Fabrication and Properties of a 4 × 4 LiNbO₃ Optical Matrix Switch *¹

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To realize channel cross-connecting in optical communications systems, a high speed optical matrix switch was fabricated using z-cut LiNbO₃. Four 2 × 2 directional couplers were integrated on one substrate for construction of a 4 × 4 switch. Single-mode optical waveguides were formed by Ti-diffusion at a wet O₂ atmosphere. Ti-diffusion profile, refractive index variation and waveguide morphology were analyzed by SIMS, Prism coupler and SEM, respectively. The optical properties of the fabricated switch was measured in terms of insertion loss, cross-talk, spectral flatness and switching speed.

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1. Introduction

An optical matrix switch is a key component for WDM (wavelength division multiplexing) OXC (optical cross-connect) and an optical packet switch. Recently various types of optical switches were developed, and they can be categorized into three groups in respect of operation. One is to utilize optical mirrors to change optical beam paths, which appeals great interests due to the development of micro-electro-mechanical system (MEMS) technology.¹ Other is to employ acousto-optic deflection where optical beam paths are changed by the degree of deflection.² In the other, switching is achieved by constructing directional couplers in optical waveguides.

Waveguide switches show high speed response time while MEMS switches are strong in extending input/output ports. Thus, waveguide devices are used for high speed switching and MEMS technologies are utilized for multi-port matrix switches. Thermo-optic effect and electro-optic effect can be exploited for waveguide devices, and the representative material showing a high electro-optic coefficient is Lithium Niobate (LiNbO₃). Commercially available LiNbO₃ wafer is Li-deficient in composition (the typical mole ratio of Li : Nb = 48.5 : 51.5). The stoichiometric LiNbO₃ with an Li : Nb ratio ≈ 1 : 1 was reported to have an electro-optic coefficient 20% higher than that of non-stoichiometric LiNbO₃ and to have been commercialized recently.

In this work, to realize a high speed optical matrix switches, channel-type optical waveguides were used, which were formed by Ti-indiffusion on z-cut LiNbO₃ wafers. The width and separation of Ti-strip were calculated so that the driving voltage for switching should be less than 5 V. The waveguide structure and dimension were optimized by numerical analysis such as a normal mode theory and a semi-vectorial finite difference method.

The switch unit of a 4 × 4 matrix switch was a 2 × 2 directional coupler, four of which were integrated into one matrix switch. Since the device properties, particularly insertion loss and the degree of integration, are affected decisively by bending structure, bending loss was calculated for various bending shapes; linear, sine, cosine and double arc bending shapes, respectively.

2. Single-mode Waveguide Fabrication

Figure 1 illustrates the procedure of Ti-diffused optical waveguide fabrication. The Ti layer, deposited on a z-cut LiNbO₃ wafer by an E-beam system, was patterned by UV-lithography and etching and was in-diffused at 1050°C and wet O₂ atmosphere. The O₂ atmosphere prohibits the Ti:LiNbO₃ from degraded crystallinity. The amount of O₂ flowed onto the wafer affected the surface morphology after

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diffusion. Excess or insufficient O\textsubscript{2} made the surface rough, as shown in Fig. 2, while a smooth and clean surface was obtained at proper O\textsubscript{2} amount.

It has been reported that Ti:LiNbO\textsubscript{3} waveguide, which have a refractive index higher than LiNbO\textsubscript{3}, is formed by Ti oxidation at temperature above \(\sim 700^\circ\text{C}\), followed by formation of (Ti\textsubscript{0.65}Nb\textsubscript{0.35})O\textsubscript{2} phase.\textsuperscript{3} This phase grows epitaxially on a z-cut LiNbO\textsubscript{3} wafer and acts as a source of Ti to the wafer inside during a diffusion processing. It is known that the water vapor content affects significantly the diffusion length in a lateral direction but does not affect in a depth direction.\textsuperscript{4,5}

The refractive index profile in a depth direction of Ti-diffused waveguide is important in determination of mode matching between fiber core and surface scattering. Figure 3 shows depth-directional index profiles of Ti:LiNbO\textsubscript{3} waveguides which were formed from different Ti thickness and different diffusion conditions, which are summarized in Table 1. The refractive index was measured by a prism coupler with a 45° rutile prism and a 0.6328 \(\mu\text{m}\) He/Ne laser. The refractive index increased with Ti thickness. However, as illustrated by Fig. 3, a wafer foldering method decreased the refractive indices at the surfaces, compared with a conventional method. The decrease of the index can be assumed to result from that Li ions was supplied from the dummy LiNbO\textsubscript{3} wafer used as a cap in a wafer foldering method. Decreased of the refractive index is found in a stoichiometric LiNbO\textsubscript{3}, which contains more Li ions than general LiNbO\textsubscript{3}.

### 3. Waveguide-type Optical Matrix Switch Design

Figures 4(a) and (b) show a schematic of a two-waveguide directional coupler, which is a unit device of a matrix switch, and a cross-section of a coupling region, respectively. As shown in Fig. 4(a), the two waveguide directional coupler consists of input/output ports, which have S-bend structures, and an interaction region where lights propagating along two waveguides couple each other. To reduce the propagation loss of TM mode by metal electrodes, a SiO\textsubscript{2} buffer layer was deposited between electrode and waveguide. The normal mode theory was applied to obtain the coupler length, \(l_c\).

#### 3.1 Normal mode theory

In a normal mode theory, two waveguides are dealt as a single waveguide where two eigenmode, \(\beta_e\) (even) and \(\beta_o\) (odd), always exist. An incident beam to one of two waveguides is completely coupled to the other when the phase difference between the even mode and the odd mode is \(\pi\) after the beam travels along the directional coupler by \(l_c\). This condition can be expressed as

\[
l_c = \frac{\pi}{\beta_e - \beta_o}
\]

where \(\beta_e\) and \(\beta_o\) can be derived by semi-vectorial finite difference method or semi-vectorial finite element method.

#### 3.2 Driving voltage

Electrical field induces the change of a propagation constant of each waveguide. The difference of propagation constants, \(\Delta\beta\), can be expressed as a switching voltage, \(V_{SW}\), as

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**Table 1** Description of samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ti thickness</th>
<th>Diffusion method</th>
<th>Diffusion condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>110 nm</td>
<td>Conventional</td>
<td>Temperature: 1050°C</td>
</tr>
<tr>
<td>B</td>
<td>110 nm</td>
<td>Wafer foldering</td>
<td>Ramp time: 2 h, 95°C</td>
</tr>
<tr>
<td>C</td>
<td>90 nm</td>
<td>Conventional</td>
<td>Diffusion: 8 h, wet O\textsubscript{2} bubbling</td>
</tr>
<tr>
<td>D</td>
<td>90 nm</td>
<td>Wafer foldering</td>
<td>natural cooling</td>
</tr>
</tbody>
</table>

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**Fig. 2** Surface photographs (\(\times\)1000) of waveguides Ti-indiffused at atmosphere of (a) excess O\textsubscript{2} and (b) 2 bubbles of O\textsubscript{2}.

**Fig. 3** The refractive index profiles, in a depth direction, of a z-cut Ti:LiNbO\textsubscript{3} after diffusion. Ti strip thickness was 110 nm for (a) and (b), and 90 nm for (c) and (d), respectively. The curves and (c) depict the index profiles when diffusion was conducted at only wet O\textsubscript{2} atmosphere, and (b) and (d) depict the profiles when a wafer foldering method was also accompanied.

**Fig. 4** Schematics of (a) a directional coupler switch unit and (b) cross-section of a directional coupler.


\[ \Delta \beta = k_0 \left[ \Delta n_1 + \Delta n_2 \right] = \frac{2\pi}{\lambda} \left[ \frac{1}{2} n_3^2 r_{33} (\Gamma_1 + \Gamma_2) \right] \frac{V_{SW}}{S} \] (2)

where

\[ \Gamma \cong \frac{\iint E_{op}^2 \cdot E_{el} \, dx \, dy}{\iint E_{op}^2 \, dx \, dy} \] (3)

where \( S \) and \( \Gamma_{1,2} \) are the separation between two electrodes and an overlap factor, respectively, and \( n_3^2 r_{33} = 3.06 \times 10^{-4} \text{ m}^2/\text{V}. \) In a direction coupler, the condition for switching is

bar state: \( \Delta \beta L/\pi = |\Delta \beta_1 + \Delta \beta_2| L/\pi = \sqrt{3} \) (4a)
cross state: \( \Delta \beta = 0, L = l_c \) (4b)

Accordingly, optical switching voltage, \( V_{SW} \), is

\[ V_{SW} = \sqrt{3} \cdot \frac{\lambda}{n_3^2 r_{33} (\Gamma_1 + \Gamma_2)} \frac{S}{l_c} \] (5)

3.3 Simulation for coupling length and driving voltage

\( \beta_e \) and \( \beta_o \) was obtained using semi-vectorial difference method, and the coupling length for switching was derived from eq. (1). Since a parasitic coupling is generated at the point where two S-bend waveguides approach each other, the directional coupler was fabricated, in practice, to have the coupling length slightly different from the simulation results.

The analysis conditions, to obtain \( \beta_e \) and \( \beta_o \) of the directional coupler using a semi-vectorial difference method, is summarized in Table 2. The analysis plane was partitioned to have grid spacing of \( dx = 0.3 \mu \text{m} \) and \( dy = 0.3 \mu \text{m}. \) To increase the computing efficiency, the grids was inhomogeneously meshed.

3.4 Bending loss in S-bend structures

The S-bend of a waveguide-type directional coupler is the most important part in device performance. Bending loss is greatly depend on the bending structure. In this work, bending loss for several structures, such as linear, sine, cosine and double arc structures, was calculated to find an optimized switch structure. A semi-vectorial difference beam propagation method and a transparent boundary condition were used for bending loss analysis.

The gap between waveguides of input (or output) ports, waveguide width and waveguide separation in a coupling region was given as 250 \( \mu \text{m} \), 7 \( \mu \text{m} \) and 7 \( \mu \text{m} \), respectively. The bending loss is a function of not only the bending structure but also the length of the S-bending region, \( L \) (refer to Fig. 5(a)). As \( L \) increases, the bending loss decreases and then is saturated. For example, the bending loss for a double arc bending structure decreases rapidly in the region of \( L = 1000 \) to 2000 \( \mu \text{m} \) but is saturated above \( L = \sim 4000 \mu \text{m} \), which is depicted in Fig. 6.

The bending loss, calculated under the design conditions \((W = 7 \mu \text{m}, S = 7 \mu \text{m}, L = 4000 \mu \text{m})\), for several bending structures are summarized and depicted in Table 3 and Fig. 7, respectively. The linear bends yielded significant loss, and the cosine bending structure showed the minimum loss contrary to expectation.

### Table 2

<table>
<thead>
<tr>
<th>Polarization</th>
<th>Wave-length</th>
<th>Diffusion temp.</th>
<th>Diffusion time</th>
<th>Ti strip thickness</th>
<th>dn/dc</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE mode</td>
<td>1.55 ( \mu \text{m} )</td>
<td>1050°C</td>
<td>6h</td>
<td>95 nm</td>
<td>0.625</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Bend</th>
<th>Linear</th>
<th>Sine</th>
<th>Double arc</th>
<th>Cosine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss (dB)</td>
<td>3.8823</td>
<td>0.1867</td>
<td>0.12</td>
<td>0.0367</td>
</tr>
</tbody>
</table>

\( (W = 7 \mu \text{m}, S = 7 \mu \text{m}, x = 125 - (W + S)/2, L = 4000 \mu \text{m}) \)
4. Optical Matrix Switch Fabrication and Results

According to the simulation results, an \(4 \times 4\) optical matrix switch was fabricated having four directional coupler switches as a \(2 \times 2\) optical switch, of which dimension was; \(W = 7 \mu m, S = 7 \mu m\) and \(L = 8000 \mu m\). The waveguide between input (output) ports and the coupling regions was patterned to have a cosine bending structure and was lengthened to \(8000 \mu m\) to reduce a bending loss further. The waveguide was produced by Ti-indiffusion as shown in Fig. 1 and electrode was deposited on the waveguide by an E-beam evaporator. Figures 8(a) and (b) show microscopic-photographs (\(\times 1000\) magnification) waveguide patterns in bending regions and a crossing region, respectively, both of which are cosine-bending shaped. The fabricated switch chip was pigtailed with 4-core fiber blocks to connect with optical input/output ports by using a UV-curable epoxy to minimize light-reflection from the end surfaces of \(LiNbO_3\) chip or fiber block. PMFs (Polarization maintenance fibers) were used for input ports to make only TM mode incident to the \(LiNbO_3\) chip and to utilize an electro-optic effect of a \(z\)-cut \(LiNbO_3\) wafer. Finally, the pigtailed switch chip was packaged inside a metal housing, and switch electrodes was connected with a 5-pin MT connector by an Au-wire bonding technique for switch operation. The photograph of a packaged matrix switch is given in Fig. 9.

The properties and performance of the fabricated optical switch were measured mainly in terms of insertion loss, switching speed, cross-talk (port isolation) and wavelength dependent loss. Prior to characterization of a \(4 \times 4\) matrix switch, a \(2 \times 2\) optical switch (directional coupler) was tested for more fundamental analysis of the matrix switch.

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REFERENCES