Topology Optimized Integrated SiN Mode Converters

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***Abstract*—We present compact, low-loss silicon nitride mode converters designed using topology optimization and fabricated on a commercial silicon foundry. We experimentally demonstrate efficient mode conversion (-0.32 dB for TE_{00} to TE_{01} and -0.52 dB for TE_{00} to TE_{02}), both within 0.4 dB of simulation.**

Keywords—silicon nitride, topology optimization, multimode converters

I. Introduction

Control of multiple waveguide modes provides additional degrees of freedom (DoF) for optical processing within an integrated platform. As example, mode division multiplexing uses these additional DoF to dramatically increase the link capacity of traditional wavelength division multiplexing links [1]. An important component of these systems is compact, low-loss mode converters. SiN clad in SiO_2 provides high index contrast which can be leveraged by topology optimization to produce devices with a smaller footprint than conventional mode converters and that are capable of high power handling [2]. Topology optimization is a gradient-based design algorithm which divides a design region into thousands of pixels that continuously evolve between the design materials to optimize device performance as parameterized by user-defined figures of merit. The optimized devices have freeform and often nonintuitive topologies with excellent performance.

II. Design

A. Device Optimization

We used topology optimization to design a TE_{00} to TE_{01} and a TE_{00} to TE_{02} mode converter using the open-source finite-difference time domain Maxwell solver Meep [3] with a built-in density-based hybrid time-frequency adjoint solver [4]. The mode converters were designed using a 14 x 6 µm design region between 3.5 µm SiN waveguides. We heuristically chose these dimensions because they yielded sufficient conversion efficiency but observed that larger dimensions generally enable more efficient devices. Since the TE_{00} and TE_{02} fields are symmetric, we enforced a symmetry condition across the length of the design region to guarantee a symmetric solution. We defined one objective function at five frequencies between 1530 and 1580 nm which ensured broadband transmission across c-band. Each objective function was the overlap integral between the fields at the output waveguide and the intended mode profile. To ensure flat-band response, we performed a minimax optimization over the five objectives. The designs were optimized over three design epochs with an increasing binarization factor β of 8, 16, and 32. Using multiple binarization factors provided the optimizer freedom to transverse the cost space early in the optimization and that the final design was binary [4]. On the final epoch, we also enforced the length scale and area specifications listed in the foundry design rule checks (DRC) by adding additional constraints [5]. The TE_{00} to TE_{01} converter was optimized for 338 iterations and achieved -0.18 dB coupling efficiency. The TE_{00} to TE_{01} converter was optimized for 178 iterations and achieved -0.26 dB coupling efficiency.

B. Layout

The mode converters were fabricated using the Global Foundries 45SPCLO process in the SiN layer. We fabricated testing structures consisting of stock Si grating couplers, Si to SiN tapers, and SiN bends. To convert to a multimode waveguide, we designed a SiN taper from the stock 1.1 µm waveguide to a 3.5 µm waveguide using topology optimization. The coupling efficiency of the taper was experimentally determined to be -0.08 dB across the band of interest and was calibrated out of the converter loss calculation. The layout structure is displayed in Fig 1a where the purple and red represent the Si and poly-Si layers and the green represents the SiN layer. To mitigate measurement variability in the loss calculation, we fabricated testing structures with 2, 4, 8, and 16 cascaded mode converters (Fig. 1a) and performed a best-fit interpolation to assess the loss of a single device.

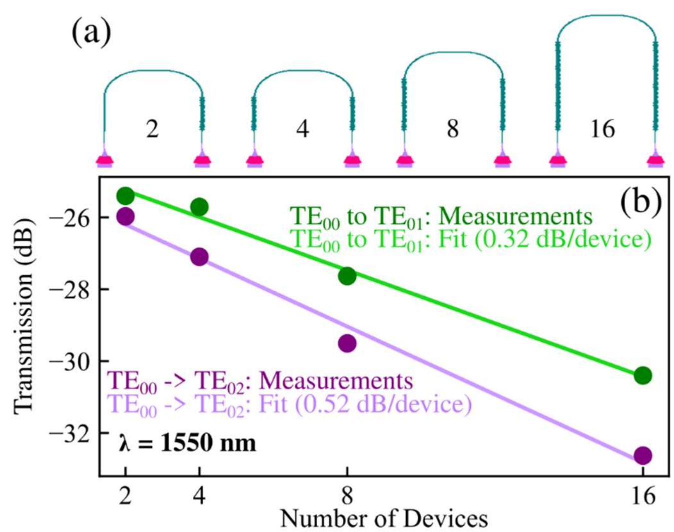

Fig. 1. We fabricated multiple testing structures increasing the number of back-to-back devices (a) to accurately assess the loss of a single devices by calculating the best-fit line whose slope represents the loss in a single device (b). This process was repeated across the entire measurement band.

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III. Experimental Results

We characterized each loopback structure using a standard fiber-array setup with a 127 µm pitch. We performed a frequency sweep on each test structure using a Keysight 8164B inside and outside the design band and calculated the best-fit slope at each wavelength in the sweep (Fig 2b, Fig 3b). This approach both calibrates out the loopback loss and averages the response of multiple devices in case of fabrication or measurement variability. We performed these measurements using our automated testing setup based on the open-source repository LabExt [6] to ensure repeatability. Furthermore, all measurements were taken within 10 minutes to mitigate variation due to slow environmental changes. For the TE_{00} to TE_{01} converter, we measure peak coupling efficiency of -0.32 dB (Fig 2b), within 0.27 dB of simulation across the design band. For the TE_{00} to TE_{02} converter we measure peak coupling efficiency of -0.52 dB (Fig 3b), within 0.4 dB of simulation across the design band. The performance degradation in the measured data is because we manually corrected some features that did not satisfy DRC, which could be avoided by more aggressively applying the constraints. Both devices display less than 0.15 dB transmission difference across the design band as a consequence of the minimax optimization. The continuous wave operation of both devices (Fig 3a, Fig 3b) demonstrates the high conversion efficiency, and a small amount of field is evident leaving the structures as scattering loss. Further testing structures are needed to characterize the intermodal crosstalk of these devices.

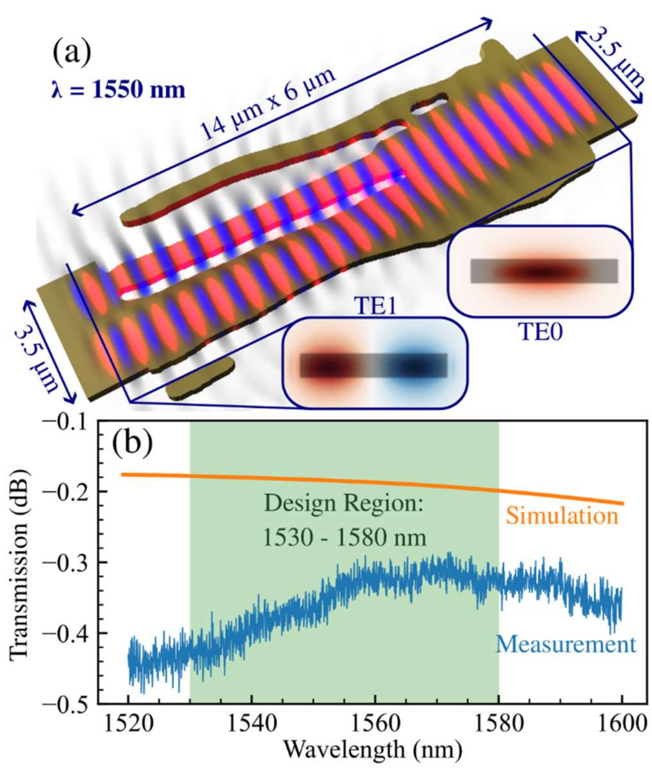

Fig. 2. The y-polarized electric field of the TE_{00} to TE_{01} converter is rendered illustrating the conversion between the fundamental mode and the second TE mode at λ = 1550 nm (a). The coupling efficiency is -0.32 dB and the simulation and measurement data agree within 0.27 dB across the intended design region from 1530 – 1580 nm (b).

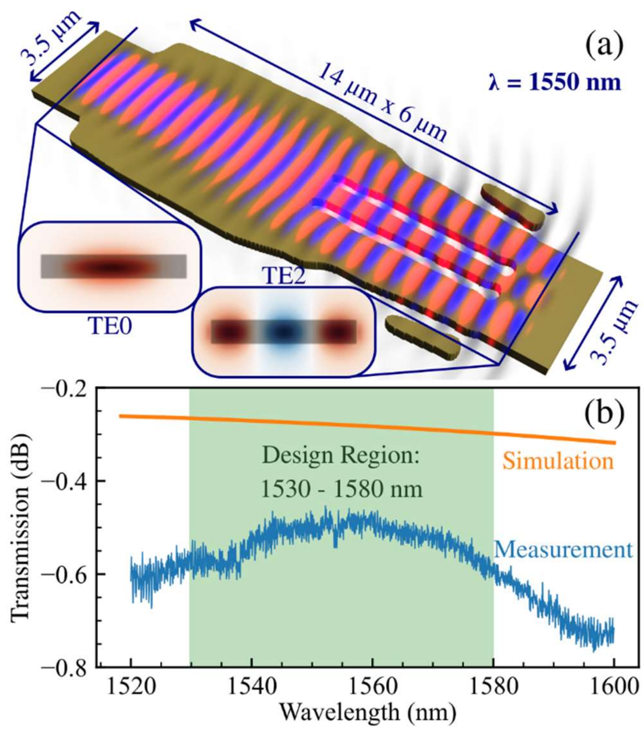

Fig. 3. The TE_{00} to TE_{02} converter is excited with the fundametal mode at λ = 1550 nm which is converted into the TE_{02} mode (a). The design was optimized from 1530 – 1580 nm, which is denoted by the shaded green region (b). Across the design band, the simulated and experimental coupling efficiency agree within 0.4 dB.

IV. Conclusion

We designed two integrated photonic mode converters: one that converts from the fundamental mode to the TE_{01} mode and another that converts the fundamental mode to the TE_{02} mode. These devices were designed in SiN to leverage the material benefits such as high-power handling and high index contrast. Future work includes leveraging the wide transparency window of SiN to create mode converters and grating couplers for the visible wavelengths, measuring the multimodal crosstalk of our current devices, and designing a multimode transmitter in SiN.

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