A silicon-on-insulator polarization diversity scheme in the mid-infrared

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Abstract: We propose a silicon-on-insulator (SOI) polarization diversity scheme in the mid-infrared wavelength range. In consideration of absorption loss in silicon dioxide (SiO2), the polarization splitter-rotator (PSR) is designed and optimized with silicon nitride (SiN) upper-cladding and SiO2 lower-cladding. This asymmetry allows the PSR, which consists of mode-conversion tapers and subsequent mode-sorting asymmetric Y-junctions, to be fabricated with a simple one-step etching process. Simulation shows that our PSR has good performance with low mode conversion loss (< 0.25 dB) and low crosstalk (< –18 dB) in a very large wavelength range from 4.0 μm to 4.4 μm. The PSR also exhibits large fabrication tolerance with respect to the size deviations in waveguide width, height and refractive index of the upper-cladding. Additionally, PSR devices based on Y-junctions with SiO2 upper-cladding, and SiN upper- and lower-claddings are designed for potential applications at shorter and longer wavelengths, respectively. These PSR devices could facilitate the development of silicon photonic devices in the mid-infrared.

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References and links


1. Introduction

Silicon (Si) photonics, which takes full advantage of the well-established complementary metal oxide semiconductor (CMOS) processing, offers compact device footprint, high level of integration and low manufacturing cost [1, 2]. While the initial applications have been in optical communications at near infrared, within the recent five years, the scope of Si photonics has expanded to the mid-infrared wavelength range (>2 μm), with an interest to explore various sensing applications on a “lab-on-a-chip” platform [3–6]. Many components of mid-infrared Si photonics have been demonstrated, including waveguides [7], ring resonators [8], electro-optic/thermo-optic modulators [9, 10], photodetectors [11], arrayed waveguide gratings (AWGs) [12], multimode interference (MMI) couplers [13], grating couplers [14], etc. However, the high-index-contrast between Si and its cladding leads to large structural birefringence, i.e., the difference in the effective refractive indices of the guided modes of different polarizations. Polarization diversity schemes [15] which can separate and convert the incoming light of random polarization into two beams with identical polarization has been proposed and/or demonstrated at telecommunication bands [16–30]. However, polarization diversity schemes in the mid-infrared, to the best of our knowledge, have not been investigated yet.

To achieve polarization diversity for Si photonics at mid-infrared, we propose a silicon-on-insulator (SOI) polarization splitter and rotator (PSR) consisting of assisted mode conversion tapers and subsequent mode-sorting asymmetric Y-junction, which potentially has broadband properties according to our previous investigations [19]. Compared to near-infrared photonics, an important difference at mid-infrared is that silicon dioxide (SiO₂) may have strong absorption thus making them unsuitable as a cladding material. Recently, Lin et. al. reported a silicon nitride (SiN) photonic platform for mid-infrared applications and SiN has a broad transparent window up to 7 μm wavelength [31, 32]. Therefore, we adopt SiN here as the upper-cladding for the PSR device to potentially reduce the absorption loss at >4.0 μm wavelength [31–33]. In addition, we investigate SiO₂ as upper-cladding for PSR devices operating at shorter wavelength (~3.3 μm) and SiN as both upper- and lower-cladding for longer wavelength (~6.9 μm).
2. Device design

Figure 1(a) illustrates our proposed PSR device designed in a Si strip waveguide overlaid by SiN cladding. Even though Si has a broad transparent window up to 8 μm, the optical loss of SiO₂ sharply increases beyond 3.6 μm wavelength [33]. To suppress the absorption loss caused by SiO₂, a thicker Si layer with H = 600 nm is used so that the field intensity diminishes close to zero at the Si/SiO₂ interface [13]. Furthermore, we propose SiN, which has low absorption loss up to 7 μm wavelength as the upper-cladding for the PSR device [31–33]. Since SiN has a larger refractive index than SiO₂, there will be more power distributed in the upper-cladding, which is also helpful to reduce the absorption loss in the lower SiO₂ cladding layer. More importantly, introducing SiN as upper cladding in polarization rotating devices (e.g., polarization rotator [34] or PSR [35]) breaks the symmetry of the waveguide cross-section, and PSR devices based on Y-junctions can be realized with only one etch step.

The proposed PSR consists of a mode-conversion taper and a subsequent asymmetric Y-junction. This mode-conversion taper with SiN upper-cladding has a similar operation principle to Dai’s design, which can convert the input fundamental transverse-magnetic (TM₀) mode into the first-order transverse-electric (TE₁) mode while the input zero-order transverse-electric (TE₀) mode remains unchanged [22]. The operation principle of the subsequent asymmetric Y-junction is based on mode-sorting [36]. For Y-junctions with a small angle between the output arms, the mode in the input stem will propagate through the Y-junction and adiabatically evolve into the mode in the arm that has the closest effective refractive index with that of the input mode. If the design parameters of the Y-junction (e.g., the waveguide widths, Y-junction length, etc.) are appropriately optimized, the converted TE₁ mode will emerge as the TE₀ mode in port 2 and the input TE₀ mode will output in port 1, respectively.

Figure 1(b) shows the effective refractive indices of the first three modes in the cross-section of a strip waveguide with SiN upper-cladding and SiO₂ lower-cladding at 4.0 μm wavelength. We used the refractive index of Si₃N₄ for SiN claddings in this work [37] and the change of the refractive index due to the fabrication will be discussed in the next section. The simulation was performed by a full-vector finite difference method (FDM) in a commercial software, FIMMWAVE. We note that there is a hybrid mode region when the waveguide width increases from W₁ = 2.1 μm to W₂ = 2.4 μm. The hybrid modes are not purely polarized modes and the mode profiles of these two hybrid modes show that the minor-component (Eₓ or Eᵧ) is comparable to the corresponding major-component (Eᵧ or Eₓ), which implies the hybrid modes have the properties of both the TM₀ and TE₁ modes. For example, the second mode (i.e., the first hybrid mode) has an extra TE₁ part which is increased with the waveguide width and causes a discontinuity in the effective refractive index of the TM₀ mode. So when the waveguide width increases, there is a mode conversion from the TM₀ to TE₁ modes [22, 38]. After completing the mode conversion from the TM₀ mode to the TE₁ mode in the second section of this taper, the third part of the taper should maintain the completed mode conversion and avoid the TE₁ mode converting back to the TM₀ mode undesirably. So we choose W₃ = 2.65 μm at the taper end to ensure the difference between the effective refractive indices of the TE₁ mode and TM₀ mode is sufficiently large. A larger W₃ will require a longer taper to reduce the mode transition loss. In the design of the Y-junction, the widths of the arms satisfy the relationship as Wₐ + Wₓ = W₃, where Wₐ and Wₓ is the width of the narrow and wide output arm, respectively. One can note that Wₐ can be chosen in a broad range (shaded pink) based on the mode-sorting principle of the asymmetric Y-junction. However, when Wₐ decreases, the field intensity in the Si core decreases and more optical power will enter the SiO₂ cladding. As a result, the absorption loss will increase.
Fig. 1. (a) Schematic of the proposed PSR device which consists of a three-stage taper and a mode-sorting asymmetric Y-junction. (b) Effective refractive indices of the first three modes in a Si waveguide with SiN upper-cladding and SiO2 lower-cladding at 4.0 μm wavelength.

Figure 2(a) shows the conversion efficiency from the TM0 mode to the TE1 and TM0 modes in the overall taper with different lengths (L1, L2). The simulation was performed by FIMMPROP based on an eigen-mode expansion (EME) method at 4.0 μm wavelength. The ripples in the curves are likely caused by the undesired mode interference or reflection in the taper, which could be improved with increase of L1. In addition, if L2 is large enough, the conversion efficiency from the TM0 mode to the TE1 mode will be increased with L1. Here we choose L1 = 60 μm and L2 = 150 μm to achieve a > 99% conversion efficiency. A longer taper will improve the conversion efficiency, but at the expense of a larger device footprint. The inset of Fig. 2(a) shows the mode propagation in this taper for the input TM0 mode. It can be seen that the mode conversion in the taper is achieved as expected and the TM0 mode first evolves into the hybrid mode, and then emerges as the TE1 mode with high efficiency. Figure 2(b) shows the mode conversion efficiency in the Y-junction for the input TE1 mode with different narrow arm widths Wn. When Wn varies in a relatively large range from 1.305 μm to 1.005 μm, high mode conversion efficiency with correct mode-sorting can be achieved and the conversion efficiency increases with the length L_y of the Y-junction. The large range of Wn within which high mode conversion efficiency can be obtained suggests a large fabrication tolerance. Here we choose Wn = 1.245 μm and L_y = 200 μm for the Y-junction design.

Fig. 2. (a) Mode conversion efficiency for the input TM0 mode as a function of L2 for L1 varying from 10 μm (black) to 60 μm (pink), where L1 is set to L1(W3-W2)/(W1-W0). Insets: mode propagation in the taper when L1 = 60 μm and L2 = 150 μm, and the mode profiles in the cross-section along this taper. (b) Mode conversion efficiency in the Y-junction for the TE1 input with different widths of the narrow arm Wn changing from 1.305 μm (black) to 1.005 μm (light blue). All the simulations were performed at 4.0 μm wavelength.
3. Device performance characterization and fabrication tolerance analysis

Figures 3(a) and 3(b) show the mode propagation in the Y-junction-based PSR for the input TE\textsubscript{0} and TM\textsubscript{0} mode, respectively. It can be seen that the incoming TM\textsubscript{0} mode is evolved into the TE\textsubscript{1} mode in the three-stage taper and then evolves to the TE\textsubscript{0} mode in the port 2, whereas the input TE\textsubscript{0} mode only propagates through the taper and outputs in the port 1. This device has a relatively large length of ~470 μm, which may lead to a large dispersion for pulsed inputs. However, there are likely some potential improvement to reduce the taper length by using other taper shapes (e.g., parabolic or sinusoidal) [39] or adopting multi-variable optimizations (e.g., the genetic algorithm and particle swarm optimization) [40].

The PSR device performances are usually characterized by insertion loss (IL), crosstalk (XT) and polarization extinction ratio (PER) for each input polarization. The IL for the input TE\textsubscript{0} and TM\textsubscript{0} mode is defined as
\[
IL_{TE} = -10\log_{10}\left(\frac{P_{Port_{TE0}}}{P_{In_{TE0}}}\right)
\]
and
\[
IL_{TM} = -10\log_{10}\left(\frac{P_{Port_{TM0}}}{P_{In_{TM0}}}\right),
\]
respectively. The XT for the input TE\textsubscript{0} and TM\textsubscript{0} mode is defined as
\[
XT_{TE} = 10\log_{10}\left[\frac{P_{Port_{TE0}}}{P_{Port_{TE0}}}\right]
\]
and
\[
XT_{TM} = 10\log_{10}\left[\frac{P_{Port_{TM0}}}{P_{Port_{TM0}}}\right],
\]
respectively. The PER for the input TE\textsubscript{0} and TM\textsubscript{0} mode is defined as
\[
PER_{TE} = 10\log_{10}\left[\frac{P_{Port_{TE0}}}{P_{Port_{TE0}}}\right]
\]
and
\[
PER_{TM} = 10\log_{10}\left[\frac{P_{Port_{TM0}}}{P_{Port_{TM0}}}\right],
\]
respectively. Here \(P_{Port_{mode}}\) is defined as the detected power of the mode in the port. Figure 3(c) shows the wavelength dependence of the transmission characteristics for both polarizations. For the input TE\textsubscript{0} mode, the PSR exhibits a good performance of < 0.06 dB IL\textsubscript{TE} with better than −28 dB XT\textsubscript{TE} from 4.0 μm to 4.4 μm wavelengths. The corresponding PER\textsubscript{TE} is always below −40 dB due to the highly efficient mode sorting effect. At such a low magnitude, the simulation accuracy is not guaranteed, so we didn’t further expand the vertical axis to the magnitude where the detailed profiles of PER\textsubscript{TE} can be shown. For the input TM\textsubscript{0} mode, the performances are slightly degraded due to a more complex mode conversion. Nevertheless, the performance metrics remain stable with < 0.25 dB IL\textsubscript{TM} and < −18 dB XT\textsubscript{TM} in this wavelength range.

We also simulated the absorption loss of this PSR device due to SiO\textsubscript{2} bottom cladding by adding the absorption coefficient of SiO\textsubscript{2} into the previous model [37]. The simulated absorption loss is as low as < 0.13 dB and < 0.17 dB in the wavelength range from 4 μm to 4.4 μm for the TE\textsubscript{0} and TM\textsubscript{0} inputs, respectively.

The fabrication tolerance analysis is further performed with respect to the deviations in waveguide width ΔW, height ΔH, and refractive index of the upper-cladding Δn\textsubscript{SiN}.
respectively, as shown in Figs. 4(a)-4(c). For small waveguide width deviations (small $\Delta W$), the performance metrics for both polarizations are not affected considerably due to the relatively large waveguide width, $W$. For example, there is only $\sim 0.1$ dB variation of IL when $\Delta W = \pm 100$ nm. For the other two types of deviations, the performance of the TM$_0$ mode is more sensitive than that of the TE$_0$ mode. The performance metrics for the TE$_0$ mode remain very stable because there is no mode conversion in the taper section and the TE$_0$ mode always emerges at the wide port. For the TM$_0$ mode, these two fabrication errors may degrade the mode conversion to the TE$_1$ mode in the taper and then cause some unwanted modes at the outputs of the Y-junction. Nevertheless, the PSR device exhibits decent performance with $\text{IL}_{TM} < 0.4$ dB and $\text{XT}_{TM} < -12$ dB for large deviations of $\Delta H = \pm 80$ nm and $\Delta n_{\text{SiN}}/n_{\text{SiN}} = \pm 10\%$. We note that it is particularly important to have a large tolerance to the refractive index of SiN, as it varies substantially with deposition conditions.

Fig. 4. (a)-(c) Analysis of fabrication tolerance with respect to the parameter deviations in waveguide width $\Delta W$, height $\Delta H$ and refractive index of the upper-cladding $\Delta n_{\text{SiN}}$, respectively. The simulation wavelength is 4.0 $\mu$m. The curves below $-40$ dB are not shown due to simulation accuracy, e.g., PER$_{TE}$ and part of PER$_{TM}$.

In addition to the mode conversion loss considered in above, the scattering loss due to the waveguide surface roughness is highly detrimental to the total loss of this device in practice. Scattering loss could be reduced by optimizing fabrication process, such as photolithography and etching [41]. Even though the PSR shows good performance with relaxed fabrication tolerance, it would be necessary to improve the shape and quality of the corner between the arms of the Y-junction in practice. This is because some reflection will arise from a sharp corner while a flattened or rounded corner may disturb the mode sorting. Fortunately, some experimental results about the asymmetric Y-junctions in the mode-division-multiplexing (MDM) applications have been reported [42, 43] and improved schemes have been demonstrated to reduce the Y-junction loss considerably [44].

4. PSR devices operating at other mid-IR wavelengths using SiO$_2$ or SiN cladding

For applications with shorter operating wavelengths, SiO$_2$ is an alternative upper-cladding material with an acceptable absorption loss at wavelengths $< 4$ $\mu$m [33]. Recently, some mid-infrared devices fully cladded by SiO$_2$ were reported with reasonably low loss [12], which demonstrates potential possibilities of achieving a PSR device with SiO$_2$ upper-cladding. Figure 5(a) illustrates a PSR device with SiO$_2$ upper- and bottom-claddings, which consists of an asymmetric Y-junction and a bi-level mode conversion taper. Since the waveguide has the same upper- and lower-claddings, a bi-level taper is adopted to break the symmetry in the waveguide cross-section and achieve the TE$_0$ to TE$_1$ mode conversion [45]. Using the same simulation method earlier in this manuscript and our previous work [19, 20], we designed and optimized the taper section and Y-junction for this PSR device with SiO$_2$ upper- and bottom-claddings to achieve good performance at 3.3 $\mu$m wavelength. The simulated IL and XT performances for different inputs are $< 0.1$ dB and $< -30$ dB, respectively. Figures 5(b) and 5(c) show the mode propagation in the device for the TE$_0$ and TM$_0$ inputs, respectively. It can
be seen that the TE₀ input is transmitted to port 1 while the TM₀ input is first converted to TE₁ mode and finally comes out at port 2.

![Fig. 5. The PSR device with SiO₂ upper- and lower-claddings. (a) Schematic of the device based on an asymmetric Y-junction and a bi-level mode-conversion taper. The taper has a waveguide height of 0.45 μm and a slab height of 0.20 μm. (b-c) Mode propagation in the overall device at 3.3 μm wavelength for the TE₀ and TM₀ input, respectively.](image)

To completely eliminate the loss caused by SiO₂ absorption, it is desirable to use SiN for both upper- and lower-cladding. Fabricating such structures is challenging as crystalline silicon on SiN is not readily available, but one could still start with silicon-on-insulator (SOI) wafers and define the Si patterns using suitable lithography. After the deposition of SiN upper cladding, one could open holes in the SiN cladding near the devices. Since hydrofluoric acid (HF) has a much higher etch rate for SiO₂ than for Si and SiN, one could remove the bottom SiO₂ cladding by dipping the wafer into HF [8]. The Si device will then be released from the Si substrate but fixed to the upper SiN cladding. Note that only in a small area, i.e., the immediate vicinity of the waveguide and Y-junction, would the SiO₂ lower-cladding be removed. A similar process, albeit removing the silicon substrate underneath a polysilicon waveguide, has been demonstrated without obvious deformation, i.e., sagging, in the suspended structure (see Fig. 2 of ref [46].). A chemical vapor deposition of SiN could then fill the gaps between the Si devices and the Si substrate, thus achieving a Si PSR fully cladded in SiN. Figure 6(a) shows the schematic of a PSR device with SiN upper- and lower-cladding consisting of a Y-junction and a bi-level taper. This device is designed and optimized at 6.9 μm wavelength, so the device length is accordingly enlarged to ~1 mm. Figures 6(b) and 6(c) show the mode propagation of the overall device for TE₀ and TM₀ inputs, respectively, and suggest that the mode conversion is accurate and efficient. For longer wavelength range, the absorption loss may be improved by using air upper-cladding and etching away the oxide under-cladding layer to form a suspended structure [8].
Fig. 6. The PSR device with SiN upper- and lower-claddings. (a) Schematic of the device based on an asymmetric Y-junction and a bi-level mode-conversion taper. The taper has a waveguide height of 0.80 μm and a slab height of 0.35 μm. (b-c) Mode propagation in the overall device at 6.9 μm wavelength for TE₀ and TM₀ inputs, respectively.

5. Conclusion

In summary, PSR-based polarization diversity schemes in the mid-infrared wavelength range are investigated for the first time, to the best of our knowledge. With consideration of material absorption loss, PSR devices operating at different wavelengths are designed and optimized based on mode conversion tapers and mode-sorting asymmetric Y-junctions. In particular, we propose SiN as the waveguide cladding, either as upper-cladding or as both upper and lower-cladding, to reduce the SiO₂ absorption loss at wavelengths larger than 4 μm. We believe our investigation should facilitate the Si photonic device development and system integration for various mid-infrared applications at different wavelength ranges.

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