Observation of Second Harmonic and Sum Frequency in an Optically Poled Si_3N_4 Waveguide

Davide Grassani[1], Adrien Billat[1], Martin Pfeiffer[2], Tobias Kippenberg[2], Camille-Sophie Brès[1]

[1]*Ecole Polytechnique Fédérale de Lausanne, Photonic System Laboratory (PHOSL), CH-1015 Lausanne Switzerland*
[2]*Ecole Polytechnique Fédérale de Lausanne,Laboratory for Photonics and Quantum Measurements (LPQM), CH-1015, Switzerland*
davide.grassani@epfl.ch

Abstract: Enhanced second order nonlinear processes in a Si_3N_4 waveguide following optically induced $\chi^{(2)}$ is demonstrated, enabling the detection of a frequency doubled pulsed train and SFG with >-37 dB conversion efficiency for 18 W pump peak power.

OCIS codes: (190.4390) Nonlinear optics, integrated optics; (190.2620) Harmonic generation and mixing.

1. Introduction

Photonic platforms hold the promise to enable compact, high efficient and low cost devices integrating different optical functionalities. One of the best realizations of this paradigm has been the integration of nonlinear optical capabilities using silicon-on-insulator (SOI) substrates and CMOS technology, employing waveguide materials like silicon, silicon dioxide (SiO_2) and silicon nitride (SiN). Leveraging high mode field confinement and large Kerr ($\chi^{(3)}$) nonlinearity, such platforms have been employed for parametric wavelength converters and amplifiers [1], Raman lasers [2], supercontinuum [3], or non-classical photon sources [4]. Unfortunately, material symmetry inhibits 2^{nd} order optical nonlinearity, preventing $\chi^{(2)}$ functionalities in CMOS-based devices. We recently showed that a narrow-bandwidth 100 W level telecom laser can inscribe a periodic electric field inside a SiN waveguide through the coherent photogalvanic effect, breaking the material symmetry and resulting in a $\chi^{(2)}$ grating with periodicity allowing quasi-phase-matching for second harmonic generation (SHG) [5]. Here we show that following the all-optical $\chi^{(2)}$ grating inscription, a frequency doubled pulse train can be detected on a silicon detector. We also demonstrate that sum frequency generation (SFG) from the telecommunication window is unlocked with >-37 dB of conversion efficiency (CE).

2. Experiment and results

A 5.6 cm long waveguide made of stochiometric SiN buried in SiO_2 is fabricated following the Damascene process [6] with $1.7\mu m$ width and $0.87\mu m$ height. Input coupling losses at 1550 nm on the fundamental mode are estimated at 4 dB while the linear propagation loss is 0.2 dB/cm. A $\chi^{(2)}$ grating is inscribed in the waveguide by injecting a 1544 nm pulsed pump with 200 ps pulses at 25 MHz repetition rate. The coupled pump power is 27.2 dBm average (100 W peak). Following the grating inscription, the pump (p) and its frequency doubled wave (SH) are quasi phase matched by the grating with period $\Lambda = 2\pi/|\beta_{sh} - 2\beta_p|$ where β is the mode propagation constant [5].

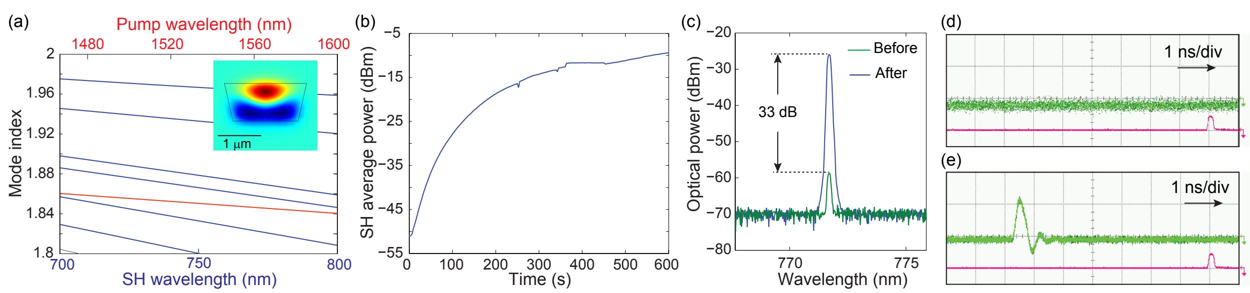

Fig. 1. (a) Index matching curves for the pump fundamental TE mode (red), and higher order TE modes at the SH wavelengths (blue). Inset: mode profile of 7^{th} TE mode. (b) SH peak growth for a 100 W peak 1544 nm pump. (c) SH spectrum before and after $\chi^{(2)}$ grating inscription when probed with 90 mW average 1544 nm signal. Telecom (pink) and SH (green) pulse train: (d) before and (e) after grating inscription. Vertical axis: pink - 50mV/div, green - 2.7mV/div (for d) and 5mV/div (for e).

While $\chi^{(2)}$ theoretically vanishes in the dipole approximation for SiN, bulk second order nonlinearity and symmetry breaking at the interface can lead to a native weak SHG, the SH being generated on a higher order mode (Fig. 1a).

Indeed, at the start of the process, a weak SH is detected with -52 dBm of average power (Fig. 1b). With time the SH power grows substantially due to charge separation, saturating at -10 dBm after several minutes. Once saturation is reached, the pump is turned off and the waveguide is probed with a low power signal (90 mW average, 18 W peak). The SH spectrum before and after all-optical grating inscription is shown in Fig. 1c, highlighting a 33 dB enhancement. The SH signal is also sent to a silicon detector and observed on an oscilloscope. Before grating inscription, the 200 ps pulses could not be detected (Fig. 1d). After optical pumping, the pulse train is converted with excellent quality (Fig. 1e). We measure SH pulses shorter than 350 ps, limited by the silicon detector 1 GHz bandwidth. However due to the almost instantaneous nature of parametric processes, we expect a SH pulse duration matching that of the telecom pulse.

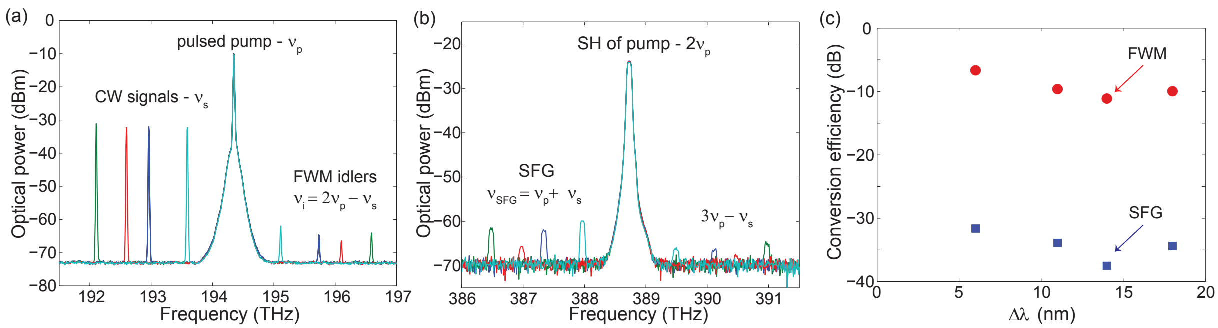

Fig. 2. Superimposed spectra waveguide output in (a) the telecom band (32 dB attenuation before OSA) and (b) the frequency doubled band. (c) CE of FWM and SFG as a function of $\Delta\lambda$ the detuning between the 1544 nm pump and telecom signals.

The waveguide was subsequently tested for SFG between a pump positioned at wavelength ν_p and a signal at ν_s leading to the generation of an idler wave at $\nu_{SFG} = \nu_p + \nu_s$. In this case the phase mismatch is given by $\beta_p + \beta_s - \beta_{SFG}$. The pulsed pump was positioned at 1544 nm and the continuous wave (CW) signal was tuned between 1550 nm and 1562 nm. The coupled average power is 90 mW (18 W peak) for the pump and 1 mW for the signal. The spectra, plotted in frequency for simplicity, at the ouput of the waveguide are shown in Fig. 2a, b. Four wave mixing (FWM) takes place between the pulsed pump and the CW signals within the telecom band resulting in pulsed waves at $\nu_i = 2\nu_p - \nu_s$. This FWM CE is evaluated to be between -6 and -10 dB, as plotted in Fig. 2c. We estimate the nonlinear coefficient γ = 0.4 $W^{-1}m^{-1}$, consistent with previous measurements. In addition, SH of the pump at $2\nu_p$ is generated together with the pulsed SFG idlers at ν_{SFG} (Fig. 2b). It should be noted that before $\chi^{(2)}$ grating inscription, only the weak pump SH is observed without any SFG signature. The CE of the SFG process, estimated as P_s/P_{SFG}, with P_s the the telecom signal CW power and P_{SFG} the peak power of the SFG idler, is between -32 dB and -37.7 dB as shown in Fig. 2c. In order to estimate the conversion efficiency, a 5 dB outcoupling loss for the SFG wave (generated on a higher order mode) is taken into account. No detectable SH from the signals are generated, as the waveguide is not phase matched for those wavelengths. FWM process in the frequency doubled band and SFG between the FWM idlers and the pump also result in the generation of high frequency waves positioned at $3\nu_p - \nu_s$. We note that the bandwidth of the SFG process seems larger than expected, which could be due to thermal effects.

We showed that the straightforward all-optical method used to induce second order nonlinearity in a CMOS-compatible material enables efficiencies compatible with the detection of frequency doubled pulsed trains and SFG within the telecom band. The efficiencies are comparable to the ones reported in resonant structures [7] but with the added benefit of all-optical reconfigurability and unconstrained operating wavelength.

This work was supported by the European Research Council under grant agreement ERC-2012-StG 306630-MATISSE.

1. X. Liu, et al., “Mid-infrared optical parametric amplifier using silicon nanophotonic waveguides,” Nat. Photonics **4**, 557 (2010).
2. H. Rong, et al. “A continuous-wave Raman silicon laser,” Nature **433**, 725-728 (2005).
3. D. Grassani, et al., “Mid-infrared supercontiunuum generation in a SiN waveguide pumped at 1.55 micron,” Frontiers in Optics FTu5D.3 (2016).
4. N. C. Harris, et al. “Integrated source of spectrally filtered correlated photons for large-scale quantum photonic systems” Phys. Rev. X 4, 110 (2014).
5. A. Billat, et al., “Large second harmonic generation enhancement in Si_3N_4 waveguide by all-optically induced quasi-phase-matching,” Nature Communications **8**, 1016 (2017).
6. M.H.P. Pfeiffer et al. “Photonic Damascene process for integrated high-Q microresonator based nonlinear photonics,” Optica **3**, 20 (2016).
7. J. S. Levy, et al,“Harmonic generation in silicon nitride ring resonators,” Opt. Express 19, 11415 (2011).