Slow-light Enhanced Nonlinear Optics in Silicon Photonic Crystal Waveguides

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Abstract — We report slow-light enhanced nonlinear optics including third harmonic generation and self-phase modulation in dispersion engineered 2D silicon photonic crystal waveguides.

1. INTRODUCTION

There has been growing interest in slow light due to its potential application for optical delay lines and nonlinear optical signal processing [1]. The increase of the optical energy density due to spatial pulse compression in the slow light regime is regarded as a means for enhancing nonlinear phenomena such as Raman scattering, 2nd and 3rd harmonic generation or frequency conversion. However, apart from theoretical predictions this enhancement process has not been systematically demonstrated to date, partly due to the high dispersion that typically accompanies slow light, causing pulse distortion that compromises its benefit. Planar PhC waveguides, which combine a periodic lattice of air holes and a vertical step index waveguide, offer a unique platform to engineer the dispersion properties of light at the micrometer scale [2]. This architecture has proven to be effective and flexible to control both the speed of light and its associated dispersion in chip-scale devices. The last point is crucial for nonlinear optics as large dispersion is typically associated with slow light modes that tends to dramatically distort and stretch slow light pulses, compromising the pulse spatial compression related benefit of slow light [3]. Such a large dispersion has restricted the demonstration of nonlinear effects — such as stimulated Raman scattering or Self Phase Modulation (SPM) — in standard \(W_1\) PhC waveguides to the fast light regime and using long (\(\sim 1\) mm) waveguides. Very recently, several approaches have been successfully investigated to engineer the dispersion of slow light modes and to optimize the bandwidth-delay product in planar PhC waveguides [2, 4]. These efforts make it now possible to implement slow light in practical nonlinear functions. Combining optical confinement and dispersion engineering through the use of optimized 2D PhC waveguides is highly promising because \(I_\omega\) is related to the peak power \((P_\omega)\) through

\[
I_\omega \propto \frac{P_\omega}{A_\omega} \frac{n_g}{n} \tag{1}
\]

where \(A_\omega\) and \(n_g\) are the effective area and group index of the fundamental mode, respectively.

Hence, by exploiting the extreme concentration of optical energy afforded by tight confinement of light within the high index, sub-\(\mu\)m scale \((A_\omega \sim 0.4 \mu m^2)\) silicon PhC waveguides and spatial pulse compression in the slow light \((v_g = c/40)\) regime, we significantly reduce the peak pump power required to observe nonlinear effects to the order of a few watts.

Here, we demonstrate slow light enhancement of nonlinear processes in engineered silicon PhC waveguides, including third harmonic generation (THG) and self phase modulation (SPM). Both the strong optical confinement within the waveguide and the slow light \((c/40)\) mode supported by the PhC structure have enabled us to observe visible green light \((520\) nm) at low \((\sim several\) watts) peak pump powers at 1560 nm [5]. This is 5–6 orders of magnitude lower than previous free-space coupling experiments in porous silicon PhC geometries [6], and even 100x that of THG in quasi-phasematched KTP waveguides [7], and is a result of the increased optical energy density in our slow light PhC waveguide. We also report the experimental observation of slow light enhanced self-phase modulation (SPM) exhibited by picosecond-pulses propagating through silicon PhC waveguides as short as \(80 \mu m\) [8]. Both of these are made possible due to engineering the PhC geometry to provide a series of waveguides with a controlled low group velocity ranging between \(c/20\) and \(c/50\) with a limited group velocity dispersion associated with the slow light regime over at least...
5 nm bandwidth for all of the guides. The experimental results are supported by Split-Step-Fourier-Method (SSFM) modeling, including Two Photon Absorption (TPA) and free carrier (FC) effects in silicon, which gives further insight into the various contributions of these effects to both the output pulse signature and the power transfer function. In particular, both experiment and simulation highlight the reinforcement of TPA and FC effects in the slow light regime.

2. EXPERIMENT

The structures were fabricated on a SOITEC silicon-on-insulator wafer comprising a 220 nm thick silicon layer on 2 µm of silica using e-beam lithography and Reactive Ion Etching. The total length of the waveguide structure is 0.9 mm; it comprises an 80 µm long suspended silicon PhC waveguide and two 0.4 mm long, 3 µm wide ridge access waveguides on both sides that are tapered down to 0.7 µm close to the PhC section. The PhC W1 waveguide consists of a triangular lattice of air holes with a period \( a \) of \( \sim 410 \) nm, and hole radii of \( \sim 0.3a \), where one row of holes has been omitted along the \( \Gamma K \) direction. To enhance coupling from the access ridges into the slow light PhC waveguide, an intermediate region consisting of ten periods of PhC waveguide with a “stretched” lattice of period \( \sim 440 \) nm was added at either end of the slow light PhC waveguide. The PhC waveguides were engineered to display slow group velocity with low dispersion over a substantial bandwidth (> 5 nm) by appropriately shifting the two rows of holes adjacent to the W1 PhC waveguide [2]. Figure 1(b) shows a typical measured group index dispersion of the fundamental mode of 3 engineered PhC waveguides with a group index \( (n_g) \) of varying from \( c/20 \) to \( c/50 \) over \( > 7 \) nm at 1557 nm. Their parameters are summarized in [2, 8]. Figure 2 shows the band diagram of the waveguide studied for the THG experiments, both at the fundamental and third harmonic wavelengths, as well as the group index and loss versus wavelength. The device was probed using a polarization controlled, near transform-limited, figure-of-8 fibre laser, tunable over the C-band. The pulses (sech\(^2\) shaped, \( \sim 1.5 \) ps long, FWHM \( \sim 2 \) nm, 4 MHz) were amplified through

![Figure 1](image1.png)

**Figure 1:** (a) (Left) SEM image of photonic crystal waveguide as well as (bottom) schematic showing strategy for engineering wide bandwidth low dispersion regions. (b) Right: dispersion diagram for different waveguides engineered to have high group indices.

![Figure 2](image2.png)

**Figure 2:** (a) Left: waveguide dispersion for fundamental (bottom) and third harmonic (top) wavelengths. (b) Right: group index and transmission versus wavelength.
an EDFA and launched (TE polarized) into the waveguide, using lensed fibres with a 2.5 µm focal length. The coupling loss to the chip was obtained from modelling of the Self Phase Modulation experiments. When launching the pulses into the PhC waveguide, we observed green light emitted from the surface of the chip by eye (Figure 3) emitted at an angle ∼ 10° from the vertical, in the backward direction. Imaging the emission onto a calibrated linear CCD camera (linearised, fixed gain, calibrated using a low RIN doubled Nd:YAG laser diode) with a 0.25 N.A. microscope objective revealed that it is localized above the PhC waveguide, and decays exponentially along its length (Figure 3). The total emitted green power at 520 nm ± 5 nm shows a cubic dependence on the coupled pump power up to ∼ 65 µW. At higher pump powers, a slight saturation occurs in the fundamental power transmission due to two-photon and subsequent free-carrier absorption. We observed a maximum THG output of ∼10 pW for 80 µW (10 W) average (peak) pump power. In order to minimize effects of propagation such as dispersion and nonlinear absorption, to determine the dependence of the THG efficiency solely on group velocity, we restricted our measurements of the THG to a within 5 µm of the PhC waveguide entrance, much smaller than the dispersion length associated with the GVD, even in the “fast light” regime. The self-phase modulation experiments were carried out by varying the input power and monitoring the output spectra on a spectrum analyzer (OSA).

3. RESULTS AND DISCUSSION

Figure 3 shows the observed THG from the waveguide as well as a schematic indicating the exit angle. Figure 4(a) shows the power dependence of the THG for as a function of input power for different wavelengths (corresponding to different group indices). The power dependence displays a clear enhancement for pump wavelengths near 1557 nm where the group velocity is lowest. Equation (1) predicts a cubic dependence on $n_g$ of the THG power obtained at a fixed pump power. In order to minimize the nonlinear loss saturation effect discussed above at all wavelengths though, we chose instead to plot the input power density ($P_ω/A_ω$) required to produce a constant (and sufficiently low) THG output power (∼0.4 pW) as the wavelength (hence group index $n_g$) is varied. The results show very good agreement with a 1/$n_g$ variation, as expected from $P_ω/A_ω \propto I_ω/n_g$. Note both the trend and the variation in enhancement is well accounted for by using only the experimentally measured group velocity dispersion of Fig. 2. It is clear that a contribution from any

![Figure 3: (a) Left: Microscope image of third harmonic generation from sample and (b) Right: diagram showing green light emitted at 10°.](image)

![Figure 4: (a) Left: Third harmonic power (top) versus coupled input power for different wavelengths and (right) THG efficiency versus $n_g$.](image)
other effect would cause a discrepancy with experiment — particularly if the wavelength variation were different to that of $n_g$ and so these results demonstrate direct slow-light enhancement of this nonlinear process.

Our experiments were performed with $\sim 10$ W peak pump powers, corresponding to a reduction of 5 to 6 orders of magnitude compared to previous reports of THG in silicon [6,9,10]. Even more significantly, this work represents a nearly 100-fold reduction in pump power relative to fully phase-matched THG in PPLN/KTP waveguides [7]. Although a comparable power density ($\sim$GW/cm$^2$) has been achieved in ultra-high $Q$ ($>10^7$) cavities [11], the advantage of the PhC waveguide approach is that the full bandwidth of short optical pulses can be accommodated. We estimate our conversion efficiency $\eta$ to be $\sim 10^{-7}$ (or $5 \times 10^{-10}$ for 1 W of peak pump power), which represents an increase of 5 orders of magnitude over that reported in 3D polystyrene PhCs ($\eta \sim 10^{-15}$ for 1 W peak pump power as inferred from the quoted value of $\eta \sim 10^{-5}$ at $P_\omega = 10$ MW) [12]. This efficiency could be further improved, e.g., by decreasing the effective area ($\eta \propto 1/A_{eff}^3$) or the group velocity ($\eta \propto n_g^3$). A group velocity of $c/80$ can be reasonably well achieved with this PhC waveguide design — this would provide an order of magnitude improvement in $\eta$. Efficiency could also be improved at high pump powers by reducing the free-carrier lifetime through techniques such as ion implantation to reduce nonlinear loss of the pump.

Besides tight optical confinement and slow light, the 2D PhC geometry offers additional versatility to improve the third-harmonic generation and extraction efficiency. In periodic structures, the phase matching condition, $\Delta k = 0$, is relaxed to $\Delta k = \pm mG$, where $mG$ can be any reciprocal lattice wave-vector, increasing the possibilities for phase matching. Perhaps more importantly in our case, since the absorption length at $3\omega$ is extremely short (3 dB/µm absorption loss at 520 nm in silicon), the PhC also provides a suitable platform for extracting light by coupling to surface radiating modes above the light-line. The directive nature of the emission ($\sim 10^\circ$) as well as the absence of green emission from the access waveguides, suggests that a component of the third-harmonic Bloch mode in the PhC lies above the light line, as illustrated by the band structure in Figure 2. This provides a mechanism for the THG to be extracted out-of-plane. However, because

Figure 5: Output spectra of PhC waveguides for different input powers showing strong self phase modulation (SPM) enhanced by slow-light.
the $3\omega$ Bloch mode also contains harmonic components well confined in the PhC slab below the light line, the measured pico-watt level of green emission is expected to be significantly lower than the total THG power generated in the PhC waveguide. The conversion efficiency reported above is therefore a conservative estimate.

For the SPM measurements, we first probed two reference structures. The first one is a 0.9 mm long, 3 µm wide ridge waveguide similar to the access ridges. The second one comprises an 80 µm long, 0.7 µm wide nanowire that is similar to the tapered ridges on both sides of the PhC section; on both sides of the nanowire, the access waveguide is tapered identically to the tapers coupling to the PhC guides therefore providing a reference fast waveguide with the same degree of optical confinement as the PhC waveguide. Figure 5 shows the spectra obtained while varying the input peak power between 2 W and 45 W. The actual peak power coupled inside the structures was $\sim 20\%$ of this. The 1.2-ps pulses were spectrally broadened due to SPM experienced in both reference waveguides. Note the slightly broader effect through the nanowire reference, as expected due to its higher optical confinement. Figure 5 also shows the spectra obtained when probing the 4 slow light waveguides with group velocities ranging between $c/20$ and $c/50$. These four sets of spectra exhibit SPM-induced spectral broadening when increasing power with a much larger effect than for either of the two reference structures. This clearly demonstrates the dominant contribution of the 80 µm slow PhC waveguides on the output spectral signatures observed in Figure 5. Most importantly, the observed spectral broadening through the slow light waveguides increases with the waveguide group index. Note that this slow light enhanced spectral broadening is more striking at lower coupled powers (7.5 W or 15 W for instance). In addition, the pulse spectra associated with the PhC waveguides become both asymmetric and strongly shifted towards blue when increasing input powers and the waveguide group index.

4. CONCLUSION

We demonstrate slow-light enhancement of nonlinear effects undergone by picosecond-pulses propagating through dispersion engineered 80 µm long silicon PhC waveguides with group velocities ranging between $c/20$ and $c/50$. The comparison of the respective output spectral signatures through fast and slow waveguides reveals significant enhancement in both SPM induced spectral broadening and optical third harmonic generation (THG).

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