On-chip Optical Isolators

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Abstract: Magneto-optical phase shift is effective to realize on-chip optical isolators. Optical isolators are fabricated on SOI platforms with isolation ratios of 30 and 16 dB for TM and TE mode input, respectively.
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1. Introduction

An optical isolator allows light waves to propagate in a specified direction and not in the opposite direction. By virtue of this behavior, the isolator plays an essential role in preventing undesired optical feedback from interacting with optical active devices. The demand for integrating optical isolators continues to grow.

Current optical isolators employ the Faraday effect, in which a polarization plane rotates in different ways depending on the light propagation direction. In order to apply the same principle of magneto-optical polarization rotation to waveguide optical isolators, it is needed to realize phase matching between TE and TM modes propagating in the waveguide. It is required to control waveguide parameters stringently for balancing the various contributions to the waveguide birefringence. The tolerances in the manufacturing process make it difficult to achieve the required control especially in high-index contrast waveguides [1]. An isolator based on the magneto-optical phase shift has an advantage over one based on the polarization rotation [2]. That is, by using the magneto-optical phase shift, the isolator can operate in a single polarization, which eliminates the issues associated with the phase matching between TE- and TM-mode light waves.

Another issue in realizing on-chip optical isolators is the integration of a magneto-optical material on a commonly used waveguide platform like silicon and III-V compound semiconductor. Magneto-optical garnet is the best candidate in optical fiber communication wavelength bands because of its large first-order magneto-optical effect and low optical absorption. However, it is quite difficult to grow high-quality garnet crystals on waveguide platforms like silicon and III-V. We developed a surface activated direct bonding technique for integrating a single-crystalline magneto-optical garnet on silicon and III-V waveguides [3]. In this article, we present magneto-optical isolators fabricated by bonding a single-crystalline magneto-optical garnet on silicon waveguides.

2. MZI optical isolator

The structure of an SOI waveguide optical isolator is shown in Fig. 1(a) [4]. The device is based on a Mach-Zehnder interferometer (MZI), which is composed of 3×2 couplers, magneto-optical phase shifters and phase bias. The magneto-optical phase shifters are installed in the interferometer arms with a magneto-optical garnet $(CeY)_3Fe_5O_{12}$ (Ce:YIG) cladding layer directly bonded on silicon waveguides. A magnetostatic field is applied in the direction transverse to the light propagation in the Ce:YIG film plane to saturate its magnetization. By virtue of the first-order magneto-optical effect, the propagation constant of TM modes propagating in the magnetized waveguide changes from that propagating in a non-magnetized waveguide. Different changes in the propagation constant are brought about depending on the propagation direction as well as the magnetization direction. This is known as a nonreciprocal phase shift. Since the external magnetic fields are applied in anti-parallel directions in two arms of MZI, different magneto-optical phase changes are induced in the two arms. Therefore, the phase difference is brought about between the two arms, which can be set to $-\pi/2$ by adjusting the magneto-optical effect or length of magneto-optical phase shifter. This phase difference is cancelled by the $\pi/2$ phase bias installed in the left arm. Hence, the light wave propagating in the waveguide arms becomes in phase and interferes constructively in the output 3×2 coupler. This corresponds to the forward direction.

In the backward direction, the magneto-optical phase difference changes its sign, i.e., $\pi/2$, due to its nonreciprocal behavior. Because the phase bias is independent of propagation direction, it yields a $\pi/2$ phase difference in the left arm. A total phase difference between the two arms becomes π. This results in destructive interference at the left coupler. The light wave does not come out at the initial input port.

An isolator was fabricated in a 220-nm-thick and 450-nm-wide silicon waveguide on an SOI wafer with a 3-μm-thick BOX layer. A single-crystalline Ce:YIG was directly bonded after a N_2-plasma assisted surface activation process. The transmittance of the fabricated device was measured by launching TM-polarized light. The light wave transmitted through the device was coupled to an output optical fiber. An external magneto-static field was applied to Ce:YIG transverse to the propagation direction in the film plane with a permanent magnet of three poles located above the device.

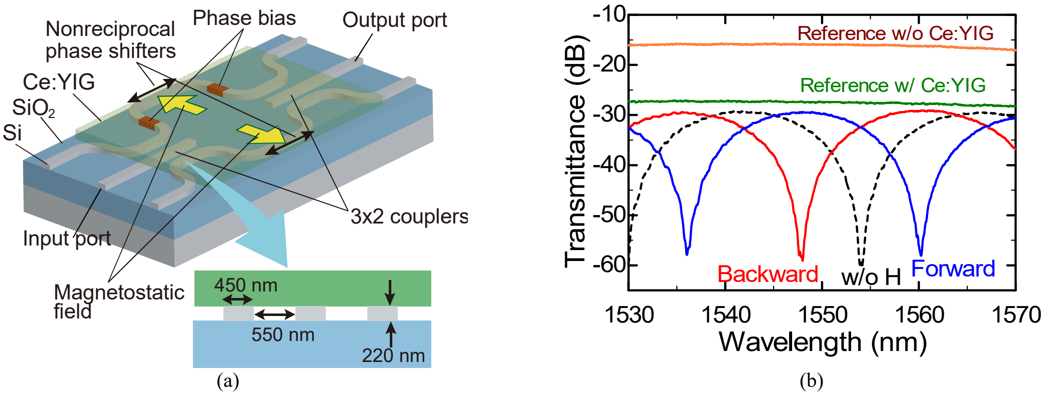

Fig. 1. (a)Schematic illustration of MZI optical isolator and (b)its measured transmittances [4].

The measured fiber-to-fiber transmittances are shown in Fig. 1(b) [4]. In the measured transmittance, the coupling losses between the fibers and the device are included. The blue and red lines show the forward and backward transmittances, respectively. Different transmittances are observed depending on the propagation direction. An isolation ratio, which is defined by the ratio of the forward to the backward transmittance, is measured to be 30 dB. An insertion loss of ~13 dB is attributable to the optical absorption of the TM mode in a Ce:YIG cladding layer (~3.7 dB/mm × ~1.5 mm) and the mode mismatch at the interface between the air cladding and the Ce:YIG cladding waveguides (4.3 dB × 2 facets).

An isolation bandwidth can be widened by adjusting a phase bias. We demonstrated an isolator having an isolation >20 dB in an 8-nm wavelength range [5]. Also, the temperature independent isolation performance has been achieved in a temperature range of 20-60 °C by canceling the temperature dependences of magneto-optical effect and refractive indices [6].

3. TE mode isolator

The MZI-based isolators work for a TM mode input, because the magneto-optical phase shift is experienced only by TM modes. In order to develop an isolator that works for a TE mode input, we proposed and demonstrated a novel optical isolator based on the TE-TM half mode conversion together with a magneto-optical phase shift for the TM mode [7].

The optical isolator is schematically shown in Fig. 2. 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 fundamental TE mode. The access waveguides are connected to the tapered mode converters with a lateral offset of 0.335 μm so that the fundamental TE mode launched from 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. 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. Adiabatic conversion occurs between TE_1 and TM_0 modes in a tapered waveguide. 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.

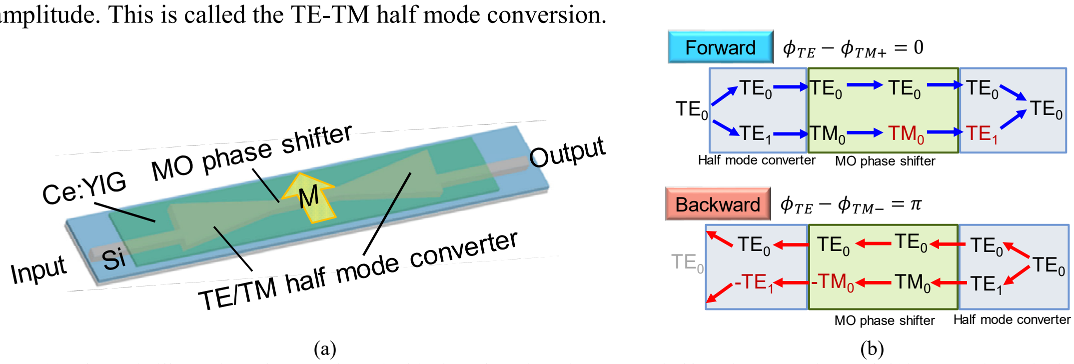

Fig. 2. (a)Schematic illustration of TE mode optical isolator based on the TE-TM half mode conversion and (b)its operation principle

The magneto-optical phase shifter is composed of a 770-nm-wide silicon waveguide with a 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. In the forward direction, in-phase TE_0 and TM_0 modes are coupled in the output TE-TM half mode converter, and are converted to the fundamental TE mode of the access waveguide. 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 converted from 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 interface between the access waveguide and the half-mode converter. No output is obtained in the access waveguide.

The measured fiber-to-fiber transmittances are shown in Fig. 3. An isolation ratio of 16 dB, which is estimated by taking into account the effect of fringes due to the Fabry-Perot resonance, is observed at a wavelength of 1561 nm. 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 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 the device is considerably small. In the present device, the insertion loss is expected to be lower than the MZI isolator, 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.

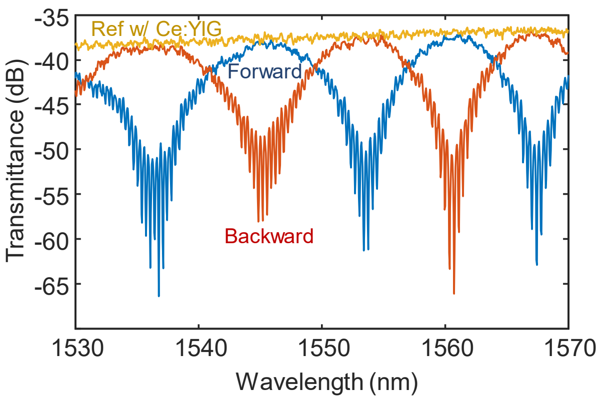

Fig. 3. Measured transmittance of TE mode isolator [7].

4. Conclusions

Silicon waveguide optical isolators were fabricated by directly bonding a single-crystalline Ce:YIG with a N_2 plasma assisted surface activated direct bonding technique. Optical isolations of 30 dB and 16 dB were successfully demonstrated in an MZI-based isolator for TM mode input and in a TE-TM half mode conversion isolator for TE mode input, respectively.

Acknowledgments

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