Metamaterial-engineered silicon devices fabricated with deep UV immersion lithography

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Subwavelength grating (SWG) metamaterials have enabled the realization of silicon photonic devices with unprecedented performance. However, most successful SWG realizations relied on electron-beam lithography, compromising the scalability of the approach. Here, we report SWG metamaterial engineered devices fabricated with deep-ultraviolet immersion lithography in a 300-mm silicon-on-insulator technology.

Keywords: *subwavelength grating; metamaterial; silicon photonics; multi-mode interference coupler; beam splitter; ring resonator; immersion deep-UV lithography*

INTRODUCTION

The use of subwavelength grating (SWG) metamaterials opened a powerful degree of freedom in the development of silicon photonic devices, offering the possibility to control the effective refractive index of the material. This is achieved because dielectric structures arranged at a distance substantially smaller than the wavelength of the propagating light effectively acts as a homogeneous material whose optical properties (e.g., effective index, dispersion, and anisotropy) are determined by the geometry of the unit cells [1,2]. Since their initial introduction, SWGs enabled the demonstration of a vast number of silicon photonic devices with record performance, e.g., edge couplers, surface gratings, resonators, filters, and multi-mode interference (MMIs) couplers, to name a few [3-6]. The use of a graded index SWG metamaterial has also been recently proposed for devices realized in III-V membranes on silicon [7].

The fabrication of SWG metamaterials uses the same process of conventional waveguides and can hence be easily implemented in established platforms. However, the need to maintain the grating period smaller than the wavelength of light often creates small features that may be challenging to fabricate in a reliable and reproducible way using dry deep-ultraviolet (DUV) lithography [8]. One possibility is to constrain the minimum feature size above the resolution limit of dry DUV lithography, typically in the order of 120 nm. However, this constraints the available design space and the range of achievable properties of the effective material, ultimately impacting the performance of the devices. Alternatively, electron-beam lithography offers higher resolution but at the expense of a vastly reduces throughput mostly compatible with research or small volume productions.

In order to overcome this limitations, we explore here the use of immersion DUV lithography for the fabrication of photonic devices based on SWG metamaterials. Immersion DUV lithography is compatible with high-volume production and, compared to dry lithography, allows achieving a three-fold improvement in device size reproducibility, reduced line edge roughness, and sufficient resolution to pattern feature with sizes close to 60 nm [9]. We take advantage of the significant quality improvement offered by immersion DUV lithography by exploiting a 300-mm silicon-on-insulator (SOI) fabrication platform to experimentally demonstrate two SWG-engineered devices with high performance, i.e., a broadband integrated beam splitter and ring resonator with low thermal sensitivity. Both devices have a silicon thickness of 300 nm and nominal minimum feature sizes of 75 nm for the splitter and 100 nm for the ring, below the resolution capabilities of dry DUV lithography. The beam splitter is based on an SWG engineered multi-mode interference (MMI) coupler [10] and exhibits low excess losses below 1 dB with negligible power imbalance and phase errors over a bandwidth of 186 nm near λ = 1550 nm. The ring resonators operate for transverse-magnetic polarization at a wavelength near 1310 nm, with a measured thermal shift of the resonant wavelength of only ~30 pm/°C, a two-fold reduction compared to standard silicon ring resonators [11].

RESULTS

MMIs exploit multi-mode interference in a large waveguide section to achieve beam splitting. Since interference is defined by the wavelength-dependent relative phase delays between the modes, bandwidth is typically limited to about 100 nm to ensure an insertion loss penalty smaller than 1 dB in 2 × 2 MMIs with solid silicon cores [12]. Here we used an SWG metamaterial to realize the multi-mode waveguide section in order to exploit its anisotropy, as first proposed by Halir et al. [10]. By controlling the dispersion of the effective material index, it is possible to reduce the wavelength dependence of the difference between the propagation constants of the modes and increase the MMI bandwidth. We consider in particular a TE polarized light in a silicon core thickness of 300 nm with 2 µm buried oxide (BOX), and 2 µm upper cladding. The period of the metamaterial is Λ = 150 nm and the duty cycle DC = 0.5, resulting in minimum feature size of 75 nm. The width of the multi-mode section is chosen as 3.5 µm and the length 18 µm (120 periods for the SWG). The width of the access waveguides is 1.7 µm while the 0.4-µm-wide silicon wire waveguides are widened to 1 µm and adiabatic transitions are used between the solid core waveguides and the SWG access waveguides. The distance between the access waveguides is 2.17 µm. Figure 1a shows an SEM picture of the realized MMI before deposition of the SiO_2 upper cladding. The device was characterized using asymmetric Mach–Zehnder interferometers and a reference waveguide for transmission normalization. The experimental results are shown in Figs. 1b-d. Insertion losses and power imbalance remain smaller than 1 dB in the entire wavelength range between 1490 nm and 1680 nm. Regarding phase error measurements, an increased noise can be observed for λ < 1500 nm. Despite this, phase errors smaller than ±6° are obtained for λ > 1494 nm. Our sources do not extend beyond λ = 1680 nm, preventing measurements at longer wavelengths. Aiming for excess losses and imbalance below 1 dB and phase error smaller than 6°, these results yield an experimentally measured bandwidth of at least 186 nm.

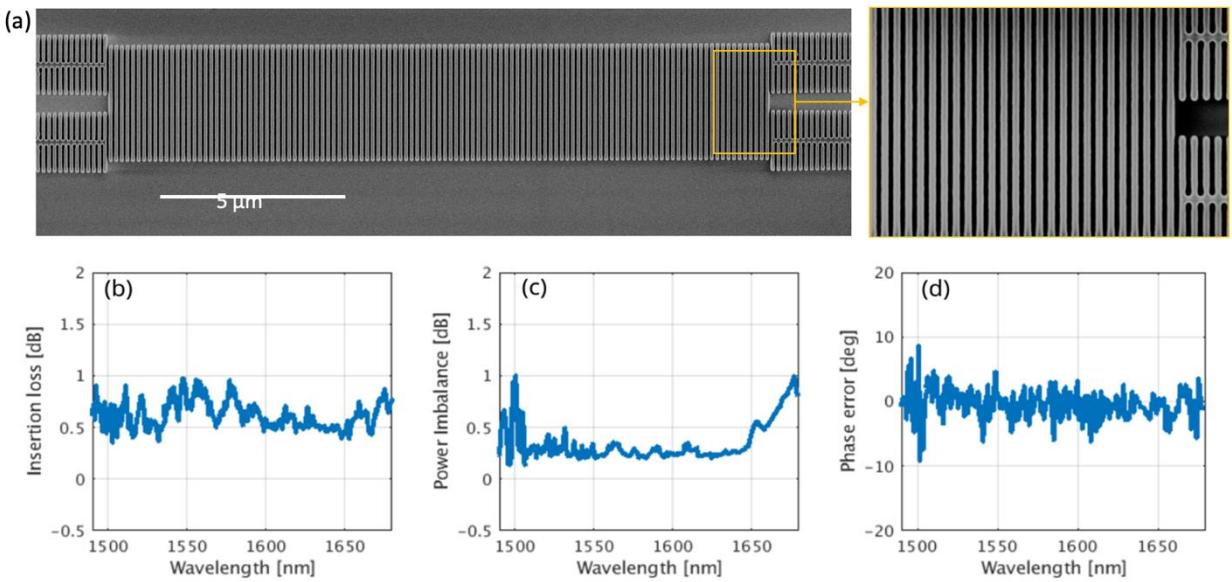

Fig. 1. Experimental characterization of the SWG-engineered beam splitter fabricated on a 300-mm SOI platform using immersion DUV lithography. (a) SEM image before the deposition of the upper cladding, showing the quality of the fabrication. (b) Measured insertion loss, (c) power imbalance, and (d) phase error of the beam splitter. The fabricated MMI shows high performance over a 186-nm bandwidth, with losses and imbalance smaller than 1 dB and phase error less than 6°.

Ring resonators are key components for applications, including optical modulators, communications, and sensing. The position of the resonance wavelength is highly sensitive to temperature variations due to the comparatively high thermal coefficient of silicon ($dn_{Si}/dT = 1.9\times10^{-4}$ °C^{-1}), hampering stable operation. Here, we exploit the ability of SWG-engineered waveguides to delocalize the optical mode, reducing the overlap with silicon and hence the thermally-induced resonance wavelength shift [13]. The ring resonators are optimized for TM polarization near 1310 nm wavelength. Figure 2a shows the SEM image of a fabricated SWG ring with a period of 200 nm and a duty cycle of 0.5 and a waveguide width of 750 nm. Figure 2b shows the measured transmittance spectra for different temperatures between 20 °C and 30 °C. The quality factor of the resonator is Q ~ 5000 and extinction ratio exceeding 15 dB. From the resonance wavelength shift, we estimate a thermal dependence of ~30 pm/°C. For comparison, in Fig 2c we show the measured resonance shift of a ring resonator implemented with a conventional strip waveguide (400 nm width and 300 nm thickness) and our SWG resonator, both for TM polarization and 1310 nm wavelength. The SWG approach yields a two-fold reduction of the thermally-induced resonance shift.

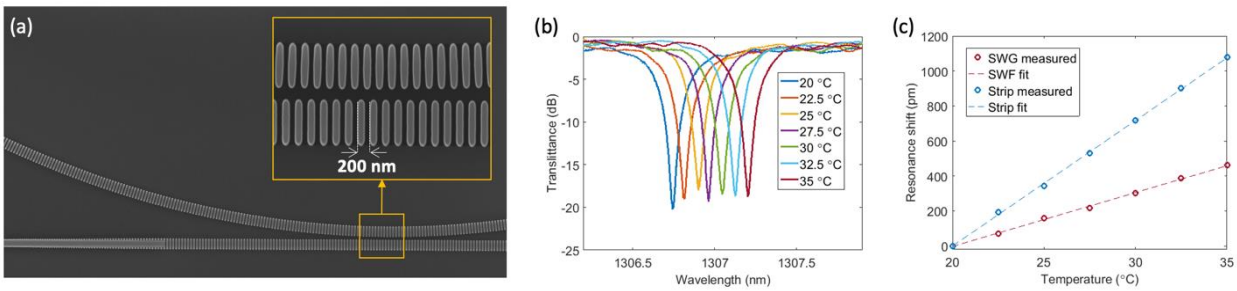

Fig. 2. Experimental characterization of the SWG-engineered ring resonator fabricated on a 300-mm SOI platform using immersion DUV lithography. (a) SEM image before the deposition of the upper cladding. (b) Measured transmittance spectra for different temperatures (c) Comparison of measured thermally-induced shift of the resonance for ring resonators implemented with conventional strip waveguide and SWG waveguide.

DISCUSSION

We have reported on the implementation of SWG metamaterial-engineered devices using a 300-mm SOI fabrication platform with DUV immersion lithography. The high resolution of immersion lithography allowed designs with nominal feature size down to 75 nm. These results show the feasibility of the implementation of SWG metamaterials with a fabrication process compatible with high-volume production, with excellent prospects for bringing the potentialities of metamaterial refractive index engineering toward commercial exploitation. This opens a new path for the fabrication of high-performance devices such as fiber-to-chip couplers, power and polarization splitters, and spectral filters, to name a few, for a wide range of applications, including coherent communications, quantum photonics, sensing, and spectrometry.

Acknowledgements: This work was partially supported by Technological Research Institute (IRT) Nanoelectronics Nano 2022 and Important Project of Common European interest (IPCEI).

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