Horizontal slot-based polarization beam splitter on Silicon Nitride

(Student paper)

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ABSTRACT

We present a compact broadband silicon nitride polarization beam splitter, based on a horizontal directional coupler consisting of a slot and a strip waveguide featuring high polarization selectivity across the entire 1500-1600nm wavelength span. Broadband 3D-FDTD numerical simulations reveal a performance of more than 19.4dB Polarization Extinction Ratio (PER) for TE polarization with a peak value of 41.6dB at 1550nm, while for the TM polarization the selectivity is higher than 12.2dB in the same 100nm wavelength range. The insertion losses for both polarizations are lower than 0.3dB in alignment with the low propagation properties of the SiN platform. The design is also tolerant to fabrication thickness errors and ultra-compact in terms of footprint.

Keywords: Polarization beam splitter, Directional coupling, Phase matching, Horizontal slot waveguide, Silicon nitride, Photonic integrated circuit

1. INTRODUCTION

Polarization Beam Splitter (PBS) is a key component for Photonics Integrated Circuits (PICs) targeting a plethora of applications requiring polarization management. In Si platform this type of devices is already mature with commercialization taking place in various examples with the most prominent one being the dual polarization coherent receivers [1]. The large refractive index difference of SOI enables large effective index mismatch between TE and TM polarization that renders rather easy obtaining high performance in terms of polarization selectivity, broadband operation and low loss. In SiN, though, the TE and TM mode exhibit almost the same effective refractive indexes for thicknesses above 400nm that impose severe difficulties in obtaining high performance PBSs. To tackle this issue, hybrid Si and SiN platform solutions of directional coupling and multimode interference PBS have been presented in [2] and [3], respectively, that guide TE and TM modes to different ports. The only similar work in pure SiN platform was reported in [4] that exploits a quite complex single layer and dual stage directional coupling configuration and works in the O-band. The design, though, is susceptible to fabrication errors with experimental devices exhibiting only 10dB PER for 90nm span and has also large footprint with a length of 122μm in the coupling region only.

In this paper, we propose through 2D eigenmode analysis and 3D-FDTD simulations, a PBS design on the SiN platform that achieves wideband polarization splitting based on horizontal directional coupling between a strip and a slot SiN waveguide. The proposed design achieves PER higher than 19.4dB over the wavelength range of 1500nm to 1600nm for the TE polarization at the through port, with a maximum value of 41.6dB at 1550nm. At the cross port, for the TM polarization the PER is higher than 12.2dB for the same wavelength span. The corresponding insertion losses of the TM and TE modes are below -0.12dB and -0.3dB, respectively, in agreement with low propagation losses of the SiN platform. A fabrication tolerance analysis reveals also that a thickness accuracy of ±25nm for the strip waveguide does not impose severe degradation on the PER performance of the PBS, maintaining a PER value higher than 12dB for both ports. The device is also only 36.45μm long that renders its footprint ultra-small.

2. DEVICE STRUCTURE AND PRINCIPLE

Figure 1(a) illustrates the 3D geometric model of the SiN PBS consisting of a 800nm wide strip and a slot waveguide. The width and thickness of the waveguides do not exceed 800nm in order to ensure that no higher modes are excited that severely complexe the directional coupling analysis. The whole device is covered by a SiO_2 cladding of n=1.45, while for SiN the refractive index was set at n=1.974 both at 1550nm. The gap between the two waveguides in the coupling region is 300nm and increases along the 50μm radius S-bend section. Figure 1(a) shows also the coupling region with length L_c, where light is exchanged between the two types of waveguides. The proposed PBS splits the light injected to the strip waveguide based on its polarization to the slot and strip waveguides referred also as cross and through ports, respectively. Polarization selectivity is achieved by ensuring phase matching of the TM polarized light that leads via directional coupling to the cross port, while the phase mismatched TE polarized light continues to propagate to the through port. After the polarization selectivity at the PBS no polarization rotation is performed.

Phase matching condition for the TM polarization is obtained for the right combination of the slot's gap, *g*, and the thickness of the strip, *t*, values (Fig. (1(a)). The gap *g* in the slot waveguide after the coupling region is linearly decreased to zero through a 15μm long taper for achieving smooth transition of the propagating field. On the other hand, phase mismatching for the TE polarization is achieved by adjusting the cross sections of the two waveguides, so as to induce the highest possible difference between the effective indices. With the medium refractive index contrast of the SiN technology though, the targeted conditions are not easily met.

The analysis for the optimization of the PBS design starts with the calculation of the effective refractive indices of the supported TE and TM fundamental modes in the slot waveguide at 1550nm wavelength. By varying the slot gap *g* we calculate the $\Delta n_{eff} = n_{eff}^{TM} - n_{eff}^{TE}$ difference through 2D FDTD eigenmode analysis for 800nm slot waveguide thickness. The maximum difference Δn_{eff} according to the results of Fig. 1(b) is produced for a gap of 250nm, where TM and TE effective indices are 1.579 and 1.533, respectively. Subsequently, the effective indices of the TM and TE supported modes are calculated for the strip waveguide by varying the thickness, *t*. The results of Fig. 1(c) reveal that for a slot waveguide with 250nm gap and strip waveguide with 472nm thickness the maximum effective TE mode indices difference is extracted, equal to 0.0862.

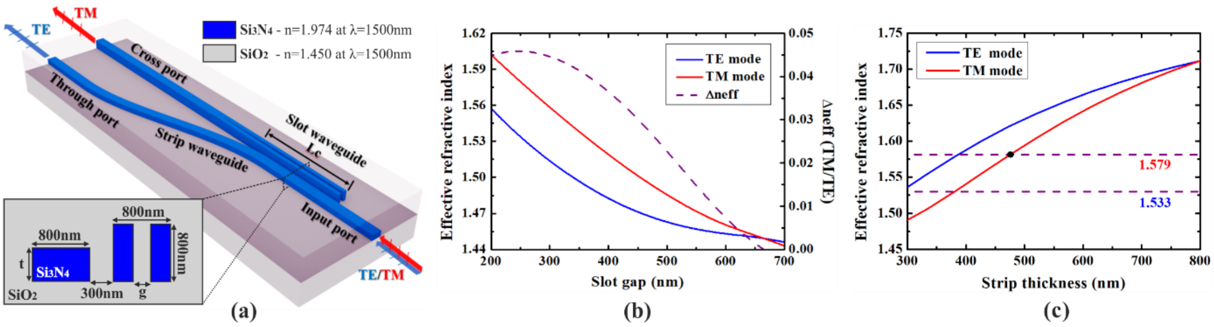


Figure 1: (a) 3D geometry of the proposed PBS and the cross section of the strip and slot waveguide; (b) Effective refractive indices of the fundamental TM and TE modes and their difference versus the gap of the slot; (c) Effective mode indices versus the strip thickness.

The required length to efficiently couple the TM polarization to the cross port is the beat length L_π calculated from the following well known equation [5]:

$$L_\pi = \frac{\lambda}{2\left(n_{TM0} - n_{TM1}\right)}, \tag{1}$$

where λ is the wavelength of light in vacuum, and n_{TM0} and n_{TM1} the effective mode indices for the even and odd TM eigenmodes, respectively. Setting g=250nm and t=472nm, the corresponding value of the beat length is estimated 15.17μm, but taking under consideration the contribution of the S-bend region to light coupling, the appropriate coupling length L_c should be lower than this value. The exact value of L_c was calculated by a parametric sweep in a 3D-FDTD simulation setup with the results depicted in Figure 2(a). The transmission of the TM mode to the through and cross ports when varying L_c reveals an optimum value at 11.2μm for 1550nm wavelength. Figures 2(b) and (c) present the top view of the electric field distributions of the TM and TE modes for the optimum L_c length for TM and TE input polarization, respectively. The simulation results reckon a transmission loss of -0.07dB to the cross port and -42.18dB to the through port for TM and TE modes, respectively. These values confirm that the TM polarized light is coupled and transferred to the slot waveguide, whereas the TE polarization is propagating in the strip waveguide without significant coupling to the slot, according to the design parameters selection. The S-bend at the through port does not impose any further insertion losses and the polarization rotation in this section is lower than -55.7dB. The total length of the proposed PBS, considering the coupling length L_c and S-bend region length, is only 36.45μm that renders its footprint very small and easily insertable in SiN based PICs.

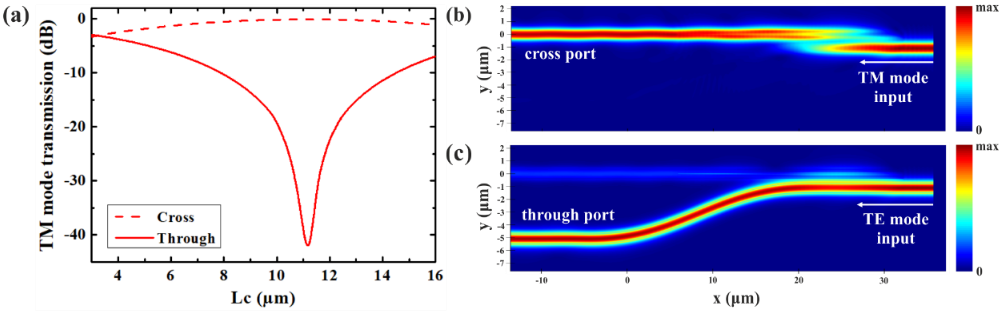


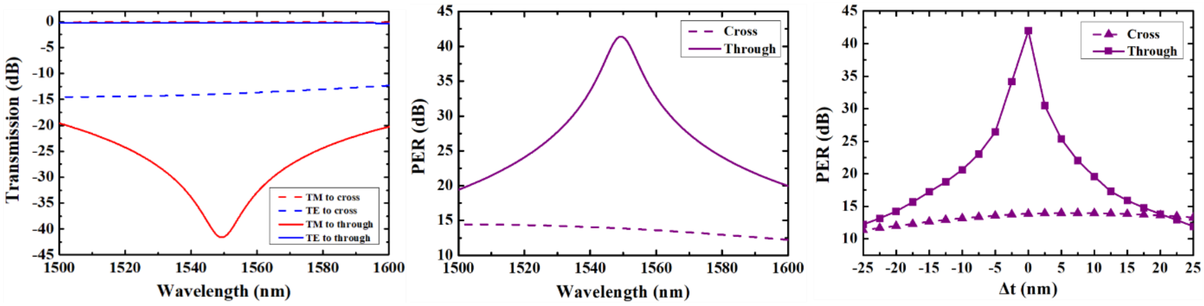
Figure 2: (a) TM mode losses at the cross and through ports versus the coupling length L_c; (b), (c) Electric field distributions of the TM and TE modes with optimum L_c value.

3. DEVICE PERFORMANCE AND FABRICATION TOLERANCE ANALYSIS

Due to the phase matching condition, the TM mode coupling to the cross port is sensitive to wavelength changes and Fig. 3(a) presents the wavelength dependent performance of the optimum design. The insertion losses of the TM and TE modes are above -0.12dB and -0.3dB, respectively, over the entire wavelength range of 1500-1600nm. The polarization extinction ratios (PER) for the cross and through ports are calculated as follows [6]:

$$PER_{cross} = -10\log\frac{T_{TE,cross}}{T_{TM,cross}}, \quad (2) \qquad\qquad PER_{through} = -10\log\frac{T_{TM,through}}{T_{TE,through}}, \quad (3)$$

where $T_{TE,cross}$, $T_{TE,through}$, $T_{TM,cross}$ and $T_{TM,through}$ are the TE and TM mode transmissions to the cross and through ports, as indicated.



(a) (b) (c)

Figure 3: (a) Broadband transmission of TM and TE modes in each port; (b) PER spectra; (c) Error tolerance for strip thickness variation.

Figure 3(b) depicts the calculated PER in the through port, where a maximum value of 41.6dB is recorded at 1550nm, remaining above the 19.4dB threshold across the whole span of 1500-1600nm. For the cross port, the PER remains rather constant, with a value varying between 12.2-14.4dB in the same wavelength range. Finally, Fig. 3(c) shows the fabrication error tolerance of the proposed PBS in terms of strip waveguide thickness. The PER is higher than 11.3dB at 1550nm for a Δt error of ±25nm from the optimum value of 472nm at both ports, demonstrating high performance in combination with large fabrication tolerances. Finally, when the gap at the strip waveguide is narrowed down to 200nm instead of the ideal 0nm for compatibility with 248nm DUV lithography, the PER of TM and TE polarizations at 1550nm are 17dB and 29.8dB, respectively.

4. CONCLUSIONS

We propose a fabrication-tolerant polarization beam splitter design at the SiN platform based on the horizontal directional coupling mechanism. The PBS comprises of a strip and a slot waveguide featuring a total length of only 36.45μm. With 3D-FDTD simulations, the performance of the PBS in terms of PER is calculated higher than 19.4dB for the TE polarization and higher than 12.2dB for the TM one, across the entire 1500-1600nm wavelength span. The design is also fabrication tolerant in terms of strip waveguide thickness by providing more than 11.3dB PER for ±25nm variation from the optimum 472nm value.

ACKNOWLEDGEMENTS

This work is supported by the European H2020 ICT MOICANA (contract no. 780537) project.

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