European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Ultra-Broadband Silicon Dual-Polarization Mode-Order Converter Assisted with Subwavelength Gratings

Zhe Yuan, Yongchen Wang, Mengfan Cheng, Qi Yang, Ming Tang, Deming Liu, Lei Deng

School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, 430074, China, denglei_hust@mail.hust.edu.cn

Abstract *We demonstrate an ultra-broadband dual-polarization mode-order converter using subwavelength gratings. The device with 1dB bandwidth over 380nm is achieved in simulation. The fabricated device has low insertion loss (<1.59dB), low crosstalk (<-15.6dB), and 1dB bandwidth exceeds 80nm which is larger than the reported highest level. ©2022 The Author(s)*

Introduction

With the increasing demand for communication capacity, the research on mode division multiplexing (MDM) transmission technology has become one of the most attractive technologies in the future optical fiber communication system. The MDM method utilizes the orthogonality of the different eigenmodes in the waveguide to multiplex the information over multimode waveguides. Lots of multimode devices have been reported to use in MDM systems [1-4]. Among these devices, the broadband mode-order converter, which is used to switch signals carried on modes with different mode orders in a large bandwidth, serves as a key device to realize multimode transmission and optical switching networks.

The simultaneous mode and polarization division multiplexing (PDM-MDM) technique is a promising technology for optical fiber communication in the future. Compared with the MDM transmission strategy, it can double the transmission capacity. However, the effective indices of transverse electrical (TE) and transverse magnetic (TM) modes are very different in waveguides, which makes it difficult to realize high-efficiency parallel mode-order conversion of two polarizations with a mode-order converter in identical device geometry. Several dual-polarization mode-order converters (DPMOCs) have been reported, such as using Si-Si_3N_4 phase plate waveguide [5] or optical metasurface based on inverse-design methods [6]. Nevertheless, these devices can only achieve a bandwidth of less than 40nm in experiments. This limits the application of technologies such as ultra-wideband wavelength division multiplexing (WDM) to expand transmission capacity.

The subwavelength grating (SWG) waveguide, which has effective capabilities of diffraction suppression and refractive index manipulation [7], has been extensively researched recently. In this work, we propose an ultra-broadband mode-order converter for both TE and TM modes for the first time. By introducing the SWG waveguide into Mach–Zehnder interferometer (MZI) based mode-order converter, the effective indices of TE and TM modes are manipulated simultaneously, contributing to the parallel mode-order conversion process for both polarizations. The device with 1 dB bandwidth over 380 nm is achieved in simulation. In the experimental demonstration, the SWG-assisted DPMOC is successfully fabricated, and its footprint is as small as 18.4 μm×2.5 μm. Meanwhile, limited by the wavelength range of the light source, the measured bandwidth of low insertion loss (<1.59 dB) and low crosstalk (CT) (<-15.6 dB) for both polarizations can cover the wavelength range from 1530 to 1610 nm.

Device structure and principle

Fig. 1 shows the three-dimensional (3D) schematic of the proposed ultra-broadband DPMOC together with a cross-sectional view of the input waveguide and an enlarged view of the SWG structure. This chip is based on the 340 nm thick silicon platform surrounded by a silicon dioxide (SiO_2) upper cladding and buried oxide

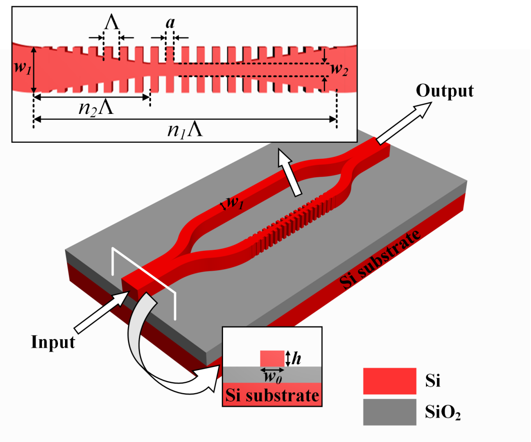

Fig. 1: 3D schematic of the proposed DPMOC, together with a cross-sectional view of the input waveguide and an enlarged view of the SWG structure.

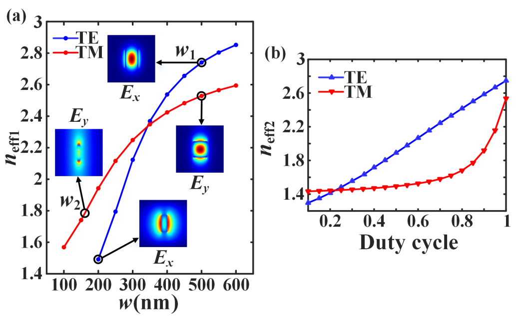

Fig. 2: (a) The effective indices of TE and TM fundamental modes in 340 nm strip waveguide with width varied. (b) The effective indices of TE and TM fundamental modes in 340 nm SWG waveguide with duty cycle varied.

(BOX) layer. Si and SiO_2 refractive indices are $n_{Si}(\lambda_0)$ = 3.476 and $n_{SiO2}(\lambda_0)$ = 1.444 at the wavelength of λ_0 = 1550 nm. One arm of the MZI-based mode-order converter is a strip waveguide and the other arm is the SWG waveguide structure, where the width of the SWG structure is w_1. The whole SWG structure has the same pitch width of Λ and duty cycle of a/Λ. As shown in Fig. 1, the tapered and inverse-tapered waveguides, which have the same tapered length of $n_2\Lambda$ and taper tip-width of w_2, are connected by a short narrow nanowire, and they are all embedded in the SWG-wire structure.

The three-dimensional finite-difference time-domain (3D-FDTD) method is implemented to analyze the modal characteristics of strip waveguides and the SWG waveguide. Fig. 2(a) shows the effective indices n_{eff1} of guided fundamental TE and TM modes for the strip waveguide as its width varies. It can be inferred that ultra-high birefringence exists in the silicon nanophotonic waveguides, which results in very different effective indices between TE and TM modes. It is worth mentioning that the TE_0 mode becomes leaky when w<0.2 μm. Fig. 2(b) shows the effective indices n_{eff2} of guided fundamental TE and TM modes for the SWG waveguide as the duty cycle varies. Here the width of the SWG waveguide w_1 is 0.5 μm. By selecting the right duty cycle, the effective indices difference δn of modes for both polarization between the two MZI arms can be the same, and in this way, the device is polarization insensitive. Meanwhile, the MZI-based mode-order converter with engineered SWG has a δn that is less dependent on wavelength [8].

To reduce the loss caused by the mutation of waveguide width, the tapered and inverse-tapered waveguides are introduced to connect with input and output waveguides, respectively. On the other hand, the total length of the tapered and inverse-tapered waveguide is not as small as to be negligible compared to DPMOC, so the change in the effective indices introduced by them must be taken into account. By co-optimizing the number of periods of SWG, the parameters of tapered and middle narrow waveguides, DPMOC with high performance and ultra broadband can be designed.

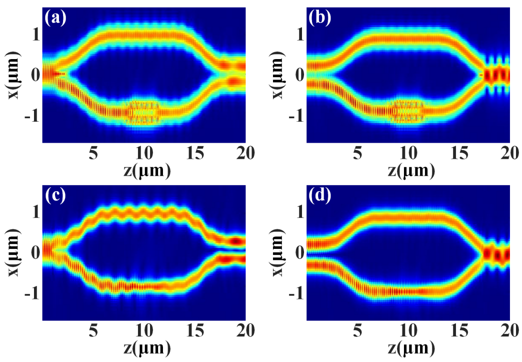

Fig. 3: Distribution of simulated electric field at 1550 nm when (a) TE_0, (b) TE_1, (c) TM_0 and (d) TM_1 mode is input into the proposed DPMOC, respectively.

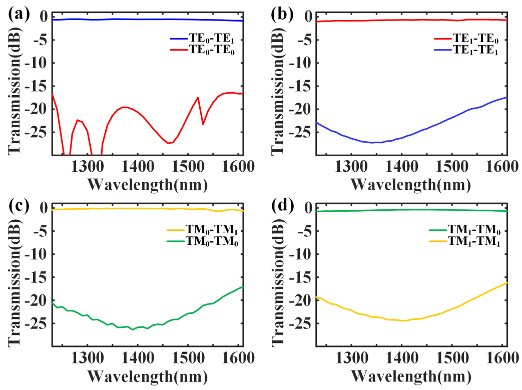

Fig. 4: Simulated transmission spectra when (a) TE_0, (b) TE_1, (c) TM_0, (d) TM_1 mode is input into the proposed DPMOC, respectively.

Figs. 3(a)-3(d) show the distribution of the simulated electric field at 1550 nm when four different modes are input to the DPMOC. It can be seen that this device can realize TE_0-TE_1, TE_1-TE_0, TM_0-TM_1, and TM_1-TM_0 mode conversion process simultaneously, and the mode profile at the output has a very high mode purity. Figs. 4(a)-4(d) show the simulated transmission spectra of four-mode input. It can be seen that the transmission efficiency of each output is higher than -0.88 dB and the crosstalk is below -16.4 dB in the wavelength range from 1230 ~ 1610 nm. The transmission response is almost flat, with a very small drop at longer wavelengths. It can be inferred that the optical bandwidths of all the four modes are wider than 380 nm.

Experimental results

The designed DPMOC has been fabricated on a standard SOI wafer with 340-nm-thick top silicon and 2-μm-thick buried dioxide. The pattern was

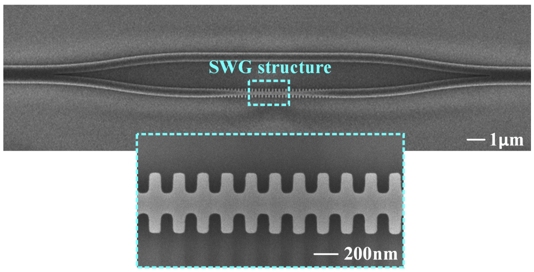

Fig. 5: SEM images of the proposed DPMOC and detail view of SWG-based structure.

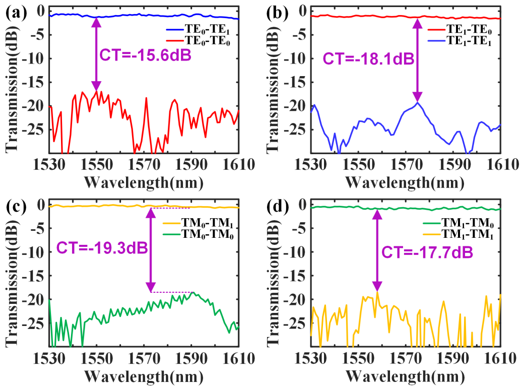

Fig. 6: Measured transmission spectra when (a) TE_0, (b) TE_1, (c) TM_0, (d) TM_1 mode is input into the proposed DPMOC, respectively.

defined using 100 keV electron beam lithography (EBL) and the photoresist is AR-P 6200. An inductively coupled plasma (ICP) dry-etching process is used to transfer the pattern to the silicon layer. Finally, a 2-μm-thick silica layer has been deposited as the upper cladding using a plasma-enhanced chemical vapor deposition (PECVD) process at 300°C. Fig. 5 shows the top-view scanning electron microscope (SEM) picture of the fabricated DPMOC along with an enlarged view of the SWG-based structure. It is captured before the upper silica cladding is deposited. The focused TE/TM-polarized grating couplers (GC) working for the corresponding wavelength band have been fabricated at the input/output ends to couple light between the fibers and the silicon waveguides.

The experimental setup consists of an amplified spontaneous emission (ASE), a polarization controller, a fiber-chip coupling stage, and an optical spectrum analyzer (OSA) to obtain the spectrum of the output optical signal. Figs. 6(a)-6(d) depicts the measured transmission spectra of the device injected with $TE_0/TE_1/TM_0/TM_1$ modes, respectively. The results have been normalized according to the reference GCs fabricated on the same wafer. It can be seen that the measurement results of the four modes agree well with the simulation results. The insertion loss of DPMOC for each mode is less than 1.59 dB and the crosstalk is less than -15.6 dB in the range of 1530 nm to 1610 nm. The additional losses caused by fabrication errors lead to a slight deterioration in device performance compared to simulation predictions. It can be noted that the measured crosstalk of TE polarized modes is slightly higher than the simulation, while the measured crosstalk of TM polarized modes is slightly lower than the simulation. Comparing these results with the simulation of fabrication errors, it can be inferred that the duty cycle of SWG is larger than expected. Due to the limitation of the light source, we cannot obtain the device performance in a wider wavelength range. Nevertheless, based on the quite flat measured transmission spectra, it can be inferred that the actual 1 dB bandwidth is much larger than 80nm. For the sake of comparison, Table 1 shows the performance of other reported DPMOCs.

Conclusions

A DPMOC with high performance and ultra broadband has been proposed and demonstrated for the first time by introducing the SWG structure into the MZI-based mode-order converter. Simulation results show that the proposed device has a large 1 dB bandwidth over 380 nm. The fabricated DPMOC has a low insertion loss of less than 1.59 dB and low crosstalk of less than -15.6 dB in the wide bandwidth over 80 nm. This device could be potentially used for the deployment of ultra-broadband PDM-MDM transmission.

Acknowledgments

National Key Research and Development Program of China (2018YFB1800904).

References

[1] B. E. Abu-elmaaty, M. S. Sayed, R. K. Pokharel, and H. M. H. Shalaby, "General silicon-on-insulator

Tab. 1: Comparison Between the reported DPMOCs.

Reference	Platform	Insertion loss (dB)	Crosstalk (dB)	1 dB Bandwidth (nm)
[5]*	SOI/Si_3N_4	> 2.79	-	< 100
[6]	SOI	< 2.3	< -11.8	< 40
This work* (simulated)	SOI	< 0.88	< -16.4	> 380
This work (measured)	SOI	< 1.59	< -15.6	> 80

*Values marked with an asterisk correspond to simulation results.

higher-order mode converter based on substrip dielectric waveguides", *Applied Optics*, vol. 58, no. 7, p. 1763, 2019, DOI: 10.1364/AO.58.001763.

[2] Y. He, Y. Zhang, Q. Zhu, S. An, R. Cao, X. Guo, C. Qiu, and Y. Su, “Silicon High-Order Mode (De)Multiplexer on Single Polarization,” *Journal of Lightwave Technology*, vol. 36, no. 24, pp. 5746–5753, 2018, DOI: 10.1109/JLT.2018.2878529.

[3] Y. Liu, Z. Zhong, S. Wang, Y. Liu, Y. Yao, J. Du, Q. Song, and K. Xu, “Four-mode waveguide crossing via digitized meta-structure,” in *Optical Fiber Communication Conference (OFC) 2021*, Washington, DC, 2021, p. F2B.3. DOI: 10.1364/OFC.2021.F2B.3.

[4] C. Sun, Y. Yu, G. Chen, and X. Zhang, “On-chip switch for reconfigurable mode-multiplexing optical network,” *Optics Express*, vol. 24, no. 19, p. 21722, 2016, DOI: 10.1364/OE.24.021722.

[5] B. E. Abu-elmaaty, M. S. Sayed, H. M. H. Shalaby, R. K. Pokharel, and A. Srivastava, “Silicon-on-Insulator Fundamental to First-Order Dual Polarization Mode Converter based on Si-Si_3N_4 Phase Plate Waveguide,” in *2018 20th International Conference on Transparent Optical Networks (ICTON)*, Bucharest, 2018, pp. 1–4. DOI: 10.1109/ICTON.2018.8473997.

[6] H. Jia, H. Chen, J. Yang, H. Xiao, W. Chen, and Y. Tian, “Ultra-compact dual-polarization silicon mode-order converter,” *Optics Letters*, vol. 44, no. 17, p. 4179, 2019, DOI: 10.1364/OL.44.004179.

[7] R. Halir, A. Ortega-Moñux, D. Benedikovic, G. Z. Mashanovich, J. G. Wangüemert-Pérez, J. H. Schmid, Í, Molina-Fernández, and P. Cheben, “Subwavelength-Grating Metamaterial Structures for Silicon Photonic Devices,” *Proceedings of the IEEE*, vol. 106, no. 12, pp. 2144–2157, 2018, DOI: 10.1109/JPROC.2018.2851614.

[8] Y. Wang, Z Lu, M Ma, H Yun, F Zhang, N. A. F. Jaeger, and L Chrostowski, “Compact Broadband Directional Couplers Using Subwavelength Gratings,” *IEEE Photonics Journal*, vol. 8, no. 3, pp. 1–8, 2016, DOI: 10.1109/JPHOT.2016.2574335.