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Proposal of Si Waveguide Optical Isolator Based on Nonreciprocal TE-TM Mode Conversion Using Magneto-optical Phase Shift for TM mode

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Abstract: A novel Si waveguide optical isolator is proposed based on the nonreciprocal TE-TM mode conversion using the magneto-optical phase shift for the TM mode. A maximum isolation of 31 dB is demonstrated at a wavelength of 1545 nm for the TM mode input.

1. Introduction

Silicon optical waveguides formed on a silicon-on-insulator (SOI) wafer have the high refractive index contrast, which is useful for constructing photonic integrated circuits (PICs) with small footprints. In PICs, an optical isolator is an important component for stabilizing the operation of optical active devices such as semiconductor lasers and optical amplifiers. There have been proposed and demonstrated several types of SOI waveguide optical isolators. We demonstrated a silicon waveguide optical isolator based on a Mach-Zehnder interferometer with a high isolation of >30 dB [1]. Also, temperature-insensitive optical isolation >20 dB was realized in a temperature range of 20-60 °C [2]. These devices work for a fundamental TM mode, since the nonreciprocal function is provided by a magneto-optical phase shift given only for TM modes. On the other hand, most optical active devices such as a hybrid laser operate in the TE mode. It is needed to develop an isolator that works for the TE mode. In this article, we propose a novel optical isolator based on nonreciprocal TE-TM mode conversion, which is realized by combining 45° polarization rotators and a magneto-optical phase shifter for the TM mode.

2. Operation Principle

The schematic structure of proposed optical isolator is shown in Fig. 1, which consists of two 45° polarization rotator and a magneto-optical phase shifter. The structure of 45° polarization rotator is shown in Fig. 2. It is known that the polarization can be rotated when the waveguide has asymmetry. When we choose a proper geometry and refractive index of an asymmetric waveguide, the optical axes of two eigen modes are rotated by 45° from the substrate normal. The tapered waveguide with asymmetric slit position rotates the polarization of input TE mode by 45° (Fig. 3(b)). In other words, the input TE mode is converted into TE and TM modes with an equal amplitude.

In the nonreciprocal phase shifter composed of a Si waveguide with a magneto-optical garnet $(YCe)_3Fe_5O_{12}$ (Ce:YIG) upper cladding layer, these two modes propagate independently. While propagating the phase shifter, only the TM mode experiences a magneto-optical phase shift. In the forward direction, at the end of the magneto-optical phase shifter, TE and TM modes are set to be in-phase by adjusting the propagation distance as well as the width of the phase shifter. Thus, a 45° inclined polarized light (Fig. 3(c)) is launched into the right polarization rotator. It is rotated by -45° in the rotator and re-converted into a TE mode at the output end (Fig. 3(d)). Therefore, in the forward direction, the input TE mode is output as the TE mode.

In the backward direction, π phase difference is introduced between TE and TM modes after propagating the magneto-optical phase shifter because of a nonreciprocal nature of the phase shifter to the TM mode. Since the TE and TM modes are out-of-phase, they form a -45° inclined polarization (Fig. 3(g)). The -45° polarized light is rotated by -45° to be a -90° polarization, i.e., TM mode, in the left polarization rotator (Fig. 3(h)). Therefore, in the backward direction, the input TE mode is converted into the TM mode, which can be selectively removed.

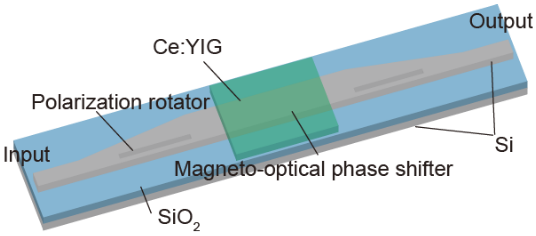

Fig. 1. Structure of proposed optical isolator

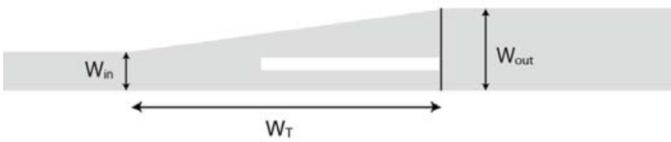

Fig. 2. Structure of 45° polarization rotator

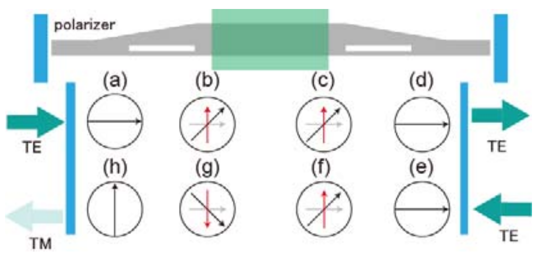

Fig. 3. Diagram of polarization states in the isolator

3. Design

We designed the asymmetric slit waveguide TE-TM mode converter that provided a 45°rotation of optical axes [3]. By gradually changing the waveguide width from a standard Si waveguide (W_{in}=500 nm) to this structure, the input TE fundamental mode is converted to 45° polarized light at the end of the rotator (W_{out}=1010 nm). We adopted a 400-μm-long tapered structure in the following fabrication.

The thickness of Si waveguide is set to be 220 nm in order to obtain a maximum magneto-optical phase shift, which contributes to reducing the footprint of the device. The length of magneto-optical phase shifter needed for obtaining π phase difference between forward and backward TM modes is calculated to be 455 μm for a 1010-nm-wide Si waveguide at a wavelength of 1550 nm.

4. Fabrication and Characterization

The Si waveguide including an asymmetric slit waveguide was formed in a 220-nm thick Si layer on a SOI wafer by using an electron-beam lithography followed by a SF_6 reactive ion etching with a SiO_2 mask. A single-crystalline Ce:YIG layer was directly bonded on the Si waveguide using a surface activated direct bonding technique. Due to the limitation of our fabrication, we used a 1500-μm-long Ce:YIG upper cladding waveguide as a magneto-optical phase shifter in a fabricated device.

At first, we examined the magneto-optical phase shift. A TM mode was launched to a fabricated device through a focusing lens module with a polarizer. The lightwave transmitted through the device was measured through another focusing lens module with a polarizer by an optical spectrum analyzer. Figure 4 shows the spectra of measured transmittance of the output TM mode. When a TE mode was generated in the device, it propagated in a magneto-optical phase shifter with a different propagation constant from the TM mode. Thus, the interference between TE and TM modes was observed in a transmitted output. By applying a magneto-static field to Ce:YIG transverse to the propagation direction, a magneto-optical phase shift is induced only for the TM mode. That is, the propagation constant of the TM mode is slightly decreased compared with a non-magnetized case. The TE mode is not affected by the magneto-optical effect [1]. Because of this, the interference spectrum is shifted to a shorter wavelength side in case of the forward propagation. When the propagation direction is reversed, the TM mode suffers from a different magneto-optical phase shift. The propagation constant is slightly increased compared with a non-magnetized case. This, in turn, results in the spectrum shift to a longer wavelength side. As a result, different transmittances are observed depending on the propagation direction. An isolation of 31 dB, which is defined by the transmittance ratio of the forward to the backward direction, is observed at a wavelength of 1545 nm. Non-periodical and irregular interference spectra can be attributed to non-identical polarization rotations in the input and output rotators.

A similar measurement was done by launching a TE fundamental mode to the device and by measuring the transmitted TE mode. We could observe an interference spectrum. However, no spectrum shift was observed by applying a magneto-static field. By measuring the free-spectral range (FSR) of the interference spectrum, we found that the interference was brought about by fundamental TE_0 and higher-order TE_1 modes propagated in the phase shifter waveguide.

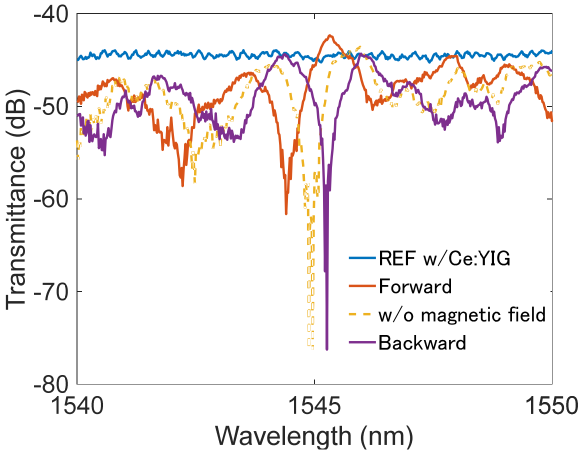

Fig. 4. Measured TM mode transmittance for TM mode input

5. Conclusion

We proposed a novel Si waveguide optical isolator composed of two 45° polarization rotators and a magneto-optical phase shifter for the TM mode. The device has the advantage that it works for the TE mode input. An optical isolation of 31 dB was successfully demonstrated at a wavelength of 1545 nm for the TM mode input. However, the device did not operate for the TE mode input. In order to realize the TE mode operation, the device must be properly designed so as not to excite higher-order TE modes.

Acknowledgments

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