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Fabrication-Robust Silicon Photonics Platform in Standard 220 nm Silicon Processes

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***Abstract*—We present a fabrication-robust silicon photonics platform compatible with standard 220 nm silicon thickness. Our generalized design methodology shows a 4× energy reduction over standard filter designs and was validated in a 300 mm foundry process, showing a promising avenue for reducing thermal tuning energy.**

I. Introduction

The high index contrast between silicon and silicon dioxide in silicon-on-insulator (SOI) photonics processes presents a double-edged sword: while it enables compact device foot-prints and unparalleled density, it additionally leads to high sensitivity to nanometer-scale fabrication variations. It is well known that increasing the dimensions of the waveguide leads to a reduction in effective index sensitivity to fabrication errors, at the expense of the waveguide supporting higher-order modes. As such, previous demonstrations have only used wide waveguides to reduce effective index variations in straight sections which avoids exciting higher-order modes in sharp bends [1].

Here, we demonstrate a universal design methodology for creating fabrication-robust silicon photonic circuits in standard foundry process flows using wide multi-mode waveguides in the pure single-mode regime. To maintain single-mode operation through compact bends, we employ Euler curves which adiabatically vary the radius of curvature such that the optical mode does not experience any abrupt discontinuities that typically lead to higher-order mode excitation. A representative phase-sensitive device, the ring-assisted Mach Zehnder interferometer (RMZI), was fabricated using both e-beam prototyping and in a commercial 300 mm foundry to validate the approach. The fabricated devices show uniform performance from die-to-die in both cases, demonstrating the universality of the platform.

II. Design Methodology and Results

Commercial SOI photonics foundries have generally converged on a 220 nm silicon waveguide layer thickness [2], which restricts the only geometric degree of freedom to waveguide width for wire waveguides. Adhering to this constraint, we judiciously widen our nominal waveguides from 480 nm to 1.2 μm, leading to less effective index sensitivity to width variations as well as reduced modal overlap with rough sidewalls. For wide multimode waveguides, radial bends lead to significant radiation loss as well as parasitic higher-order mode conversion due to the abrupt mode discontinuity. To maintain adiabaticity and thus avoid mode mismatch, Euler curves of the same 1.2 μm width are used to preserve pure single-mode operation with minimal loss and parasitic mode conversion (Fig. 1a). Previous demonstrations have similarly used adiabatic bends with wide waveguides to avoid exciting higher order modes in sharp bends, although for the purpose of achieving ultra-high quality factor resonators [3], [4].

The RMZI structure is chosen as a representative device since its spectrum is highly sensitive to both the effective index of the ring resonator as well as the phase imparted by the path imbalance in the bottom arm [5]. For splitting and recombining at the MZI input/output, 3.5 μm × 43.1 μm 50-50 MMIs are used. To achieve the desired phase response for flat-top pass-bands, the ring is highly overcoupled ($\kappa^2 \approx 0.9$) using a compact 3.5 μm × 21.6 μm MMI. By using MMIs with 1.2 μm port widths, the need for waveguide tapering is eliminated (Fig. 1c-d). To quantify the energy savings of the fabrication-robust design compared to conventional designs, effective index perturbations for $\approx 3\sigma$ width deviations (+/- 5 nm) were simulated using Lumerical MODE for both 480 nm and 1.2 μm waveguide widths. These effective index variations were then converted into phase errors for a 400 GHz-spaced RMZI design, which were used in S-parameter circuit simulations in Lumerical INTERCONNECT to quantify the induced spectral shift from the nominal design. Assuming a state-of-the-art thermal tuning efficiency for undercut heaters of $P_\pi = 5$ mW [6] and an experimentally measured thermal shift of 9.74 GHz/K, the worst-case thermal tuning energy was calculated for both cases, demonstrating a 4× improvement for the 1.2 μm waveguides (Fig. 1b).

The representative RMZI devices were fabricated in both e-beam and high volume 300 mm deep ultraviolet (DUV) processes to validate the approach (Fig. 1c-d). The measured spectra are in good agreement between the two cases (Fig. 1e) with minor differences likely due to slight changes in fabricated MMI dimensions which can induce different excess loss characteristics as well as different splitting ratios and bandwidths. However, both devices show usable bandwidths greater than 60 nm with flat-top pass- and stop-bands and cross-talk suppression greater than 13 dB over the entire range. Furthermore, the ideal spectral profile is maintained between spatially distanced devices on different die and thus validates the robustness of the design to fabrication variations (Fig. 1f).

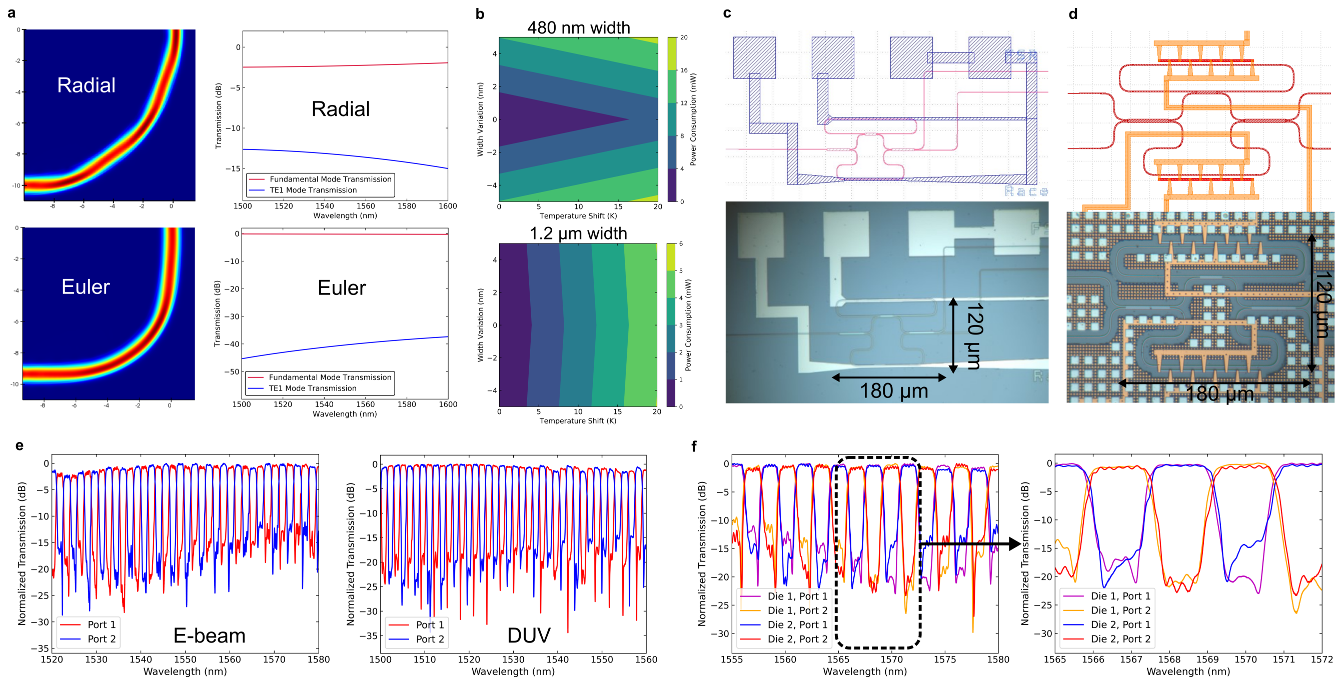

Fig. 1. (a) Comparison of simulated field profiles and transmission characteristics for 1.2 μm wide 90 degree radial and Euler bends occupying the same 10 μm $\times$ 10 μm footprint, indicating large losses and parasitic mode conversion for the radial case while the Euler case displays nearly lossless transmission with -40 dB TE_0 to TE_1 conversion. (b) Comparison of energy consumption as a function of width variation and temperature fluctuation between nominal (480 nm) and widened (1.2 μm) waveguide RMZIs showing a 4$\times$ improvement in worst-case energy expenditure. (c) Layout and microscope image of the fabricated e-beam prototype device using platinum heaters. (d) Layout and microscope image of the fabricated 300 mm DUV device using doped silicon heaters. (e) Spectral comparison for the two fabricated devices with no thermal tuning, showing the desired flat pass-band response in both cases. (f) Die-to-die comparison for both output ports showing uniform performance for spatially distanced devices.

III. Conclusion

We have proposed and experimentally demonstrated a design methodology which greatly reduces random phase errors due to fabrication variations in silicon photonic circuits. Experimentally measured data and simulated worst-case fabrication variations show a 4$\times$ reduction in the required thermal tuning energy compared to conventional designs. Furthermore, the platform is fully passive and does not require post-fabrication trimming or exotic process changes [7]. By using compact Euler bends to maintain single mode operation, devices can simultaneously achieve a small footprint and low sensitivity to fabrication variations, which are key metrics for future energy efficient and bandwidth dense interconnects.

Future directions for this work include wafer-scale quantification of phase errors, width optimization, and incorporation of active devices such as micro-ring modulators. This demonstration provides a promising direction for dramatically reducing the required thermal tuning energy, especially when coupled with highly efficient tuners such as undercut heaters, in any phase-sensitive systems such as wavelength division multiplexing filters, optical phased arrays, and large-scale switch fabrics.

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