Polarization coupler for polarization-rotating Mach-Zehnder interferometer

Daiki Minemura\textsuperscript{1, a),} Shuyuan Liu\textsuperscript{1,} Yuya Shoji\textsuperscript{1,} and Tetsuya Mizumoto\textsuperscript{1}

Abstract We propose a 3 dB polarization coupler in which the input light of the TE mode is converted into two out-of-phase TM modes, and the input light of the TM mode is split into two in-phase TM modes. This was designed with a 3-steps taper structure. When a Mach-Zehnder interferometer (MZI) is composed of the proposed 3 dB coupler, the polarization of the output light is rotated depending on the phase difference between the two arms. By incorporating optical phase shifters, polarization rotation can be controlled in MZ devices. In this study, we optimized the design of the proposed 3 dB coupler, and numerically demonstrated polarization rotation in an MZI with the proposed couplers, depending on the phase difference between the two arms.

Keywords: polarization coupler, polarization rotation, phase shifter, MZI, silicon photonics, magneto-optical device

Classification: Integrated optoelectronics (lasers and optoelectronic devices, silicon photonics, planar lightwave circuits, polymer optical circuits, etc.)

1. Introduction

Recently, silicon photonics has been actively researched for their use in optical communication systems. Photonic circuits—with Si waveguides on silicon-on-insulator wafers—have refractive indices of 3.476 and 1.444 for the Si core and SiO\textsubscript{2} cladding, respectively, and the difference in refractive index between the core and cladding enables strong light confinement. Therefore, silicon photonics is effective in compact optical circuits and high-density integration for establishing photonics integrated circuits (PICs).

In PICs, the polarization rotator is important for polarization diversity and polarization control systems [1, 2, 3, 4, 5, 6]. Conventionally, to realize mode conversion between the transverse electric (TE) and transverse magnetic (TM) modes, the optical axis is rotated by 45° similar to a half-wave plate by employing a waveguide structure with asymmetry in the horizontal and vertical directions [7, 8, 9, 10, 11, 12, 13]. Otherwise, mode evolutions with asymmetric rib waveguides or taper stacking are utilized [14, 15, 16, 17]. However, to fabricate these devices, high accuracy is required in multiple lithography and etching processes. To avoid these problems, mode conversions between the TE 1st mode with odd function and TM 0th mode were developed, using tapered waveguides with asymmetry only in the vertical direction [18, 19, 20, 21, 22, 23].

In this study, we propose a 3 dB polarization coupler. The input light of the TE mode is converted into two out-of-phase TM modes and divided into two waveguides. Simultaneously, the input light of the TM mode is split into two in-phase TM modes and divided similar to a Y-splitter. When a Mach-Zehnder interferometer (MZI) is composed of the proposed 3 dB coupler, the polarization of the output light is rotated depending on the phase difference between the two arms. This MZI can operate as a tunable polarization rotator, and is simpler than conventional polarization rotators [3, 4, 5, 6, 21]. By incorporating optical phase shifters, such as MZ switches or modulators, polarization rotation can be controlled. Because the TM mode lights propagate in the MZI arms, the MZI is also useful for waveguide optical isolators operating with magneto-optical effects that are induced only in the TM mode [24, 25, 26, 27, 28, 29, 30]. First, we discuss the principle of conversion from the input TE mode into two out-of-phase TM modes in the coupler. Next, we design a 3-steps taper structure, and optimize the taper lengths to realize efficient mode conversion and low loss splitting. Finally, we numerically demonstrate a polarization rotation in an MZI with the proposed couplers, depending on the phase difference between the two arms.

2. Operation principle

Fig. 1 shows a schematic of the proposed 3 dB polarization coupler with an Si waveguide core on the SiO\textsubscript{2} layer and a CeY\textsubscript{2}Fe\textsubscript{5}O\textsubscript{12} (Ce:YIG) upper cladding layer. Ce:YIG is a magneto-optical material that is used in optical isolators [27, 28, 29, 30]. The refractive indices of Si, SiO\textsubscript{2}, and Ce:YIG are 3.476, 1.444, and 2.2, respectively, at the wavelength of 1.55 μm. Therefore, the waveguide exhibits asymmetry in the vertical direction between the upper and lower cladding layers. In this study, the height of Si is fixed at 0.22 μm, which is the standard for silicon photonics. The center waveguide was narrowed by a taper and terminated at the end. The width of the side waveguides was first widened and maintained by two output waveguides. Fig. 2 shows...
of center waveguide width \(w_c\) when the width of side waveguides is \(w_s = 0.5 \mu m\) and the gap was 0.2 \(\mu m\). Here, the TE\(_c\) and TM\(_c\) modes denote lights whose fields are mainly confined in the center waveguide. In addition, the TE\(_{c-S-IP}\), TE\(_{c-OP}\), TM\(_{c-IP}\), and TM\(_{c-OP}\) modes denote lights whose fields are mainly confined in the side waveguides, and their phases are the same (in-phase) or opposite (out-of-phase), respectively. When \(w_c\) is wider than \(w_s = 0.5 \mu m\), \(n_{eff}\) of the TE\(_c\) mode is higher than that of the TE\(_{c-IP}\) and TE\(_{c-OP}\) modes.

As \(w_c\) becomes narrow, \(n_{eff}\) of the TE\(_c\) mode decreases steeply. At \(w_c = w_s = 0.5 \mu m\), the TE\(_c\), TE\(_{c-IP}\), and TE\(_{c-OP}\) modes are hybridized to construct coupling modes. In addition, the TM\(_{c-S-IP}\) mode is a hybrid mode of the TM\(_c\) and TM\(_{c-IP}\) modes as the waveguide widths are close. Although \(n_{eff}\) of the TE\(_c\) and TM\(_{c-S-IP}\) modes cross at approximately \(w_c = 0.385 \mu m\), they are not transformed into each other because the electric fields are orthogonal and the symmetry in the electric field distribution does not allow mode hybridization. The TE\(_c\) and TM\(_{c-OP}\) modes are hybridized between \(w_c = 0.37\) and 0.38 \(\mu m\) because of the asymmetry in the electric field distribution, and therefore, transformed into each other. This is because the hybrid modes of the TE\(_c\) and TM\(_{c-OP}\) modes can have an oblique electric field in a zigzag direction when the waveguide has asymmetry in the vertical direction, as depicted in Fig. 2(a). For second taper, considering fabrication accuracy, we employ the initial and end widths of center waveguides of 0.38 \(\mu m\) and 0.37 \(\mu m\), respectively. In the proposed coupler with 3-steps taper, the input light of the TE\(_c\) mode at the waveguide with a width of 0.45 \(\mu m\) excites the TM\(_c\) mode at the first taper. The TE\(_c\) mode is converted into the TM\(_{c-OP}\) mode at the second taper, and divided into two TM\(_{OP}\) modes in the output waveguide through the third taper, as shown in Fig. 2(a).

Next, we discuss the mode split of the input TM mode into two TM\(_{OP}\) modes in the coupler. The input light of the TM mode at the input waveguide with a width of 0.45 \(\mu m\) excites the TM\(_{c-S-IP}\) mode at the first taper. The TM\(_{c-S-IP}\) mode is not converted into another mode, and gradually transformed into TM\(_{OP}\) mode at the second and third tapers because of the narrowing of the center waveguide. The TM\(_{OP}\) mode is divided into two TM\(_{OP}\) modes at the end of the third taper, as shown in Fig. 2(b).

### 3. Design of taper length

According to the aforementioned operation principle, we set the waveguide width of 3-steps taper, as shown in Fig. 4. In this section, we optimize taper lengths \(L_1\), \(L_2\), and \(L_3\) to maximize the conversion efficiency and minimize excess loss. We used the eigenmode expansion method with a finite-difference mode solver. The size of the computational region in the cross section was fixed at 4 × 4 \(\mu m\), which contained three waveguides and the total thickness of the materials. The other parameters are shown in Fig. 4. The input waveguide with a width of 0.45 \(\mu m\) and two output waveguides, each with a width of 0.50 \(\mu m\), are connected to the coupler. We evaluated the transmittance from the input waveguide to the sum of the output waveguides.
3.1 Design of the first taper

First, we simulate the conversion efficiency as the initial width of the side waveguides ($w_{\text{initial}}$). Here, we set $L_1 = 10 \, \mu m$, $L_2 = 200 \, \mu m$, and $L_3 = 10 \, \mu m$. Fig. 5 shows the simulation results of transmittance from the TM to TM$_{\text{IP}}$ modes and from the TE to TM$_{\text{OP}}$ modes at the output waveguide. Here, considering fabrication accuracy, the width is assumed to be $0.05 \, \mu m$ or more. The transmittance from the TM to TM$_{\text{IP}}$ modes is lower at the wider $w_{\text{initial}}$ because it causes excess loss owing to abrupt change. However, the transmittance from the TE to TM$_{\text{OP}}$ modes shows a V-shaped tendency. This is related to the excitation of the TE$_c$ mode, which has an opposite phase in the side waveguide. Consequently, considering the reduction of excess loss, we employed $w_{\text{initial}} = 0.05 \, \mu m$.

Next, we simulated length $L_1$ of the first taper. Fig. 6 shows the simulation results. As $L_1$ becomes longer, the transmittance from the TE to TM$_{\text{OP}}$ modes decreases. This is because the input TE mode is coupled to the side waveguides as the TE$_{\text{c}}$ mode when the taper is gradual. To efficiently excite the TE$_c$ mode, $L_1$ should be as short as possible. However, the reflections are as large as $-36.3 \, \text{dB (TE)}$ and $-44.2 \, \text{dB (TM)}$ for $L_1 = 0 \, \mu m$. In this study, we employed $L_1 = 3 \, \mu m$ because the reflections are as small as $-71.6 \, \text{dB (TE)}$ and $-50.43 \, \text{dB (TM)}$.

3.2 Design of the second taper

Next, we simulated length $L_2$ of the second taper, which is the most important factor for the mode conversion from the TE into TM$_{\text{OP}}$ modes. Fig. 7 shows the simulation results. The transmittance of the TM$_{\text{OP}}$ mode is higher for a longer $L_2$. This means sufficient mode conversion from the TE$_c$ to TM$_{\text{OP}}$ modes is obtained over $L_2 = 150 \, \mu m$. The decrease at approximately $L_2 = 320 \, \mu m$ is because the converted light is recoupled to the center waveguide, owing to mode coupling. The split from TM into TM$_{\text{IP}}$ does not depend on $L_2$ because the coupling is induced similar to a Y-splitter. Therefore, we employed the first peak at $L_2 = 188 \, \mu m$ for the second taper.

3.3 Design of the third taper

Next, we simulated $L_3$ of the third taper. Fig. 8 shows the simulation results. Thus, we employed $L_3 = 3 \, \mu m$, at which the TE mode is mostly converted into the TM$_{\text{OP}}$ mode with least loss.

3.4 Electric field distribution

Finally, we obtained the designed parameters of 3-steps taper as $L_1 = 3 \, \mu m$, $L_2 = 188 \, \mu m$, and $L_3 = 3 \, \mu m$. The total size of the 3-steps taper was 194 $\mu m$. The $E_x$ and $E_y$ field distributions along the propagation for the input light of the TE and TM modes are shown in Figs. 9 and 10, respectively. $E_x$ of the input TE mode is converted into $E_y$ with out-of-phase in the side waveguides. The transmittances for the input TE and TM modes were 87.8% (TE$\rightarrow$TM$_{\text{OP}}$) and 93.5% (TM$\rightarrow$TM$_{\text{IP}}$), respectively. The conversion of the TM mode into the TE$_{\text{OP}}$ mode occurs at 4.7%.

4. Application of proposed coupler to MZI device

A tunable polarization controller can be realized by combining a 3 dB polarization coupler with an MZI. We simulated...
Fig. 9 Electric field distributions propagating in 3 dB polarization coupler for the input light of the TE mode.

Fig. 10 Electric field distributions propagating in 3 dB polarization coupler for the input light of the TM mode.

Fig. 11 Electric field distributions propagating in the MZI combined with the 3 dB polarization coupler with in-phase for the input of (a) TE mode and (b) TM mode; the output polarization is not rotated (TE→TE, TM→TM).

Fig. 12 Electric field distributions propagating in the MZI combined with the 3 dB polarization coupler with out-of-phase for the input of (a) TE mode and (b) TM mode; the output polarization is rotated 90° (TE→TM, TM→TE).

Fig. 11 shows the simulation results when the phase difference is in-phase. Although the 3 dB coupler converts polarization for the input TE mode, it was canceled at the output coupler. The input TM mode was split and recoupled at the output coupler. Therefore, the polarization of the output light was identical to that of the input light. The transmittances for the input TE and TM modes were 92.9% (TE→TE) and 84.8% (TM→TM), respectively. Fig. 12 shows the simulation results when the phase difference is out-of-phase. Here, the polarization of the output light is rotated 90° to that of the input light; that is, the input TE mode is converted into the output TM mode and vice versa. The transmittances for the input TE and TM modes were 88.1% (TE→TM) and 87.8% (TM→TE), respectively. When the phase difference was between 0 and π, the output light was a mixture of the TE and TM modes. The ellipticity (phase difference between the two modes) can be controlled when a polarization-dependent phase shifter is installed at the output waveguide. For application to a magneto-optical isolator, a waveguide polarizer was installed at the input and output waveguides, to eliminate nonreciprocal polarization rotation.
5. Conclusion

We proposed a 3 dB polarization controller that can be used as a tunable polarization controller for MZI configuration. The operation principle is based on mode coupling in a 3-steps taper with three adjacent waveguides. Because the operation requires a waveguide structure with asymmetry only in the vertical direction, it can be applied to several types of optical devices with different cladding layers or rib waveguides. We optimized the taper design with a waveguide structure for a Si-based magneto-optical isolator. The total device size was 194 μm for the 3 dB coupler. The transmittances were 87.8% (TE→TM with out-of-phase) and 93.5% (TM→TM with in-phase). A tunable polarization controller of the MZI was numerically demonstrated. The transmittances were 92.9% (TE→TE), 84.8% (TM→TM), 88.1% (TE→TM), and 87.8% (TM→TE).

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