Efficient Second Harmonic Generation in Thin-film Lithium Niobate Waveguides

1st Hanwen Li
State Key Laboratory for Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University
Hangzhou, China
lihw21@zju.edu.cn

2nd Weixi Liu
State Key Laboratory for Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University
Hangzhou, China
liuweixi@zju.edu.cn

3rd Bin Chen
State Key Laboratory for Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University
Hangzhou, China
cbin@zju.edu.cn

4th Liu Liu
State Key Laboratory for Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University
Hangzhou, China
liuliuopt@zju.edu.cn

5th Daoxin Dai
State Key Laboratory for Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University
Hangzhou, China
dxdai@zju.edu.cn

6th Yaocheng Shi*
State Key Laboratory for Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University
Hangzhou, China
*yaocheng@zju.edu.cn

***Abstract*—We propose and demonstrate a thin-film periodically poled lithium niobate waveguide with high conversion efficiency for second-harmonic generation. Normalized conversion efficiency up to 3100 $\%W^{-1}cm^{-2}$ is achieved with 1555 nm pump wavelength.**

Keywords—thin-film lithium niobate, waveguide, second-harmonic generation, quasi-phase matching

I. Introduction

Second-order nonlinear process (SONP) is key to many modern photonics applications including wavelength conversion [1], photon pairs generation [2] and supercontinuum generation [3]. Lithium niobate (LN) has been widely utilized for SONP owing to its wide transparency range and large nonlinear coefficients. However, due to the small core-to-cladding refractive index difference, traditional bulk LN waveguides confront a weak optical confinement which results in high pump power and long interaction length. With the improved nano-structuring techniques, thin film LN (TFLN) is especially attractive for its stronger optical confinement and higher photon density compared to traditional bulk LN. Also, periodically poled lithium niobate (PPLN) takes the advantage of the largest nonlinear coefficient tensor d_{33} while achieving the quasi-phase matching (QPM) condition between fundamental modes in ridge waveguides. In the field of nonlinear process, tight light confinement and large mode overlap can lead to a significant improvement of the nonlinear conversion efficiency. However, to fully develop the performance of PPLN ridge waveguides, problems including observing the reversed domains conveniently, optimizing parameters for a perfect periodical poling and improving the coupling efficiency of the devices remain to be settled.

In this work, we design and fabricate a thin-film PPLN waveguide for second-harmonic generation (SHG). Poling parameters and electrode materials are characterized and optimized. A ~60% duty cycle of reversed domains is observed by piezoresponse force microscopy (PFM). A normalized conversion efficiency up to 3100 $\%W^{-1}cm^{-2}$ at 1555 nm pump wavelength has been achieved.

II. Design

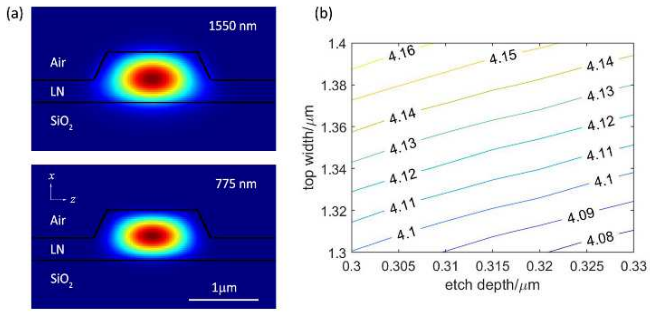

Fig. 1. (a) TE_{00} mode profiles at 1550 nm and 775 nm; (b) Numerical calculated poling period for quasi-phase matching with different waveguide widths and etching depths.

On x-cut lithium niobate on insulator (LNOI) platform, fundamental transverse-electric (TE_{00}) modes for both first-harmonic (FH) and second-harmonic (SH) wavelengths are considered to ensure high optical confinement and large mode overlap. Fig. 1(a) show the TE_{00} mode profiles at 1550 nm and 775 nm simulated with Lumerical MODE solutions. To meet the phase matching conditions, the poling period Λ for SHG should be

$$\Lambda = \frac{2\pi}{\Delta k} = \frac{\lambda_{FH}}{2(n_{FH}-n_{SH})} \quad (1)$$

where λ_{FH} is the FH wavelength and n_{FH} , n_{SH} are the effective refractive indices of the TE_{00} mode at FH and SH wavelength respectively. The poling period as a function of waveguide width and etching depth is shown in Fig. 1(b).

For undepleted phase-matched SHG, the nonlinearity is measured by normalized conversion efficiency η [4]:

$$\eta = \frac{2\lambda_{FH}^2 d_{eff}^2}{n_{FH}^2 n_{SH} \epsilon_0 c^3} \cdot \frac{A_{SH}}{A_{FH}^2} \quad (2)$$

where $d_{eff} = 2d_{33}/\pi$ is the effective nonlinear coefficient for quasi-phase matched interactions in LN and $d_{33} = 27$ pm/V for 1550 nm pump light, ϵ_0 is the vacuum permittivity, c is the light speed in vacuum, A_{FH}, A_{SH} are mode areas defined as

$$A = \int \mathrm{Re}\left[E_x H_z^* \text{-} E_z H_x^*\right] \mathrm{d}x\mathrm{d}z \quad (3)$$

where $E_{x,z}$ and $H_{x,z}$ are the normalized electric and magnetic fields of waveguide modes in x or z direction. It is clear that η is governed by the effective nonlinear coefficient and the mode areas of the involving FH and SH modes. In our design, the theoretical value for η reaches 3670 $\%W^{-1}cm^{-2}$ with 1550 nm pump wavelength. In comparison, normalized SHG conversion efficiencies in TFLN waveguides using modal phase matching (MPM) are usually one or two orders of magnitude lower.

III. Fabrication

The waveguides are fabricated on a x-cut Magnesium-oxide- (MgO-) doped thin-film LNOI from NANOLN, with a 600-nm-thick LN thin film bonded on a 2-μm-thick silicon dioxide layer. MgO doping can reduce the coercive field required in poling from 21 kV/mm to 4 kV/mm [5]. Poling electrodes consisting of a 100 nm insulator, a 15 nm titanium adhesion layer and a 200 nm gold layer, are first patterned using a standard photolithography and followed by a liftoff process. The bottomed insulation layer is introduced to reduce leakage current which severely affect the growing of the reversed domains. We use electrodes with small duty ratio (~0.3) and round tips to help center nucleation and produce narrower domains [6]. A schematic of the electrodes is shown in Fig. 2(a). Then several pulses of ~400V are applied to inverse the domains periodically, with the sample emerged in oil to prevent air breakdown. The domains are imaged by PFM, which provides high-resolution images without damaging the surface of the sample. Reversed domains with a ~60% duty cycle is shown in Fig. 2(b). Poling parameters including number of pulses, pulse ramp time/duration/down time, pulse period and poling voltage can be optimized by checking poling quality in PFM images. After poling, ridge waveguides are patterned using electron-beam lithography and dry etching process. Optical and scanning-electron micrographs of the waveguides are shown in Fig. 2(c-d). Finally the waveguide facets are diced and polished for end coupling.

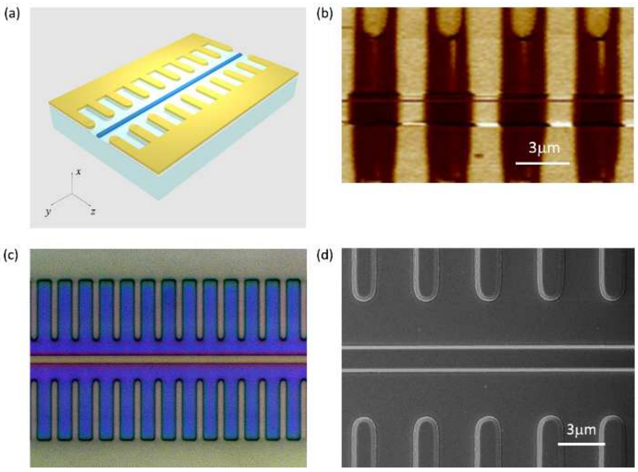

Fig. 2. (a) Schematic of the PPLN waveguide with poling electrodes; (b) PFM phase image of inverted domains (dark brown) on the surface; (c-d) Optical (c) and scanning-electron (d) micrograph of the PPLN waveguide.

IV. Results

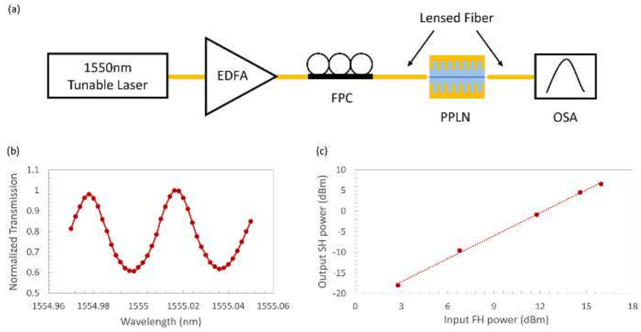

Fig. 3. (a) Schematic of experiment setup. (b) The spectrum of Fabry-Perot resonances formed by the PPLN waveguide and its two facets. (c) Linear correlation of the SH power and the FH power in SHG.

The experiment setup is shown in Fig. 3(a). Pump light from a continuous-wave (CW) tunable laser is directly coupled into the waveguide using a lensed fiber. A fiber polarization controller (FPC) is used to control the FH light to be TE polarization. The generated SH light is collected using another lensed fiber together with the residual FH light and monitored by an optical spectrum analyzer (OSA).

To evaluate the coupling loss and propagation loss of PPLN waveguide, the Fabry-Perot (FP) method [7] is applied. The normalized spectrum of FP resonances in the waveguide is shown in Fig. 3(b). With the facet reflectivity simulated by Lumerical FDTD solutions, the estimated coupling loss is 3.2 dB/facet and propagation loss of FH light is 0.4 dB/cm.

Fig. 3(c) shows the measured output SH power as a function of input FH power with 1555 nm pump light. The linear relation shows the result are in good agreement with the theory, which indicates that the SHG process in the waveguide has not reach the saturation. The measured η reaches $3100\%W^{-1}cm^{-2}$. We believe that lower measured η compared to theoretical calculation is mainly due to non-ideal poling duty cycle and fabrication errors in the photolithography and etching process.

In summary, we demonstrate a thin-film PPLN waveguide and acquire a high SHG normalized conversion efficiency of $3100\%W^{-1}cm^{-2}$. A 3.2 dB/facet coupling loss and a 0.4 dB/cm propagation loss of FH light are also achieved. Our work will pave the way for high-efficient nonlinear frequency conversion.

Acknowledgment

The work is supported by the National Natural Science Foundation of China (62135011; 62105286); "Pioneer" and "Leading Goose" R&D Program of Zhejiang (2022C01103), the Fundamental Research Funds for the Central Universities.

References

[1] J. Zhao, M. Rüsing, U. A. Javid, et al. "Shallow-etched thin-film lithium niobate waveguides for highly-efficient second-harmonic generation," Opt. Express, vol. 28, no. 13, pp. 19669-19682, June 2020.

[2] U. A. Javid, J. Ling, J. Staffa, et al. "Ultrabroadband entangled photons on a nanophotonic chip," Phys. Rev. Letters, vol. 127, no. 18, pp. 183601, October 2021.

[3] M. Jankowski, C. Langrock, B. Desiatov, et al. "Ultrabroadband Nonlinear Optics in Nanophotonic Periodically Poled Lithium Niobate Waveguides," Optica, vol. 7, no. 1, pp. 40-46, January 2020.

[4] C. Wang, C. Langrock, A. Marandi, et al. "Ultrahigh-efficiency wavelength conversion in nanophotonic periodically poled lithium

niobate waveguides," Optica, vol. 5, no. 11, pp. 1438-1441, November 2018.

[5] K. Mizuuchi, A. Morikawa, T. Sugita, and K. Yamamoto, "Electric-field poling in Mg-doped $LiNbO_3$," J. Appl. Physics, vol. 96, no. 11, pp. 6585-6590, November 2004.

[6] J. T. Nagy and R. M. Reano. "Reducing leakage current during periodic poling of ion-sliced x-cut MgO doped lithium niobate thin films," Opt. Mater. Express, vol. 9, no. 7, pp. 3146-3155, July 2019.

[7] M. F. Volk, S. Suntsov, C. E. Rüter and D. Kip. "Low loss ridge waveguides in lithium niobate thin films by optical grade diamond blade dicing," Opt. Express, vol. 24, no. 2, pp. 1386-1391, January 2016.