

Silicon Photonic S-Bent Directional Coupler with Low Wavelength-Dependent Coupling Variation

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Abstract: We experimentally demonstrate a silicon photonic S-bent directional coupler achieving a coupling variation of only 0.065 over an 80 nm wavelength range, showing superior broadband performance with a fabrication-friendly minimum feature size of 200 nm.

1. Introduction

Strip waveguides are the most widely used elements for light manipulation in silicon photonics, offering tight mode confinement and small bending radii for compact integration. When two strip waveguides are placed in close proximity, evanescent coupling occurs, forming a directional coupler (DC) capable of splitting or combining optical signals. However, conventional straight DCs suffer from strong wavelength dependence due to dispersion in strip waveguides, resulting in limited operational bandwidth. Specifically, a 0.5:0.5 straight strip DC achieves the desired coupling ratio at only a single wavelength, exhibiting significant coupling variations across the spectrum. Bent DCs have been proposed to address the bandwidth limitations of conventional straight DCs. By introducing asymmetry through waveguide bending, bent DCs offer improved fabrication tolerance and broadband coupling performance [1]. Recently, we derived an analytical model describing the broadband behavior of bent DCs and achieved a new benchmark in bent DC performance [2]. Here, we present further findings on the wavelength-dependent coupling degradation of bent DCs at large coupling gaps and propose an S-bent DC design to overcome this limitation. At a coupling gap of 200 nm, a 0.5:0.5 straight DC exhibits a coupling variation of 0.298 over an 80 nm wavelength range covering the C-band, while the proposed S-bent DC is experimentally demonstrated to achieve a significantly reduced coupling variation of 0.065.

2. Analysis of coupling variations

According to coupled mode theory, the cross coupling ratio can be expressed as

$$\kappa^2 = m \sin^2(\beta_c x + \phi), \quad (1)$$

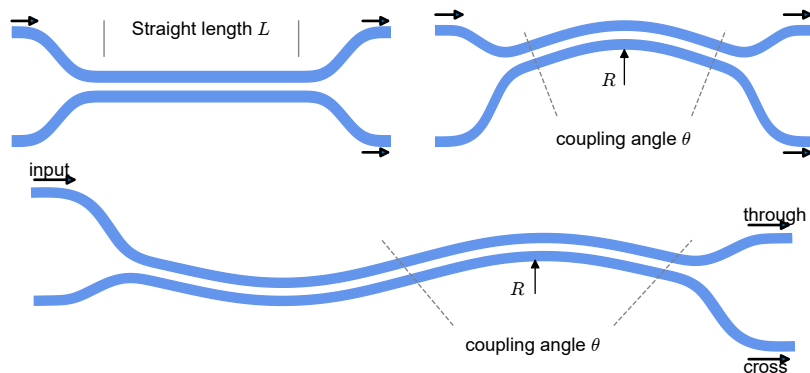


Fig. 1. The schematics of the traditional straight DC with L as the coupling length (a), bent DC (b), and S-bent DC (c) with coupling radius R and coupling angle θ .

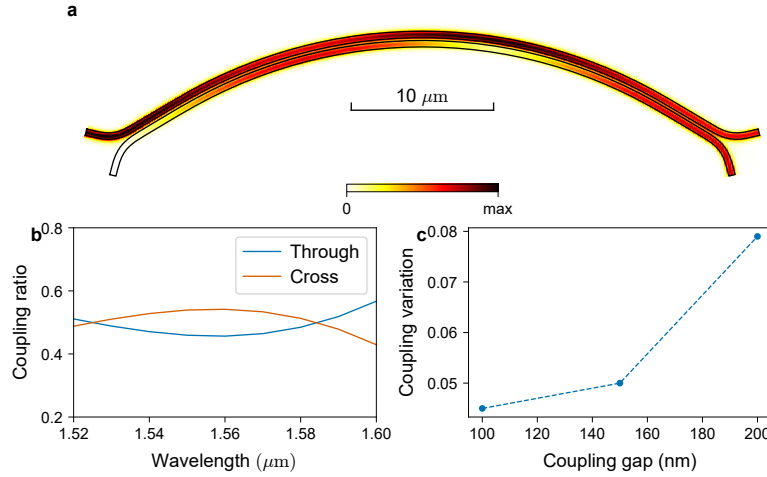


Fig. 2. 3D simulation of the bent DC at 200 nm coupling gap with $R = 33 \mu\text{m}$ and $\theta = 52^\circ$. (a) Light propagation and cross coupling along the bent DC splitter. (b) Simulated coupling ratio over 80 nm wavelength range. (c) Simulated coupling variation at different coupling gaps.

while the through coupling ratio is given by $r^2 = 1 - \kappa^2$ in a lossless coupler. Here, $x = L$ denotes the coupling length for a straight DC (Fig. 1a), and $x = \theta$ indicates the coupling angle for a bent DC (Fig. 1b). The parameter ϕ accounts for the coupling contributed from the input and output connection bends. The parameter β_c represents the coupling strength per unit length or angle, and m is the maximum achievable coupling ratio. The wavelength dependence of the coupling ratio κ^2 can be derived as [2]:

$$\frac{d\kappa^2}{d\lambda} = \frac{dm}{d\lambda} \sin^2(\beta_c l + \phi) + m \left(l \frac{d\beta_c}{d\lambda} + \frac{d\phi}{d\lambda} \right) \sin(2(\beta_c l + \phi)). \quad (2)$$

Conventional straight DCs, consisting of two identical parallel strip waveguides, typically exhibit strong wavelength dependence because $m = 1$ for all wavelengths, such that $\frac{d\kappa^2}{d\lambda} = \left(l \frac{d\beta_c}{d\lambda} + \frac{d\phi}{d\lambda} \right) \sin(2(\beta_c l + \phi))$. Bent DCs achieve broadband operation by splitting the wavelength dependence into two terms as shown in Eq. 2, which cancel each other in properly optimized designs [2]. Fig. 2a shows the simulation of an optimized broadband bent DC with a 0.5:0.5 coupling ratio at a 200 nm coupling gap. The spectrum demonstrates a coupling variation of 0.079 over an 80 nm wavelength range (Fig. 2b). The achievable minimum coupling variation of the bent DC is limited by the coupling gap. As the coupling gap increases from 100 nm to 200 nm, the coupling variation rises from 0.045 to 0.079, as shown in Fig. 2c. To further reduce the wavelength dependence of directional couplers, especially for larger coupling gaps, we propose the S-bent DC design as shown in Fig. 1c. The S-bent DC consists of two bends connected in series such that the two terms in Eq. 2 are split into four terms. With increased degrees of freedom in the design, a lower coupling variation compared to the bent DC can be achieved when the four terms are properly optimized to balance each other.

3. S-bent DC demonstration

To realize a 0.5:0.5 coupler, we experimentally demonstrate the S-bent DC for the C-band wavelength range. The waveguide width and coupling gap are chosen to be 450 nm and 200 nm respectively, which are compatible with most popular silicon photonics foundries. The S-bent DC consists of two identical segments, each with a coupling radius R of $28 \mu\text{m}$ and a coupling angle θ of 19° . All bends in the design employ low-loss third-order polynomial interconnected circular (TOPIC) bends [3], which ensure both continuous curvature and curvature derivative at all connections. Fig. 3a shows an optical microscope image of the S-bent DC fabricated using imec's iSiPP50G platform with 220 nm silicon-on-insulator (SOI) technology. For benchmarking purposes, we also fabricate a conventional straight DC with a 200 nm coupling gap and a coupling length of $6.91 \mu\text{m}$. The measured coupling variation of the straight DC is 0.298, as shown in Fig. 3b. In contrast, the S-bent DC achieves a significantly reduced coupling variation of 0.065 over an 80 nm wavelength range (Fig. 3c). This superior broadband performance at a large coupling gap is further validated through comparison with the reported strip DCs in the literature, as illustrated in Fig. 3d. The excess loss of this device is <0.2 dB, which requires further measurement for precise characterization.

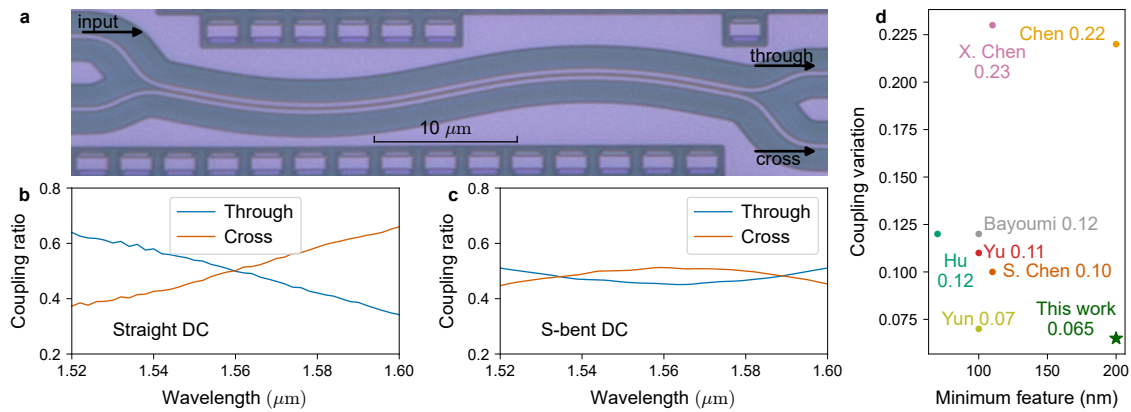


Fig. 3. (a) Microscope image of the fabricated S-bent DC. The measured coupling ratios of the straight DC (b) and S-bent DC (c). (d) Coupling variation in experimentally demonstrated strip DCs over ≥ 80 nm wavelength range covering the C-band: Bayoumi [4], Yu [5], Yun [6], X. Chen [7], Chen [8], Hu [9], and S. Chen [10].

4. Conclusion

We have experimentally demonstrated an S-bent directional coupler achieving superior broadband performance with a coupling variation of only 0.065 over an 80 nm wavelength range in the C-band. By employing two serially connected strip coupling bends, the S-bent DC design provides additional degrees of freedom to minimize wavelength-dependent coupling variations, particularly at larger coupling gaps where conventional bent DCs exhibit performance degradation. At a coupling gap of 200 nm—a fabrication-friendly dimension compatible with most silicon photonics foundries—this S-bent design represents a significant advancement in broadband strip directional coupler technology, offering enhanced performance without the requirement for small feature sizes.

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References

1. C. Doerr, M. Cappuzzo, E. Chen, A. Wong-Foy, L. Gomez, A. Griffin, and L. Buhl, “Bending of a planar lightwave circuit 2/spl times/2 coupler to desensitize it to wavelength, polarization, and fabrication changes,” *IEEE Photonics Technol. Lett.* **17**, 1211–1213 (2005).
2. A. H. El-Saeed, A. Elshazly, H. Kobbi, R. Magdziak, G. Lepage, C. Marchese, J. R. Vaskasi, S. Bipul, D. Bode, M. E. Filipcic, D. Velenis, M. Chakrabarti, P. D. Heyn, P. Verheyen, P. Absil, F. Ferraro, Y. Ban, J. V. Campenhout, W. Bogaerts, and Q. Deng, “Low-loss silicon directional coupler with arbitrary coupling ratios for broadband wavelength operation based on bent waveguides,” *J. Light. Technol.* **42**, 6011–6018 (2024).
3. Q. Deng, A. H. El-Saeed, A. Elshazly, G. Lepage, C. Marchese, P. Neutens, H. Kobbi, R. Magdziak, J. De Coster, J. R. Vaskasi, M. Kim, Y. Tong, N. Singh, M. E. Filipcic, P. Van Dorpe, K. Croes, M. Chakrabarti, D. Velenis, P. De Heyn, P. Verheyen, P. Absil, F. Ferraro, Y. Ban, and J. Van Campenhout, “Low-loss and low-power silicon ring based wdm 32×100 ghz filter enabled by a novel bend design,” *Laser & Photonics Rev.* **19** (2024).
4. A. Bayoumi, M. Oktay, A. Elshazly, H. Kobbi, R. Magdziak, G. Lepage, C. Marchese, J. Rahimi Vaskasi, S. Bipul, D. Bode, D. Velenis, M. Chakrabarti, P. Verheyen, P. Absil, F. Ferraro, Y. Ban, J. Van Campenhout, W. Bogaerts, and Q. Deng, “Enhanced operation range of silicon mzi filters using a broadband bent directional coupler,” *IEEE Photonics Technol. Lett.* **37**, 501–504 (2025).
5. L. Yu, J. Guo, H. Xiang, C. Liu, Y. Zhao, and D. Dai, “High-performance 2x2 bent directional couplers designed with an efficient semi-inverse design method,” *J. Light. Technol.* **42**, 1–8 (2023).
6. H. Yun, L. Chrostowski, and N. A. F. Jaeger, “Ultra-broadband 2x2 adiabatic 3db coupler using subwavelength-grating-assisted silicon-on-insulator strip waveguides,” *Opt. Lett.* **43**, 1935 (2018).
7. X. Chen, W. Liu, Y. Zhang, and Y. Shi, “Polarization-insensitive broadband 2×2 3 dB power splitter based on silicon-bent directional couplers,” *Opt. Lett.* **42**, 3738 (2017).
8. G. F. R. Chen, J. R. Ong, T. Y. L. Ang, S. T. Lim, C. E. Png, and D. T. H. Tan, “Broadband Silicon-On-Insulator directional couplers using a combination of straight and curved waveguide sections,” *Sci. Reports* **7**, 7246 (2017).
9. R. Hu, L. Sun, Z. Zhang, Q. Sun, Y. Pan, and Y. Su, “Ultrabroadband and compact 2x2 3-dB coupler based on trapezoidal subwavelength gratings,” *Opt. Express* **31**, 23542 (2023).
10. S. Chen, Y. Shi, S. He, and D. Dai, “Low-loss and broadband 2x2 silicon thermo-optic mach-zehnder switch with bent directional couplers,” *Opt. Lett.* **41**, 836 (2016).