Hybrid integration of a polarization independent optical circulator

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ABSTRACT

Nonreciprocal optical functionalities like optical isolators and circulators are key components for the suppression of unwanted optical feedback in lasers and are also widely used for light routing in fiber-based measurement systems such as optical coherence tomography. Therefore, they are important building blocks in integrated optics, which promises further miniaturization and cost reduction of optical elements for telecom, datacom, and sensing applications.

In this work, we experimentally demonstrate a four-port polarization independent optical circulator on a polymer-based hybrid integration platform. The circulator consists of polymer waveguides and two thin-film polarization beam splitters (PBSs) inserted into waveguides via etched slots. Crystalline, pre-magnetized bulk Faraday rotators (FRs) and half-wave plates (HWPs) are inserted into free-space sections, formed by pairs of waveguide butt-coupled GRIN lenses.

For a first demonstrator, on-chip losses down to 5 dB and optical isolations up to 24 dB were measured, depending on the different input and output constellations, as well as the polarization. By applying an external magnetic field opposite to the magnetization of the faraday rotators, it is possible to repole the magneto-optic material, leading to reversely circulating light inside the device. This enables optical switching between ports in form of a latching switch, which maintains its state after removing the external magnetic field.

Keywords: photonic integration, polymer waveguides, optical isolators, optical circulators, nonreciprocal elements

1. INTRODUCTION

Optical circulators are three or more port optical components that allow light circulation between specific ports while simultaneously optically isolating other input ports. They are widely used whenever bidirectional operation along optical fibers is required, for example in sensing applications like optical coherence tomography (OCT) [1], but also in telecommunications e.g. for separation of up- and downstream signals in bidirectional optical transceivers [2]. Since standard optical single mode fibers create random polarization rotations, polarization independent operation of optical circulators is required for fiber-based applications [3]. An integrated polarization independent optical circulator based on a Mach Zehnder interferometer has already been demonstrated by Sugimoto et al. [4]. However, circulators in sensing systems are still based on free-space optics, since they show better performance in terms of insertion loss and optical isolation. In this work, we propose and demonstrate a polarization independent circulator based on the hybrid integration of Faraday rotators, half wave plates (HWPs) and polarization beam splitters (PBSs) into a polymer integration platform. The circulator consists of passive polymer-based embedded single mode waveguides with etched slots in order to insert the aforementioned optical functionalities. Since the Faraday rotators are magneto optic bulk crystals, collimating optics in form of graded index (GRIN) lenses are required to construct a free beam section [5]. The schematic layout of the circulator is depicted in Figure 1.

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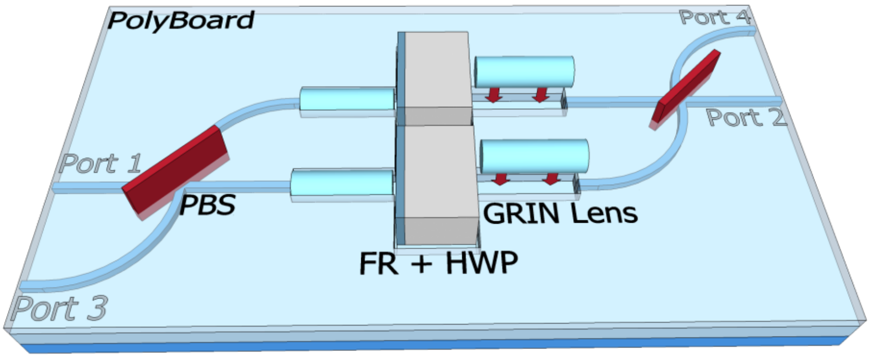

Figure 1. Schematic layout of the four-port optical circulator. It consists of two polarization beam splitters/combiners (PBSs) and two Faraday rotators and half wave plates (HWPs) integrated via an on-chip collimated beam section created by two pairs of waveguide coupled GRIN lenses and passive polymer waveguides (dark blue).

2. WORKING PRINCIPLE

The circulator consists of two PBSs, that transmit TE polarized light and reflect TM polarized light in a 90° angle, two -45° Faraday rotators and two HWPs with an optical axis of 22.5°, all connected via polymer waveguides. Light coupled into port 1 is split into TE and TM polarization at the first PBS (Figure 2a). In forward transmission, i.e. from left to right of the device, the combination of -45° Faraday rotator and 22.5° HWP create a nonreciprocal polarization shift from TE to TM and TM to TE polarization. At the second PBS, TE and TM polarization are recombined and guided to port 2. Light coupled into port 2 maintains its polarization state after passing the HWP and Faraday rotator in backward transmission from right to left. Due to the maintained polarization state in backward transmission, the light is recombined at the second PBS and guided to port 3 instead of port 1, thus optically isolating port 1. In general, light is transmitted from port 1 → port 2 → port 3 → port 4 → port 1. The Faraday rotators are magnetized rare earth iron garnets (RIGs) that are latched to either a nonreciprocal 45° or -45° polarization rotation. It is possible to use an external magnetic field to repole the Faraday rotators and the direction of the Faraday rotation, which reverses the operation of the optical circulator, leading to transmission from port 1 → port 4 → port 3 → port 2 → port 1. This enables switching between the output ports 2 and ports 4 with the circulator maintaining its state even after switching off the magnetic field (Figure 2c and 2d), thus creating a latching switch similar to [6].

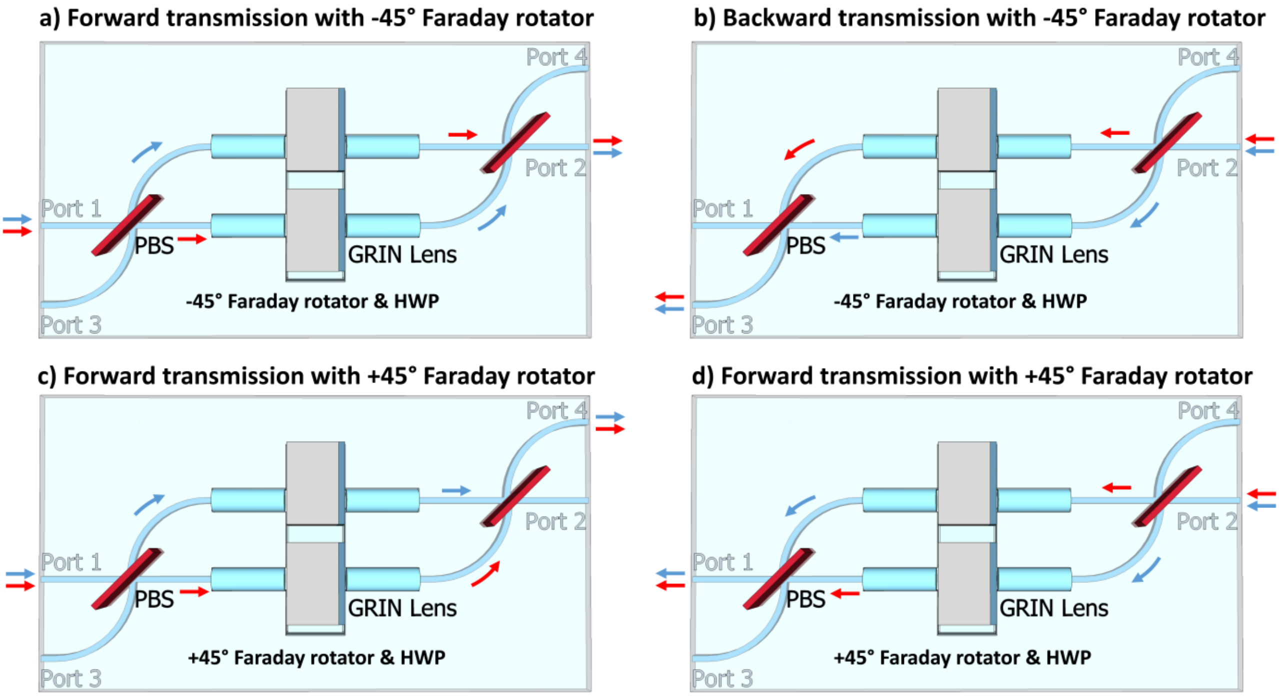

Figure 2. Working principle of the optical circulator in forward and backward transmission for TE (red arrows) and TM (blue arrows) polarized light with a -45° Faraday rotator (a, b) and a +45° Faraday rotator (c,d). The output port depends on the magnetization and direction of Faraday rotation of the Faraday rotator.

3. FABRICATION

The circulator consists of polymer waveguides embedded in a polymer cladding with a refractive index difference of $\Delta n = 0.03$. The quadratic cross-section of the waveguides is 3.2 µm x 3.2 µm. Core and cladding material are deposited by spin coating of the polymer as a liquid resin and are UV cured and hard baked. Structuring of the polymer waveguides is done by photolithography and reactive ion etching. In order to integrate the thin film elements and bulk Faraday rotators on chip, slots for the filter insertion are etched into the polymer waveguides. The PBS filters with a thickness of 12.3 µm are inserted directly into two slots. Waveguides at the slot waveguide interface are tapered in order to reduce the beam divergence and loss inside the filter sections. The Faraday rotators have a thickness of ~485 µm and require collimating optics in order to compensate the beam divergence of the waveguide free-space interface. For both free-space sections required to integrate a Faraday rotator, GRIN lenses are coupled to the input and output waveguide. The first GRIN lens collimates the divergent beam of the waveguide and creates a parallel beam inside the free-space section, with the second GRIN lens coupling the light back into the polymer waveguide. The GRIN lenses have a core/cladding diameter of 105 µm / 125 µm with a numerical aperture of NA=0.25. The alignment is done passively via etched U-grooves with a very defined depth and width, matching the geometry of the GRIN lenses. This free-space section enables the insertion of magneto optic bulk materials such as the Faraday rotators. The 45° Faraday rotators consist of a pre-magnetized Bismuth doped rare earth iron garnet with optical losses below 0.05 dB at 1550 nm. A 15 µm thick birefringent polyimide film with an optical axis of 22.5° is used as a HWP, which is glued directly to the right facet of the Faraday rotator. All optical components are fixed with index matching glue inside the slots. The fabricated device is shown in Figure 3.

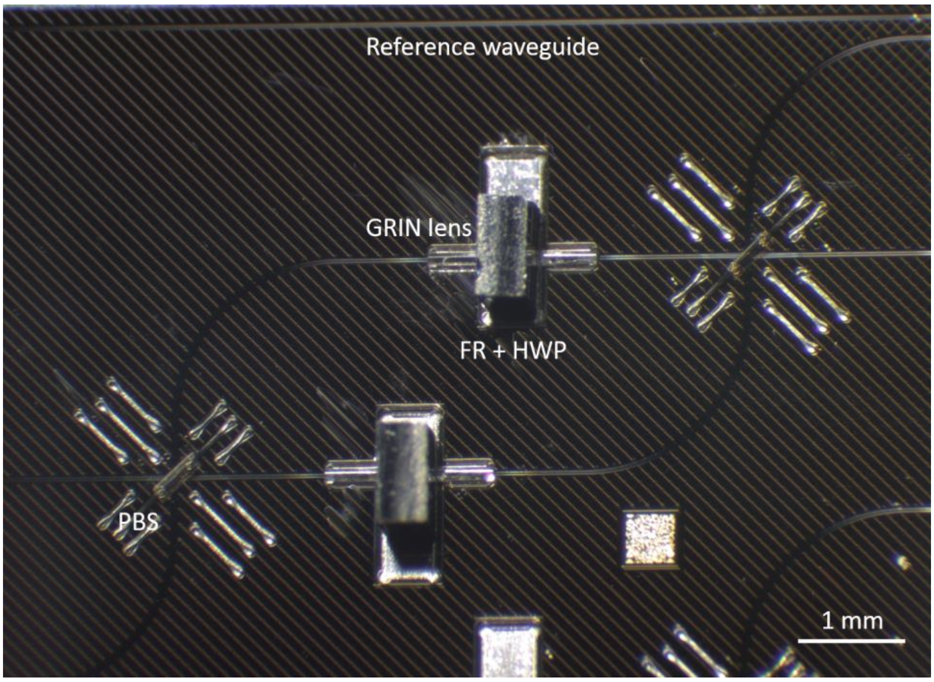

Figure 3. Optical circulator, consisting of polymer embedded single mode waveguides, PBSs, HWPs and Faraday rotators that are inserted via on-chip free-space sections created by waveguide coupled GRIN lenses. The fabricated device has length of 9 mm and a width of 7 mm.

4. CHARACTERIZATION

The optical circulator is characterized by measuring the insertion loss of TE and TM polarization for all combinations input and output ports in forward and backward direction. The measurements are shown in Figure 4 .

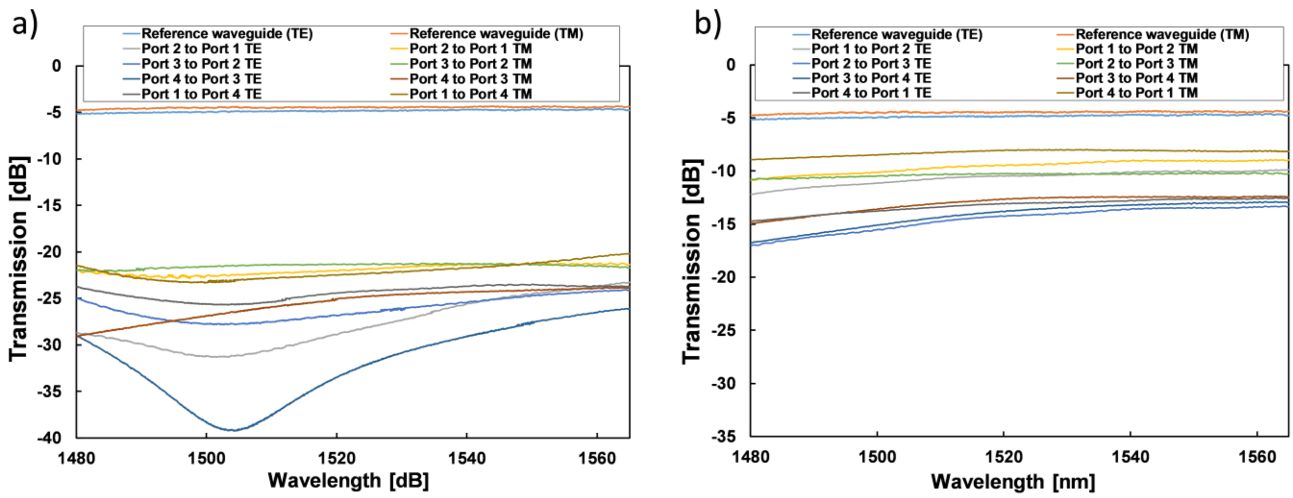

Figure 4. Measured insertion loss, including fiber-chip coupling losses of ~1.5 dB per facet, in forward (a) and backward (b) transmission for all ports in TE and TM polarization.

Depending on input and output port and the chosen polarization, insertion losses between 8 dB and 13 dB were measured in transmission at 1550 nm. In the reverse / isolation direction, insertion losses between 21 dB and 27 dB were measured. The specific values for all ports in forward and backward direction and the corresponding isolation ratios at 1550 nm are listed in Table 1.

Table 1. Insertion loss for all constellations of input and output ports at 1550 nm.

	Forward transmission [dB]	Backward transmission [dB]	Isolation [dB]
port 1 → port 2 (TE)	10.0	24.5	14.4
port 1 → port 2 (TM)	9.2	21.3	12.3
port 2 → port 3 (TE)	13.5	24.7	11.2
port 2 → port 3 (TM)	10.2	21.3	11.1
port 3 → port 4 (TE)	13.0	27.5	14.5
port 3 → port 4 (TM)	12.5	24.1	11.6
port 4 → port 1 (TE)	12.6	23.5	10.9
port 4 → port 1 (TM)	8.1	21.2	13.1
Reference waveguide (TE)	4.3	4.3	-
Reference waveguide (TM)	4.6	4.6	-

Considering the fiber-chip coupling loss of 1.5 dB per facet and subtracting the total 3 dB from the measured insertion loss, minimal on-chip loss of 5.1 dB were achieved for TM polarized light from port 4 to port 1. The high imbalance in forward transmission of 5 dB between the lowest and highest loss path is a result of the different optical paths and the loss contribution of the elements inside. In general, the free-space sections with Faraday rotator and HWP add 2 - 3 dB with an imbalance of 1 dB between the upper and lower free-space section due to a misalignment of the GRIN lenses during the UV curing process of the index matching glue. The PBSs add 3 dB in transmission and 1 dB in reflection to the total loss. The high transmission loss of the PBSs is caused by a suboptimal slot thickness, which leads to higher losses inside the unguided free-space section. An optical isolation of >11 dB was achieved across the whole C-band, with a peak isolation of 24 dB at 1505 nm. The reason for the shifted isolation peak is most likely an angular misalignment between the Faraday rotators and the optical axis of the polyimide HWPs, which is stated to be ±1° in the specifications. In future iterations we will use quartz based HWPs with a higher extinction ratio than polyimide HWPs to further improve the isolation ratio.

As mentioned in section 2, repoling the magnetization of the Faraday rotators leads to a reversed Faraday rotation, which allows active switching between the ports. This is demonstrated in Figure 5 for port 1 as input and port 2 and port 4 as the output ports. For a Faraday rotation of -45°, port 2 is the output port and port 4 is optically isolated. For a Faraday rotation of 45°, port 4 is the output port and port 2 is optically isolated. To demonstrate the switching, the Faraday rotators are manually repoled with a permanent magnet. After removing the permanent magnet, the optical circulator maintains its new output state indefinitely.

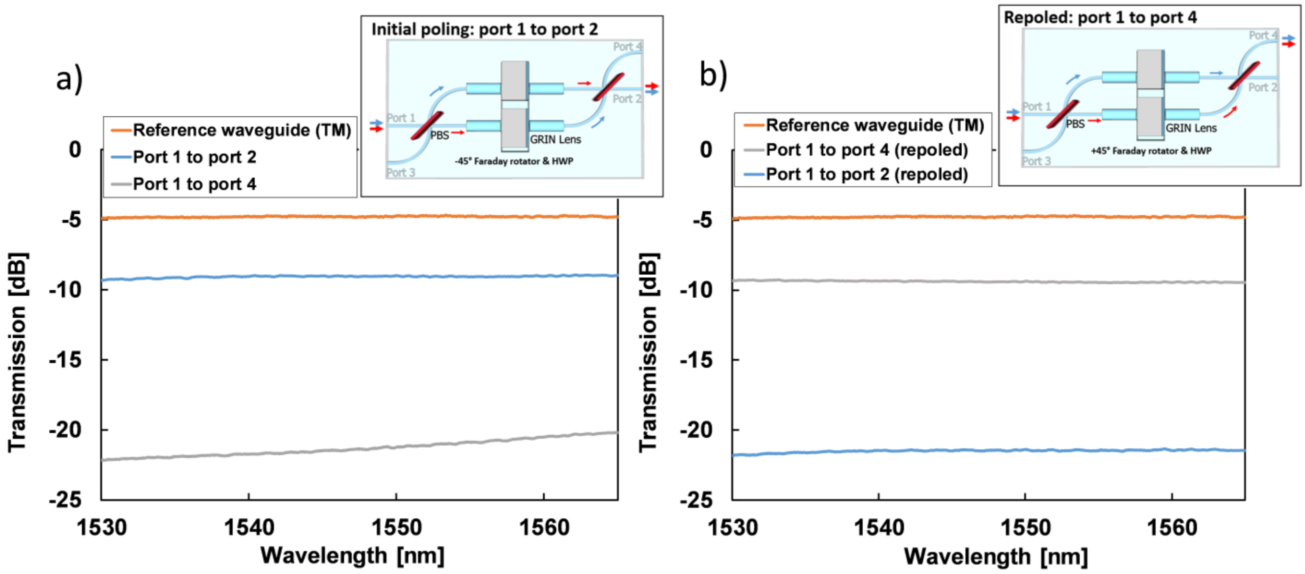

Figure 5. Repoling between the ports enables switching as illustrated in Figure 2 (a) and (c). Here, switching is demonstrated for port 1 as the input port and port 2 and 4 as the output ports. a) Initial poling with transmission from port 1 to port 2 and optical isolation of port 4. b) Repoled Faraday rotators with transmission from port 1 to port 4 and optical isolation of port 2.

Adding an electro magnet to the fabricated device could enable the fabrication of a latching switch based on the optical circulator. A concept for this device is shown in Figure 6. Depending on the direction of the applied current and thus the magnetic field, the latching switch switches between ports.

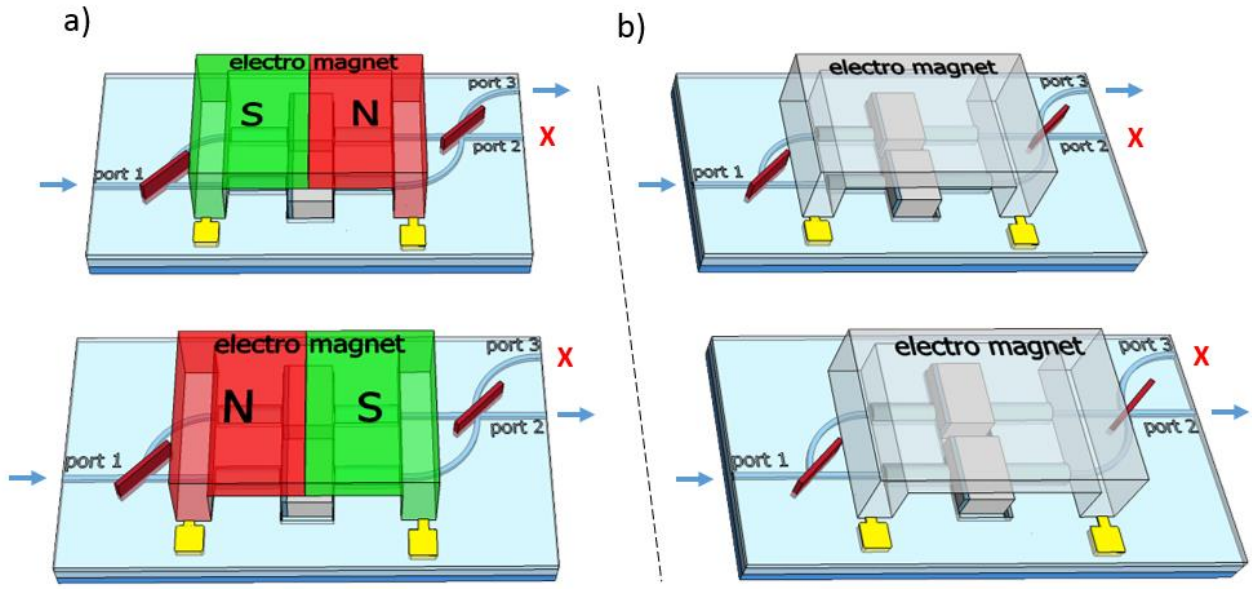

Figure 6. Concept of a latching switch based on the optical circulator with an added electromagnet. Depending on the applied current and magnetic field, the Faraday rotators are poled or repoled (a). After switching off the electro magnet, the Faraday rotators and the circulator maintain their polarization state indefinitely (b).

5. CONCLUSION

We designed and fabricated a first demonstrator of an integrated polarization independent circulator on a polymer hybrid integration platform. The device is based on the integration of bulk Faraday rotators integrated via on-chip free-space sections, created by waveguide coupled GRIN lenses and thin film elements for nonreciprocal and reciprocal polarization handling. On-chip losses of 5-11 dB with an optical isolation of >10 dB across the C-band and a peak isolation of 24 dB were achieved for the fabricated device. By optimization of the single building blocks it should be possible to reduce the minimal loss of the device to 3 dB, while simultaneously reducing the imbalance between the different ports. Repoling of the premagnetized Faraday rotators with a magnet reverses the transmission direction of the circulator, which enables active switching in the form of a latching switch between the output ports. This could be realized by implementing an electro magnet on top of the fabricated device.

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