

Slow Light Enhanced Nonlinear Effects in Silicon Photonic Crystal Waveguides

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Abstract: We experimentally investigate the slow light enhancement of nonlinear effects such as self-phase modulation, two-photon absorption and free carriers, through dispersion-engineered silicon photonic crystal waveguides. We also observe emission of visible light through third-harmonic generation.

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1. Introduction

There has been growing interest in slow light photonic crystal (PhC) waveguides due to their high potential for applications in nonlinear photonics [1]. While the high degree of optical confinement in sub-micrometer sized silicon nanowires has recently led to the realisation of various nonlinear functions that are compact and operate at low powers [2], adding slow light to the equation is expected to further improve the performance of these devices. It has long been predicted that the slow light enhancement of light-matter interaction should induce a reduction of either the physical length of waveguide or input power needed to observe nonlinear phenomena such as stimulated Raman scattering or harmonic generation [3,4]. However, demonstrations of such enhancement process are still rare [5] and preliminary, partly due to the challenging increase of coupling loss, linear [6] and nonlinear losses as well as the large high order dispersion that typically cause pulse distortion in the slow light regime [7].

Planar PhCs represent an attractive platform for integrating many optical functions onto a single compact chip. In addition to providing a tight confinement of light, PhC waveguides can be engineered so that both the speed of light and its associated dispersion can be fully controlled over a substantial bandwidth close to 10nm [8,9].

Here, we report the experimental enhancement of nonlinear effects undergone by picosecond pulses propagating in the slow light regime across silicon PhC waveguides as short as 80 μm . We show in particular how pulse spectral broadening due to self-phase modulation (SPM) is reinforced by slow light along with two photon absorption (TPA) and free carrier (FC) effects. This demonstration relies on the engineering of the slow light mode dispersion in PhC waveguides and is supported by simulations based on the split step Fourier method (SSFM) modelling. We report another nonlinear process enhanced by slow light in these PhC waveguides: the emission of visible light through third-harmonic generation. The PhC structure plays a critical role for extracting light in a spectral window where the absorption of silicon is strong.

2. Dispersion engineering of silicon slow light PhC waveguides

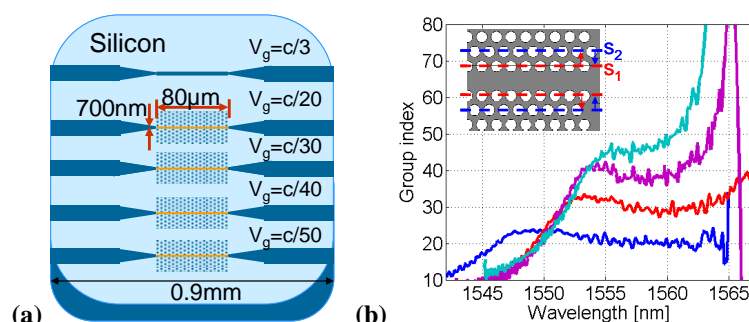


Fig. 1. (a) Schematic of the silicon chip including a series of PhC waveguides with various group velocities connected to ridge access waveguides. (b) Group index dispersion measured on the PhC waveguides (from Ref [10]). The inset shows how the dispersion of these waveguides is engineered by shifting the first and second neighbouring holes outwards and inwards the center of the waveguides.

The waveguide structures consist of 80 μm long PhC waveguides coupled on both sides to two 0.4mm long ridge access waveguides, whose width is tapered down from 3 μm to 0.7 μm (see Fig. 1a). The PhC waveguide is created from a triangular lattice of air holes with a period a of 414nm and a hole radii of 0.286 a etched in a 220nm thick

silicon membrane suspended in air. The dispersion of the PhC waveguide is engineered by appropriately shifting the position of the first two rows of holes adjacent to the center of the waveguide [9]. This approach provides us with a series of optimized PhC waveguides with various and controlled group velocities (between $c/20$ and $c/50$) that are constant over a substantial bandwidth ($> 5\text{nm}$). Figure 1b shows the measured group index dispersion associated to these engineered slow light PhC waveguides. The silicon chip also includes a reference “fast” waveguide that consists of a 700nm wide silicon nanowire with similar length and ridge access waveguides to the slow light PhC waveguides (see Fig. 1a).

3. Nonlinear spectral signature of picosecond pulses for varying group velocities

Nonlinear transmission measurements were performed by using a figure-of-8 mode-locked fiber laser that generates close to Fourier transform limited 1.2 ps pulses at a 4 MHz repetition rate around 1550 nm. At output, an optical spectrum analyzer was used to measure the pulse spectral signature. TE polarised modes were primarily excited in the waveguides. We coupled the light in and out of the structures using lensed fibers that provide a total insertion loss of about 15 dB. We estimate the coupled peak power to be around 20% of the input peak power.

Figures 2(a-c) show the spectra of the output pulses arising from the fast reference waveguide (a), the PhC waveguide with a group index of ~ 30 (b) and ~ 50 (c) for various coupled peak powers between 0.4 W and 45 W. When increasing the peak power, spectral broadening is observed for all waveguides, a signature of the SPM experienced by the pulses as they propagate through the nonlinear waveguides. The spectral broadening is larger for higher group indices and the associated enhancement is more striking at low powers. In addition, the pulse spectra associated to the slowest PhC waveguide become both asymmetric and shifted towards blue for increasing powers.

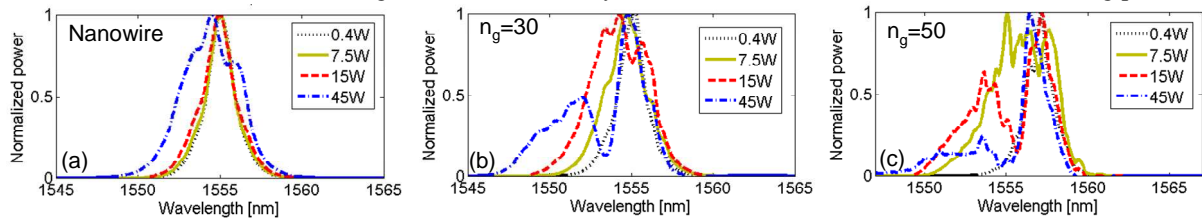


Fig. 2. (a-c) Output pulse spectra measured from the reference “fast” waveguide (a), and PhC waveguides with group indices of 30 (b) and 50 (c).

Using the SSFM to solve numerically the nonlinear Schrodinger equation in the presence of TPA and FC [10], we obtain a qualitative agreement with the above pulse signatures. In addition to the enhancement of the SPM-induced spectral broadening for the slowest waveguides, the simulations show an enhanced blue shift in the slow light regime due to both increased interaction with the FC and reinforced FC generation through slow light enhanced TPA. The reinforcement of these two nonlinear loss terms (TPA and FC) strongly reduces the output power, as attested by the saturation behaviour observed at high powers for the slowest waveguides, both experimentally and from the simulations (see Fig. 3a). When including all additional losses in the slow light regime, we still get a net enhancement of the pulse spectral broadening, as displayed on Figure 3(b).

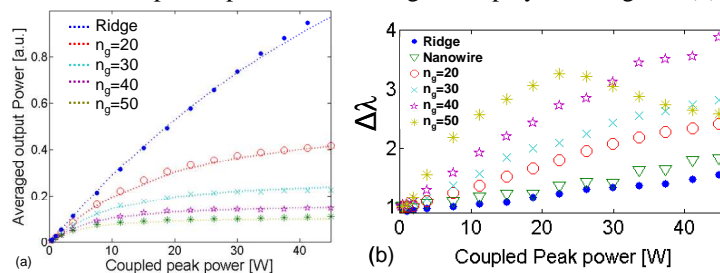


Fig. 3 (a) Transmitted power versus coupled peak power for a reference fast waveguide, and PhC waveguides with group index $n_g \sim 20, 30, 40$ and 50, from experiments (dots) and simulations (dotted lines). (b) Associated spectral broadening measured from the same waveguides.

These results show that despite the increase of propagation losses and nonlinear absorption in the slow light regime, 80 μm long PhC waveguides still produce enhanced SPM as compared to fast PhC waveguides. This highlights the potential interest of short slow light PhC silicon waveguides for low power all-optical regeneration [11], while it reveals their limitation at high powers or for long PhC waveguides dominated by loss.

4. Emission of visible light through third-harmonic generation

Using the same PhC platform, we studied the influence of slow light on another nonlinear process: third-harmonic generation. The waveguide structures and conditions of excitation are similar to the experiment described above.

When coupling to the PhC waveguide with near-infrared picosecond pulses, we observe the emission of green light coming from the top of the chip and localized around the PhC section (see Fig. 4(a,c)). The associated wavelength is found at $520\text{nm} \pm 5\text{nm}$, while the green emitted power measured with a linear CCD camera varies with the cube of the fundamental input power, both of which are expected for the third harmonic generated from the 1560nm pump. A slight deviation from the cubic trend is yet observed at higher powers due to the increase of nonlinear loss.

By tuning the wavelength of the near-infrared pulses over a 10nm range for a fixed PhC waveguide, we investigate the dependence of this nonlinear process on the group velocity of the fundamental mode and observe a strong variation of the conversion efficiency. From the measured waveguide dispersion, we plot on Fig. 4c the required peak power density needed to generate a constant green light power as a function of the fundamental group index. The input power density strongly decreases for increasing group index and roughly follows a $1/n_g$ trend, as expected from the n_g -enhancement of the optical energy density inside the PhC waveguide [12].

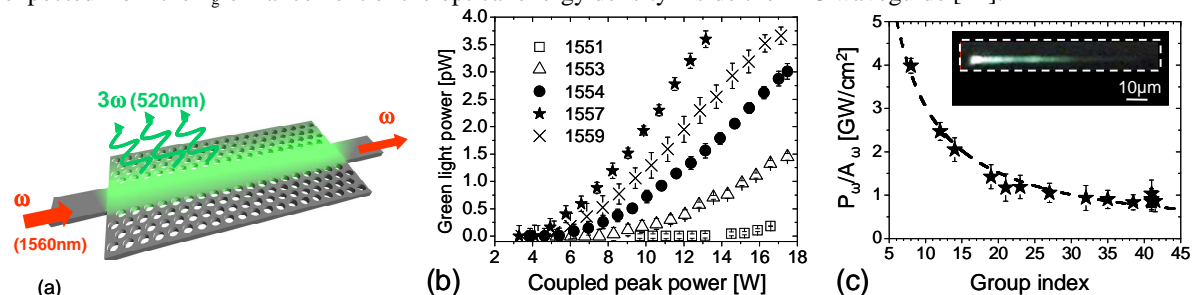


Fig. 4. (a) Schematic of the third harmonic generation experiment. (b) Green light power versus pump power for various wavelength of the pump. (c) Peak power density of the pump needed to produce a constant level of green light power ($\sim 0.2\text{pW}$) versus the pump group index. The inset shows the image collected with the CCD and the green light localized along the PhC waveguide (dashed white box).

5. Conclusion

In conclusion, we have demonstrated the slow light enhancement of various nonlinear processes, such as self-phase modulation, two photon absorption, free carrier effects and third harmonic generation by launching picosecond pulses into $80\ \mu\text{m}$ long silicon PhC waveguides with group velocities ranging from $c/10$ to $c/50$. The net enhancement of self phase modulation is reduced by the simultaneous reinforcement of nonlinear losses, as attested both experimentally and from simulations on the slowest waveguides. This study highlights the potential of short slow light PhC waveguides in silicon at low powers. The observation of visible green light emission through third harmonic generation increases the number of opportunities offered by the integrated silicon platform, and reveals the critical role played by the PhC for light extraction.

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6. References

- [1] T. Baba, "Slow light in photonic crystals," *Nature Photonics* **2**, 465-473 (2008).
- [2] Foster et al. "Nonlinear optics in photonic nanowires" *Opt. Express* **16**, 1300 (2008).
- [3] M. Soljagic, S. G. Johnson, S. H. Fan, M. Ibanescu, E. and J. D. Joannopoulos, "Photonic-crystal slow-light enhancement of nonlinear phase sensitivity," *JOSA B* **19**, 2052-2059 (2002).
- [4] J. E. McMillan, X. D. Yang, N. C. Panoiu, R. M. Osgood, and C. W. Wong, "Enhanced stimulated Raman scattering in slow-light photonic crystal waveguides" *Opt. Lett.* **31**, 1235-1237 (2006).
- [5] A. Baron, A. Rysanyanskiy, N. Dubreuil, P. Delaye, Q. Vy Tran, S. Combric, A. de Rossi, R. Frey, G. Roosen, "Light localization induced enhancement of third order nonlinearities in a GaAs photonic crystal waveguide" *Opt. Express* **17**, 552-557 (2009).
- [6] S. Hughes, L. Ramunno, J. F. Young, and J. E. Sipe, "Extrinsic optical scattering loss in photonic crystal waveguides: role of fabrication disorder and photon group velocity," *Phys. Rev. Lett.* **94**, 0339031-0339034 (2005).
- [7] R. J. P. Engelen, Y. Sugimoto, Y. Watanabe, J. P. Korterik, N. Ikeda, N. F. van Hulst, K. Asakawa and L. Kuipers, "The effect of higher-order dispersion on slow light propagation in photonic crystal waveguides," *Opt. Express* **14**, 1658-1672 (2006).
- [8] S. Kubo, D. Mori, and T. Baba, "Low-group-velocity and low-dispersion slow light in photonic crystal waveguides," *Opt. Lett.* **32**, 2981-2983 (2007).
- [9] J. Li, TP. White, LO. Faolain, A. Gomez-Iglesias, and TF. Krauss, "Systematic design of flat band slow light in photonic crystal waveguides," *Opt. Express* **16**, 6227-6232 (2008).
- [10] C. Monat, B. Corcoran, M. Ebnali-Heidari, C. Grillet, B. J. Eggleton, T. P. White, L. O'Faolain, T. F. Krauss, "Slow light enhancement of nonlinear effects in silicon engineered photonic crystal waveguides" *Opt. Express* **17**, 2944-2953 (2009)
- [11] V. G. Ta'eed, M. Shokoh-Saremi, L. Fu, I. C. M. Littler, D. J. Moss, M. Rochette, B. J. Eggleton, Y. Ruan, B. Luther-Davies, "Self-phase modulation-based integrated optical regeneration in chalcogenide waveguides," *Ieee J. Selected Topics in Quantum Electron.* **12**, 360-370 (2006).
- [12] B. Corcoran, C. Monat, C. Grillet, D. J. Moss, B. J. Eggleton, T. P. White, L. O'Faolain, T. F. Krauss, "Green light emission in silicon via slow light enhanced third harmonic generation in photonic crystal waveguides" accepted for publication in *Nature Photonics*.