Low-Crosstalk High-Order Mode Silicon Fiber-Chip Coupler by Utilizing Apodized Double Part Gratings With Mode Selective Trident

Weilun Zhang, Mengyuan Ye, Yunlong Li, Li Liu, Xiangyu Guo, and Yu Yu, *Member, IEEE*

***Abstract*—We propose and experimentally demonstrate a silicon integrated high-order mode fiber-chip coupler. By utilizing a structure of apodized double-part gratings with mode selective trident, TE_1 mode can be coupled with low mode crosstalk. Design details and the corresponding simulation results are presented. The coupler is fabricated on silicon integrated platform. Measured results show the loss is 4.68 dB for TE_1-LP_{11} mode coupling with the mode crosstalk <-23 dB. The proposed coupler could be utilized in the advanced mode division multiplexing (MDM) system.**

***Index Terms*—Few-mode fiber, grating coupler, high-order mode, integrated optics.**

I. Introduction

In ORDER to satisfy the demand of ultra-high data capacity in optical communication networks, various multiplexing techniques have been utilized, such as wavelength division multiplexing (WDM) [1] and polarization division multiplexing (PDM) [2]. In the past decade, MDM technology attracts more and more attention due to its ability on further increasing the transmission capacity by introducing high-order modes [3]. MDM technique within few-mode fiber (FMF) is widely studied as a promising solution to improve the data capacity with controllable mode manipulation [4], [5]. On the other hand, silicon photonics is commonly regarded as a promising candidate for next generation optical network because of low cost, high refractive index contrast, and compatibility with matured CMOS technologies [6], [7]. Hence, coupler utilized as the bridge of FMF and silicon integrated chip is highly desired. However, efficient FMF-chip coupling with low mode crosstalk is still a challenge due to the large mismatch between FMF modes and integrated waveguide mode.

Manuscript received 19 January 2023; revised 14 February 2023; accepted 20 February 2023. Date of publication 22 February 2023; date of current version 2 March 2023. This work was supported by the National Natural Science Foundation of China under Grants 62205312, 61911530161, and 62175220. *(Corresponding author: Mengyuan Ye.)*

Weilun Zhang, Mengyuan Ye, Yunlong Li, and Li Liu are with the School of Automation, China University of Geosciences, Wuhan 430074, China, and also with the Hubei Key Laboratory of Advanced Control and Intelligent Automation for Complex Systems, Wuhan 430074, China (e-mail: weilun@cug.edu.cn; yemy@cug.edu.cn; liyunlong@cug.edu.cn; liliu@cug.edu.cn).

Xiangyu Guo and Yu Yu are with the Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: m202173359@hust.edu.cn; yuyu@mail.hust.edu.cn).

Digital Object Identifier 10.1109/JPHOT.2023.3247980

Edge coupler (EC) and grating coupler (GC) are two common interfaces for chip-fiber coupling. High-order mode coupling within EC scheme [8], [9], [10], [11], [12] show a broadband and polarization independent operation ability. However, it is crucial to carefully select the FMF geometry for efficient coupling. Furthermore, another limitation of EC schemes is its incompatibility with wafer-level testing of photonic devices. Alternatively, GC schemes provide a flexible solution as any point on the chip could be accessed with much relaxed tolerances on fiber alignment [13], [14], [15]. As the most popular solution for fiber-chip coupling, GC schemes for high-order mode coupling are also developed [16], [17], [18], [19], [20]. Typically, wide grating region with long taper is required for efficient mode match between FMF and chip. However such design suffers from large mode crosstalk and large footprint. Recently, a high-order mode coupler utilizing a double-part GC combined with mode selective Y-junction was proposed to achieve both low loss and compact footprint [21]. However, on-chip mode crosstalk is hard to eliminate within the Y-junction. To eliminate on-chip mode crosstalk, structures based on 3D graphene structure [22] and phase-shifted long-period grating [23] have been proposed, demonstrating low insertion loss with high mode extinction ratio. However, large footprint and lack of CMOS compatibility limited their practical application. Therefore, it is still a challenge to realize a compact, CMOS compatible and low crosstalk high-order mode coupler for practical system.

In this paper, we propose and experimentally demonstrate a low-crosstalk high-order mode fiber-chip coupler based on silicon-on-insulator (SOI) platform. By utilizing apodized double-part gratings with mode selective trident, TE_1-LP_{11} mode coupling with low crosstalk could be achieved within the footprint $\sim$270 μm. Design details and the corresponding simulation results are presented. Measured results show the loss is 4.68 dB for TE_1-LP_{11} mode coupling with the mode crosstalk <-23 dB. The proposed coupler could be utilized in the advanced MDM system.

II. Structure Design and Simulation

Schematic of the proposed high-order mode fiber-chip coupler is shown in Fig. 1. The proposed device consists of a mode selective trident and apodized double-part gratings. Due to inevitable on-chip crosstalk, unwanted TE_0 mode will be launched into the coupler with the TE_1 mode. By carefully selecting width and gap

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

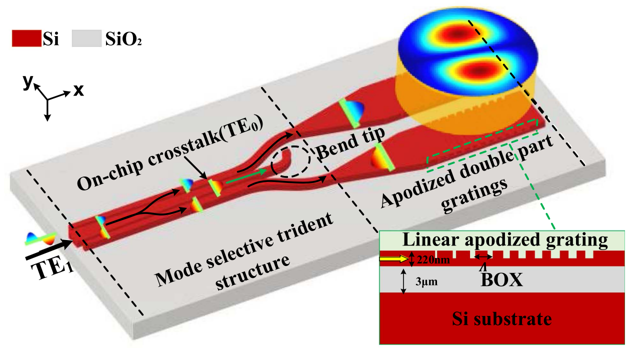

Fig. 1. Schematic of proposed higher-order mode grating coupler.

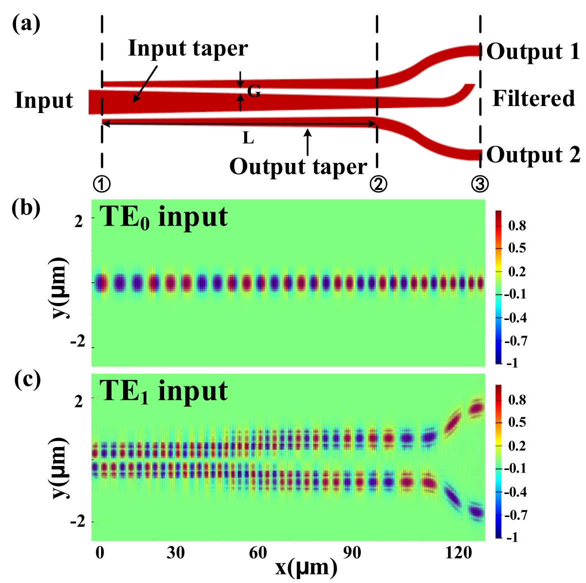

Fig. 2. (a) Structure of the trident; (b) simulated mode field propagation results for TE_0 and (c) TE_1 mode.

of the trident, TE_1 mode at the input port could be coupled into two side tapers adiabatically with identical intensity and phase difference of π, while TE_0 mode will transmit through the central waveguide and eliminated by the bend tip filter. Thus the low crosstalk mode selective coupling can be achieved. 150 μm long linear tapers are utilized to connect the trident and apodized double-part gratings, for adiabatic mode size conversion. The double-part gratings are designed to convert two petal modes in silicon waveguide into LP_{11} mode in FMF. To be noted, apodized design is utilized for the double-part gratings to reduce the coupling loss.

A. Trident Structure

The trident structure is designed to couple TE_1 mode signal and filter TE_0 mode crosstalk launched at the input port. As shown in Fig. 2(a), structure of the trident consists of one input taper, two output tapers and a bend tip filter. Based on the principle of mode evolution, width of the tapers is properly chosen to realize adiabatic TE_1 mode coupling into output tapers while the TE_0 mode maintained at the input taper. Here, the width of the input taper is set from 0.82 μm to 0.57 μm, whereas the width of the output taper varies from 0.2 μm to 0.45 μm. The coupling length of the taper (L) and the gap between two adjacent tapers (G) are optimized to be 100 μm and 200 nm to realize adiabatic TE_1 mode coupling.

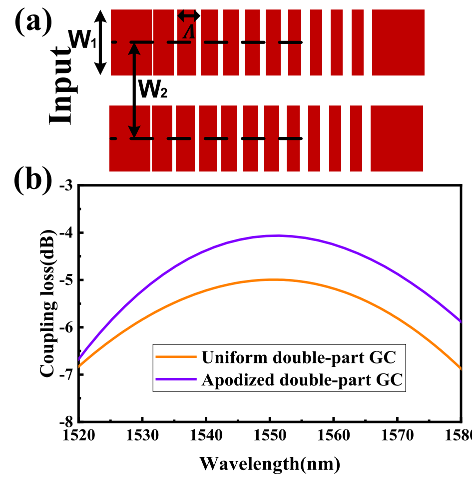

Fig. 3. (a) Top view of the apodized double-part gratings. (b) simulated coupling loss of the apodized and uniform GCs.

Simulated mode field propagation results are shown in Fig. 2(b) and (c), indicating output mode field with identical intensity and phase difference of π at end of the two output tapers for TE_1 mode input, while TE_0 mode propagates through the input taper. In addition, a bend tip filter is utilized at end of the input taper to eliminate unwanted TE_0 mode. The bend waveguide is designed to change the TE_0 mode transmission direction, and thus ensure the unwanted mode not coupling into the gratings. The following tip structure is utilized to avoid light reflection, by squeezing the unwanted TE_0 mode out from the silicon waveguide.

B. Apodized Double-Part Gratings

The double-part gratings are further designed to convert two petal modes in silicon waveguide into LP_{11} mode in FMF. Top view of the double-part gratings is shown in Fig. 3(a). In order to match the LP_{11} mode in FMF, the width of gratings W_1 is optimized to be 6 μm, and the gap W_2 is chosen to be 8 μm. To further reduce the coupling loss, apodized design is utilized for the double-part gratings. Duty cycle of the gratings increases linearly from 0.3 to 0.55, with a fixed grating period (Λ) of 630 nm. The number of grating teeth is optimized to be 22, which is sufficient to reduce the lateral transmittance. To compare the performance of apodized GC with uniform GC, simulations on coupling loss for both schemes are performed. Fig. 3(b) shows the simulation results, demonstrating $\sim$1.2 dB coupling loss improvement could be achieved by utilizing the apodized double-part gratings.

C. Performance Analysis

Fig. 4 shows the simulated insertion loss and mode crosstalk of the proposed device. Insertion loss could be divided into two

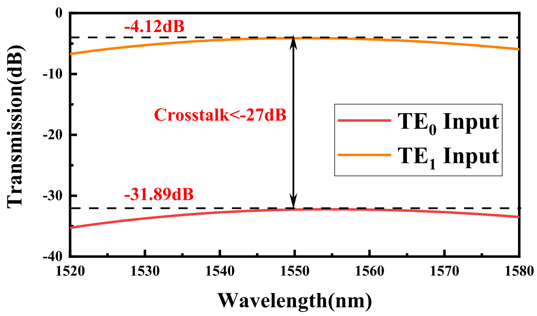

Fig. 4. Simulated transmission spectra of the proposed device.

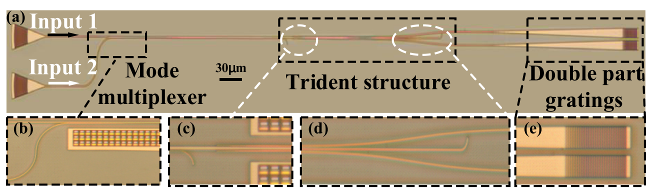

Fig. 5. (a) Full device image, zoom-in image of (b) the mode multiplexer, (c) the input of the trident, (d) the output of the trident, (e) the double-part gratings.

parts, namely mode propagation loss in the trident and mode coupling loss between GC and FMF. The simulation results show that the mode propagation loss in the trident is ~0.1 dB, and the mode coupling loss is ~ 4.12 dB. Mode crosstalk of the proposed device is introduced by the mode interference occurred in both fiber-chip coupling and on-chip mode propagation. Fiber-chip coupling crosstalk could be avoided by utilizing the double part gratings, by separating the two petal modes And the mode selective trident is utilized to filter out the on-chip crosstalk. Simulation results show the mode crosstalk can be suppressed to be <−27 dB by utilizing the bend tip filter.

III. Fabrication

The proposed high-order mode grating coupler is fabricated on an SOI wafer with a 220 nm thick top silicon layer and Box layer of 2 μm. 248 nm deep ultraviolet photolithography and inductively coupled plasma (ICP) etching are used to form the waveguide structure. The microscope images of the fabricated device are presented in Fig. 5(a)–(e). In order to generate TE_1 mode for device performance testing, additional mode multiplexer was fabricated, as shown in Fig. 5(b). Insertion losses of the fabricated mode multiplexer for TE_0 and TE_1 mode are measured to be 0.3 dB and 0.6 dB, respectively.

IV. Measurement and Result

The experimental setup is shown in Fig. 6. A broadband source (BS, ALS-CL-15-B-FA) is utilized to generate a continuous wave in 1520–1580 nm, a polarization beam splitter (PBS, PBC1550SM-FC) and a polarization controller (PC) are cascaded to fix a linear polarized state. The output LP_{01} mode from the PC is coupled into the on-chip device. The output mode from the designed high-order mode grating coupler is coupled by a FMF, and collected by the optical spectrum analyzer (OSA, AQ6370D) for performance analysis. Besides, an infra-red charge-coupled device (CCD, Bobcat-320-Gated) camera is utilized to capture the output field profiles from the FMF output. The core and cladding diameters of the utilized FMF are 14 μm and 125 μm, with the refractive indices of 1.448 and 1.444, respectively.

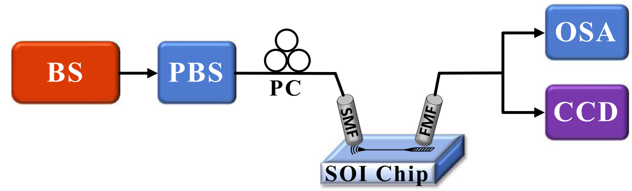

Fig. 6. The measurement setup.

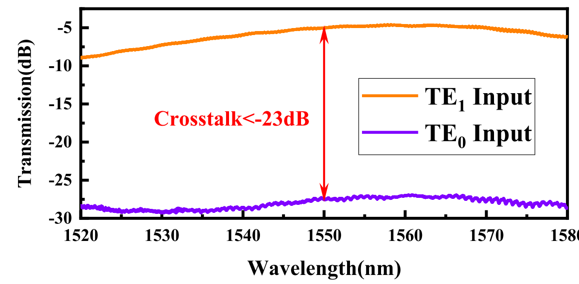

Fig. 7. Measured output transmission spectra with TE_0 and TE_1 mode inputs.

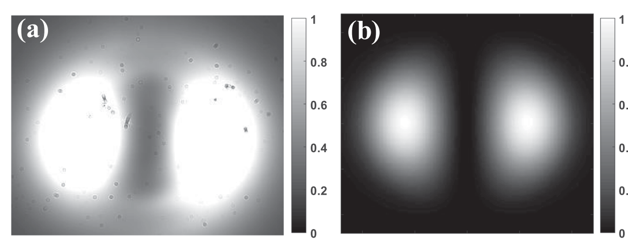

Fig. 8. (a) CCD-captured mode field of FMF with TE_1 mode input. (b) Ideal LP_{11} mode field.

Measured transmission spectra of the fabricated high-order mode grating coupler are shown in Fig. 7. The spectra have been normalized by deducting the losses caused by the input grating couplers and mode multiplexer. For TE_1-LP_{11} mode coupling, insertion loss ~4.68 dB with 1 dB bandwidth~34 nm is measured. To measure the mode crosstalk, TE_0 mode is also launched into the device. Measure results show the mode crosstalk is ~23 dB, indicating low-crosstalk operation is successfully achieved.

To verify the high-order mode coupling of the device more intuitively, an infra-red CCD is utilized to capture the output mode field of the FMF. The captured mode field with TE_1 mode input is shown in Fig. 8(a). As a comparison, mode profile of ideal LP_{11} mode profile is plotted in Fig. 8(b). Through overlap integration between the captured and ideal mode profiles, one can verify that efficient TE_1-LP_{11} mode coupling is successfully achieved.

V. Conclusion

In conclusion, we propose and experimentally demonstrate a high-order mode silicon fiber-chip coupler. By utilizing apodized double-part gratings with mode selective trident, TE_1-LP_{11} mode coupling with low crosstalk could be achieved within the footprint $\sim$270 μm. Design details and the corresponding simulation results are presented. The proposed device is successfully fabricated on SOI platform. Measured results show insertion loss of the fabricated device is $\sim$4.68 dB, while mode crosstalk is <-23 dB. The proposed high-order mode grating coupler could be utilized in the advanced MDM system.

References

[1] M. J. Paniccia, "A perfect marriage: Optics and silicon," *Optik Photonik*, vol. 6, no. 2, pp. 34–38, 2011.

[2] C. R. Doerr and T. F. Taunay, "Silicon photonics core-, wavelength-, and polarization-diversity receiver," *IEEE Photon. Technol. Lett.*, vol. 23, no. 9, pp. 597–599, May 2011.

[3] C. Li, D. Liu, and D. Dai, "Multimode silicon photonics," *Nanophotonics*, vol. 8, no. 2, pp. 227–247, 2019.

[4] D. Richardson, J. Fini, and L. E. Nelson, "Space-division multiplexing in optical fibres," *Nature Photon.*, vol. 7, no. 5, pp. 354–362, 2013.

[5] N. Borhani, E. Kakkava, C. Moser, and D. Psaltis, "Learning to see through multimode fibers," *Optica*, vol. 5, no. 8, pp. 960–966. 2018.

[6] A. Rahim, T. Spusens, R. Baets, and W. Bogaerts, "Open-access silicon photonics: Current status and emerging initiatives," *Proc. IEEE*, vol. 106, no. 12, pp. 2313–2330, Dec. 2018.

[7] S. Y. Siew et al., "Review of silicon photonics technology and platform development," *J. Lightw. Technol.*, vol. 39, no. 13, pp. 4374–4389, Jul. 2021.

[8] M. Ye, W. Zhang, Y. Li, L. Liu, X. Guo, and Y. Yu, "Efficient dual-mode fiber-chip edge coupler using an adiabatic mode evolution trident," *IEEE Photon. Technol. Lett.*, vol. 34, no. 22, pp. 1234–1237, Nov. 2022.

[9] W. Shen, J. Du, J. Xiong, L. Ma, and Z. He, "Silicon-integrated dual-mode fiber-to-chip edge coupler for 2 × 100 Gbps/lambda MDM optical interconnection," *Opt. Exp.*, vol. 28, no. 22, pp. 33254–33262, 2020.

[10] Y. Lai, Y. Yu, S. Fu, J. Xu, P. P. Shum, and X. Zhang, "Efficient spot size converter for higher-order mode fiber-chip coupling," *Opt. Lett.*, vol. 42, no. 18, pp. 3702–3705, 2017,.

[11] L. Cheng et al., "Ultra-compact dual-mode mode-size converter for silicon photonic few-mode fiber interfaces," *Opt. Exp.*, vol. 29, no. 21, pp. 33728–33740, 2021.

[12] Z. Li, Y. Lai, Y. Yu, and X. Zhang, "Reconfigurable fiber-chip mode converter with efficient multi-mode coupling function," *IEEE Photon. Technol. Lett.*, vol. 32, no. 7, pp. 371–374, Apr. 2020.

[13] A. Mekis et al., "A grating-coupler-enabled CMOS photonics platform," *IEEE J. Sel. Topics Quantum Electron.*, vol. 17, no. 3, pp. 597–608, May/Jun. 2011.

[14] T. Watanabe, Y. Fedoryshyn, and J. Leuthold, "2-D grating couplers for vertical fiber coupling in two polarizations," *IEEE Photon. J.*, vol. 11, no. 4. Aug. 2019, Art. no. 7904709.

[15] Y. Xue, H. Chen, Y. Bao, J. Dong, and X. Zhang, "Two-dimensional silicon photonic grating coupler with low polarization-dependent loss and high tolerance," *Opt. Exp.*, vol. 27, no. 16, pp. 22268–22274, 2019.

[16] Y. Tong, W. Zhou, X. Wu, and H. K. Tsang, "Efficient mode multiplexer for few-mode fibers using integrated silicon-on-insulator waveguide grating coupler," *IEEE J. Quantum Electron.*, vol. 56, no. 1, Feb. 2020, Art. no. 8400107.

[17] J. L. Pita Ruiz et al., "Efficient integrated tri-modal coupler for few-mode fibers," *Opt. Exp.*, vol. 30, no. 2, pp. 2539–2546, 2022.

[18] D. Garcia-Rodriguez, J. L. Corral, A. Griol, and R. Llorente, "Bimodal grating coupler design on SOI technology for mode division multiplexing at 1550 nm," *Opt. Exp.*, vol. 26, pp. 19445–19455, 2018.

[19] Y. Ding, H. Ou, J. Xu, M. Xiong, and C. Peucheret, "On-chip mode multiplexer based on a single grating coupler," in *Proc. IEEE Photon. Conf.*, 2012, pp. 707–708.

[20] X. Zhou and H. K. Tsang, "High efficiency multimode waveguide grating coupler for few-mode fibers," *IEEE Photon. J.*, vol. 14, no. 4, Aug. 2022, Art. no. 6643405.

[21] Y. Lai, Y. Yu, S. Fu, J. Xu, P. P. Shum, and X. Zhang, "Compact double-part grating coupler for higher-order mode coupling," *Opt. Lett.*, vol. 43, no. 13, pp. 3172–3175, 2018.

[22] Q. Huang and K. S. Chiang, "Polarization-insensitive ultra-broadband mode filter based on a 3D graphene structure buried in an optical waveguide," *Optica*, vol. 7, no. 7, pp. 744–745, 2020.

[23] Q. Huang, W. Wang, W. Jin, and K. S. Chiang, "Ultra-broadband mode filter based on phase-shifted long-period grating," *IEEE Photon. Technol. Lett.*, vol. 31, no. 13, pp. 1052–1055, Jul. 2019.