Ultra-compact Silicon Polarization Beam Splitter with a Short Coupling Length of 0.768 μm

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Abstract: We demonstrate an ultra-compact silicon polarization beam splitter with a coupling length of 0.768 μm. Lower than 2-dB insertion losses and over 10-dB extinction ratios are achieved over a wavelength range of 60 nm.

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1. Introduction

Silicon waveguides have large birefringence values due to the high index-contrast between the silicon core and the silica or air cladding, which results in polarization-sensitivity. Polarization beam splitters (PBSs), as fundamental polarization handling devices, are widely used in photonic integrated circuits (PICs). Many schemes have been reported to realize PBSs, such as the multimode interference (MMI) structure [1], directional coupler [2], out-of-plane grating [3], asymmetrical Mach-Zehnder interferometer (MZI) [4], grating-assisted contra-directional coupler [5], and others [6, 7]. In [6], a PBS based on a bent directional coupler was demonstrated with a coupling length of 4.5 μm and a footprint of 10 × 3 μm^2. Recently, a topology-photonic PBS was reported with a compact footprint of 2.4 × 2.4 μm^2 [7], which required a small feature size in its fabrication.

In this paper, we demonstrate a bent directional coupler PBS with an ultra-small footprint of 1.5 × 1.35 μm^2. Compared with the previously reported bent directional coupler PBS with a footprint of 10 × 3 μm^2 [6], the radius of the bend in our PBS is designed to be 3 μm to achieve the ultra-compact footprint. To further reduce the coupling length and the footprint in our design, the inner bend waveguide of our PBS is set as the bar waveguide which is different from the design in [6]. This enables stronger TM polarization coupling due to the fact that the TM-polarized light leaks more easily into the outer bend waveguide than the TE-polarized light. The TE-polarized light goes through the bar waveguide without any significant coupling due to the large phase mismatch. The sharp bend generally leads to high optical propagation loss, but the loss can be kept below a reasonable level by reducing the bend length and through modern fabrication processes [8]. Based on the design of the ultra-small bend radius of 3 μm and the fact that the inner bend is set as the bar waveguide in our device, a short bend length of 0.768 μm is enough to couple most of the TM-polarized light from the inner bend to the cross waveguide, and the loss of the proposed PBS can be controlled to < 2 dB. Another sharp bend with a radius of 0.75 μm is connected to the bar port to filter out the residual TM polarization and therefore achieve certain polarization extinction ratios (PERs). Silica is used as the upper cladding in the device. The measured insertion losses are < 2 dB in the wavelength range of 1510 nm ~ 1570 nm for both polarizations. The PERs are > 10 dB and ~ 10 dB for the TE and TM polarizations, respectively.

2. Device design and fabrication

Figure 1 shows the schematic structure of the proposed bent directional coupler PBS. Two parallel sharp bent waveguides with bend radii of ~ 3 μm are designed to couple the TM polarization. Different from the design of the bent PBS [6], the inner bend waveguide is set as the bar waveguide to reduce the coupling length due to the fact that the TM-polarized light is easier to couple from the inner bend to the outer bend. The optical path length (OPL) of the TM polarization in the bar waveguide is equal to the OPL in the cross waveguide, i.e., the phase matching condition is satisfied for the TM polarization coupling, while there is a significant mismatch for the OPLs of the TE polarization. When the TM-polarized light is injected into the Input port, strong coupling occurs between the bar waveguide and the cross waveguide under the satisfied phase matching condition, then the TM-polarized light is transferred from the bar waveguide to the cross waveguide and outputs at the cross port, while the residual TM-polarized light is filtered out by the sharp bend in the bar port. For the TE polarization, the light goes straight through and outputs at the bar port. The TE- and TM- polarized lights are then separated by the bent directional coupler structure.

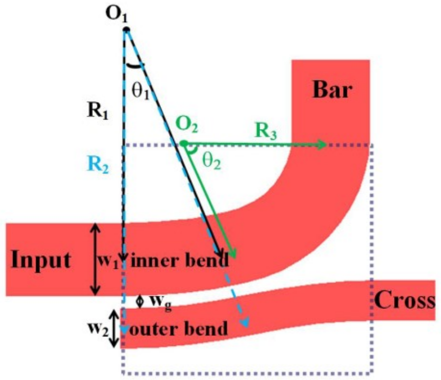

Fig. 1 Schematic structure of the ultra-compact PBS based on a bent directional coupler.

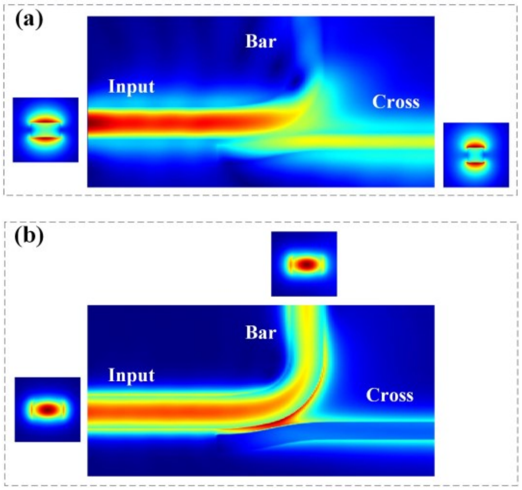

Fig. 2 Simulated electric field distribution in the PBS for the (a) TM light input; (b) TE light input.

The PBS device is designed on a silicon-on-insulator (SOI) wafer (220-nm-thick silicon on 3000-nm-thick silica). The radius of the bar waveguide is R_1 = 3 μm. The width of bar and cross waveguides are w_1 = 432 nm and w_2 = 220 nm, respectively. The gap between the bar and cross waveguide is w_g = 80 nm. The radius of the cross waveguide R_2 is calculated by $R_2 = R_1 + w_1/2 + w_g + w_2/2$. The radius of the bend in the bar port is R_3 = 0.75 μm to filter out the remaining TM-polarized light. The angle of the coupling region is θ_1 = 13 degrees, which is enough to couple most TM-polarized light from the bar waveguide to the cross waveguide. The coupling length L_c is calculated by $L_c = R_2 \sin\theta_1$ = 0.768 μm. The footprint of the PBS is 1.5 × 1.35 μm^2. If a TM-polarized light is injected, the OPLs of two waveguides are matched, i.e., OPL= $n_1 k_0 R_1 \theta_1 = n_2 k_0 R_2 \theta_1$ [6], where n_1 and n_2 are the effective refractive indices of the TM polarization in the inner and outer bends, respectively, k_0 is the wavenumber in vacuum, and R_1 and R_2 are the radii of two bend waveguides. If a TE-polarized light is injected, the OPLs of two waveguides are not matched. The electric field distributions in the xy plane of the proposed PBS are shown in Figs. 2 (a) and (b), which are simulated by three-dimensional finite-difference time-domain (3D-FDTD) methods. The insets represent the electric field distribution in the yz plane at the input and output ports. It can be seen that the TM polarization is coupled to the cross waveguide and outputs from the cross port, while the TE polarization outputs from the bar port. The residual TM light is filtered out by the sharp bend in the bar port as shown in Fig. 2 (a).

In the experiment, electron-beam lithography (Vistec EBPG 5200) was used to define the patterns on the ZEP520 resist. Inductively coupled plasma (ICP) dry etching was used to transfer the patterns to the top silicon layer. Upper silica cladding was deposited by plasma enhanced chemical vapor deposition (PECVD). Figs. 3 (a) and (b) show the scanning electron microscope (SEM) images of a fabricated bent directional coupler PBS before depositing the silica cladding.

3. Experimental results

A tunable laser (Keysight 81960A) and an optical power meter (Keysight 81636B) were used for the characterization of the fabricated PBSs. On-chip polarization dependent grating couplers were used to couple the TE- and TM- polarized lights into/out-of the chip. Two identical PBSs were fabricated on the same chip to characterize the performance for the TM- and TE- polarized light inputs, respectively [9]. Figures 4 (a) and (b) show the measured transmission responses of the fabricated PBS at the cross and bar ports for the TM and TE polarization inputs, respectively. The spectra are normalized by the transmission of a straight waveguide with grating couplers. For the TM polarization, the PER is ~ 10 dB and insertion loss is < 1.5 dB in the wavelength range from 1510 nm to 1570 nm. For the TE polarization, the PER is > 10 dB and insertion loss is < 2 dB in the wavelength range of 1510 nm to ~ 1570 nm.

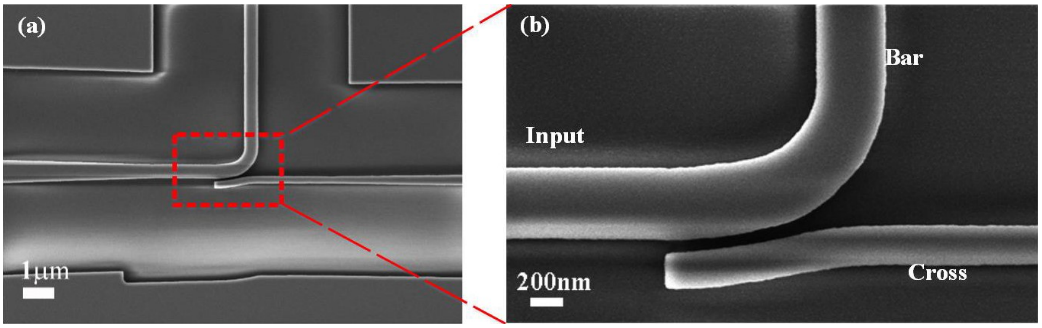

Fig. 3 SEM image of a fabricated PBS.

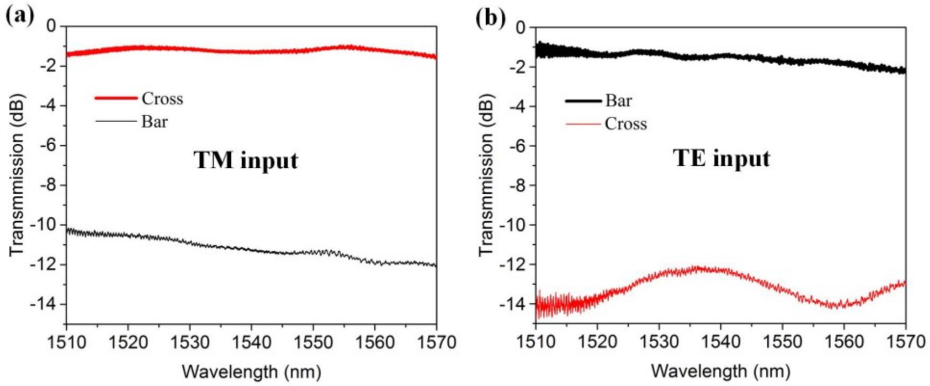

Fig. 4 Measured responses at the cross and bar ports for the (a) TM-polarization; (b) TE-polarization inputs.

4. Conclusions

In summary, we have proposed and experimentally demonstrated an ultra-compact silicon PBS based on a sharp bent directional coupler with a footprint of $1.5 \times 1.35\ \mu m^2$ and a coupling length of 0.768 μm. Our PBS device achieves the smallest footprint, to the best of our knowledge. The experiment results show that the PER is ~ 10 dB and insertion loss is < 1.5 dB for the TM polarization; while the PER is > 10 dB and insertion loss is < 2 dB for the TE polarization in a wavelength range of 60 nm.

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