Ultra-efficient and highly tunable frequency conversion in Z-cut periodically poled lithium niobate nanowaveguides

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Abstract: We demonstrate ultra-efficient ($\sim 1900 \pm 500\% W^{-1} cm^{-2}$) and highly tunable ($\sim$ 1.71 nm/K) second harmonic generation from 1530 to 1583 nm via type-0 phase matching in Z-cut periodically poled lithium niobate nanowavguides.

1. Introduction

Thin-film lithium niobate on insulator (LNOI) has been explored to enhance second harmonic (SH) generation's efficiency [1,2] and its thermal tunability [3]. The current approaches suffer from the trade-off between efficiency and tunability [1–3]. To achieve large tunability, type-I phase matching scheme [3,4] is implemented to access the largest thermal-optic birefringence. However, this scheme is utilizing nonlinear tensor d_{31} (4.7 pm/V) instead of the largest d_{33} (27 pm/V), hence capped the maximum achievable efficiency by 20 times. On the other hand, type-0 phase matching scheme [1,2] has highly restricted tunability due to its weak thermal-optic coefficient despite significantly more efficient by accessing largest d_{33}. Here, we explore another degree of freedom, i.e. group velocity mismatch (GVM), to improve thermal tunability while maintaining ultra-high conversion efficiency. GVM engineering is constrained in previous cases [3,4] for the following reasons. First, modal phase matching in [3] requires the refractive indices of fundamental and SH modes to be equal. Therefore the geometry of the waveguide is firstly determined by the phase matching condition, leaving no room for further GVM engineering. Second, the GVM engineering is difficult to achieve in conventional periodically poled lithium niobate (PPLN) waveguide [4], due to its weak mode confinement and limited fabrication approaches. In this work, these constraints could be relieved in PPLN nanowaveguides, by the means of engineering GVM with different waveguide geometry while applying appropriate poling period to compensate vector mismatch Δk for achieving quasi- phase matching.

2. Results

According to the definition of $GVM = \frac{1}{v_{g1}} - \frac{1}{v_{g2}}$, we further modify thermal tunability equation [3] to:

$$\frac{\Delta\omega_1}{\Delta T} = \frac{\frac{\partial n_1}{\partial T} - \frac{\partial n_2}{\partial T}}{-GVM\frac{c}{\omega_1}}, \tag{1}$$

where n_1 and n_2 are the refractive indices for fundamental and second harmonic modes, ω is angular frequency of SH light and T is temperature. By manipulating the GVM, we are able to change the amplitude of the tunability as well as the direction. As shown in Fig.1, we first perform optical mode and temperature dependency simulation. It shows opposite temperature dependency compared with conventional cases [1–4]. The distinct behavior implies that they have different signs in GVM. Thus, by engineering the geometry of waveguide, we futher reduce the $|\text{GVM}|$ to be 180 fs/mm, usually > 400 fs/mm [4]. Here as proof-of-principle, we didn't further optimize it toward zero GVM. With the chosen geometry, the poling period for type-0 phase matching is calculated to be 3.8 μm.

The PPLN waveguides are fabricated on an Z-cut LNOI wafer (NANOLN Inc.), which is a 700 nm thick LN bonded on a 2-μm thermally grown silicon dioxide layer above a silicon substrate. We use bi-layer e-beam resist and define the poling electrodes by using e-beam lithography (EBL). Then 30-nm Cr and 60-nm Au layers are deposited via e-beam evaporation. The desirable poling electrode pattern is then created by a metal lift-off process. We apply several 1-ms high voltage (~550 V) electrical pulses on the poling pads to form the domain inversion region. The whole sample is placed on high temperature ($\sim 300°C$) hotplate during poling. Then a second EBL is carried out to define the LN waveguide in the poled region. Using a similar process described in [2,5,6], an optimized process is used to etch the waveguide structure. The device is cladded with 2-μm silicon dioxide.

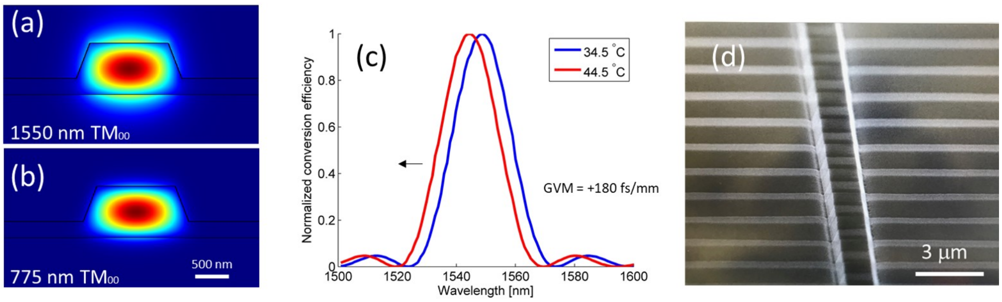

Fig. 1. (a-b) Simulated mode profiles for 1550 nm and 775 nm quasi-TM$_{00}$ mode. Cross-section is 700×1500 nm and etched depth is 480 nm and 220 nm LN slab is remained. Simulated sidewall angle in is 62°. (c) Simulated phase matching curves with positive GVM (180 fs/mm) blue shifting with 0.6 nm/K thermal tunability. (d) SEM images of PPLN nanowaveguide with 3.8 μm period.

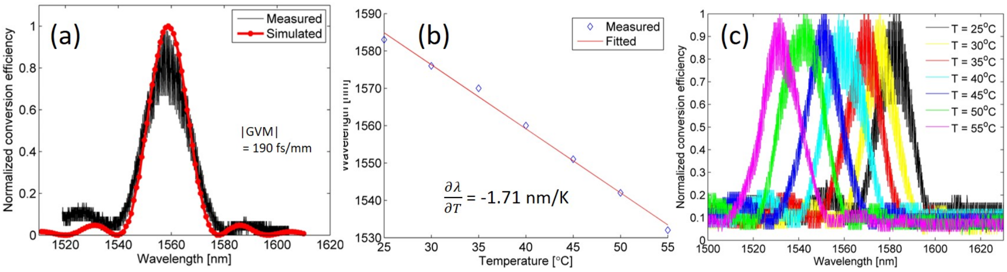

Fig. 2. (a) Measured phase matching curves. The extracted |GVM| is 190 fs/mm.(b) Measured temperature dependency of the phase matched pump wavelength. The tunability is fitted to be -1.71 nm/K. (c) Measured phase matching curve of waveguide at various temperatures.

A continuous-wave (CW) tunable laser (Santec 550, 1500-1630 nm) is used as pump laser along with a fiber polarization controller to excite the fundamental quasi-TM mode in the PPLN nanowaveguide. Two tapered fibers (2 μm spot diameter, OZ optics) serve as the input/output coupling. The coupling loss at 1550 nm and 775 nm are 5.4 (± 0.3 dB) and 4.7 (± 0.3 dB), respectively. By using standard Fabry-Perot method described in [2], the propagation loss at 1550 nm are extracted to be about 2 dB/cm. As shown in Fig.2 (a), it shows a very good sinc-like curve, which indicates high quality poling. The extracted absolute value of GVM is 190 fs/mm. The highest measured efficiency is up to 2400 $\%W^{-1}cm^{-2}$ at T = 55°C. Next we study the temperature tunability, it shows opposite temperature dependency with blue shifting in wavelength (-1.71 nm/K) (see Fig.2 (b)). To verify its broad tunability, we measure the evolution of the phase matching curve during the thermal tuning, as shown in Fig.2 (c). It shows excellent consistency across entire telecom C-band with ± 500% variation in efficiency due to coupling and temperature stability. In addition to thermal optical effect, the waveguide is also experiencing various effects, such as thermal expansion and pyroelectric effect. Hence the measured tunability is higher than simulated result.

In summary, we have studied the effect of GVM mismatch on the thermal tunability of phase matching in Z-cut PPLN nanowaveguides. We demonstrated ultra-efficient ($\sim$ 1900 ± 500$\%W^{-1}cm^{-2}$) and highly tunable ($\sim$1.71 nm/K) frequency conversion on chip. Among other applications, our device shows the potential for the coherent light generation from visible to mid-IR spectra with high wavelength tunability and energy efficiency.

Acknowledgement: The research was supported in part by National Science Foundation (Award #1641094 & #1842680). Device fabrication was performed at ASRC, CUNY.

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