On-chip polarization handling for silicon photonics

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Novel silicon-based, ultra-small devices can split and rotate transverse-electric and transverse-magnetic components.

Many communications technologies, such as optical interconnects, require ultra-high data-transmission capacity. Silicon photonics has become very popular for these applications because of the potential to combine high performance with low-cost fabrication.1–5 Besides silicon photonics, polarization-multiplexing is another attractive, low-cost, and simple way to increase transmission capacity that can be applied to many technologies. For example, on-chip polarization handling plays a key role in coherent optical communication. Furthermore, polarization-diversity technology can enable nanosized polarization-transparent silicon photonic integrated circuits (PICs),6,7 and is essential for realizing integrated photonic quantum circuits.8

In order to satisfy increasing demand for high data transmission capacity, we have been working to develop ultrasmall silicon components with polarization diversity by utilizing the large birefringence (∼10⁻¹¹) of silicon-on-insulator (SOI) nanowires. The design of these components is simple and a wide array of devices can be fabricated easily, including a polarization beam splitter (PBS), polarization rotator (PR) and polarization splitter-rotator.

Our PBSs are based on an asymmetrical coupling system that consists of an SOI-nanowire and a nanoslot waveguide: see Figure 1(a) and (b). The S-bend section for the waveguide also acts as a mode converter between the input/output SOI-nanowire and the waveguide, keeping the PBS compact. In the coupling region, these two waveguides are designed to satisfy the phase-matching condition for transverse-magnetic (TM) polarized light so that it is completely coupled to the cross port when an appropriate length is chosen for the coupling. The phase matching condition is not satisfied for transverse-electric (TE) polarized light and consequently it goes through the SOI-nanowire with little coupling: see Figure 1(c) and (d).

Another type of ultra-short PBS9 that we have designed is based on an asymmetrical coupling system with a bent coupler: see Figure 2(a) and (b). The S-bend section not only decouples the two bent waveguides, but also functions as a TE-passed polarization filter when the bending radius is small. A cascaded compact polarizer like this enables a high extinction ratio in a broad wavelength range and also results in large fabrication tolerances. The bent coupling section is designed to satisfy the phase-matching condition for TM polarization to allow complete cross-coupling: see Figure 2(c). For TE polarization there is almost no coupling because of the phase mismatch: see Figure 2(d).

In comparison with polarization beam splitters, it is even more difficult to realize on-chip polarization rotation because a planar

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waveguide usually maintains polarization. We designed a novel polarization rotator by using an SOI nanowire with a cut corner, whose two lowest-order modes are almost fully hybridized: see Figure 3(a) and (b). When light enters the PR, these two hybridized modes are both excited and two-mode interference takes place: see Figure 3(c) and (d). To the best of our knowledge, our polarization rotator is the shortest in existence, with a length of \( \approx 7\mu m \). A modified polarization rotator configuration has also been demonstrated experimentally.\(^{11}\)

We have also designed a component that achieves polarization splitting and rotation simultaneously. This part, which can be easily fabricated in a one-step etching process, consists of an adiabatic taper and an asymmetrical directional coupler: see Figure 4(a) and (b).\(^{13}\) With the adiabatic taper, the input TM fundamental mode (TM\(_0\)) is converted to the first high-order TE mode (TE\(_1\)) by utilizing mode hybridization in the SOI nanowires with air or silicon nitride as the upper cladding. We have observed such a mode conversion in submicron SOI waveguide tapers both theoretically and experimentally.\(^{14}\) We use a cascaded asymmetrical directional coupler to couple the generated TE\(_1\) mode to the TE fundamental mode (TE\(_0\)) of the adjacent narrow waveguide: see Figure 4(c). On the other hand, no mode conversion or coupling occurs for the launched TE\(_0\) mode: see Figure 4(d). In this way, polarization splitting and rotation are realized simultaneously.

![Figure 2](image1.png)

**Figure 2.** (a) SEM image of the ultra-short PBS based on a bent coupler. (b) Schematic configuration. Device dimensions are: bending angle of the coupler, \( \theta = 13^\circ \); radii of curvature, \( R_1 = 19.3\mu m, R_2 = 20.0\mu m \), and widths \( w_1 = 0.534\mu m, w_2 = 0.46\mu m \), and \( w_3 = 203nm \). (c) TM mode and (d) TE mode propagation of light. \( L_{TX} \) and \( L_{LY} \): Lateral and longitudinal offsets of the S-bend connecting to the coupling region, respectively. \( R_0 \): Bending radius.

![Figure 3](image2.png)

**Figure 3.** (a) The configuration of our polarization rotator. (b) The cross section for the polarization rotation section, where the dimensions of the cut corner are width \( W_e = 240nm \), and height \( H_e = 240nm \). (c) and (d) The electrical fields in the x-direction (E\(_x\)) and y-direction (E\(_y\)) in the polarization rotation section, respectively.\(^{11}\)

![Figure 4](image3.png)

**Figure 4.** (a) 3D view and (b) top view of the structure of the polarization splitter-rotator, consisting of a taper and an asymmetrical directional coupler.\(^{13}\) The relevant dimensions of the component are: device lengths \( L_{tp1} = 4\mu m, L_{tp2} = 44\mu m, L_{tp3} = L_{tp1}(w_3 - w_2)/(w_1 - w_0), L_{dc} = 7.0\mu m \) and device widths \( w_0 = 0.54\mu m, w_1 = 0.69\mu m, w_2 = 0.83\mu m, w_3 = 0.9\mu m, w_4 = 0.15\mu m \). (c) TM-polarized and (d) TE-polarized light propagation. \( L_{tpout} \): Length of the taper section connected with the coupling region. \( w_{out} \): Width of the output section. \( w_4 \): Width of the narrow waveguide in the coupling region.

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Polarization diversity technology is a general solution for making polarization-transparent photonic integrated circuits based on SOI-nanowires.\textsuperscript{6,7} We have developed a novel approach for a polarization-insensitive arrayed waveguide grating (AWG) (de)multiplexer by using a grating-based in-line PBS in each arrayed waveguide: see Figure 5.\textsuperscript{15} With the in-line PBS and photonic crystal reflectors, the two polarizations (TE and TM) pass through different light-paths. The polarization dependence of both the central channel wavelength and the channel spacing can be modified by adjusting the light-paths, i.e., by optimizing the core width, \(w_{co2}\), and length, \(L_{2j} (= L_{20} + j\Delta L_2)\), of the second section. The reflective-type structure in this design also keeps the AWG (de)multiplexer compact.

In summary, we have developed ultra-compact devices for polarization diversity using simple design and fabrication processes. Such designs make on-chip polarization handling available for integrated photonic quantum circuits, coherent optical communications, polarization multiplexing systems, and polarization-transparent silicon PICs. By utilizing these polarization diversity components with phase-shifters and amplitude controllers, it is even possible to realize low-cost and compact polarization-management systems on a chip. Future work will integrate these polarization diversity components with active devices.

This research is partially supported by an 863 project (Ministry of Science and Technology of China, 2011AA010301), the Nature Science Foundation of China (NSFC, 61077040), Zhejiang provincial grant (Z201121938) of China, and Defense Advanced Research Projects Agency Microsystems Technology Office (DARPA MTO) under contract HR0011-10-1-0079. The authors thank Yaocheng Shi, Sailing He, and Yongbo Tang for their useful discussions and contributions.

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References