Ultra-compact and Highly Efficient Polarization Splitter and Rotator Based on a Silicon Bent Directional Coupler

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Abstract: *An ultra-compact (coupling length ~ 8.77 μm) silicon polarization splitter and rotator is demonstrated based on a bent directional coupler. The peak TM-TE coupling efficiency reaches 96.6%. The crosstalk values are < -10 dB over a wavelength range of 40 nm.*

Introduction

Silicon photonic integrated devices based on nano-waveguides suffer severe polarization-sensitivity issues due to the large structural birefringence. Polarization diversity scheme is a general solution to eliminate the polarization sensitivities. Polarization splitting and rotating devices are key components in the scheme[1]. Many mechanisms can be applied to realize polarization splitter and rotator (PSR) devices, including mode coupling[2-4], mode evolution[5], and mode hybridization[6]. If two orthogonal modes have equal effective refractive indices, cross-polarization coupling occurs between the waveguides, and one mode can be effectively converted to the other one. An efficient PSR based on an asymmetrical directional coupler with a coupling length of 36.8 μm was demonstrated[7], a total insertion loss of 0.6 dB and an extinction ratio of 12 dB were obtained. A PSR based on a tapered directional coupler was demonstrated to improve fabrication-tolerance[8], similar high conversion efficiencies were achieved, and the coupling length was 140 μm. These schemes based on cross-polarization coupling only need a single step of exposure and etching, thus significantly simplify the fabrication process.

In this paper, we propose and experimentally demonstrate an ultra-compact highly efficient PSR based on a silicon bent directional coupler structure. TM-TE cross-polarization coupling occurs between the two parallel bent waveguides. The coupling length is 8.77 μm. To the best of our knowledge, our device achieves the shortest coupling length. The device is fabricated by a single step of exposure and etching. Efficient polarization splitting and rotating are simultaneously achieved in the device. The peak TM-TE polarization conversion efficiency (PCE) reaches 96.6%, and the PCEs remain higher than 89.1% in the wavelength range of 1560 nm ~ 1600 nm. The crosstalk values at the Cross and Bar ports are lower than -14 and -10 dB over a wavelength range of 40 nm, respectively.

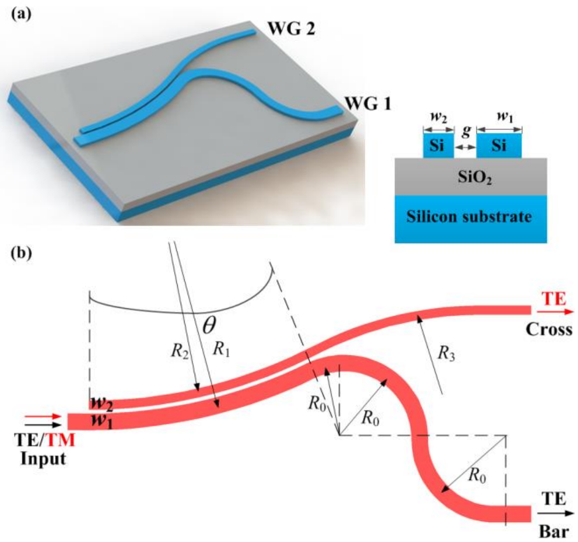

Fig. 1: Schematic configuration of the proposed silicon PSR.

Device structure and operation principle

The 3D and top views of the structure of the proposed PSR device are sketched in Fig. 1(a) and (b), respectively. It consists of two parallel silicon bent waveguides (WG 1 and WG 2) coupled to each other. To achieve an efficient TM-TE cross-polarization conversion, a material which is different from the bottom silicon oxide layer should be applied as the top cladding layer. Air is adopted as the top cladding in our design. The widths of the two bent waveguides are optimized so that the fundamental TM mode in WG 1 and the fundamental TE mode in WG 2 have equal optical path lengths, i.e., the phase matching condition is satisfied. In this case, an efficient TM-TE cross-polarization coupling between the two bent waveguides is obtained.

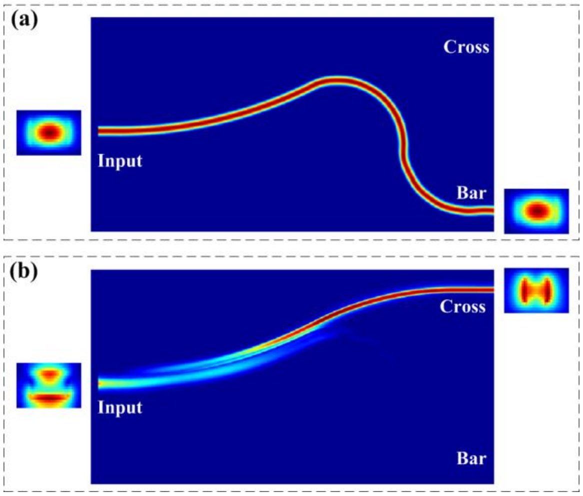

Fig. 2: (a)-(b) Simulated power distributions in the PSR for the TE- and TM-polarized inputs, respectively.

The TM-polarized light is coupled to WG 2 and simultaneously converted to the TE-polarized light. High efficiency TE-polarized light is obtained at the Cross port. On the other hand, due to the birefringence of the silicon nanowire waveguides, the phase matching conditions between the TE mode in WG 1 and any guided mode in WG 2 cannot be satisfied. Thus, the TE-polaried light passes through the WG 1 without coupling and outputs at the Bar port.

The thickness of the top silicon layer of the silicon-on-insulator (SOI) wafer is 220 nm. The effective indices of the two bent waveguides are calculated by the finite-difference time-domain (FDTD) method. The widths of the two bent waveguides, WG 1 and WG 2, are chosen to be w_1 = 620 and w_2 = 325 nm, respectively. In this case, the cross-polarization coupling between the two bent waveguides are achieved. Adiabatic tapers are used for coupling to a normal single-mode silicon waveguide at the input and output ports. The bending radius of WG 1 is R_1 = 20 μm. The gap between the two bent waveguides is g = 145 nm, which is large enough to simplify the fabrication process. The bending radius of WG 2 is $R_2 = R_1 - (w_1 + w_2) / 2 - g = 19.378$ μm. The angle θ of the coupling region is optimized to be 26°, and the corresponding coupling length is $L_c = R_1 \sin(\theta) = 8.77$ μm. The bends with bending radius R_0 = 3 μm at the Bar port are designed to filter the undesired TM-polarized light and separate the two output waveuides. The bend at the Cross port has a radius of R_3 = 14 μm.

The propagation of the optical field in the proposed PSR device is investigated by three-dimensional FDTD method, as depicted in Fig. 2. The insets show the mode distributions of input and output ports. Note that the simulated mode distribution of the Cross port for the TM-polarized input shows that the output is the fundamental TE mode supported by a waveguide with the width of 325 nm. The TM-polarized light is coupled and simultaneously converted to the TE-polarized light, then outputs from the Cross port; while the TE-polarized light passes through the waveguide and outputs from the Bar port.

Fig. 3: Scanning electron microscope (SEM) photo of the fabricated PSR based on a bent directional coupler.

Device fabrication and measured results

A number of PSR devices were fabricated on a SOI wafer (220-nm-thick silicon on 3-μm-thick BOX layer) by a single step of E-beam lithography (Vistec EBPG 5200) and inductively coupled plasma (ICP) dry etching. A scanning electron microscope (SEM) photo of a fabricated PSR based on a bent directional coupler is shown in Fig. 3.

To characterize the TM-TE coupling efficiency and crosstalk performance of the PSR, four identical PSRs were fabricated to measure the transmission responses of TE-TE, TE-TM, TM-TE, TM-TM transmissions at the Cross and Bar ports, respectively. Grating couplers were used to couple the TE- and TM- polarized lights into/out of the chip. A tunable continuous wave (CW) laser was used to characterize the fabricated devices. The output spectra were recorded by an optical power meter. The PSR transmission spectra can be obtained by scanning the laser wavelength and recording the output power. Both the TE and TM grating couplers were designed to have high polarization selectivity[9]. The coupling losses of the TE- and TM- polarized grating couplers were 5.6 dB/port and 7.0 dB/port at the central wavelengths of the gratings, respectively.

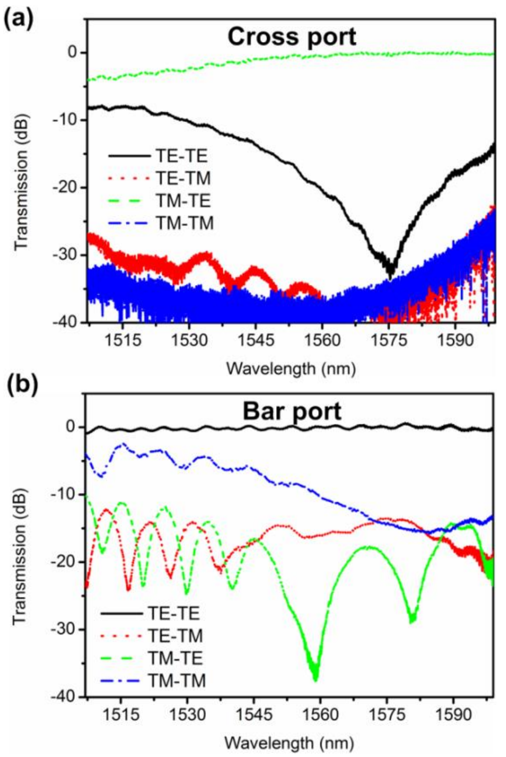

Fig. 4: Measured transmission responses of the fabricated PSRs between different polarized modes from the input port to (a) the Cross port and (b) the Bar port.

Figures 4(a) and (b) show the measured transmission responses of the fabricated PSRs between different polarized modes from the input port to the Cross port and the Bar port, respectively. The responses are normalized to the transmission of a straight waveguide with grating couplers. For the TM-polarized input light, high-efficiency TE-polarized light output is obtained at the Cross port, as shown in the dashed green curve of Fig. 4(a). The TM-TE coupling efficiency is a key parameter of the rotator. The TM-TE PCE is defined as $C_{TM-TE} = T_{TM-TE} / (T_{TM-TE} + T_{TM-TM})$. The PCE reaches its maximum of 96.6% at $\lambda = 1575.39$ nm, which corresponds to an insertion loss of 0.15 dB. In the wavelength range of 1560 nm ~ 1600 nm, the PCEs and the insertion losses remain better than 89.1% and 0.5 dB, respectively. The crosstalk value at the Cross port is lower than -14 dB in the wavelength range of 1560 nm ~ 1600 nm. For the TE-polarized input light, high-efficiency TE-polarized light outputs from the Bar port, as shown in the solid black curve of Fig. 4(b). The insertion loss is lower than 0.3 dB in the wavelength range of 1507 nm ~ 1600 nm. The crosstalk value at the Bar port is lower than -10 dB in the wavelength range of 1560 nm ~ 1600 nm.

Conclusion

We have proposed and experimentally demonstrated an ultra-compact silicon PSR based on a bent directional coupler. The PSR is based on the cross-polarization coupling effect between the two parallel bent waveguides with air top-cladding, which is realized by a single etch process. The coupling length is as short as 8.77 μm. The measurement results show that, the device can work as an efficient polarization splitter and rotator simultaneously. The peak TM-TE PCE reaches 96.6%, and the PCEs keep higher than 89.1% in the wavelength range of 1560 nm ~ 1600 nm. The crosstalk values at the Cross and Bar ports are lower than -14 and -10 dB over the wavelength range of 40 nm, respectively.

Acknowledgements

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References

[1] D. Dai *et al.*, "Polarization management for silicon photonic integrated circuits," *Laser Photonics Rev.,* Vol. **7**, no. 3, p. 303 (2013).

[2] D. Dai *et al.*, "Novel ultra-short and ultra-broadband polarization beam splitter based on a bent directional coupler," *Opt. Express,* Vol. **19**, no. 19, p. 18614 (2011).

[3] J. Wang *et al.*, "Design of a SiO2 top-cladding and compact polarization splitter-rotator based on a rib directional coupler," *Opt. Express,* Vol. **22**, no. 4, p. 4137 (2014).

[4] Y. Ding *et al.*, "Wideband polarization splitter and rotator with large fabrication tolerance and simple fabrication process," *Opt. Lett.,* Vol. **38**, no. 8, p. 1227 (2013).

[5] J. Zhang *et al.*, "Silicon waveguide-based mode-evolution polarization rotator," in *SPIE Photonics Europe*, p. 77190C-8 (2010).

[6] A. Xie *et al.*, "Efficient silicon polarization rotator based on mode-hybridization in a double-stair waveguide," *Opt. Express,* Vol. **23**, no. 4, p. 3960 (2015).

[7] L. Liu *et al.*, "Silicon-on-insulator polarization splitting and rotating device for polarization diversity circuits," *Opt. Express,* Vol. **19**, no. 13, p. 12646 (2011).

[8] Y. Ding *et al.*, "Fabrication tolerant polarization splitter and rotator based on a tapered directional coupler," *Opt. Express,* Vol. **20**, no. 18, p. 20021 (2012).

[9] D. Taillaert *et al.*, "Compact efficient broadband grating coupler for silicon-on-insulator waveguides," *Opt. Lett.,* vol. **29**, no. 23, p. 2749 (2004).