Backward Second-Harmonic Generation in Optically Poled Silicon Nitride Waveguides

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Abstract: We report the inscription of quasi-phase-matching gratings in silicon nitride waveguides for backward second-harmonic-generation enabled by all-optical poling, therefore, circumventing the difficulties in inscribing poled domains with ultra-short periods.

1. Introduction

Second-order nonlinear processes using quasi-phase-matching (QPM) gratings have been well studied in non-centrosymmetric media. While the largest body of work involves forward second-harmonic generation (FSHG) (Fig 1a), it has been shown that SHG can occur for a pump and SH wave traveling in opposite directions, called backward SHG (BSHG). This opens the possibility to implement novel applications such as mirrorless OPOs [1] or to produce extremely narrow QPM bandwidth, which could be an advantage for the quality of SPDC processes [2]. There have been several candidates for BSHG such as periodically poled lithium niobate (PPLN) [3], stacked metasurfaces [4], and negative index materials [5]. Because of the need for very short QPM periods in order to compensate for large wavevector mismatch (see Fig.1a) the fabrication of BSHG devices is very complex. Alternatively, higher order QPM can be implemented, yet in such case the device suffers from low efficiency.

Silicon nitride (Si_3N_4) provides an adaptable platform for scalable, low-cost third-order ($\chi^{(3)}$) integrated nonlinear applications such as four-wave mixing and Kerr comb generation. Moreover, its lack of second-order nonlinearity ($\chi^{(2)}$) has been overcome with the inscription of an effective $\chi^{(2)}$ through all-optical poling (AOP) [6–8], in which self-organized QPM gratings are optically introduced. Recently, seeded AOP has shown to offer new opportunities in further controlling the grating inscription [9]. Yet, until now, only forward SHG was demonstrated in such structures.

In this work, for the first time, we demonstrate AOP enabled first order QPM gratings for BSHG achieving on-chip conversion efficiency (CE) of $1.04 \times 10^{-4}\%/W$, which is comparable with the highest CE value reached in bulk PPLN [3]. We achieve this by AOP using counter-propagating coherent pump and SH seed light, bypassing the complex fabrication steps utilized in other platforms. We also confirm that BSHG allows for narrow bandwidth SH generation as well as low thermal sensitivity.

2. Results and Discussion

The QPM gratings in an AOP process are formed due to the coherent photogalvanic effect [10] and can be obtained solely by launching a pump wave in a waveguide, or by a seeded process where both the pump and its SH are simultaneously launched. In the process, the periodicity of $\chi^{(2)}$ automatically compensates the wavevector mismatch of the pump and SH. As such by injecting the pump and its SH from opposite sides of the waveguide, QPM for BSHG can be achieved. After AOP, the CE for BSHG becomes

$$\mathrm{CE} = \frac{P_{2\omega}}{P_{\omega}^2} = \frac{\omega^2 L^2 (\chi^{(2)})^2}{2\varepsilon_0 c^3 n_{\omega}^2 n_{2\omega}} \frac{S_{2\omega}}{S_{\omega}^2} \left(\frac{\sin\left(\frac{\Delta\beta L}{2}\right)}{\left(\frac{\Delta\beta L}{2}\right)} \right)^2 \tag{1}$$

where $\Delta\beta$ is the net wavevector mismatch after AOP, i.e., $\Delta\beta = k_{2\omega} + 2k_{\omega} - \Delta k$, L is the grating length, $n_{\omega/2\omega}$, and $S_{\omega/2\omega}$ are the effective refractive indices and mode areas of pump and SH, respectively.

We performed the experimental demonstration of BSHG in an integrated Si_3N_4 waveguide buried in SiO_2. It has a cross section of $1.3\,\mu\mathrm{m} \times 0.8\,\mu\mathrm{m}$ and is folded in 7 meanders for a total length of 3.5 cm, including input and output tapers. Backward seeded AOP is initiated by 1550 nm light together with its second-harmonic, externally generate using a nonlinear crystal (PPKTP). The 1550 nm pump was initially shaped in 5 ns pulses at 1 MHz repetition-rate and was amplified as to reach peak power up to 5 W in the waveguide [6]. The pump and its SH (0.54 mW average on-chip) are injected in the waveguide from the opposite sides as shown in Fig. 1b.

After backward AOP, the SH seed is stopped using a beam blocker and the performance of the inscribed grating is quantified using CW pump light. We monitor the power of the generated BSHG (on detector D2) as a function of pump power and confirm the power scaling with a slope of 2 as shown in Fig 1c. We also measure the CE spectrum for both BSHG and FSHG (on detector D1). The experimental data and the fits using eq. (1) are shown

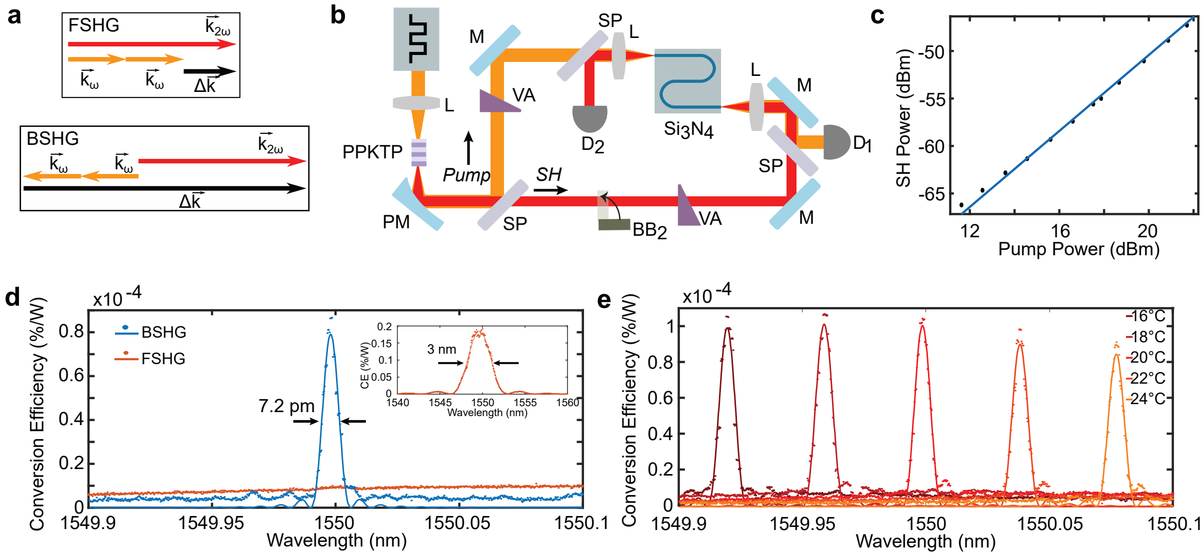

Fig. 1: a) Phase-matching diagram for forward and backward SHG. b) Seeding setup for Backward AOP. BB: Beam Block, VA: Variable Attenuator, M: Mirror, SP: Dichroic Mirror Short Pass, L: Lens, PM: Parabolic Mirror, L: lens, D: detector. c) On chip SH power with respect to the on chip CW probe power. Line is a fit with a slope of 2. d) Experimental BSHG CE spectrum (blue dots) and fit (blue solid line) FSHG CE spectrum shown in red for backward poling. Inset: FSHG CE spectrum of forward poling. e) Temperature tuning of QPM grating.

in Fig 1d. We clearly see that forward SH is not generated while BSHG occurs with a very narrow bandwidth of 7.2 pm and a peak efficiency estimated around $1.04 \times 10^{-4}\%/W$. This can be compared to FSHG in the same waveguide but after forward poling (see Fig.1d inset) which results in a much broaded bandwidth of 3 nm, as expected. From the fit of the backward AOP CE spectrum, we extract the grating period, $\chi^{(2)}$ and grating length to be 206.3 nm, 1.46×10^{-3} pm/V and 3.5 cm (i.e. the entire waveguide length), respectively. The efficiency of the backward poling is at the moment much lower than for forward poling and is currently being studied but could be due to some intrinsic limitations. The position of the CE peak can be thermally tuned [11]. For BSHG, the thermal tuning of the CE becomes

$$\Delta\lambda = \frac{\frac{\partial n^t_{eff}}{\partial T}}{\frac{n^t_{eff}}{\lambda} - \frac{\partial n^t_{eff}}{\partial \lambda}} \Delta T \tag{2}$$

where $n^t_{eff} = n_\omega + n_{2\omega}$, ΔT is the detuning in temperature, $\Delta\lambda$ is the resulting detuning in wavelength. We experimentally investigate the thermal sensitivity of BSHG as shown in Fig. 1e by varying the chip temperature. We extract a low thermal shift of the QPM peak to be 19 pm/°C.

In conclusion, the results present a straightforward way to inscribe QPM gratings for BSHG in a CMOS compatible platform with efficiencies comparable to the highest one achieved in PPLN. The experimentally retrieved bandwidth and thermal response agree with the theory. AOP allows for the inscription of extremely short QPM periods that are technically challenging with standard electrical poling techniques.

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