

# US Patent & Trademark Office

## Patent Public Search | Text View

---

United States Patent	12386214
Kind Code	B2
Date of Patent	August 12, 2025
Inventor(s)	Utsunomiya; Hajime et al.

---

### Optical modulator and driving method of optical modulation element

---

#### 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  $V_n$ , the control unit sets an operating point  $V_d$  in a range of  $V_n + 0.50V\pi \leq V_d \leq V_n + 0.75V\pi$  or  $V_n - 0.75V\pi \leq V_d \leq V_n - 0.50V\pi$  and sets an applied voltage width  $V_{pp}$ , which is an amplitude of an applied voltage applied to the optical modulation element, in a range of  $0.22V\pi \leq V_{pp} \leq 0.50V\pi$ .

---

<b>Inventors:</b>	Utsunomiya; Hajime (Tokyo, JP), Kikukawa; Takashi (Tokyo, JP)
<b>Applicant:</b>	TDK CORPORATION (Tokyo, JP)
<b>Family ID:</b>	1000008750566
<b>Assignee:</b>	TDK CORPORATION (Tokyo, JP)
<b>Appl. No.:</b>	17/928386
<b>Filed (or PCT Filed):</b>	June 18, 2021
<b>PCT No.:</b>	PCT/JP2021/023145
<b>PCT Pub. No.:</b>	WO2022/034742
<b>PCT Pub. Date:</b>	February 17, 2022

#### Prior Publication Data

<b>Document Identifier</b>	<b>Publication Date</b>
US 20230213791 A1	Jul. 06, 2023

#### Foreign Application Priority Data

**Publication Classification****Int. Cl.:** G02F1/035 (20060101); G02F1/01 (20060101)**U.S. Cl.:****CPC** G02F1/035 (20130101); G02F1/0123 (20130101);**Field of Classification Search****CPC:** G02F (1/0123); G02F (1/035)

---

**References Cited****U.S. PATENT DOCUMENTS**

<b>Patent No.</b>	<b>Issued Date</b>	<b>Patentee Name</b>	<b>U.S. Cl.</b>	<b>CPC</b>
6334004	12/2000	Ohkuma et al.	N/A	N/A
8849071	12/2013	Kissa	385/50	G02F 1/225
10243667	12/2018	Iwata	N/A	H04B 10/50575
12242143	12/2024	Yoshida	N/A	G02F 1/035
12248205	12/2024	Utsunomiya	N/A	G02F 1/0316
2002/0146190	12/2001	Doi	385/40	G02F 1/2255
2015/0138619	12/2014	Iwatsuka et al.	N/A	N/A
2018/0294888	12/2017	Iwata et al.	N/A	N/A
2022/0276513	12/2021	Utsunomiya	N/A	G02F 1/212
2023/0213791	12/2022	Utsunomiya	385/2	G02F 1/2255
2023/0229030	12/2022	Utsunomiya	385/2	G02F 1/035

**FOREIGN PATENT DOCUMENTS**

<b>Patent No.</b>	<b>Application Date</b>	<b>Country</b>	<b>CPC</b>
H09-211400	12/1996	JP	N/A
2000-180804	12/1999	JP	N/A
2004-037695	12/2003	JP	N/A
4164179	12/2007	JP	N/A
2015-102686	12/2014	JP	N/A
2018-182465	12/2017	JP	N/A
2019-045880	12/2018	JP	N/A

**OTHER PUBLICATIONS**

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

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

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

---

## Background/Summary

### TECHNICAL FIELD

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

(2) 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

(3) 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.

(4) 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.

(5) 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

(6) [Patent Document 1]

(7) 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

(8) 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.

(9) 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.

(10) 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

(11) (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  $V_n$ , the control unit sets an operating point  $V_d$  in a range of  $V_n + 0.50V\pi \leq V_d \leq V_n + 0.75V\pi$  or  $V_n - 0.75V\pi \leq V_d \leq V_n - 0.50V\pi$  and sets an applied voltage width  $V_{pp}$ , which is an amplitude of an applied voltage applied to the optical modulation element, in a range of  $0.22V\pi \leq V_{pp} \leq 0.50V\pi$ .

(12) (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.

(13) (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  $V_d$  in a range of  $V_n + 0.50V\pi \leq V_d \leq V_n + 0.75V\pi$  or  $V_n - 0.75V\pi \leq V_d \leq V_n - 0.50V\pi$ , when a half-wave voltage of the optical modulation element is  $V\pi$  and a null point voltage of the optical modulation element is  $V_n$ ; and setting an applied voltage width  $V_{pp}$ , which is an amplitude of an applied voltage applied to the optical modulation element, in a range of  $0.22V\pi \leq V_{pp} \leq 0.50V\pi$ .

(14) (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

(15) 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.

---

## 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 of an optical modulation element according to the first embodiment.

(3) FIG. 3 is a plan view of the 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 diagram showing a relationship between an applied voltage and an output of the optical modulator according to the first embodiment.

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

(7) 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.

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

## DESCRIPTION OF EMBODIMENTS

(9) 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.

(10) 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.

(11) 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.

(12) The optical modulation element **100** converts an electrical signal into an optical signal. The optical modulation element **100** converts input light **L.sub.in** that has been input into an output light **L.sub.out** according to a modulation signal **Sm**.

(13) The drive circuit **110** applies a modulation voltage **V<sub>m</sub>** according to the modulation signal **Sm** to the optical modulation element **100**. The DC bias application circuit **120** applies a DC bias voltage **V<sub>dc</sub>** 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 **V<sub>dc</sub>** output from the DC bias application circuit **120**. When the DC bias voltage **V<sub>dc</sub>** is adjusted, an operating point **V<sub>d</sub>** to be described later is controlled.

(14) 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**.

(15) 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.

(16) 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**.

(17) 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 **40a** of the oxide film **40**. The first surface **40a** 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 **40a** 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  $\mu\text{m}$  or more and 5.0  $\mu\text{m}$  or less, and a height of the ridge-shaped portion (protrusion height from the first surface **40a**) is, for example, 0.1  $\mu\text{m}$  or more and 1.0  $\mu\text{m}$  or less.

(18) 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  $2\theta$ - $\theta$  X-ray diffraction. Also, the oxide film **40** may be a lithium niobate film provided on a Si substrate via SiO.sub.2.

(19) A composition of the lithium niobate is Li.sub.xNbA.sub.yO.sub.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.

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

(21) The electrodes **23** and **24** are electrodes that apply the DC bias voltage  $V_{dc}$  to the optical waveguide **10**. A first end **23a** of the electrode **23** and a first end **24a** 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  $V_{dc}$  to the optical modulation element **100**.

(22) 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.

(23) Also, when the DC bias voltage  $V_{dc}$  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**.

(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**.

(25) 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<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, MgF<sub>2</sub>, La<sub>2</sub>O<sub>3</sub>, ZnO, HfO<sub>2</sub>, MgO, Y<sub>2</sub>O<sub>3</sub>, CaF<sub>2</sub>, In<sub>2</sub>O<sub>3</sub>, or the like, or a mixture thereof.

(26) 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.

(27) The optical modulation element **100** converts an electrical signal into an optical signal. The optical modulation element **100** modulates the input light L<sub>sub.in</sub> into the output light L<sub>sub.out</sub>. First, a modulation operation of the optical modulation element **100** will be described.

(28) The input light L<sub>sub.in</sub> 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.

(29) 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  $+\Delta n$  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  $n$ .

(30) 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<sub>sub.out</sub>. The output light L<sub>sub.out</sub> 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<sub>sub.out</sub> 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  $\pi$ , the light intensifies each other, and when the phase difference is an odd multiple of  $\pi$ , the light weakens each other. With such a procedure, the optical modulation element **100** modulates the input light L<sub>sub.in</sub> into the output light L<sub>sub.out</sub> according to the electrical signal.

(31) The modulation voltage  $V_m$  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  $V_{dc}$  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  $V_d$  of the optical modulation element **100** by controlling the DC bias voltage  $V_{dc}$ . The operating point  $V_d$  refers to a

voltage that is a center of a modulation voltage amplitude.

(32) The DC bias control circuit **130** is configured to set the operating point  $V_d$  of the optical modulation element **100** within a voltage width  $R1$ . The voltage width  $R1$  is defined by a half-wave voltage  $V_\pi$  and a null point voltage  $V_n$ .

(33) 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.

(34) Next, the null point voltage  $V_n$  and the half-wave voltage  $V_\pi$  will be described.

(35) 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.

(36) 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  $V_n$ . The null point voltage  $V_n$  can be ascertained by measuring a voltage when a light output from the optical modulation element **100** is minimized. Specifically, the null point voltage  $V_n$  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.

(37) The half-wave voltage (half-wave phase modulation voltage) is a voltage for making a phase difference of light  $180^\circ$  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  $V_\pi$ . When a voltage exceeding the null point voltage  $V_n$  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  $V_\pi$ . The half-wave voltage  $V_\pi$  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  $V_\pi$  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.

(38) The half-wave voltage  $V_\pi$  of the optical modulation element **100** changes according to a configuration of the optical modulation element **100**. The half-wave voltage  $V_\pi$  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  $V_\pi$  reduces, and when the interaction length becomes small, the half-wave voltage  $V_\pi$  increases.

(39) 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  $V_\pi$  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  $V\pi$  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  $V_d$  within the voltage width **R1** and controls an applied voltage width  $V_{pp}$  to be described later.

(40) The voltage width **R1** is in a range of  $V_n+0.50V\pi$  or more and  $V_n+0.75V\pi$  or less, or  $V_n-0.75V\pi$  or more and  $V_n-0.50V\pi$  or less. That is, the operating point  $V_d$  is designed to satisfy the following relational expression.

$$V_n+0.50V\pi \leq V_d \leq V_n+0.75V\pi \text{ or } V_n-0.75V\pi \leq V_d \leq V_n-0.50V\pi$$

(41) The operating point  $V_d$  may fluctuate due to a temperature of a usage environment or the like. If the operating point  $V_d$  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  $V_d$  based on, for example, branched light **L.sub.b** branched off from the output light **L.sub.out**.

(42) The drive circuit **110** controls the applied voltage width  $V_{pp}$  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.

(43) FIG. 6 is a diagram for explaining the applied voltage width  $V_{pp}$  of the optical modulator **200** according to the first embodiment. FIG. 6 is a diagram in which a description of the applied voltage width  $V_{pp}$  is added to FIG. 5.

(44) The applied voltage width  $V_{pp}$  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  $V_d$  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  $V_{pp}$  with the operating point  $V_d$  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  $V_{pp}$ .

(45) For example, when the operating point  $V_d$  is  $V_n+0.5\pi$  and the applied voltage width  $V_{pp}$  is a half-wave voltage  $V\pi$ , a voltage in a range of  $V_n$  to  $V_n+V\pi$  is applied to the optical modulation element **100**. The output from the optical modulation element **100** is minimum when an applied voltage is  $V_n$  and is maximum when the applied voltage is  $V_n+V\pi$ . That is, when the applied voltage width  $V_{pp}$  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.

(46) The drive circuit **110** is configured to set the applied voltage width  $V_{pp}$  applied to the optical modulation element **100** in a range of  $0.22V\pi \leq V_{pp} \leq 0.50V\pi$ .

(47) The applied voltage width  $V_{pp}$  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.

(48) 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.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 a maximum value and a minimum value of the output light **L.sub.out**.

(49) As shown in FIGS. 5 and 7, when the operating point  $V_d$  is set within the voltage width **R1**

and the applied voltage width  $V_{pp}$  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  $L_{sub.out}$  is relatively large.

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

(51) 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  $L_{sub.out}$  of the optical modulation element **100** is sufficiently large, sufficient sensitivity can be obtained. For example, if the operating point  $V_d$  is set within the voltage width  $R1$  and the applied voltage width  $V_{pp}$  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.

(52) Here, as shown in FIG. 7, an extinction ratio is small in a region in which the amount of light of the output light  $L_{sub.out}$  of the optical modulation element **100** is sufficiently large. For example, under the condition that the applied voltage width  $V_{pp}$  is the same, when the operating point  $V_d$  is set at a position away from the null point voltage  $V_n$ , an amount of light increases compared to a case in which the operating point  $V_d$  is set in the vicinity of the null point voltage  $V_n$ , 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  $V_d$  is set within the voltage width  $R1$  and the applied voltage width  $V_{pp}$  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.

(53) 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  $V_{pp}$  is set within a predetermined range, the optical modulator **200** can be driven at a low voltage.

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

(55) 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.

(56) For example, the operating point  $V_d$  may be set in a range of  $V_n + 0.62V_\pi \leq V_d \leq V_n + 0.75V_\pi$  or  $V_n - 0.75V_\pi \leq V_d \leq V_n - 0.62V_\pi$ , and the applied voltage width  $V_{pp}$  may be set in a range of  $0.32V_\pi \leq V_{pp} \leq 0.50V_\pi$ . In this case, a modulation loss of the optical modulation element **100** can be made 2 dB or less.

(57) Also, for example, the operating point  $V_d$  may be set in a range of  $V_n + 0.62V_\pi \leq V_d \leq V_n + 0.73V_\pi$  or  $V_n - 0.73V_\pi \leq V_d \leq V_n - 0.62V_\pi$ , and the applied voltage width  $V_{pp}$  may be set in a range of  $0.32V_\pi \leq V_{pp} \leq 0.50V_\pi$ . At a position at which the output of the output light  $L_{sub.out}$  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.

(58) 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**.

(59) 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**.

(60) The electrodes **61** and **62** are electrodes that apply the modulation voltage  $V_m$  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 **61a** of the electrode **61** is connected to the power supply **31**, and a second end **61b** is connected to the terminating resistor **32**. A first end **62a** of the electrode **62** is connected to the power supply **31**, and a second end **62b** is connected to the terminating resistor **32**. The electrodes **63** and **64** are electrodes that apply the DC bias voltage  $V_{dc}$  to the optical waveguide **50**. A first end **63a** of the electrode **63** and a first end **64a** of the electrode **64** are connected to the power supply **33**.

(61) 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.

(62) 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**.

(63) 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  $\mu\text{m}$  or less and preferably 50  $\mu\text{m}$  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

(64) **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 **40a** 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 Branched light  $V_d$  Operating point  $V_n$  Null point voltage  $V_{\pi}$  Half-wave voltage  $V_{pp}$  Applied voltage width

## Claims

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  $V_{\pi}$  and a null point voltage of the optical modulation element is  $V_n$ , the control unit sets an operating point  $V_d$  in a range of  $V_n + 0.50V_{\pi} \leq V_d \leq V_n + 0.75V_{\pi}$  or  $V_n - 0.75V_{\pi} \leq V_d \leq V_n - 0.50V_{\pi}$  and sets an applied voltage width  $V_{pp}$ , which is an amplitude of an applied voltage applied to the optical modulation element, in a range of  $0.22V_{\pi} \leq V_{pp} \leq 0.50V_{\pi}$ .

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  $V_d$  in a range of  $V_n + 0.50V_\pi \leq V_d \leq V_n + 0.75V_\pi$  or  $V_n - 0.75V_\pi \leq V_d \leq V_n - 0.50V_\pi$ , when a half-wave voltage of the optical modulation element is  $V_\pi$  and a null point voltage of the optical modulation element is  $V_n$ ; and setting an applied voltage width  $V_{pp}$ , which is an amplitude of an applied voltage applied to the optical modulation element, in a range of  $0.22V_\pi \leq V_{pp} \leq 0.50V_\pi$ .

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.

---