Reconfigurable integrated optical circulator

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Abstract: We demonstrate an integrated four-port optical circulator on silicon with 12dB isolation ratio. By locally switching the direction of the magnetic field on chip, we can dynamically reconfigure or shut off the circulation.
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1. Introduction

Optical circulators are a necessary, but challenging device to integrate in photonic integrated circuits. They are widely used in WDM networks, optical amplifiers, and optical sensing systems. Previous demonstrations on chip rely on the magneto-optic effect in cerium substituted yttrium iron garnet (Ce:YIG) to generate a nonreciprocal phase shift (NRPS). These devices are based on an unbalanced Mach-Zehnder interferometer (MZI) architecture, and use an external permanent magnet to apply the necessary magnetic field [1,2]. An alternate design is to utilize a microring which significantly reduces the footprint of the device [3], and several isolators have been demonstrated with this approach [4,5]. In this work, we present the first microring based optical circulator on silicon with a radius of only 20μm. Instead of using a permanent magnet, we use a gold microstrip that is integrated on chip to apply a current induced magnetic field [6]. We experimentally achieve 12dB of isolation for the circulator, and demonstrate that the circulation direction is reversible by flipping the direction of the field (i.e., reversing the current), which was previously not achievable. Further, transmission at the operating wavelength can be shut off in both directions.

2. Design

The device is an add-drop silicon microring based filter with a bonded cerium substituted yttrium iron garnet layer on top. On the substituted gadolinium gallium garnet (SGGG) backside of the bonded die, we pattern a microstrip, which closely follows the shape of the ring, as shown in Fig. 1a. Any current that flows in microstrip will induce a radially inward or outwards magnetic field with respect to the ring. This field causes NRPS between the clockwise (CW) and the counter-clockwise (CCW) transverse magnetic (TM) modes in the ring, which leads to a different phase constant between the two modes and, consequently, a resonance wavelength split (RWS).

Since we do not use a permanent magnet, we can easily switch the direction of the field by reversing the direction of the current. This is shown in Fig. 1b, in which the operating wavelength is aligned with the CW resonance (red) when the field is radially inwards. In this configuration, TM light from port 1 excites the CW mode in the ring, and is dropped to port 4. The full circulation flow in this configuration is 1→4→3→2→1. When the field is switched to be radially outward, the CW resonance wavelength shifts, and is no longer matched to the operating wavelength. The operating wavelength is now aligned to the CCW resonance. Therefore, light from port 1 will instead be passed through to port 2, and the circulation is now 1→2→3→4→1.

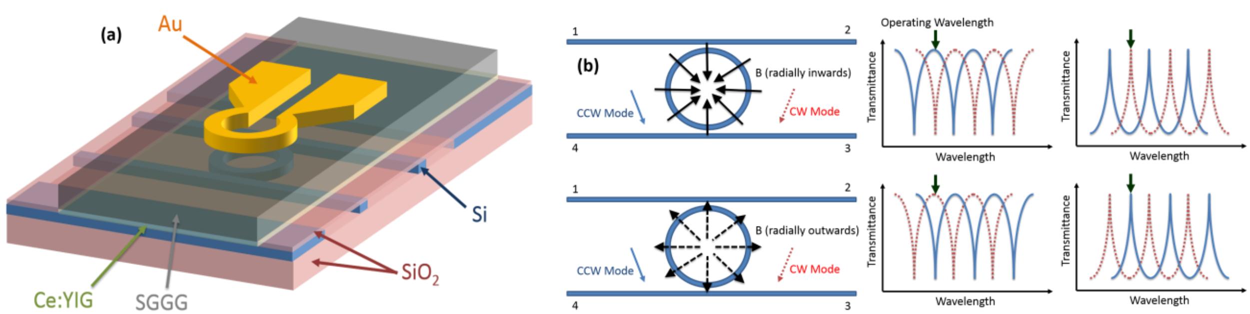

Figure 1: (a) Schematic of the microring optical circulator. (b) The optical circulator can be configured on one of two ways depending on whether the magnetic field is radially inwards (top) or outwards (bottom).

3. Fabrication and Characterization

Silicon waveguides are patterned on a 230 nm thick SOI wafer using DUV lithography, and then dry etched. A 400 nm thick single crystal Ce:YiG layer was grown on a 300 μm thick SGGG substrate, and then diced into 3.5 mm × 10 mm dies. Following an O_2 plasma activation of both the garnet and silicon surfaces, the Ce:YiG die is directly bonded onto the Si waveguides. The resulting bond is annealed at 200°C under pressure. Next, 1 μm of SiO_2 is sputtered to serve as an upper cladding, as well as protect the exposed Si waveguides that are not covered by the bonded die. Using a mechanical lapping technique, the SGGG substrate on the bonded die is thinned down from 300 μm to ~ 10 μm. Finally, 1.5 μm thick Ti/Au metal is patterned onto the back of the SGGG substrate using i-line lithography and subsequent metal liftoff. The width of the metal microstrip is 3μm. Multiple turns of microstrip can be used with two levels of metal to reduce the current required, as is done with magnetic recording heads.

We characterize the circulator by injecting light from a tunable laser source through a polarization maintaining fiber that is aligned to the TM mode of the waveguide in port 1. Then, we couple both the through (port 2) and drop (port 4) ports of the device to single mode fiber, apply a current through the microstrip to generate the magnetic field, and then observe the output power as the tunable laser is swept. Finally, we flip the direction of the current to change the configuration of the circulator. In Fig. 2a, we show the spectrum of both the through and drop ports in both configurations for +/-200mA of current. We measure a 0.32nm nonreciprocal RWS in the TM mode for these two configurations and 12dB of optical isolation. If we operate at 1558nm and apply -200mA of current, then light will be dropped from port 1 to port 4 with 5dB of loss. If we instead apply +200mA of current, then light will be passed through from port 1 to port 2 with 1 dB of loss. Due to symmetry in the scattering matrix of the circulator, inputs at other ports of the device will show similar behavior.

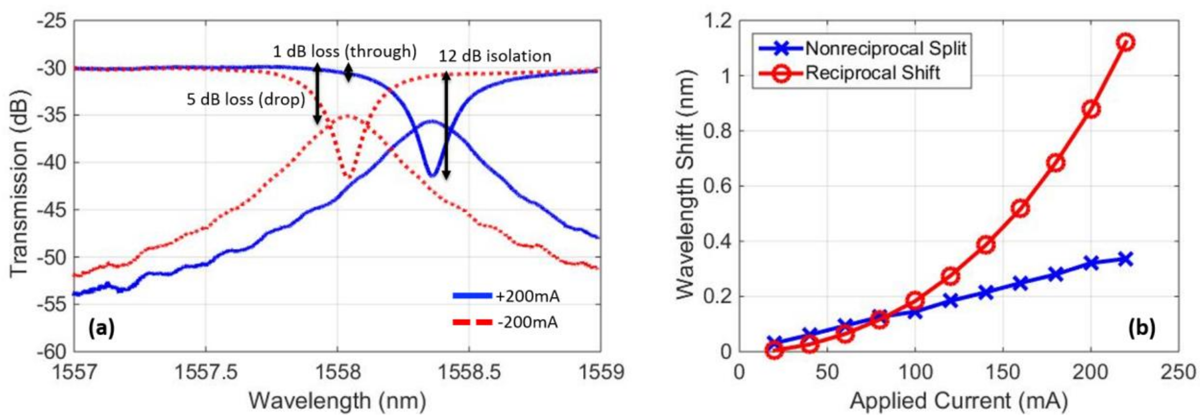

Figure 2: (a) Transmission spectrum at the through and drop ports of the circulator. (b) The nonreciprocal split (blue) and thermal induced redshift (red) of the resonance wavelength as a function of the applied current in the device.

In Fig. 2b, we show the nonreciprocal RWS between CW and CCW resonances as a function of the applied current in the microstrip. Due to saturation effects in the magnetization of the Ce:YIG, there is a maximum RWS that can be obtained. However, we have not reached that point yet, suggesting that a further improvement can be made by thinning the SGGG further as to produce a stronger magnetic field. Furthermore, we also notice a thermally induced redshift caused by Joule heating, which is denoted as the reciprocal shift. This can be used to tune the operating wavelength of the circulator, which is important for a narrowband device such as this one. It can also be used to shut off transmission in both directions with an isolation of 12 dB. In this device, the magnetic and thermal properties are inherently coupled due to the single microstrip. We can improve the tunability of the device by introducing a separate heater and decoupling these two effects.

In conclusion, we present the first microring based optical circulator on silicon, and experimentally measure 12dB of isolation. We also demonstrate that the circulator can operate in one of two configurations, depending on the direction of the magnetic field.

4. References

[1] S. Ghosh, et al. "Adhesively bonded Ce: YIG/SOI integrated optical circulator," Opt. Lett. **38**(6), 965-967 (2013).
[2] Y. Shoji, et al. "Optical nonreciprocal devices based on magneto-optical phase shift in silicon photonics," J. Opt **18**(1) 013001 (2015).
[3] P. Pintus, et al. "Integrated TE and TM optical circulators on ultra-low-loss silicon nitride platform," Opt. Express **21**(4) 5041-5052 (2013).
[4] L. Bi, et al. "On-chip optical isolation in monolithically integrated non-reciprocal optical resonators," Nat. Photon.**5**, 758-762 (2011).
[5] M.-C. Tien, et al. "Silicon ring isolators with bonded nonreciprocal magneto-optic garnets," Opt. Express **19**, 11740-11745 (2011).
[6] D. Huang, et al. "Silicon microring isolator with large optical isolation and low loss" to be presented at OFC 2016 (2016).