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Filling in the missing link: monolithic optical isolators on silicon with high performance, broadband operation, and polarization diversity

Hu, Juejun, Zhang, Yan, Du, Qingyang, Wang, Chuangtang, Fakhrul, Takian, et al.
Filling in the missing link: monolithic optical isolators on silicon with high performance, broadband operation, and polarization diversity

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ABSTRACT

On-chip optical isolators constitute an essential building block for photonic integrated circuits. Monolithic magneto-optical isolators on silicon, while featuring unique benefits such as scalable integration and processing, fully passive operation, large dynamic range, and simple device architecture, have been limited by their far inferior performances compared to their bulk counterparts. Here we discuss our recent work combining garnet material development and isolator device design innovation, which leads to a monolithic optical isolator with an unprecedented low insertion loss of 3 dB and an isolation ratio up to 40 dB. To further overcome the bandwidth and polarization limitations, we demonstrated broadband optical isolators capable of operating for both TM and TE modes. These results open up exciting opportunities for scalable integration of nonreciprocal optical devices with chip-scale photonic circuits.

Keywords: Optical isolators, magnetooptics, photonic integration, nonreciprocal photonics

1. INTRODUCTION

Nonreciprocal optical devices are essential for controlling the flow of light in photonic systems. Realizing optical isolation on-chip by breaking optical reciprocity has been a major goal of the integrated photonics community\textsuperscript{1-7}. 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\textsuperscript{8,9} or active modulation of the refractive index\textsuperscript{10-12}. Passive devices using magnetooptical (MO) effects are one of the most attractive solutions\textsuperscript{13}. MO devices may be based on mode conversion via the Faraday effect\textsuperscript{14-16} 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)\textsuperscript{17-25}. 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\textsuperscript{26-32}. Integration of garnet into silicon PICs has been accomplished via wafer bonding\textsuperscript{33} and via monolithic integration\textsuperscript{34,35}.

Considerable progress has been made 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 but with low isolation bandwidth\textsuperscript{30}. MZIs exhibit higher bandwidth, and TM MZI devices have been fabricated on single-crystal garnets\textsuperscript{24} or by wafer bonding\textsuperscript{33}. However, on-chip lasers produce transverse electric (TE) light whose isolation requires symmetry breaking transverse to the waveguide\textsuperscript{36}. TE isolation has been demonstrated by Faraday rotation (FR)\textsuperscript{16}, by device fabrication on single-crystal Ce:YIG\textsuperscript{37}, and by combination of a TM isolator with mode converters\textsuperscript{38-41}.

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Here we address all the aforementioned requirements for practical on-chip optical isolation by demonstrating monolithically integrated magneto-optical isolators operating for both TE and TM modes with high isolation ratios, low insertion losses, small footprints, and broadband optical isolation.

2. HIGH-PERFORMANCE TM RING ISOLATOR

The isolator design is depicted in Figure 1a (perspective view) and 1b (cross-section)\(^2\). The basic building block of the isolator is a nonreciprocal magneto-optical resonator comprising striploaded waveguides on a deposited \(\text{Ce}_x\text{Y}_{1-x}\text{Fe}_5\text{O}_{12}\) (Ce:YIG) film. The film is deposited on a planar silica-on-silicon layer and is fully crystallized into the garnet phase (confirmed by X-ray diffraction and vibrating sample magnetometry measurements). By sandwiching a vertically tapered oxide spacer layer between the strip-loaded waveguide core and the Ce:YIG film, only a fraction of the microring is in direct contact with the Ce:YIG layer and magneto-optically active. The oxide taper creates an adiabatic mode transformer, which minimizes scattering and Fresnel reflection losses between waveguide sections with and without the spacer layer. The design therefore eliminates the two dominant sources of parasitic optical losses, i.e., absorption from secondary phases and waveguide junction scattering, which underpins the superior isolation performance we experimentally obtained in the device.

![Figure 1. (a) Tilted-view and (b) cross-sectional schematic of the new isolator design; (c) nonreciprocal phase shift and waveguide figure of merit computed as functions of the strip-loaded waveguide core refractive index: the insets are modal profiles of strip-loaded waveguides when the core material is chosen as silicon nitride \((n = 2.0)\), GeSbSe glass \((n = 2.7)\), and amorphous silicon \((n = 3.6)\), where the scale bars correspond to 500 nm; (d) fabrication process for the isolator device.](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

The design also features an added benefit through enhancing nonreciprocity in the waveguide. The unsubstituted YIG seed layer exhibits Faraday rotation with a sign opposite to that of Ce:YIG\(^4\), which partially cancels out the waveguide NRPS. The deleterious effect is aggravated in the traditional waveguide structure as the YIG layer sits directly on top of the Si core, thereby having large spatial overlap with the evanescent field. In the strip-loaded waveguide configuration, the effect is alleviated since the Ce:YIG layer rather than the YIG layer is in direct contact with the waveguide core. Our numerical modeling suggests that the configuration contributes to a 26% enhancement in NRPS of the waveguide.

The isolator design is further optimized through judicious choice of the waveguide core material. Figure 1c plots the simulated NRPS and FOM of the strip-loaded waveguide on Ce:YIG as functions of the refractive index of the core material. Here, the waveguide FOM (a dimensionless quantity) is defined as:

\[
\text{FOM}_{\text{WG}} = \frac{\Delta \beta}{\alpha},
\]

where \(\Delta \beta\) denotes the waveguide NRPS for the quasi-TM mode, i.e., the propagation constant difference of forward and backward propagating modes in the waveguide (in radian per cm), and \(\alpha\) gives the waveguide propagation loss (in cm\(^{-1}\)).
In Figure 2c, the waveguide dimensions are optimized to achieve maximum waveguide FOM for each core material index value while ensuring single-mode operation. The simulations show that, while NRPS monotonically rises with increasing refractive index of the core over the range of indices considered, modal confinement in the Ce:YIG layer and hence optical loss also grows as a result of the reduced core thickness and increasing field discontinuity at the boundaries. The tradeoff therefore points to an optimal core index of 2.6 to reach the maximum waveguide FOM.

Based on this insight, we selected Ge$_{22}$Sb$_{18}$Se$_{60}$ (GeSbSe), a chalcogenide glass (ChG), as the waveguide core material. The glass has a refractive index of 2.7 near 1550 nm wavelength, close to the optimal value of 2.6. The chemical stability and optical transparency of GeSbSe glasses have also been experimentally established$^{44-47}$. Moreover, we have already matured fabrication protocols for low-loss ChG photonic devices including on-chip resonators with quality factors (Q-factors) exceeding one million$^{48}$ and applied the technique to realize a wide array of functional photonic components and systems$^{49-55}$. The low deposition and processing temperatures of ChG further mitigates the risk of film cracking or delamination due to thermal stress accumulation$^{56,57}$. We note that the isolator architecture is, however, generic and can also make use of other low-loss deposited dielectric materials such as silicon nitride$^{58}$ and amorphous silicon$^{59}$ as the waveguide core. Additionally, the strip-loaded waveguide layout as well as the low-loss vertical taper structure are equally applicable to enhancing the performance of other isolator device platforms such as those based on Mach–Zehnder interferometers (MZIs). The process flow to fabricate the isolator structure is shown in Figure 1d.

Figure 2a illustrates a schematic diagram of the isolator characterization setup. The fabricated device was tested on a Newport Autoalign station where light was coupled in and out of the waveguides via end fire coupling through tapered fibers (Nanonics Imaging Ltd.) mounted on computerized motion stages. The device chip was covered with an index matching fluid (Cargille-Sacher Laboratories Inc.), which helps to minimize Fresnel reflection in fiber-to-chip coupling. An optical vector analyzer (OVA, Luna Innovations Inc.) with built-in external cavity tunable laser was used in conjunction with an erbium-doped fiber amplifier (Amocons Ltd.) as the interrogation light source. The waveguide output spectrum was also monitored by the OVA. During the test, a rare-earth permanent magnet was placed near one end of the device chip to impose a nearly unidirectional magnetic field of approximately 0.1 T on the devices, sufficient to saturate the magnetization of the ferrimagnetic Ce:YIG film. The isolation performance was validated by reversing the light propagation direction. The measurement was repeated five consecutive times and averaged to suppress unwanted resonant peak drift due to temperature fluctuations.

The bidirectional transmission spectra of quasi-TM mode in the isolator device are presented in Figure 2b. As shown in the figure, the device exhibits an IL as low as 3.0 dB and a high IR of 40 dB, both of which set the performance records...
for monolithic magneto-optical isolators. The spectra, averaged over five consecutive measurements, reveal a nonreciprocal resonant peak shift of \((44 \pm 4)\) pm, in agreement with our simulation results. The resonant peak positions at both forward and backward directions recorded during the five repeated measurements are plotted in Figure 2c. Wavelength dependence of the nonreciprocal resonance shift was characterized in the wavelength range of 1540 to 1590 nm. The measurement results, plotted in Figure 2d alongside simulations, indicate a nearly wavelength-independent nonreciprocal resonant peak shift resulting from two opposing contributions: at longer wavelengths, the diminished FR of Ce:YIG\(^{60}\) is balanced by a wavelength squared dependence of nonreciprocal resonance shift.

3. BROADBAND TE AND TM OPTICAL ISOLATORS ON SILICON

Figure 3. 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 \(E_x\) field distribution of the fundamental TE mode for the magneto-optical waveguide. (e) Simulated \(H_y\) field distribution of the fundamental TM mode for the magneto-optical waveguide\(^{61}\).

Figure 3(a) illustrates the generic layout of the broadband isolator, which consists of a silicon Mach–Zehnder interferometer (MZI) with serpentine waveguide arms embedded in SiO\(_2\) cladding. Window sections were etched into the top SiO\(_2\) 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 windows is covered with the MO film [Fig. 3(b)], whereas for the TE devices the waveguide top surface is masked by SiO\(_2\) such that the film only deposits on one side of the waveguide [Fig. 3(c)]. (The NRPS cancels out if the film is deposited on both sides of the waveguide.) When the film is magnetized under a unidirectional magnetic field, nonreciprocal phase shifts of opposite signs are induced in the two interferometer arms, leading to constructive (destructive) interference of forward (backward) propagating waves and optical isolation. The design therefore uniquely features a small footprint, large bandwidth, and compatibility with a simple unidirectional magnetization scheme. The simulated modal profile is shown in Figs. 3(d) and 3(e).

To fabricate the devices, SOI wafers with 220 nm device layer and 2 \(\mu m\) 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 Cl\(_2\) gases was subsequently utilized to transfer the pattern into the SOI wafer in a PlasmaTherm Etcher. 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 SiO\(_2\) 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 CHF\(_3\) 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 loaded into the pulsed laser deposition (PLD) chamber for magneto-optical thin-film deposition. Thin-film deposition utilized a KrF excimer laser source, which operates at 248 nm and at a repetition rate of 10 Hz. The fluence of the laser was determined to be 2.5 J/cm\(^2\). The
distance between the target and the substrate was fixed at 5.5 cm. 50 nm thick YIG thin films were first deposited onto the substrate at 450°C and then rapid thermal annealed at 900°C for 5 min for full crystallization. Finally, 100 nm thick Ce:YIG thin films were deposited at 650°C onto the devices.

Figure 4. Optical microscope and SEM images of the TM and TE isolators. Parts (a) and (c) show the optical microscope image for the TM and TE isolators, respectively. The scale bars are 100 μm. Parts (b) and (d) show the cross-sectional SEM image of the magneto-optical waveguides for the TM and TE isolators, respectively. The scale bars are 100 nm. In (b) and (d) the MO layer is colored in green and the Si waveguide in purple.

Figure 5. 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.
Figures 4(a) and 4(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. 4(b) and 4(d)] indicate that the Ce:YIG/YIG polycrystalline garnet-coated waveguides closely follow our designed geometries illustrated in Figs. 3(c) and 3(b).

The optical isolators were characterized on a fiber butt-coupled waveguide test station following protocols described in the previous section. The samples were maintained at room temperature with ±0.2°C accuracy during the test. Figure 5(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 fringes on the forward (red) and backward (blue) propagating spectra are detuned by approximately half a free spectral range. Figure 5(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 nonreciprocal 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 arm length imbalance. 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 5(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, 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.

4. CONCLUSIONS

In summary, we have significantly advanced the state-of-the-art in monolithic integrated optical isolators by demonstrating an on-chip isolator with a record low insertion loss of 3.0 dB and an isolation ratio of 40 dB, and realizing 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. 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 as well as isolators, magneto-optical modulators and phase shifters, and topological photonic devices based on time-reversal symmetry breaking using magneto-optical materials.

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