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Integrated polarization-independent optical isolators and circulators on an InP membrane on silicon platform

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In photonic integrated circuits (PICs), optical isolators and circulators are essential to prevent lasers from backreflections and to reroute the light flow. In this paper, an integrated polarization-independent device that can be operated as an optical isolator or an optical circulator, based on an InP membrane on silicon platform, is demonstrated. A cerium-doped yttrium iron garnet die is adhesively bonded on a Mach–Zehnder interferometer, in combination with four polarization converters. The device shows maximum optical isolations of 27.0 dB for transverse-electric (TE)-mode input and 34.0 dB for transverse-magnetic TM-mode input. The device also works as a four-port optical circulator. Optical isolations of at least 18.6 dB and 16.4 dB are measured between each circulator port pair for TE- and TM-mode input, respectively. This work could remove the optical interfaces between laser and isolator for robust production. It also provides a step forward toward a multifunctional and high-density PIC. © 2021 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

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1. INTRODUCTION

Non-reciprocal optical components, like optical isolators and circulators, are indispensable in the optical communication systems. Currently, these components are equipped with lasers and other optical components at a module level, which results in a significant proportion of package cost. Additionally, the integration of optical isolators and circulators with other integrated optical components presents crucial design and fabrication challenges [1–4]. These challenges mainly arise from the incompatibility of magneto-optic material with the semiconductor platforms that are commonly used for photonic integration.

Optical isolators and circulators are needed to protect lasers from backreflections, which could contain signals with random polarization states, phase, and intensity. To date, integrated optical isolators and circulators mainly rely on non-reciprocal phase shift (NRPS) [5], which means the forward- and backward-propagating waves have a different propagation constant when the magneto-optic (MO) material is magnetized transversely. Based on this effect, optical isolators and circulators are extensively developed in interferometric structures [6,7], like micro-ring resonators and Mach-Zehnder interferometers (MZIs). In these structures, propagating light will interfere constructively in one direction and destructively in the opposite direction. Typically, MO materials like cerium-doped yttrium iron garnet (Ce:YIG) are integrated with interferometric structures using direct or adhesive bonding [8–12]. A maximum isolation of 32 dB was measured near 1555 nm in such an interferometer [10]. However, these devices only work for TM-polarized modes because of the vertical asymmetry when Ce:YIG serves as a cladding on the waveguide layer. There are also proposed optical isolators and circulators that can work for TE-polarized light, by cascading a polarization converter (PC) with interferometric structures [13–15]. Maximal isolation of 30 dB is measured at 1555 nm, with an insertion loss of 18 dB in that case. Instead of using bonding technology to integrate Ce:YIG with interferometers, the Ce:YIG films can be deposited on the sidewalls of the waveguide with pulsed laser deposition (PLD) [16]. Monolithic integration of optical isolators and circulators is demonstrated [17–19] on silicon and silicon nitride (SiN) platforms. High-performance broadband TM (TE) isolators and circulators with 32 dB (30 dB) isolation ratio and 2.3 dB (3 dB) insertion loss are demonstrated on a silicon platform. However, these optical isolators and circulators only work for one polarization state. This capacity is not enough to accommodate the isolation needs of polarization-diverse integrated optical systems.

Integrated polarization-independent optical isolators and circulators have also been investigated in the past few decades. In 2000, Fujita et al. [20] proposed a polarization-independent waveguide optical isolator by using an asymmetric structure both in plane and out of plane and with magnetic fields applied transversely and vertically. In 2007, Yuya et al. [21] proposed a
polarization-independent isolator composed of a MZI structure, two PCs and nonreciprocal phase shifters. In 2018, Curtis et al. [22] presented the design and theoretical evaluation of a polarization-independent circulator by combining an interferometer, a half-wave plate, and a Ce:YIG Faraday rotator. In 2013, Hutchings et al. [23] proposed an integrated optical isolator based on nonreciprocal mode conversion (NRMC), which could work on both TE- and TM-mode light. Magneto-optic materials, like Ce:YIG and Bi:YIG, are sputtered on a SiN or SOI platform. An isolation of 11 dB is obtained for TE-mode light [24]. However, this design is not suitable for III-V platforms because the annealing temperature for Ce:YIG/Bi:YIG crystallization is at 900°C. To the best of our knowledge, integrated polarization-independent optical isolators and circulators have not yet been experimentally developed.

In this paper, we demonstrate an integrated non-reciprocal device by connecting PCs with a MZI structure and adhesive bonding of a Ce:YIG layer on the InP membrane on silicon (IMOS) platform [25]. Laser integration has already been demonstrated [26] as has ultracompact polarization handling [27]. This work could remove the optical interfaces between laser and isolator for robust production. The designed device can be operated as a polarization-independent isolator or as a polarization-independent circulator.

2. DEVICE DESIGN AND OPERATION PRINCIPLE

The polarization-independent isolator/circulator is a MZI and is schematically shown in Fig. 1. Two $2 \times 2$ multimode interferometers (MMIs) are placed on both sides of the device to form a four-port circulator and also an isolator when considering the port pairs on opposite sides. The $2 \times 2$ MMIs are developed for low polarization dependence and low reflection on the IMOS platform [28]. Four ultrasmall ($<10 \mu m$ length) and efficient ($>99\%$ polarization conversion efficiency) PCs are involved [27]. The PCs contain two triangular waveguides with one rectangular waveguide section in between. A set of rotated eigenmodes will be excited when a TE- or TM-polarized mode is coupled to the triangular waveguide. After propagating over a certain length, the two modes will recombine to a different polarization state. Two triangular sections are needed to achieve full TE-TM conversion. A Ce:YIG die is adhesively bonded on top of two arms of the MZI structure with a layer of benzocyclobutene (BCB) [12]. A non-reciprocal phase shift (NRPS) effect will be present for the TM mode when an external lateral magnetic field is applied [1]. The NRPS, defined as the phase shift between waves propagating in opposite directions, varies with the thickness of the BCB layer. TE and TM modes have different propagation constants in the rectangular waveguide sections, which will introduce an additional reciprocal phase shift (RPS) to the propagating light.

For the forward direction, the input signal coupled into port 1 is split into two branches by MMI 1. The signals in both branches will have equal power but a phase difference of $\pi/2$. When the input is the TE mode, it will be converted to the TM mode after passing through PC 1 in the upper branch. NRPS becomes effective on this TM mode in the upper branch part covered with Ce:YIG, when a transverse magnetic field is applied. The TM mode will be converted back to the TE mode after propagating through PC 2. In the lower branch, the TE mode will not be affected by the NRPS effect. The TE-mode signal in the lower branch will be converted to TM mode after PC 3 and back to TE mode after PC 4. PC 3 and PC 4 are used to balance possible losses from PC 1 and PC 2. The birefringence in the waveguides will cause an additional reciprocal phase shift (RPS) between the signals in the two branches. Similarly, if the input is in the TM mode, the same NRPS and RPS will be obtained, but now in the lower branch. Thus, both input polarizations will lead to equally large, but opposite, phase differences between the branches. This enables the polarization-independent behavior.

When the input light is in the TM mode and is injected from port 1, the reciprocal phase difference $\Delta \Phi_{TM,RPS}$ and the non-reciprocal phase difference $\Delta \Phi_{TM,NRPS}$ in the two branches for the forward direction can be written as

$$\Delta \Phi_{TM,RPS} = \beta_{TM,1} \cdot L_1 - (\beta_{TE,1} \cdot L_1 + \beta_{TE,2} \cdot L_2),$$

$$\Delta \Phi_{TM,NRPS} = \beta_{TM,2} \cdot L_2,$$

where $\beta_{TE,1}$ ($\beta_{TE,2}$) is the propagation constant of TE-mode light that propagates in the branches without (with) a Ce:YIG layer. $\beta_{TM,1}$ ($\beta_{TM,2}$) is the propagation constant of the TM mode that propagates in the branches without (with) a Ce:YIG layer in the

![Fig.1. Schematic of the device.](image-url)
forward direction. $L_1$ is the length without a Ce:YIG layer. $L_2$ is the length of with a Ce:YIG layer in the branches.

The output power in the two output ports for the forward direction can be written as

$$I_2 = A^2 \sin^2 \left( \frac{\Delta \phi_{TM, RPS} + \Delta \phi_{TM, NRPS}}{2} \right).$$

$$I_4 = A^2 \cos^2 \left( \frac{\Delta \phi_{TM, RPS} + \Delta \phi_{TM, NRPS}}{2} \right).$$

where $A$ is the amplitude of the input light.

Thus, the output power in the two ports can be tuned with $\Delta \phi_{TM, RPS}$ and $\Delta \phi_{TM, NRPS}$. When $\Delta \phi_{TM, RPS}$ is $\pi/2 + 2 n \pi$ (where $n$ is an integer) and $\Delta \phi_{TM, NRPS}$ is $\pi/2 + 2 m \pi$ (where $m$ is an integer), light in the two branches is out of phase and is coupled out from port 2.

For the backward direction, the reciprocal phase difference $\Delta \phi_{TM, RPS}'$ and the non-reciprocal phase difference $\Delta \phi_{TM, NRPS}'$ for TM-mode light injected from port 2 in the two branches are

$$\Delta \phi_{TM, RPS}' = \Delta \phi_{TM, RPS},$$

$$\Delta \phi_{TM, NRPS}' = - \beta_{TM, 2} \cdot L_2 = - \Delta \phi_{TM, NRPS}.$$ (5)

(6)

The output power in the two output ports for the backward direction can be written as

$$I_1 = A^2 \sin^2 \left( \frac{\Delta \phi_{TM, RPS} - \Delta \phi_{TM, NRPS}}{2} \right).$$

$$I_3 = A^2 \cos^2 \left( \frac{\Delta \phi_{TM, RPS} - \Delta \phi_{TM, NRPS}}{2} \right).$$

The output power in the two ports 1, 3 is also tuned with $\Delta \phi_{TM, RPS}$ and $\Delta \phi_{TM, NRPS}$. When $\Delta \phi_{TM, RPS}$ is $\pi/2 + 2 n \pi$ and $\Delta \phi_{TM, NRPS}$ is $\pi/2 + 2 m \pi$, light in the two branches is in phase and is coupled out from port 3.

When the phase conditions mentioned above are matched, the TM-mode light injected in port 1 will be coupled out from port 2, while the TM-mode light injected in port 2 will be coupled out from port 3. Thus, an optical isolation can be achieved between port 1 and port 2, which means this device can work as an optical isolator. Furthermore, light in port 3 is directed to port 4, and input at port 4 is directed to port 1. Thus, a four-port circulator operation is realized.

This device also works on the same principle when the input signal is TE mode. If the TE-mode light is injected in port 1, the reciprocal phase difference $\Delta \phi_{TE, RPS}$ and non-reciprocal phase difference $\Delta \phi_{TE, NRPS}$ in the two branches for the forward direction can be written as

$$\Delta \phi_{TE, RPS} = (\beta_{TE, 1} \cdot L_1 + \beta_{TE, 2} \cdot L_2) - \beta_{TM, 1} \cdot L_1 = - \Delta \phi_{TM, RPS}.$$ (9)

$$\Delta \phi_{TE, NRPS} = - \beta_{TM, 2} \cdot L_2 = - \Delta \phi_{TM, NRPS}.$$ (10)

The output power in the two output ports for the backward direction can be written as

$$I_1 = A^2 \sin^2 \left( \frac{\Delta \phi_{TE, RPS} + \Delta \phi_{TE, NRPS}}{2} \right) = A^2 \sin^2 \left( \frac{\Delta \phi_{TM, RPS} + \Delta \phi_{TM, NRPS}}{2} \right).$$

$$I_3 = A^2 \cos^2 \left( \frac{\Delta \phi_{TE, RPS} + \Delta \phi_{TE, NRPS}}{2} \right) = A^2 \cos^2 \left( \frac{\Delta \phi_{TM, RPS} + \Delta \phi_{TM, NRPS}}{2} \right).$$

These are identical to Eqs. (3) and (4). When $\Delta \phi_{TM, RPS}$ is $\pi/2 + 2 n \pi$ and $\Delta \phi_{TM, NRPS}$ is $\pi/2 + 2 m \pi$, light in the two branches is out of phase and is coupled out from port 2.

For the backward direction, the reciprocal phase difference and the non-reciprocal phase difference in the two branches for TE-mode light injected in port 2 can be written as

$$\Delta \phi_{TE, RPS}' = \Delta \phi_{TE, RPS} = - \Delta \phi_{TM, RPS},$$

$$\Delta \phi_{TE, NRPS}' = \beta_{TM, 2} \cdot L_2 = \Delta \phi_{TM, NRPS}.$$ (13)

(14)

The output power in the two output ports for the backward direction can be written as

$$I_1 = A^2 \sin^2 \left( \frac{\Delta \phi_{TE, RPS} + \Delta \phi_{TE, NRPS}'}{2} \right) = A^2 \sin^2 \left( \frac{\Delta \phi_{TM, RPS} - \Delta \phi_{TM, NRPS}}{2} \right).$$

$$I_3 = A^2 \cos^2 \left( \frac{\Delta \phi_{TE, RPS} + \Delta \phi_{TE, NRPS}'}{2} \right) = A^2 \cos^2 \left( \frac{\Delta \phi_{TM, RPS} - \Delta \phi_{TM, NRPS}}{2} \right).$$

These expressions are identical to Eqs. (7) and (8). The output power in the two ports 1, 3 can also be tuned with $\Delta \phi_{TM, RPS}$ and $\Delta \phi_{TM, NRPS}$. When $\Delta \phi_{TM, RPS}$ is $\pi/2 + 2 n \pi$ and $\Delta \phi_{TM, NRPS}$ is $\pi/2 + 2 m \pi$, light in the two branches is in phase and is coupled out from port 3. An optical isolator or a four-port circulator operation for both TM- and TE-mode light can thus be realized if the phase conditions are matched.

3. SIMULATION AND FABRICATION

The waveguide cross-section dimensions and assembly for the magneto-optic layer are explored through a sequence of field propagation calculations. The TM mode will undergo a NRPS when interacting with the Ce:YIG layer, which is magnetized along the transverse direction [the y direction in Fig. 2(b)]. The cross section of the InP waveguide bonded to a Ce:YIG layer is shown in Fig. 2(a). The Ce:YIG layer with a thickness of 500 nm is sputtered on a substituted gadolinium gallium garnet (SGGG) substrate. The waveguide section is 400 nm in width and 300 nm in height and is fabricated on the IMOS platform [26]. The high refractive index contrast between InP and silicon dioxide create a high confinement of the modes. Only fundamental TE and TM modes can exist. The electric field distribution of the fundamental TM mode is shown in Fig. 2(b). The electrical field is interrupted at the interface of different layers.

Several parameters (size of Ce:YIG die, Faraday rotation coefficient of Ce:YIG, and thickness of the bonding layer) will affect NRPS [29]. In this case, Ce:YIG has a Faraday rotation coefficient of 4500'°/cm at 1550 nm and has a die size of 4 mm × 4 mm.
Fig. 2. (a) Cross section of the IMOS waveguide bonded with Ce:YIG. (b) Electric field distribution of the fundamental TM mode.

Fig. 3. NRPS of TM mode as a function of BCB thickness at a wavelength of 1550 nm.

The thickness of SiO\textsubscript{2} between BCB and InP is designed for 50 nm. NRPS as a function of the thickness of the BCB layer is analyzed using a 3D finite-difference time domain (FDTD) solver and is shown in Fig. 3. In the FDTD solver, the phase difference of the TM-polarized wave at a wavelength of 1550 nm for different BCB thicknesses in opposite propagating directions is calculated. The simulation results show that at most a 72 nm thick BCB layer is needed to reach $\pi$ non-reciprocal phase difference for Ce:YIG with 4 mm length.

The designed device is fabricated on the IMOS platform [25]. The main steps of the process flow are shown in Fig. 4.

1. The typical layer stack of a passive IMOS wafer contains a 300 nm InP layer on top of a 100 nm InGaAs etch-stop layer on InP the substrate. An additional 20 nm InGaAsP layer and a 140 nm InP layer are added for the PCs. A 50 nm SiN layer is deposited on the wafer as a hard mask and a layer of positive electron-beam resist (ZEP 520A) is spin-coated on SiN.

2. The areas for trenches are opened by an electron-beam lithography (EBL) step. A CH\textsubscript{3}F\textsubscript{3} based reactive ion etching (RIE) step is performed to transfer the pattern to the SiN layer. Then H\textsubscript{3}PO\textsubscript{4} : HCl (4:1) and H\textsubscript{2}SO\textsubscript{4} : H\textsubscript{2}O : H\textsubscript{2}O (1:1:10) are used, respectively, to remove 300 nm InP layer and 100 nm InGaAs layer from the opening areas. Initial slopes are formed in the top two layers because of the selective wet etch with etch-stop layers.

3. An EBL step is performed on a new layer of ZEP 520A, which is spin-coated on a new 50 nm SiN layer. The vertical sidewalls of the rectangular waveguides and the triangular waveguides are patterned in the same step. A CH\textsubscript{4}/H\textsubscript{2} based RIE step is used to etch the InP layer.

4. A 100 nm SiN layer is deposited, and another EBL step is performed to expose the areas where the slopes for PCs are to be completed, while protecting the rest of the wafer, including the dry-etched vertical sidewalls. The etch time of the CHF\textsubscript{3} based RIE step is well controlled so that the sidewall of the PC is covered with SiN. Then the triangular sections are created using H\textsubscript{3}PO\textsubscript{4} : HCl (4:1) and H\textsubscript{2}SO\textsubscript{4} : H\textsubscript{2}O : H\textsubscript{2}O (1:1:10) to selectively wet etch the InP and InGaAsP layer [27].

5. 400 nm SiO\textsubscript{2} layers are deposited on the IMOS wafer and a Si wafer. A layer of diluted BCB (Cyclotene 3022-46: Mesitylene 1:5 v/v) is spin-coated at 4000 rpm for 30 s (a 70 ± 5 nm thick BCB
layer is found with reflectometry using this recipe) on the SiO$_2$ layer. The Ce:YIG dies are cleaned using acetone and isopropylalcohol (IPA). They are aligned and attached on top of the IMOS waveguides. Finally, the dies are bonded on the IMOS wafer in the bonder under a pressure of 1.6 MPa for 1 h at 280°C in a N$_2$ environment.

A SEM image of the waveguides entering the bonded Ce:YIG region is shown in Fig. 5(a). PCs can also be observed in this image. A photograph of the IMOS wafer bonded with Ce:YIG dies is shown in Fig. 5(b).

### 4. DEVICE CHARACTERIZATION

A grating-coupler setup is used to characterize the device. TE (TM) grating couplers are used to couple TE (TM) light into or out of the device with fibres. A Nd-Fe-B magnet is placed about 5 cm away from the Ce:YIG die to provide a static TM field. The magnitude of this field at the Ce:YIG die is over 50 Oe (measured with a gaussmeter). This is strong enough to saturate the Ce:YIG layer [9]. To characterize the device as an optical isolator, the transmission spectra of port 2 and port 3 are recorded from both TE and TM grating couplers for forward and backward propagation direction.

The transmission spectra of the TE-mode light between port 2 and port 3 are shown in Fig. 6(a). The wavelength shift between the spectra of two transmission directions is around 1.2 nm. The optical isolation is defined as the difference of transmission between forward and backward directions for a certain pair of ports. An optical isolation of 24.1 dB is measured at 1539.6 nm. Figure 6(b) shows the transmission spectra of TM-mode light between port 2 and port 3. A wavelength shift of around 1.2 nm is again obtained. An optical isolation of 34.0 dB is measured at 1539.2 nm. The 1.2 nm wavelength shift for both TE- and...
TM-mode light corresponds to a reciprocal phase shift of $\pi/2$ and a non-reciprocal phase difference of $\pi$. Thus, a polarization-independent optical isolator can be achieved when taking port 2 and port 3 as functional ports. Similar results are obtained between other port pairs on the opposite side of the MZI. The wavelength where the maximum isolation is achieved for TE- and TM-mode light differs by 0.4 nm. This offset comes from a polarization-dependent phase error in the waveguide section between PCs. The phase error can be fixed by adding a phase shifter between the PCs.

To characterize the device as an optical circulator, the transmission spectra of the four ports are recorded from both TE and TM grating couplers for forward and backward propagation direction. The transmission spectra of TE light input in clockwise direction (Port 1 $\rightarrow$ Port 2 $\rightarrow$ Port 3 $\rightarrow$ Port 4 $\rightarrow$ Port 1) and counterclockwise direction (Port 1 $\rightarrow$ Port 4 $\rightarrow$ Port 3 $\rightarrow$ Port 2 $\rightarrow$ Port 1) are shown in Figs. 7(a) and 7(b). The measured transmittance of two cascaded TE grating couplers is also shown in Fig. 7(a). The operating wavelengths in the clockwise direction and counterclockwise directions are highlighted with the dashed vertical line and the solid vertical line, respectively.

The transmittance of the TE mode at 1539.6 nm is summarized in Table 1 for the four input/output ports. The transmittance for clockwise direction at this wavelength is between $-36.9$ and $-34.0$ dB. As shown in Fig. 7(a), the fiber-to-waveguide coupling loss is measured as 13.8 dB. A 3 dB coupler is placed at the output port to split the light to TE and TM grating couplers. The PC gives around 1.0 dB loss, and the $2 \times 2$ MMI gives around 1.0 dB loss. Another 3.0 dB loss is observed from the device with Ce:YIG compared to the device without Ce:YIG. This excess loss is attributed to optical absorption of Ce:YIG and to scattering and reflection at the boundaries between the BCB and Ce:YIG cladding regions. The remaining insertion loss is attributed to the propagation loss of the waveguide, which is around 22.0 dB/cm in this fabrication run. In this device, the waveguide section is 5 mm long, which will bring around 11.0 dB loss. The large waveguide loss is attributed to the sidewall roughness induced during the EBL step. A record low waveguide loss of 1.3 dB/cm was demonstrated on the IMOS platform utilizing 193 nm deep UV lithography [30], which could reduce the waveguide loss significantly. The insertion losses can be further improved by shortening the length of the Ce:YIG die (the length of the waveguide section covered with Ce:YIG is shortened as well then), optimizing the design of the PCs and MMIs. The measured optical isolations are 27.0 dB and 24.1 dB for the cross-port pairs, while optical isolations for the bar-port pairs are 19.9 dB.
and 18.6 dB. The variations of the optical isolations for cross- and bar-port pairs are caused by the imbalanced power splitting ratio of the 2 × 2 MMI, which is designed considering an air cladding. This can be improved by optimizing the dimension of the 2 × 2 MMI considering BCB cladding.

The transmission spectra of TM light input for the clockwise direction and counterclockwise direction are shown in Figs. 7(c) and 7(d). The measured transmittance of two cascaded TM grating couplers is shown in Fig. 7(c). The operating wavelengths in the clockwise direction and counte-clockwise direction are highlighted with the dashed vertical line and the solid vertical line, respectively.

The transmittance of TM mode at 1539.2 nm is summarized in Table 2 for the four input/output ports. The transmittance for clockwise direction at this wavelength is between −27.8 dB and −31.3 dB. The insertion loss for the TM mode is less than the insertion loss for the TE mode. This is because the TE mode suffers from more propagation loss from the sidewall roughness, due to the mode distribution in the waveguide. The measured optical isolations are 30.9 dB and 34.0 dB for the cross-port pairs, while optical isolations for the bar-port pairs are 16.8 dB and 16.4 dB. The difference of optical isolations between the cross and bar configurations for the TM mode is larger than the difference for the TE mode. In this device, the power splitting ratio is closer to 50:50 for the TE mode than for the TM mode. This can be improved by optimizing the 2 × 2 MMI design.

5. CONCLUSION
An integrated polarization-independent optical non-reciprocal device is experimentally demonstrated for the first time. It is realized with adhesively bonding a Ce:YIG die to a MZI-based structure on the IMOS platform. The device works as an optical isolator between ports at the opposite side of the MZI. The device shows maximum optical isolations of 27.0 dB and 34.0 dB for TE- and TM-mode input, respectively. The structure can also function as an optical circulator when using all the four input/output port combinations. For TE-polarized light, 27.0 dB and 24.1 dB optical isolations are obtained for the cross-port pairs, while 19.9 dB and 18.6 dB optical isolations are measured for the bar-port pairs. For TM-mode light, 30.9 dB and 34.0 dB optical isolations for the cross-port pairs and 16.8 dB and 16.4 dB optical isolations for the bar-port pairs are obtained. The 2 × 2 MMI design needs to be optimized to reduce the imbalanced power splitting ratio for both the TE and TM mode. This device is demonstrated on a platform that has been shown to integrate active and passive photonic components, especially amplifiers and lasers, on one platform. It provides a step forward toward a multifunctional and high-density photonic integrated circuit.

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