Dispersion-engineered nanophotonic devices based on subwavelength metamaterial waveguides

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***Abstract*—Subwavelength metamaterial waveguides are becoming an essential tool for the design of high-performance nanophotonic devices implemented on the silicon-on-insulator platform. Here we focus on dispersion engineering and present our latest advances in this field, including mode multiplexers/demultiplexers and passive phase shifters with ultra-broad bandwidths.**

Keywords—subwavelength gratings, metamaterials, dispersion engineering, ultra-broadband, mode converter and multiplexer, phase shifter, silicon-on-insulator, silicon photonics

I. INTRODUCTION

In recent years, the silicon-on-insulator (SOI) platform has become ubiquitous for the implementation of photonic integrated circuits (PICs) operating at the near-infrared band [1]. This material platform leverages the maturity of complementary metal-oxide-semiconductor (CMOS) fabrication processes reached by the microelectronics industry, resulting in an affordable mass production. In addition to the cost effectiveness, the high refractive index contrast of the SOI platform enables to increase the number of photonic devices integrated on a single chip and, at the same time, the development of more complex systems. However, this large difference between the refractive index of the silicon waveguide core and the silicon dioxide (SiO_2) layers (i.e. $\Delta n \approx 2$) also poses important limitations, namely a strong modal dispersion and a high birefringence between the transverse electric (TE) and transverse magnetic (TM) polarizations. While the former results in photonic devices with narrow operating bandwidth, the latter typically limits their operation to a single polarization state of light waves, both limiting the performance of Si photonic devices. To overcome these constraints, subwavelength grating (SWG) metamaterial waveguides have been postulated as an essential tool for the design of high-performance nanophotonic devices implemented on the SOI platform [2].

II. SUBWAVELENGTH METAMATERIALS

Figure 1(a) shows the schematic of an SWG metamaterial waveguide, which is composed of different dielectric materials that alternate with a period (Λ) smaller than half the wavelength of the light propagating through the structure, thus preventing both diffraction and Bragg reflection. The key concept is that the silicon SWG waveguide is an inhomogeneous isotropic medium that acts as a homogeneous anisotropic medium [3] as shown in Fig. 1(b), specifically as a uniaxial crystal [4] with a refractive index tensor $\boldsymbol{n_{eq}} = \mathrm{diag}[n_{xx}, n_{xx}, n_{zz}]$. In this way, designers can leverage the extended design space in order to tailor the optical properties of the equivalent anisotropic metamaterial and develop novel photonic devices with enhanced performance. Depending on the optical property exploited for the design, applications of SWG metamaterial waveguides can be divided into three groups: local refractive index, anisotropy and dispersion engineering [5-7].

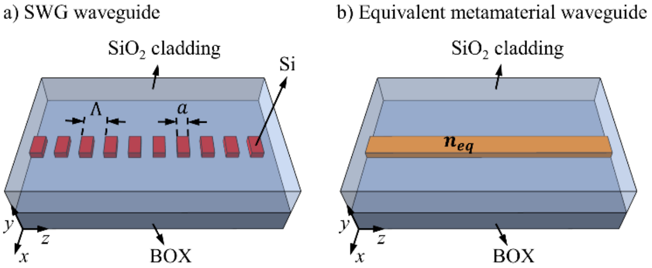

Fig. 1. (a) Schematic of a silicon SWG waveguide surrounded by a buried oxide layer and a SiO_2 upper cladding. (b) Schematic of the equivalent anisotropic metamaterial defined with the refractive index tensor $\boldsymbol{n_{eq}}$.

In this work, we focus on engineering the dispersion properties of SWG metamaterial waveguides to achieve ultra-broadband photonic devices and present our latest advances in this field, including experimental results of a mode multiplexer-demultiplexer link and a novel 90º passive phase shifter (PS).

III. MODE CONVERTER AND MULTIPLEXER

Our mode converter and multiplexer/demultiplexer (mux/demux) is based on a multimode interference (MMI) coupler, a 90º phase shifter (PS) and a symmetric Y-junction. Theoretically, both the 90° PS and the symmetric Y-junction present low losses over a broad bandwidth; however, the use of a conventional MMI coupler would intrinsically limit the performance of the complete mode mux/demux [8]. On this account, we propose to replace the conventional MMI with an SWG MMI (see Fig. 2(a)). By judiciously choosing the duty cycle ($\mathrm{DC} = a/\Lambda$) and the period of the SWG MMI, anisotropy and dispersion can be engineered to mitigate the wavelength dependence of the MMI's beat length, thus achieving a broader operation bandwidth compared to its conventional counterpart [9].

On the other hand, the limited the limited resolution of the fabrication process typically generates a tip of non-negligible dimensions between the arms of the symmetric Y-junction, which results in the excitation of undesired higher-order modes supported by the multimode waveguide of a mux-demux link. In order to avoid this problem, two linear

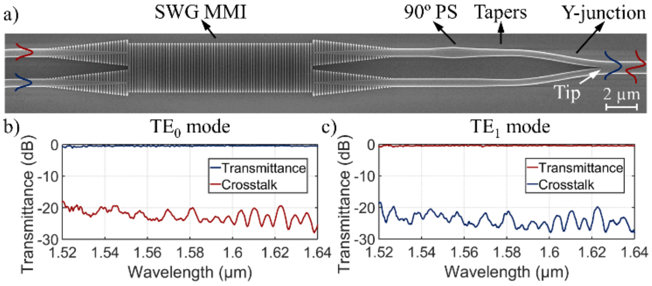

Fig. 2. (a) SEM image of the fabricated mode converter and mux/demux. Measured transmittance of the complete mux-demux link when (b) the TE$_0$ and (c) the TE$_1$ modes are generated in the multimode waveguide.

tapers between the 90° PS and the symmetric Y-junction were included in the fabricated device to reduce the arm widths of the Y-junction and thereby de width of the multimode waveguide to support only TE$_0$ and TE$_1$ modes within the 1.495 – 1.64 µm wavelength range.

A complete mux-demux link, i.e. two mode converters and mux/demux in back-to-back configuration, was fabricated using a 220-nm-thick SOI platform with a 2-µm-thick buried oxide (BOX) layer and a 2.2-µm-thick SiO$_2$ cladding. Experimental results of the optimized mux-demux link are shown in Figs. 2(b) and 2(c) for TE$_0$ and TE$_1$ modes, respectively. Insertion loss less than 1.1 dB and crosstalk better than -18 dB for both TE$_0$ and TE$_1$ modes are achieved for a broad 120 nm bandwidth (1.52 – 1.64 µm).

IV. NANOPHOTONIC PHASE SHIFTER

Optical PSs are fundamental components in PICs to induce a specific phase shift between different signals. Here we propose a passive 90º PS based on two parallel SWG metamaterial waveguides of dissimilar widths but with the same length, period and DC [10]. The widths of both waveguides must be wide enough to hold paraxiality condition and, at the same time, to improve tolerances to width deviations. To this end, SWG tapers are incorporated to perform an adiabatic transition between the non-periodic interconnection waveguides and the corresponding SWG waveguide (see Fig. 3(a)). The wavelength dependence of the phase shift error (PSE), defined as the deviation from the target 90° phase shift, can also be mitigated by properly choosing the values of Λ and DC of both SWG waveguides.

The device was fabricated on the same SOI platform as the mode converter and mux/demux. To experimentally characterize the fabricated PSs, we used Mach-Zehnder interferometer (MZI) consisting of two SWG MMIs and 14 PSs connected in series. We developed a circuit model to simulate the MZI and estimate the phase error introduced by fabrication deviations [10]. These errors were subtracted from the measured phase shift response and the resulting experimental results are shown in Fig. 3(b). A phase slope as small as 16°/µm for our proposed SWG PS, whereas a conventional PS based on two trapezoidal tapers in back-to-back yields a phase slope of 64°/µm.

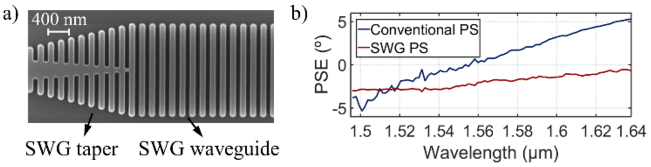

Fig. 3. (a) SEM image of the upper arm of the proposed SWG PS. (b) Measured PSE of the SWG PS (red curve) compared to the PSE of a conventional PS (blue curve).

V. CONCLUSIONS

The versatility offered by SWG metamaterial waveguides opens up a wide range of possibilities for the design of high-performance integrated optical devices. In this work, we have focused on dispersion engineering, demonstrating a mode converter and mux/demux and a passive PS with measured bandwidths in excess of 145 nm. We believe that both devices can find potential applications in future cutting-edge photonics applications. In particular, the mode converter and mux/demux is a promising candidate for the implementation of broadband integrated MDM transceivers, whereas the SWG PS has remarkable prospects in coherent communications, polarimetry, quantum photonics, sensing and high-performance MDM transceivers.

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