Broadband Quasi-Phase-Matching in All-Optically Poled Stoichiometric Silicon Nitride Waveguides

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Abstract: We show how broadband (>30nm) quasi-phase matching in all-optically poled Si_3N_4 waveguides provides a platform for efficient sum-frequency generation, and for femtosecond pulse processing such as f_{CEO} detection without the need for group velocity engineering.

1. Introduction

Stoichiometric silicon nitride (Si_3N_4) has become one of the most widely utilized platforms in integrated photonics and its nonlinear optical properties based on the third order susceptibility $\chi^{(3)}$ have been leveraged for applications such as supercontinuum generation, frequency comb generation or four-wave-mixing (FWM). Unfortunately, due to the amorphous nature of Si_3N_4, second order nonlinearity ($\chi^{(2)}$) is not present. We recently showed that an effective $\chi^{(2)}$ can be induced in Si_3N_4 waveguides by using all-optical poling [1]. In this approach, a self-organized nonlinear grating is inscribed in the waveguide resulting in efficient quasi-phase-matching (QPM) for second-harmonic generation (SHG). Studies of the properties of QPM revealed that although such self-organized gratings can be inscribed in waveguides regardless of their dimensions, the cross-section strongly influences the resulting spectral response. We observed that in large cross-section waveguides, induced mode mixing during all-optical poling causes the conversion efficiency to be spectrally broadened, following simultaneous inscriptions of gratings with varying periods. In this contribution, we specifically leverage broadband $\chi^{(2)}$ responses of all-optically poled Si_3N_4 waveguides. High conversion efficiency covering more than 30 nm at the 1.55 µm pump wavelength on the one hand allows for efficient broadband sum-frequency generation (SFG), and on the other supports processing with femtosecond (fs) pulses without requiring group velocity dispersion engineering of the waveguide. We demonstrate the latter with a frequency comb carrier envelope offset frequency detection proof of principle experiment.

2. Poling and SFG

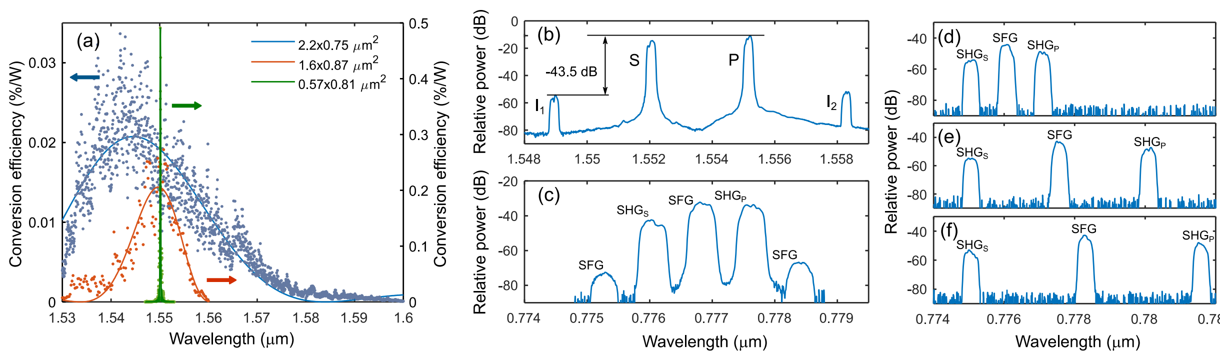

Fig. 1. (a) QPM response and fits of poled Si_3N_4 waveguides with cross-section of 2.2x0.75 µm² (primary y axis), 1.6x0.87 µm² and 0.57x0.81 µm² (secondary y axis). Calculated effective grating lengths of 0.91 mm, 10.9 mm and 40.8 mm, respectively. (b) FWM in waveguides with cross-section of 2.2x0.75 µm²; P: pump, S: signal, I_1 and I_2: idlers. (c) corresponding SHG and SFG with P power 150.6 mW and S power of 45.7 mW; (d)–(f) SHG and SFG with 38 mW P at 1.554, 1.56 and 1.563 µm, respectively.

The waveguides used in this study are prepared using the photonics Damascene process [2]. The Si_3N_4 waveguides are buried in SiO_2 with input and output tapers, folded in meanders with bends having radius of 75 µm. We perform all-optical poling as described in [1], using a 1 ns 5 MHz pulsed pump with peak power up to 110 W. In Fig. 1(a) we show the QPM spectral response of all-optically poled Si_3N_4 waveguides with cross-section of 2.2x0.75 µm², 1.6x0.87 µm² and 0.57x0.81 µm². The experimental measurements of QPM graph are fitted with a sinc-squared function which allows to extract the effective grating length. Higher conversion efficiency is reached in waveguides with smaller cross-section due to smaller mode sizes and therefore higher intensity of field in the waveguide. Due to mode mixing taking place in the waveguides the QPM response is broadened causing the effective length to be much smaller than the actual length of the grating [3]. This is especially pronounced in waveguides with large cross-section. As can be seen in Fig. 1 the SH response for 2.2x0.75 μm^2 has a bandwidth of 30 nm which can be used for efficient SFG. The various mixing processes are monitored after coupling a continuous wave (CW) strong pump at 1.555 μm and a CW signal at 1.552 μm into the poled waveguide. Due to $\chi^{(3)}$, FWM generates two idlers in the telecom band as shown in Fig. 1(b). The pump, signal and FWM idlers result in the generation of two SHG peaks and three SFG peaks as evident in Fig. 1(c). In Fig. 1(d)-(f) we show the tuning of SFG by varying the pump location from 1.554 μm to 1.563 μm while signal is kept at 1.55 μm. Only three peaks are visible due to lower power of the pump. The measured conversion efficiency of SFG does not vary over the entire tuning range owing to the broadband phase matching.

3. Frequency comb offset detection

The spectrally broad response of large cross-section waveguides can also be leveraged for processing with ultra-short pulses. In Fig. 2(a) we plot the measured relative power of SH generated in waveguides with cross-section of 1.6x0.87 μm^2 and 0.57x0.81 μm^2, respectively, after coupling a 1.56 μm fs laser light (Toptica FemtoFErb). In the large cross-section waveguide the SH of the femtosecond laser is efficiently generated despite the fact that group-velocity phase matching is not satisfied, as had to be done in [4]. Lifting this requirement, provides much more flexibility and tunability. We employ this phenomenon to retrieve the f_{ceo} of the femtosecond source using the setup depicted in Fig. 2(b). Here the beam from the light source is split into two and delivered to two Si_3N_4 waveguides. One of the waveguides has dimensions of 2.65x0.78 μm^2 and is dispersion engineered to generate a dispersive wave at around 780 nm which is where the SH of the pump is located. The other beam is guided to a waveguide with cross-section of 1.6x0.87 μm^2 which shows broadband conversion efficiency after all-optical poling. After collecting the output beams at a detector we retrieve the beatnotes as displayed in Fig. 2(c). Here the f_{rep} corresponds to 100 MHz which is the repetition rate of the pulses from the laser. The f_{ceo} is detected with a signal-to-noise-ratio (SNR) at 21 dB when the coupled average power into the poled waveguide is 0 dBm resulting in -28 dBm average SH power. As further increase in coupled power leads to grating erasure, improvement of the SNR requires improving the grating strength during the poling stage

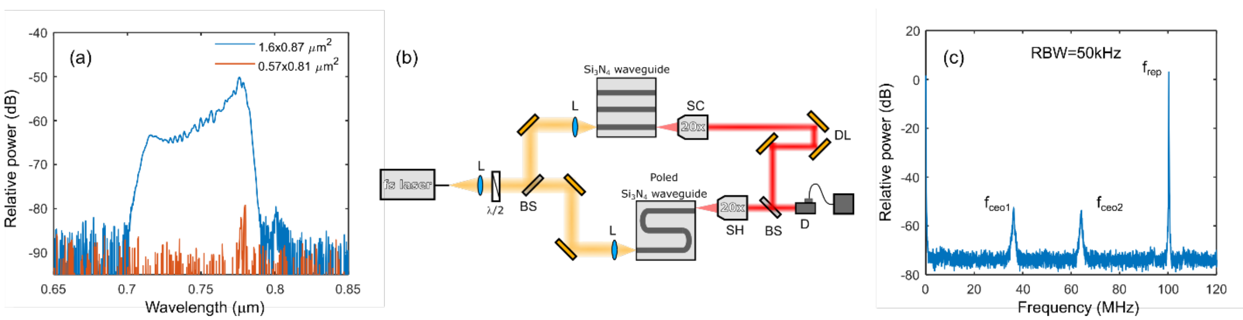

Fig. 2. (a) Relative power of SH from 1.56 μm fs source generated in poled waveguides with cross-section of 1.6x0.87 μm^2 and 0.57x0.81 μm^2. (b) Setup for f_{ceo} retrieval; λ/2 – half-wave plate, BS – beamsplitter, L – lens, DL – a delay line, D – detecting unit (coupler, fiber and detector/optical spectrum analyzer). (c) Measured beatnotes. Resolution of 4 kHz and RBW of 50 kHz.

In conclusion we have shown that broadband conversion in all-optically poled large cross-section waveguides, represents a useful platform of increasing the reach of second order frequency mixing processes and for processing of large bandwidth signals, such as femtosecond pulses.

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