US Patent & Trademark Office
Patent Public Search | Text View

United States Patent 12386213
Kind Code B2
Date of Patent August 12, 2025
Inventor(s) Utsunomiya; Hajime et al.

Optical modulator and method for driving optical modulation element

Abstract

This optical modulator includes an optical modulation element having a first optical waveguide, a second optical waveguide, a first electrode configured to apply an electric field to the first optical waveguide, and a second electrode configured to apply 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. The control unit sets Vpp to $0.06 \times V\pi \leq Vpp \leq 0.4 \times V\pi$ when a half-wavelength voltage of the optical modulation element is Vπ and an applied voltage width that is an amplitude of an applied voltage applied to the optical modulation element is Vpp, and sets $Vn \leq Vmin \leq Vn + 0.29 \times V\pi$ or $Vn - 0.29 \times V\pi \leq Vmax \leq Vn$ when a minimum value and a maximum value of a voltage applied to the optical modulation element are respectively Vmin and Vmax and a null point voltage of the optical modulation element is Vn.

Inventors:	**Utsunomiya; Hajime (Tokyo, JP), Kikukawa; Takashi (Tokyo, JP)**
Applicant:	**TDK CORPORATION** (Tokyo, JP)
Family ID:	**1000008750563**
Assignee:	**TDK CORPORATION (Tokyo, JP)**
Appl. No.:	**17/924533**
Filed (or PCT Filed):	**July 13, 2021**
PCT No.:	**PCT/JP2021/026211**
PCT Pub. No.:	**WO2022/034766**
PCT Pub. Date:	February 17, 2022

Prior Publication Data

Document Identifier	Publication Date
US 20230229030 A1	Jul. 20, 2023

Foreign Application Priority Data

JP	2020-135860	Aug. 11, 2020

Publication Classification

Int. Cl.: **G02F1/035** (20060101); **G02F1/21** (20060101); **G02F1/225** (20060101)

U.S. Cl.:

CPC **G02F1/035** (20130101); **G02F1/212** (20210101); **G02F1/225** (20130101); G02F2202/20 (20130101)

Field of Classification Search

CPC: G02F (1/035); G02F (1/212); G02F (1/225); G02F (2202/20)

USPC: 385/2

References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
6334004	12/2000	Ohkuma et al.	N/A	N/A
2004/0061922	12/2003	Mauro et al.	N/A	N/A
2015/0138619	12/2014	Iwatsuka et al.	N/A	N/A
2023/0176403	12/2022	Utsunomiya	385/2	G02F 1/035
2023/0213791	12/2022	Utsunomiya	385/2	G02F 1/2255

FOREIGN PATENT DOCUMENTS

Patent No.	Application Date	Country	CPC
2000-180804	12/1999	JP	N/A
2004-037695	12/2003	JP	N/A
4164179	12/2007	JP	N/A
2019-045880	12/2018	JP	N/A

OTHER PUBLICATIONS

Sep. 14, 2021 Search Report issued in International Patent Application No. PCT/JP2021/026211. cited by applicant

Translation of Dec. 6, 2022 Office Action issued in Japanese Patent Application No. 2020-135860. cited by applicant

Primary Examiner: Blevins; Jerry M

Attorney, Agent or Firm: Oliff PLC

Background/Summary

TECHNICAL FIELD

(1) The present invention relates to an optical modulator and a method for driving an optical modulation element. This application claims the benefit of priority from Japanese Patent Application No. 2020-135860, filed on Aug. 11, 2020, the content of which is incorporated herein.

BACKGROUND ART

(2) The volume of communication has increased drastically with the spread of the Internet, and the importance of optical fiber communication has risen significantly. Optical fiber communication, in which an electrical signal is converted into an optical signal and the optical signal is transmitted through an optical fiber, is characterized by a wide band, a low loss, and resistance to noise.

(3) Optical modulators convert an electrical signal into an optical signal. For example, Patent Document 1 and Patent Document 2 disclose Mach-Zehnder-type optical modulators in which optical waveguides are formed by Ti (titanium) diffusion near a surface of a lithium niobate single crystal substrate. In addition, Patent Document 2 discloses that an operating point drift of the optical modulator is corrected. The optical modulators disclosed in Patent Document 1 and Patent Document 2 operate at a high speed such as 40 Gb/s or faster but have a long overall length such as around 10 cm.

(4) In contrast, Patent Document 3 discloses a Mach-Zehnder-type optical modulator using a c-axis-oriented lithium niobate film. Compared to an optical modulator using a lithium niobate single crystal substrate, an optical modulator using a lithium niobate film has a small size and uses a low drive voltage.

CITATION LIST

Patent Document

(5) [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

(6) Since optical modulators using lithium niobate have a large extinction ratio and can be operated in a high-frequency band, they are used for long-distance communication such as inter-city communication. In addition, since optical modulators using indium phosphide can also be operated in a high-frequency band, they are expected to be used for long-distance communication. Meanwhile, in recent years, there has also been increase in short/intermediate-range communication within a data center or between data centers, and a large extinction ratio is not required for such application. Therefore, there are cases in which optical modulators using silicon are used or there are cases in which emitted light is directly modulated by a laser diode drive circuit without using an optical modulator. In optical modulators using silicon, miniaturization and low-voltage driving, specifically 5 mm or shorter and 2.4 V or lower are realized, but they cannot cope with operation in a high-frequency band.

(7) Meanwhile, miniaturization and low-voltage driving are required in order to apply optical modulators which can be operated in a high-frequency band, such as optical modulators using lithium niobate or optical modulators using indium phosphide, to communication within a data center or between data centers. Regarding optical modulators using a lithium niobate film, although a drive voltage can be reduced compared to an optical modulator in which an optical waveguide is formed near a surface of a lithium niobate single crystal substrate by Ti diffusion, there is a need to further reduce the drive voltage in order to substitute for an optical modulator using silicon. In ordinary Mach-Zehnder-type optical modulators, this drive voltage corresponds to a half-wavelength voltage (half-wavelength phase modulation voltage) that is a voltage for setting a phase difference of light to 180°, and a voltage value thereof increases in accordance with miniaturization of the optical modulator. Specifically, in Reference 3 as well, when an interaction length is set to 5

mm, $V\pi$ becomes 4.8 V, and it cannot be used as the optical modulator for a data center described above. There is a need to set the drive voltage to be equal to or less than 50% of $V\pi$, practically equal to or less than 40%, preferably equal to or less than 35%, and more preferably equal to or less than 30%. Therefore, in order to cope with both miniaturization and low-voltage driving of an optical modulator, there is a need to perform operation at a drive voltage lower than the half-wavelength voltage $V\pi$(0.4 $V\pi$ or lower). In addition, an extinction ratio is also required to be set to 3 dB or larger.
(8) The present invention has been made in consideration of the foregoing problems, and an object thereof is to provide an optical modulator capable of obtaining an extinction ratio of 3 dB or larger when being operated at a drive voltage lower than a half-wavelength voltage, and a driving method in which an optical modulation element is driven at a drive voltage lower than a half-wavelength voltage while an extinction ratio of 3 dB or larger is secured.
Solution to Problem
(9) (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 configured to apply an electric field to the first optical waveguide, and a second electrode configured to apply 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. The control unit sets Vpp to $0.06\times V\pi \leq Vpp \leq 0.4\times V\pi$ when a half-wavelength voltage of the optical modulation element is $V\pi$ and an applied voltage width that is an amplitude of an applied voltage applied to the optical modulation element is Vpp, and sets $Vn \leq Vmin \leq Vn+0.29\times V\pi$ or $Vn-0.29\times V\pi \leq Vmax \leq Vn$ when a minimum value and a maximum value of a voltage applied to the optical modulation element are respectively Vmin and Vmax and a null point voltage of the optical modulation element is Vn.
(10) (2) In the optical modulator according to the foregoing aspect, the first optical waveguide and the second optical waveguide each may include a ridge-shaped portion protruding from a first surface of a lithium niobate film.
(11) (3) A method for driving an optical modulation element according to a second aspect is a method for driving an optical modulation element having a first optical waveguide, a second optical waveguide, a first electrode at a position overlapping the first optical waveguide in a plan view, and a second electrode at a position overlapping the second optical waveguide in a plan view. Vpp is set to $0.06\times V\pi \leq Vpp \leq 0.4\times V\pi$ when a half-wavelength voltage of the optical modulation element is $V\pi$ and an applied voltage width that is an amplitude of an applied voltage applied to the optical modulation element is Vpp, and $Vn \leq Vmin \leq Vn+0.29\times V\pi$ or $Vn-0.29\times V\pi \leq Vmax \leq Vn$ is set when a minimum value and a maximum value of a voltage applied to the optical modulation element are respectively Vmin and Vmax and a null point voltage of the optical modulation element is Vn.
(12) (4) In the method for driving an optical modulation element according to the foregoing aspect, the first optical waveguide and the second optical waveguide each may include a ridge-shaped portion protruding from a first surface of a lithium niobate film.
Advantageous Effects of Invention
(13) In the optical modulator and the method for driving an optical modulation element according to the foregoing aspect, it is possible to perform operation at a drive voltage lower than a half-wavelength voltage and to obtain an extinction ratio of 3 dB or larger.

Description

BRIEF DESCRIPTION OF DRAWINGS
(1) FIG. **1** is a block diagram of an optical modulator according to a first embodiment.
(2) FIG. **2** is a plan view of an optical waveguide according to the first embodiment.

(3) FIG. **3** is a plan view of an optical modulation element according to the first embodiment.
(4) FIG. **4** is a cross-sectional view of the optical modulation element according to the first embodiment.
(5) FIG. **5** is a view illustrating a relationship between an applied voltage and an output of the optical modulator according to the first embodiment.
(6) FIG. **6** is an explanatory view of a voltage width R1 of the optical modulator according to the first embodiment.
(7) FIG. **7** is a view illustrating a relationship between an applied voltage and an extinction ratio of the optical modulator according to the first embodiment.
(8) FIG. **8** is an explanatory view of a voltage width R2 of the optical modulator according to the first embodiment.
(9) FIG. **9** is a plan view of an optical modulation element according to a first modification example.

DESCRIPTION OF EMBODIMENT

(10) Hereinafter, the present embodiment will be described in detail suitably with reference to the drawings. In the drawings used in the following description, in order to make characteristics easy to understand, characteristic parts may be illustrated in an enlarged manner for the sake of convenience, and dimensional ratios or the like of each constituent element may differ from actual values thereof. Materials, dimensions, and the like exemplified in the following description are examples. The present invention is not limited thereto and can be suitably changed and performed within a range exhibiting the effects of the present invention.
(11) First, directions will be defined. One direction on one surface of a substrate Sb will be referred to as an x direction, and a direction orthogonal to the x direction will be referred to as a y direction. For example, the x direction is 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 orthogonal 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”. The upward and downward directions do not necessarily coincide with the direction in which the force of gravity acts.
(12) FIG. **1** is a block diagram of an optical modulator **200** according to a first embodiment. The optical modulator **200** has an optical modulation element **100**, a drive circuit **110**, a DC bias application circuit **120**, and a DC bias control circuit **130**. A control unit of the optical modulator **200** has the drive circuit **110**, the DC bias application circuit **120**, and the DC bias control circuit **130**.
(13) The optical modulation element **100** converts an electrical signal into an optical signal. The optical modulation element **100** converts input light L.sub.in, which has been input thereto, into output light L.sub.out in accordance with a modulation signal Sm.
(14) The drive circuit **110** applies a modulation voltage Vm corresponding to the modulation signal Sm to the optical modulation element **100**. An applied voltage width of a modulation signal at this time will be regarded as Vpp. 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.sub.out and controls the DC bias voltage Vdc output from the DC bias application circuit **120**. An operating point Vd (which will be described below) is controlled by adjusting this DC bias voltage Vdc.
(15) FIG. **2** is a plan view of an optical waveguide **10** of the optical modulation element **100** viewed in the z direction. FIG. **3** is a plan view of the optical modulation element **100** viewed in the z direction. FIG. **4** is a cross section cut along X1-X1′ in FIG. **3**. The optical modulation element **100** has the optical waveguide **10** and electrodes **21**, **22**, **23**, and **24**.
(16) The optical modulation element **100** is located on the substrate Sb. The substrate Sb need only be a substrate on which an oxide film **40** such as a lithium niobate film can be formed as an

epitaxial film, and it is preferably a sapphire single crystal substrate or a silicon single crystal substrate. A crystal orientation of the substrate Sb is not particularly limited. The lithium niobate film has properties of being easily formed as a c-axis-oriented epitaxial film with respect to the substrate Sb having various crystal orientations. Since a crystal constituting a c-axis-oriented lithium niobate film has three-fold symmetry, it is desired that the substrate Sb (base material) also have the same symmetry. In the case of a sapphire single crystal substrate, a substrate of a c-plane is preferable, and in the case of a silicon single crystal substrate, a substrate of a (**111**) plane is preferable.

(17) The optical waveguide **10** is a light passage in which light is propagated. For example, the optical waveguide **10** has 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**. For example, the first optical waveguide **11** and the second optical waveguide **12** extend in the x direction. The first optical waveguide **11** and the second optical waveguide **12** have substantially the same length in the x direction. The branch portion **15** is located between the input path **13**, and the first optical waveguide **11** and the second optical waveguide **12**. The input path **13** leads to the first optical waveguide **11** and the second optical waveguide **12** with the branch portion **15** therebetween. The coupling portion **16** is located 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** lead to the output path **14** with the coupling portion **16** therebetween.

(18) 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 in a part other than the ridge-shaped portions of the oxide film **40**. The ridge-shaped portions protrude in the z direction from the first surface **40***a* and extend along the optical waveguide **10**. The shape of an X1-X1′ cross section (a cross section perpendicular to a traveling direction of light) of each ridge-shaped portion may be any shape as long as it is a shape capable of guiding light, and it may be a dome shape, a triangular shape, or a rectangular shape, for example. The width of each ridge-shaped portion in the y direction is 0.3 μm to 5.0 μm, for example, and the height of each ridge-shaped portion (protrusion height from the first surface **40***a*) is 0.1 μm to 1.0 μm, for example. The ridge-shaped portions are constituted of the same material as the oxide film **40**.

(19) For example, the oxide film **40** is a c-axis-oriented lithium niobate film. For example, the oxide film **40** is an epitaxial film epitaxially grown on the substrate Sb. An epitaxial film indicates a single crystal film of which the crystal orientation is aligned by the substrate (base material). An epitaxial film is a film which has a single crystal orientation in the z direction and an in-plane (xy) direction and in which crystals are oriented in a manner of being aligned together in an x axis direction, a y axis direction, and a z axis direction. For example, it is possible to verify whether or not there is an epitaxial film by checking a peak intensity and a pole at an orientation position in 2θ-θ X-ray diffraction. In addition, the oxide film **40** may be a lithium niobate film provided on a Si substrate with SiO.sub.2 therebetween.

(20) Specifically, when measurement is performed by 2θ-θ X-ray diffraction, all peak intensities other than that on a target surface are equal to or less than 10% and preferably equal to or less than 5% of the maximum peak intensity of the target surface. For example, when the oxide film **40** is a c-axis-oriented epitaxial film, the peak intensity other than that in a (00L) plane is equal to or less than 10% and preferably equal to or less than 5% of the maximum peak intensity of the (00L) plane. Here, (00L) is generic expression of equivalent planes such as (001) and (002).

(21) In addition, conditions for checking the peak intensity at the orientation position described above simply indicate orientations in one direction. Thus, even if the condition described above is obtained, when the crystal orientations are not aligned within a plane, the X-ray intensity at a particular angular position does not increase and no pole is seen. For example, when the oxide film is a lithium niobate film, since LiNbO.sub.3 has a crystal structure of a trigonal system, there are

three poles of $LiNbO_3$ (014) in a single crystal. In the case of lithium niobate, it is known to epitaxially grow in a so-called twin crystal state in which crystals rotated about the c axis by 180° are symmetrically coupled. In this case, since two of three poles are in a symmetrically coupled state, there are six poles. In addition, when a lithium niobate film is formed on a silicon single crystal substrate of a (**100**) plane, since a substrate has four-fold symmetry, 12 poles (4×3) are observed. In the present disclosure, an epitaxial film also includes a lithium niobate film which has epitaxially grown in a twin crystal state.

(22) The composition of lithium niobate is $Li_xNbA_yO_z$. A is an element other than Li, Nb, and O. The subscript x is 0.5 or more and 1.2 or less and preferably 0.9 or more and 1.05 or less. The subscript y is 0 or more and 0.5 or less. The subscript z is 1.5 or more and 4.0 or less and preferably 2.5 or more and 3.5 or less. Examples of the element of A include K, Na, Rb, Cs, Be, Mg, Ca, Sr, Ba, Ti, Zr, Hf, V, Cr, Mo, W, Fe, Co, Ni, Zn, Sc, and Ce, and two or more kinds of these elements may be combined.

(23) The film thickness of the oxide film **40** is 2 μm or smaller, for example. The film thickness of the oxide film **40** is a film thickness of a part other than the ridge-shaped portions. If the film thickness of the oxide film **40** is large, there is concern that crystallinity may deteriorate. In addition, the film thickness of the oxide film **40** is approximately 1/10 or larger than the wavelength of light used, for example. If the film thickness of the oxide film **40** is small, confinement of light becomes weak, and light leaks to the substrate Sb or a buffer layer **30**. If the film thickness of the oxide film **40** is small, even if an electric field is applied to the oxide film **40**, there is concern that change in effective refractive index of the optical waveguide **10** may decrease.

(24) The electrodes **21** and **22** are electrodes for applying 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* is connected to a terminal 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 terminal resistor **32**. The power supply **31** is a part of the drive circuit **110** for applying the modulation voltage Vm to the optical modulation element **100**.

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

(26) In FIG. **3**, line widths and line spacings of the electrode **21** and the electrode **22** disposed in a parallel manner are made wider than actual measurements for better visibility. For this reason, although the length of a part in which the electrode **21** and the first optical waveguide **11** overlap (interaction length) and the length of a part in which the electrode **22** and the second optical waveguide **12** overlap (interaction length) appear different, the lengths (interaction lengths) thereof are substantially the same. Similarly, the length of a part in which the electrode **23** and the first optical waveguide **11** overlap (interaction length) and the length of a part in which the electrode **24** and the second optical waveguide **12** overlap (interaction length) are substantially the same.

(27) In addition, when the DC bias voltage Vdc overlaps the electrodes **21** and **22**, the electrodes **23** and **24** may not be provided. In addition, ground electrodes may be provided around the electrodes **21**, **22**, **23**, and **24**.

(28) The electrodes **21**, **22**, **23**, and **24** are located on the oxide film **40** with the buffer layer **30** sandwiched therebetween. Each of the electrodes **21** and **23** can apply an electric field to the first optical waveguide **11**. Each of the electrodes **21** and **23** is located at a position overlapping the first optical waveguide **11** in a plan view in the z direction, for example. Each of the electrode **21** is located above the first optical waveguide **11**. Each of the electrodes **22** and **24** can apply an electric field to the second optical waveguide **12**. Each of the electrodes **22** and **24** is located at a position overlapping the second optical waveguide **12** in a plan view in the z direction, for example. The

electrodes **22** and **24** are located above the second optical waveguide **12**.
(29) The buffer layer **30** is located between the optical waveguide **10** and the electrodes **21**, **22**, **23**, and **24**. The buffer layer **30** covers and protects the ridge-shaped portions. In addition, the buffer layer **30** prevents light propagated through the optical waveguide **10** from being absorbed into the electrodes **21**, **22**, **23**, and **24**. The buffer layer **30** has a lower refractive index than the oxide film **40**. Examples of the buffer layer **30** include SiO_2, Al_2O_3, MgF_2, La_2O_3, ZnO, HfO_2, MgO, Y_2O_3, CaF_2, and In_2O_3, or a mixture of these.
(30) The optical modulation element **100** can be produced by a known method. For example, the optical modulation element **100** is manufactured using a semiconductor process such as epitaxial growth, photolithography, etching, vapor phase growth, or metallization.
(31) The optical modulation element **100** converts an electrical signal into an optical signal. The optical modulation element **100** modulates the input light L_{in} to the output light L_{out}. First, modulation operation of the optical modulation element **100** will be described.
(32) The input light L_{in} input from the input path **13** branches into the first optical waveguide **11** and the second optical waveguide **12** and is propagated. The phase difference between light propagated through the first optical waveguide **11** and light propagated through the second optical waveguide **12** is zero at the point of time it branches.
(33) Next, an applied voltage is applied to a part between the electrode **21** and the electrode **22**. For example, differential signals having the same absolute values, polarities opposite to each other, and phases not deviating from each other may be respectively applied to the electrode **21** and the electrode **22**. The refractive indices of the first optical waveguide **11** and the second optical waveguide **12** change due to an electro-optic effect. For example, the refractive index of the first optical waveguide **11** changes by $+\Delta n$ from a reference refractive index n, and the refractive index of the second optical waveguide **12** changes by $-\Delta n$ from the reference refractive index n.
(34) The difference between the refractive indices of the first optical waveguide **11** and the second optical waveguide **12** creates a phase difference between light propagated through the first optical waveguide **11** and light propagated through the second optical waveguide **12**. Rays of light propagated through the first optical waveguide **11** and the second optical waveguide **12** join together in the output path **14** and are output as the output light L_{out}. The output light L_{out} is superimposed light of light propagated through the first optical waveguide **11** and light propagated through the second optical waveguide **12**. The intensity of the output light L_{out} changes in accordance with the phase difference between light propagated through the first optical waveguide **11** and light propagated through the second optical waveguide **12**. For example, when the phase difference is an even multiple of π, rays of the light are mutually intensified, and when the phase difference is an odd multiple of π, rays of the light are mutually weakened. In such a procedure, the optical modulation element **100** modulates the input light L_{in} to the output light L_{out} in accordance with an electrical signal.
(35) The modulation voltage Vm corresponding to a modulation signal is applied to the electrodes **21** and **22** for applying a modulation voltage of the optical modulation element **100**. A voltage applied to the electrodes **23** and **24** for applying a DC bias voltage, namely, 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 is a voltage at the center of the amplitude of a modulation voltage.
(36) The DC bias control circuit **130** controls an operating point voltage Vd such that a minimum value voltage Vmin of the optical modulation element **100** is within a voltage width R1 as illustrated in FIG. **5** when the minimum value voltage Vmin of an applied voltage is larger than a null point voltage Vn (which will be described below). The operating point voltage Vd is a midpoint between the minimum value voltage Vmin and a maximum value voltage Vmax of an

applied voltage. The voltage width R1 is defined by a half-wavelength voltage Vπ and the null point voltage Vn.
(37) The voltage width R1 is a range of Vn to Vn+0.291 Vπ. When the minimum value voltage Vmin of the applied voltage Vpp is the null point voltage Vn or larger, the minimum value voltage Vmin is designed to satisfy the following Expression (1), as illustrated in FIG. **6**.

$$Vn \leq \mathrm{Vmin} \leq Vn+0.29V\pi \qquad (1)$$

In addition, when the maximum value voltage Vmax of an applied voltage is the null point voltage Vn or smaller, the maximum value voltage Vmax is designed to satisfy the following Expression (2), as illustrated in FIG. **8**.

$$Vn-0.29V\pi \leq \mathrm{Vmax} \leq Vn \qquad (2)$$

(38) Optical modulation by the optical modulation element **100** will be described using FIG. **5**. FIG. **5** is a view illustrating a relationship between an applied voltage and an output of the optical modulator **200** according to the first embodiment. In FIG. **5**, the horizontal axis indicates a voltage applied to the optical modulation element **100**, and the vertical axis indicates a standardized output from the optical modulation element **100**. An output is standardized as “1” when the phase difference between light propagated through the first optical waveguide **11** and light propagated through the second optical waveguide **12** is zero.
(39) Next, the null point voltage Vn and the half-wavelength voltage Vπ will be described. The output of the optical modulation element **100** is maximized when the applied voltage is zero. This is because the phase difference between light propagated through the first optical waveguide **11** and light propagated through the second optical waveguide **12** is zero when the applied voltage is zero. As the applied voltage is increased, an output from the optical modulation element **100** gradually decreases and becomes extremely small at a certain point. The voltage at which an output from the optical modulation element **100** becomes extremely small is the null point voltage Vn. A half-wavelength voltage (half-wavelength phase modulation voltage) is a voltage for making the phase difference of light **1800** using a Mach-Zehnder-type optical modulator, and a voltage width in which an output from the optical modulation element **100** reaches the minimum from the maximum corresponding to the half-wavelength voltage Vπ. If a voltage exceeding the null point voltage Vn is applied, an output from the optical modulation element **100** periodically changes. An output from the optical modulation element **100** repeats the maximum and the minimum for each half-wavelength voltage Vπ.
(40) The half-wavelength voltage Vπ of the optical modulation element **100** changes depending on the constitution of the optical modulation element **100**. The half-wavelength voltage Vπ changes depending on the length of the electrode **21** on the first optical waveguide **11** and the length of the electrode **22** on the second optical waveguide **12**. The length is a length in a propagation direction of light. In the case of FIG. **3**, it is a length of a part of the electrode **21** overlapping the first optical waveguide **11** or a length of a part of the electrode **22** overlapping the second optical waveguide **12**. This length is referred to as an interaction length. If the interaction length is long, the half-wavelength voltage Vπ decreases, and if the interaction length is short, the half-wavelength voltage Vπ increases.
(41) Since an optical modulation element using a lithium niobate thin film can efficiently apply an electric field to the optical waveguides compared to an optical modulation element using bulk lithium niobate, the half-wavelength voltage Vπ can be reduced. However, the optical modulation element **100** needs to be further miniaturized in order to be assembled in a transceiver for a data center, and the interaction length of the optical modulation element **100** needs to be shortened. In addition, the interaction length needs to be shortened in order to widen a modulation frequency band of the optical modulation element **100**. Meanwhile, since the half-wavelength voltage Vπ increases by shortening the interaction length, the drive voltage (applied voltage width Vpp) needs to be set to 0.4 Vπ or lower.
(42) The operating point voltage Vd may fluctuate due to a temperature or the like of a usage

environment. When the operating point voltage Vd fluctuates while being used, the minimum value voltage Vmin and the maximum value voltage Vmax of the applied voltage width Vpp are corrected by the DC bias control circuit **130** to be in a range of voltage widths R1 and R2. For example, the DC bias control circuit **130** corrects fluctuation of the operating point on the basis of branch light L.sub.b which has branched from the output light L.sub.out.
(43) In addition, the drive circuit **110** also 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, which is converted into an optical signal, to the optical modulation element **100**. For example, the drive circuit **110** includes a power supply, a driver, and the like.
(44) The drive circuit **110** controls the applied voltage width Vpp applied to the optical modulation element **100** in a range of $0.06\times V\pi \leq Vpp \leq 0.4\times V\pi$.
(45) FIG. **6** is an explanatory view of the applied voltage width Vpp of the optical modulator **200** according to the first embodiment. FIG. **6** is a view illustrated by adding description of the applied voltage width Vpp to FIG. **5**.
(46) The applied voltage width Vpp is in a range of a voltage utilized when the optical modulation element **100** is operated. When the minimum value and the maximum value of an applied voltage are respectively set to the minimum value voltage Vmin and the maximum value voltage Vmax, the applied voltage width Vpp is expressed by Vmax-Vmin. A voltage within a predetermined range is applied to the optical modulation element **100** while having the operating point voltage Vd as the midpoint. A high-frequency voltage of the applied voltage width Vpp is applied to the optical modulation element **100**. An output from the optical modulation element **100** changes in accordance with the range of Vmax and Vmin.
(47) For example, when the minimum value voltage Vmin is Vn and the applied voltage width Vpp is the half-wavelength voltage Vπ, a voltage within a range of Vn to Vn+Vπ is normally applied to the optical modulation element **100**. An output from the optical modulation element **100** is minimized when an applied voltage is Vn and is maximized when an applied voltage is Vn+Vπ. A variation width of an output of the optical modulation element **100** is maximized by changing an applied voltage between Vn and Vn+Vπ. Meanwhile, a drive voltage required to drive the optical modulation element **100** increases.
(48) FIG. **7** is a view illustrating a relationship between an applied voltage and an extinction ratio of the optical modulator **200** according to the first embodiment. In FIG. **7**, the horizontal axis indicates a voltage applied to the optical modulation element **100**, and the vertical axis indicates a ratio of the output light L.sub.out at an applied voltage and the output light L.sub.out at a null point voltage. The extinction ratio is a ratio of the maximum value and the minimum value of the output light L.sub.out within a range of an applied voltage.
(49) As illustrated in FIGS. **5** and **7**, when the minimum value voltage Vmin is set within the voltage width R1, the optical modulation element **100** operates in a region in which the quantity of the output light L.sub.out is relatively small, but the relative extinction ratio with respect to the applied voltage width Vpp can be increased.
(50) Here, as illustrated in FIG. **7**, in a region in which the quantity of the output light L.sub.out of the optical modulation element **100** is sufficiently small (in the vicinity of the null point voltage Vn), change in extinction ratio is significant. An extinction ratio required for an optical modulator for a data center needs to be 3 dB or larger and is more preferably 6 dB or larger. A region having a large amount of change in extinction ratio can be utilized by setting the minimum value voltage Vmin within the voltage width R1, and a high extinction ratio can be obtained at a low drive voltage (0.4 Vπ or lower).
(51) In addition, in the optical modulation element **100** using a lithium niobate film, if it is intended to maximize the extinction ratio, the drive voltage increases. However, it is possible to secure an extinction ratio of 3 dB or larger which can be used for a data center and to perform low-voltage

driving (0.4 $V\pi$ or lower) by setting the minimum value voltage Vmin within R1 and setting the applied voltage width Vpp in a range of $0.06\times V\pi \le Vpp \le 0.4\times V\pi$.

(52) As described above, the optical modulator **200** according to the first embodiment can secure an extinction ratio of 3 dB or larger and perform low-voltage driving (0.4 $V\pi$ or lower). The drive voltage is required to be $0.4\times V\pi$ or lower, more preferably $0.35\times V\pi$ or lower, further preferably $0.3\times V\pi$ or lower, and most preferably $0.25\times V\pi$ or lower. Further, it is preferable to set the operating point such that the extinction ratio shown in Table 1 becomes 6 dB or larger with a drive voltage of $0.4\times V\pi$ or lower. Table 1 is a table showing a relationship among the minimum value voltage Vmin, the applied voltage width Vpp, and the extinction ratio. Both the minimum value voltage Vmin and the applied voltage width Vpp are values standardized by the half-wavelength voltage. In Table 1, the first column indicates the minimum value voltage ($Vmin/V\pi$), and the first row indicates $Vpp/V\pi$. In Table 1, the value of each cell indicates the extinction ratio (dB) when the minimum value voltage in the row where the cell belongs and Vpp in the column where the cell belongs are combined. For example, when the minimum value voltage ($Vmin/V\pi$) is 1.00 and $Vpp/V\pi$ is 0.25, the extinction ratio is 16.7 dB.

(53) For example, when the drive voltage is set to $0.4\times V\pi$, it is preferable to set the operating point Vd such that the minimum value voltage Vmin of the applied voltage width Vpp is within a range of Vn to $Vn+0.29\ V\pi$. In addition, when the drive voltage is set to $0.35\times V\pi$, it is preferable to set the operating point Vd such that the minimum value voltage Vmin of the applied voltage width Vpp is within a range of Vn to $Vn+0.27\ V\pi$. In addition, when the drive voltage is set to $0.3\times V\pi$, it is preferable to set the operating point Vd such that the minimum value voltage Vmin of the applied voltage width Vpp is within a range of Vn to $Vn+0.24\ V\pi$. In addition, when the drive voltage is set to $0.25\times V\pi$, it is preferable to set the operating point Vd such that the minimum value voltage Vmin of the applied voltage width Vpp is within a range of Vn to $Vn+0.21\ V\pi$.

(54) TABLE-US-00001 TABLE 1

Minimum value voltage	Vpp = 0.25	Vpp = 0.30	Vpp = 0.35	Vpp = 0.40
1.00	16.7	18.2	19.4	20.4
1.01	16.7	18.1	19.3	20.3
1.02	16.2	17.5	18.7	19.6
1.03	15.3	16.6	17.7	18.6
1.04	14.4	15.7	16.7	17.6
1.05	13.5	14.7	15.7	16.6
1.06	12.7	13.8	14.8	15.6
1.07	11.9	13.0	14.0	14.8
1.08	11.2	12.3	13.2	14.0
1.09	10.6	11.6	12.5	13.3
1.10	10.0	11.0	11.9	12.6
1.11	9.5	10.5	11.3	12.0
1.12	9.0	10.0	10.8	11.5
1.13	8.6	9.5	10.3	10.9
1.14	8.2	9.1	9.8	10.5
1.15	7.8	8.7	9.4	10.0
1.16	7.5	8.3	9.0	9.6
1.17	7.2	8.0	8.7	9.2
1.18	6.9	7.7	8.3	8.9
1.19	6.6	7.4	8.0	8.6
1.20	6.3	7.1	7.7	8.2
1.21	6.1	6.8	7.4	7.9
1.22	5.9	6.6	7.2	7.7
1.23	5.7	6.3	6.9	7.4
1.24	5.5	6.1	6.7	7.1
1.25	5.3	5.9	6.4	6.9
1.26	5.1	5.7	6.2	6.7
1.27	4.9	5.5	6.0	6.4
1.28	4.7	5.3	5.8	6.2
1.29	4.6	5.1	5.6	6.0

(55) Thus far, the optical modulator **200** according to the first embodiment has been described as an example, but the present invention is not limited to the first embodiment and various modifications can be made.

(56) For example, the applied voltage width Vpp may be set to $0.06\times V\pi \le Vpp \le 0.35\times V\pi$. In this case, the extinction ratio of the optical modulator **200** can be set to 3 dB or larger at a smaller applied voltage.

(57) In addition, for example, the applied voltage width Vpp may be set to $0.06\times V\pi \le Vpp \le 0.3\times V\pi$. In this case, the extinction ratio of the optical modulator **200** can be set to 3 dB or larger at a much smaller applied voltage than when the applied voltage width Vpp is set to $0.06\times V\pi \le Vpp \le 0.35\times V\pi$. More preferably, the applied voltage width Vpp is $0.06\times V\pi \le Vpp \le 0.25\times V\pi$.

(58) When Vpp is set to $0.4\times V\pi$ or lower, it is preferable to set the operating point voltage Vd such that the minimum value voltage Vmin of Vpp becomes $Vn \le Vmin \le Vn+0.29\times V\pi$. When Vpp is set to $0.35\times V\pi$ or lower, it is preferable to set the operating point voltage Vd such that the minimum value voltage Vmin becomes $Vn \le Vmin \le Vn+0.27\times V\pi$. When Vpp is set to $0.3\times V\pi$ or lower, it is preferable to set the operating point voltage Vd such that the minimum value voltage Vmin of Vpp becomes $Vn \le Vmin \le Vn+0.24\times V\pi$. When Vpp is set to $0.25\times V\pi$ or lower, it is preferable to set the operating point voltage Vd such that the minimum value voltage Vmin of Vpp becomes

$Vn \le Vmin \le Vn + 0.21 \times V\pi$.

(59) In FIG. **6**, the minimum value voltage Vmin of the applied voltage width Vpp is set in a range of the voltage width R1, but the maximum value voltage Vmax of the applied voltage width Vpp may be set in a range of the voltage width R2 as shown in FIG. **8**. In this case, the voltage width R2 is defined by the half-wavelength voltage Vπ and the null point voltage Vn. Specifically, the voltage width R2 is a range of $Vn-0.29 \times V\pi$ to Vn. That is, the maximum value voltage Vmax is designed to satisfy the foregoing Expression (2).

$$Vn-0.29\times V\pi \le V\mathrm{max} \le Vn \qquad (2)$$

(60) The extinction ratio can be 3 dB or larger at an applied voltage with the applied voltage width Vpp in a range of $0.06 \times V\pi \le Vpp \le 0.4 \times V\pi$ by setting Vmax a range of $Vn-0.29 \times V\pi$ to Vn. Further, while the drive voltage is $0.4 \times V\pi$ or lower, it is more preferable to set the operating point such that the extinction ratio becomes 6 dB or larger.

(61) For example, in a case of setting the voltage width R2 to a side smaller than the null point voltage Vn, when the drive voltage is set to $0.4 \times V\pi$, it is preferable to set the operating point Vd such that the maximum value voltage Vmax of the applied voltage width Vpp is within a range of Vn to $Vn-0.29\ V\pi$. In addition, when the drive voltage is set to $0.35 \times V\pi$, it is preferable to set the operating point Vd such that the maximum value voltage Vmax of the applied voltage width Vpp is within a range of Vn to $Vn-0.27\ V\pi$. In addition, when the drive voltage is set to $0.3 \times V\pi$, it is preferable to set the operating point Vd such that the maximum value voltage Vmax of the applied voltage width Vpp is within a range of Vn to $Vn-0.24 \times V\pi$. In addition, when the drive voltage is set to $0.25 \times V\pi$, it is preferable to set the operating point Vd such that the maximum value voltage Vmax of the applied voltage width Vpp is within a range of Vn to $Vn-0.21\ V\pi$.

(62) For example, the applied voltage width Vpp may be set to $0.06 \times V\pi \le Vpp \le 0.35 \times V\pi$. In this case, the extinction ratio of the optical modulator **200** can be set to 3 dB or larger at a smaller applied voltage.

(63) In addition, for example, the applied voltage width Vpp may be set to $0.06 \times V\pi \le Vpp \le 0.3 \times V\pi$. In this case, the extinction ratio of the optical modulator **200** can be set to 3 dB or larger at a much smaller applied voltage than when the applied voltage width Vpp is set to $0.06 \times V\pi \le Vpp \le 0.35 \times V\pi$. The more preferable applied voltage width Vpp is $0.06 \times V\pi \le Vpp \le 0.25 \times V\pi$.

(64) When Vpp is set to $0.4 \times V\pi$ or lower, it is preferable to set the operating point voltage Vd such that the maximum value voltage Vmax of Vpp becomes $Vn-0.29 \times V\pi \le Vmaxb \le Vn$. When Vpp is set to $0.35 \times V\pi$ or lower, it is preferable to set the operating point voltage Vd such that the maximum value voltage Vmax of Vpp becomes $Vn-0.27 \times V\pi \le Vmax \le Vn$. When Vpp is set to $0.3 \times V\pi$ or lower, it is preferable to set the operating point voltage Vd such that the maximum value voltage Vmax of Vpp becomes $Vn-0.24 \times V\pi \le Vmax \le Vn$. When Vpp is set to $0.25 \times V\pi$ or lower, it is preferable to set the operating point voltage Vd such that the maximum value voltage Vmax of Vpp becomes $Vn-0.21 \times V\pi \le Vmax \le Vn$.

(65) In addition, in the foregoing form, the control unit controls the operating point voltage Vd of the optical modulation element **100** but may control the minimum value voltage Vmin or the maximum value voltage Vmax.

(66) As in FIG. **9**, in an optical modulation element **101** according to the present embodiment, a first optical waveguide **51** and a second optical waveguide **52** may be curved. FIG. **9** is a plan view of the optical modulation element **101** according to a first modification in a plan view in the z direction. The optical modulation element **101** has an optical waveguide **50** and electrodes **61**, **62**, **63**, and **64**.

(67) The optical waveguide **50** has the first optical waveguide **51**, the 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** differs from the optical waveguide **10** in that the first optical waveguide **51** and the second optical waveguide **52** are curved in the middle thereof. The optical waveguide **50** is otherwise similar to the optical waveguide **10**.

(68) The electrodes **61** and **62** are electrodes for applying the modulation voltage Vm to the optical waveguide **50**. The electrode **61** is an example of the first electrode, and the electrode **62** is an example of the 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 terminal 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 terminal resistor **32**. The electrodes **63** and **64** are electrodes for applying the DC bias Vdc to the optical waveguide **50**. A first end **63***a* of the electrode **63** and a first end **64***a* of the power supply **64** are connected to the power supply **33**.
(69) In FIG. **9**, since the line widths and the line spacings of the electrode **61** and the electrode **62** disposed in a parallel manner are made wider, although the length of a part in which the electrode **61** and the first optical waveguide **51** overlap and the length of a part in which the electrode **62** and the second optical waveguide **52** overlap are illustrated such that they are different, the lengths thereof are substantially the same. Similarly, the length of a part in which the electrode **63** and the first optical waveguide **51** overlap and the length of a part in which the electrode **64** and the second optical waveguide **52** overlap are substantially the same.
(70) The electrode **61** and the electrode **62** differ 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**. Each of the electrodes **61**, **62**, **63**, and **64** is otherwise similar to each of the electrodes **21**, **22**, **23**, and **24**.
(71) In the optical modulation element **101**, since the first optical waveguide **51** and the second optical waveguide **52** are curved, the element size in the x direction is small. For example, the optical modulation element **101** can be realized to have an element size of 100 mm.sup.2 or smaller and preferably 50 mm.sup.2 or smaller. An optical modulator for a data center is required to be miniaturized. Since the optical waveguide **50** is curved, the optical modulation element **101** can also be accommodated in a small-sized region corresponding to an existing optical modulator for a data center.
REFERENCE SIGNS LIST
(72) **10**, **50** Optical waveguide **11**, **51** First optical waveguide **12**, **52** Second optical waveguide **13**, **53** Input path **14**, **54** Output path **15**, **55** Branch portion **16**, **56** 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.sub.in Input light L.sub.out Output light L.sub.b Branch light Vmin Minimum value voltage Vmax Maximum value voltage Vd Operating point voltage Vn Null point voltage Vπ Half-wavelength voltage Vpp Applied voltage width

Claims

1. An optical modulator comprising: an optical modulation element having a first optical waveguide, a second optical waveguide, a first electrode configured to apply an electric field to the first optical waveguide, and a second electrode configured to apply 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, wherein the control unit sets Vpp to $0.06\times V\pi \leq Vpp \leq 0.4\times V\pi$ when a half-wavelength voltage of the optical modulation element is Vπ and an applied voltage width that is an amplitude of the applied voltage applied to the optical modulation element is Vpp, and sets $Vn \leq Vmin \leq Vn+0.29\times V\pi$ or $Vn-0.29\times V\pi \leq Vmax \leq Vn$ when a minimum value and a maximum value of a voltage applied to the optical modulation element are respectively Vmin and Vmax and a null point voltage of the optical modulation element is Vn, wherein the optical modulation element is configured to have an extinction ratio of 3 dB or larger when being operated at a drive voltage lower than the half-wavelength voltage.
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 method comprising driving an optical modulation element having a first optical waveguide, a second optical waveguide, a first electrode at a position overlapping the first optical waveguide in a plan view, and a second electrode at a position overlapping the second optical waveguide in a plan view, wherein Vpp is set to $0.06 \times V\pi \leq Vpp \leq 0.4 \times V\pi$ when a half-wavelength voltage of the optical modulation element is $V\pi$ and an applied voltage width that is an amplitude of the applied voltage applied to the optical modulation element is Vpp, $Vn \leq Vmin \leq Vn + 0.29 \times V\pi$ or $Vn - 0.29 \times V\pi \leq Vmax \leq Vn$ is set when a minimum value and a maximum value of a voltage applied to the optical modulation element are respectively Vmin and Vmax and a null point voltage of the optical modulation element is Vn, and the optical modulation element has an extinction ratio of 3 dB or larger while being driven at a drive voltage lower than the half-wavelength voltage.

4. The method for driving 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.