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Optical Nonreciprocal Devices Fabricated with Directly Bonded Magneto-Optical Garnet

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Abstract: Optical isolator and circulator are fabricated by directly bonding a single-crystalline magneto-optical garnet on silicon waveguides. An isolation of ≥30 dB has been obtained in fabricated devices.
OCIS codes: (160.3820) Magneto-optical materials; (230.3240) Isolators.

1. Introduction

An optical isolator is a one-way device, which allows light waves to propagate only in a specified direction. The isolator plays an essential role in preventing undesired back reflections from interacting with optical active devices. An optical circulator transmits an optical signal input at the first port to the second port, whereas an input at the second port is transmitted to the third port. Photonic circuits that process counter-propagating light waves are realizable by using such a function.

Current optical isolators and circulators employ the polarization rotation dependent on the propagation direction, which is given by the Faraday effect. It is needed to take phase matching between TE and TM modes if one applies the same principle to waveguide devices. Stringent control is needed in fabricating waveguides to achieve this. It is impractical in silicon waveguides [1]. In contrast, use of the magneto-optical (MO) phase shift has a distinct advantage over the polarization rotation. The isolator and circulator functions are realizable in a single polarization by using the MO phase shift. Hence, it is not necessary to take the phase matching between TE- and TM-mode light waves.

Another issue is how to integrate a material having a large MO effect on silicon. We developed a surface activated direct bonding technique to integrate a single-crystalline garnet having a large first-order MO effect on silicon waveguides [2]. In this article, we present nonreciprocal devices fabricated by this technique.

2. Operation principle

Optical isolators and circulators are realized by installing MO phase shifters in a Mach Zehnder interferometer (MZI) as shown in Fig. 1. An MO material is placed as an upper cladding layer and is magnetized in the film plane transverse to the light propagation direction in the MO phase shifter. When the TM-mode light wave is propagated in such a waveguide, it experiences the phase shift caused by the first-order MO effect, which is dependent on the light propagation direction as well as the magnetization direction of MO material [3].

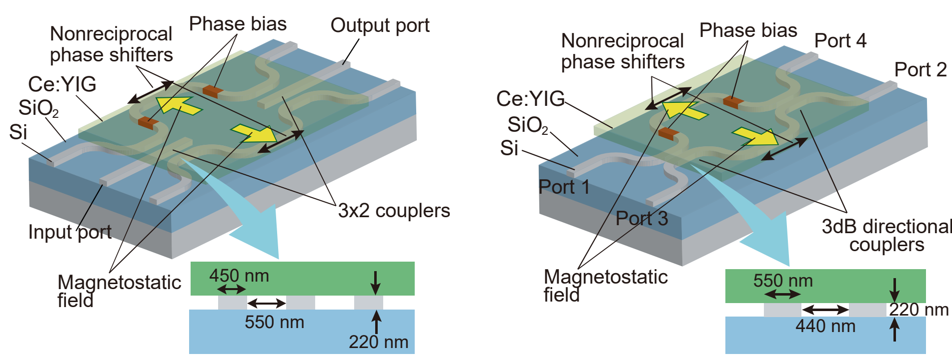

Fig. 1. Schematic illustration of optical (a)isolator and (b)circulator with a bonded Ce:YIG upper cladding layer [3].

Different MO phase shifts are induced in MZI arms by applying external magnetostatic fields in antiparallel directions in the two arms. The phase difference is set to $-\pi/2$ by adjusting the MO effect or length of the MO phase shifter in the forward propagation. The phase difference is cancelled by a phase bias of $\pi/2 + 2m\pi$ (m: integer) in the left arm. Hence, the light wave propagating in the interferometer arms interferes constructively in the output coupler and emerges at the output port of the isolator (Fig. 1(a)). The MO phase difference changes its sign (i.e.,

$\pi/2$) in the backward direction. Because the phase bias remains with a $\pi/2 + 2\,m\pi$ phase difference, the light wave propagating in the two arms interferes destructively in the left coupler. No light is output at the initial input port of isolator. A waveguide optical circulator can be built by replacing 3×2 branching/coupling devices with 3-dB directional couplers as shown in Fig. 1(b).

3. Device fabrication and characterization

A 450-nm or 550-nm-wide MZI waveguide was formed by using a SF_6 reactive ion etching technique in a 220-nm-thick silicon layer of the silicon-on-insulator wafer having a 3-μm-thick buried oxide layer. A 500-nm-thick single-crystalline garnet $CeY_2Fe_5O_{12}$ (Ce:YIG) layer was grown on a (111)-oriented $(GdCa)_3(GaMgZr)_5O_{12}$ substrate. Ce:YIG has a saturation Faraday rotation of −4500 °/cm at λ = 1550 nm. A 1.5×1.5 mm^2 Ce:YIG die was directly bonded on the silicon waveguide by using a N_2-plasma assisted surface activated bonding technique. In the bonding process, a pressure of 5 MPa was applied to the samples at 200°C [4].

The maximum isolation ratio, which was defined as the transmittance ratio of the forward to the backward direction, was measured to be 30 dB at λ = 1548 nm in a fabricated isolator [3]. A 20 dB isolation bandwidth of 8 nm was obtained by properly designing the phase bias [4]. The temperature dependence of MZI isolator is determined mainly by the temperature dependence of the material refractive indices and of the MO effect. Furuya et al. demonstrated the constant backward transmittance in an MZI isolator at temperatures between 20 and 60°C by balancing the temperature dependence of the MO phase shift and phase bias in the backward direction [5]. Also, the isolator for a TE mode input was realized by integrating a TM mode isolator with a TE-TM mode converter [6].

Table 1 summarizes the measured fiber-to-fiber transmittance of fabricated silicon waveguide circulator. An input from port 1 is conducted mainly to port 2, whereas an input from port 2 is conducted to port 3 with an isolation ratio of 32.7 dB for port 1. Similarly, inputs from ports 3 and 4 are conducted to ports 4 and 1, respectively. A circulator operation has been successfully demonstrated in [7].

Table 1. Transmittance for the input/output port combinations measured at λ = 1543 nm [7].

Input	Fiber-to-fiber transmittance measured at output [dB]			
	port 1	port 2	port 3	port 4
port 1	–	−36.8	–	−64.9
port 2	−69.5	–	−36.4	–
port 3	–	−65.5	–	−35.8
port 4	−36.8	–	−69.3	–

4. Conclusions

Optical nonreciprocal devices were fabricated by directly bonding an MO garnet on silicon waveguides. The bonding technique is advantageous compared with state-of-the-art deposition techniques, since it enables to employ a single-crystalline magneto-optical garnet having a large MO effect. The optical isolator and circulator employing an MO phase shift in an MZI exhibited an isolation ratio of ≥30 dB at a 1550-nm-wavelength band. The isolation bandwidth was increased by properly setting a phase bias. Also, an MZI isolator having a temperature-independent backward transmittance was realized by balancing the temperature dependence of the MO phase shift and phase bias.

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