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Invited Paper

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.

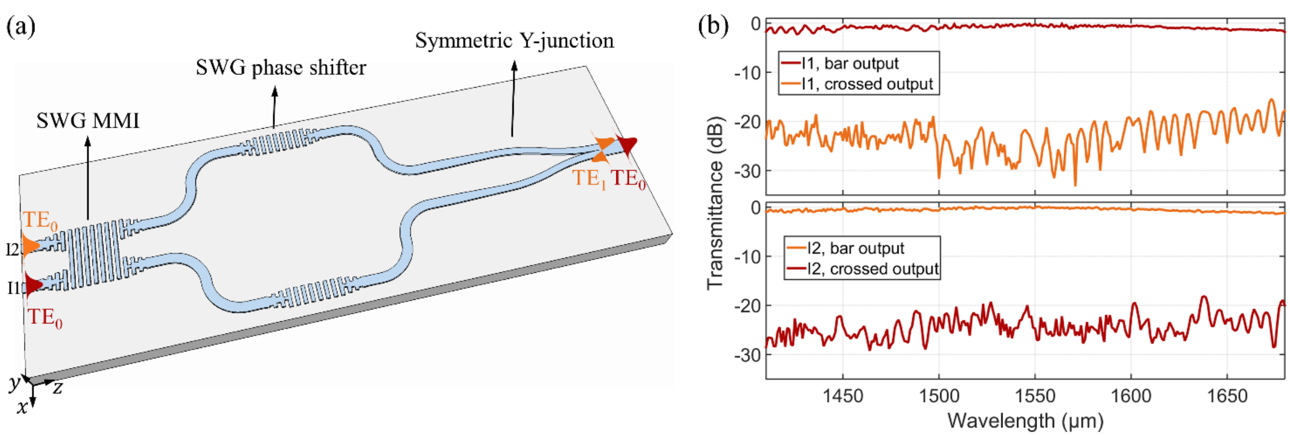

Figure 1. (a) Three-dimensional schematic of a two-mode multiplexer comprising an SWG MMI, an SWG phase shifter and a symmetric Y-junction. (b) Measured transmittance of the complete multiplexer-demultiplexer link.

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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