** according to the first embodiment can be driven at a low voltage and has little modulation loss.

As described above, the optical modulator **200** according to the first embodiment has been described as an example, but the present disclosure is not limited to the first embodiment, and various modifications can be made.

For example, the operating point Vd may be set in a range of $Vn+0.62V\pi \leq Vd \leq Vn+0.75V\pi$ or $Vn-0.75V\pi \leq Vd \leq Vn-0.62V\pi$, and the applied voltage width Vpp may be set in a range of $0.32V\pi \leq Vpp \leq 0.50V\pi$. In this case, a modulation loss of the optical modulation element **100** can be made 2 dB or less.

Also, for example, the operating point Vd may be set in a range of $Vn+0.62V\pi \leq Vd \leq Vn+0.73V\pi$ or $Vn-0.73V\pi \leq Vd \leq Vn-0.62V\pi$, and the applied voltage width Vpp may be set in a range of $0.32V\pi \leq Vpp \leq 0.50V\pi$. At a position at which the output of the output light L_{out} is maximum, distortion is likely to occur in the signal. Waveform distortion of a reproduced signal can be suppressed by avoiding a region in which the distortion is likely to occur.

Also, FIG. **8** is a plan view of an optical modulation element **101** according to a first modified example from the z direction. The optical modulation element **101** includes an optical waveguide **50** and electrodes **61**, **62**, **63**, and **64**.

The optical waveguide **50** includes a first optical waveguide **51**, a second optical waveguide **52**, an input path **53**, an output path **54**, a branch portion **55**, and a coupling portion **56**. The optical waveguide **50** is different from the optical waveguide **10** in that the first optical waveguide **51** and the second optical waveguide **52** are curved in the middle. Other points of the optical waveguide **50** are the same as those of the optical waveguide **10**.

The electrodes **61** and **62** are electrodes that apply the modulation voltage Vm to the optical waveguide **50**. The electrode **61** is an example of a first electrode, and the electrode **62** is an example of a second electrode. A first end **61***a* of the electrode **61** is connected to the power supply **31**, and a second end **61***b* is connected to the terminating resistor **32**. A first end **62***a* of the electrode **62** is connected to the power supply **31**, and a second end **62***b* is connected to the terminating resistor **32**. The electrodes **63** and **64** are electrodes that apply the DC bias voltage Vdc to the optical waveguide **50**. A first end **63***a* of the electrode **63** and a first end **64***a* of the electrode **64** are connected to the power supply **33**.

In FIG. **8**, since line widths of and a distance between the electrodes **61** and **62** disposed in parallel are made larger, a length of a portion in which the electrode **61** and the first optical waveguide **51** overlap and a length of a portion in which the electrode **62** and the second optical waveguide **52** overlap are shown to be different, but these lengths are substantially the same. Similarly, a length of a portion in which the electrode **63** and the first optical waveguide **51** overlap and a length of a portion in which the electrode **64** and the second optical waveguide **52** overlap are substantially the same.

The electrode **61** and the electrode **62** are different from the electrode **21** and the electrode **22** in that they are curved along the first optical waveguide **51** and the second optical waveguide **52**. The other points of the electrodes **61**, **62**, **63**, and **64** are the same as those of the electrodes **21**, **22**, **23**, and **24**.

The optical modulation element **101** has a small element size in the x direction because the first optical waveguide **51** and the second optical waveguide **52** are curved. The optical modulation element **101** can realize an element size of, for example, 100 mm^2 or less and preferably 50 mm^2 or less. An optical modulator for a data center is required to be miniaturized. When the optical waveguide **50** is bent, the optical modulation element **101** can be housed in region of a small size corresponding to an existing optical modulator for a data center.

REFERENCE SIGNS LIST

10, **50** Optical waveguide
11, **51** First optical waveguide
12, **52** Second optical waveguide
13, **53** Input path
14, **54** Output path
15 Branch portion
16 Coupling portion
21, **22**, **23**, **24**, **61**, **62**, **63**, **64** Electrode

30 Buffer layer
40 Oxide film
40*a* First surface
100, **101** Optical modulation element
110 Drive circuit
120 DC bias application circuit
130 DC bias control circuit
200 Optical modulator
L_{in} Input light
L_{out} Output light
L_b Branched light
Vd Operating point
Vn Null point voltage
Vπ Half-wave voltage
Vpp Applied voltage width

What is claimed is:

1. An optical modulator comprising:

an optical modulation element including a first optical waveguide, a second optical waveguide, a first electrode and a third electrode that apply electric fields to different portions of the first optical waveguide, and a second electrode and a fourth electrode that apply electric fields to different portions of the second optical waveguide; and

a control unit configured to control an applied voltage between the first electrode, the second electrode, the third electrode and the fourth electrode, wherein

a length of a portion in which the first electrode and the first optical waveguide overlap and a length of a portion in which the second electrode and the second optical waveguide overlap are substantially the same,

a length of a portion in which the third electrode and the first optical waveguide overlap and a length of a portion in which the fourth electrode and the second optical waveguide overlap are substantially the same, and

when a half-wave voltage of the optical modulation element is Vπ and a null point voltage of the optical modulation element is Vn, the control unit sets an operating point Vd in a range of $Vn+0.50V\pi \leq Vd \leq Vn+0.75V\pi$ or $Vn-0.75V\pi \leq Vd \leq Vn-0.50V\pi$ and sets an applied voltage width Vpp, which is an amplitude of an applied voltage applied to the optical modulation element, in a range of $0.22V\pi \leq Vpp \leq 0.50V\pi$.

2. The optical modulator according to claim **1**, wherein the first optical waveguide and the second optical waveguide each include a ridge-shaped portion protruding from a first surface of a lithium niobate film.

3. A driving method of an optical modulation element including a first optical waveguide, a second optical waveguide, a first electrode and a third electrode that are at positions overlapping different portions of the first optical waveguide in a plan view, and a second electrode and a fourth electrode that are at positions overlapping different portions of the second optical waveguide in a plan view, a length of a portion in which the first electrode and the first optical waveguide overlap and a length of a portion in which the second electrode and the second optical waveguide overlap being substantially the same, a length of a portion in which the third electrode and the first optical waveguide overlap and a length of a portion in which the fourth electrode and the second optical waveguide overlap being substantially the same, the driving method comprising:

controlling the first electrode, the second electrode, the third electrode and the fourth electrode, and setting an operating point Vd in a range of $Vn+0.50V\pi \leq Vd \leq Vn+0.75V\pi$ or $Vn-0.75V\pi \leq Vd \leq Vn-0.50V\pi$, when a half-wave voltage of the optical modulation element is Vπ and a null point voltage of the optical modulation element is Vn; and

setting an applied voltage width Vpp, which is an amplitude of an applied voltage applied to the optical modulation element, in a range of $0.22V\pi \leq Vpp \leq 0.50V\pi$.

4. The driving method of an optical modulation element according to claim **3**, wherein the first optical waveguide and the second optical waveguide each include a ridge-shaped portion protruding from a first surface of a lithium niobate film.

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