Fabrication-tolerant and CMOS-compatible polarization splitter and rotator based on a compact bent-tapered directional coupler

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Fabrication-tolerant and CMOS-compatible polarization splitter and rotator based on a compact bent-tapered directional coupler

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ABSTRACT

In this paper, we demonstrate a broadband, low-loss, compact, and fabrication-tolerant polarization splitter and rotator (PSR) on a silicon-on-insulator platform. The PSR is based on an asymmetric directional coupler (ADC), which is covered with SiO$_2$ from the top to make it compatible with the standard metal back end of line (BEOL) process. Conventional ADC-based PSRs suffer from stringent fabrication requirements and relatively low bandwidth, while the proposed bent-tapered design is highly insensitive to the fabrication errors (>70 nm tolerance on the coupling gap) with an enlarged bandwidth and a compact footprint of 53 $\mu$m × 7 $\mu$m. It yields a polarization conversion loss less than 0.7 dB, a transverse electric (TE) insertion loss better than 0.3 dB, an ultra-low crosstalk with the TE extinction better than 30 dB, and the transverse magnetic extinction better than 25 dB, over a 200 nm wavelength range (1.5 $\mu$m–1.7 $\mu$m), in both ports. At the 1.55 $\mu$m wavelength, the calculated ultra-low polarization conversion loss and TE insertion loss are 0.27 dB and 0.08 dB, respectively.

I. INTRODUCTION

Controlling the polarization of light as it propagates and different modes get coupled is a subject of perennial interest in optics and photonics, notably within the context of silicon photonics.

Silicon photonics has shown great potential as it promises compact footprint and low-energy high-bandwidth technology to integrate optical circuits on a silicon chip, driven by its compatibility with complementary metal-oxide semiconductor (CMOS) processes. A compact and dense integration of silicon photonics devices is achieved due to a large refractive index contrast, but the performance of the devices is strongly dependent on the polarization state of the input light. An accurate control of the transverse electric (TE) and transverse magnetic (TM) polarization components is required and can be achieved using polarization diversity circuits, with important building blocks such as polarization splitters (PS) and polarization rotators (PR).

Several on-chip polarizers have been developed on a silicon-on-insulator (SOI) platform, such as polarizers based on plasmonic structures, periodically structured waveguides (WG), adiabatic bends, and partially etched waveguides. Various on-chip PSs have been successfully reported in the literature, implemented as directional couplers (DC), periodic structures, multimode interference structures, hybrid plasmonic waveguides, slot waveguides, and tapered structures. The polarization rotator (PR) is another way to control the polarization by rotating or converting one polarization state (TE/TM) to the other polarization state (TM/TE). The waveguide modes are hybridized due to the vertical and horizontal symmetry breaking, making it possible to rotate the optical power.

Polarization splitter and rotator (PSR) is the most effective technique. It splits and rotates one polarization state simultaneously. The underlying mechanism for the PSR is the fact that one specific polarization state is coupled to the other polarization state of the adjacent waveguide. PSRs based on asymmetric directional couplers...
have great potential as they are compact and exhibit high polarization conversion efficiency. Such designs have been reported in the literature, where the vertical symmetry was broken using an air over-cladding.\textsuperscript{45–48} Nevertheless, the partially etched waveguide can be utilized with silicon dioxide top cladding in order to break a vertical symmetry,\textsuperscript{49,50} making it compatible with the standard metal back end of line (BEOL) process. Another issue with such PSRs is that their performances are highly sensitive to fabrication errors. These can be greatly reduced by utilizing straight tapered waveguides, but at an expense of longer footprints, as presented in Refs. 51–53. The footprint of the PSR can be greatly reduced by using the bent directional coupler as reported in Ref. 54; however, waveguide dimensions are fixed and require stringent fabrication to achieve a reliable performance.

In this work, we present a novel PSR based on a bent and tapered ADC, making it compact and insensitive to fabrication errors. The performance of the PSR is broadband because different wavelengths become phase-matched at different positions along the tapered path. Furthermore, a ridge waveguide is used with SiO\textsubscript{2} top cladding in order to make it compatible with the standard metal BEOL process.

II. PRINCIPLE, DESIGN, AND SIMULATION OF PSR

The basic principle of PSR is based on the fact that the phase matching condition (i.e., the effective refractive index of the fundamental TM mode in one waveguide is equal to the effective refractive index of the fundamental TE mode in the closely placed waveguide) must be satisfied. However, such designs are highly sensitive to fabrication errors, and the phase matching can be easily destroyed by fabricated critical dimensions, deviating by only a few nanometers. For instance, a small width deviation in one waveguide requires an adjustment in the adjacent waveguide in order to maintain the phase matching. To resolve this issue, a tapered DC-based PSR was presented in Ref. 52. These tapered waveguides help in achieving horizontal symmetry breaking, which is essential for polarization rotation. However, a top cladding of air was employed to break the vertical symmetry. As an alternative, vertical symmetry can be broken by using partially etched (ridge) waveguides with SiO\textsubscript{2} top cladding, making it compatible with the standard metal BEOL process as reported in Ref. 51. As these designs utilize straight tapered sections, they have relatively long footprints. In our proposed design, the footprint is reduced greatly by using the bent and tapered ADC, making it compact, fabrication tolerant, and more manufacturable. A comparison of our PSR with other ADC-based PSRs is presented in Table I. Our proposed PSR exhibit the following characteristics:

- Broadband, over a 200 nm wavelength range.
- Extremely low TE IL, 0.08 dB at the 1.55 μm wavelength.
- PCL is better than 0.27 dB at the 1.55 μm wavelength.
- Ultra-low crosstalk with the TE extinction better than 30 dB and the TM extinction better than 25 dB, over a 200 nm wavelength range, in both ports.
- Compact footprint of 53 μm × 7 μm.
- Highly insensitive to the fabrication errors (>70 nm tolerance on the coupling gap).
- Insensitive to the length of ADC.
- Compatible with the standard metal BEOL process.

The proposed TM-rotated and TE-thru PSR is schematically depicted in Fig. 1. Figure 1(a) shows a top view of the proposed design, which is surrounded by silicon dioxide. A 3D view and cross-sectional view (cross section C) are shown in Figs. 1(b) and 1(c), respectively. It is defined on a 220 nm-thick SOI platform with a 2 μm-thick buried oxide layer. The coupling section of PSR is composed of two parallel bent waveguides, coupling a ridge waveguide to a strip waveguide with an appropriate coupling length. The strip waveguide is 220 nm-thick, while the ridge waveguide is composed of a 220 nm-thick ridge section and a 90 nm-thick slab section, as shown in Fig. 1(c). The strip waveguide and the slab section of the ridge waveguide are designed as tapers to ensure a broadband and fabrication-friendly PSR operation. The strip waveguide is tapered

<table>
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<th>Coupled waveguides of ADC</th>
<th>Top cladding</th>
<th>Waveguide widths tapered/fixed</th>
<th>Sensitivity to fab. errors</th>
<th>Bent/straight ADC</th>
<th>Total PSR length</th>
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FIG. 1. Schematic illustration of the proposed PSR: (a) top view with all design parameters shown, (b) 3D view, and (c) a cross-sectional view (cross section C) depicting a strip waveguide placed closely to the input ridge waveguide with the coupling gap (Gap). The strip waveguide is tapered from $w_1$ (250 nm) to $w_2$ (350 nm), and while the ridge section of the ridge waveguide has a fixed width of 500 nm, the width of the slab section increases from $w_3$ (200 nm) to $w_4$ (500 nm), (d) calculated TE and TM mode effective indices in both waveguides, as a function of wavelength, at cross section B.

From $w_1$ (250 nm) to $w_2$ (350 nm). While the ridge section of the ridge waveguide has a fixed width of 500 nm, the width of the slab section increases from $w_3$ (200 nm) to $w_4$ (500 nm), as depicted in the insets of Fig. 1(a). The separation between the strip and ridge waveguides is defined as Gap (150 nm), which is kept constant along the curved path.

Both fundamental modes are launched into the ridge waveguide from the left side, and a small bend section at the left side of the drop port is used to achieve a smooth transition of the refractive index. The widths of the three silicon layers in the coupling region are carefully selected to satisfy the phase matching condition for the TM mode along the tapered path. The tapered silicon layers efficiently compensate for fabrication process variations, confirming the device operation under relaxed manufacturing tolerances. Figure 1(d) shows the effective refractive index plots at cross section B, where the desired phase matching is achieved for the TM mode. Under moderate width deviation due to the fabrication process, the phase matching can be easily destroyed. However, as two silicon layers are tapered, the phase matching position can still be fulfilled at a certain position along the path. Once the phase matching is achieved at a certain position along the tapered curvature, the converted power is maintained as the phase matching is no longer satisfied for the rest of the bent taper, relaxing the fabrication error sensitivity of PSR and making it insensitive to the length of the ADC. Another interesting point is that the phase matching positions are slightly different for different wavelengths. These positions can easily be found along the tapered path, leading to a broadband PSR operation.

Figure 1(d) shows that the phase matching condition for the TE input mode is not satisfied, and it passes through the ridge waveguide and outputs at the thru port. In order to realize no coupling of the TE mode, a significant difference between the effective index of the TE mode in both waveguides must be maintained. Conversely, the TM power must be transferred to the strip waveguide and rotated to the TE mode simultaneously. In order to realize a strong polarization rotation, the TM effective index in the input ridge waveguide and the TE effective index in the tapered strip waveguide must be similar. Figure 1(d) shows the effective indices of the fundamental modes in both waveguides as the wavelength increases from 1.5 $\mu$m to 1.6 $\mu$m. It indicates that the TE effective index in the ridge waveguide (blue curve) is significantly different from the TM and TE effective indices in the strip waveguide (red dotted and green curves). Consequently, there is no TE coupling due to a large mode mismatch. On the other hand, the TM effective index in the ridge waveguide (black dotted curve) is close enough to the TE effective index in the strip waveguide (green curve) to satisfy the phase matching condition. It confirms strong TM to TE cross-polarization coupling between two parallel bent waveguides when they are placed closely with an appropriate gap (Gap = 150 nm). Moreover, the curvature of the bent DC and the optimized waveguide dimensions confirm that their optical path lengths are equal as shown in the following equation:

$$\text{optical path length} = n_{\text{TM-ridge}}k_0R_{\text{ridge}}\theta = n_{\text{TE-strip}}k_0R_{\text{strip}}\theta, \quad (1)$$

where $n_{\text{TM-ridge}}$ and $n_{\text{TE-strip}}$ are effective refractive indices of TM and TE modes in the ridge and strip waveguides, respectively, $R_{\text{ridge}}$ and $R_{\text{strip}}$ are the curvatures of the bent DC and the strip waveguide, respectively.
and \( R_{\text{strip}} \) are the corresponding bending radii, and \( k_0 \) and \( \theta \) are the vacuum wave number and arc angle of the coupling region, respectively. The coupling region is based on an adiabatic bend,\(^{18}\) with \( R_{\text{edge}} = 70 \, \mu\text{m} \) (\( R_{\text{strip}} = 69.3 \, \mu\text{m} \)), which is necessary to achieve low bending loss for both polarizations and to confirm strong cross-polarization coupling in the tapered bends. The arc angle is optimized to be \( \theta = 35^\circ \), leading to a coupling length of \( L_c = R_{\text{edge}} \theta \approx 42 \, \mu\text{m} \). The total length of our PSR is \( \approx 53 \, \mu\text{m} \), and its width is \( \approx 7 \, \mu\text{m} \). At the end of the coupling region, a bent waveguide is added in the thru port with a minimum radius of curvature, \( R_3 = 5 \, \mu\text{m} \), to decouple the waveguides. An additional adiabatic S-shaped bend that separates both ports and works as a TE-pass polarizer has also been introduced right after the \( R_3 \)-radius bend. In previous studies, constant radius bends have been utilized to make two waveguides separated, but we use a TE-pass adiabatic bend with \( R_{\text{min}} = 1.3 \, \mu\text{m} \) and two different angles of 120\(^\circ\) and 90\(^\circ\) [as shown in Fig. 1(a)]. This TE-pass bent waveguide will allow the TE mode to propagate, but the TM mode will radiate out, leading to a high extinction ratio (ER) (i.e., a high loss for the TM polarization relative to TE) in the thru port. The TE-pass adiabatic bend has been fixed between the thru and drop ports, and this is the space that has not been used in previous designs, thus making the proposed PSR more area efficient.

A number of numerical techniques are available for simulating coupled mode propagation from analytical approximations to the 3D finite difference time-domain method (FDTD) chosen in:

**FIG. 2.** Electric field intensities along the propagation distance of PSR with the 150 nm coupling gap at the 1550 nm wavelength: [(a)–(c)] modes in cross sections A–C with the TM input, [(d)–(f)] modes in cross sections A–C with the TE input, (g) illustration of the top view of light propagation depicting TM mode entering the input port is coupled adiabatically to the TE mode at the drop port, and (h) TE mode passes through the thru port.
We have used the numerical package in our simulations, with refractive indices of 3.45 and 1.45 for the silicon and SiO$_2$, respectively (at a wavelength of 1550 nm).

The cross-polarization coupling in the proposed PSR can be explained using Fig. 2, which shows the amplitude of electric field intensity in the three cross sections, after launching both fundamental modes at the 1550 nm wavelength. Figures 2(a)–2(c) show the electric fields when the TM mode is launched, while Figs. 2(d)–2(f) depict the fields when the TE mode enters from the input side, in cross sections A–C, respectively. In cross section A, both TM and TE modes are well confined in the input ridge waveguide as shown in Figs. 2(a) and 2(d), respectively. The TE mode stays in the ridge waveguide along the coupling region with no coupling to the strip waveguide, as shown in cross section B [Fig. 2(e)] and cross section C [Fig. 2(f)]. On the other hand, the TM mode is gradually coupled to the strip waveguide as a TE mode and an equal fraction of both modes is seen in cross section B [Fig. 2(b)]. Finally, the total power is carried by the strip waveguide as a TE mode, as shown in cross section C [Fig. 2(c)].

FIG. 4. Spectral responses of the proposed PSR with different curves correspond to different coupling gaps: (a) TE drop port, TE input; (b) TE thru port, TE input; (c) TE reflection; (d) TE converted power at the drop port, TM input; (e) TM thru port, TM input; (f) TM reflection; (g) TM drop port, TE input; (h) TM thru port, TE input; (i) TM drop port, TM input; and (j) TE thru port, TM input.
The spectral responses of PSR were simulated using the 3D FDTD method, as shown in Fig. 3. The transmitted powers at the output of the thru and drop ports were calculated after launching each mode at the input. The simulation results show the TM–TE polarization converted transmission at the drop port, which is needed to evaluate polarization conversion loss (PCL), plotted as a red curve in Fig. 3(c). A magnified view of this transmission is shown as a red curve in Fig. 3(b). It shows that the PCL is less than 0.7 dB from 1500 nm to 1700 nm wavelength and even less than 0.4 dB over the whole C-band. Furthermore, it shows an ultralow conversion loss of 0.27 dB at the communication wavelength of 1550 nm. The green curve in Fig. 3(a) plots the thru port transmission for the TE polarization [which is negative of the insertion loss (IL), i.e., TE loss in the thru port]. A magnified view of this curve is shown in green in Fig. 3(b). It yields an IL less than 0.3 dB over the 200 nm wavelength range and less than 0.1 dB over the entire C-band. Moreover, an extremely small TE IL of 0.08 dB is calculated at the 1550 nm wavelength. The crosstalk values are below −30 dB for the TE mode and below −25 dB for the TM mode, as shown from the red curve of Fig. 3(a) and yellow curve of Fig. 3(c), respectively. Furthermore, with the input TE mode, extremely small TM powers are calculated at both ports, leading to a significant reduction in the crosstalk, as shown in Fig. 3(a) (yellow and black curves). Additionally, a high extinction of TM and TE modes is observed at the drop port and thru port, respectively, when the TM mode is launched at the input [Fig. 3(c)] (black and green curves).

III. FABRICATION TOLERANCE ANALYSIS

The proposed design can be fabricated by using the standard CMOS fabrication process with two etch-step lithography. However, a small change in physical dimensions and misalignment of the mask layers can destroy the conversion efficiency. In order to investigate the fabrication tolerance of the PSR, the PCL, IL, and crosstalk values are studied as functions of wavelength, etch depth of the slab, and coupling gap. Two mask layers are needed for the fabrication process where one is used to pattern the 220 nm-thick silicon layers and the other is used to form a 90 nm-thick slab section of the ridge waveguide. Any misalignment of the mask layers can lead to a narrow or wide coupling gap between the strip and ridge waveguides. The narrow and wide coupling gaps result in a strong and weak cross-coupling, respectively. The dependence of IL, PCL, and crosstalks is studied with different coupling gaps, as shown in Fig. 4. For the TM input mode, the PCL shows great tolerance to the change in the coupling gap from 130 nm to 200 nm, as depicted in Fig. 4(d). However, a further increase in the gap (220 nm) leads to an increased PCL due to the weak interaction of the input mode with the adjacent waveguide. In addition, properly decreasing the gap (<130 nm) can shorten the coupling length, but at the cost of stringent fabrication requirements. Consequently, increasing the gap from 200 nm to 220 nm, the PCL grows slightly above 1 dB at the smaller wavelengths. However, extremely small PCL values are observed at the communication wavelength of 1550 nm. For the TE input, the IL is less than 0.3 dB over a 200 nm wavelength range, indicating that the TE mode propagation is independent of all coupling gaps, as shown in Fig. 4(b). For TE input polarization, the crosstalks of the TM mode (at the drop port) and TM mode (at both ports) are shown in Figs. 4(a), 4(g), and 4(h). For TM input polarization, the crosstalks of the TE mode (at the thru port) and the TM mode (at both ports) are shown in Figs. 4(i), 4(e), and 4(l), confirming that the ultrahigh and broadband crosstalk values are maintained for all gaps. The back reflection loss of both modes is studied for all gaps to ensure the system’s stability. It is measured at the input port and defined as the ratio of reflected power and the input mode power of the same polarization, as shown in Figs. 4(c) and 4(f), for the TE and TM modes, respectively.
where the TE reflection is always below $-40$ dB over the entire bandwidth. The TM reflected power is lower than $-30$ dB, which is slightly higher than the TE reflections. This can be explained because of more reflection and scattering in the cross-coupling region.

The fabrication errors due to different slab depths are also investigated with a fixed coupling gap of 200 nm. The PCL, IL, and crosstalks at both ports are plotted as a function of wavelength, with different curves corresponding to different slab depths, as shown in Fig. 5. Figures 5(a), 5(e), 5(f), 5(d), 5(g), and 5(h) depict that the crosstalks of the TE and TM modes are well below $-30$ dB and $-20$ dB, respectively, demonstrating the broadband fabrication resilience performance. The TE IL is below 0.3 dB for all slab depths, over the entire bandwidth, as conveyed by the overlapping curves in Fig. 5(c). On the other hand, the PCL is slightly sensitive to the etched slab depth, as shown in Fig. 5(b). It is necessary to control the slab thickness in the range of 80 nm–110 nm. Due to the curved and tapered structures, the polarization conversion remains broadband and tapered waveguides are used to reduce the risk of degraded performance.

IV. CONCLUSION

In summary, a compact 53 μm-long PSR is proposed based on an asymmetric directional coupler. A polarization conversion loss below 0.7 dB and a TE insertion loss below 0.3 dB, over a 200 nm wavelength range, are exhibited. Our polarization splitter and rotator design shows ultra-low crosstalks with the TE extinction better than 30 dB and a TM extinction better than 25 dB in both ports, over the entire 200 nm wavelength range (1500 nm–1700 nm). Due to the tapered waveguides, once the phase matching is fulfilled at a certain position along the curved path, the transferred power is maintained in the drop port as the phase matching is no longer satisfied for the rest of the bent taper, making the device insensitive to the length of the asymmetric directional coupler. The proposed device is compatible with the standard metal back end of the line process. Due to the bent-tapered silicon layers, it is one of the most fabrication tolerant and compact designs in the literature, exhibiting a tolerance of $>70$ nm on the coupling gap.

SUPPLEMENTARY MATERIAL

See the supplementary material for X–Y coordinates for the thru and drop ports of the polarization splitter and rotator for implementation on 220 nm-thick and 90 nm-thick Si layers (SOI platform). The coordinates can be easily imported into a GDSII file for patterning.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this study are available within the article and its supplementary material.

REFERENCES


