Ultra-broadband and Low-loss Polarization Beam Splitter on Silicon

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Abstract: We realized a polarization beam splitter with low loss of <1 dB and high extinction ratio of >20 dB in an ultra-broad bandwidth from 1400nm to 1700nm using a pair of cascaded dual-core adiabatic tapers. © 2020 The Author(s)

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1. Introduction

As one of the fundamental elements for optical systems, polarization beam splitters (PBSs) have been developed successfully worldwide in the past years by utilizing silicon-on-insulator (SOI) nanophotonic wires and have played important roles for many applications, such as the polarization-diversity technology for polarization-transparent photonic integration circuits (PICs) [1] as well as coherent optical transceivers [2] and quantum communication [3]. There have been many different structures available for realizing compact PBSs as proposed theoretically and demonstrated experimentally, e.g., asymmetric directional couplers (ADCs) [4], multimode interference structures [6], grating-assistant structures [7], hybrid plasmonic Y-branches [8], subwavelength-grating (SWG) couplers [9], etc. For PBSs, it is often desired to achieve low losses and high extinction ratios in an ultra-broad wavelength-band, which is usually a big challenge due to the strong waveguide dispersion. When using SWGs, the wavelength dependence of the photonic device can be manipulated through the refractive index engineering method and thus it is possible to achieve a broad bandwidth.

In this letter, we propose and realize a novel silicon PBS with low excess losses (EL) and high extinction ratio (ER) over ultra-broad bandwidth by introducing a pair of cascaded dual-core adiabatic tapers, which consists of a tapered SWG waveguide and regular adiabatic tapered waveguide. In particular, the present structure can work very well even for silicon photonic nanowires with relatively low birefringence, which is very attractive. For example, for the popular design with the silicon core height h_{co}= 340 nm, the birefringence becomes much lower than that for the case of h_{co} = 220 nm. It is actually not easy to realize high-performance PBS for the case of h_{co}= 340 nm. For the present PBS, the measured bandwidths for achieving an ER of >20dB are as large as 230nm for both TE- and TM-polarizations, while the measured ELs are less than 1dB in an ultrabroad band of 270nm. The ER remains higher than 20 dB for both polarizations even when the width variation is as large as +20/–20 nm. To the best of our knowledge, this is one of the best on-chip PBSs reported to date.

2. Structure, fabrication and characterization.

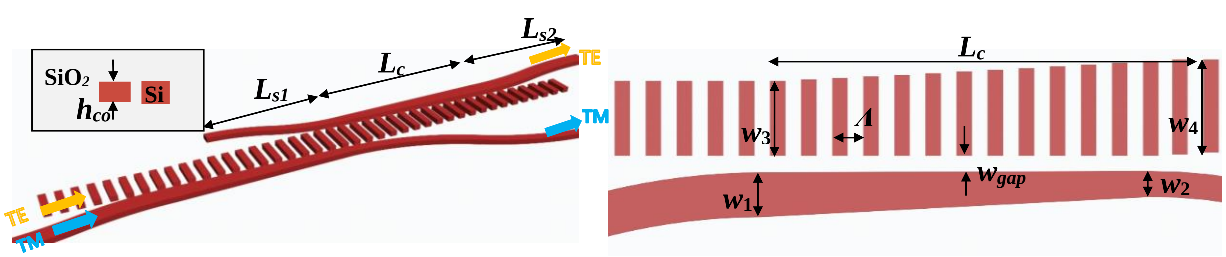

Fig. 1 Schematic configuration of the proposed PBS.

Fig. 1 shows the schematic configuration of the proposed PBS based on cascaded adiabatic dual-core tapers consisting of a strip waveguide taper and an SWG waveguide taper. Here the SOI wafer with a 340nm-thick silicon core-layer is used. For the SWG, the period Λ and the duty cycle η are chosen as Λ=240nm, and η=0.5. For the input and output waveguides, the core width is w_1=320nm to ensure the single-mode operation. The gap width is chosen as w_{gap}=120nm, which is large enough for the fabrication in our lab and helps achieve a compact size. For the S-bends connected at both input/output ends, the lateral and longitudinal offsets are chosen as L_y=1.5μm and L_{s1}=L_{s2}=20μm, respectively, so that the two S-bend waveguides are long enough to minimize their excess losses and make sure that dual-core waveguide system is adiabatic. The SOI strip waveguide has weak birefringence while the SWG waveguide has strong birefringence according to the effective medium theory.

The SWG structure is equivalent as a homogeneous effective medium, whose refractive index is determined by the duty cycle according to the following equations [11],

$$\mathrm{n}_o^2 = n_{Si}^2 \cdot \eta + n_{SiO2}^2(1-\eta)\ , \tag{1}$$

$$\mathrm{n}_e^2 = n_{Si}^{-2} \cdot \eta + n_{SiO2}^{-2}(1-\eta)\ , \tag{2}$$

where n_{Si} and n_{SiO2} are the refractive indices of the silicon and silica. On the other hand, it indicates that the device consisting of SWG waveguides is usually very sensitive to the variation of the duty circle due to the fabrication errors, which always happens. As it is well known, adiabatic taper structures usually have large fabrication tolerance [12]. Therefore, in this paper, we propose an adiabatic taper structure for realizing silicon PBS with SWG waveguides in order to achieve relatively large fabrication tolerance.

According to the design rules for adiabatic dual-core tapers given in [12], we chose the core widths as w_2=280nm, w_3=600nm, and w_4=850nm, so that the designed PBS can work well even when the duty cycle varies from 0.46 to 0.54, corresponding to the width variation of ±10nm for the strip waveguide. For the present PBS, the TE_0 mode launched from the SOI strip waveguide could be extracted to the SWG waveguide completely when choosing the length L_c of the coupling region appropriately. In this way, the TE_0 mode could be coupled to the cross port connected with a regular SOI strip waveguide through the second stage of dual-core adiabatic taper. With this design, no converters are needed to connect the SWG waveguide and the SOI strip waveguide.

For the design, a 3D finite-difference time domain method (FDTD, *Lumerical* FDTD Solutions) was used to simulate the light propagation in the PBS as the period number N of the SWG in the coupling region varies. It is noticed that there is no almost residual power at the through port over an ultra-broad band from 1400nm to 1700nm when choosing N =70 for the TE-polarization mode. On the other hand, for the TM_0 mode launched from the input port, light goes through the super-mode evolution region without any change of power almost and finally outputs from the through port with a low loss. In this way, the TE_0 and TM_0 can be separated within a short length. Fig. 2(a)-(b) show the simulated light propagation in the designed PBS when the TM_0 and TE_0 modes are launched from the input port at λ=1.55 μm. As it can be seen, the TM_0 mode outputs from the through port with a low loss, while the launched TE_0 mode is coupled into the SWG adiabatic taper first and then converted into the TE_0 mode in the strip waveguide for the cross port by using the cascaded inverse adiabatic taper. Fig. 2(c)-(d) respectively show the simulated result for the wavelength dependence of the ELs and the ERs of the designed PBS for TE- and TM- polarizations with η= 0.5. It can be seen that the PBS can obtain a high ER of >20dB and a low EL of < 0.3 dB over a broad bandwidth from 1.4μm to 1.7μm for both TE_0- and TM_0-polarization mode.

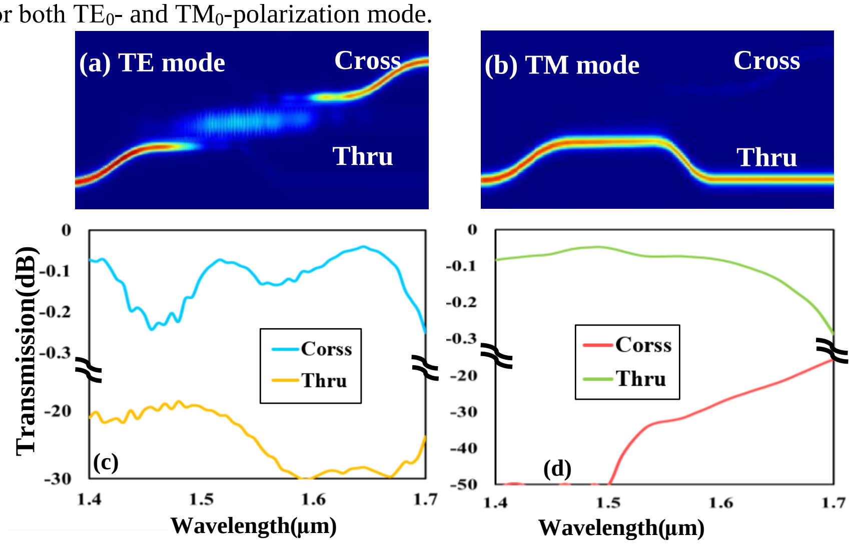

Fig. 2 Simulated light propagation in the designed PBS (@ λ=1.55 μm) when TE (a) and TM (b) polarization modes are launched, respectively. Here Λ=240nm, and η=0.5. The wavelength dependence of the transmissions when the TE_0 (c) and TM_0 (d) modes are launched respectively.

Fig. 3(a)-(b) shows the microscope image picture of the fabricated PBS. The input ports and output ports of the PBS were connected with TM-type and TE-type grating couplers, as shown in Fig. 3 (a)-(b). Here the focused grating couplers were used because it is compact. However, the working bandwidth for the focusing coupler is still limited. It is possible to tune the tilt angle θ_{fiber} of the fiber probe to partially overcome such obstacles. The super-continuum light source was used in our experiments.

Fig. 3 (c)-(d) show the measured ELs and ERs of the fabricated PBS for both TE- and TM- polarizations. The results are normalized by the transmission of a straight singlemode SOI strip waveguide on the same chip. For TE-polarization mode, the bandwidths for achieving an ER of ~20dB, ~25dB are 270 nm and 255 nm. For TM-polarization, the bandwidths for an ER of ~ 20dB, ~25dB are 230nm and 220nm. From Fig. 3 (c)-(d), it can be seen the ER at the wavelength ranges of λ<1440nm and λ>1650nm decreased, which is partially due to the limitation of the detection sensitivity of the OSA and the bandwidth of the grating couplers.

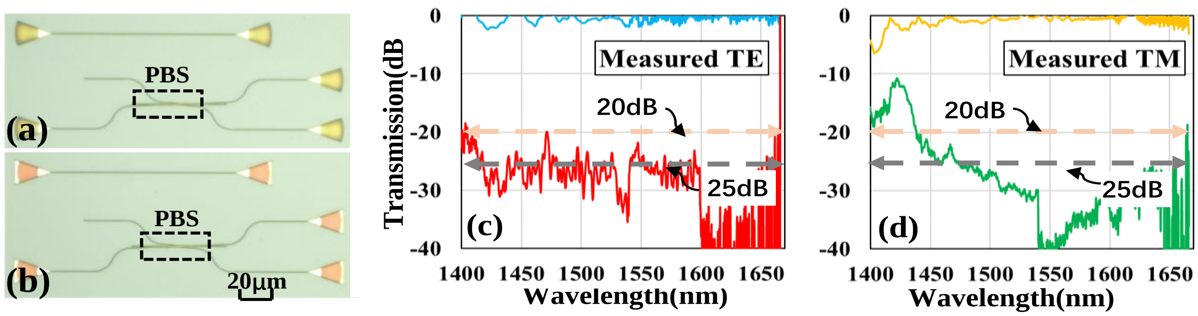

Fig. 3 Microscope pictures for TM (a) and TE(b) polarization modes, and measured ELs and ERs of the fabricated PBS. (c) TE; (d) TM.

3. Conclusion

We have proposed and demonstrated a novel ultra-broadband PBS with low ELs and high ERs by using a pair of cascaded dual-core adiabatic tapers on 340nm-thick SOI waveguides. The dual-core adiabatic taper consists of a strip waveguide core and a SWG waveguide core. The length of the mode-evolution region is 33.6μm and the fabrication needs one etching step only. For the fabricated PBS, the ER and EL have bandwidths as large as ~270nm, and ~240nm for achieving an ER of >20dB, and >25dB respectively. The measured ELs are <1dB in an ultra-broad band of ~270nm. In particular, the present PBS can work very well even when $\Delta\eta = \pm 0.04$ and $\Delta w = \pm 20$nm, which indicates a large fabrication tolerance for modern nano-fabrication. To the best of our knowledge, this is one of the best silicon PBSs with a large fabrication tolerance, as well as low ELs and high ERs over an ultra-broad band.

4. Acknowledgement

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