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Silicon photonic mode multiplexers based on subwavelength metamaterials and on-chip beam forming

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ABSTRACT

Integration of photonic circuits on silicon offers a unique opportunity to address the scaling of inter- and intra-chip communications in an energy-efficient and cost-effective manner. Mode-division multiplexing (MDM) is deemed as one of the most promising technologies to increase aggregated data bandwidth and avoid a communication capacity crunch. In this invited talk, we review our latest advances on integrated silicon mode multiplexers, including new topologies based on subwavelength grating (SWG) metamaterials for extended broadband operation and higher-order mode support. Specifically, we report on an ultra-broadband multiplexer based on a phase shifter and a multimode interference (MMI) coupler both engineered with subwavelength metamaterials. Experimental measurements of a complete multiplexer-demultiplexer link show losses lower than 2 dB and crosstalk below -17 dB over a bandwidth of 245 nm (1427 – 1672 nm).

Keywords: Photonic integrated circuits, silicon photonics, mode-division multiplexing, subwavelength gratings, metamaterials

1. INTRODUCTION

Over the last few decades, the digital revolution has generated a globally interconnected society with a burgeoning appetite for information. Data creation is expected to grow exponentially in the forthcoming years with a predicted annual rate of 163 zettabytes by 2025 [1]. This data-driven scenario, combined with the cloud nature of many new applications, has led to the creation of hyperscale data centers where information is processed and transferred internally on a massive scale [2]. However, the breakdown of Dennard scaling has resulted in the impossibility of increasing clock frequencies of modern central processing units, shifting the focus to multicore processors as an alternative way to improve the performance of modern data centers. On-chip interconnects must typically support data rates on the order of several TB/s without generating excessive heat [3]. The use of metallic wires leads to physical bottlenecks that limit the bandwidth, operating speed, and power consumption of inter- and intra-chip communications, becoming a constraint for on-chip ultra-dense optical transmission and high-speed data computing [4-6].

Integration of photonic circuits on silicon offers a unique opportunity to address this challenge in an energy-efficient and cost-effective manner [7], as it benefits from the mature manufacturing infrastructure of the complementary metal-oxide-semiconductor microelectronics industry. Current silicon-based optical interconnects rely on wavelength-division-

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multiplexing (WDM) technique, where a limited bandwidth is exploited to carry different data channels at distinct wavelengths. Mode-division multiplexing (MDM) is deemed as one of the most promising technologies to increase aggregated data bandwidth and avoid a communication capacity crunch [8]. In MDM, each spatial mode encodes an independent data channel sharing the same wavelength. Thus, mode (de)multiplexers play a key role in any MDM system to convert fundamental modes into higher-order modes and combine them into a multimode waveguide, or vice versa. Several mode multiplexers have been reported, including asymmetric Y-junctions, asymmetric directional couplers, adiabatic tapers, adiabatic couplers, devices based on multimode interference (MMI) couplers, pixelated-meta structures and bent directional couplers, to name a few [9-15]. Nevertheless, these conventional approaches are limited either by poor crosstalk values, narrow bandwidths, or large device footprints.

2. TWO-MODE MULTIPLEXER BASED ON SUBWAVELENGTH METAMATERIALS

Since their first demonstration in 2006, silicon subwavelength grating (SWG) metamaterials have emerged as a powerful tool for designing high-performance photonic integrated devices [16,17]. An SWG is a nanostructured waveguide with a period less than half the wavelength of the propagating light, suppressing diffractive effects and allowing propagation of Floquet-Bloch modes [18]. These periodic structures synthesize different homogeneous metamaterials (i.e., non-periodic artificial materials) whose optical properties can be tailored by judicious design of the grating geometry. The extended design space provided by SWG waveguides has been exploited to demonstrate silicon photonic devices with unprecedented performance, such as highly-efficient fiber-chip couplers, high-performance filters and ultra-broadband beam splitters and phase shifters, among many others [19-22]. Similarly, SWGs have been successfully applied to many mode multiplexers improving their performance in terms of loss, crosstalk, bandwidth, or their size [23-26]. Nevertheless, in most cases, there is still a trade-off between the aforementioned metrics and only one or a couple of them can be optimized at a time.

Recently, we have reported on a new two-mode multiplexer based on subwavelength-metamaterial-engineered MMI and phase shifter that overcomes the intrinsic wavelength-dependent performance of conventional counterparts [27]. Figure 1(a) shows a three-dimensional schematic of our proposed device, comprising an SWG MMI, SWG phase shifter and a symmetric Y-junction. Low insertion losses are achieved by engineering the dispersion of the modes in the MMI section, which flattens the beat length, while low crosstalk values are ensured by the low phase errors introduced by both the SWG MMI and the SWG phase shifter. The device was fabricated on a silicon-on-insulator (SOI) platform with 220-nm-thick silicon guiding layer and 2.2-µm-thick SiO_2 cladding, and subsequently characterized in a multiplexer-demultiplexer arrangement. The complete link exhibits insertion losses lower than 2 dB and crosstalk below -17.2 dB modes in the 1427 – 1672 nm wavelength range (245 nm) for fundamental and first-order transverse-electric (TE), as shown in Fig. 1(b). The bandwidth of this device is twice that of its counterpart with a conventional phase shifter [28]. Moreover, to the best of our knowledge, this device is one of the demonstrated two-mode multiplexers with the broadest bandwidth while maintaining low loss and crosstalk.

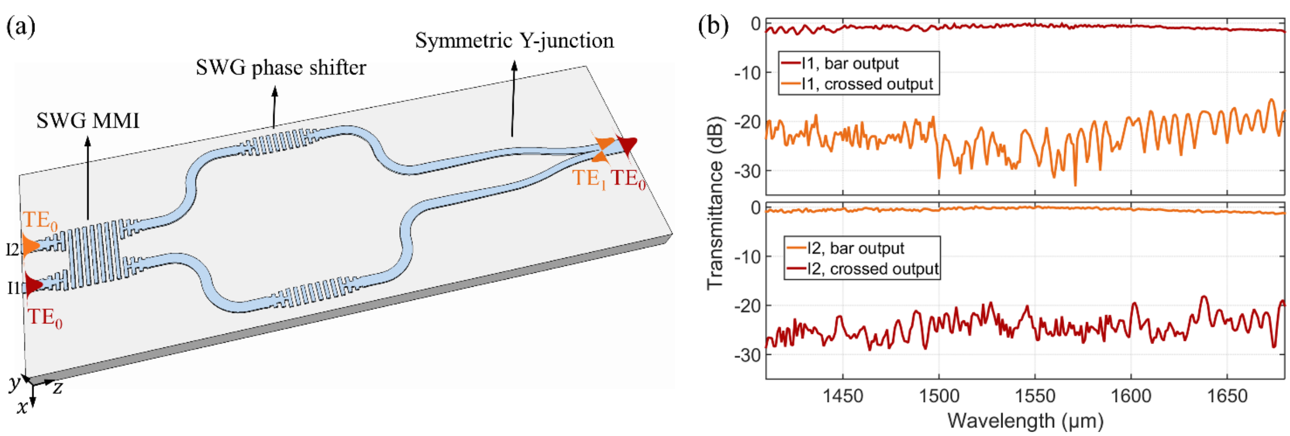

Figure 1. (a) Three-dimensional schematic of a two-mode multiplexer comprising an SWG MMI, an SWG phase shifter and a symmetric Y-junction. (b) Measured transmittance of the complete multiplexer-demultiplexer link.

3. CONCLUSIONS

In conclusion, we present novel mode multiplexers that significantly improve the performance of devices reported in the state of the art. By judicious design of subwavelength metamaterials, low loss and crosstalk can be attained when detuning from the design wavelength, which is not feasible with a multiplexer based on conventional components. The outstanding performance offered by our proposed device will pave the way for broadband datacom applications and high-speed data computing.

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REFERENCES

[1] Reinsel, D., Gantz, J. and Rydning, J., "Data age 2025: The evolution of data to life-critical," IDC White Paper 1 (2017).
[2] Cheng, Q., Bahadori, M., Glick, M., Rumley, S. and Bergman, K., "Recent advances in optical technologies for data centers: a review," Optica 5(11), 1354-1370 (2018).
[3] Young, I. A., Mohammed, E., Liao, J. T. S., Kern, A. M., Palermo, S., Block, B. A., Reshotko, M. R. and Chang, P. L. D., "Optical I/O technology for Tera-scale computing," IEEE J. Solid-State Circuits 45(1), 235-248 (2010).
[4] Kim, N. S., Austin, T., Blaauw, D., Mudge, T., Flautner, K., Hu, J. S., Irwin, M. J., Kandemir, M. and Narayanan, V., "Computer 36(12), 68-75 (2003),"
[5] Esmaeilzadeh, H., Blem, E., Amant, R. S., Sankaralingam, K. and Burger, D., "Dark silicon and the end of multicore scaling," IEEE Micro 32(3), 122-134 (2012).
[6] Miller, D. A. B., "Attojoule optoelectronics for low-energy information processing and communications," J. Lightwave Technol. 35(3), 346-396 (2017).
[7] Chen, X., Milosevic, M. M., Stanković, S., Reynolds, S., Domínguez Bucio, T., Li, K., Thomson, D. J., Gardes, F. and Reed, G. T., "The emergence of silicon photonics as a flexible technology platform," Proc. IEEE 106(12), 2101-2116 (2018).
[8] Dai, D. and Bowers, J. E., "Silicon-based on-chip multiplexing technologies and devices for Peta-bit optical interconnects," Nanophotonics 3(4-5), 283-311 (2014).
[9] Li, H., Wang, P., Yang, T., Dai, T., Wang, G., Li, S., Chen, W. and Yang, J., "Experimental demonstration of a broadband two-mode multi/demultiplexer based on asymmetric Y-junctions," Opt. Laser Technol. 100, 7-11 (2018).
[10] Dai, D., Wang, J. and Shi, Y., "Silicon mode (de)multiplexer enabling high capacity photonic networks-on-chip with a single-wavelength-carrier light," Opt. Lett. 38(9), 1422-1424 (2013).
[11] Sun, C., Yu, Y., Ye, M., Chen, G. and Zhang, X., "An ultra-low crosstalk and broadband two-mode (de) multiplexer based on adiabatic couplers," Sci. Rep. 6(1), 38494 (2016).
[12] Ding, Y., Xu, J., Da Ros, F., Huang, B., Ou, H. and Peucheret, C., "On-chip two-mode division multiplexing using tapered directional coupler-based mode multiplexer and demultiplexer," Opt. Express 21(8), 10376-10382 (2013).
[13] Li, Y., Li, C., Li, C., Cheng, B. and Xue, C., "Compact two-mode (de)multiplexer based on symmetric Y-junction and multimode interference waveguides," Opt. Express 22(5), 5781-5786 (2014).
[14] Chang, W., Lu, L., Ren, X., Li, D., Pan, Z., Cheng, M., Liu, D. and Zhang, M., "Ultra-compact mode (de) multiplexer based on subwavelength asymmetric Y-junction," Opt. Express 26(3), 8162-8170 (2018).

[15] Mehrabi, K., Zarifkar, A. and Babaei, M., "Compact, high-performance, and fabrication friendly two-mode division multiplexer based on a silicon bent directional coupler," Appl. Opt. 59(12), 3645-3651 (2020).
[16] Cheben, P., Xu, D.-X., Janz, S. and Densmore, A., "Subwavelength waveguide grating for mode conversion and light coupling in integrated optics," Opt. Express 14(11), 4695-4702 (2006).
[17] Luque-González, J. M., Sánchez-Postigo, A., Hadij-ElHouati, A., Ortega-Moñux, A., Wangüemert-Pérez, J. G., Schmid, J. H., Cheben, P., Molina-Fernández, Í. and Halir, R., "A review of silicon subwavelength gratings: building break-through devices with anisotropic metamaterials," Nanophotonics 10(11), 2765-2797 (2021).
[18] Cheben, P., Halir, R., Schmid, J. H., Atwater, H. A. and Smith, D., "Subwavelength integrated photonics," Nature 560(7720), 565-572 (2018).
[19] Benedikovic, D., Alonso-Ramos, C., Pérez-Galacho, D., Guerber, S., Vakarin, V., Marcaud, G., Le Roux, X., Cassan, E., Marris-Morini, D., Cheben, P., Boeuf, F., Baudot, C. and Vivien, L., "L-shaped fiber-chip grating couplers with high directionality and low reflectivity fabricated with deep-UV lithography," Opt. Lett. 42(17),3439-3442 (2017).
[20] Cheben, P., Čtyroký, J., Schmid, J. H., Wang, S., Lapointe, J., Wangüemert-Pérez, J. G., Molina-Fernández, Í., Ortega-Moñux, A., Halir, R., Melati, D., Xu, D.-X., Janz, S. and Dado, M., "Bragg filter bandwidth engineering in subwavelength grating metamaterial waveguides," Opt. Lett. 44(4), 1043-1046 (2019).
[21] Halir, R., Cheben, P., Luque-González, J. M., Sarmiento-Merenguel, J. D., Schmid, J. H., Wangüemert-Pérez, G., Xu, D.-X., Wang, S., Ortega-Moñux, A. and Molina-Fernández, Í., "Ultra-broadband nanophotonic beamsplitter using an anisotropic sub-wavelength metamaterial," Laser Photonics Rev. 10(6), 1039-1046 (2016).
[22] González-Andrade, D., Luque-González, J. M., Wangüemert-Pérez, J. G., Ortega-Moñux, A., Cheben, P., Molina-Fernández, Í. and V. Velasco, A., "Ultra-broadband nanophotonic phase shifter based on subwavelength metamaterial waveguides," Photonics Res. 8(3) 359-367 (2020).
[23] Xu, L., Wang, Y., Mao, D., Zhang, J., Xing, Z., El-Fiky, E., Saber, M. G., Kumar, A., D'Mello, Y., Jacques, M. and V. Plant, D., "Ultra-broadband and compact two-mode multiplexer based on subwavelength-grating-slot-assisted adiabatic coupler for the silicon on-insulator platform," J. Light Technol. 37 (23), 5790-5800 (2019).
[24] González-Andrade, D., Wangüemert-Pérez, J. G., V. Velasco, A., Ortega-Moñux, A., Herrero-Bermello, A., Molina-Fernández, I., Halir, R. and Cheben P., "Ultra-broadband mode converter and multiplexer based on sub-wavelength structures," IEEE Photonics J. 10(2), 2201010 (2018).
[25] Jafari, Z., Zarifkar, A. and Miri, M., "Compact fabrication-tolerant subwavelength-grating-based two-mode division (de) multiplexer," Appl. Opt. 56(26), 7311-7319 (2017).
[26] Jiang, W., Hu, J., Mao, S., Zhang, H., Zhou, L. and Rahman, B. A., "Broadband silicon-four mode (de) multiplexer using subwavelength grating-assisted triple-waveguide couplers," J. Light. Technol. 39 (15), 5042-5047 (2021).
[27] González-Andrade, D., Fernández de Cabo, R., Vilas, J., Olivares, I., Dias, A., Luque-González, J. M., Wangüemert-Pérez, J. G., Ortega-Moñux, A., Molina-Fernández, Í., Halir, R., Cheben, P. and V. Velasco, A., "Mode converter and multiplexer with a subwavelength phase shifter for extended broadband operation," IEEE Photon. Technol. Lett. 33(22), 1262-1265 (2021).
[28] González-Andrade, D., Dias, A., Wangüemert-Pérez, J. G., Ortega-Moñux, A., Molina-Fernández, Í., Halir, R., Cheben, P. and V. Velasco, A., "Experimental demonstration of a broadband mode converter and multiplexer based on subwavelength grating waveguides," Opt. Laser Technol. 129, 106297 (2020).