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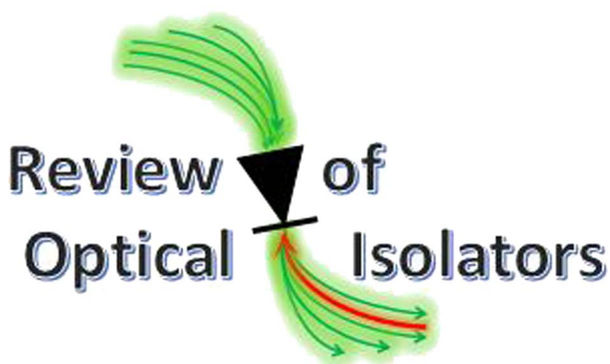

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Integrated Magneto-Optical Materials and Isolators: A Review

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Abstract: Many novel materials and device designs have been proposed as photonic analogs to electrical diodes over the last four decades. This paper seeks to revisit these materials and designs as advanced technologies may enable experimental realization that was not possible upon conception of several of these designs. The background behind integration challenges, including waveguide birefringence, fabrication tolerances, garnet/semiconductor mismatch, and optimized interfaces will hopefully spark new ideas that will finally enable the realization of integrated optical isolators and circulators.

Index Terms: YIG, isolators, circulators, nonreciprocal optics, Faraday rotation, beatlength, quasi phase matching, birefringences, non-reciprocal phase shift, NRPS, wafer-bonding, Bi:YIG, Ce:YIG, push/pull.

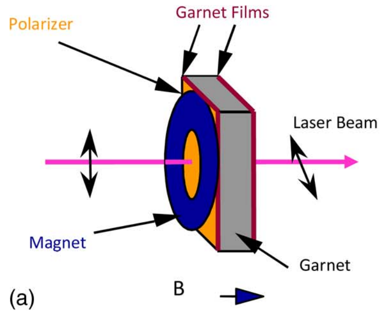
1. Introduction

The goal of integrated magneto-optical isolators is to incorporate nonreciprocal devices onto photonic platforms in order to achieve the photonic analog of the integrated electrical diode. Such devices are designed to protect source lasers from light that is reflected off any of the optical interfaces within a photonic integrated circuit. At the most fundamental level, photonic integrated circuits require light sources integrated with modulators and detectors that are specific to the desired application. "Insertion loss" arises from reflections at these device interfaces. Even a simple back-of-the-envelope calculation demonstrates that a significant amount of the light emitted from a source will be back-reflected at each interface

$$\%R = \left[\frac{n_1 - n_2}{n_1 + n_2}\right]^2 \times 100\% \tag{1}$$

where n_1 and n_2 are the refractive indices of the media on either side of the interface or the effective guided-mode indices in the case of a waveguide. The principal reason for an isolator in front of a laser or optical amplifier is that back-reflections can lead to injection noise which may be detrimental to the operation of the system. Nonreciprocal photonics are also used in circulators, which are an essential component for complex optical systems.

As with many optical devices, the first isolators were bulk components, in this case blocking reflections using a phenomenon known as Faraday rotation in which linearly polarized light is



(b) $$\varepsilon = \begin{pmatrix} \varepsilon_{xx} & 0 & i\varepsilon_{xz} \\ 0 & \varepsilon_{yy} & 0 \\ -i\varepsilon_{xz} & 0 & \varepsilon_{zz} \end{pmatrix} = \begin{pmatrix} 4.41 & 0 & i\varepsilon_{xz} \\ 0 & 4.41 & 0 \\ -i\varepsilon_{xz} & 0 & 4.41 \end{pmatrix}$$

Fig. 1. (a) Bulk component optical isolator. Light passes through a polarizer and is then rotated by $\theta_F = V\ B\ l$, where $\theta_F(= 45^\circ)$ is the Faraday rotation, B is the field shown above, and l is the pathlength of the light inside the garnet films. Backward propagating light will rotate another 45° and be blocked from the source by the polarizer. (b) The dielectric tensor of a magneto-optical material, using a typical value of n (2.1) for iron garnets.

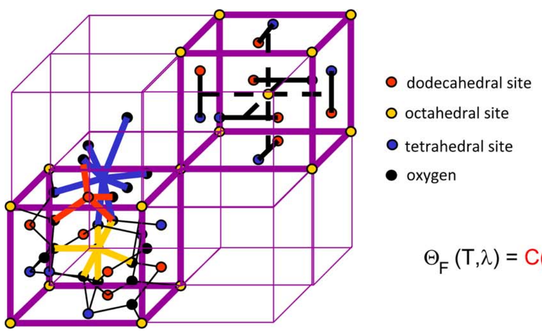


Fig. 2. The garnet structure via two representations.

rotated as it propagates parallel to a magnetic field, as shown in Fig. 1(a). In such a device, the polarizer is aligned with the source such that the forward propagating light can pass into the field-biased magneto-optical (MO) medium where the polarization is rotated 45°, e.g., clockwise. Any reflections from the optical system will pass back through the MO medium, this time against the applied field. So the polarization will rotate 45° counter-clockwise with respect to this backward propagation, which is another 45° clockwise with respect to the source, and this reflected light is then blocked by the polarizer. Mathematically, magneto-optical phenomena are represented by off-diagonal terms in the dielectric tensor, shown in Fig. 1(b). The Faraday rotation (θ_F in rad/m) is related to this term by $\varepsilon_{xy} = \theta_F^* 2n_o/k_o$, where n_o is the refractive index and k_o the vacuum wavenumber.

These bulk isolators use thick magneto-optical garnet films that are grown on garnet substrates. The development of appropriate liquid phase epitaxy (LPE) processes and of appropriate garnet substrates were significant technological challenges in the 1970s and 1980s [1]. LPE films continue to be developed for new devices in novel applications, such as magneto-optical imaging of magnetic flux leakage, which is important in fields as diverse as security to superconductors [2], [3].

In determining the best materials for nonreciprocal magneto-optical devices, the figure of merit is the magneto-optical activity, such as Faraday rotation, divided by the optical loss. Several materials have been studied that have excellent magneto-optical activity, but also losses that are too high to allow sufficient light to transmit into the circuit [4]. Other materials have very low loss, but not enough MO activity for reasonably sized devices [5]. At the telecommunications wavelengths of 1.3 and 1.55 μm in the near infrared (NIR), iron garnets, such as yttrium iron garnet (e.g., YIG, $Y_3Fe_5O_{12}$), have the highest figures of merit of any known material by several orders of magnitude. Its complex structure, Fig. 2, can accommodate half of the periodic table, and the net

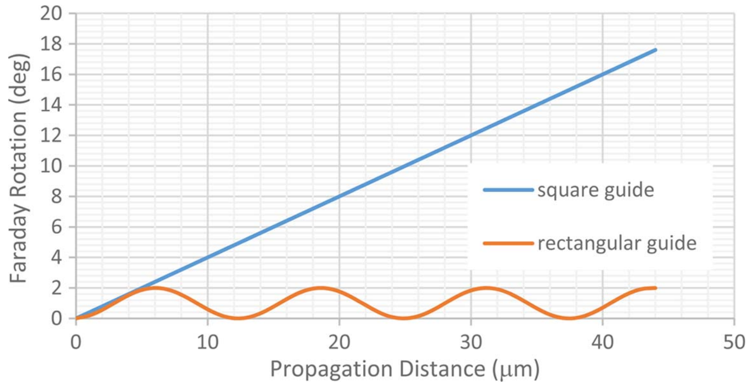


Fig. 3. Faraday rotation in square versus rectangular waveguides demonstrating the shape-induced birefringence where a mismatch in propagation constants between TE and TM modes prevents complete energy conversion.

magnetization and net Faraday rotation are dependent on contributions from each of the three cation sublattices.

2. Integrated Faraday Rotation Devices

However, garnets are not easy to integrate onto photonics platforms, such as Si and III-V semiconductors, because thermal anneals are required to obtain the garnet phase but the thermal expansion is mismatched with these substrates. Therefore, early researchers used garnet devices on garnet substrates to investigate waveguide devices. In 1972, Wang *et al.* [6] proposed mode conversion schemes using a scattering matrix approach with matrix elements representing the TE-to-TE and TM-to-TM reflection coefficients at the film surfaces and the TE-to-TM and TM-to-TE conversion factors, or coupling efficiencies. From the beginning, it was clear that shape-induced birefringence would be a major hurtle for non-reciprocal waveguide devices because it leads to a mismatch in the modal propagation constants. For effective Faraday rotation, there must be coherent conversion between TE and TM modes, but when a mismatch exists, complete energy transfer between the modes is not possible. Fig. 3 shows a comparison of Faraday rotation, or mode conversion, for waveguides with square versus rectangular cross-sections with shape as the only source of birefringence.

The first garnet waveguide and subsequent devices were realized by Tien *et al.* in 1972 [7], [8]. They used YIG that had been developed for bubble memories on lattice matched $Gd_3Ga_5O_{12}$ substrates, and they measured the index of refraction of various garnets, including iron, gallium and aluminum garnets ($n = 2.22, 1.94$, and 1.82, respectively at a wavelength of 1.523 μm). The first waveguide device was a modulator in which a periodic magnetic field was applied to a garnet waveguide using a serpentine conductor. The period of the conductor matched the "beating" of the waveguide, such as that seen in Fig. 3. Modulation up to the limit of measurement (300 MHz) was possible with the coupling efficiency between TE and TM modes equal to 52%. Tseng *et al.* showed that a periodic Permalloy layer placed on top of a garnet waveguide could be used to obtain a coupling efficiency of 80% for higher order modes [9].

Once Bi-substituted YIG was discovered to have much higher Faraday rotations than unsubstituted YIG [10], Van Engen *et al.* [11] used these Bi:YIG garnets to obtain 90% mode conversions (again higher order modes) but high fields were required due to a strong out-of-plane magnetic anisotropy. This new anisotropy caused a birefringence that was opposite in sign to the shape-birefringence [12], [13], and Okuda *et al.* found the two could be balanced to obtain 95% TE-TM mode conversion for lower order modes (m_0, m_1). They also found that fine adjustments in shape anisotropy by acid etching could be used to nearly perfectly cancel the shape anisotropy with stress- or growth-induced birefringence such that they achieved 80% lower order mode conversion with very low applied fields [14], [15].

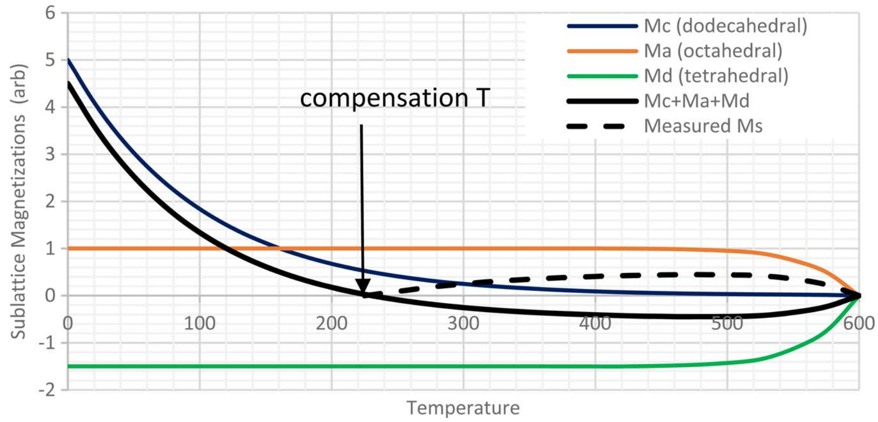


Fig. 4. Sublattice magnetizations sum to zero at the compensation temperature. The Faraday rotation changes sign at this point.

Meanwhile, more device designs began to emerge, including designs in 1973 by Warner *et al.* [16] that used gyrotropic (magneto-optical) and anisotropic (birefringent) materials to achieve a nonreciprocal mode conversion in series with a polarization filter. In 1974, Yamamoto and Makimoto used a matrix theory (similar to that used in circuit theory) for anisotropic and gyrotropic materials to design novel non-reciprocal photonic devices such as gyrators, unidirectional mode converters, differential phase shifters, isolators and circulators [17]. A few years later, an anisotropic cladding was proposed and experimentally realized [18], [19] where the ordinary/extraordinary refractive indices that were higher/lower than the garnet waveguide in order to obtain "semi-leaky" waveguides. Nonreciprocal magneto-optical and reciprocal cladding-induced mode conversions were designed to be equal but opposite in the forward direction, so TE modes would experience little loss. In the reverse direction, TM modes were generated and leaked away due to the higher-index (ordinary) cladding. Kirsch *et al.* obtained 10 dB insertion loss with a low field (40 Oe), and theoretical results indicated 1 dB/0.1 Oe could be achieved [19]. In 1977, Castera and Hepner proposed a tandem isolator design in which a mode-selection polarizer, a 45° Faraday rotator, and a 180° magnetic linear birefringence (MLB) phase shifter were all cascaded within a single garnet film using an evaporated Al cladding, a parallel magnetic field, and a transverse magnetic field, respectively [20]. The first (metal-coated) stage acted as a polarizer due to preferential TM mode attenuation. Mizumoto *et al.* later proposed a similar isolator using the Faraday and Cotton-Mouton (a.k.a. MLB) effects [21].

These waveguides designs required mode conversion that was similar to that used in bulk isolators, but they needed to match TE and TM propagation constants by fine-tuning the waveguide dimensions which was difficult with the lithography of the time. Therefore, much of the integrated garnet work in the 1980s continued to focus on complete elimination of birefringence to enable waveguides to exhibit full Faraday rotation. Hemme *et al.* used (110) orthorhombic garnet films for fine tuning the phase matching [22]. Ando *et al.* [23] found that the sign and magnitude of growth-induced anisotropy could be controlled without dependence on lattice mismatching, and with Murata in 1985, they used $(BiNdLu)_3(FeAlLu)_5O_{12}$ to achieve complete mode conversion with 8 Oe applied fields [24]. Often, a fine-tuning last step involved an acid etch to vary the final shape of the guides. A thorough review of techniques to eliminate birefringence is given in ref. [1].

Due to the tight fabrication tolerances required to completely eliminate birefringence, efforts also continued on periodic magnetization reversals to counteract shape birefringence. Wolfe *et al.* proposed a laser anneal in which Ga diffused from the tetrahedral sites to the octahedral sites such that the resulting garnet had periodic changes in composition to be on either side of the compensation temperature [25]. This compensation temperature is the point at which the magnetizations of the garnet sublattices sum to zero net moment, Fig. 4. Above this temperature, the Faraday rotation is positive with respect to the applied field, but below this point, the rotation is negative.

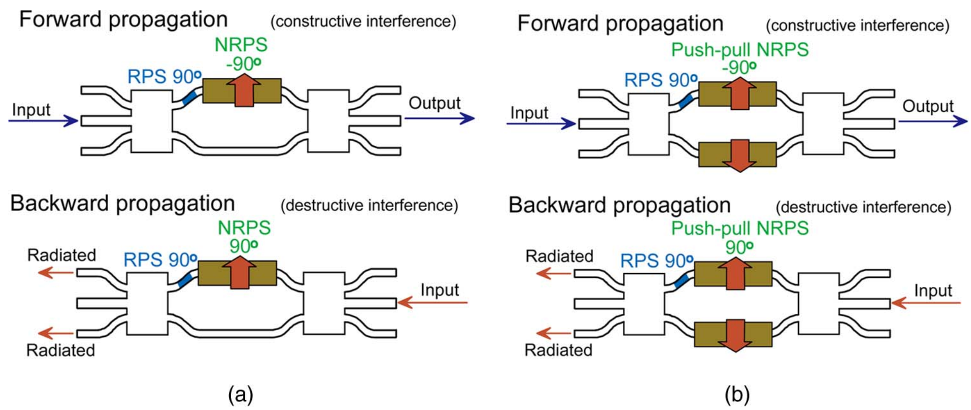


Fig. 5. Schematics of Mach–Zehnder Interferometers. (a) Shows one nonreciprocal branch, (b) has two nonreciprocal branches. Both require reciprocal phase shifters (RPSs) such that propagating light interferes constructively forward and destructively backward

Ando *et al.* employed laser annealing on a larger scale to eliminate the growth-induced anisotropy which caused the magnetization of their garnet films to lie out of the plane [26]. A compact tandem (Faraday/Cotton-Mouton) isolator was proposed that only required an in-plane field of 25 Oe, where an annealed region was used for the Faraday rotator and an adjacent as-grown region was used for the Cotton-Mouton reciprocal mode converter [26]. Compensation annealing for reversed sign has since been used in many designs, including interferometers and ring resonators, as will be discussed below.

3. Novel Device Phenomena

Meanwhile, devices using another magneto-optical phenomenon had been proposed and were gaining popularity. Nonreciprocal phase shifting (NRPS) of the TM modes had been proposed by Yamamoto and Makimoto in 1974 [17]. The following year, Auracher and Witte proposed an interferometer, Fig. 5, in which one branch would experience a nonreciprocal phase delay [27]. Each end of the interferometer would connect to a 3 dB coupler such that the two branches would interfere constructively in the forward direction, and destructively in the backward direction. Mizumoto *et al.* experimentally verified the NRPS effect using YIG in 1982 [28] and Bi-substituted YIG in 1986 [29], and several designs for interferometers began to be explored [30]. The advantage of the interferometer design was that waveguide phase matching was no longer required. The disadvantage was that the tight tolerances now reside with the couplers between the branches and the branch lengths.

The NRPS devices also required lateral confinement of the light by etching ridges into the garnet slabs, something that was desired in Faraday isolators, but not necessarily required. In 1982, Ando *et al.* demonstrated that YIG absorbs Ar-laser light preferentially to GGG substrates, and as such laser heating during a phosphoric etch was used both to etch waveguides in planar YIG films [31] and also to flatten surfaces in buried waveguides [32]. Okamura *et al.* used an ion beam to etch ridges including successful Y-couplers and interferometers [33], while Pross *et al.* fabricated buried channel waveguides by wet-etching garnet layers before depositing top-cladding layers [34]. Wolfe *et al.* also etched ridges into YIG slabs which, combined with surface etching to fine-tune shape birefringence, led to an isolation ratio of 35 dB in the Faraday configuration at the telecommunication wavelength of 1550 nm [35].

Later, novel enhancement of Faraday rotation was shown using one-dimensional photonic crystals which were essentially variations on Bragg reflectors or Fabry–Perot resonators that used garnet films stacked with other dielectric films with a garnet "defect" layer [36]. Fully garnet photonic crystals were also grown epitaxially by varying the garnet composition versus layer [37]. Subsequently a fascinating array of various 1D, 2D, and 3D photonic crystals have been demonstrated

[38]–[40]. Levy *et al.* explored the first integrated 1D photonic crystal using Ce:YIG/GGG films, but the 3x enhancement in Faraday rotation was only useful in-plane with lateral confinement [41]. Li and Levy later showed that 1D photonic crystals could be obtained in such waveguide structures using focused ion beams to etch vertical periodic structures in order to open a photonic bandgap for enhanced magneto-optical waveguides [42], [43]. Other interesting designs by this group include unidirectional Bloch oscillations in a waveguide array [44]. 2D photonic crystal structures have also been theoretically explored by Wang and Fan [45], [46]. The footprint for this type of device can be as small as a few wavelengths, which makes them appealing, but the low index of refraction of garnet makes it difficult to open a complete photonic bandgap. However, Mondal and Stadler used this effect to propose polarizers for integrated Faraday rotators [47]. Reciprocal polarization mode converters have also been proposed by Hutchings, Holmes *et al.* for the integrated polarization selection necessary in Faraday rotation devices [48], [49].

4. Integration With Semiconductors

By the 1990s, it was widely recognized that high-performance fiber optic systems would benefit greatly from integrated isolators [50]. For photonic integrated circuits (PICs) and optoelectronic integrated circuits (OEICs) to be fully integrated, that is source-integrated, garnets had to be integrated with semiconductors. For example isolators should be integrated directly in front of the lasers they were designed to protect if the laser source was to be integrated with the rest of the circuit. Razeghi *et al.* grew III-V quantum wells directly onto a GGG substrate by metal-organic chemical vapor deposition [51]. Haisma *et al.* were able to epitaxially grow GaAs [52] and InP [53] on garnet substrates by modifying the garnet composition such that lattice-matching was possible in specific geometries. Mizumoto instead used an InGaAs layer to lattice match to GGG and then grew InP on top of the ternary layer [54]. A break-through discovery in 1995 showed that direct wafer bonding could be used to integrate a magneto-optical garnet onto semiconductors [55]. Here, the MO garnet (e.g.: YIG) was grown on its ideal garnet substrate (e.g.: GGG), and then it was wafer bonded onto a semiconductor substrate for hybrid integration [55]. The next year Stadler *et al.* used metallorganic chemical vapor deposition to deposit garnets monolithically onto InP and GaAs substrates using MgO buffer layers [56], [57]. Later, Holmes and Hutchings used sputtering to integrate garnet on III-V structures for Faraday rotation, and although crystallization was incomplete, they were able to use quasi phase matching to overcome the birefringence limitation to the Faraday rotation effect [49], [58].

Further integration included the magnetic bias needed for the Faraday rotators. Mizumoto incorporated an integrated magnetic bias by depositing a gold electrode on top of a silica cladding and using a current to supply a transverse bias [59]. Levy *et al.* placed FeCo (grown on GaAs substrates) on top of YIG/GGG waveguides, and they later directly deposited permanent magnet films onto a cladding layer of SiO_2 [60], [61]. The latter also involved an Al compliant layer to accommodate stresses due to differences in thermal expansion of these various materials.

Gomi *et al.* [62] used sputter epitaxy to discover a new Ce-substituted garnet that possessed even larger magneto-optic coefficients than Bi-substituted garnets [63]. These new garnets were quickly adopted into ridge devices [44], [64]–[68]. Sputtering also meant that the garnets could potentially be integrated with silica [66]. Silica circuits were hybrid designs with elaborately textured substrates to enable device alignments, and 25 dB isolation was obtained with only 3.2 dB insertion loss [66]. Other low-loss oxide devices were also emerging using sputtering for monolithic integration of materials, such as aluminum oxide, which could be used for passive waveguides and also doped for optical amplification [69], [70]. Pulsed laser deposition (PLD) epitaxy onto garnet substrates was also demonstrated [71]–[73] as a method to explore new garnet compositions for optimizing Faraday rotation with co-doped Ce, Bi:YIG producing the highest Faraday rotation reported to date (10 000 deg/cm) [71], [72]. Sputtering of YIG directly on Si had not been achieved except in very early papers for bubble memory where the light propagation was through the thickness, and not in the plane, of the garnet films [74]. Sputtered YIG for photonics was attempted,

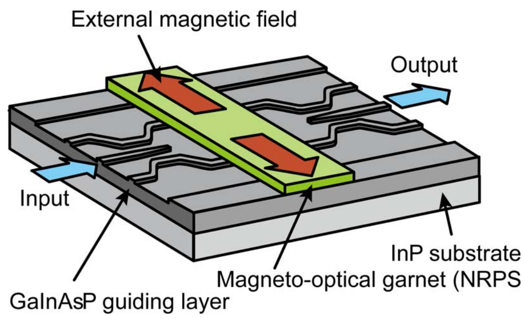


Fig. 6. Semiconductor core isolator proposed in 1997 by Yokoi *et al.* [89].

but simple phase information was usually given (e.g., X-ray diffraction), and waveguide losses were not reported due to microcracks in the films from thermal mismatch which prevented guiding.

However, the novel integration and highly gyrotropic materials inspired new ideas that enabled shorter device footprints. Radiatively-coupled magneto-optical waveguides and Mach–Zehnder interferometers were designed [75]–[78] to have efficient mode conversion and polarization-independent functionality. The latter theoretical designs involved horizontal and vertical domain walls, again suggesting compensation annealing to achieve NRPS in both TE and TM modes. A good review of various designs can be found in ref. [79]. Also, realization of some of these designs was achieved [80]–[84], for example using a polarization converter [85]–[87] in each branch of the MZI [84].

A new idea was presented at the first Materials Research Society symposium on Integrated Magneto-Optics: Materials and Devices [88]. Yokoi and Mizumoto [89] had proposed for the first time an isolator in which the guiding layer itself would be a III-V semiconductor core with the magneto-optical garnet as a cladding, Fig. 6. Using a transverse magnetic field, NRPS was achieved via an evanescent wave that extended into the cladding [89], [90].

Considering that lasers were semiconductor components, this idea meant that propagating light did not have to exit high index semiconductors ($n > 3$) to go into a low n medium (air $= 1$, garnets $<$ 2.2). With large differences in n, the reflected power can be quite high even at one interface, see Eqn. (1). Also, the number of semiconductor photonic devices was growing, so there was a potential to keep the light entirely inside semiconductors throughout the circuit for fully integrated photonic integrated circuits (PICs) and optoelectronic ICs (OEIC). Semiconductor cores also enabled new solutions to mode-beating involving ion-implantation intermixing [91]–[93].

It should be noted that the isolator itself could have a semiconducting core IF the garnet cladding could be incorporated in close contact to the core. The evanescent wave in the cladding fades exponentially with distance from the core, so the magneto-optical material should be incorporated with as little intermediate layers as possible (e.g., seedlayers). In addition to wafer-bonding and the attempts at monolithic integration, Levy *et al.* developed a new technique called crystal ion slicing to remove YIG from its GGG substrate for hybrid integration with Si photonics. The process involved ion implantation of YIG on GGG which led to a defective layer under the YIG that was selectively etched by subsequent wet etching [94].

The difficulty of garnet integration led several researchers to attempt rare-earth and transition-metal doping of III-V semiconductors for devices in which the magneto-optical core itself would be InP or InGaAsP, and Verdet constants up to 10deg/mm/T were achieved [95], [96]. Unfortunately, despite the ease of integration and refractive index match, devices would require 5000 Oe fields and mm-long pathlengths at telecommunication wavelengths. In addition, the materials were paramagnetic so they were difficult to saturate with external fields. Later, Verdet constants were enhanced via bandgap engineering, but the values of 33 deg/mm/T still required very high fields (1T) for designs with reasonably short lengths [97]–[99]. Diluted magnetic II-VI semiconductors, such as CdMnTe and CdMnHgTe [100], were proposed and used as an optical isolator on a GaAs substrate, but their performance degraded upon integration of other optical components.

Three other approaches for facile integration of nonreciprocal devices with semiconductor-compatible materials required active structures, unlike the passive garnet structures. The first design involved nonreciprocal loss (NRL) devices using standard semiconductor core guides that were proposed [101] and achieved [102], [103] using claddings of thin oxides with a ferromagnetic metal on top. The TM waves experienced different losses at the metal interface similar to the early mode-selecting polarizers [21], but now the losses varied depending on the orientation of the propagation in relation to the magnetization of the metal. To mitigate insertion losses, the semiconductor cores were designed to include active amplification [104]–[107]. The drawback of such an approach was that additional noise was introduced through amplified spontaneous emission from the amplifier. A second design involved ferromagnetic metal-semiconductor interfaces where surface plasmons propagated with nonrecriprocal behavior. Despite large losses, the designs were PIC-compatible with large bandwidths, and new promising designs have recently been proposed [108]. A third design that was experimentally verified used indirect interband photonic transitions to actively modify the refractive index along a guide such that forward and backward traveling modes experienced different propagation constants [109], [110].

5. Silicon-on-Insulator Devices and Semiconductor-Compatible Materials

For miniaturized devices with low-power requirements, integration of garnet with semiconductors is still preferred. Although the silicon-on-insulator platform does not lend itself readily to optical sources, it has been demonstrated that low optical losses and the current fabrication technologies allow for complex and flexible photonic integrated circuits, potentially compatible with CMOS. The first Si-core nonreciprocal device was proposed by Yokoi *et al.* where direct wafer bonding of Ce:YIG was used to integrate a garnet cladding on Si-on-insulator (SOI) guides [111]. The key to this structure was the low-index (SiO_2) lower cladding which provided an asymmetry [112] that enhanced the interaction of the propagating mode with the top garnet cladding, leading to remarkable enhancement in the NRPS [112], [113]. The first silicon-core isolator, using NRPS in a Mach–Zehnder Interferometer (MZI) configuration, had 21 dB optical isolation with 8 dB insertion loss at 1559 nm [114]. Recently, a similar Ce:YIG-bonded MZI optical isolator employing a GaInAsP-core was also demonstrated with an isolation ratio of 28.3 dB with 15 dB insertion loss at 1558 nm [115]. Optical circulators [116] can also be achieved using NRPS in Ce:YIG-cladded semiconductor-core MZI's that have 3 dB 2×2 couplers on either side as opposed to the Y-couplers or 3×2 couplers used in optical isolators. These structures magnetize the branches of the MZI in opposite directions to obtain a "push/pull" effect which allows shorter devices than those with phase shift in only one branch, Fig. 6. One concern with MZI designs is the small bandwidth for wavelengths at which high isolation can be obtained. This can be mitigated if the reciprocal phase shifter can cancel the wavelength dependence of the nonreciprocal phase shifter [117].

Most of these NRPS structures using semiconductor cores were simulated and realized with direct wafer bonding. In addition, changes in the sign of Faraday rotation were obtained by inhomogeneously applied magnetic fields. However, Ghosh *et al.* produced novel results by simple, yet elegant, adhesive bonding of Ce:YIG to SOI guides using benzocyclobutene (BCB) [118], [119]. They demonstrated interferometer structures that obtained "push/pull" phase shifts by elongating the branches of the interferometer in the transverse direction such that a uniform external magnetic field in the longitudinal direction biased both NRPS sections [118]. This integration process is straightforward, but the adhesive layer must be very thin as the influence of the garnet will decay exponentially with this layer's thickness [116].

To continue miniaturization of isolators, ring resonators were proposed in which two straight "busline" waveguides were coupled to a ring located between them either horizontally or vertically [120], [121]. In order to provide isolation, garnet-core rings have been designed with concentric domains, although higher Faraday rotations were used in the simulations than can be obtained by laser annealing [120]. Other designs involve garnet claddings either wafer-bonded or deposited onto part of the ring [122], [123] with a magnetic field applied radially. The key to these designs is an induced NRPS in the ring that causes clockwise and counter-clockwise propagating modes to

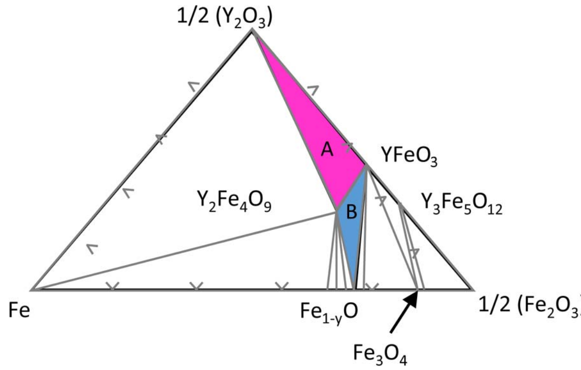


Fig. 7. Ternary phase diagram with $Y_2O_3 - Fe_2O_3$ binary on upper, right side and oxygen deficiency occurring with distance from this side. Compatibility triangles A and B show the phases present. in furnace annealed films that were Fe or Y deficient.

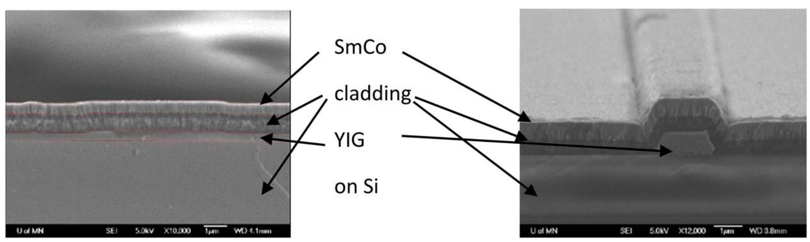


Fig. 8. SEM images of etched garnet waveguides on oxide-cladded Si wafers with fully-integrated permanent magnet film. (a) Ion milling polycrystalline garnet produced shallow ridges, but smooth sidewalls (not shown) compared to wet etching. (b) Wet etching as-deposited (amorphous) Y-Fe-O films yielded complete ridge waveguides with smooth sidewalls. The losses were measured $<$ 1 dB/mm.

experience resonance at different wavelengths. At a given wavelength, one direction (eg: backward propagation) will couple out of the busline into the ring, but the other direction (eg: forward) will not. This concept has been studied theoretically with designs that involve various biasing, such as ring magnets that can bias the entire ring radially [124], and cores of low loss Si_3N_4 [125], [126].

Although wafer-bonding has shown excellent results, monolithic growth of garnet onto these miniaturized devices is desirable in many cases for easy fabrication. However, microcracking and secondary phases have been problematic for garnet films that were thick enough for waveguiding in the near infrared [126]. To obtain single phase garnet on non-garnet substrates, the Y:Fe stoichiometry had to be precisely maintained. However, phase analysis revealed that complete oxidation improved the probability of obtaining garnet, as can be seen in Fig. 7 [131]. Films grown on non-garnet substrates, including semiconductors, would land in the compatibility triangles A or B if they were Y-rich or Fe-rich, respectively, neither of which included the garnet phase. However, rapid thermal annealing (RTA) in a fully oxidizing environment ensured that the sample would stay within the $Y_2O_3 - Fe_2O_3$ binary side of the diagram, and single phase YIG was obtained over a wide range of Y:Fe stoichiometries. The strain during annealing was overcome using wet etching prior to annealing. Previous wet-etching of polycrystalline films had led to rough sidewalls from grain boundary etching, yet ion etching was too slow and expensive to yield complete ridge waveguides, Fig. 8 (left). Wet-etching of as-deposited amorphous Y-Fe-O films yielded smooth sidewalls and complete ridges [127], [128] that could be measured in waveguide configuration for the first time with $<$ 1 dB/mm loss, Fig. 8 (right). [129], [130].

Rapid thermal annealing could also be used with garnet films deposited on top of ridge waveguides because the cladding/guide area was similarly reduced [132]. Other area reductions were obtained using windows opened in oxide claddings [122] or lift-off [58]. The former was used to coat semiconductor-core ring devices with an undoped seedlayer, followed by a Ce-doped cladding [122].

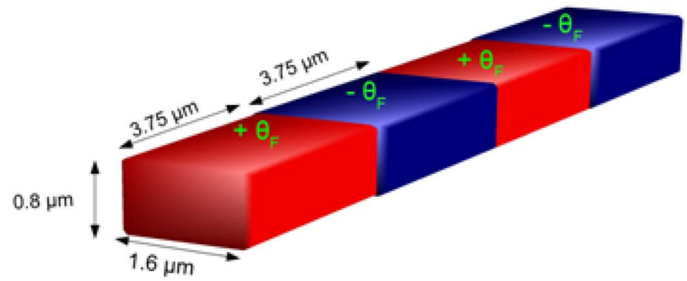


Fig. 9. Waveguide design with alternating segments of positive and negative Faraday rotation.

The lift-off was used to vary the cladding between MO Ce:YIG and silica in order to mitigate birefringence via quasi phase matching in Faraday-rotating semiconducting core devices. The oxygen RTA YIG seedlayers have successfully enhanced subsequent growth of Ce- or Bi-doped YIG claddings [122]. When doping garnets by this process, care must be taken to fully crystallize the garnet layers, or reduced magneto-optical interactions will result [58], [122].

Optimization of the seedlayers and annealing is on-going in the literature [125] and new techniques, such as electron backscattered diffraction (EBSD) have revealed the true crystalline nature of the films (see Block *et al.* this issue). The latter is important since the XRD shown in most of the literature does not reveal amorphous phases. As mentioned previously, reduction of the seedlayer thickness is important to maximize the interactions between the propagating mode and the MO cladding. But it is also important to realize that undoped YIG seedlayers have positive gyrotropy, while Ce- and Bi-doped YIG both have negative gyrotropy. Therefore, new negative gyrotropy or nonmagnetic garnets should be used as seedlayers for these large gyrotropy garnets.

Finally, garnets with negative and positive gyrotropy can be easily patterned by today's lithographical methods that would allow "push/pull" devices with total Faraday rotations that are closer to simulated values than those obtained using traditional laser-anneal patterning of Ga-garnets. Fig. 9 shows an example of alternating YIG/Ce:YIG which has a beatlength (see Fig. 3) of 7.5 μm according to FDTD simulations.[1] If the waveguide had been solely comprised of Ce:YIG, the Faraday rotation would only have oscillated between 1.5° and 0° due to birefringence. By alternating YIG and Ce:YIG as shown, 45° will be obtained using a 350 μm-long device. This push/pull (Ce:YIG/YIG) simulation used realistic values of $\Theta_F = -3000°$ cm^{-1} (typical for Ce garnets that are monolithically integrated) and $\Theta_F = +250°$ cm^{-1} for YIG. This device could be fabricated using a 0.8 μm-thick YIG film that is patterned in 3.75 μm wide strips where the areas between the strips would not be fully etched down to the substrate. After RTA, Ce:YIG could then be deposited on top of the thin regions which would act as seedlayers for the Ce:YIG. Finally, ridges would be etched perpendicular to the strips to obtain the periodic waveguides shown in Fig. 9. Device sizes of 350 μm are comparable to other published isolator designs but without narrow-band ring or interferometer structures. This quasi phase matching method can also be used with garnet-cladded rectangular Si waveguides that experience birefringence [49].

6. Conclusion

This review article summarized the history of nonreciprocal photonic devices as a tribute to the significant developments that shaped this field. Beginning with substantial developments in LPE-grown garnets that moved beyond bubble memories, the discoveries of new materials and processes have provided necessary breakthroughs to keep the research active. New device designs have been proposed to move from bulk components to waveguide devices, overcoming new challenges such as birefringence and using new physical phenomena such as nonreciprocal phase shift. Semiconductor-core devices have been enabled experimentally using wafer-bonding for close

[1]The authors thank summer REU researcher Harold Haldren from Liberty University for simulations.

contact between the propagating mode and the active cladding. Novel device ideas, such as photonic crystals, ring resonators, and interferometers, continue to promise miniaturized devices for PICs and OEICs. Additionally, new monolithic techniques with push/pull designs are in development to provide easy fabrication of scalable devices and also arrays of devices. These techniques strive to reach the gold standard performance of wafer-bonded garnets. The authors hope this paper inspires new device architectures and new garnet chemistries such that fully functional isolators will soon be realized with optimized performance at small footprints and low powers for products in the near future.

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