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Low-loss waveguide optical isolator with tapered mode converter and magneto-optical phase shifter for TE mode input

RYUSUKE YAMAGUCHI,1 YUYA SHOJI,1,2,* AND TETSUYA MIZUMOTO1,2

1Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8552, Japan
2Laboratory for Future Interdisciplinary Research of Science and Technology, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8552, Japan
*shoji@ee.e.titech.ac.jp

Abstract: We propose and demonstrate a novel low-loss waveguide optical isolator with tapered mode converter and magneto-optical phase shifter. The principle of operation of the isolator is based on the superposition of the TE and TM modes. The two different modes become direction-dependent due to a magneto-optical phase shift affecting the TM mode. We designed a tapered mode converter in order to generate the TE and TM modes with equal amplitude when the waveguide is excited with a TE mode input. We successfully demonstrated that the fabricated device acts as an isolator showing a different transmittance between forward and backward directions. The maximum isolation measured is 16 dB at a wavelength of 1561 nm for a TE mode input.

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1. Introduction

Semiconductor lasers and semiconductor optical amplifiers are widely used in optical fiber communication systems. When backward reflections are launched into these devices, their performance degrades, becoming afflicted by instability due to intensity and phase noises. To avoid these problems, optical isolators that allow one-way lightwave transmission are installed, along with active optical devices, in the optical fiber communication systems. Bulk-type optical isolators are commercially available and still widely used, but they are difficult to integrate with optical active devices.

Silicon photonic waveguides on a silicon-on-insulator (SOI) wafer are useful for constructing photonic integrated circuits (PICs) with small footprints. Waveguide optical isolators are highly demanded for silicon PICs. Strict optical isolation, independent of light intensity, has been realized with both electro-optical and magneto-optical effects. Electro-optical types use dynamic optical modulators which can be fabricated with CMOS compatible processes. However, they can cause additional losses and power consumption [1–3]. On the other hand, magneto-optical materials are not compatible with silicon. Magnetic metals are lossy and growth of magneto-optical garnet on silicon is still challenging [4,5]. So far, magneto-optical isolators fabricated by direct bonding technology have been realized with superior performance [6–11]. These isolators are configured as Mach-Zehnder interferometers (MZI) or ring resonators. They work with a fundamental TM mode input since the non-reciprocal function is provided by a magneto-optical phase shift that occurs only for TM modes propagating in a silicon waveguide with a bonded garnet upper cladding layer. On the other hand, most optical active devices operate in the TE mode. In order to realize the desired magneto-optical phase shift while having a TE mode input, a lateral asymmetry in waveguide structure is needed. This makes the fabrication process rather complicated. Waveguide integrated TE-TM mode converters with magneto-optical TM mode isolator represent a straightforward approach to the realization of optical isolators that work with TE mode input [6,10].
In this article, we propose a novel waveguide optical isolator with incorporated TE-TM half mode converters and a magneto-optical phase shifter for the TM mode. Optical isolation is achieved via a phase difference between reciprocal TE and nonreciprocal TM propagations. Thanks to the new configuration, scattering loss at the magneto-optical garnet boundaries can be reduced. Moreover, our proposed configuration needs simply an external, one directional applied magnetic field rather than the anti-parallel or radial one needed for MZI or ring resonator configurations. Consequently, the device has both simple structure and small footprint. We also designed and implemented a tapered TE-TM half mode converter. Finally, we fabricated the proposed optical isolator and demonstrated optical isolation along with low insertion loss.

2. Operation principle

The schematic of the proposed optical isolator is shown in Fig. 1. It consists of two tapered TE-TM mode converters and a magneto-optical phase shifter. The device operation is based on the interference between the TE and TM modes propagating in the magneto-optical phase shifter, the upper cladding layer of which consists of a magneto-optical garnet. In the magneto-optical phase shifter of the proposed device, an external magnetic field is applied in only one direction, whereas it is applied in anti-parallel directions in other previous MZI devices. This can reduce the device footprint and allows denser integration. The tapered TE-TM mode converter works as a 3 dB power divider and as a combiner of TE and TM modes mediated by higher TE modes. The input and output light show both a TE field configuration. It provides one-way light propagation using nonreciprocal phase shift for the TM mode.

![Fig. 1. Structure of the proposed waveguide optical isolator. Ce:YIG is directly bonded on a Si waveguide as an upper cladding layer and magnetized in the film plane by an external magnetic field. Lower shows mode excitation and transition inside the device.](image)

The structure of the tapered TE-TM mode converter is shown in Fig. 2(a). We show how to design the dimensional parameters of the tapered mode converter in Section 3.1. The design principle is herein explained. An input waveguide is connected to the tapered mode converter so that the launched TE₀ mode light is converted into TE₀ and TE₁ modes with equal amplitude at the interface of the narrow and wide waveguides. This is similar to what happens in a multimode interference (MMI) coupler. Hereafter we call this interface an MMI junction. It is known that mode conversion occurs between the TE₁ and TM₀ when the effective refractive indices match each other in a vertically asymmetric waveguide where the refractive indices of the upper and lower cladding layers are different [12]. This mode conversion occurs adiabatically in a tapered region around the index-matching point. Figure 2(b) shows that the TM₀ mode is generated while the electromagnetic field is propagating in the tapered structure. In order to expand the region in which this modal conversion happens efficiently, we use a three-step taper. In this way, the input fundamental TE₀ mode is converted into TE₀ and TM₀ modes with equal amplitude.
The magneto-optical phase shifter is composed of a Si waveguide with an upper cladding layer of magneto-optical garnet CeY$_2$Fe$_5$O$_{12}$ (Ce:YIG) which has a Faraday rotation coefficient of $-4500 ^\circ$/cm [13,14]. Since the waveguide is asymmetric in the vertical direction, a magneto-optical phase shift is generated for the TM modes when an external magnetic field is applied in the film plane [15]. The TE$_0$ and TM$_0$ modes propagate independently in the waveguide, but the TM$_0$ mode experiences a magneto-optical phase shift. We adjust the propagation distance of the magneto-optical phase shifter so that the TE$_0$ and TM$_0$ modes are respectively in-phase and out-of-phase in the forward and backward directions.

In the forward direction, TE mode input light is converted within the input tapered TE-TM mode converter into TE$_0$ and TM$_0$ modes with an equal amplitude. After propagating in the magneto-optical phase shifter, the two modes become in phase. In the output tapered TE-TM mode converter, TM$_0$ mode is re-converted into TE$_1$ mode, and then the TE$_0$ and TE$_1$ interfere constructively at the output MMI junction. They are finally coupled to the output waveguide as a TE mode as shown in Fig. 3(a). In the backward direction, TE mode light launched from the output waveguide is converted in the tapered TE-TM mode converter into TE$_0$ and TM$_0$ modes. In this direction, a $\pi$ phase difference is introduced between TE$_0$ and TM$_0$ modes after propagating in the magneto-optical phase shifter due to the nonreciprocal phase shift affecting the TM mode. The TE$_1$ mode resulting from the conversion of the TM$_0$ mode is phase shifted in respect to the TE$_0$ mode by $\pi$, TE$_0$ and TE$_1$ modes interfere destructively at the MMI junction. Therefore, in the backward direction, the input TE mode light is not coupled to the input port, but is scattered at the MMI junction as shown in Fig. 3(b). In this way, the characteristic modus operandi of an isolator is achieved.
3. Design and fabrication

3.1 Design

We designed the MMI junction so that the TE₀ and the TE₁ modes could be excited with an equal amplitude. The power ratio of the two modes depends on the position of the input waveguide relative to the MMI junction. Figure 4 shows how the excited mode ratio depends on the offset between the center of the tapered waveguide and that of the narrow waveguide connected to the taper. The widths of the narrow waveguide and the taper end are respectively 0.5 μm and 1.5 μm. Figure 4 also shows that the power of the TE₀ and the TE₁ modes become equal when the offset is 0.335 μm. Although the TE₂ mode is excited at the junction, we adopted a width of 1.5 μm at the taper end in view of the possibility to include the design an optical circulator.

Figure 5(a) shows calculated effective refractive indices of propagation mode as a function of waveguide width. The index matching between the TE₁ and TM₀ modes occurs when the waveguide is 0.85-μm wide. Figure 5(b) shows calculated transmittance of the TE₀ and TM₀ modes in the tapered middle section. The length of the tapered middle section of the waveguide is 200 μm because a gradual change in width is needed in order to have enough
TE-TM mode conversion. TE\textsubscript{1} mode light at the 1.5-μm-wide waveguide is efficiently converted into the TM\textsubscript{0} mode at the end of the tapered waveguide.

The thickness of Si waveguide is chosen to be 220 nm in order to obtain maximum magneto-optical phase shift, which contributes to reducing the footprint of the device. Figure 6 shows the magneto-optical phase shift calculated at a wavelength of 1550 nm as a function of waveguide width. The waveguide width of magneto-optical phase shifter is 0.77 μm because the wider waveguide provides larger magneto-optical phase shift, while it is less than 0.85 μm in order to achieve the best compromise with TE-TM mode converter. The length required for a phase difference of π between the forward and backward TM\textsubscript{0} modes is calculated to be 520 μm for the 770-nm-wide Si waveguide at a wavelength of 1550 nm.

Let us mention the robustness of this device with respect to fabrication variability on a scale of several tens nanometer. A change in TE-TM mode conversion efficiency is negligible owing to the tapered structure. The excitation ratio of TE\textsubscript{0} and TE\textsubscript{1} modes is dominated by the offset of input waveguide. The magneto-optical phase shift is also robust against a change in waveguide width. The operation bandwidth, determined by the difference in a propagation constant between TE\textsubscript{0} and TM\textsubscript{0} modes, is insensitive to such a dimensional change because changes in two modes are almost equal. Since the absolute phase of propagating light is hardly determined in the Si photonic waveguides, a thermal tuning is useful to control the central operating wavelength.

Fig. 5. (a)Dependence of effective indices of Si waveguide with a Ce:YIG cladding layer. (b)The taper length dependence of modal power for TE\textsubscript{0} and TM\textsubscript{0} modes propagating in the tapered middle section of TE-TM mode converter.

Fig. 6. Magneto-optical phase shift of TM\textsubscript{0} mode calculated at a wavelength of 1550 nm as a function of silicon waveguide width. Two curves correspond to the electromagnetic fields of propagation mode shown by the respective color in Fig. 5(a).
3.2 Fabrication

The waveguide was formed in a 220-nm thick Si layer on a SOI wafer using electron-beam lithography followed by a SF₆ reactive ion etching with SiO₂ mask. A 500-nm-thick single-crystalline Ce:YIG layer grown on a SGGG substrate was directly bonded on a silicon waveguide using a surface activated direct bonding technique. We applied pressure of 12 MPa at the temperature of 200 °C in the bonding process. Due to our limited wafer manipulation capability, we used a 1500-μm-square Ce:YIG die, which was large enough to cover the whole device. Figure 7 shows a microscopic image of the fabricated isolator.

![Microscopic image of the fabricated isolator](image)

**Fig. 7.** Microscopic image of the fabricated isolator. 1500-μm-square Ce:YIG/SGGG die was directly bonded on Si waveguides.

4. Characterization

The transmittance of the fabricated device was measured using a fiber-device-fiber setup. TE-polarized light from an amplified spontaneous emission light source was launched into our device through a focusing lens module with a polarizer. The light transmitted through the device was coupled to an output optical fiber by another focusing lens module with a polarizer. The fiber-to-fiber transmittance was measured using a spectrum analyzer. An external magnetic field of ~100 Oe was applied to the Ce:YIG layer transversally to the propagation direction in the film plane via a two poles permanent magnet located above the device. The magnetic field direction was reversed by inverting the permanent magnet. Reversing the direction of the magnetic field applied to the Ce:YIG layer reverses the propagation direction because of the symmetry of the device. Hereafter we call these two situations forward and backward propagations respectively.

Figure 8 shows the measured transmission spectra of TE mode. The coupling losses between the input and output lens modules and the device are included in the measured transmittance. The blue and red lines show the forward and backward transmittances, respectively. The TM₀ mode converted from the TE₁ mode is propagated in the magneto-optical phase shifter with a different propagation constant from the one characterizing the TE₀ mode. The interference between TE₀ and TE₁ modes was observed in the transmitted output.

When an external magnetic field is applied, different transmittances are observed depending on the direction of propagation. An applied magnetic field causes a magneto-optical phase shift in the TM mode. The propagation constant of the TM mode is slightly higher in the forward propagation in comparison to the non-magnetized case. The TE mode is not affected by the magneto-optical effect. Because of this, the interference spectrum is blue-shifted. When the propagation direction is reversed, the magneto-optical phase shift changes its sign. In this case, the propagation constant is slightly less than in the non-magnetized case. This, in turn, results in a red shift of the spectrum. As a result, different transmittances are observed depending on the propagation direction. The fringe present in the spectra was induced by Fabry-Perot resonance between the input and output MMI junctions. The actual
transmittance level would be the middle between the top and bottom of the fringe in a linear scale. For example, an actual backward transmittance is estimated to be -53.6 dB at a wavelength of 1561 nm. An isolation ratio of 16 dB, which is defined by the ratio of the forward to the backward transmittance, is obtained at this wavelength. The isolation bandwidth is determined by the free-spectral range due to TE and TM mode phase difference.

Fig. 8. Measured transmittance spectra of our fabricated optical isolator. Blue and red lines are the transmittances of the isolator for forward and backward directions, respectively. Orange line is the transmittance of the reference waveguide with a Ce:YIG upper cladding layer.

The orange line in Fig. 8 shows the transmittance of the reference waveguide adjacent to the isolator where a Ce:YIG upper cladding layer is bonded. Although the transmittance of a waveguide without a Ce:YIG upper cladding layer is not shown, it was at the same level of the one we measured on our device or worse. This means that the insertion loss of this device was considerably small. The previously reported MZI optical isolator has a large insertion loss of ~13 dB [7]. The loss is due to mode mismatch at the interface between the air cladding and the Ce:YIG cladding waveguides and optical absorption of the TM mode in the Ce:YIG cladding layer. On the other hand, losses associated with mode mismatch and optical absorption are smaller for the TE mode in comparison to the TM mode, because the TE mode is better confined in the waveguide than the TM mode. We simulated loss due to the mode mismatch and the optical absorption of Ce:YIG for the TE and TM modes at a wavelength of 1550 nm. The mode mismatch loss was calculated by eigen-mode expansion method. The absorption loss was calculated with a Ce:YIG material loss of ~5 dB/mm and a confinement factor multiplied by the propagation length. Table 1 summarized the loss breakdown of MZI and proposed configurations. The simulation results show lower insertion loss of the proposed configuration compared with the MZI isolator. The proposed optical isolator keeps the TM mode to the minimum necessary. The TE mode propagates across the interface between the air cladding and the Ce:YIG cladding waveguides. This opens an avenue for the realization of low loss optical isolators.

Table 1. Simulated loss breakdown of optical isolator

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<th>Proposed configuration</th>
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<td>Mode mismatch loss</td>
<td>4.3 dB × 2 facets (TMn)</td>
<td>0.19 dB × 2 facets (TE0)</td>
</tr>
<tr>
<td>Absorption loss</td>
<td>3.7 dB/mm × ~1.5 mm (TMn)</td>
<td>1.2 dB/mm × ~1.6 mm (TE0)</td>
</tr>
<tr>
<td></td>
<td>3.7 dB/mm × ~0.5 mm (TM0)</td>
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<tr>
<td>Total loss</td>
<td>14.2 dB</td>
<td>3.4 dB</td>
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5. Conclusion

We proposed a novel waveguide optical isolator composed of two tapered TE-TM mode converters and a magneto-optical phase shifter for the TM mode. The device has two main advantages, namely TE mode input operation and ease of magnetization. An optical isolation of 16 dB was demonstrated at a wavelength of 1561 nm for the TE mode input. To obtain higher extinction, splitting ratio of TE to TM mode in the interferometer should be optimized considering their different propagation losses. Very low loss operation was realized because of good light confinement of the TE mode. The Fabry-Perot resonance can be reduced by connecting output ports for radiating light outside the device in order to prevent the destructive interference.

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References