

Independent phase matching for TE and TM polarization in directional couplers with tilted subwavelength structures

(Student Paper)

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ABSTRACT

Tilted subwavelength gratings (SWGs) are promising structures for birefringence control and polarization management in integrated photonic waveguides. Here we show how tilted SWGs can be used to design a directional coupler based polarization beam splitter which is symmetric for TM polarization but asymmetric for TE polarization. Using this approach, we develop a polarization beam splitter with calculated insertion loss below 1 dB and an extinction ratio better than 20 dB over a bandwidth of 86 nm. The fabricated device shows negligible insertion loss and an extinction ratio over 15 dB over a bandwidth of 72 nm.

Keywords: Photonic integrated devices, polarization management, subwavelength gratings.

1. INTRODUCTION

Polarization beam splitters (PBS) are key building blocks in high index contrast platforms as silicon-on-insulator. Among different approaches to implement PBS, directional couplers are typically used. In an asymmetric configuration, that is, when the two parallel waveguides of the directional coupler have substantially different propagation constants, only light of one polarization couples to the cross port, while the other polarization remains in the input waveguide [see Fig. 1(a)]. To achieve the required asymmetry, different solutions have been explored, such as adding different materials [2], or using multiple etch steps [3]. However, the existing methods often complicate device fabrication or result in long devices. Another promising approach to break the waveguide symmetry, which can be implemented with a single etch step, is the utilization of subwavelength grating (SWG) waveguides [4-5]. The SWG structures enable the lithographic definition of optical metamaterials which can be engineered to gain control over material anisotropy [5-6]. Specifically, recently demonstrated tilted SWG structures provide control over TE (in-plane) polarization while TM (out-of-plane) polarization remains virtually unaltered [7-8]. Therefore, SWGs are promising structures to break the coupler symmetry using a standard fabrication process.

Here we present a directional coupler with one arm comprising a tilted SWG waveguide while the other arm is a conventional SWG waveguide [See Fig. 1]. The TM polarized mode is only minimally affected by the tilt of the silicon blocks [7], so that for this polarization both waveguides have similar optical properties, and the phase matching condition is fulfilled. However, for TE polarization the symmetry is effectively broken and there is no phase matching. Our 3D-FDTD simulations predict an extinction ratio (ER) better than 20 dB over a bandwidth of 86 nm with negligible insertion loss (IL). The device has been fabricated in a 220 nm SOI platform, yielding an ER above 15 dB over a 72 nm bandwidth with subdecibel losses. Our device offers the advantage of control over the polarization properties enabled by tilted SWGs, opening a new method to design polarization diversity devices.

2. DESIGN OF THE POLARIZATION BEAM SPLITTER DIRECTIONAL COUPLER

The design of this directional coupler based PBS (DC-PBS) is carried out in the following two steps. First, we break the symmetry of the device for TE polarization by tilting the segments of the SWG waveguide in the upper arm of the directional coupler. Second, we optimize the device for the TM polarization by adding a silicon strip between the two waveguides.

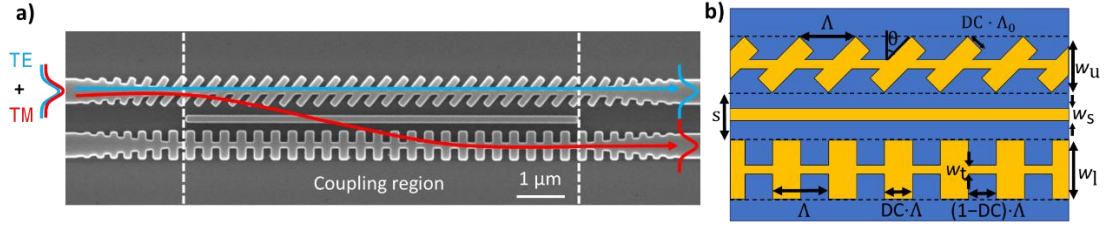


Figure 1. (a) Scanning Electron Microscope image of the polarization beam splitter directional coupler (before SiO₂ cladding deposition). The segments of the upper waveguide are tilted to independently control the phase matching conditions for TE and TM polarization. (b) Schematic of the coupling region.

2.1 Breaking the phase matching condition for the TE polarization

To demonstrate the principle of operation, we study a simplified geometry comprising two parallel SWG waveguides, brought into proximity to allow some power exchange. Referring to Fig. 1(b), the two SWG waveguides are $w_u = w_l = 0.6 \mu\text{m}$ wide, with a nominal period $\Lambda_0 = 275 \text{ nm}$, a 50% duty cycle and a tip width $w_t = 100 \text{ nm}$. To illustrate how the tilt of the subwavelength segments optically decouples the two waveguides for TE polarization while permitting phase matching for TM polarization, we simulate the propagation of the fundamental TE and TM mode along the structures shown in Fig. 2(a) ($\theta = 0^\circ$) and Fig. 2(b) ($\theta = 40^\circ$). We observe that the tilt effectively suppresses power transfer for the TE polarized mode while the behavior for the TM polarized mode remains virtually unchanged. In Fig. 3(a) we show the insertion loss and extinction ratio of the structure for $\theta = 40^\circ$, calculated as: $IL^{\text{TE}} = \frac{P_{\text{BAR}}^{\text{TE}}}{P_{\text{IN}}^{\text{TE}}}$, $IL^{\text{TM}} = \frac{P_{\text{CROSS}}^{\text{TM}}}{P_{\text{IN}}^{\text{TM}}}$, $ER^{\text{TE}} = \frac{P_{\text{CROSS}}^{\text{TE}}}{P_{\text{BAR}}^{\text{TE}}}$, $ER^{\text{TM}} = \frac{P_{\text{BAR}}^{\text{TM}}}{P_{\text{CROSS}}^{\text{TM}}}$.

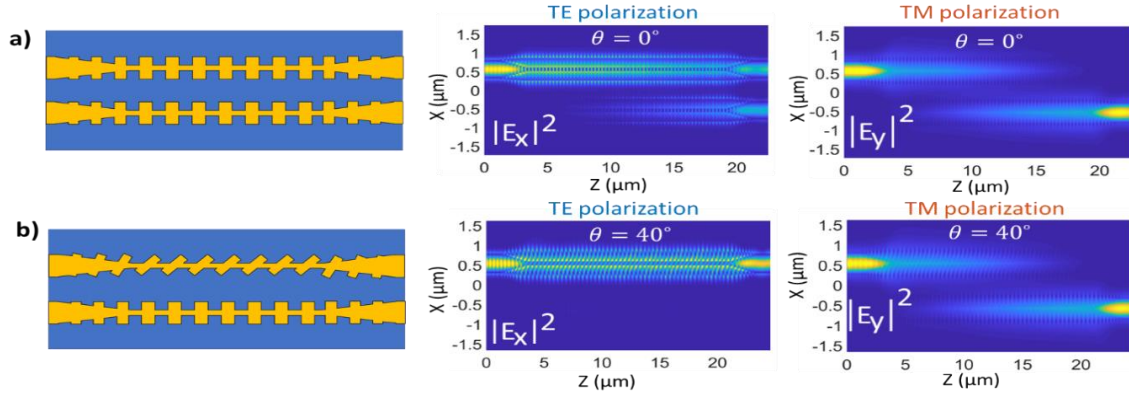


Figure 2. (a) Schematics of the proposed DC-PBS for a tilt angle of $\theta=0^\circ$ and 3D-FDTD simulations of the main component E-field propagation for TE and TM polarizations. (b) Schematic representation of the DC-PBS for a tilt angle of $\theta=40^\circ$ and 3D-FDTD simulations of the main component E-field propagation for the TE and TM polarizations.

2.2 Optimizing the device behavior for the TM polarization

Once the index symmetry is broken for TE polarization, we optimize the device behavior for the TM polarization. This optimization process is done by adding a central silicon strip between the two waveguides [See Fig. 1]. Intuitively, this silicon strip allows to independently control the even supermode, while only slightly affecting the odd supermode. This behavior can be estimated by calculating the coupling length of the devices given by $L_{\pi}^{\text{TM}}(\lambda) = \lambda / [2(n_1^{\text{TM}}(\lambda) - n_2^{\text{TM}}(\lambda))]$ where $n_{1,2}^{\text{TM}}$ are the effective indices of the even and the odd TM polarized supermodes. Figure 3(b) show the calculated coupling length as a function of the wavelength, revealing that the central silicon strip not only reduces the device length but also flattens the wavelength response. In Fig. 3(a) we show the improvement in the device performance when the 150 nm wide silicon strip is added. The optimized design yields an ER more than 20 dB over an 86 nm bandwidth with negligible insertion loss.

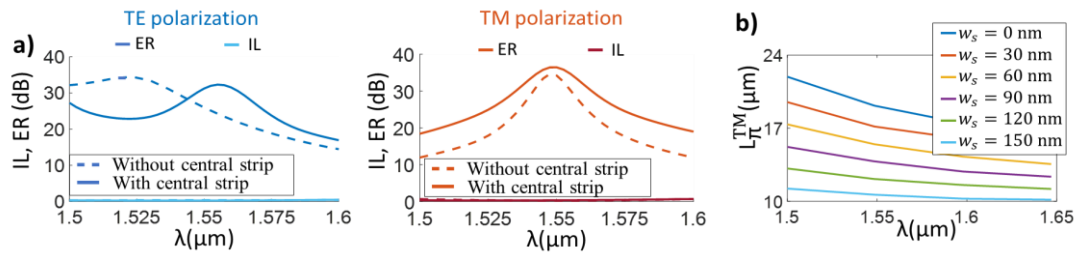


Figure 3. (a) Insertion Loss and Extinction Ratio, for TE and TM polarizations, of the tilted SWG directional coupler with and without the central silicon strip. (b) TM polarization coupling length for the proposed tilted SWG DC-PBS for different silicon strip widths.

3. EXPERIMENTAL RESULTS

The device has been fabricated using e-beam lithography on a 220-nm SOI wafer, with a 2- μm -thick buried oxide (BOX) and a 2.2- μm -thick SiO_2 upper cladding. Fig. 4(a) shows the measured insertion loss and extinction ratio of the fabricated device. For long wavelengths, the device performance is limited by the extinction ratio of the TE polarization. However, increasing the duty cycle from 50% to 60% enhances the modal confinement for TE polarization, thereby suppressing the coupling to the TE port, while only slightly changing the phase matching condition for TM polarization [see Fig. 4(b)].

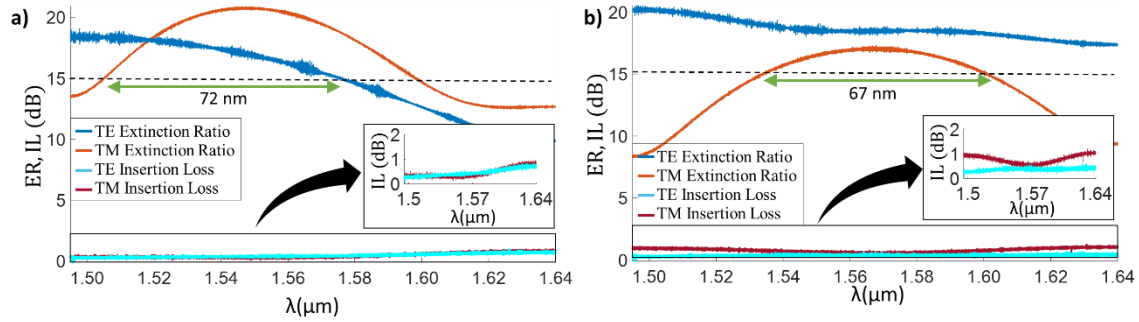


Figure 4. (a) Measured extinction ratio and insertion loss for the nominal device. The IL is below 1 dB and ER is higher than 15 dB over a bandwidth of 72 nm (b) Measured extinction ratio and insertion loss for a +10% duty cycle biased device. The IL is below 1 dB and the ER is >15 dB over a bandwidth of 67 nm.

4. CONCLUSIONS

In this work we leverage the capability of tilted SWG waveguides to independently control the phase matching condition for TE and TM polarizations in a directional coupler. Based on this principle, we design a directional coupler based polarization beam splitter with measured polarization extinction ratio of >15 dB over a 72 nm bandwidth and a negligible insertion loss. The proposed strategy of controlling the symmetry of the DC-PBS presents an example of the excellent potential that tilted SWGs provide to the optical designer for polarization management control in integrated photonic devices.

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