On-chip optical interconnects based on silicon photonics technology have attracted significant attention in the past decade due to their compatibility with the mature complementary metal oxide semiconductor (CMOS) process, strong optical confinement, and the potential to realize the monolithic integration of optical and electronic components, which provide both cost and performance advantages. Several silicon photonic platforms have been demonstrated, and various optical interconnect devices have been developed. The high level of integration also helps bring the design and production of systems into reality that otherwise would be too costly or complex to be developed in other material systems, such as wavelength division multiplexer (CWDM) and diplexer/triplexer fiber-to-the-home systems. The fabrication tolerance of the design is also analyzed, showing that the device performance is quite stable with normal manufacturing errors in silicon photonics foundries.

Design of an ultra-broadband and fabrication-tolerant silicon polarization rotator splitter with SiO₂ top cladding

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An ultra-broadband and fabrication-tolerant silicon polarization rotator splitter is proposed in this Letter. Benefiting from the broadband and low-loss characteristics of the bi-level taper and counter-tapered coupler, the designed device has a simulated insertion loss and crosstalk of less than 0.2 and −15 dB in the waveband from 1290 to 1610 nm. These characteristics make it valuable in applications with large bandwidth requirements, such as full-grid coarse wavelength division multiplexer (CWDM) and diplexer/triplexer fiber-to-the-home systems. The fabrication tolerance of the design is also analyzed, showing that the device performance is quite stable with normal manufacturing errors in silicon photonics foundries.

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Figure 1 shows the schematic of the proposed device, where the dark blue regions represent the Si waveguides and light blue regions represent the partially etched slab...
waveguide. Table 1 lists the parameters and corresponding values of the proposed device. Silicon-on-insulator (SOI) wafers with a top silicon thickness $H$ of 220 nm are used, and a slab height $H_{\text{slab}}$ of 90 nm is selected to be compatible with the standard fabrication process in a silicon photonic foundry\cite{13}. The device is composed of an adiabatic bi-level taper and a mode-evolution counter-tapered coupler. A standard SiO$_2$ top cladding is used due to the asymmetric cross section of the rib waveguide. Both the TE$_0$ and TM$_0$ modes are launched into the left port of the bus waveguide, as shown in Fig. 1. The TE$_0$ mode directly passes through the device and outputs from the through port. The TM$_0$ mode will be converted to the TE$_1$ mode first by the bi-level taper and then coupled to the TE$_0$ mode in the cross port after passing through the counter-tapered coupler. In this way, the TE$_0$ and TM$_0$ polarizations are separated and output as TE$_0$ modes at two ports. To obtain a broad operation bandwidth, both the bi-level taper and mode-evolution counter-tapered coupler are carefully optimized.

A bi-level taper with an asymmetrical waveguide cross section is utilized to realize a highly efficient TM$_0$-to-TE$_1$ mode conversion. Due to the mode hybridization in the asymmetric waveguide cross section, mode conversion between the TM fundamental mode and higher-order TE modes is observed\cite{14}. To obtain a broad bandwidth covering the entire waveband from 1310 to 1550 nm, the device is optimized at two wavelengths of 1310 and 1550 nm. Effective indices of the first three modes (TE$_0$, TM$_0$, and TE$_1$) in the cross section along the proposed bi-level taper are calculated with a commercial simulation software package (FIMMWAVE) and shown in Fig. 2(a).

### Table 1. Parameters and Corresponding Values of the Proposed Device

<table>
<thead>
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<th>Parameters</th>
<th>Values ($\mu$m)</th>
<th>Parameters</th>
<th>Values ($\mu$m)</th>
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<td>$W_0$</td>
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<td>$W_x$</td>
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<td>$W_g$</td>
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<td>$L_{tp4}$</td>
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<tr>
<td>$W_7$</td>
<td>0.45</td>
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Fig. 2(a). The brown dashed circles in Fig. 2(a) show the mode hybridizations between the TM$_0$ and TE$_1$ modes at the rib/slab waveguide widths around $W_0$(0.48 $\mu$m)/$W_g$(0.15 $\mu$m) at the two wavelengths. A bi-level taper with rib widths/slab widths increased from $W_0$(0.45 $\mu$m)/$W_g$(0.5 $\mu$m) to $W_1$(0.55 $\mu$m)/$W_g$(0.5 $\mu$m) is designed. $W_1$(0.55 $\mu$m)/$W_g$(0.5 $\mu$m) are selected to avoid the back conversion from the TE$_1$ mode to the TM$_0$ mode. The taper length $L_{tp1}$ is also a factor determining $W_1$ and $W_g$. Figure 2(b) shows the electric field profiles of the first two modes in the cross section along this taper at the wavelength of 1310 nm. The first mode, which is identified as a TE$_0$ mode, directly passes the bi-level taper. The second mode is a TM$_0$ mode at the beginning of the taper and converted into a TE$_1$ mode after passing through the taper, which is also shown by straight and dashed arrows in Fig. 2(a). In the mode hybridization region, the minor component ($E_x$ or $E_y$) is comparable to the corresponding major component ($E_y$ or $E_x$), which leads to the mode conversion between the TM$_0$ and TE$_1$ modes\cite{14}, as shown in Fig. 2(b).

To obtain an efficient mode conversion, the taper lengths $L_{tp1}$ and $L_{tp2}$ need careful optimizations. The second taper with a length of $L_{tp2}$ is designed after the conversion section to transform the rib waveguide to a channel one; this is shown in Fig. 1. The $W_2$ of 0.75 $\mu$m is selected such that the effective mode indices of the TE$_1$ and TM$_0$ modes are separated wide enough so that the TE$_1$ mode will not convert back to the TM$_0$ mode.
Fig. 3. (a) The mode conversion efficiency from the TM₀ mode to TE₁ mode in the bi-level taper as the L_{tp1} varies with the second taper length L_{tp2} of 15, 20, and 25 μm at the wavelength of 1310 nm (dashed) and 1550 nm (straight). (b) Wavelength dependence of the mode conversion efficiency when L_{tp1} = 28.5 μm and L_{tp2} = 25 μm. Inset: simulated electric field intensity distributions in the bi-level taper as the TM₀ mode launched at 1310 and 1550 nm wavelengths.

Meanwhile, a larger W₂ requires a longer taper to reduce the transition loss. The three-dimensional simulation software FIMMPROP based on the eigen-mode expansion (EME) method is used to find L_{tp1} and L_{tp2}. Figure 3(a) shows the simulated conversion efficiencies as a function of L_{tp1} with L_{tp2} of 15, 20, and 25 μm at both 1310 and 1550 nm wavelengths. The conversion efficiencies increase with increasing L_{tp1} for all three L_{tp2} and reach nearly 100% when L_{tp1} is large enough. One can also note that there are some notable ripples with a shorter L_{tp1} (<25 μm), which are likely caused by undesired modes interferences or reflections in the taper and could be eliminated with the increase of L_{tp1} and L_{tp2}. An L_{tp1} of 28.5 μm and an L_{tp2} of 25 μm are selected to achieve high efficiency mode conversions for the two wavelengths of 1310 and 1550 nm. The relation between conversion efficiency and wavelength is finally simulated with FIMMPROP and shown in Fig. 3(b). A conversion efficiency larger than 99% is obtained from the wavelength of 1.27 to 1.59 μm, which verified our design method using two wavelengths of 1310 and 1550 nm. The inset of Fig. 3(b) clearly shows the simulated electric field intensity distributions in this bi-level taper with the TM₀ mode launched at 1310 and 1550 nm wavelengths.

A counter-tapered coupler that has two waveguides with the cores counter tapered is designed after the bi-level taper to couple the obtained TE₁ mode in the bus waveguide to the TE₀ mode in the cross port. An adiabatic taper with a length of L_{tp1} is designed to connect the bi-level taper and counter-tapered coupler. The operation principle is based on mode evolution. Unlike the directional coupler based on interference theory, the counter-tapered couplers are approximate adiabatic devices and do not rely on precise phase conditions to be satisfied over an extended length, which permits ultra-wideband mode division operations. A more detailed discussion of the counter-tapered coupler can be found in Refs. [15, 16]. An S-type bend with a radius of R is utilized to alleviate the coupling between the through and cross waveguides.

FIMMWAVE is used to calculate the effective indices of the TE₀ mode and TE₁ mode in the through waveguide and the TE₀ mode in the cross waveguide at the two wavelengths of 1310 and 1550 nm, as shown in Fig. 4(a). The width of the through waveguide decreases from 0.72 μm (W₃) to 0.5 μm (W₄), whereas the width of the cross waveguide increases from 0.18 μm (W₅) to 0.4 μm (W₆). Effective index cross points or phase-matching points between the TE₁ mode in the through waveguide and the TE₀ mode in the cross one can be found in Fig. 4(a) for both wavelengths of 1310 and 1550 nm; these are circled by brown dashed lines. This indicates the TE₁ mode in the through waveguide would convert to the TE₀ mode in the cross one with a properly designed coupler length L_{tp3}. The end widths of the two tapers are carefully selected to ensure not only the existence of index cross points, but also that no converted modes couple back. Unexpected coupling between the two TE₀ modes in through and cross WGs is eliminated with a larger through WG width W₄.

The taper length is also an important factor in selecting the taper end width. Figure 4(b) shows the simulated mode conversion loss as the function of coupler length L_{tp3} at the wavelengths of 1310 and 1550 nm. The mode conversion loss decreases as L_{tp3} increases, and a very low loss of less than 0.1 dB can be achieved when L_{tp3} > 190 μm at both wavelengths of 1310 and 1550 nm. An L_{tp3} of 200 μm is selected considering the device loss and footprint. Conversion losses are finally simulated with FIMMPROP and shown in the inset of Fig. 4(b). Losses less than 0.2 dB can be obtained in the wavelength range from 1.29 to 1.63 μm. A larger coupler length would further reduce the conversion loss of modes with wavelengths.
smaller than 1310 nm. Figures 4(c) and 4(d) show the simulated electric field intensity distribution in this counter-tapered coupler with the TE1 mode launched at wavelengths 1310 and 1550 nm, respectively. One can note that the mode conversions from the TE1 mode to TE0 mode in this coupler are achieved as expected. For TE0 mode input, it will pass through the coupler directly, as no index cross points and mode coupling occur between the two waveguides.

FIMMPROP is used to verify the performance of the complete device. The PRS device performances are usually characterized by IL and CT for each input polarization. Figure 5(a) shows the wavelength dependence of the IL and CT for the TE0 mode and TM0 mode. CT and IL of less than $-15$ and $-0.2$ dB are obtained from the wavelength of 1290 to 1610 nm for both input modes, respectively. With such a broad operating bandwidth, this device offers great potential in silicon photonic systems, especially in applications requiring a large operation waveband, such as WDM PONs for FTTH. Figures 5(b)–5(g) show the simulated electric field intensity distribution in the designed PRS at the wavelengths of 1310, 1490, and 1550 nm. For all three wavelengths, the launched TM0 modes output from the cross port of the PRS after conversion to the TE0 modes. Meanwhile, the input TE0 modes output from the through port directly, which confirms our previous design.

The IL and CT gradually degrade for the TM0 mode input when the wavelength falls short of 1310 nm, as shown in Fig. 5(a), but this can be improved by increasing the coupler length $L_{tp3}$ of the counter-tapered coupler. Meanwhile, the CT of the TM0 mode has some ripples that can be improved by increasing the lengths $L_{tp1}$ and $L_{tp2}$ of the bi-level taper. The CT gradually increases with the increasing wavelength for both two modes, which is caused by the coupling between the S-type output waveguide and straight output that can be further improved by design optimization.

The fabrication tolerance is investigated for the proposed PRS. Performance degradations for the TM0 and TE0 mode inputs are simulated. Figures 6(a)–6(c) show the wavelength dependence of the IL and CT with a top silicon thickness variation of $\Delta H$, a slab height variation of $\Delta h$, and a waveguide width variation of $\Delta W$, which includes the bi-level taper and counter-tapered coupler as the TM0 mode input. The performance metrics remain stable with a width variation of $\pm 40$ nm and top silicon thickness or slab height variation of $\pm 10$ nm in the whole operation waveband. As no mode conversion and coupling occur in the PRS for the TE0 mode input, the performance metrics remain stable with the above variation for the TE0 mode input through our simulation. Manufacturing deviations with a top silicon thickness variation of $\pm 5$ nm and linewidth variations $<1\%$ are demonstrated in silicon photonic platforms[11,12], which are smaller than the fabrication tolerances of the design. Due to the adiabatic conversion and coupling of modes in the bi-level taper and counter-tapered coupler, the width, thickness, or wavelength variation only lead to the position shift of the mode

Fig. 5. (a) Wavelength dependence of the PRS performance in terms of the IL and CT for different launched modes. (b)–(g) Simulated electric field intensity distributions in our proposed PRS as the TE0 mode and TM0 mode launched at the wavelengths of 1310, 1490, and 1550 nm.

Fig. 6. Fabrication tolerance analysis for the wavelength dependence of IL and CT with (a) the top silicon thickness variation $\Delta H$, (b) the slab height variation $\Delta h$, and (c) the waveguide width variation $\Delta W$ of the whole device as the TM0 mode launched.
hybridizations and phase-matching points and will not affect the PRS performance seriously. Compared to the previously reported PSGC\cite{17} and PRS\cite{8}, this device has an ultra-broad operating bandwidth and large fabrication tolerance, which offers potentials in applications requiring a large operation bandwidth such as WDM PONs for FTTH.

In addition, only the mode conversion loss is considered in this work. The scattering loss due to the side-wall roughness of the waveguide is extremely detrimental to the total loss of this PRS in practice. This kind of loss could be significantly reduced by optimizing the fabrication process, such as photolithography and etching processes\cite{18}. To further reduce the size, a narrower gap of $W_g$ could be selected to enhance the coupling strength, and thus, a smaller coupler length $L_{tp3}$ can be obtained. On the other hand, the bi-level tapers could be optimized by adopting some other shapes (e.g., parabolic or sinusoidal) with multi-variable optimization\cite{19} to reduce the device length.

In conclusion, an ultra-broadband and fabrication-tolerant silicon PRS based on a cascaded adiabatic taper and mode-evolution counter-tapered coupler is proposed in this Letter. IL and CT of less than 0.2 and $-15$ dB are obtained, respectively, with a bandwidth as large as 320 nm. Due to the asymmetric cross section of the rib waveguide, a standard SiO$_2$ top cladding is used, eliminating the need for silicon nitride or air cladding. The performance degradation due to fabrication errors is also analyzed, showing that the device is quite robust, with tolerances greater than the manufacturing deviations of mature silicon photonic platforms. With such a broad operating bandwidth and robust performance, this device offers great potential in silicon photonic systems, especially in applications requiring large bandwidths such as WDM PONs for FTTH.

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References