Mid-IR All-Optical Poling in Silicon Nitride Waveguides

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Integrated silicon nitride (SiN_x) waveguides and microresonators are extensively studied for nonlinear demonstrations, including parametric amplification, optical parametric oscillation and supercontinuum generation, since SiN_x is a mature, versatile and efficient platform for third-order nonlinearity. Recently, its lack of second-order nonlinearity ($\chi^{(2)}$) has been overcome with all-optical poling (AOP) [1], relying on multiphoton absorption interference of optical fields to inscribe a $\chi^{(2)}$ through coherent photogalvanic effect (PGE) [2]. As such a self-organized quasi-phase matching (QPM) grating for second-harmonic generation (SHG) can be spontaneously obtained by solely launching a pump light in a waveguide, or in a seeded fashion by also injecting the pump SH which reduces the time and power requirements and increases the achievable efficiencies [2]. While the existence of trap states in SiN_x makes it possible to unlock the coherent PGE, measurements on trap locations indicate that traps in stochiometric SiN_x are 1.4 eV deep [3]. As such previous demonstrations were focused on pumping at 1550 nm (SH with 1.6 eV energy) [1] and 1064 nm (SH with 2.3 eV energy) [4] for stochiometric SiN_x (Si_3N_4). However, the depth of the traps is a limitation for AOP for longer wavelengths. In this work, we demonstrate all-optical inscription of QPM gratings in the 2000 nm region leveraging silicon-rich SiN_x waveguides.

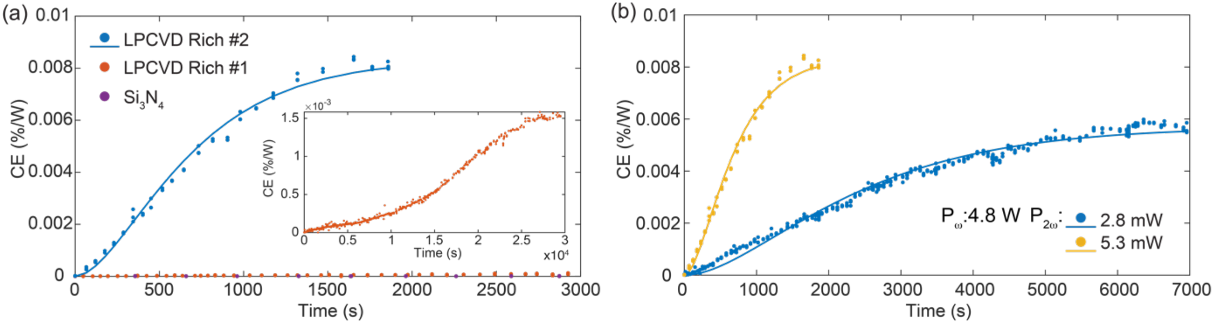

Fig. 1 a) Experimental SHG CE (power of SH over square of the pump power) at 2000nm from SiNx waveguides with different silicon concentration (dotted) and fit using eq. from ref. [2] (line). AOP only occurs in the non-stochiometric SiN_x waveguides. b) SHG CE as seed power is varied while the pump power is constant in silicon-rich waveguides.

A 2003 nm pulsed source (1ns with 5 MHz repetition rate) is obtained by modulating a DFB laser. We can reach a peak power of 5 W inside the waveguide after amplification with a thulium doped fiber amplifier. The SH of the 2003 nm light is externally generated via a nonlinear crystal, and starts the seeded AOP process in a similar setup as depicted in ref. [2]. In Fig. 1a, we show the optical poling results at 2003 nm in Si_3N_4 and silicon-rich SiN_x waveguides buried in SiO_2. The latter has a 0.9 μm × 0.8 μm cross section and a length of 9 mm, including input and output tapers. They are fabricated by CEA Leti with low-pressure chemical vapor deposition with varied NH_3 and DCS gas precursors ratios. NH_3/DCS ratios are approximately 1:2 and 1:5 and refractive indices of 2.05 and 2.08 at 633 nm wavelength, for #1 and #2, respectively. The Si_3N_4 waveguides have similar dimensions. We only observed SHG in silicon-rich waveguides in agreement with the experimental electronic structure in ref. [3]. Increasing the silicon ratio of SiN_x reduces the time it takes for the process to saturate from 8.3 hours to 30 minutes as well as increases the maximum efficiency. In addition, when with higher seeded SH power, the speed and efficiency of the process are improved due to the increase of the induced photoconductivity seen in Fig. 1b. For the highest obtained CE, $\chi^{(2)}$ is measured to be $\chi^{(2)} = \sqrt{2c^3\epsilon_0\bar{n}^2\eta_{2\omega}\bar{S}/\omega L} = 0.04$ pm/V, where c, ϵ_0, $\bar{n}$, $\bar{S}$ and $\eta_{2\omega}$ are speed of light, free space permittivity, effective refractive index, effective area and CE, respectively. This result is comparable to the second-order nonlinearity in 1550 nm in stochiometric SiN_x [2].

In conclusion, the results present a straightforward way to inscribe QPM gratings at 2000 nm in a CMOS compatible platform with obtained $\chi^{(2)}$ comparable to the ones at 1550 nm. AOP of silicon-rich SiN_x extends the window of $\chi^{(2)}$ nonlinearity closer to the mid-infrared regime.

Funding by ERC PISSARRO (ERC-2017-CoG 771647). Authors acknowledge A. Stroganov from LIGENTEC for fabrication of the Si_3N_4 waveguide.

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