Design of a Polarization-Insensitive and High-Efficiency Coplanar Edge Coupler for Silicon Photonics by Using a Polished Conical Silicon-Cored-Fiber

Sung-Pu Yang, *Member, IEEE*, Chao-Hsin Wu, *Member, IEEE*, and Lon A. Wang

***Abstract*—Optical coupling between an external optical fiber and a silicon waveguide is vital for successful silicon photonics applications. Direct edge coupling has been desirable but challenging in the past to substitute for bulky, non-coplanar grating-assisted coupling. A silicon-cored fiber (SCF) is proposed as a novel solution for coplanar light coupling from an incoming fiber to a silicon waveguide. The simulation results show that an optimized polished conical SCF coupler can reach very high coupling efficiencies in both TE and TM modes and with low polarization dependence.**

***Index Terms*—Fiber-to-chip coupling, edge coupling, silicon-cored fiber.**

I. Introduction

FIBER-TO-CHIP coupling from a light source to a silicon-on-insulator platform is a crucial topic in silicon photonics. The frequently used vertical coupling assisted by a grating coupler has good misalignment tolerance. However, the high polarization dependence may limit its applications. Although an approach like two-dimensional grating has been reported to alleviate the problem [1], the non-coplanar layout of vertical coupling with a silicon chip makes the whole setup bulky. Compared with the grating couplers, other commonly-seen edge couplers are anticipated to have better packing density and integrate more seamlessly with silicon chips [2]. Still, polarization dependence could be an issue. The polarization of propagating light often randomly varies with time in a fiber network and thus becomes unpredictable. When a coupler is polarization sensitive, uncertain polarization may cause a significant drop in coupling efficiency if any disturbance happens to the fiber. As a result, it is essential to ensure low polarization dependence for a fiber-to-chip coupler.

One reported approach to obtain insensitive polarization is to use an on-chip spot-size converter, especially an inverse taper waveguide structure [3], [4], [5]. By carefully deciding the waveguide dimension, light from an optical fiber could be coupled under the phase-matching condition and achieve polarization-insensitive coupling. Another purpose of using the tapered waveguide structure is to decrease the significant effective refractive index difference between SMF and silicon waveguide and to increase alignment tolerance. However, the inherent difference in refractive index between SMF and silicon waveguide unavoidably induces the generation of Fresnel loss.

Therefore, in this work, we propose a novel polished conical silicon-cored fiber (SCF) edge coupler as an alternative so that we can obtain polarization-insensitive coplanar fiber-to-chip coupling and eliminate the Fresnel loss.

One end of an SCF is to be spliced with a commercial SMF with low splicing loss by using, for example, a tapered SCF with nano-spike and direct splicing with a tapered SMF [6]. To reduce the Fresnel reflection loss between an SCF and a commercial SMF, using microstructures on the end-face of the SCF would be effective [7]. A solution-based metal-assisted chemical etching method was employed to create anti-reflection structures on the end surface of a silicon-cored fiber. Experimental results have shown that the measured reflectance of the etched silicon area of an SCF could reach 0.11 dB loss, significantly decreasing the Fresnel loss between SCF and SMF, and thus achieving low splicing and insertion losses of the proposed coupler. The other end of SCF is to be designed to edge-couple to a silicon

Manuscript received 30 June 2023; revised 10 November 2023; accepted 2 December 2023. Date of publication 6 December 2023; date of current version 8 January 2024. This work was supported in part by the National Science and Technology Council of Taiwan under Grants 110-2221-E-002-138, 111-2221-E-002-072, 111-2221-E-002-051-MY3, 111-2622-8-002-001, 111-2218-E-002-025, 111-2622-8-002-032, 111-3114-E-002-001, 111-2119-M-002-008, 112-2119-M-002-013, 112-2119-M-002-015, and 112-2923-E-002-008-MY3, in part by the National Chung-Shan Institute of Science and Technology under Grants NCSIST-ACOM-111-6712002 and NCSIST-ACOM-112-6712002, in part by the National Taiwan University under Grant 112L7860, in part by NTUS Innovation Cooperation under Grant 11112071002, in part by the Powerchip Semiconductor Manufac-turing Corporation under Grants 12H1004-C15, 12H1004-C16, and 12H1004-C17, and in part by AU Optronics under Grant 110HZT9B001. *(Corresponding author: Sung-Pu Yang.)*

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Digital Object Identifier 10.1109/JPHOT.2023.3340025

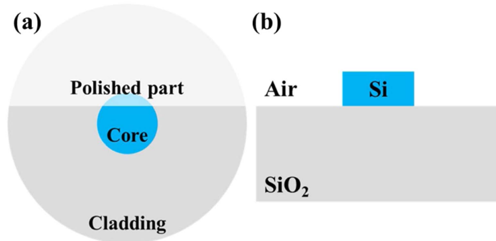

Fig. 1. Schematics of (a) a D-shaped SCF cross-section and (b) the Si SMWG applied in the simulation.

waveguide and will be described in detail later. Since both the SCF's core and a silicon waveguide on a silicon chip are made from silicon, the inherent Fresnel reflection loss between a traditional glass fiber and a silicon waveguide would be eliminated. To couple with a silicon waveguide, an SCF's shape can be transformed from a point-symmetrical circle to a line-symmetric semicircle, like a rectangular waveguide, so that the behavior of the electric field polarization would be closer to that of a rectangular silicon waveguide. By shaping the geometry as mentioned, both TE and TM polarization could achieve high coupling efficiency, and polarization-insensitive coupling can thus be obtained.

II. Structure Design and Simulation

To design a polarization-insensitive coupler, we first consider a D-shaped SCF cross-section and a silicon single-mode strip waveguide (Si SMWG) as shown in Fig. 1. The refractive index of silicon is set to be around 3.48, according to the Sellmeier relations [8], [9]; the refractive index of silica is set to 1.45; the refractive index of air is set to 1. The height and the width of Si SMWG are set to 220 nm and 500 nm, respectively, with a buried-oxide layer beneath the waveguide. The purpose of choosing a strip waveguide is to facilitate the initial verification. We can utilize a ready-made SOI wafer and the lithography process with a few steps to produce a strip waveguide with controllable dimensions. The electric field intensity distributions at 1550 nm wavelength are acquired through the two-dimensional (2D) finite element method (FEM) in Rsoft.

The mode match between the polished conical SCF coupler and the Si SMWG is quantified by the modal overlap integral η, which can be expressed as:

$$\eta = \frac{\left|\int_A E_1^* E_2 dA\right|^2}{\int_A |E_1|^2 dA \cdot \int_A |E_2|^2 dA} \tag{1}$$

where A is the area of integration and E_1, E_2 are the electric fields of the output mode of the polished conical SCF and the mode of Si SMWG acquired from FEM, respectively. It is worth mentioning that the effect of diameter variation along the coupler on light propagation is not considered. Fig. 2(a) shows the effective mode indices of a half-polished conical SCF. The intersection of the effective mode index between the polished conical SCF and the Si SMWG proves the inherent advantage of eliminating the Fresnel loss by using SCF. Moreover, the results of effective mode indices also indicate that to obtain a small difference in coupling efficiency between different polarizations, the diameter of the SCF should be approximately between the two intersection points. Although the tip diameter may be smaller than 500 nm, the feasibility of fabricating a tapered SCF with a sub-micrometer tip by sleeving the SCF into a hollow core fiber (HCF) before the tapering process has already been verified [7].

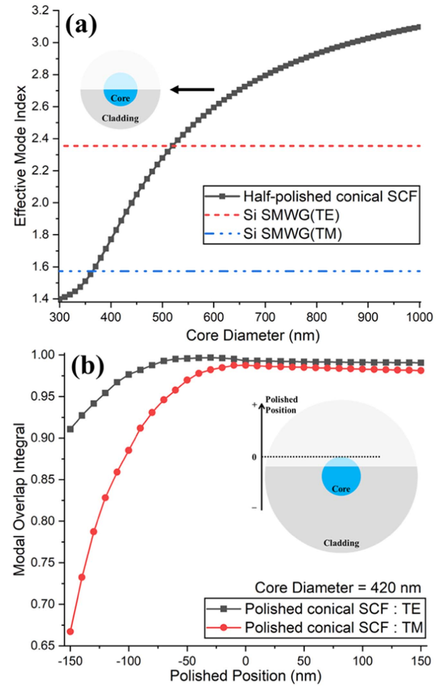

Fig. 2. (a) Calculated effective mode index of the eigenmodes in the Si SMWG and the polished conical SCF, where the polished conical SCF is half-polished. It shows the inherent advantage of SCF eliminating refractive index mismatch. (b) Variations of the modal overlap integral when the polished position changes while the core diameter is fixed at 420 nm.

Fig. 2(b) shows the variations of the modal overlap integral as the polished position changes. According to Fig. 2(b), when the polished position has not yet reached the core boundary, it will have little impact on the modal overlap integral. This is because the strong light confinement caused by the large refractive index difference results in an evanescent field with a short distance and low intensity. Then, when the polished position has just reached the core boundary and is further over a short range, the modal overlap integral will rise slightly. However, the modal overlap integral will drop rapidly and significantly when the polished position goes downward. Because our goal is to increase coupling efficiency and reduce polarization dependence simultaneously, we decide that the best choice is when the polishing position is right on the border of the core. Furthermore, in our previous works, side polishing has been used to fabricate the Schottky photodetector and to design the slot waveguide sensor [10], [11], [12]. In both applications, we have proved that the strong light field confinement of SCF can be extended to the D-shaped regions while maintaining the single-mode operation. Under this polishing condition, the modal overlap integral is greater than 0.95, leading to a coupling loss of around 0.1 dB.

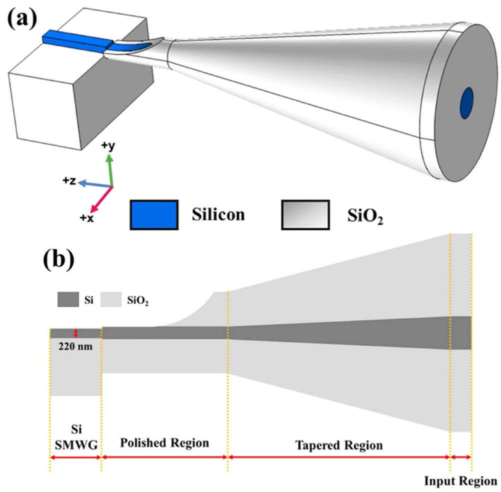

Fig. 3. (a) Three-dimensional schematic of the overall coupling scheme. (b) Two-dimensional schematic and the defined terms of the overall coupling scheme.

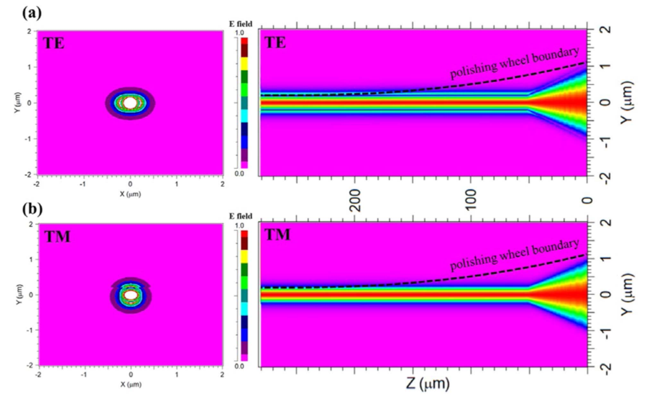

Fig. 4. x-y cross-section view of the output electric field at the tip and the y-z cross-section electric field propagation along the polished conical coupler for (a) TE mode and (b) TM mode.

III. Analysis of Coupling Efficiency

According to the 2D simulation results, we then calculate the coupling efficiency using the three-dimensional (3D) beam propagation method (BPM) and finite-difference time-domain (FDTD) method in Rsoft. The 3D schematic and the y-z cross-section view of the coupler design are shown in Fig. 3. The input region represents the original SCF that has not been tapered or polished. After that, the tapered region will reduce the diameter of the SCF. After the tapered region, there will be a part of the SCF that maintains the diameter. In this region, the geometry of SCF will be further changed by side polishing and is thus defined as the polished region.

To allow the incident light, the input region could be directly connected to another SCF. On the other hand, it has been proved that the higher-order modes excitation caused by the coupling between SMF and multimode fiber could be effectively avoided by employing techniques such as selective mode excitation [13], off-set launching [14], or mode field matched center launching [15]. Moreover, Fresnel reflection between a commercial SMF and an SCF can be significantly reduced by the microstructures made over the end-face of the SCF, as mentioned previously. As a result, the direct connection between SMF and the input region of the polished conical SCF coupler is also a feasible option.

The parameters are set as follows: the input core diameter at the input region is 2 μm, the core diameter at the end of the tapered region is 420 nm, and the polished position defined in Fig. 2 is zero. The length of the polished area should be as short as possible while maintaining single-mode propagation and not affecting other structures.

Next, the 3D BPM is first applied to simulate the mode conversion along the coupler. Fig. 4 shows an x-y cross-section view of the output electric field at the tip and the y-z cross-section electric field propagation along the coupler. Both cross-sectional views show that the design of the polished conical SCF coupler allows light to be transmitted stably in the coupler and maintains a low-order mode. The slight change in the optical field in the polished region also suggests that the side-polishing will indeed compress the optical field. This is due to the upper medium changing from glass to air with a smaller refractive index, so the larger refractive index difference makes the light more concentrated in the silicon core. Overall, it was proved that the light could propagate with extremely low loss and reach our expected modal overlap with Si SMWG. The modal overlap integral of the output electric field from the proposed coupler and the electric field of Si SMWG acquired from FEM is calculated based on (1). The calculated coupling losses for TE mode and TM mode are around 0.11 dB and 0.13 dB, respectively.

Finally, the FDTD is performed and the x-z cross-section view is shown in Fig. 5. A coupling loss of 0.14 dB for TE mode and 0.16 dB for TM mode are obtained. The coupling efficiency slightly differs from the best value obtained from the modal overlap integral of 2D FEM and 3D BPM. This may be because the linear taper does not fully meet the adiabatic conditions and induce the coupling to the higher-order modes. The higher-order modes could possibly scatter out of the silicon core and induce excessive losses. The coupling efficiency of TE mode is higher than that of TM mode, consistent with the previous analysis of modal overlap integral. The difference in coupling loss corresponding to different polarizations is merely 0.016 dB, proving a low polarization dependence could be obtained for the polished conical SCF edge coupler. On the other hand, the simulation also shows little variation within the 1500~1600 nm wavelength of C-band, due to the extremely small change in the refractive index of Si and SiO_2. The difference in coupling efficiency of TE mode within this wavelength range does not exceed 0.5%, and the difference of TM mode does not exceed 2%. Furthermore, the misalignment tolerance of the optimized coupler, which is shown in Fig. 6, is also calculated in FDTD, assuming the tolerable excessive loss for misalignment is -3 dB. For TE mode, the x-axis misalignment tolerance is about 326 nm and the y-axis misalignment is about 339 nm. For TM mode, the x-axis misalignment tolerance is about 415 nm and the y-axis misalignment is about 337 nm. Due to the slightly larger area of the electric field distribution,

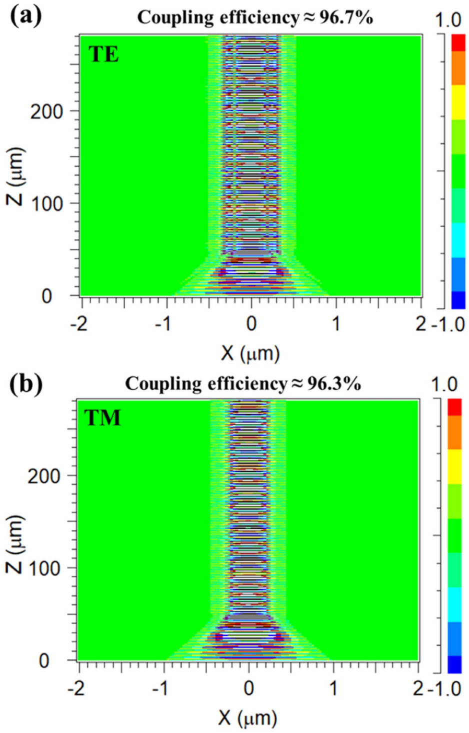

Fig. 5. FDTD simulation shows the coupling efficiency reaches (a) about 96.7% for TE mode, and (b) about 96.3% for TM mode, meaning that the polarization penalty is merely 0.016 dB.

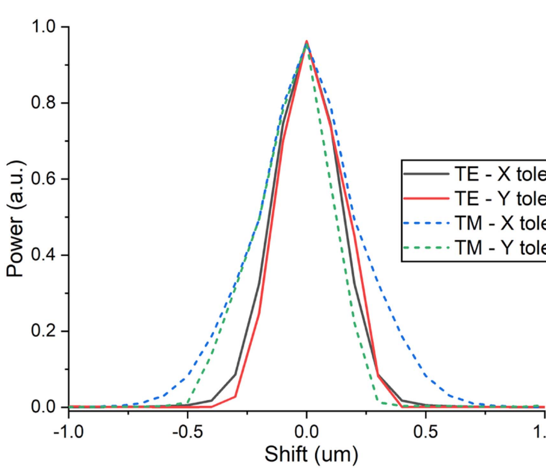

Fig. 6. Misalignment tolerance of the polished conical SCF coupler. The positive and negative directions of the two axes are plotted according to the definition in Fig. 3(a).

TM mode has better misalgnment tolerance than TE mode. On the other hand, although our proposed SCF coupler inherently has the outstanding advantage that the effective refractive index is the same as the silicon waveguide, the optical field is more confined in the core compared with commercial SMF, leading to a smaller alignment tolerance. Still, the value of misalignment tolerance is close to the core diameter of the proposed coupler design, implying that the coupling scheme is still applicable in the real-world experiment.

IV. Conclusion

A novel SCF-based coupler with a polished conical shape is proposed and optimized at 1550 nm wavelength to achieve polarization-insensitive fiber-to-chip coplanar edge coupling. The simulated results show that a high coupling efficiency of ∼96.7% and ∼96.3% can be obtained in TE and TM modes, respectively. A polarization penalty of only −0.016 dB proves the coupler performs a polarization-insensitive coupling. Compared to the grating-assisted non-coplanar coupler, a polished conical SCF coupler may provide an alternative light coupling commonly required between an incoming optical fiber and a silicon waveguide in silicon photonics.

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