Monolithically integrated magneto-optical isolators, circulators and phase shifters on SiN photonics

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Abstract: We report monolithically integrated magneto-optical isolators, circulators on SiN with 30 dB isolation ratio, -28 dB cross-talk, 54 nm 20 dB isolation bandwidth, and 2.7 dB insertion loss. Compact magneto-optical phase shifter arrays with $V_{\pi}L$=0.3 V·cm were also developed, allowing the development of MHz speed optical phased arrays on SiN.

1. Introduction

SiN is an important photonic platform for optical communication, data communication and LIDAR applications. [1] However, due to the passive material nature, it lacks key functionalities such as optical isolation, circulation, and modulation. Magneto-optical (MO) thin films are promising candidates for above functionalities. Rare earth iron garnets (RIG) show comparable refractive index (n=2.3) [2] to SiN (n=2.0), allowing the construction of hybrid waveguides, optical isolators and circulators with SiN.[3-5] However, large scale integration of MO thin films and high performance devices on SiN is still absent. In this work, we report monolithic integration of optical isolators, circulators and phase shifters on SiN using MO thin films. We show sputter deposited Ce:YIG thin films with across wafer thickness homogeneity better than ±3% on a 4 inch oxidized Si substrate and SiN waveguides. Broadband optical isolators and circulators are fabricated. By design and fabrication of a permalloy based electromagnet on-chip, we also demonstrated a low driving voltage and thermo-optic effect free MO phase shifter on SiN.

2. Device Design and Experiments

SiN photonic integrated circuits (PICs) were processed in a standard silicon photonics foundry. 400 nm thick LPCVD grown SiN were used to fabricate the 800 nm wide channel waveguides with propagation loss < 0.4 dB/cm in the C band. The SiO_2 top-cladding were partially etched to expose the SiN waveguide core surface in a BEOL process. [3] Optical isolators and circulators were designed based on the Mach-Zenhder Interferometers (MZIs) structures [3,6]. 130 nm thick Ce:YIG thin films on top of a 50 nm thick yttrium iron garnet (YIG) seed layer were deposited on the SiN PICs by radio-frequency sputtering or pulsed laser deposition (PLD). The Ce:YIG thin films were crystallized by rapid thermal annealing at 850 ℃ for 5 min for sputtering, or high temperature deposition at 750 ℃ for pulsed laser deposition (PLD). The MO films were characterized by magneto-optical ellipsometry. The devices were characterized by an end-coupled system with lens tipped fibers. [3,6]

3. Results and Discussion

Fig. 1a shows the Ce:YIG/YIG thin film fabricated by off-axis rf sputtering on SiO_2/Si wafers. The X-ray diffraction patterns taken from different locations on the wafer are almost identical as shown in Fig. 1b. The refractive index of Ce:YIG was measured to be n=2.24 at 1550 nm wavelength. The off-diagonal component of the permittivity tensor was calculated by measuring the Muller Matrix under magnetic field, as shown in Fig. 1c. [7] This set-up allows non-invasive measurement of the thickness and optical constants across a whole 4” SiO_2/Si wafer. The measured real part of the off-diagonal component of Ce:YIG was 0.0049 at 1550 nm, agreeing well with its Faraday rotation angle of 2349 deg/cm. As shown in Fig. 1d-1g, the sputtered Ce:YIG thin film shows thickness, refractive index and off-diagonal permittivity homogeneity better than ±3%, ±5% and ± 6%, respectively across the 4” wafer.

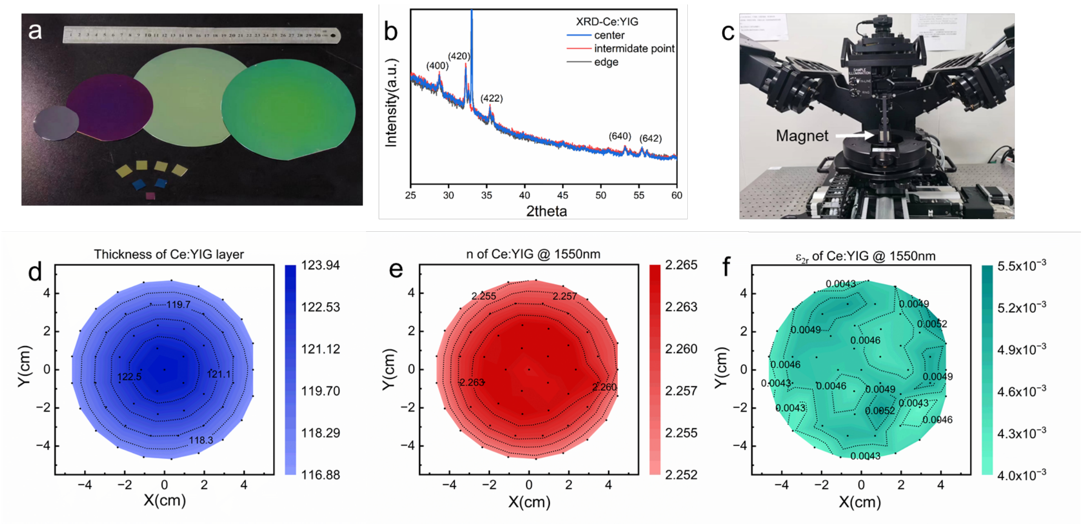

Fig. 1 (a) Wafer scale Ce:YIG on SiO_2/Si (b) XRD pattern of Ce:YIG at difference locations on a 4 inch Si wafer (c) The MO ellipsometry set-up (d) The thickness (e) index and (f) real part of the permittivity tensor of Ce:YIG across a 4 inch Si wafer

Fig. 2a shows the sketch of a SiN 2 × 2 MZI. The device shows bar or cross transmission for forward and backward propagations, respectively. Thus, it operates as an isolator or a four-port circulator. The process flow is shown in Fig. 2b. The YIG and Ce:YIG thin films were deposited after SiN fabrication and oxide cladding etch. Fig. 2c-2e shows the measured transmission spectrum of SiN TM, TE isolators and a broadband TM circulator respectively. The devices showed 2.3 dB/3 dB insertion loss, 32 dB/30 dB isolation ratio for TM/TE isolators respectively. To further improve the isolation bandwidth, we introduced dispersion engineered SiN waveguides to compensate the MO material dispersion. Theoretically, the 30 dB isolation bandwidth can reach 240 nm wavelength across the S, C and L bands. Despite of fabrication errors, we still observed 29 nm 20 dB isolation bandwidth experimentally as shown in Fig. 2e. The bandwidth can be further enlarged by thermo-optically finetune the phase shift of SiN, leading to 54 nm 20 dB isolation bandwidth (data not shown). As a circulator, the device showed cross-talk lower than -28 dB. The performance of these devices are comparable or even superior compared to their SOI counterparts.[2]

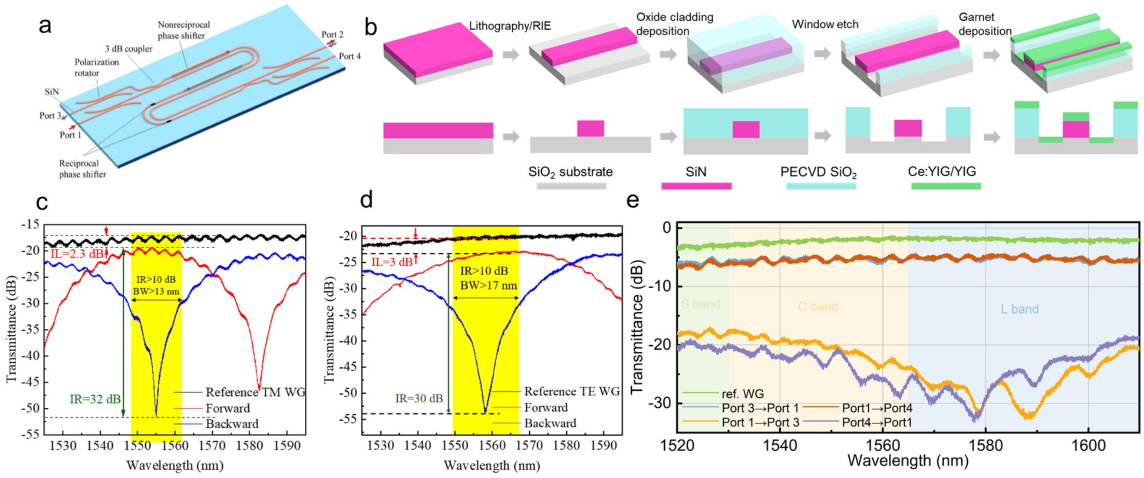

Fig. 2 (a) Sketch of an MZI type SiN optical isolator (b) Process flow of the MO isolator and circulator devices Transmission spectrum of a (c) TM and (d) TE mode isolator on SiN[3] (e) A broadband MO circulator on SiN

The MO/SiN waveguides can also operate as phase shifters by switching the magnetization of Ce:YIG in-plane with applied electric current. Although demonstrated recently on SOI[4, 5], such devices were not fabricated on SiN due to the high refractive index of the single crystal garnet substrate(n=2.0), which may cause leakage when bonded to SiN. This problem is solved in deposited MO/SiN waveguides with air cladding. In our devices, we introduced an electromagnet on either side of the MO SiN, as shown in Fig. 3a. Permalloy (NiFe) thin films were used as the core of the electromagnet, which showed soft magnetic properties with saturation magnetic field ~20 Oe. The NiFe was first magnetized by flowing current in Au. Then it magnetized the MO films. Thanks to the small mode size in MO/SiN waveguides, the NiFe thin films can be placed at only 2.5 μm away from the MO/SiN waveguide center, providing up to 240 Oe magnetic field upon its magnetization, sufficient to saturate Ce:YIG. Using this method, a MO ring resonator showed 17 rad/cm phase shift under 80 mA applied current and applied voltage of 1.6 V, corresponding to $V_{\pi}L$=0.3 V·cm, as shown in Fig. 3b. We further demonstrated parallel integration of such phase shifters to form a MO phased array (MOPA) device on SOI, as shown in Fig. 3c. The 1 × 8 MO phased array consisted of eight MO waveguides with light splitting MMI tree. By applying different current, a nonreciprocal phase gradient was achieved in the waveguide array. The output light was steered by the MO phased array in ±21° angle range with a modulation speed of 1 MHz, as shown inf Fig. 3d. These results demonstrate the scalability of MO phase shifters for SiN PIC applications.

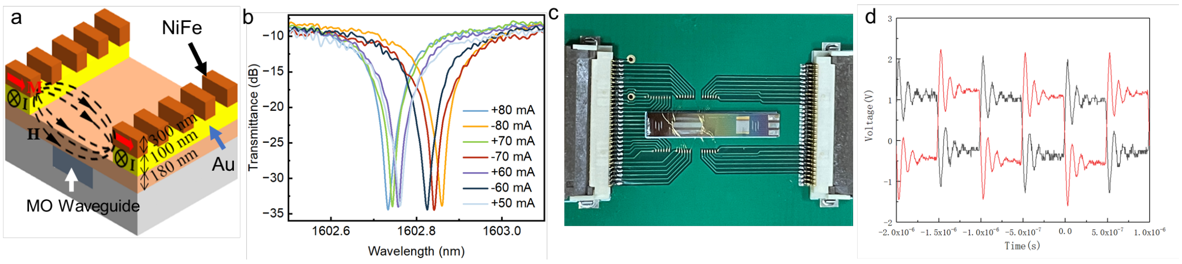

Fig. 3 (a) Sketch of a SiN MO phase shifter (b) Resonance peak shift of a MO/SiN ring resonator upon flowing current in Au electrodes (c) Optical image of a 1×8 MOPA (d) Photovoltage collected on two photodetectors upon steering the light beam at 1 MHz.

4. Conclusion

We demonstration SiN integrated magneto-optical isolator, circulator and phase shifters. The devices showed ~30 dB isolation ratio, -28 dB cross-talk, 54 nm 20 dB isolation bandwidth and 2.7 dB insertion loss. The MO nonreciprocal phase shifter showed $V_{\pi}L$ of 0.3 V·cm with good scalability. These devices are promising to provide key functionalities for SiN PICs.

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