# Slow Light Enhanced Third-Harmonic Generation in Silicon Photonic Crystal Waveguides

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## Abstract

*We report visible (green) third-harmonic generation in silicon by launching near-infrared picosecond pulses into highly confined photonic crystal waveguides. We demonstrate slow light enhancement of this nonlinear process.*

## 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 [2] 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 photonic crystals (PhCs) represent an attractive platform for integrating many optical functions onto a single compact chip. In addition, PhC waveguides can be engineered so that both the dispersion and group velocity can be fully controlled, thereby producing slow light modes with limited dispersion over a substantial bandwidth [3].

Here, we demonstrate slow light enhancement of a nonlinear process, namely third harmonic generation (THG), into an engineered silicon PhC waveguide. This is the first time that visible THG has been observed in integrated nanophotonic silicon devices. The PhC structure allows for light extraction in a spectral window where silicon absorption is strong. Both the tight optical confinement within the waveguide and the slow light (c/40) mode supported by the PhC structure increase the optical energy density in the waveguide, enabling us to observe visible green light (at 520 nm) at low (~ several watts) near-infrared peak pump powers. This is 5-6 orders of magnitude lower than previous free-space coupling experiments in porous silicon PhC geometries [4].

## Slow light silicon photonic crystal waveguide

Figure 1 shows an SEM picture of the PhC structure. It consists of a 220nm thick silicon membrane suspended in air with a lattice constant of a=414nm and hole radii of 0.286a. The PhC waveguide is 80µm long, with the first 10 periods of the waveguide "stretched" by 10% to enhance coupling to the slow light mode. The engineered PhC design consists of laterally shifting the first two rows of holes adjacent to the missing row of holes forming the waveguide [5]. The short PhC section is connected to two tapered ridge access waveguides to improve light insertion.

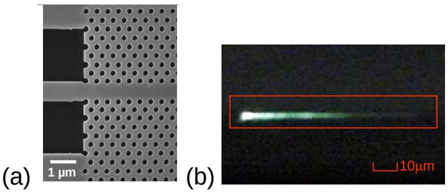

*Figure 1: (a )Scanning Electron Micrograph of the silicon PhC waveguide. (b) visible green emission measured from the top of the PhC waveguide.*

The waveguide structure was fabricated by e-beam lithography and reactive ion etching of a SOITEC silicon-on-insulator wafer.

The engineered PhC waveguide displays a high, relatively constant, group index ($n_g$) around 1560nm. However, to investigate the effect of group velocity, we exploit here the peculiar dispersion between 1550nm and 1559nm, over which the experimentally measured group velocity of the PhC fundamental mode varies by a factor of 4 (between c/10 and c/40), as displayed on Fig.2.

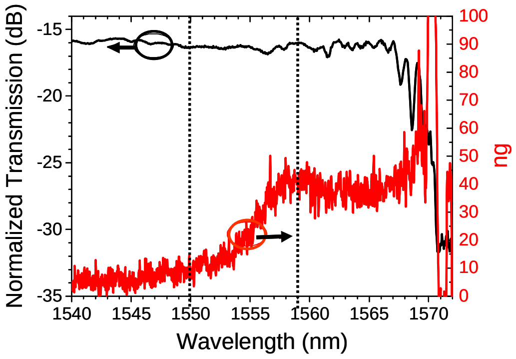

*Figure 2: Experimental group index dispersion of the PhC waveguide (right) and measured transmission (left). The dotted lines indicate the probed window.*

## Results and discussion

The waveguide is probed with near-transform-limited 1.5 ps pulses generated by a Figure-of-8 Er-fibre mode-locked laser at a repetition rate of 4MHz and around 1560nm. We use lensed fibers to couple TE-polarised light into the waveguide. The total (fiber to fiber) insertion loss is about 16dB, with a coupling efficiency of ~15%. The maximum peak pump power coupled into the waveguide is therefore of ~30W.

When coupling to the PhC waveguide, a visible green emission coming from the top of the sample is observed by the naked eye. Using a 0.25 N.A. microscope objective, we collect, image and measure the visible light power onto a linear and calibrated CCD camera. The emitted green light is localized along the 80µm long PhC waveguide (see Fig. 1(b)), and its wavelength is found at 520nm ± 5nm using interference filters, as expected for the third harmonic generated from a 1560nm pump. In addition, the green emitted power is found to vary with the cube of the fundamental input power (see Fig. 3), which further confirms the THG nature of the visible emission process. Yet, figure 3 shows a slight deviation from this trend at high input powers due to saturation effects related to two photon absorption and free carrier absorption, which are also visible through the saturation of the transmitted output power.

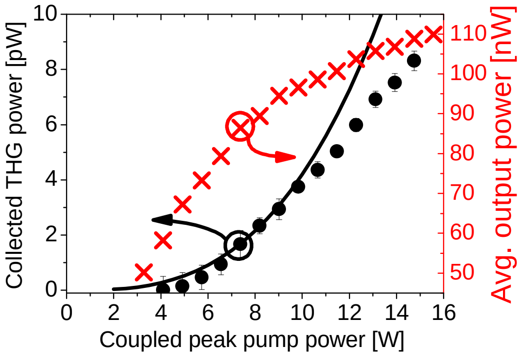

*Figure 3: THG power (left) and transmitted average output power (right) versus the coupled pump peak power.*

We investigate the dependence of this nonlinear process on the group velocity of the fundamental mode by varying the pump wavelength between 1550nm and 1559nm. Figure 4(a) shows that the conversion efficiency strongly varies within this spectral window. Using the $n_g$-dispersion of Fig. 2, we plot on Figure 4(b) the required input intensity that is necessary to obtain a constant THG power versus the fundamental mode group index. The chosen THG power is sufficiently low to minimize the nonlinear loss at all wavelengths. The curve is fitted reasonably well with a $1/n_g$ trend, as is expected from the $n_g$-enhancement of the optical energy density inside the PhC waveguide. Although the measured conversion efficiency is moderate (~ 5 x $10^{-10}$ for 1W of peak pump power), it compares favourably well with the value ($10^{-15}$ for 1W peak pump power) reported in a polystyrene 3D PhC [6]. In addition, the investigated PhC waveguide was not optimized for improving phase matching between the fundamental and the third harmonic, which is another degree of freedom for increasing the THG efficiency [6].

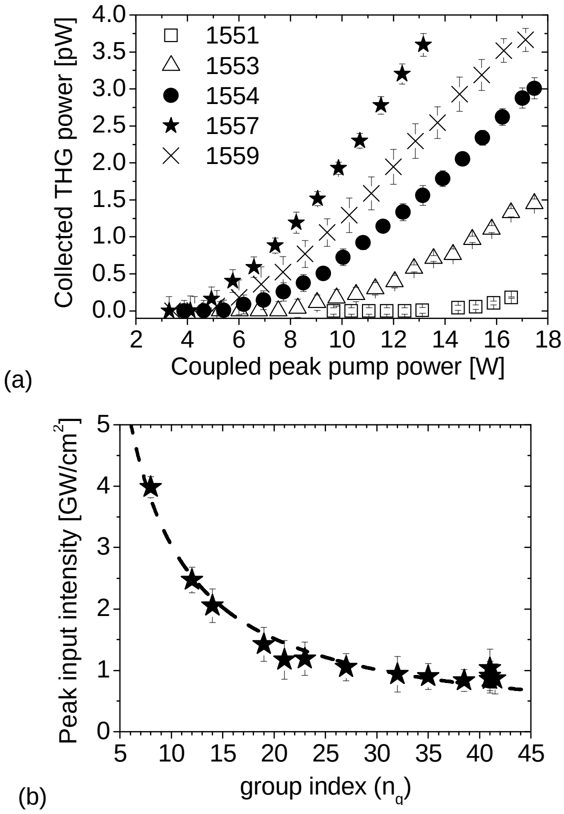

*Figure 4: (a) Third harmonic power versus coupled input power for different wavlengths. (b) Input pump power necessary to obtain a constant THG power (=0.5pW) versus both input wavelength and group index. The dashed line corresponds to a $1/n_g$ fit.*

## Conclusion

We have reported the generation of visible emission from a tightly confined silicon PhC waveguide at moderate peak powers (~several watts). We have shown that this nonlinear process is strongly enhanced in the slow light regime.

## References

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