Slow light enhanced third-harmonic generation in silicon photonic crystal waveguides

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Abstract

We report visible third-harmonic generation in silicon by launching near-infrared picosecond pulses into highly confined photonic crystal waveguides. We demonstrate the 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 highly 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] to date, such enhancement has not been systematically demonstrated. This is partly due to the typical high dispersion that accompanies slow light and which causes pulse distortion, thereby compromising the benefit due to slow light.

Planar photonic crystals (PhCs) represent an attractive platform for integrating many optical functions onto a single and 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 third harmonic generation is observed in integrated nanophotonic silicon devices. Due to the strong optical confinement within the waveguide and the slow light (c/40) mode supported by the PhC structure, we have measured visible green light (at 520 nm) for moderate (~ several watts) input peak powers at 1560 nm. Measurable THG at this power, which is much lower (by 5-6 orders of magnitude) than in previous free-space probe experiments in porous silicon PhC geometries [4], is enabled by the increased intensity into the slow light PhC waveguide.

Slow light silicon photonic crystal structure

Figure 1 shows a 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 80 µm 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 shifting the first two rows of holes adjacent to the missing row of holes forming the waveguide and perpendicular to the direction of propagation [5]. Two 3 µm wide ridge access waveguides encompass the short PhC waveguide to improve the light insertion.

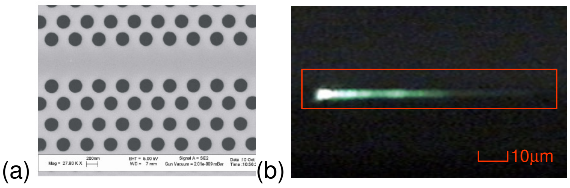

Figure 1: (a)Scanning Electron Micrograph of the PhC engineered waveguide. (b) visible green emission measured from the top of the PhC waveguide with a CCD camera

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.

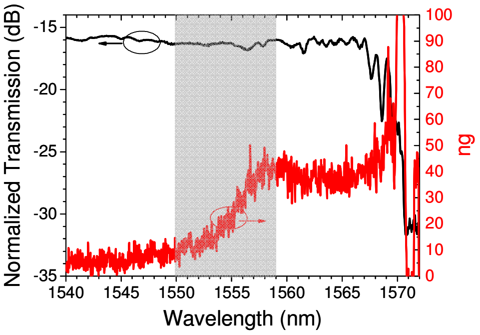

Figure 2: Experimental group index dispersion of the PhC waveguide (right) and measured transmission (left)

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 above 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 (see Fig. 3).

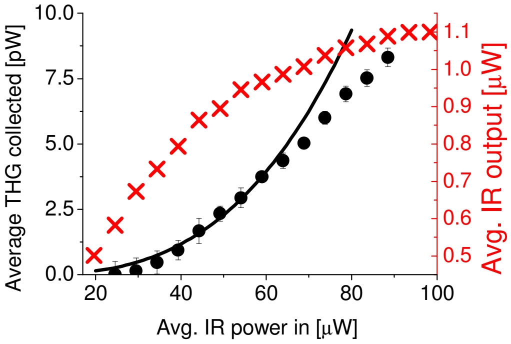

Figure 3: Experimental group index dispersion of the PhC waveguide (right) and measured transmission (left)

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 ($\sim 10^{-7}$), it compares favourably well with the 10^{-5} value reported in a polystyrene 3D PhC that was obtained for megawatt peak pump powers [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].

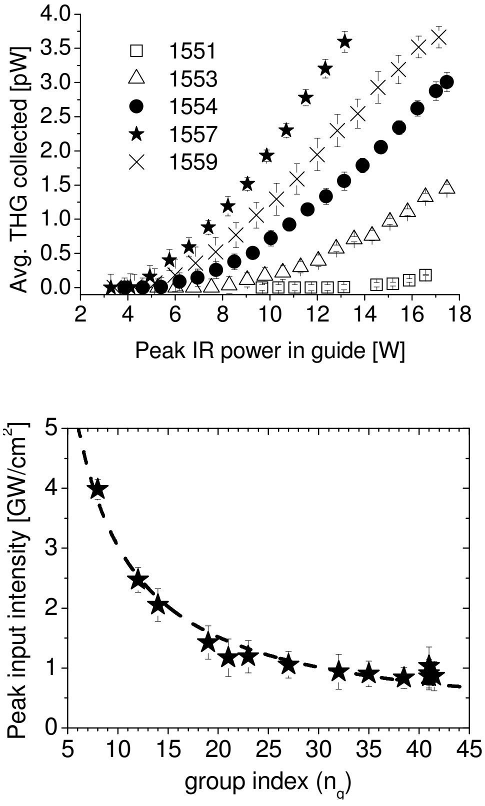

Figure 4: (a) Third harmonic power versus coupled input power for different wavlengths. (b) Input power necessary to obtain a constant THG power (=0.5pW) versus both input wavelength and group index. The dashed line corresponds to a $1/n_g$ fit.

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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