Ultra-broadband Polarization Beam Splitter Based on a Tapered Bent Directional Coupler

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***Abstract*—We numerically propose an ultra-broadband polarization beam splitter based on a tapered bent directional coupler. Lower than 1-dB insertion losses and over 10-dB extinction ratios of TE_0 mode and TM_0 mode are obtained over a wavelength range of 200 nm.**

Keywords* — *Integrated optics devices, Polarization-selective devices*，*Polarization beam splitter

I. Introduction

Silicon photonics is attractive thanks to its compact footprint and the CMOS compatibility [1]. Due to the high index-contrast between the silicon core and the cladding/buried SiO_2 of silicon-on-insulator (SOI) platform, silicon waveguides have large birefringence values, which result in polarization sensitivity and polarization-related dispersion. This problem can be solved by utilizing various polarization handling devices, such as polarization beam splitters (PBSs) and polarization rotators (PRs). PBSs are widely used and have been implemented on SOI platforms in various schemes, such as directional couplers (DC) [1], slot waveguides [2], multimode interferences (MMI) [3], asymmetrical Mach-Zehnder interferometers (MZI) [4] and grating-assisted contra-directional couplers (GACC) [5].

There are two ways to improve the bandwidth performance of PBS, including bent DC-PBS and tapered DC-PBS [1] [8]. The first scheme utilizes bent waveguide structure, which can reduce the wavelength sensitivity for power and polarization splitter [6]. The PBSs based on traditional bent DC are easy to fabricate, but the bandwidths of those PBSs are limited to C+L band (~100 nm). Two or more DC-based PBSs could be cascaded to improve the performance [7], but the footprints of those structures were not compact enough, leading to high insertion loss (IL). In Ref. [8] [9], another effective scheme was proposed to increase the bandwidth of the coupling devices. The method is to increase the coupling lengths with tapered straight waveguide. It has been used to achieve an ultra-broadband PBS through long straight tapered DC over a wavelength range of 120 nm. It is possible to combine these two methods (tapered DC and bent coupling structure) to realize a more broadband PBS.

In this paper, we numerically propose a PBS based on a tapered bent directional coupler. The PBS comprises two bent waveguides with opposite and slow width variations. We design the proposed long tapered bent DC-PBS such that the TM_0 mode is almost completely coupled to the cross port while most of the TE_0 mode is still in the through port over a broad bandwidth. The simulation results show that the proposed PBS has a broad bandwidth about 200 nm. Compared with the previous work on PBSs, the proposed PBS achieves a higher extinction ratio (ER) and a lower IL in a broad wavelength range. Simulation results show that the ILs of the proposed PBS are < 0.48 dB and < 0.63 dB over 1400 nm - 1600 nm for the TE and TM polarizations, respectively. The ERs in the whole operation bandwidth are higher than 10 dB for the TE and TM polarizations, respectively. Compared with the no-tapered bent DC-PBS, our design shows an improvement of the device bandwidth.

II. Device Design and Principle

The three−dimensional (3D) view and the top view structures of the proposed tapered bent directional coupler PBS are shown in Fig 1. Different from the structure of the traditional bent DC-PBSs, whose widths of the waveguides are constant, the widths of upper and bottom waveguides are both tapered. When the TM-polarized light is injected into the input port, the optical path lengths (OPLs) of two waveguides are matched, strong coupling happens between the upper waveguide and the bottom waveguide under the phase matching condition [1] i.e., OPL= $n_T k_0 R_1 \theta = n_C k_0 R_3 \theta$, where n_T and n_C are the effective refractive indices of the through and cross waveguide, respectively, k_0 is the wavenumber in vacuum, and R_1 and R_2 are the radii of two bent waveguides. Then the TM-polarized light is transferred from the upper waveguide to the bottom waveguide and outputs from the cross port, while the residual TM-polarized light is filtered out by the 3 μm radius bent waveguide in the through port. For the TE-polarized light, the light goes straight and outputs from the through port due to the phase mismatch.

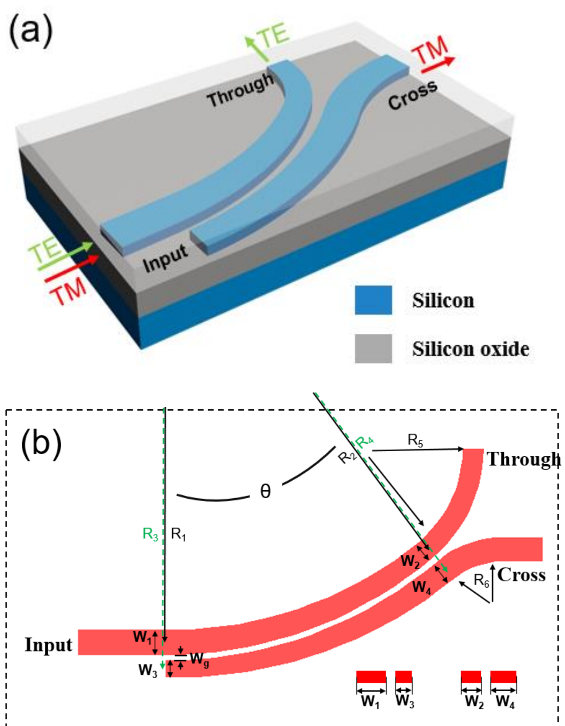


Fig. 1. Schematic structure of the broadband PBS based on a tapered bent directional coupler (a) the 3D view (b) the top view

Our device is based on a SOI platform with 220 nm height covered by a SiO_2 upper-cladding (n_{Si} = 3.47 and n_{SiO2} = 1.44). Two tapered bent waveguides are designed to split the TE_0 mode and TM_0 mode. The radius and the width of the end of through waveguide are R_2 = 20 μm and w_2 = 500 nm. The outer radius of the upper bent waveguide is $R_2 + w_2/2$ = 20.25 μm which is fixed. Also, the gap between the through and cross waveguide is always w_g = 150 nm. Different from the traditional bent DC-PBS [1], whose widths of two waveguides are fixed, in our design, the width of the upper waveguide is tapered from w_1 = 723 nm to w_2 = 500 nm. The width of the bottom waveguide is tapered from w_3 = 400 nm to w_4 = 635 nm. Then we can calculate the initial radius of the through waveguide R_1 and the radius of the cross waveguide R_3 by

$$R_1 = R_2 + w_2/2 - w_1/2.$$

$$R_3 = R_2 + w_2/2 + w_g + w_3/2.$$

$$R_4 = R_3 - w_3/2 + w_4/2. \quad (1)$$

The radius of the cascaded bent waveguide in the through port is R_5 = 3 μm to filter out the undesired TM-polarized light at through port and improve the ER. The angle of the coupling region is θ = 40 degrees. The coupling length is calculated by $R_3 \sin\theta$ = 13.22 μm, which is long enough to couple most TM-polarized light and get broader bandwidth according to Ref. [6]. Although the width is tapered in our design, the OPLs of two waveguides can be equal. When a TE-polarized light is injected, the OPLs of two waveguides are not matched. So the design can split the TE and TM polarized lights.

III. Simulation Results

By simulating the proposed PBS with three-dimensional finite-difference time-domain (3D-FDTD) methods, we can get the electric field distributions in the xy plane, which are shown in Figs. 2 (a) and (b). The insets represent the distribution of electric fields in the yz plane of the input and output ports. It can be seen that the TM-polarized light is coupled to the cross waveguide and outputs from the cross port, while the injected TE-polarized light goes through and outputs from the through port. As shown in the Fig. 2(b), the remaining TM-polarized light is filtered out by the sharp bend in the through port. One can notice that the TE-polarized light has very weak coupling to the cross port.

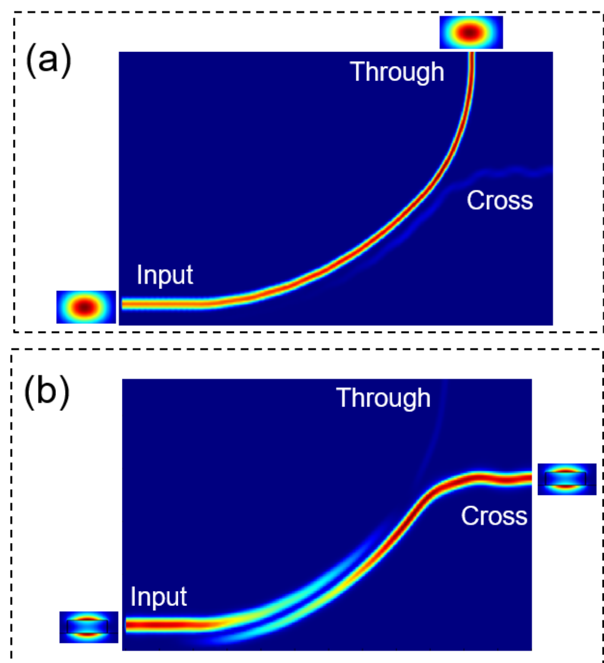
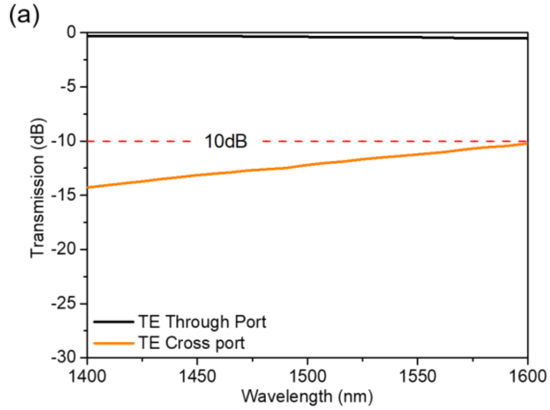


Fig. 2. Simulated electric field distribution in the PBS for the (a) TE light input; (b) TM light input.

Fig 3(a) and (b) show the simulated spectral responses of the proposed tapered bent DC-PBS for the

TE and TM polarization inputs, respectively. It can be seen that, the PBS has a broad bandwidth (1400 nm-1600 nm) with an ER larger than 10 dB and an IL lower than ~0.63 dB for TM polarization. For TE polarization, the ER is also larger than 10 dB and the IL is lower than ~0.48 dB over 1400-1600 nm. Fig 3(b) shows the simulation results of tapered bent DC-PBS and traditional bent DC-PBS for TM-polarized light inputs. Compared with the bent DC−PBS without tapered waveguides, the proposed tapered bent DC-PBS has an obvious performance improvement of IL and ER over 200 nm bandwidth. Furthermore, we can improve the ER by cascading this tapered bent DC-PBS.



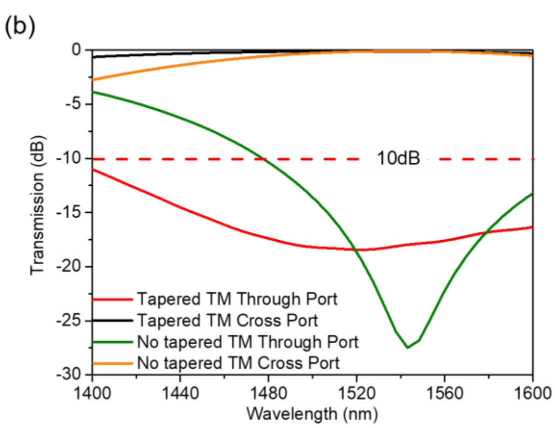


Fig. 3. Simulated results at the through and cross ports for the (a) TE polarization input. (b) TM polarization input.

IV. Conclusion

In summary, we have proposed and simulated an ultra-broadband PBS based on tapered bent DC. The ILs are < 0.48 dB and < 0.63 dB over 1400 nm-1600 nm for the TE and TM polarizations, respectively. The ERs are > 10 dB for TE and TM polarizations respectively in the operation bandwidth.

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