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

Boris Zabelich, Ezgi Sahin, Ozan Yakar, Edgars Nitiss, Camille-Sophie Brès
Ecole Polytechnique Fédérale de Lausanne, Photonic Systems Laboratory, 1015 Lausanne, Switzerland

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$_3$N$_4$) 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 $\beta_\omega$ 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: $|\beta_{2\omega} - 2\beta_\omega| = |\beta_\omega - \beta_{\text{idler}}|$, with $\beta_\omega$, $\beta_{\text{idler}}$, $\beta$ the propagation constants at the DFG pump, signal and idler wavelengths, respectively.

We show here that after all-optical poling at telecommunication wavelength, non-degenerate DFG towards the mid-IR is possible by exploiting waveguide dispersion engineering. To do so, a waveguide with 2.0 $\times$ 0.75 $\mu$m$^2$ 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 $\Lambda$ 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 845 nm to 884 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 $P/(P_p P_s)$ with $P$ the powers of the respective waves, is plotted in Fig. 1c and compared to the theoretical model, showing a good agreement.

These results clearly demonstrate the possibility of DFG in all-optically poled Si$_3$N$_4$ 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