Ultra-Compact Silicon Mode (De)Multiplexer Based on Single Dielectric Slot

Yaotian Zhao, Jinlong Xiang, Yu He, Xuhan Guo* and Yikai Su

State Key Laboratory of Advanced Optical Communication Systems and Networks Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.
*guoxuhan@sjtu.edu.cn

Abstract *A two-mode (de)multiplexer is demonstrated by mode coupling control based on a single dielectric slot. The input light could be coupled into a TE_0 or TE_1 mode with low insertion losses (<0.5 dB), low crosstalk (<–10 dB) and state-of-the-art compact size of 1.8×1 μm².*

Introduction

Silicon-on-insulator (SOI) platform has been developed successfully for various applications due to the maturity process technology and unique material properties[1], and mode-division multiplexing (MDM) technologies based on SOI platform are attracting more and more attention as one of the most promising technologies to further increase on-chip communication capacity[2]. The introduction of higher-order modes could effectively increase channel numbers for data transmission in a multimode waveguide, thus one essential device is the mode (de)multiplexer to multiplexing different optical carrier signals onto a single multimode waveguide with different guided modes. The methods used to manipulate modes could be largely group into three categories[3]: phase matching, beam shaping and coherent scattering. For example, based on the phase matching method, asymmetric directional couplers (ADCs) can couple a given mode of one waveguide into the desired mode of another waveguide. This kind of device could be scaled for very high-order modes[4][5], yet the fabrication tolerance is a major impediment due to the critical phase-matching condition. While based on the beam shaping method, mode converters realized by Mach-Zehnder interferometers (MZI) benefit from reasonably good fabrication tolerance and wide bandwidth[6], but they could not well address the challenge of compact footprints for high-density integrations.

In recent years, a new method employing dielectric metasurface structures have emerged for mode-order conversions[2] [3]. This method is burgeoning because it could realize high-quality mode conversion with small footprints as well as retain good performance. Dielectric metasurface structures has been widely studied for spatial mode conversion between two different guided modes in a single waveguide[7] [8], however, few work is reported for dielectric metasurface structures employed for mode (de)multiplexers. Our previous work has investigated the principle of two modes conversion manipulated by dielectric slots used for mode converters[9], here we further extend this concept for a two-mode (de)multiplexer for on-chop MDM system.

In this paper, we propose an ultra-compact and low-loss two-mode (de)multiplexer exploiting only a single fully etched dielectric slot. As the etched dielectric slot could well manipulate the coupling between different guided modes, the light of fundamental TE_0 mode launched from the upper port would be "unaffectedly" maintained as TE_0 mode, while the light forms the lower port would be coupled into the TE_1 mode. These two-mode multiplexing could be realized within a 1.8μm-long slot. As in our previous work the mode conversion by single slot etch is demonstrated explicitly[9], this device is characterized by mirroring the device itself to further explore the multiplexing function. The measured insertion losses are less than 0.5 dB with crosstalk less than –10 dB.

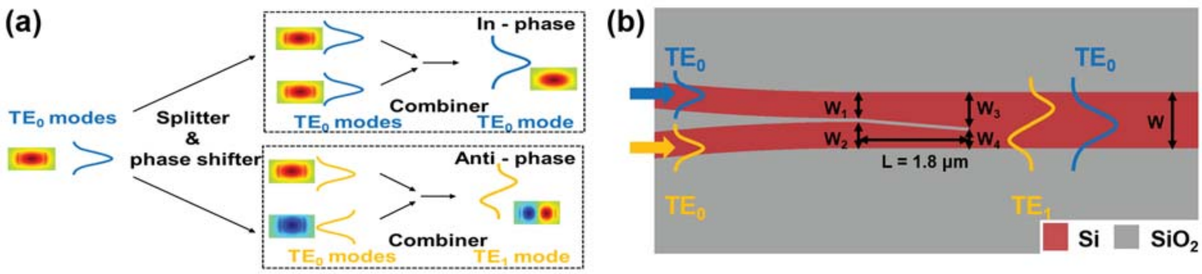

Fig. 1: Schematic diagram of (a) the beam shaping method and (b) the proposed TE_0 and TE_1 mode (de)multiplexers

2020 European Conference on Optical Communications (ECOC) | 978-1-7281-7361-0/20/$31.00 ©2020 IEEE | DOI: 10.1109/ECOC48923.2020.9333165

978-1-7281-7361-0/20/$31.00 ©2020 IEEE

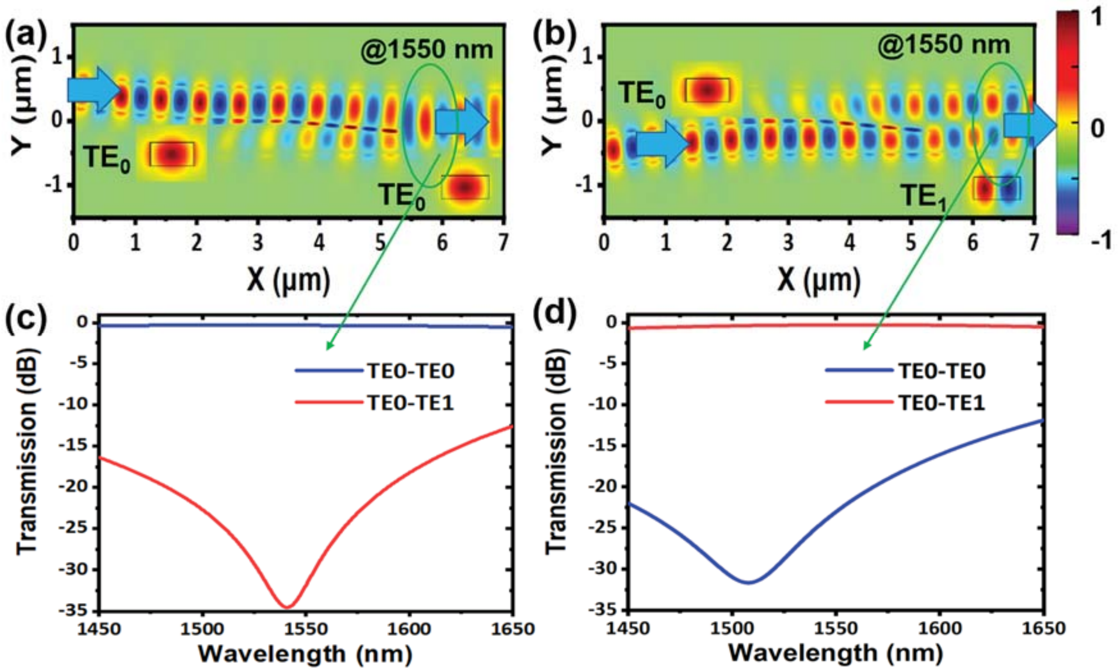

Fig. 2: Simulated electric field (E_y) distributions at 1550 nm when (a) light launched from the upper waveguide and (b) from the lower waveguide. Simulated transmission spectra of selected modes when (c) light launched from the upper waveguide and (d) from the lower waveguide.

Operation principle and structure design

The working principle of the mode (de)multiplexer could be explained with the beam shaping method similar to MZI-based mode converters[6]. As shown in figure 1(a), two in-phase TE_0 modes would combine and produce a TE_0 mode directly. On the other hand, two antiphase TE_0 modes would combine to TE_1 mode due to their similar mode profiles and large electric field overlap[6].

Figure 1(b) schematically presents our proposed TE_0 and TE_1 mode (de)multiplexer. The device is designed on a standard SOI platform, and the working principle could be explained as follows: The fully etched slot could divide the silicon bus waveguide into two taper waveguides: the upper wide waveguide and the lower narrow waveguide. When the light is launched from the upper waveguide into the slot waveguide, two phenomena would take effect simultaneously. Firstly, the light would gradually couple in to the lower waveguide as a result of evanescent wave coupling. Secondly, since the two waveguides have different widths, the propagation constants would be different, hence leading to a phase differences during the light propagation. Note that the phase in the driven field of evanescent wave coupling always lags by 90°[10], and the taper could be designed to introduce another 90° phase delay, thereby leading to 0° or 180° phase differences between the two mode fields, thus generating the TE_0 or TE_1 mode respectively. When the light in two waveguides have equal power and in-phase, the same TE_0 mode would be “unaffectedly” regenerated in the bus waveguide. Likewise, when the light launched from the lower waveguide, two antiphase TE_0-like modes would be generated to produce a TE_1 mode. In our design shown in figure 1(b), W_1, W_2, W_3 and W_4 are optimized by iterative algorithms and set to be 475 nm, 475 nm, 640 nm and 310 nm respectively. The slot is fully etched with the width of 50 nm to introduce strong coupling between different guided modes in the waveguide, thereby leading to a short coupling length. The silicon waveguide width W is set to be 1 μm to support both the TE_0 and TE_1 modes.

Simulation results

The three-dimensional finite-difference time-domain (3D-FDTD) method is implemented to evaluate the performance of our proposed device. Figures 2(a) and 2(b) show the simulated electric field (E_y) distribution at the wavelength of 1550 nm. It can be seen that the input TE_0 mode from the upper waveguide is gradually coupled into the lower waveguide and the in-phase condition is finally achieved, thus “unaffectedly” regenerating the TE_0 mode. Similarly, when the light launched from the lower waveguide, the antiphase condition would be achieved to generate a TE_1 mode. Figures 2(c) and 2(d) show the simulated transmission spectra when the light launched from the upper or lower port respectively. We use a mode expansion solver to monitor the transmission spectra of a selected waveguide mode. Specifically, for light injected from the upper port, the TE_0-to-TE_0 conversion losses are

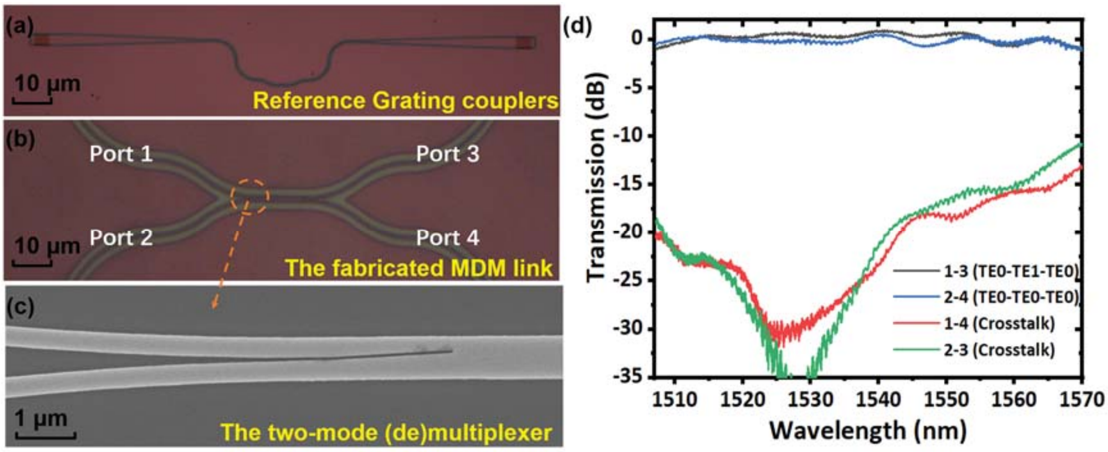

Fig. 3: Optical microscope photos of (a) reference grating couplers, (b) the fabricated MDM link consisting of two mode (de)multiplexers. (c) SEM photo of the single dielectric slot mode (de)multiplexer. (d) Measured transmission spectra normolized by the grating couplers.

less than 0.5 dB and the TE_0-to-TE_1 crosstalk is lower than –12 dB over an ultra large bandwidth of 200 nm from 1450 nm to 1650 nm (conversion loss of 0.29 dB and crosstalk of –31 dB at 1550 nm). And for light injected from the lower port, the TE_0-to-TE_1 conversion losses are less than 0.64 dB and the TE_0-to-TE_0 crosstalk is lower than –11.5 dB from 1450 to 1650 nm (conversion loss of 0.23 dB and crosstalk of –23 dB at 1550 nm).

Fabrication and measurement

The device has been fabricated on the standard SOI platform with 220 nm top silicon and 1μm-thick silicon dioxide cladding. The structures are patterned by e-beam lithography (Vistec EBPG 5200+) and inductively coupled plasma etching (SPTS, DRIE-I), and the silicon dioxide cladding is deposited by plasma-enhanced chemical vapour deposition (PECVD, Oxford). The device is characterized mainly by an optical power meter (Keysight, N7744A) and a tunable continuous wave laser (Keysight, 81960A). Figures 3(a)-(c) show the optical microscope and scanning electron microscope (SEM) photos of the fabricated structures. Figures 3(a) presents the reference grating couplers used for normalizing the measured data. The device was measured by the self-mirroring structure as shown in Figure 3(b). Besides, in our previous work of dielectric slot mode converters, we have also shown good performance of the TE_0-to-TE_1 mode conversion measured by ADCs[9]. The measured responses are presented in figure 3(d), and the legend *"i - j"* means the light is injected from port *i* and measured at port *j* [see figure 2(d)]. The transmission spectra indicate that the insertion losses are less than 1 dB (thus 0.5 dB for a single device) with the crosstalk less than –10 dB from 1510 nm to 1570 nm. The bandwidth measured is limited by the source laser bandwidth (Keysight, 81960A, 1507 nm~1620 nm) and the wavelength dependent grating coupler. Broader bandwidth could be expected with larger-range tunable laser sources and using edge coupler.

Tab. 1: Comparison of Some Experimentally Demonstrated Mode (De)Multiplexers

Structure	Size (μm²)	IL (dB)	CT (dB)	BW (nm)
Y-junction[11]	180×2	1.5	−19	90
SWG Adiabatic Coupler[12]	55×3	2.6	−18.8	130
ADC[13]	50×1.3	0.3	−16	100
MMI[14]	7.24×1.5	2	−15	50
Inverse design[15]	3×2.4	1	−24	60
Dielectric slot (This work)	1.8×1	0.5	−10	60

IL: insertion loss, CT: crosstalk, BW: bandwidth.

Conclusions

In summary, we have proposed and experimentally demonstrated an ultra-compact two mode (de)multiplex based on a simple single dielectric slot, which could manipulate two modes coupling simultaneously. Table1 compares the device experimental performances with other up-to-date on-chip mode (de)multiplexers. Our proposed device has shown an ultra-compact footprint of only 1.8×1 μm², which is the most compact for a mode (de)multiplexer until now. The device also has low insertion losses of 0.5 dB with low crosstalk less than –10 dB. A larger operation bandwidth of 200 nm is possible but limited by the experimental equipment and utilized couplers. We hope our proposed device could further promote the development of high-density MDM systems.

References

[1] P. Dong, Y. K. Chen, G. H. Duan, and D. T. Neilson, “Silicon photonic devices and integrated circuits,” *Nanophotonics*, vol. 3, no. 4–5, pp. 215–228, 2014.

[2] C. Li, D. Liu, and D. Dai, “Multimode silicon photonics,” *Nanophotonics*, vol. 8, no. 2, pp. 227–247, 2018.

[3] Y. Su, Y. Zhang, C. Qiu, X. Guo, and L. Sun, “Silicon Photonic Platform for Passive Waveguide Devices: Materials, Fabrication, and Applications,” *Adv. Mater. Technol.*, vol. 5, no. 8, pp. 1–19, 2020.

[4] Y. He *et al.*, “Silicon high-order mode (De)multiplexer on single polarization,” *J. Light. Technol.*, vol. 36, no. 24, pp. 5746–5753, 2018.

[5] J. Wang, S. He, and D. Dai, “On-chip silicon 8-channel hybrid (de)multiplexer enabling simultaneous mode- and polarization-division-multiplexing,” *Laser Photonics Rev.*, vol. 8, no. 2, pp. 18–22, 2014.

[6] C. Sun, Y. Yu, G. Chen, and X. Zhang, “On-chip switch for reconfigurable mode-multiplexing optical network,” *Opt. Express*, vol. 24, no. 19, p. 21722, 2016.

[7] C.-C. Huang and C.-C. Huang, “Mode conversion by refractive-index perturbation based on a single trench on a silicon waveguide,” *Opt. Express*, vol. 28, no. 13, pp. 18986–18999, 2020.

[8] H. Wang, Y. Zhang, Y. He, Q. Zhu, L. Sun, and Y. Su, “Compact Silicon Waveguide Mode Converter Employing Dielectric Metasurface Structure,” *Adv. Opt. Mater.*, vol. 7, no. 4, pp. 1–6, 2019.

[9] Y. Zhao *et al.*, “Ultra-compact silicon mode-order converters based on dielectric slots,” *Opt. Lett.*, vol. 45, no. 13, pp. 3797–3800, 2020.

[10] C. Pollock and M. Lipson, *Integrated photonics*, vol. 20, no. 25. Springer, 2003.

[11] Z. Zhang, Y. Yu, and S. Fu, “Broadband On-Chip Mode-Division Multiplexer Based on Adiabatic Couplers and Symmetric Y-Junction,” *IEEE Photonics J.*, vol. 9, no. 2, 2017.

[12] L. Xu *et al.*, “Ultra-Broadband and Compact Two-Mode Multiplexer Based on Subwavelength-Grating-Slot-Assisted Adiabatic Coupler for the Silicon-on-Insulator Platform,” *J. Light. Technol.*, vol. 37, no. 23, pp. 5790–5800, 2019.

[13] Y. Ding, J. Xu, F. Da Ros, B. Huang, H. Ou, and C. Peucheret, “On-chip two-mode division multiplexing using tapered directional coupler-based mode multiplexer and demultiplexer,” *Opt. Express*, vol. 21, no. 8, p. 10376, 2013.

[14] Z. Wang, C. Yao, Y. Zhang, and Y. Su, “Ultra-Compact and Broadband Silicon Two-Mode Multiplexer Based on Asymmetric Shallow Etching on a Multi-Mode Interferometer,” *2020 Opt. Fiber Commun. Conf. Exhib. OFC 2020 - Proc.*, vol. 1, pp. 5–7, 2020.

[15] W. Chang *et al.*, “Ultra-compact mode (de) multiplexer based on subwavelength asymmetric Y-junction,” *Opt. Express*, vol. 26, no. 7, p. 8162, 2018.