

Ultra-low-loss silicon photonic polarization beam splitter in C-band

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Abstract—We demonstrate an ultra-low-loss C-band polarization beam splitter (PBS) based on an asymmetric bent directional coupler on a silicon-on-insulator (SOI) platform, employing third-order polynomial interconnected circular (TOPIC) bends to minimize bend losses. The PBS insertion loss (IL) is accurately extracted by cascading up to 40 identical devices and applying linear regression. At 1550 nm wavelength, the fabricated PBS achieves an IL of 0.015 ± 0.005 dB and 0.043 ± 0.008 dB for TM and TE input, respectively. Over the 1500–1600 nm wavelength range, the IL remains below 0.461 ± 0.014 dB for TM and 0.058 ± 0.003 dB for TE, with a 20 dB extinction ratio bandwidth of 30 nm for both polarizations. Wafer-level characterization across 26 dies confirms the design robustness and fabrication tolerance.

Index Terms—polarization management, silicon photonics, PBS, C-band, low-loss.

I. INTRODUCTION

In silicon photonics, the silicon-on-insulator (SOI) platform stands out for its ability to support highly compact and densely integrated components, owing to its large refractive index contrast and compatibility with standard CMOS fabrication [1]. These attributes make SOI-based photonic circuits particularly well suited for optical communication systems, where demands for higher data throughput and greater integration density continue to grow. However, a fundamental challenge in SOI-based PICs is the pronounced birefringence of silicon waveguides, originating from both their geometry and stress effects, which introduces strong polarization sensitivity and can degrade overall device performance [2]. To mitigate this issue, various polarization-management components have been proposed, among which polarization beam splitters (PBSs) play a key role by enabling the separation and recombination of orthogonal polarization states.

Among various approaches to realizing PBSs in silicon photonics, strip Asymmetric Directional Couplers (ADCs)

stand out for their inherently low insertion loss, making them particularly attractive for dense photonic integration [3], [4], [5], [6], [7]. The operating principle of ADC-based PBSs is to introduce asymmetry that allows only one polarization state to satisfy the phase-matching condition and be efficiently coupled, while the other remains phase-mismatched and largely uncoupled. Straight ADCs with asymmetry introduced by tapered waveguides have been widely explored for C-band PBS applications, with the lowest reported insertion losses (ILs) of 0.22 dB for TM input and 0.17 dB for TE input [6]. An alternative approach to introducing asymmetry in an ADC-based PBS is through waveguide bending [8], [9], [10], [11]. For C-band operation, the lowest reported IL for a bent-DC PBS is 0.1 dB for TM input and 0.35 dB for TE input [9]. However, the reported insertion losses for C-band bent-DC PBSs remain comparatively high. We believe the potential of bent-DC PBSs for C-band applications has not been fully exploited. In our previous work, we demonstrated an ultra-low-loss O-band bent-DC PBS employing third-order polynomial interconnected circular (TOPIC) bends [12]. In this paper, we apply the same TOPIC-bend concept to realize a bent-DC PBS designed and optimized for C-band operation [13]. The experimentally demonstrated PBS achieves an IL of 0.015 ± 0.005 dB and 0.043 ± 0.008 dB for TM and TE input light, respectively, at the wavelength of 1550 nm.

II. PRINCIPLE AND THEORY

The proposed bent-DC PBS, illustrated in Fig. 1, comprises two parallel bent strip waveguides that form the coupling region, where the inner waveguide subtends a larger angle to ensure sufficient separation from the outer waveguide beyond the coupling region. The TOPIC bend approach is employed for all bends to minimize bend losses [13]. The waveguide stack is based on a 220-nm-thick SOI platform with a silicon oxide cladding. Since the device targets C-band operation, where stronger evanescent coupling is expected, a relatively large coupling gap of $g = 320$ nm is chosen, while the outer waveguide width w_2 is set to 450 nm, corresponding to the standard single-mode waveguide width for C-band operation.

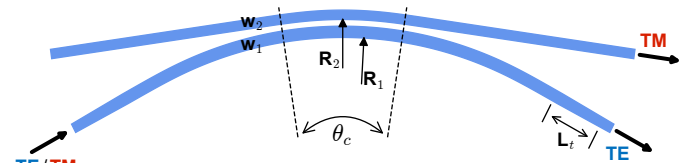


Fig. 1. Schematic illustration of the proposed bent directional coupler PBS.

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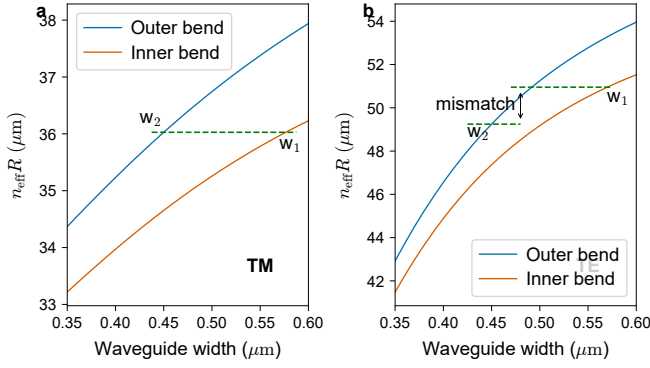


Fig. 2. The $n_{\text{eff}}R$ of the outer and inner bends as a function of waveguide width for (a) TM and (b) TE modes, illustrating the phase-matching condition for TM polarization and the phase mismatch for TE polarization. At $w_2 = 0.45 \mu\text{m}$, the TM phase-matched w_1 is found to be $0.57 \mu\text{m}$.

In the C-band, the weaker confinement of the TM mode leads to higher bend losses compared to the O-band at the same bend radius. Therefore, in this design, the outer waveguide radius R_2 is chosen to be $21 \mu\text{m}$, while the inner waveguide radius is defined as $R_1 = R_2 - g - w_1$. The inner waveguide width w_1 and the circular coupling angle θ_c are the key design parameters: w_1 is chosen to satisfy the phase-matching condition for TM polarization, while θ_c is tuned to achieve complete TM cross-coupling.

The mode-coupling theory for bent directional couplers is detailed in Ref. [14]; here, we focus on the phase-matching and coupling conditions relevant to the proposed PBS. To achieve strong TM cross-coupling, the phase-matching condition must be fulfilled [15]; this requires equal optical path lengths along the outer and inner coupling bends, i.e., $n_{\text{eff}2}R_2 = n_{\text{eff}1}R_1$, where $n_{\text{eff}1}$ and $n_{\text{eff}2}$ denote the effective refractive indices of the inner and outer coupling bends, respectively. At the same time, a significant phase mismatch is preserved for the TE polarization, which prevents appreciable cross-coupling of TE input light. Fig. 2 shows the simulated values for both TM and TE polarizations as a function of waveguide width; subsequently, the inner waveguide width w_1 satisfying the TM phase-matching condition and polarization-splitting operation is found. A straight taper of length $L_t = 3 \mu\text{m}$ is then used to transition the inner waveguide width to the standard single-mode width, as indicated in Fig. 1. The optimum coupling angle θ_c for complete TM cross-coupling is subsequently obtained through 3D simulations, as shown in Fig. 3.

III. FABRICATION AND CHARACTERIZATION

The proposed PBS was fabricated on the imec 200 mm Multi Project Wafer (MPW) silicon photonics platform (iSiPP50G), employing 220 nm SOI technology with a $2 \mu\text{m}$ top oxide cladding layer. Figure 4(a) shows the fabricated PBS device, highlighting its input, cross, and through ports. The PBS IL is defined as the negative of the normalized transmission at the desired port, corresponding to the through port for TE input and the cross port for TM input. The ER is defined as the ratio between the optical powers at the desired and crosstalk ports, where the crosstalk port corresponds to the

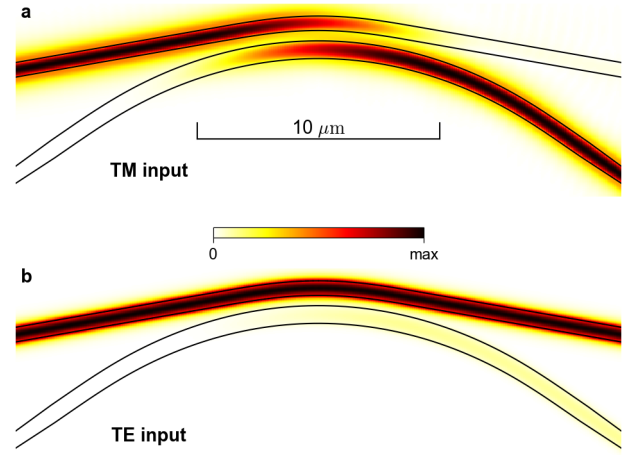


Fig. 3. The simulated light propagation in the proposed bent-DC PBS design with TM (a) and TE (b) input. The structure is modeled with $R_2 = 21 \mu\text{m}$ and a coupling gap $g = 0.32 \mu\text{m}$. The outer waveguide width is $w_2 = 0.45 \mu\text{m}$, and the optimum inner waveguide width is found to be $w_1 = 0.55 \mu\text{m}$. The difference between the phase-matched and 3D-simulated w_1 values arises because the port separation routing and the TOPIC transition segments introduce non-phase-matched TM coupling, leading to a slight shift to w_1 to achieve maximum TM cross-coupling. The circular coupling angle of the outer waveguide is $\theta_c = 5^\circ$, in addition to a TOPIC transition angle of 5° on each side of the coupling angle to minimize transition losses. An additional 40° is appended to the circular segment of the inner coupling bend to ensure adequate spatial separation between the taper and the coupling region. The inner waveguide taper length is $L_t = 3 \mu\text{m}$. The simulation is performed by 3D full-vector finite element method (FEM) using COMSOL Multiphysics. The refractive indices of silicon and silicon dioxide are set to 3.4784 and 1.4657, respectively, at the operating wavelength of 1550 nm .

cross port for TE input and the through port for TM input. To accurately characterize the PBS IL, multiple identical devices were cascaded to suppress the measurement uncertainty, following the methodology established in our earlier work [12]. Cascades of $n = 10, 26$, and 40 PBSs were characterized, and a linear regression of the total transmission as a function of n was performed at each wavelength. The slope of this fit directly provides the normalized transmission spectrum of a single-PBS device. The PBS extinction ratio (ER) was measured by launching light into the bottom input port and recording the output power at the respective cross-talk port (through port for TM input and cross port for TE input). The measured transmission spectra are presented in Fig. 4(b) and (c). At 1550 nm , the insertion losses are as low as 0.011 dB and 0.026 dB , with ER of 32.2 dB and 20.7 dB for TM and TE input light, respectively. The 20 dB extinction ratio bandwidth (BW₂₀), defined as the wavelength range maintaining at least 20 dB ER, is 30 nm for TM input and greater than 75 nm for TE input. Across the 100 nm wavelength range ($1500\text{--}1600 \text{ nm}$), the IL remains below 0.48 dB and 0.056 dB for TM and TE input light, respectively. The wavelength sensitivity observed for TM input is characteristic of directional couplers and arises from the inherent wavelength dependence of evanescent coupling. In contrast, TE light propagates directly to the through port without coupling, resulting in a relatively flat spectral response.

A full wafer with 26 dies was characterized to verify PBS design reliability and tolerance. The wafer-level IL for

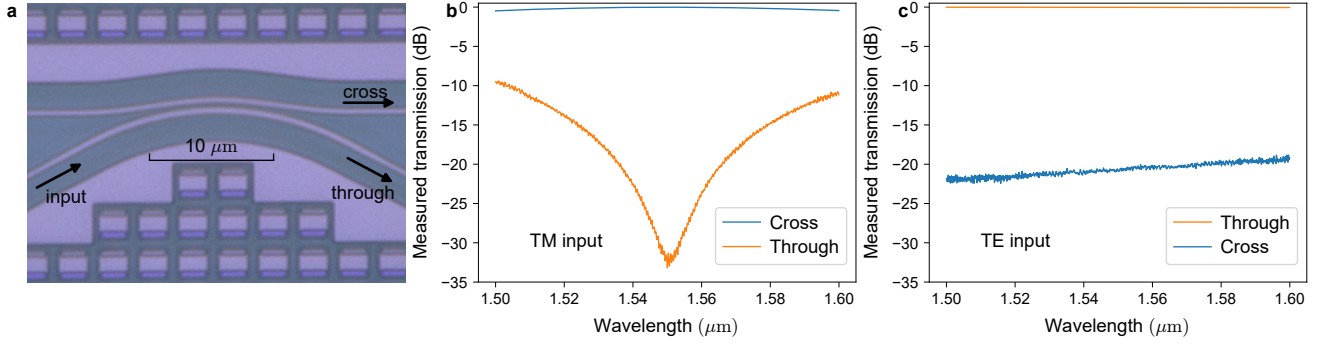


Fig. 4. Microscope image (a), and the measured transmission spectra for TM (b) and TE (c) input light of the fabricated bent-DC PBS device. The inner waveguide width $w_1 = 0.54 \mu\text{m}$, and the circular coupling angle $\theta_c = 6^\circ$, while the rest of the geometrical parameters are as reported in Fig. 3. The fabricated PBS footprint is only $10 \times 30 \mu\text{m}^2$. The slight differences between the experimentally optimized and simulated values of w_1 and θ_c can be attributed to fabrication-induced geometrical variations.

TM input light is illustrated in Fig. 5(a) over the 100 nm wavelength range and in Fig. 5(b) at 1550 nm wavelength. The TM mode is selected for this analysis because, unlike the uncoupled TE mode, it undergoes cross-coupling and is therefore more susceptible to fabrication variations and wavelength-dependent effects. Across the wafer, the PBS consistently demonstrates TM IL lower than 0.5 dB across the 1500–1600 nm wavelength range, with a maximum IL of 0.026 dB at 1550 nm wavelength. Only minor performance variations are observed across the wafer, including at the edge dies. These variations are primarily attributed to the PBS coupling region, where evanescent mode coupling is sensitive to geometrical variations, such as deviations in waveguide width and coupling gap. However, the short coupling region of the C-band PBS limits the accumulated impact of these variations, thereby contributing to the observed fabrication tolerance. Statistical analysis of the wafer-level transmission spectra for TM and TE input is presented in Fig. 5(c) and Fig. 5(d), respectively, with the mean and standard deviation used to quantify performance variations across the wafer. For TM input, the PBS exhibits a mean BW20 of 30 nm and an ER of 29 ± 3.5 dB at 1550 nm wavelength. For TE input, the mean BW20 is 30 nm, with an ER of 19.4 ± 1.1 dB at 1550 nm wavelength. A closer examination of the IL variations for both polarizations is presented in Fig. 5(e). At 1550 nm wavelength, the TM mode exhibits an IL of 0.015 ± 0.005 dB, whereas the TE mode shows an IL of 0.043 ± 0.008 dB. Across the 100 nm wavelength range (1500–1600 nm), the IL stays below 0.461 ± 0.014 dB for the TM mode and below 0.058 ± 0.003 dB for the TE mode. These wafer-level measurements inherently account for combined process-induced variations in key geometrical parameters, such as the coupling gap and waveguide dimensions, providing direct experimental evidence of the fabrication tolerance of the proposed PBS. Collectively, these findings confirm the reliability and robustness of the proposed PBS design in wafer-scale mass production, underscoring its suitability for practical applications. As summarized in Table I, the benchmark comparison highlights our design as an ultra-low-loss PBS. Combined with its excellent fabrication tolerance, the device serves as a practical building block for low-loss polarization diversity circuits.

TABLE I
PERFORMANCE COMPARISON OF EXPERIMENTALLY DEMONSTRATED SOI-BASED PBSS OPERATING IN THE C-BAND.

Ref.	TE/TM peak IL (dB)	TE/TM peak ER (dB)	TE/TM BW20 (nm)	Footprint (μm^2)
[6]	0.17 / 0.22	30 / 40	175	11×4
[11]	0.6 / 0.3	26 / 30	90	14×26
[9]	0.35 / 0.1	37 / 46	135	6.9×20
[16]	0.31 / 0.84	19 / 40	0 / 65	7.2×4
[17]	0.3 / 0.1	>25	270 / 240	3×14
This work	0.043 ± 0.008 / 0.015 ± 0.005	19.4 ± 1.1 / 29 ± 3.5	30 / 30	10×30

IV. CONCLUSION

We have experimentally demonstrated a bent-DC PBS design that successfully achieves ultra-low-loss performance in the C-band using TOPIC bends on an SOI platform. Extending our previous O-band bent-DC PBS design to the C-band, this work achieves state-of-the-art performance metrics that surpass existing bent-DC PBS implementations. At 1550 nm, the device exhibits IL of 0.015 ± 0.005 dB and 0.043 ± 0.008 dB for TM and TE input light, respectively, with ER of 29 ± 3.5 dB and 19.4 ± 1.1 dB reliably across all dies in one wafer. Across 100 nm wavelength range (1500–1600 nm), IL remains below 0.461 ± 0.014 dB for TM and 0.058 ± 0.003 dB for TE. The accuracy of IL extraction through cascading methodology, combined with comprehensive wafer-level characterization across 26 dies, confirms excellent design robustness and fabrication tolerance with minimal performance variations. These results validate the effectiveness of the TOPIC bend approach for minimizing losses in bent-DC PBS structures and establish this device as a key enabling component for dense, high-performance integrated photonic circuits in next-generation optical I/O and communication systems.

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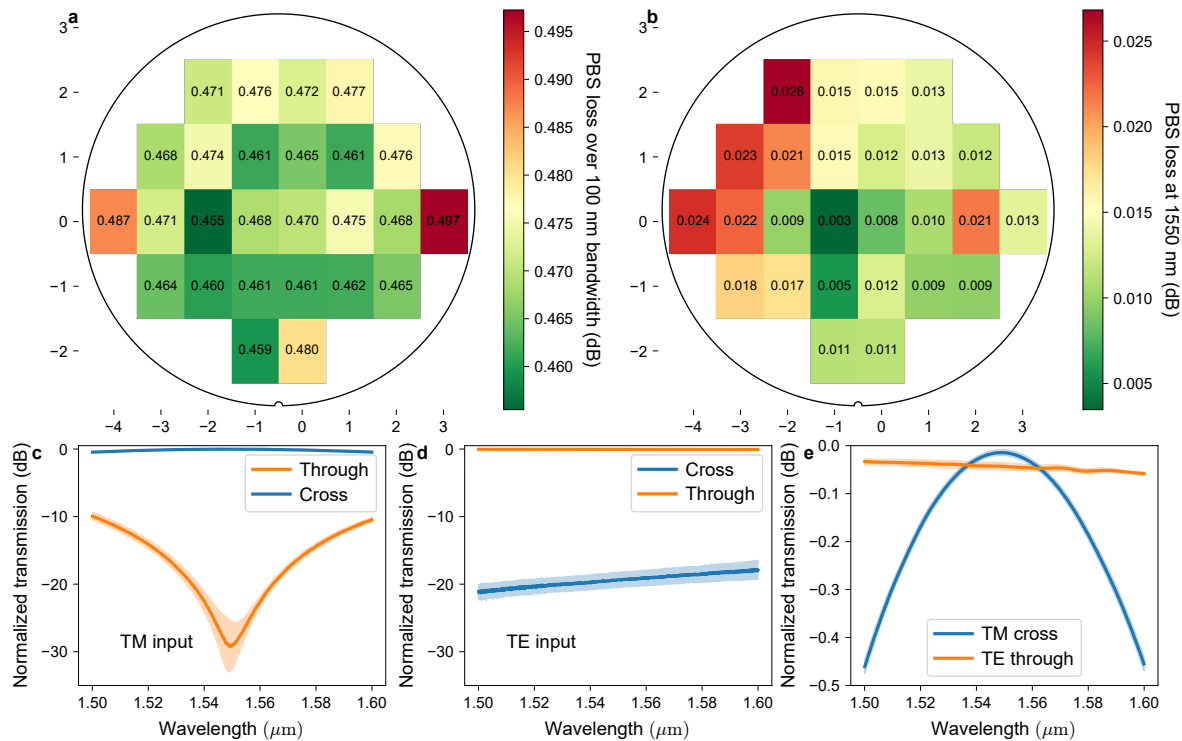


Fig. 5. The wafer mapping of the maximum PBS IL for TM input light over the 1500–1600 nm wavelength range (a) and at 1550 nm wavelength (b). The statistical analysis of the ER across the wafer for TM (c) and TE (d), respectively, and the IL for both polarizations (e). The curves are the mean values while the bands with lighter colors are the standard deviations of the measurements for all 26 dies on one wafer.

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