Difference-frequency generation in silicon nitride waveguides based on all-optical poling

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Integrated photonics leverages strong field confinement and long interaction lengths for the observation of a wide variety of nonlinear phenomena on-chip. Among them, wavelength conversion is one of the key, actively studied fields. Frequency conversion through the second-order susceptibility ($\chi^{(2)}$) is prohibited in most of the integrated photonics platforms, such as silicon, since they possess a centrosymmetric structure. Nevertheless, second-order nonlinear processes, such as sum- and difference-frequency generation (DFG), are desirable in applications for frequency comb stabilization [1] and mid-infrared (mid-IR) spectroscopy [2]. To bring efficient three-wave frequency mixing processes on silicon photonics we must first induce an effective $\chi^{(2)}$ and satisfy the phase-matching condition of the interacting waves. The former can be realized through symmetry breaking using resonant structures [3] and poling processes [4]. The latter is typically achieved by quasi-phase-matching (QPM).

Recently, the possibility of simultaneous fulfilling both requirements was demonstrated for second-harmonic generation (SHG) via all-optical poling in silicon nitride (Si_3N_4) waveguides [5]. In this method, a self-organized nonlinear grating is inscribed inside the waveguide by injecting high power nanosecond pump pulses [6]. The grating period naturally satisfies QPM for SHG and is given by $\Lambda = 2\pi/|\beta_{2\omega}-2\beta_{\omega}|$, with β_{ω} and $\beta_{2\omega}$ the propagation constants at poling pump and its SH wavelengths. Based on such inscribed grating, DFG could also be efficiently achieved given: $|\beta_{2\omega}-2\beta_{\omega}|=|\beta_p-\beta_s-\beta_i|$, with β_p, β_s, β_i the propagation constants at the DFG pump, signal and idler wavelengths, respectively.

We show here that after all-optical poling at telecommunication wavelength, non-degenerative DFG towards the mid-IR is possible by exploiting waveguide dispersion engineering. To do so, a waveguide with 2.0 x 0.75 μm^2 cross-section and 5.5 cm length is initially poled at 1560 nm in TE polarization. The effective $\chi^{(2)}$ and length of the inscribed grating are derived from SHG conversion efficiency (CE) measurement and Λ is theoretically calculated. Based on such parameters, we can simulate the DFG CE as shown in Fig. 1a. We observed that QPM for non-degenerate DFG in such waveguide is possible given a ~845 nm pump and a ~1535 nm signal, resulting in a ~1880 nm idler. We performed the experiment, coupling a fixed signal at 1535 nm while the pump wavelength is swept from 841 nm to 848 nm, all continuous-wave. The idler was monitored using an optical spectrum analyzer as shown in Fig. 1b. The experimental on-chip CE of the DFG process given by $P_i/(P_sP_p)$ with P the powers of the respective waves, is plotted in Fig. 1c and compared to the theoretical model, showing a good agreement.

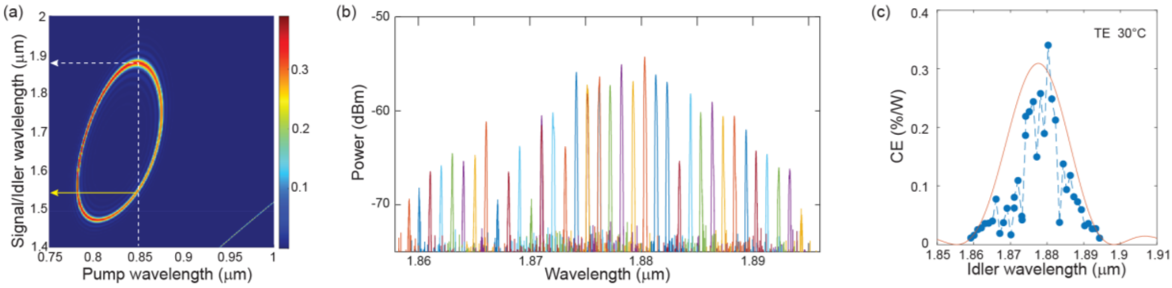

Fig. 1 (a) The CE (in %/W) simulation of DFG process in Si_3N_4 waveguide with 2.0 x 0.75 μm^2 cross-section optically poled at 1560 nm. Vertical dashed line indicates a pump wavelength; horizontal yellow and dashed arrows indicate a signal and an idler wavelengths at 1535 nm and 1880 nm, respectively. (b) Measured spectra of generated idlers using fixed signal at 1535 nm and tuned pump wavelength from 841 nm to 848 nm. (c) Theoretical (full line) and measured (dots) DFG CE as a function of idler wavelength.

These results clearly demonstrate the possibility of DFG in all-optically poled Si_3N_4 waveguides. Additional analysis on dispersion engineering has the potential to shift the position of the generated idler towards mid-IR and to expand the variety of coherent tunable sources in this region.

References

1. Telle, H. R. *et al.* Carrier-envelope offset phase control: A novel concept for absolute optical frequency measurement and ultrashort pulse generation. *Appl. Phys. B Lasers Opt.* **69**, 327–332 (1999).
2. Cruz, F. C. *et al.* Mid-infrared optical frequency combs based on difference frequency generation for dual-comb spectroscopy. *Conf. Lasers Electro-Optics Eur. - Tech. Dig.* 1138–1140 (2015).
3. Ning, T. *et al.* Efficient second-harmonic generation in silicon nitride resonant waveguide gratings. *Opt. Lett.* **37**, 4269 (2012).
4. Timurdogan, E., Poulton, C. V., Byrd, M. J. & Watts, M. R. Electric field-induced second-order nonlinear optical effects in silicon waveguides. *Nat. Photonics* **11**, 200–206 (2017).
5. Billat, A. *et al.* Large second harmonic generation enhancement in Si3N4 waveguides by all-optically induced quasi-phase-matching. *Nat. Commun.* **8**, 1–7 (2017).
6. Nitiss, E. *et al.* Formation Rules and Dynamics of Photoinduced χ(2) Gratings in Silicon Nitride Waveguides. *ACS Photonics* **7**, 147–153 (2020).