Monolithic integration of broadband optical isolators for polarization-diverse silicon photonics

YAN ZHANG,† QINGYANG DU,† CHUANGTANG WANG,† TAKIAN FAKHRUL, SHUYUAN LIU, LONGJIANG DENG,† DUANNI HUANG, PAOLO PINTUS, JOHN BOWERS, CAROLINE A. ROSS, JUEJUN HU, AND LEI BI†,*

1National Engineering Research Center of Electromagnetic Radiation Control Materials, University of Electronic Science and Technology of China, Chengdu 610054, China
2Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
3Department of Electrical and Computer Engineering, University of California, Santa Barbara (UCSB), California 93106, USA
*e-mail: caross@mit.edu
*e-mail: hujuejun@mit.edu
*Corresponding author: bilei@uestc.edu.cn

Received 28 January 2019; revised 18 March 2019; accepted 18 March 2019 (Doc. ID 358804); published 12 April 2019

Integrated optical isolators have been a longstanding challenge for photonic integrated circuits (PICs). An ideal integrated optical isolator for a PIC should be made by a monolithic process, have a small footprint, exhibit broadband and polarization-diverse operation, and be compatible with multiple materials platforms. Despite significant progress, the optical isolators reported so far do not meet all of these requirements. In this paper we present monolithically integrated broadband magneto-optical isolators on silicon and silicon nitride (SiN) platforms operating for both TE and TM modes with record-high performances, fulfilling all the essential characteristics for PIC applications. In particular, we demonstrate fully TE broadband isolators by depositing high-quality magneto-optical garnet thin films on the sidewalls of Si and SiN waveguides, a critical result for applications in TE-polarized on-chip lasers and amplifiers. This work demonstrates monolithic integration of high-performance optical isolators on-chip for polarization-diverse silicon photonic systems, enabling new pathways to impart nonreciprocal photonic functionality to a variety of integrated photonic devices.

1. INTRODUCTION

Nonreciprocal optical devices are essential for controlling the flow of light in photonic systems. These devices include optical isolators placed at the output of each laser to block back-reflected light and circulators to separate signals traveling in opposite directions. Achieving optical isolation on-chip by breaking optical reciprocity has been a major goal of the integrated photonics community [1,2]. An ideal integrated optical isolator should feature several important characteristics, including monolithic integration, high isolation ratio and low insertion loss, broadband operation, polarization diversity, and multimaterial platform compatibility. Achieving these functions in a photonic integrated circuit (PIC) is a critical challenge requiring device design combined with materials development and integration.

Several approaches have been made to achieve isolation, including the use of nonlinear effects [3,4] or active modulation of the refractive index [5,6]. Passive devices based on magneto-optical (MO) effects are one of the most attractive solutions. MO devices may be based on mode conversion via the Faraday effect [7,8] as used in bulk isolators, but the birefringence of on-chip waveguides favors devices based instead on a nonreciprocal phase shift (NRPS), including ring resonators, multimode interferometers, and Mach–Zehnder interferometers (MZIs) [9–16]. The best-performing MO materials in the near-IR communications band are yttrium iron garnets substituted with Bi or Ce to increase their Faraday rotation [17–20]. Integration of garnet into silicon PICs has been accomplished via wafer bonding [21] and via monolithic integration [18,20].

Considerable progress has been made in both device design and materials development, primarily focused on transverse magnetic (TM) mode devices in which the garnet is placed on the top or bottom surface of the waveguide. Wafer-bonded TM ring resonator (RR) isolators exhibit isolation ratios up to 32 dB and insertion losses as low as 2.3 dB [12,13] but with low isolation bandwidth. MZIs exhibit higher bandwidth, and TM MZI devices have been fabricated on single-crystal garnets [16] or by wafer bonding [14,15] (Table 1). However, on-chip lasers produce transverse electric (TE) light whose isolation requires symmetry breaking transverse to the waveguide [22]. TE isolation has been demonstrated by Faraday rotation [8], by device fabrication on single-crystal Ce:YIG [23], and by combination of a TM isolator with mode converters [24–26], but these solutions are large
in area, difficult to integrate, lossy due to extra polarization rotators, or require complex fabrication processes.

Here we address all the aforementioned requirements for practical on-chip optical isolation by demonstrating monolithically integrated magneto-optical isolators on silicon nitride (SiN) waveguides operating for both TE and TM modes with high isolation ratios, low insertion losses, small footprints, and broadband optical isolation. We demonstrate the first fully TE broadband isolator by depositing high-quality magneto-optical garnet thin films on the sidewalls of silicon interferometer waveguides and the multimaterial platform compatibility of this technology by demonstrating the first monolithic optical isolator on SiN. Both TM and TE isolators show the best performance to date among broadband optical isolators on silicon, with optical isolation up to 30 dB and insertion loss as low as 5 dB.

2. DEVICE DESIGN AND FABRICATION

Figure 1(a) illustrates the generic layout of the broadband isolator, which consists of a silicon Mach–Zehnder interferometer (MZI) with serpentine waveguide arms embedded in SiO2 cladding. Window sections were etched into the top SiO2 cladding to expose the silicon waveguide on alternating serpentine segments. A blanket magneto-optical Ce:YIG (100 nm)/YIG (50 nm) film stack was then deposited on top of the device. For the TM isolators, the entire top surface of the Si waveguide within the window is covered with the MO film [Fig. 1(b)], whereas for the TE isolators, the entire top surface of the Si waveguide within the window stack was then deposited on top of the device. For the TM isolator, a blanket magneto-optical Ce:YIG (100 nm)/YIG (50 nm) film was deposited on top of the device. For the TM isolator, the magnetic field is applied in the film plane. The TM and TE isolators were fabricated on SOI and SiN platforms. For SOI devices, MTI Corp. SOI wafers with 220 nm device layer and 2 μm buried oxide were first cleaned in piranha solutions for 10 min to remove any organic contaminations. A 4% HSQ resist (XR-1541, Dow Corning) was spun onto the wafer with thickness of ~100 nm and then exposed on an Elionix ELS-F125 electron beam lithography (EBL) system with a beam current of 8 nA. The resist was then developed in 25% tetramethylammonium hydroxide (TMAH) for 3 min to reveal a device pattern. Reactive ion etch (RIE) with Cl2 gases was subsequently utilized to transfer the pattern into the SOI wafer in a PlasmaTherm Etcher. Similarly, silicon nitride devices started from piranha cleaning a silicon wafer with 3 μm thermal oxide, and then a 400 nm SiN device layer was deposited onto the wafer by low pressure chemical vapor deposition (LPCVD).

![Fig. 1. Schematics of the TM and TE isolators. (a) Illustration of the device layout. The red arrows represent the light propagation direction. (b) Sketch of the magneto-optical waveguide cross section for the TE isolator. The magnetic field is applied perpendicular to the film plane. (c) Sketch of the magneto-optical waveguide cross section for the TM isolator. The magnetic field is applied in the film plane. (d) Simulated $E_y$ field distribution of the fundamental TE mode for the magneto-optical waveguide. (e) Simulated $H_z$ field distribution of the fundamental TM mode for the magneto-optical waveguide.](image)

$$\Delta \beta (TM) = \frac{2\beta_{TM}}{\gamma_0} \gamma H_x \partial_x H_z dx dy$$
$$\Delta \beta (TE) = \frac{2\gamma_0}{\beta_{TE}} \gamma E_x \partial_x E_z dx dy$$

where $\beta_{TM}$ and $\beta_{TE}$ are the propagation constants for the fundamental TM and TE modes, $\omega$ is the frequency, $\gamma$ is the off-diagonal component of the permittivity tensor of the magneto-optical material, $\gamma_0$ is the vacuum dielectric constant, $N$ is the power flux along the $x$ direction, $n_\gamma$ is the index of refraction of the magneto-optical material, and $H_x$ and $E_y$ are the electromagnetic fields along the $x$ direction. Considering Faraday rotations of Ce:YIG (~3000 deg/cm) and YIG (220 deg/cm, Supplement 1, Fig. S2), the simulated NRPS are 16.2 rad/cm and 18.9 rad/cm for TE and TM waveguides, respectively, which stipulate nonreciprocal phase shifter waveguide lengths of 968 μm and 830 μm to achieve a total nonreciprocal phase difference of $\pi$ on both arms. A reciprocal phase shifter (RPS) producing 50.5 $\pi$ phase shift (16 μm and 22 μm long Si waveguide for TE and TM modes, respectively) is introduced in one arm of the MZI devices, creating a total phase difference of 50$\pi$ and 51$\pi$ for the forward and backward propagating light, respectively. The serpentine MZI layout enables a small device footprint of 0.87 mm × 0.34 mm for TE isolators and 0.94 mm × 0.33 mm for TM isolators.

The TM and TE isolators were fabricated on SOI and SiN platforms. For SOI devices, MTI Corp. SOI wafers with 220 nm device layer and 2 μm buried oxide were first cleaned in piranha solutions for 10 min to remove any organic contaminations. A 4% HSQ resist (XR-1541, Dow Corning) was spun onto the wafer with thickness of ~100 nm and then exposed on an Elionix ELS-F125 electron beam lithography (EBL) system with a beam current of 8 nA. The resist was then developed in 25% tetramethylammonium hydroxide (TMAH) for 3 min to reveal a device pattern. Reactive ion etch (RIE) with Cl2 gases was subsequently utilized to transfer the pattern into the SOI wafer in a PlasmaTherm Etcher. Similarly, silicon nitride devices started from piranha cleaning a silicon wafer with 3 μm thermal oxide, and then a 400 nm SiN device layer was deposited onto the wafer by low pressure chemical vapor deposition (LPCVD).
Device patterning was performed with ZEP520A resist in the EBL system and the resist was developed in ZED-N50 for 1 min. RIE was conducted in the same etcher with a gas mixture of CHF₃ and CF₄. Starting from this point, the processes described below were identical for SOI and SiN devices. A layer of FOX-25 (Dow Corning flowable oxide) was then spun onto the wafer with a thickness of 400 nm followed by rapid thermal annealing at 800°C for 5 min to form a planarized top SiO₂ cladding. An additional 250 nm plasma enhanced chemical vapor deposition (PECVD) silicon oxide was further deposited onto the wafer to completely isolate the optical mode from interacting with Ce:YIG deposited in the next steps. Next, a second EBL process using a positive resist (ZEP520A) was carried out to pattern the window regions. Finally, for TM devices, buffered oxide etch was used to expose the silicon waveguide surface. For TE devices, RIE using a gas mixture of CHF₃ and Ar ambient was applied to etch down the silicon oxide top cladding and exposed one sidewall of the silicon waveguides. A piranha solution was used to clean the samples to remove any fluorinated polymer generated during the etching process. The as-fabricated devices were tested at least three times by reversing light propagation directions. The samples were maintained at room temperature with ±0.2°C accuracy during the test.

3. PERFORMANCE OF TE AND TM OPTICAL ISOLATORS ON SILICON

Figures 2(a) and 2(c) show top-view optical micrographs for both types of isolators. The sections with open SiO₂ windows appear darker. For the TE device, the oxide windows are smoothly curved on both ends to allow near-adiabatic mode transformation between waveguide segments with and without garnet with minimal loss. Cross-sectional scanning electron microscope (SEM) images taken within the window sections [Figs. 2(b) and 2(d)] indicate that the Ce:YIG/YIG polycrystalline garnet-coated waveguides closely follow our designed geometries illustrated in Figs. 1(c) and 1(b). The garnet thin films also exhibit excellent crystallinity and chemical homogeneity up to the Si/MO oxide interface for both devices, evidenced by high-resolution tunneling electron microscopy and energy dispersive spectroscopy analysis presented in Supplement 1, Fig. S1.

The optical isolators were characterized on a fiber butt-coupled waveguide test station. A LUNA Technology optical vector analyzer (OVA) 5000 was used to emit laser light from 1520 nm to 1610 nm. The transmitted light was then acquired by the OVA to analyze polarization-dependent transmission spectra. In a different setup, a free-space polarization control bench was used to obtain TE or TM polarized light before coupling to a polarization maintaining (PM) fiber. The linear polarized light was then butt coupled to the device for transmittance measurements with a lens-tipped PM fiber. The testing methods are detailed in Supplement 1. All devices were tested at least three times by reversing light propagation directions. The samples were maintained at room temperature with ±0.2°C accuracy during the test.

Figure 3(a) plots the transmission spectra of the TM-mode optical isolator under a uniaxially applied magnetic field of 1000 Oe, together with a reference silicon waveguide on the same chip. The interleaving fringes on the forward (red) and backward (blue) propagating spectra are detuned by approximately half a free spectral range. The result shows that the device attains a non-reciprocal phase difference of π for the forward and backward propagating modes consistent with our design. Figure 3(c) shows the measured (dots) and modeled (lines) isolation ratio and insertion loss around 1574.5 nm wavelength, where the model takes into account waveguide dispersion of the reciprocal and non-reciprocal phase shifters. The maximum isolation reaches 30 dB. The 20 dB and 10 dB isolation bandwidth of this device is 2 nm and 9 nm, respectively. The device bandwidth can be readily increased by reducing the RPS waveguide length. Across the
entire 10 dB isolation bandwidth, the device shows low insertion loss of 5–6 dB, which represents the lowest insertion loss measured in a broadband on-chip isolator.

Figure 3(b) shows the transmission spectrum of the TE-mode optical isolator. A maximum isolation ratio of 30 dB, an insertion loss of 9 dB, and a 10 dB isolation bandwidth of 2 nm are achieved at 1588 nm wavelength. To the best of our knowledge, this is the first fully TE broadband isolator integrated on silicon where no polarization rotators are required. The NRPS of this device, 3.6 rad/cm, is lower than that of the designed value of 14 rad/cm (Supplement 1, Section 6). The difference is possibly due to a lower magneto-optical effect of the Ce:YIG thin films grown on the silicon waveguide sidewalls or due to a small air gap between the Si waveguide and the MO thin films [25], which may be improved by optimization of the thin-film deposition process. The interference fringes in the transmission spectrum of this device are due to Fabry–Pérot interferences from the cleaved waveguide facets, which can be minimized by designing spot size converters or using grating couplers.

Figure 3. Forward and backward transmission spectra of the isolators. Parts (a) and (b) show the transmission spectra of the TM and TE mode isolators, respectively. The corresponding isolation ratio and insertion loss in the dashed regions are shown in (c) for the TM isolator and (d) for the TE isolator, respectively.

4. MONOLITHIC TE OPTICAL ISOLATOR ON SILICON NITRIDE

Besides Si, SiN is another standard waveguide material widely employed in silicon photonics platforms, offering unique advantages such as back-end-of-line compatibility and visible light transparency over Si. To date, integrated optical isolators have not yet been demonstrated on the SiN platform [27]. Here we further show that our monolithic approach can be equally applied to isolator integration on SiN through demonstration of the first TE-mode isolator on SiN. The isolator comprises a SiN racetrack resonator encapsulated in SiO2 cladding. A window is opened in the cladding to expose one waveguide sidewall similar to the Si TE isolator design depicted in Fig. 1(c). The fabricated device is shown in Fig. 4(a) (top-view optical micrograph) and 4(b) (cross-sectional SEM). It is worth noting that unlike the TM resonator isolator design demonstrated previously [10], the window can extend along the entire resonator without cancelling out NRPS as the magnetic field is applied along the out-of-plane direction. In our SiN device, the window covers the resonator device except the coupling section to avoid changing the coupling condition to the bus waveguide. Transmittance spectra of forward and backward propagation light are displayed in Fig. 4(c), which yields an insertion loss of 11.5 dB and an isolation ratio of 20.0 dB at resonance. We repeated the measurement multiple times, and the data in Fig. 4(d) consistently show a resonant peak shift of (15 ± 2) pm upon reversing the light propagation direction. The result unambiguously validates nonreciprocal light propagation in the SiN device.

5. DISCUSSION

To benchmark the performance of our device, Table 1 compares the device performance of broadband optical isolators on silicon. For TM devices, our device claims a high isolation ratio, the lowest insertion loss, and the smallest footprint. These results
demonstrate the possibility to monolithically integrate optical isolators on silicon with performance approaching that of bulk optical isolators [28]. For TE devices, our work demonstrates TE nonreciprocal phase shifters and optical isolators on silicon and SiN for the first time. The ability to deposit high-quality polycrystalline garnet thin films both on the top and sidewalls of Si and SiN waveguides is significant because it allows the introduction of optical nonreciprocity in planar photonic devices by filling trenches, covering nanostructures, or forming photonic crystals, thereby enabling new pathways to impart nonreciprocal photonic functionality to a variety of existing photonic integrated circuits.

The excellent performance of our devices is attributed to the exceptionally large Faraday rotation and low loss of the Ce:YIG thin films. The Faraday rotation of the film can be inferred using Eq. (1) (Supplement 1, Section 6) to be $-2960 \text{ deg/cm}$ for Ce:YIG deposited on the Si TM device. This value is significantly higher than previously reported Ce:YIG thin films deposited by PLD [10] and benefits from judicious control of the deposition oxygen partial pressure to drive higher $\text{Ce}^{3+}/\text{Ce}^{4+}$ ratios (Supplement 1, Fig. S2). The material and device losses are parameterized in Supplement 1, Section 5. Taking the TM isolator as an example, the total insertion loss of 5–6 dB mainly includes a 0.7 dB excess loss from each of the 3 dB MMI couplers, a propagation loss of 2.2–3.2 dB from the magneto-optical waveguides covered with garnet, a coupling loss of 0.25 dB/junction at the junctions between the waveguide with and without garnet, and a propagation loss of 0.36 dB from the silicon waveguides not covered by garnet. Therefore, the total insertion loss can be further reduced by optimizing the coupler and junction designs, for example, by using low-loss broadband adiabatic couplers [31] instead of MMIs, and using taper designs to minimize the waveguide junction losses. On the other hand, by further improving the Ce:YIG and YIG figure of merit [17], the material loss can be improved. Reducing the YIG seed layer thickness or using a top seed layer can also lead to a much higher device FOM by increasing coupling of light from the waveguide into

**Fig. 4.** SiN-based microring magneto-optical isolator. (a) Optical microscope image of the SiN microring isolator. The gap between the bus waveguide and the racetrack resonator is 1500 nm. (b) Cross-sectional SEM image of the SiN magneto-optical waveguide. (c) Forward and backward transmission spectrum of the isolator. The inset shows the transmission spectra of three resonance peaks of the same device. (d) The peak positions of the forward and backward propagation light for multiple measurements.

**Table 1.** Comparison of Device Performance at 1550 nm for Broadband Optical Isolators on Si

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Isolation Ratio (dB)</th>
<th>Insertion Loss (dB)</th>
<th>Size (mm × mm)</th>
<th>Monolithic/Bonding</th>
<th>Polarization</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si MZI</td>
<td>30</td>
<td>5</td>
<td>0.94 × 0.33</td>
<td>monolithic</td>
<td>TM</td>
<td>this work</td>
</tr>
<tr>
<td>Si MZI</td>
<td>30</td>
<td>9</td>
<td>0.87 × 0.34</td>
<td>monolithic</td>
<td>TE</td>
<td>this work</td>
</tr>
<tr>
<td>SiN MZI</td>
<td>18</td>
<td>10</td>
<td>3.2 × 1.0</td>
<td>monolithic</td>
<td>TE</td>
<td>this work</td>
</tr>
<tr>
<td>Si MZI</td>
<td>27</td>
<td>13</td>
<td>1.5 × 1.5</td>
<td>bonding</td>
<td>TM</td>
<td>[29]</td>
</tr>
<tr>
<td>Si MZI</td>
<td>25</td>
<td>8</td>
<td>4 × 4</td>
<td>bonding</td>
<td>TM</td>
<td>[30]</td>
</tr>
<tr>
<td>Si MZI</td>
<td>32</td>
<td>22</td>
<td>4 × 4</td>
<td>bonding</td>
<td>TE</td>
<td>[25]</td>
</tr>
<tr>
<td>Si MZI</td>
<td>30</td>
<td>8</td>
<td>1.7 × 0.3</td>
<td>bonding</td>
<td>TM</td>
<td>[14]</td>
</tr>
<tr>
<td>Si Faraday Rotator</td>
<td>11</td>
<td>4</td>
<td>4 (1D device)</td>
<td>monolithic</td>
<td>TE/TM</td>
<td>[8]</td>
</tr>
</tbody>
</table>
the Ce:YIG layer [18,20]. Therefore, a broadband monolithic isolator device with <3 dB insertion loss is well within the reach of state-of-the-art silicon photonic device technologies.

6. CONCLUSIONS
In summary, we experimentally demonstrated monolithically integrated broadband optical isolators for both TE and TM polarizations on silicon. By depositing high-quality magneto-optical garnet thin films on both the top and sidewalls of the silicon waveguides, we realized monolithic on-chip optical isolators with high isolation ratios, low insertion losses, broadband operations, and small footprints. Moreover, we also show this technology is agnostic to the waveguide material platform by experimentally realizing the first fully TE optical isolator on SiN with a high isolation ratio. The work represents an important step toward practical implementation of monolithic isolator integration on-chip with performance approaching that of traditional bulk isolators. The capability to integrate high-quality magneto-optical thin films with photonic waveguides, validated through this work, also paves the path to experimental demonstration of several theoretically proposed magneto-optical photonic crystal structures [32,33] as well as isolators, magneto-optical modulators and phase shifters, and topological photonic devices based on time-reversal symmetry breaking using magneto-optical materials [2].

Funding. National Natural Science Foundation of China (NSFC) (51522204, 61475031); Ministry of Science and Technology of the People’s Republic of China (MOST) (2016YFA0300802); National Science Foundation (NSF) (1607865).

See Supplement 1 for supporting content.

These authors contributed equally to this work.

REFERENCES