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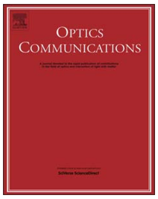

Efficient second harmonic generation in $\chi^{(2)}$ profile reconfigured lithium niobate thin film

Lutong Cai[1], Yiwen Wang[1], Hui Hu*

School of physics, Shandong University, Jinan, Shandong 250100, P. R. China

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ABSTRACT

Second harmonic wave was efficiently generated in proton exchanged lithium niobate thin film channel waveguides. Modal dispersion phase matching was achieved between two guided modes at pump and second-harmonic wavelengths with the same polarization, enabling using the largest second-order nonlinear component d_{33}. The $\chi^{(2)}$ profile in the lithium niobate thin film was reconfigured by proton exchange, leading to significantly enhanced modal overlap integral between the interacting modes. Normalized conversion efficiency up to 48% W^{-1} cm^{-2} was achieved in experiments.

1. Introduction

Second order optical nonlinearity plays an important role in frequency doubling, parameter down conversion and optical parameter oscillator/amplifier, making it have wide application in the area of light source, optical communication and quantum optics [1–4]. Lithium niobate (LN) is a remarkable nonlinear optical material due to its wide transparent window and large second-order nonlinear coefficient ($\chi^{(2)}$), especially component d_{33} [5]. Single-crystal lithium niobate thin film on insulator (LNOI), fabricated by crystal ion slicing and wafer bonding, emerges as an ideal platform for integrate optics [6]. The strong guiding of light in the submicron thin film not only greatly improves the integration of the photonic components, but also leads to prominent nonlinear phenomena and high performance photonic devices [7–10].

Efficient wavelength conversion, such as second harmonic generation (SHG), requires phase matching (PM), which is satisfied by birefringence in bulk media [11]. To use d_{33} in LN, quasi-phase-matching (QPM) is widely employed since d_{33} is difficult to be accessed with birefringent phase matching [12,13]. Recently periodically poled lithium niobate (PPLN) has been employed on LNOI [14–17], and efficient wavelength conversion was obtained [18]. Modal dispersion phase matching (MDPM) is another way to realize the efficient wavelength conversion and the fabrication is much simpler than QPM, without the formation of periodically poled structure. MDPM requires that the pump and SHG modes have identical phase velocity. To fulfill such condition, owing to the material dispersion, a higher order waveguide mode is often served as SHG mode while the fundamental waveguide mode is the pump mode [19]. Since the field distributions of the higher order waveguide modes change sign across the waveguide, the modal overlap integral between the interacting modes strongly reduces, resulting in low wavelength conversion efficiency. Some previous works propose effective solutions, such as arranging the $\chi^{(2)}$ profiles in some particular nonlinear materials like polymer [20,21]. For example, by fabricating multi-layered polymeric waveguides (styrene-maleic anhydride or polystyrene/stilbene polymer), $\chi^{(2)}$ changes its sign or is set to be zero where the electric field direction of the SHG mode inverses, leading to a enhanced SHG [20,21]. In LN, proton exchange (PE) is a conventional method to fabricated low-loss waveguides [22], and the PE region without anneal has nearly vanished $\chi^{(2)}$ [23]. Therefore, PE has potential to reconfigure the $\chi^{(2)}$ profile in the LN thin film to improve the modal overlap and thus increase the conversion efficiency. In this paper, we demonstrated that, by forming proton exchange channel waveguides and using the vanished $\chi^{(2)}$ in the PE region, the modal overlap integral overlap between quasi-TE$_{00}$ mode (pump) and quasi-TE$_{01}$ mode (SHG) significantly enhanced, making contribution to a high conversion efficiency.

2. Design

Fig. 1(a)–(c) showed the cross-section of the PE channel waveguide and the optical mode profiles of pump mode and SHG mode in x-cut LNOI, respectively. The PE region was a rectangular (W×D) with step-like index profile [22]. To use the largest component of the second-order nonlinear coefficients (d_{33}) in LN, quasi-TE$_{00}$ mode at pump

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* Corresponding author.
E-mail address: hhu@sdu.edu.cn (H. Hu).
[1] Authors contributed equally to this work.

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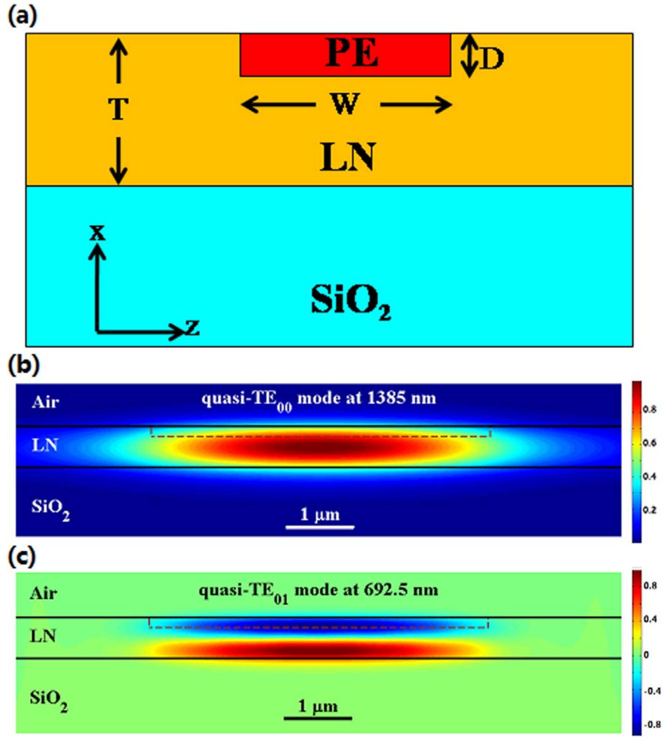

Fig. 1. (a) Schematic diagram of the waveguide cross-section. (b) and (c) Electric field (E_z) profiles of the quasi-TE_{00} mode at pump wavelength and quasi-TE_{01} mode at SHG wavelength, respectively.

wavelength and quasi-TE_{01} mode at SHG wavelength with the same polarization along the crystalline z-axis were chosen. The normalized conversion efficiency, η, was given by [24]:

$$\eta \propto [S{\cdot}\mathrm{sinc}(\Delta kL/2)]^2 \tag{1}$$

S is the modal overlap integral between the interacting waveguide modes [24]. High η required PM condition ($\Delta k=0$), under which the effective refractive index (n_{eff}) of the two modes should be equal. The relation between the n_{eff} and the wavelength is shown in Fig. 2, using T (the thickness of LN film)=591 nm and W×D=5×0.15 μm^2 (such dimension was used in the simulation in Fig. 4 to make the simulated PM wavelength consistent with the experiment result). PM was fulfilled at the wavelength of 1385 nm.

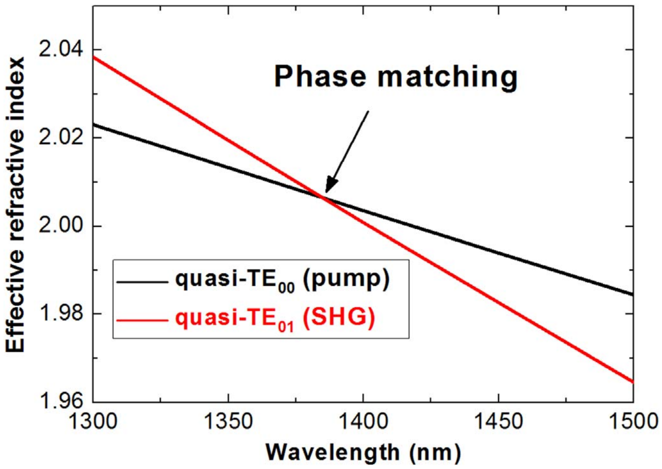

Fig. 2. Dependence of the effective refractive index of the interacting waveguide modes on the wavelength. Waveguide dimensions were T=591 nm and W×D=5×0.15 μm^2. PM occurred at 1385 nm.

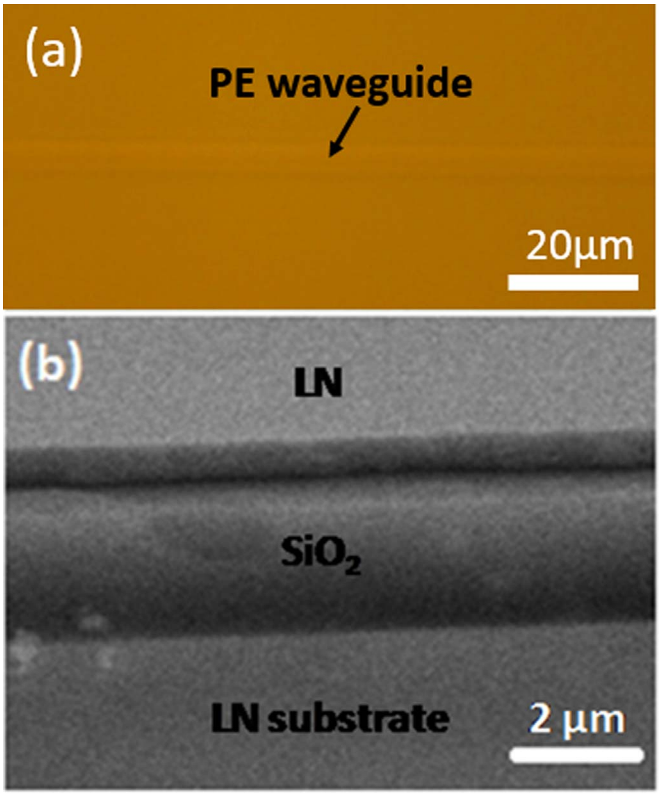

Fig. 3. (a) Optical microscope image of the top view and (b) SEM image of the cross-section of the waveguide.

Besides the PM condition, η also strongly depends on parameter S [24]:

$$S = \iint_{LN} d_{33} E^2_{z,\omega}(x,z) E_{z,2\omega}(x,z)\, dxdz \tag{2}$$

Here $E_{z,\omega}$ and $E_{z,2\omega}$ denote the z component of the electric fields of the fundamental and the second harmonic modes normalized to yield unit power ($P_y=\frac{1}{4}\iint(\mathbf{E}\times\mathbf{H}^*+\mathbf{H}\times\mathbf{E}^*)\cdot\mathbf{e_y}\, dxdz=1$), respectively. Because the sign of $E_{z,2\omega}$ inversed across the waveguide region, the cancellation between the positive and negative contributions to the integral made S low. However, the second-order nonlinear coefficient component d_{33} in the PE LN (PE region in Fig. 1(a)) was nearly zero [23], and most negative field of the quasi-TE_{01} mode located in the PE region (see Fig. 1(c)). In such configuration, the value of S was 3.2×10^{-2} $W^{3/2}/V$. T This S was approximately 7 times higher than that with non-degradation d_{33} in the PE region

3. Experiment

To fabricate channel waveguides, 100 nm thick chromium (Cr) film was deposited on a LNOI wafer with LN film thickness of approximately 600 nm (by NANOLN). 4 μm wide open channels were defined by photolithography. After the following wet etching of Cr, the pattern was transferred to the Cr mask. PE depth (D) depended on the PE temperature and time. Higher temperature and longer time would lead to a larger diffusion coefficient (faster diffusion rate) and deeper diffusion depth of H^+, respectively. In this work, PE was performed at 200 ℃ for 3 min, leading to a diffusion depth (D) of 0.16 μm (larger D would result in higher waveguide loss [22]). Finally, the Cr mask was removed by Cr etchant. The end faces were polished by chemical mechanical polishing (CMP) to facilitate the end-face coupling in optical characterization. To reduce the risk of cracks, the platen rotation velocity and polishing pressure were limited to a low level although this would lead to a low removal rate and a long polishing time. After polishing, the length of the channel waveguide was L