ECIO 2016

18TH EUROPEAN CONFERENCE ON INTEGRATED OPTICS 2016
18–20 MAY | WARSAW | POLAND

Optical Isolators and Circulators for Silicon Photonics

Tetsuya MIZUMOTO[1*], Yuya SHOJI[2]
[1]School of Engineering, Tokyo Institute of Technology,
2-12-1 Ookayama, Meguro-ku, Tokyo, 152-8552, Japan
[2]Research Institute for Science and Technology, Tokyo Institute of Technology,
2-12-1 Ookayama, Meguro-ku, Tokyo, 152-8552, Japan
[*] tmizumot@pe.titech.ac.jp

Optical isolators and circulators play unique roles in photonic circuits. Optical isolators allow light waves to propagate in pre-determined directions while preventing the propagation in other directions. This function is essential for protecting optical active devices from reflected light. Optical circulators play important roles in realizing highly functional photonic circuits. In particular, the optical circulator is necessary for processing reflected light signals in sensing applications. The magneto-optical polarization rotation, which is used in conventional isolators and circulators, cannot be applied in realizing these devices on Silicon-On-Insulator (SOI) waveguide platforms because of the phase matching issue between TE and TM modes [1]. The magneto-optical phase shift has a distinct advantage over the polarization rotation.

Isolators and circulators have been realized in SOI Mach-Zehnder interferometer (MZI) waveguides based on the magneto-optical phase shift. The structure of an MZI isolator is shown in Figure 1.

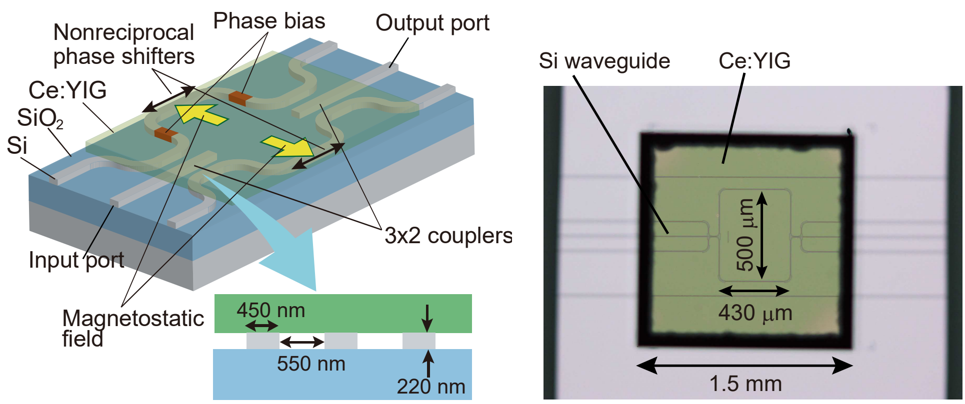

Fig. 7. SOI Mach-Zehnder optical isolator based on magneto-optical phase shift [2].

The MZI is composed of 3×2 couplers. The magneto-optical phase shifters are installed in the MZI waveguide arms where a magneto-optical garnet $(CeY)_3Fe_5O_{12}$ (Ce:YIG) is directly bonded on a silicon waveguide core as a cladding layer. A magnetostatic field is applied in the transverse direction of the light propagation in the film plane of Ce:YIG to saturate its magnetization. By virtue of the first-order magneto-optical effects, the propagation constant of TM modes propagating in the waveguide becomes different depending on the propagation direction and the direction of the applied magnetostatic field. Since the magnetostatic fields are applied in anti-parallel directions in two arms of the interferometer, the phase difference is produced between the left and right arms. The phase difference is set to be □□□□ in the forward propagation and is cancelled by the □/2 phase bias installed in the left arm. The phase bias is provided by adjusting the optical path difference between the two waveguide arms. Hence, the light wave propagating in the waveguide arms becomes in phase and interferes constructively in the output 3×2 coupler. The light wave launched into the central input port of the left hand side of the 3×2 coupler emerges at the central output port of the right 3×2 coupler. For the backward direction, the phase difference produced by the magneto-optical effect changes its sign, i.e., □/2. Because the phase bias remains to yield a □/2 phase difference, a total phase difference of □ is introduced between the two interferometer arms. Destructive interference occurs at the left coupler. The light wave does not come out at the initial input port, but instead is radiated out from the side waveguides of the 3×2 coupler. By replacing 3×2 couplers with conventional 3 dB directional couplers, the MZI functions as a four-port optical circulator. In the rightward propagation, outputs are obtained in cross ports by virtue of the in-phase interference of MZI. On the other hand, the input light is transmitted to a bar port in the leftward propagation.

In an SOI waveguide, the low refractive index of the buried oxide layer enhances the magneto-optical phase shift, which reduces the device footprints. The magneto-optical phase shift is calculated to be 3.65 and 4.80 mm^{-1} at a wavelength of 1550 nm in 450- and 550-nm-wide SOI waveguides (220-nm-thick), respectively, with a saturation Faraday rotation of □4500 deg cm^{-1} for Ce:YIG [2].

As a key technology for fabricating the SOI waveguide optical isolators and circulators, a surface activated direct bonding technique was developed. Ce:YIG is directly bonded on a silicon waveguide at 200 ^{o}C after a surface activation process by oxygen or nitrogen plasma irradiation. By virtue of this technique, we can make full use of the large Faraday rotation of single-crystalline Ce:YIG. A silicon waveguide optical isolator was demonstrated with an optical isolation of 30 dB and an insertion loss of 13 dB at a wavelength of 1548 nm [2]. Furthermore, a four port optical circulator was demonstrated with maximum isolations of 33.5 and 29.1 dB in cross and bar ports, respectively, at a wavelength of 1543 nm [3].

We have demonstrated an operation bandwidth of 8 m for >20 dB isolation [4] and a temperature insensitive isolator operation in a temperature range of 20-60 ^{o}C [5]. These are achieved by properly adjusting a phase bias. The remaining issue of insertion loss reduction is now under investigation.

References

[1] Y. Shoji, K. Miura, T. Mizumoto, *Optical nonreciprocal devices based on magneto-optical phase shift in silicon photonics*, J. Opt., vol. 18, 013001, 2016
[2] Y. Shoji, T. Mizumoto, *Magneto-optical non-reciprocal devices in silicon photonics*, Sci. Technol. Adv. Mater., vol. 15, 014602, 2014
[3] T. Mizumoto, Y. Shoji, K. Mitsuya, *Silicon waveguide optical nonreciprocal devices based on magneto-optical phase shift*, Proc. SPIE, vol. 8988, 89880C, 2014
[4] Y. Shoji, Y. Shirato, T. Mizumoto, *Silicon Mach-Zehnder interferometer optical isolator having 8 nm bandwidth*, Jpn. J. Appl. Phys., vol. 53, 022202, 2014.
[5] K. Furuya, K. Kato, Y. Shoji, T. Mizumoto, *Demonstration of an athermal waveguide optical isolator on silicon platform*, 41st European Conference on Optical Communication (ECOC 2015), Th.2.4.2, 2015.