Subwavelength nanophotonic structures in silicon waveguides

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***Abstract*—We review and discuss our recent studies of subwavelength grating (SWG) structures for engineering the refractive index of silicon microphotonic waveguides. Various applications are presented, such as fiber-chip coupling structures, waveguide crossings and athermal waveguides made with a polymer-silicon hybrid core.**

Keywords-Silicon photonics; subwavelength gratings; fiber-chip coupler; waveguide crossings; athermal waveguides;

I. INTRODUCTION

Integrated silicon photonic circuits are expected to have a major impact on optical interconnects and data transport applications in the near future, as well as being used for biosensing and spectroscopy. In the design of silicon waveguide devices the refractive index of the waveguide core is naturally assumed to be fixed, being the material refractive index of silicon. We have recently demonstrated the use of the subwavelength grating (SWG) effect to tune effectively the index of a waveguide core simply by lithographic patterning, thus introducing a new degree of freedom in silicon waveguide design. The use of SWGs with a periodicity smaller than one half of the wavelength of light to suppress any diffraction effects, as effective media with spatially averaged refractive index is already well established in free space optics [1].

II. APPLICATIONS OF THE SUBWAVELENGTH GRATING EFFECT IN SILICON PHOTONICS

An example for the application of the SWG effect to a so-called silicon photonic wire waveguide, i.e. a submicron silicon strip waveguide, is illustrated schematically in Fig. 1a. Here, periodic gaps are etched into a standard silicon photonic wire and an SWG waveguide is formed with an effective core index determined by the SWG duty ratio.

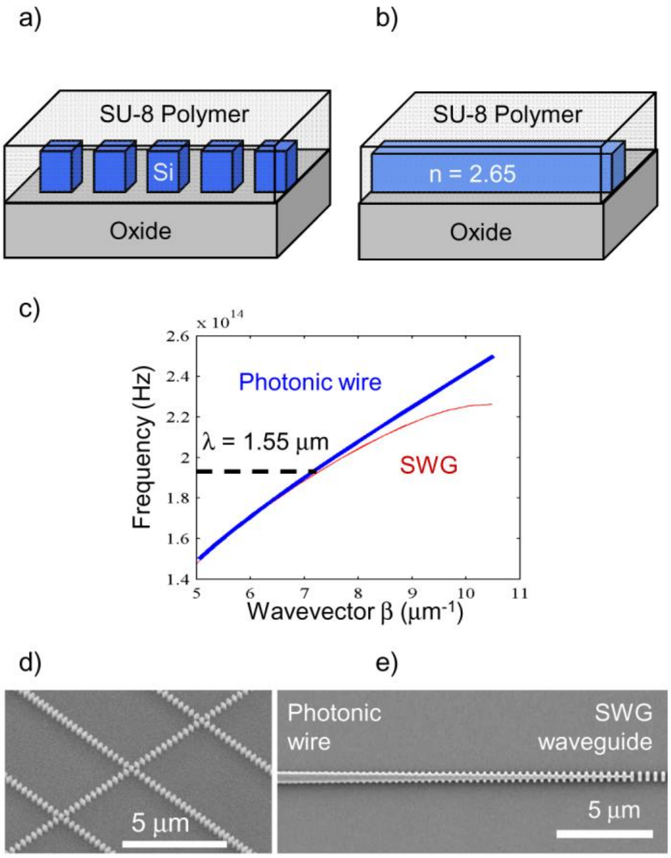

Fig. 1 a) Schematic of a silicon SWG waveguide. b) Equivalent wire waveguide with spatially averaged core index. c) Comparison of the calculated dispersion diagrams of the structures shown in a) and b). d) Scanning electron micrograph (SEM) of SWG waveguide crossings. e) SEM of low-loss SWG fiber-chip coupling structure.

To confirm theoretically the concept of spatial refractive index averaging in an SWG waveguide with period Λ = 0.3 µm and

50% duty ratio we compare its dispersion relation with that of an equivalent photonic wire waveguide with identical cross section and averaged core index of n = 2.65, as shown in Fig. 1b. The two dispersion curves are overlaid in Fig. 1c. The SWG waveguide shows the typical behaviour expected for a periodic structure, namely a flattening of the dispersion as the Bragg condition is approached at $\beta \approx 10.5\ \mu m^{-1}$, corresponding to a free space wavelength of λ = 1.33 μm. For the operating wavelength of 1.55 μm, however, the dispersion curves of the segmented and the equivalent photonic wire waveguide are well matched. Experimentally, we have observed wave guiding in SWG waveguides with a propagation loss as low as 2.1 dB/cm [2].

We have demonstrated several applications of SWG waveguides, for example highly efficient waveguide crossings as shown in Fig. 1d, which enable the design of complex high density photonic circuits [3], and photonic wire fiber-chip couplers with extremely low coupling loss as depicted in Fig. 1e and described in [4]. Refractive index engineering by SWG patterning can also be used in two dimensions for slab waveguides. This has been applied in design of a novel microspectrometer, where an SWG nanostructure fulfills a dual purpose by acting as an effective slab waveguide for diffracted light and as a lateral cladding for a channel waveguide [4]. Surface grating fiber-chip couplers with enhanced performance and reduced fabrication complexity due to the incorporation of SWG structures have also been reported [5-9].

III. ATHERMAL SILICON SWG WAVEGUIDES

We have recently used SWG waveguides to address another important issue with silicon photonic circuits, which is the temperature dependence of their optical output signals caused by the comparatively high thermo-optic (TO) material coefficient of silicon ($dn_{Si}/dT = 1.8\times10^{-4}\ K^{-1}$). The temperature dependence of silicon wire waveguides can be reduced by using a polymer overcladding with a negative TO coefficient to compensate for the silicon thermo-optic effect [10,11]. Athermal operation of waveguides, i. e. $dn_{eff}/dT = 0$, where n_{eff} is the mode effective index and T is the ambient temperature, is achieved if waveguide dimensions are chosen such that the respective overlaps of the mode with the silicon core and the polymer cladding results in a cancellation of their combined contributions to the waveguide effective TO coefficient. This can be accomplished in narrow silicon wires with a fairly delocalized mode [12], or with slot waveguides, in which a large fraction of the modal field is confined to a narrow gap filled with the low-index polymer [13]. With SWG waveguides the spatial index averaging effect can be exploited for mitigating the silicon thermo-optic effect by filling the gaps with polymer material of negative TO coefficient for an appropriate grating duty ratio.

The effect has been experimentally demonstrated in [14], where athermal waveguide behavior was observed for SWG waveguides with a composite core consisting of interlaced subwavelength segments of silicon and SU-8 polymer, the latter having a thermo-optic material coefficient of $dn_{SU8}/dT = -1.1 \times 10^{-4}\ K^{-1}$. SEM pictures of three SWG waveguides with different duty cycles are shown in Fig. 5a. In Fig. 5b the measured and calculated waveguide effective thermo-optic coefficient are shown as a function of SWG duty ratio. For increasing volume ratio of silicon material in the waveguide core the plots show a sign reversal from negative to positive thermo-optic coefficients. In other words, the thermal behavior of the SWG waveguide is dominated by the polymer material for low duty ratios and by silicon for high duty ratios. Athermal waveguide operation is achieved for an SWG duty cycle of 61%, for TE polarization and 85% for TM polarization. The challenging fabrication of SWG waveguides with high duty cycles can be circumvented by using a subwavelength *sidewall* grating (SWSG) waveguide, as shown in Fig. 2c. Our recent experimental results show that athermal SWSG waveguides can be designed for both TE and TM polarized light with duty cycles of ~50%.

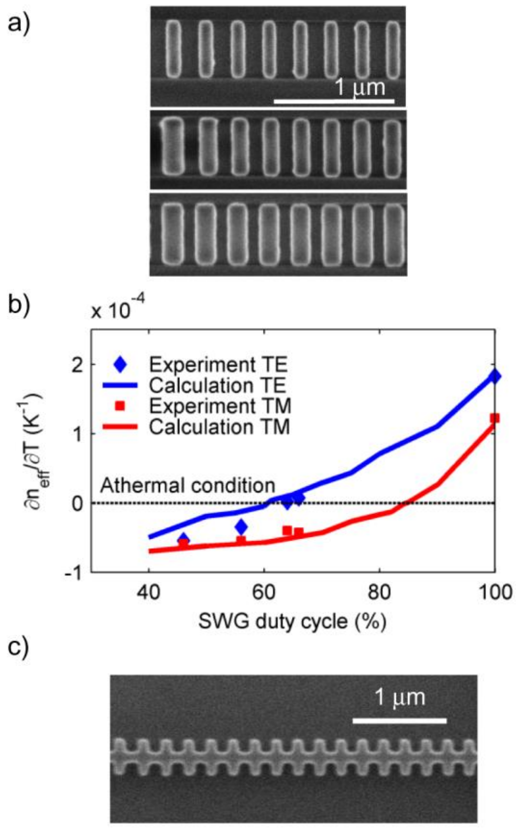

Fig. 2 a) SEM micrographs of SWG waveguides with Si duty ratios of 46%, 56% and 66%. b) Experimental and theoretical results for the effective thermo-optic coefficient of SU-8 clad silicon SWG waveguides as a function of grating duty cycle. c) SEM of a SWSG waveguide.

IV. OUTLOOK AND CONCLUSIONS

We have described a number of practical implementations of SWG structures in silicon waveguides that can improve device performance or enable novel functionalities. Several others have been published recently. Mode profile engineering as employed for the athermal SWG waveguides can also be used to achieve ultrafast nonlinear all-optical switching [15]. Engineering the refractive index of slab waveguides with SWGs may prove to be a suitable method of adapting to integrated optics conventional components such as lenses [16,17] or transmission gratings, which are common in free space optics. Calculations have shown that SWGs can be used as effective cladding material with optimized refractive index contrast in the design of multi-mode interference couplers with superior performance [18]. The numerous applications of SWGs in silicon photonics demonstrated in the past few years underline the versatility afforded by adapting this method of refractive index engineering to integrated optics.

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