Silicon Polarization Splitter and Rotator using a Subwavelength Grating based Directional Coupler

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Abstract: A compact polarization splitter-rotator is experimentally demonstrated by using a subwavelength grating waveguide based directional coupler. Over 13 dB extinction ratios for both polarizations are achieved. Large tolerance (50 nm) to waveguide-width variation is also verified.
OCIS codes: (130.3120) Integrated optics devices; (130.5440) Polarization-selective devices

1. Introduction

Photonic integrated devices on the silicon-on-insulator (SOI) platform are attractive due to the complementary-metal-oxide-semiconductor (CMOS)-compatible fabrication process. The high refractive index contrast between the silicon core and the cladding enables compact photonic devices with small footprints. However, it also results in large polarization-dependent dispersions or losses [1]. Polarization splitter-rotators (PSRs) for splitting two orthogonal polarization modes and rotating one of them by 90° are key components in polarization-diversity schemes to eliminate the polarization sensitivities [2]. Various types of the PSRs were reported based on asymmetric directional coupler [3], Y-branch splitter [4], multi-mode interferometer [5], etc. However, these PSRs show limited polarization extinction ratios (PERs < 20 dB) and are sensitive to fabrication errors. Fabrication-tolerant PSRs based on tapered directional couplers and taper-etched waveguides were proposed, at the cost of large footprints and complex fabrication process [6-8]. Recently, a compact PSR based on an asymmetrical directional coupler with a subwavelength grating (SWG) was numerically proposed [9]. By using the SWG structure, fabrication tolerances of the PSR were substantially enhanced. However, no experimental demonstration of such a SWG-based PSR was reported.

In this paper, to the best of our knowledge, we experimentally demonstrate the first silicon PSR using a SWG-based directional coupler. It consists of a silicon nanowire waveguide coupled to a SWG waveguide. Compared with the simulations in Ref. [9], the gap between the two waveguides is increased to 180 nm to relax the resolution requirement in CMOS fabrication process, and the coupling length is optimized by using 3D-FDTD method to achieve higher extinction ratios. The device is fabricated on an SOI wafer and has a total length of < 45 μm. Air is employed as the upper cladding to break the vertical symmetry and realize effective cross-polarization coupling. In most cases, waveguide width variations resulting from fabrication errors are critical constraints in the design and fabrication of the PSRs [3-5]. The SWG is a structure with a pitch smaller than the wavelength of the light propagating through the waveguide, functioning as a homogenous medium [10]. By properly designing the pitch and duty cycle of the SWG, the mode effective indices of both waveguides can vary equally if the waveguide widths fluctuate, therefore maintaining the phase-matching condition, and resulting in high tolerance to waveguide width variations. The PERs of the fabricated PSR are higher than ~13 dB and ~19 dB, and the insertion losses are lower than 1.0 dB and 1.5 dB for the TE- and TM- polarized light inputs, respectively, in the wavelength range of 1540 nm ~ 1580 nm. If the waveguide widths vary +50 nm and -50 nm, the PERs remain higher than 13 dB and 14 dB, and the insertion losses are lower than 1.0 dB and 3.3 dB for TE- and TM- polarized lights, respectively. Thus, the PSR is tolerant to large variations in waveguide width, and the waveguide depth is fixed by the single-etch process.

2. Device design and fabrication

The proposed PSR is schematically illustrated in Figs. 1(a) and (b). The device consists of a silicon nanowire waveguide (WG1) and a SWG waveguide (WG2). The equivalent material refractive index of the SWG structure can be calculated by a simplified model [11],

$$\Delta \mathrm{n}_{eq} = \delta \cdot \Delta n \tag{1}$$

where Δn_{eq} represents the refractive index difference between the equivalent material and air cladding, δ is the duty cycle, and Δn is the refractive index difference between the silicon core and air cladding. Here $\delta = 0.5$, and the SWG structure can be considered as a homogenous medium with an equivalent material refractive index of 2.235.

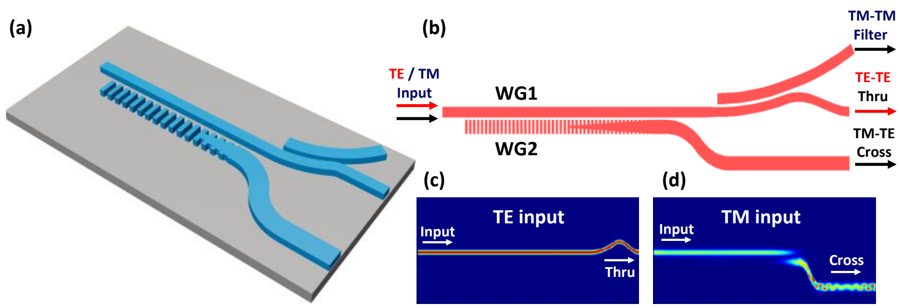

Fig. 1 Schematic structure of the SWG-PSR. (a) 3D view, (b) top view; Simulated power distributions of the SWG-PSR for (c) TE-, (d) TM-polarized light input, respectively.

The widths of both waveguides are carefully designed and optimized to satisfy the phase-matching condition for cross-polarization coupling. Therefore, the TM-polarized light is evanescently coupled from WG1 to WG2 and rotated to TE-polarized light simultaneously, therefore high efficiency TE-polarized light is obtained in the Cross port. The TE-polarized light goes through WG1 without coupling and outputs in the Thru port. Thus, the TE- and TM- polarized lights are separated and rotated by the SWG-based directional coupler. A bent directional coupler that serves as a polarization beam splitter (PBS) is cascaded to couple the residual TM-polarized light to the Filter port and ensure a high extinction ratio at the TE-thru port for the TM-polarized light input.

In the PSR structure, the thickness of the silicon waveguides is 220 nm. The widths of the waveguides are w_{g1} = 450 nm and w_{g2} = 645 nm, respectively. The period and the duty cycle of the SWG are Λ = 300 nm and 50%, respectively. The gap between the waveguides is 180 nm. The coupling length is designed to be 30 μm so that the directional coupler with the SWG operates in the telecom C band as simulated by the 3D-FDTD method. The simulated power distributions for the TE- and TM- polarized light inputs are shown in Figs. 1(c) and (d), respectively. If the TM-polarized light is injected into the Input port, the light is evanescently coupled and rotated in the cross waveguide and outputs from the Cross port. While for the TE-polarized input, the light goes through the WG1 and outputs from the Thru port.

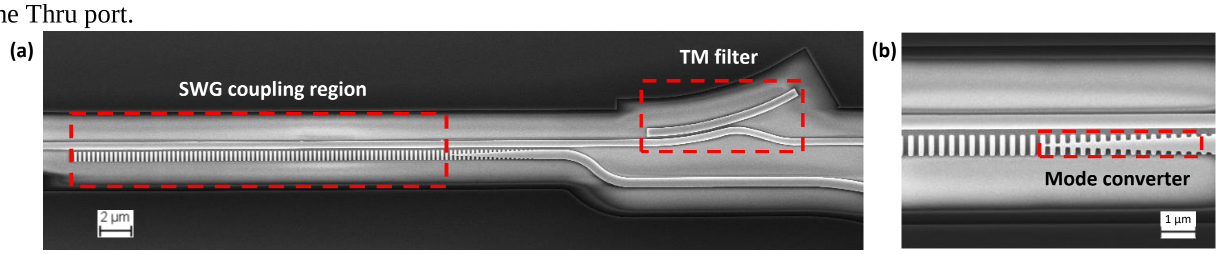

Fig. 2 (a) SEM image of the fabricated SWG-PSR, (b) zoom-in image of the SWG mode converter region.

A number of SWG-based PSRs were fabricated on a SOI wafer (220-nm-thick silicon on 3000-nm silica) with a single full-etch process. E-beam lithography (Vistec EBPG 5200) was used to define the structures on the ZEP520A resist. Then the patterns were transferred to the top silicon layer by inductively coupled plasma (ICP) dry etching using SF_6 and C_4F_8 gases. Scanning electron microscope (SEM) images of the fabricated PSR are depicted in Fig. 2.

3. Experimental results

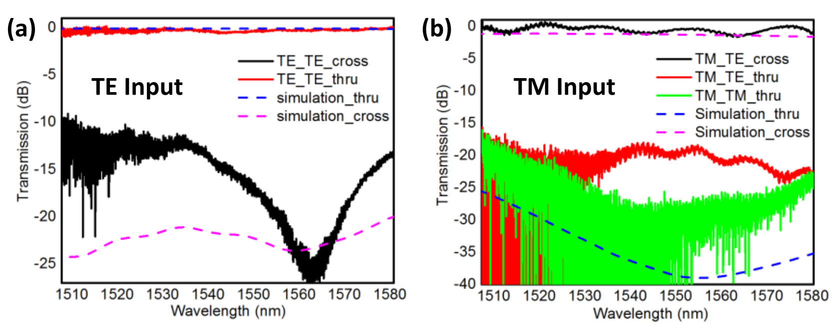

Fig. 3 Measured and simulated transmission responses at the Cross and Thru ports for the (a) TE-polarized and (b) TM-polarized light inputs, respectively.

In the experiment, three identical devices with different grating couplers were fabricated to measure the transmission responses. The TE- and TM- polarized lights from a tunable laser are coupled into/out of the silicon chip by the grating couplers, respectively. The grating couplers have >20 dB polarization selectivity. Figs. 3(a) and (b) show the measured and simulated transmission responses at the Cross and Thru ports of the fabricated PSR when the TE- and TM-polarized lights are injected, respectively. The responses are normalized by the transmission of a straight waveguide with the corresponding grating couplers. For the TE-polarized input light outputting at the Thru port, the PER is higher than ~13 dB in the wavelength range of 1540 nm ~ 1580 nm, and the insertion loss is < 1.0 dB. For the TM-polarized light, high-efficiency converted TE-polarized light outputs from the Cross port, the PER is higher than ~19 dB in the wavelength range of 1507 nm ~ 1580 nm, and the insertion loss is < 1.5 dB. Some noise observed in Fig. 3 is attributed to the received power being beyond the detection limit of the optical power meter when the signal is at the passband edge of the grating couplers. Fine tuning of the fabrication parameters is needed to further reduce the differences between the measured and simulated results.

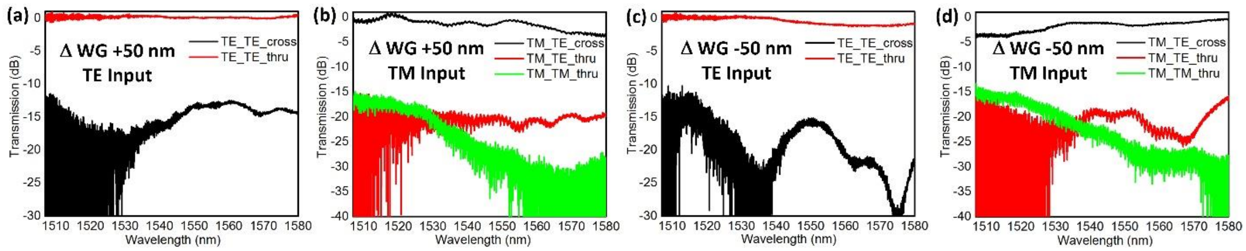

Fig. 4 Measured transmission responses of the PSRs with waveguide widths variations (a-b) +50 nm, (c-d) -50 nm, respectively.

In order to test the tolerance to waveguide width variation (ΔWG), 11 PSRs with waveguide width variations from +50 nm to -50 nm with a step of 10 nm were fabricated on the same wafer. Tab. 1 summaries the measurement results. In the worst case, the measured transmissions of the PSRs with the +50 nm and -50 nm width variations are depicted in Fig. 4. For the TE-polarized light input, the overall PER is higher than ~13 dB in the wavelength range of 1540 nm ~ 1580 nm, and the insertion loss is < 1.0 dB. While for the TM-polarized light input, the PER is higher than ~14 dB in the same wavelength range, and the insertion loss is < 3.3 dB. These results verify the large tolerance to waveguide width variations. In addition, the waveguide depth is fixed by our single full-etch process.

Table 1. Measured PERs and insertion losses of the PSRs with waveguide width variations

ΔWG(nm) /Mode	+40 /TE	+40 /TM	+30 /TE	+30 /TM	+20 /TE	+20 /TM	+10 /TE	+10 /TM	−10 /TE	−10 /TM	−20 /TE	−20 /TM	−30 /TE	−30 /TM	−40 /TE	−40 /TM
PER (dB)	13.1	15	13.5	17.1	13.1	15.8	14.1	19.2	13.2	20.1	13	19.4	13.2	17	13.8	19.2
Insertion loss (dB)	0.88	3.1	0.89	2.1	0.63	2.17	0.57	1.98	0.25	2.17	0.47	1.82	0.97	1.97	0.92	3.22

4. Conclusions

We have experimentally demonstrated a silicon PSR using a SWG based directional coupler. The PERs of the fabricated PSR are > ~13 dB and ~19 dB for the TE- and TM- polarized light inputs, respectively, in the wavelength range of 1540 nm ~ 1580 nm. If the waveguide widths vary +50 nm and -50 nm, the PERs remain higher than ~13 dB and ~14 dB, and the insertion losses are lower than 1.0 dB and 3.3 dB for the two polarizations, respectively.

References

[1] C. Manolatou, and H. A. Haus, "High density integrated optics," in Passive Components for Dense Optical Integration (Springer, 2002), pp. 97-125.

[2] B. Shen, P. Wang, R. Polson, and R. Menon, "An integrated-nanophotonics polarization beamsplitter with 2.4 × 2.4 μm^2 footprint," Nature Photonics **9**, 378-382 (2015).

[3] D. Dai, and H. Wu, "Realization of a compact polarization splitter-rotator on silicon," Optics Letters **41**, 2346-2349 (2016).

[4] W. Yuan, K. Kojima, B.Wang, T. Koike-Akino, K. Parsons, S. Nishikawa, and E. Yagyu, "Mode-evolution based polarization rotator-splitter design via simple fabrication process," Optics Express, **20**, 10163–10169 (2012).

[5] Y. Ding, H. Ou, and C. Peucheret, "Wide-band polarization splitter and rotator with large fabrication tolerance and simple fabrication process," Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference IEEE (Anaheim, 2013).

[6] Y. Ding, L. Liu, C. Peucheret, and H. Ou, "Fabrication tolerant polarization splitter and rotator based on a tapered directional coupler," Optics Express **20**, 20021-20027 (2012).

[7] X. Tu, M. Li, J. Xing, H. Fu, and D. Geng, "Compact PSR Based on an Asymmetric Bi-level Lateral Taper in an Adiabatic Directional Coupler," Journal of Lightwave Technology **34**, 985-991 (2016).

[8] Y. Xiong, D. Xu, J. H. Schmid, P. Cheben, S. Janz, and W. N. Ye, "Fabrication tolerant and broadband polarization splitter and rotator based on a taper-etched directional coupler," Optics Express **22**, 17458-65 (2014).

[9] Y. Xiong, J. G. Wangüemert-Pérez, D. Xu, J. H. Schmid, P. Cheben, and W. N. Ye, "Polarization splitter and rotator with subwavelength grating for enhanced fabrication tolerance," Optics Letters **39**, 6931-4 (2014).

[10] J. H. Schmid, P. Cheben, J. Lapointe, et al. "Silicon photonic integration with subwavelength gratings," International Conference on Transparent Optical Networks (Graz, 2014).

[11] D. Ortega, J. M. Aldariz, and J. M. Arnold, "Analysis of Quasi-Modes in Periodic Segmented Waveguides," Journal of Lightwave Technology **17**, 369-375 (1999).