# Tunable slow-light in silicon photonic subwavelength grating waveguides

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***Abstract*— Slow-light is experimentally demonstrated in subwavelength grating waveguides integrated on a silicon photonic chip. At the band-edge, a group index up to 30 is measured. We show that the band-edge wavelength varies linearly with the subwavelength grating period and can be shifted by thermal tuning.**

**Keywords— Subwavelength grating waveguide, Slow-light, Silicon photonics**

## I. Introduction

Recently, segmented subwavelength grating (SWG) waveguides have attracted much interest because of their ability to enhance the performance of various silicon photonic devices by implementing metamaterial engineering using a simple structure [1], [2]. Many integrated components have thus been optimized by exploiting the flexibility of SWG waveguides for different purposes. Examples of SWG applications include filters, polarization management devices, multimode interferometers, directional couplers, and fibre-to-chip couplers [3]. SWG waveguides with engineered mode profiles can also be used to enhance the sensitivity of on-chip sensors by increasing the overlap with the surrounding medium [4]. So far, to the best of our knowledge, demonstrations of SWG-based devices have all been based on operation in the long-wavelength (metamaterial) regime. In [5], we proposed to operate SWG waveguides near the photonic band edge to harness the slow-light effect in order to increase the light-matter interaction and improve the sensitivity of an absorption spectroscopy gas sensor [5]. In this work, we experimentally demonstrate the slow-light operation of SWG waveguides. We report a group index reaching up to 30 and slow-light regions spanning the C-band. We also show thermal tuning of the slow-light region over a >30 nm bandwidth with a 48.5 pm/mW efficiency. Such waveguides can find applications in modulators and tunable delay lines, and can enhance light-matter interaction for sensing.

## II. Design and Fabrication

SWG waveguides are made of silicon blocks of width $W$ and length $a$ positioned periodically along the waveguide propagation axis with a period, $\Lambda$. The duty-cycle, $DC$, is the ratio of silicon to cladding material along the waveguide axis, *i.e.* $DC=a/\Lambda$. Figure 1 (a) schematically depicts an SWG waveguide and Fig. 1 (b) shows a conventional strip waveguide of width $W$. The optical properties of the SWG can be controlled by engineering its duty-cycle, period and width. For a wavelength, $\lambda$, much larger than $\Lambda$, the SWG operates as a metamaterial. When $\lambda$ is of the order of $\Lambda$, the existence of a band gap in the dispersion relation prevents propagation. We define the band edge wavelength, $\lambda_{band\ edge}$, as the wavelength where the maximum group index occurs. This corresponds, in the theory, to the wavelength for which the maximal photonic density of states is obtained for the first band of the photonic band-structure [6]. We show that, when operated with a wavelength slightly above $\lambda_{band\ edge}$, the SWG waveguide exhibits a sharp variation of its effective refractive index, leading to large group index, $n_g$.

In order to measure the group index of the SWG waveguide, Mach-Zehnder interferometers (MZIs) were designed as test structures (Fig. 1c). An SWG waveguide of length $L_{SWG}$ and group index $n_{g,SWG}$ is placed in arm #1 of the MZI, while arm #2 is made of a strip waveguide of the same length with W=500 nm and $n_{g,strip}$=4.2. The difference in the optical path length due to the difference in effective refractive index creates interference fringes at the output. By measuring the free spectral range ($FSR=\lambda_{peak,i+1} - \lambda_{peak,i}$), we can determine $n_{g,SWG}$ of the SWG waveguide through:

$$n_{g,SWG} = n_{g,strip} + \lambda^2 / (L_{SWG} \cdot FSR)$$

In arm #1, the transitions from the strip to the SWG waveguides are done with linear tapers of length $L_{Taper}$=100 μm. In order to remove the taper contribution to the MZI response, a back-to-back taper ($L_{SWG}$ = 0) is added in arm #2. To tune the effective index and shift the slow-light region, a TiW heater was deposited over the SWG waveguide. In this work, all SWG waveguides have a width $W$=800 nm and a $DC$=0.5. The period, Λ, is varied from 333 to 369 nm to investigate its effect on the spectral position of

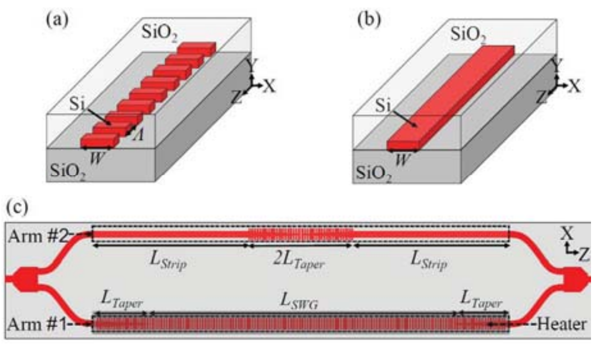


Fig. 1. Schematic of (a) an SWG waveguide of width W and period Λ, (b) a strip waveguide of width W, and (c) the Mach-Zehnder interferometer used as a test structure (not to scale).

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the slow-light region. The design was done using 3D-FDTD to simulate band structures, with the target to obtain slow-light operating devices spanning the C-band. The simulation methodology is explained in detail in [5].

The devices were fabricated by electron-beam lithography (Applied Nanotools) on silicon-on-insulator (SOI) wafers with 2.0 µm thick buried oxide layer (BOX) and 220 nm thick device layer. The chips were covered with a 2.2 µm thick $SiO_2$ layer by plasma-enhanced chemical vapor deposition. For future applications, it should be noted that all feature sizes are compatible with standard UV lithography.

## III. Experimental Results

The fundamental quasi-TE mode transmission spectra of the fabricated MZI devices are first measured without applied voltage on the heater for the different SWG periods of the SWG waveguide and $L_{SWG}$=500 µm. Fig. 2 (a) shows $n_{g,SWG}$ measured over a wavelength range of 1500-1620 nm. The measured maximum $n_{g,SWG}$ at the band edge is between 20 $\sim$ 30 for all measured devices. This is an order of magnitude larger than the measured group index of $\sim$ 1.5 reported for deep-SWG waveguides in [2]. In Fig. 2 (b), we show that the band edge wavelength $\lambda_{band\ edge}$ scales linearly, at a rate of 2.7 nm/nm, with the period of the SWG waveguide. Therefore, it is possible to design SWG waveguides operating at selected wavelength and group index by adjusting the SWG period.

We measured the transmission spectra of a device with $L_{SWG}$=200 µm and $\Lambda$=335 nm with various voltages applied to the thermal heater (resistance of $R$=200 Ω), see Fig. 3 (a). The applied voltage causes resistive heating following Joule's law ($P=V^2/R$) and changes the refractive index of the SWG waveguide by the thermo-optic effect. Fig. 3 (b) shows that the measured band edge wavelength is red-shifted linearly at a rate of 48.5 pm/mW. Thereby, it is possible to tune the operating region of the slow-light SWG waveguide over a large bandwidth and compensate fabrication variations.

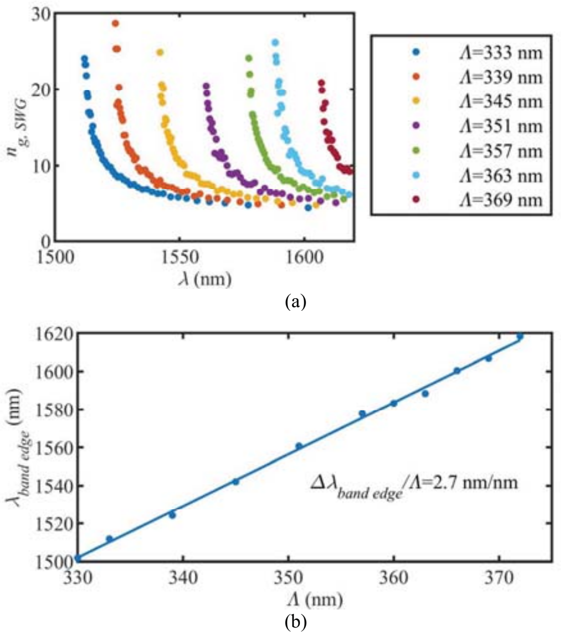


Fig. 2. (a) Measured group index as a function of wavelength for different SWG periods. (b) Measured band edge wavelength as a function of the period of the SWG waveguide. The line is a linear regression fit.

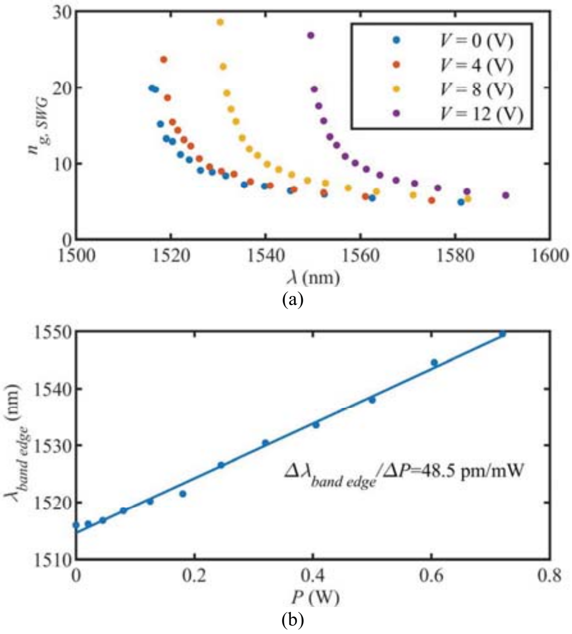


Fig. 3. (a) Measured group index for different voltages applied to the thermal resistance (b) Measured band edge wavelength as a function of the power supplied to the resistive heater.

## IV. Conclusion

In conclusion, we demonstrated silicon SWG waveguides with largely tunable group index up to 30 operating at wavelengths spanning the C-band. Such devices can be used as compact delay lines, modulators or to enhance light-matter interactions for sensing and non-linear applications.

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