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Demonstration of Silicon Waveguide Optical Isolator for TE Mode Input

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***Abstract*:** A novel silicon waveguide optical isolator is demonstrated with a maximum isolation of 28 dB for TE mode input. The isolator is based on the TE-TM half mode conversion together with a magneto-optical phase shift for TM mode.

1. Introduction

In a photonic integrated circuit, an optical isolator is an important component for stabilizing the operation of optical active devices. So far, we demonstrated a silicon waveguide optical isolator based on a Mach-Zehnder interferometer (MZI) with a high isolation >30 dB [1]. Also, temperature-insensitive isolation >20 dB was realized in a temperature range of 20-60 °C [2]. These devices work for a fundamental TM mode, because the nonreciprocal function is provided by a magneto-optical phase shift experienced only by TM modes. It is needed to develop an isolator that works for a TE mode input, since most optical active devices such as a hybrid laser operate in the TE mode. We proposed a novel optical isolator based on the TE-TM half mode conversion together with a magneto-optical phase shift for the TM mode [3]. In this article, we demonstrate that the fabricated device exhibits an isolation of 28 dB for a TE mode input.

2. Design

The proposed optical isolator is schematically shown in Fig. 1. A 220-nm-thick silicon waveguide on an SOI wafer is used to form two tapered TE-TM half mode converters and a magneto-optical phase shifter for TM_0 mode. The input and output light are the TE mode. The device works as an optical isolator based on the direction-dependent interference between TE_0 and TM_0 modes propagating in the magneto-optical phase shifter.

The structure of tapered TE-TM half mode converter is shown in Fig. 2(a). An access waveguide is connected to the tapered mode converter with an offset of 0.335 μm so that the TE mode propagating in the access waveguide excites TE_0 and TE_1 modes with an equal amplitude at the interface between the access waveguide and the tapered waveguide. This is similar to a multi-mode interference (MMI) coupler. Hereafter, we call the interface an MMI junction. It is known that conversion occurs between TE_1 and TM_0 modes when the two modes have the same effective index in a vertically asymmetric waveguide [4]. Adiabatic conversion occurs between TE_1 and TM_0 modes in a tapered waveguide as shown in Fig. 2(b). Therefore, the TE mode input from the access waveguide is converted into TE_0 and TM_0 modes with an equal amplitude. This is called the TE-TM half mode conversion.

The magneto-optical phase shifter is composed of a 770-nm-wide Si waveguide with a magneto-optical garnet $Ce_1Y_2Fe_5O_{12}$ (Ce:YIG) upper cladding layer. A magneto-static field is applied transverse to the light propagation direction to generate the magneto-optical phase shift for TM_0 mode. The TE_0 mode is not affected by the magneto-optical effect. The length of phase shifter is set to be 520 μm so that the TE_0 and TM_0 modes are in-phase and out-of-phase in the forward and backward directions, respectively.

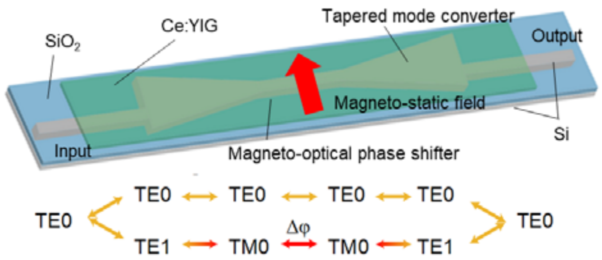

Fig. 1. Structure of the proposed optical isolator.

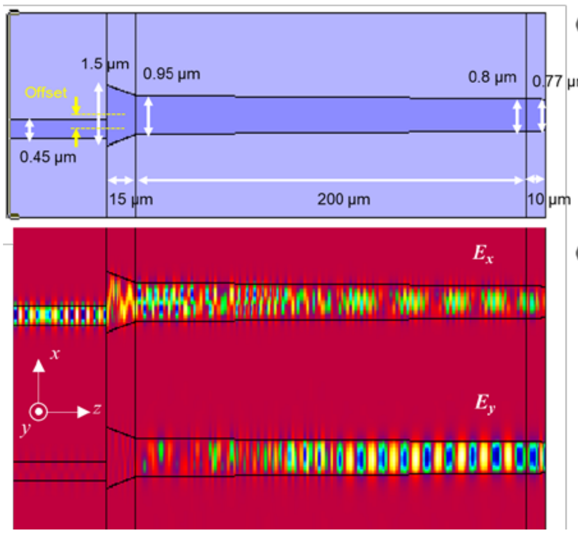

Fig. 2. (a) Structure of the tapered half mode converter.
(b)Power distribution of E_x and E_y for TE_0 mode input.

In the forward direction, in-phase TE_0 and TM_0 modes are coupled in the output TE-TM half mode converter, and are output at the access waveguide as the TE mode. In the backward direction, TE_0 and TM_0 modes become out-of-phase after propagating the magneto-optical phase shifter. The TE_1 mode resulting from the conversion of the TM_0 mode in the TE-TM half mode converter has a π phase difference with respect to the TE_0 mode. The TE_0 and TE_1 modes interfere destructively at the MMI junction, which results in no output at the access waveguide. In this way, an isolator operation is achieved.

3. Fabrication

The waveguide was formed in a 220-nm thick Si layer on a silicon-on-insulator wafer by using electron-beam lithography followed by a SF_6 reactive ion etching with SiO_2 mask. A single-crystalline Ce:YIG layer grown on a substituted GGG substrate was directly bonded on a silicon waveguide using a surface activated direct bonding technique. We applied pressure of 12 MPa at a temperature of 200 °C in the bonding process. Due to our limited wafer manipulation capability, we used a 1500 μm^2 Ce:YIG die, which was large enough to cover the whole device.

4. Characterization

The transmittance of the fabricated device was measured by launching TE-polarized light from an ASE light source through a focusing lens module with a polarizer. The light transmitted through the device was coupled to an output optical fiber by using another focusing lens module with a polarizer. An external magneto-static field was applied to Ce:YIG transverse to the propagation direction in the film plane with a permanent magnet of two poles located above the device. The magnetic field direction was reversed by inverting the permanent magnet. Reversing the direction of magneto-static field applied to Ce:YIG corresponds to reversing the propagation direction because of the symmetry of the device. Hereafter we call these two situations forward and backward propagations, respectively.

The fiber-to-fiber transmittance measured by using an optical spectrum analyzer is shown in Fig. 3. In the measured transmittance, the coupling losses between the lens modules and the device are included. The blue and red lines show the forward and backward transmittances, respectively. The TM_0 mode converted from the TE_1 mode is propagated in a magneto-optical phase shifter with a propagation constant different from the TE_0 mode. Thus, the interference between TE_0 and TE_1 modes is observed in a transmitted output.

When the direction of applied magneto-static field is reversed, the magneto-optical phase shift changes its sign, which results in the spectrum shift. As a result, different transmittances are observed depending on the propagation direction. An isolation ratio of 28 dB, which is defined by the ratio of the forward to the backward transmittance, is observed at a wavelength of 1561 nm. The noise present in the spectra was induced by the Fabry-Perot resonance between the input and output MMI junctions. The Fabry-Perot resonance can be reduced by connecting output ports for radiating light outside the device in order to prevent the destructive interference.

The orange line in Fig. 3 shows the transmittance of the reference waveguide with a Ce:YIG upper cladding layer adjacent to the isolator. Although the transmittance of waveguide without a Ce:YIG upper cladding layer is not shown, it was almost the same level. This means that the insertion loss of this device is considerably small. The previously reported MZI optical isolator had an insertion loss of ~13 dB [1]. The loss is due to the optical absorption of the TM mode in a Ce:YIG cladding layer and the mode mismatch at the interface between the air cladding and the Ce:YIG cladding waveguides. In the proposed device, the insertion loss is expected to be lower, since losses due to the optical absorption and the mode mismatch are less for the TE mode than the TM mode because of better field confinement of the TE mode.

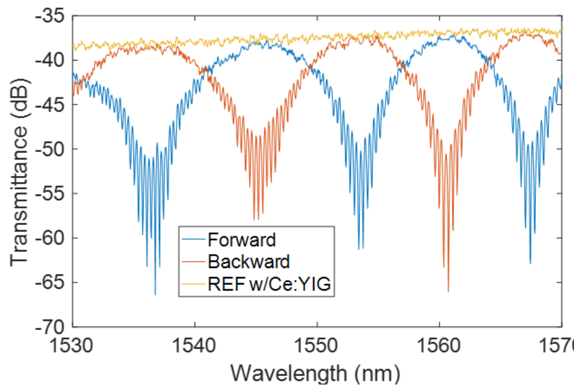

Fig. 3. Measured transmittance spectra of fabricated isolator.

5. Conclusion

A silicon waveguide optical isolator is demonstrated with an optical isolation of 28 dB for TE mode input. The device has the advantages of TE mode input operation and lower insertion loss compared with previously reported MZI isolators.

Acknowledgment

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