Subwavelength metamaterials for broadband mode multiplexing and power splitting in silicon waveguides

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Subwavelength metamaterials provide a powerful tool for the realization of compact and high-performance integrated photonic devices. In this work, we apply subwavelength metamaterials to novel devices for mode multiplexing and power splitting in silicon on insulator. We experimentally demonstrate ultra-broad operational bandwidths over 245 nm in both applications.

Keywords: *Silicon photonics, subwavelength, mode multiplexing, power splitting*

INTRODUCTION

Mode-division multiplexing (MDM) in integrated silicon photonics is emerging as a fundamental technology to address the challenge of ever-increasing global data traffic and data center demand.[1] High-performance mode converters and multiplexers/demultiplexers (MUX/DEMUX) are the fundamental building blocks at the core of MDM technologies, with current architectures including asymmetric directional couplers (ADC), asymmetric Y-junctions, adiabatic tapers, and topologies based on inverse design, among others.[2-5] In particular, MDM architectures based on multimode interference (MMI) couplers have reported good performance over a relatively wide wavelength range[6-7], although further bandwidth enhancements are still sought after. Auxiliary devices beyond MUX/DEMUX are also required in MDM systems, such as multimode power splitters. A broad range of power splitters has been proposed, including topologies based on symmetric Y-junctions, MMIs, inverse and adiabatic tapers, directional couplers, slot waveguides or photonic crystals.[8-11] In particular, symmetric Y-junctions[8] are one of the most common alternatives given their ease of design, simply consisting of a stem waveguide ramifying into two arms of the same width. However, finite resolution of fabrication processes results in deviations from the nominal design at the junction tip, and degrade the performance of the fabricated devices.

Subwavelength grating (SWG) metamaterials provide a powerful tool for improving the performance of MUX/DEMUX and power splitters, among other photonic devices.[12] SWG structures are arrangements of dielectric materials with a scale substantially smaller than the operating wavelength, hence suppressing diffractive effects and enabling dispersion engineering.[13] In the MDM field, SWGs have been applied to adiabatic couplers[14], ADCs[15] or MMI couplers[16,17]; whereas in the field of power splitting, SWG engineering has also been applied to asymmetric directional couplers[18], MMI devices[19], or Y-junctions[20], among others.

In this work, we review our latest SWG-based MUX/DEMUX and power splitter[17,20], expand on the experimental characterization of both devices, and present enhanced topologies for improved performance and additional features such as higher-order mode support. In particular, we experimentally demonstrate ultra-broad operational bandwidths over 245 nm in both SWG-enhanced mode multiplexer and power splitter.

MODE MULTIPLEXING

Our SWG MUX/DEMUX is based on the combination of a MMI, a 90° phase shifter and a symmetric Y-junction (Fig. 1). Both the MMI and the phase shifter are implemented with SWG metamaterials for enhanced bandwidth.[17] When operating as MUX, the fundamental transverse electric modes (TE_0) in ports 1 (blue) and 2 (green) are equally divided by the metamaterial-based MMI, while inducing a 90° phase shift between MMI output ports. The phase shifter delays the mode propagated through the upper arm an additional 90°, which either compensates the MMI phase shift (blue), or results in a total phase shift of 180° (green). As a result of the phase relations of the modes at the Y-junction arms, their conversion results in TE_0 (blue) or TE_1 (green) at port 3.

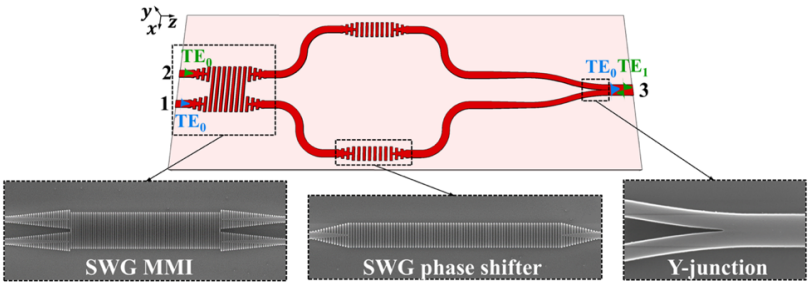

Fig. 1. Mode converter and multiplexer based on an SWG MMI, an SWG phase shifter and a symmetric Y-junction.

The SWG MUX/DEMUX was fabricated in a commercial foundry using silicon-on-insulator (SOI) wafers with a silicon thickness of 220 nm, a buried oxide (BOX) layer of 2 µm, and a 2.2 µm thick SiO_2 upper cladding oxide. SWG edge couplers were incorporated for high-efficiency input and output coupling.[21] Experimental characterization of a full MUX/DEMUX link (i.e. devices connected back-to-back), presented in Fig. 2., shows insertion losses of 2 dB and crosstalk better than -17.2 dB for the full link over a 245 nm bandwidth (1427 – 1672 nm). These results entail a 100 nm bandwidth expansion when compared to the device with a non-SWG phase shifter.[16]

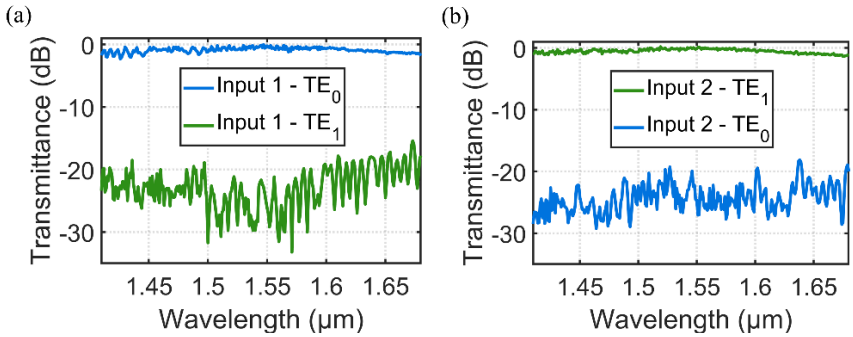

Fig. 2. Experimental transmittance measurements for the proposed mode converter and multiplexer for output modes TE_0 and TE_1, when using input 1 (a) and input 2 (b).

POWER SPLITTING

Our power splitter is based on a SWG-engineered symmetric Y-junction for reduced mode confinement at the junction tip (Fig. 3). This topology circumvents minimum feature size (MFS) limitations at the junction tip and significantly improves TE_0 excess loss (EL), at the expense of a slight increase in TE_1 loss. Arm width was optimized to minimize effective index mismatch at the interface between the stem (i.e. multimode input waveguide) and the arms.[21] The device was optimized considering two target minimum feature sizes, namely 50 nm and 100 nm. Conventional Y-junctions with the same MFS limitations were also fabricated for comparison.

Fig. 3. Scanning electron microscope image of the proposed subwavelength Y-junction

The SWG power splitter was fabricated in the same 220 nm SOI platform as the MUX/DEMUX devices. Cascaded splitters were included for accurate characterization of TE_0 loss, whereas a dual-core adiabatic taper MUX[5] was incorporated for TE_1 loss measurement. Fig. 4 shows the excess los under 0.3 dB over a 260 nm bandwidth for TE_0 in the high resolution lithography (MFS = 50 nm), and EL less than 1 dB for TE_1 within a 100 nm bandwidth.

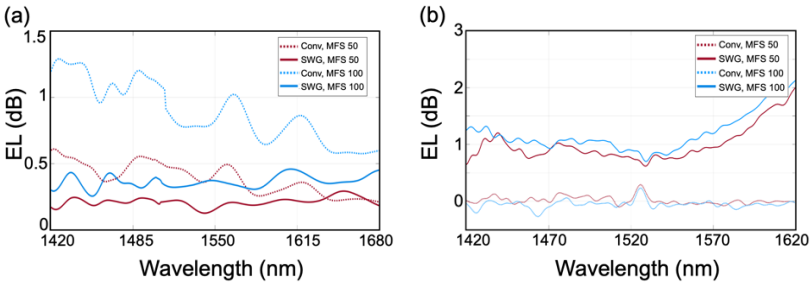

Fig. 4. Experimental excess loss of the proposed subwavelength Y-junction (solid) and a conventional Y-junction (dotted), with minimum feature sizes of 50 nm (red) and 100 nm (blue), for TE_0 (a) and TE_1 (b) modes.

CONCLUSIONS

We have presented a mode multiplexer/demultiplexer and a multimode power splitter based on SWG metamaterials. Experimental characterization of the fabricated devices demonstrates bandwidths over 245 nm in both applications.

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