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Zhangchao Huang
Nankai University

Chenghou Tu
Nankai University

Shuanggen Zhang
Tianjin University of Technology

Yongnan Li
Nankai University

Fuyun Lu
Nankai University

See next page for additional authors

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Femtosecond second-harmonic generation in periodically poled lithium niobate waveguides written by femtosecond laser pulses

Abstract

We present in this Letter the second-harmonic generation of femtosecond pulses in double-line-written waveguides fabricated in periodically poled lithium niobate (PPLN) with femtosecond laser pulses. In a 10-mm-long sample, a normalized conversion efficiency of $12.6\% \text{ W}^{-1} \text{ cm}^{-2}$ has been achieved for 40 fs pump pulses with the wavelengths centered at 1550 nm. Simulation results show that in PPLN waveguides the FWHM of wavelength tuning curve for 40 fs pump pulses is 42 nm, which is 15 times of that for 40 ps pump pulses.

Keywords

second, harmonic, femtosecond, laser, written, pulses, waveguides, generation, niobate, lithium, poled, periodically

Disciplines

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Authors

Zhangchao Huang, Chenghou Tu, Shuanggen Zhang, Yongnan Li, Fuyun Lu, Yaxian Fan, and Enbang Li



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Femtosecond second-harmonic generation in periodically poled lithium niobate waveguides written by femtosecond laser pulses

Zhangchao Huang,¹ Chenghou Tu,¹ Shuanggen Zhang,² Yongnan Li,¹ Fuyun Lu,^{1,*}
Yaxian Fan,³ and Enbang Li⁴

¹School of Physics, Nankai University, Tianjin 300071, China

²School of Electronic Information Engineering, Tianjin University of Technology, Tianjin 300384, China

³Department of Physics, Nanjing University, Nanjing 210093, China

⁴College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China

*Corresponding author: lufy@nankai.edu.cn

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We present in this Letter the second-harmonic generation of femtosecond pulses in double-line-written waveguides fabricated in periodically poled lithium niobate (PPLN) with femtosecond laser pulses. In a 10-mm-long sample, a normalized conversion efficiency of 12.6% W⁻¹ cm⁻² has been achieved for 40 fs pump pulses with the wavelengths centered at 1550 nm. Simulation results show that in PPLN waveguides the FWHM of wavelength tuning curve for 40 fs pump pulses is 42 nm, which is 15 times of that for 40 ps pump pulses. © 2010 Optical Society of America
OCIS codes: 160.4330, 140.7090, 140.3515.

Nowadays quasi-phase-matching (QPM) waveguides in periodically poled materials have become one of the best choices for frequency doubling. To fabricate channel waveguides in transparent materials, several methods have been developed, such as Ti diffusion, annealed proton exchange, Zn diffusion, and femtosecond pulse writing. In the past decade there has been a rapid development of a femtosecond pulse writing method [1–7], owing to its simple fabrication process, fast realization of three-dimensional (3D) structure, and low cost. Recently more interests have arisen on second-harmonic generation (SHG) using laser beam written waveguides. Several groups [3–7], including ours, have investigated SHG characteristics in the waveguides for cw, nanosecond pulses and picosecond pulses. To the best of the authors' knowledge, however, investigations for the transmission of femtosecond pulses in these structures are still missing.

In this Letter, we describe the frequency doubling of femtosecond pulses in laser-written periodically poled lithium niobate (PPLN) waveguides with a QPM period of 18.6 μm. The experimental results show a second-harmonic (SH) spectrum width of 4.2 nm and provide the highest normalized conversion efficiency 12.6% W⁻¹ cm⁻² in the waveguides fabricated by femtosecond laser pulses.

To describe the evolution of ultrashort pulses' SHG, assuming the slowly varying envelope approximation and neglecting the losses, we use the coupled partial differential equations [8],

$$\begin{aligned} \frac{\partial E_1}{\partial z} - \frac{i}{2} \beta_{21} \frac{\partial^2 E_1}{\partial \tau^2} &= -i \kappa d_{\text{eff}} E_2 E_1^* \exp(-i \Delta k z) \\ &- i \frac{n_2 k_1}{n_{01}} (|E_1|^2 + 2|E_2|^2) E_1, \end{aligned}$$

$$\begin{aligned} \frac{\partial E_2}{\partial z} + \left(\frac{1}{v_2} - \frac{1}{v_1} \right) \frac{\partial E_2}{\partial \tau} - \frac{i}{2} \beta_{22} \frac{\partial^2 E_2}{\partial \tau^2} &= -i \kappa d_{\text{eff}} E_1^2 \\ &\times \exp(-i \Delta k z) - i \frac{n_2 k_2}{n_{02}} (|E_2|^2 + 2|E_1|^2) E_2 \end{aligned} \quad (1)$$

where the indices 1 and 2 respectively represent fundamental and SH pulses, i refers to either the indices 1 or 2, E_i is the field amplitude, $\kappa = (2\omega^2/\varepsilon_0 c^3 n_{01}^2 n_{02} S_{\text{eff}})^{1/2}$ is the coupling coefficient, n_{0i} is the refractive index, n_2 is the third-order nonlinear refractive index, v_i is the group velocity, and β_{2i} is the group-velocity dispersion parameter. Here, $\tau = t - z/v_1$ corresponds to a frame of reference moving with the fundamental pulse at its group velocity v_1 . $\Delta k = k_2 - 2k_1 - 2\pi/\Lambda$ (Λ is the period of PPLN, and k_i is the wave vector) is the wave-vector mismatch. The shape of the input pulse is of a standard Gaussian form. For a PPLN waveguide, the effective nonlinear coefficient d_{eff} for first order QPM is $d_{\text{eff}} = 2d_{33}/\pi = 16 \text{ pm/V}$, and the effective waveguide cross section is $S_{\text{eff}} = 2.5 \times 10^{-10} \text{ m}^2$. The walk-off length can be expressed as $L_w = T_0/(1/v_2 - 1/v_1)$ (T_0 is the width of fundamental pulse).

In Fig. 1(a), we calculated the normalized SHG efficiency for 40 fs pump pulses with different central wavelengths in a PPLN waveguide with a fixed period of 18.6 μm designed for a central wavelength of 1550 nm. Every normalized efficiency is calculated from the average power of a SH pulse, which is equal to the total of the intensities at each frequency component in the spectrum. The oscillation with certain regularity appears on the curve and becomes particularly strong near 1550 nm, as shown in the inset of Fig. 1(a). The highest conversion efficiency appears in an 11 nm region from 1545 to 1556 nm. It can be seen that the highest efficiency would be achieved

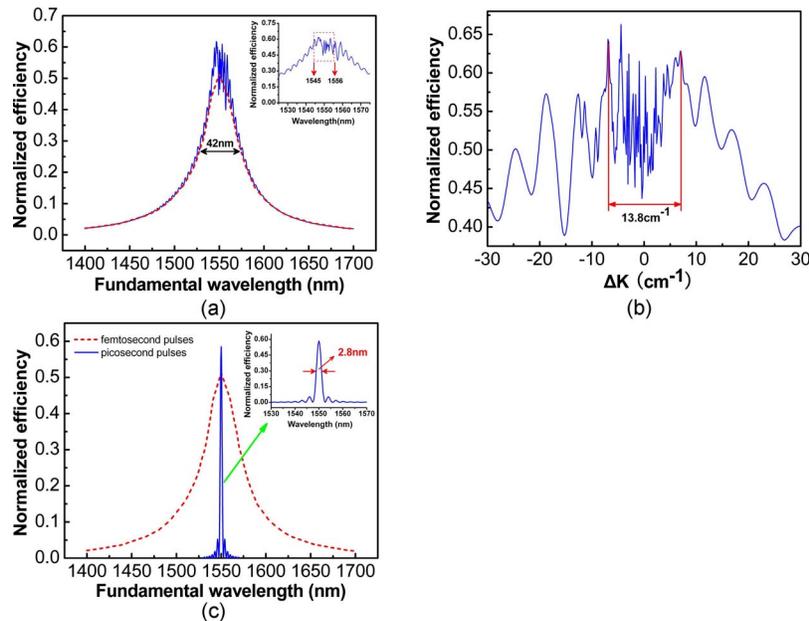


Fig. 1. (Color online) (a) Normalized SH efficiency as a function of pump pulse central wavelength. Inset, enlarged curve at the range from 1525 to 1575 nm. (b) Efficiency with the phase mismatch. (c) Contrast picture of picosecond pulses' (solid curve) and femtosecond pulses' (dashed curve) wavelength tuning curve.

among an area close to the pulse central wavelength that matches the period. The low points of different parts in the tuning curve are joined, forming the dashed curve in Fig. 1(a), which is the bottom line SH efficiency can reach. The FWHM of it is as wide as 42 nm. Figure 1(b) reveals the influence of the phase mismatch on the SHG efficiency. In a range of 13.8 cm^{-1} near $\Delta k=0$, the strong oscillation emerges and the left and right sides are not asymmetric. When the absolute value of Δk increases, the efficiency variations decrease. Figure 1(c) shows the comparison of wavelength tuning curve between 40 ps and 40 fs pump pulses in SHG processes when other conditions remain the same. The inset of Fig. 1(c) presents a magnified wavelength tuning curve of 40 ps pump pulses with an FWHM of 2.8 nm. Compared with the picosecond pulses, the femtosecond pulses are not necessarily superior in peak efficiency, but they have a much wider wavelength tuning range. For 40 fs pump pulses, this range is 15 times of that for 40 ps pulses. By utilizing a femtosecond laser source, highly efficient output of frequency doubling can be achieved in a much larger wavelength range.

In our experiment, a 10-mm-long and 0.5-mm-thick Z-cut PPLN sample with a period of $18.6 \mu\text{m}$ was used for waveguide fabrication. The PPLN sample was made by the external pulse field poling technique. The 50 fs waveguide writing pulses were from a Ti:sapphire femtosecond laser system operating at a central wavelength of 800 nm with a repetition of 1 KHz. The light was linearly polarized with polarization direction parallel to the waveguide axis and incident along the z axis of the poled sample. The laser beam was focused into the sample by a $25\times$ microscope objective (NA=0.4) and the focal point was approximately $200 \mu\text{m}$ beneath the surface of the sample. To produce a thermally stable type II wave-

guide, a pair of straight lines was written along the X direction with a velocity of $400 \mu\text{m/s}$, and the line spacing was $10 \mu\text{m}$. The single pulse energy was adjusted to $10 \mu\text{J}$. It is found from our investigation that only the light polarized along the Z axis [transverse-magnetic (TM) polarization] is guided in the laser-written lines.

The experimental arrangement of femtosecond pulses SHG (shown in Fig. 2) consisted of a femtosecond pulse laser system, which can generate 40 fs pulses over a tunable wavelength range of 1160–2600 nm at a repetition rate of 1 KHz. The PPLN waveguide was mounted on a temperature-controlled oven. A $10\times$ microscope objective (NA=0.25) was used to couple the laser beam into the PPLN waveguide.

A coupling loss of 1 dB/facet and a propagation loss of 0.8 dB/cm were measured at 1550 nm for TM polarization. The input spectral width is 75.4 nm, as depicted in Fig. 3(a). From Fig. 3(b), it can be seen that there exists a good agreement between experimental and theoretical data. The measured SH spectral width is 4.2 nm and the maximum point can be found at 774.6 nm. Corresponding to the fundamental spectrum, the width of SH spectrum is so narrow because of the large group-velocity mismatch [9]. The walk-off

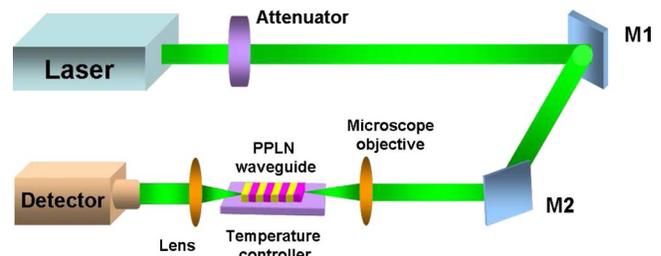


Fig. 2. (Color online) Experimental arrangement of SHG in the waveguide.

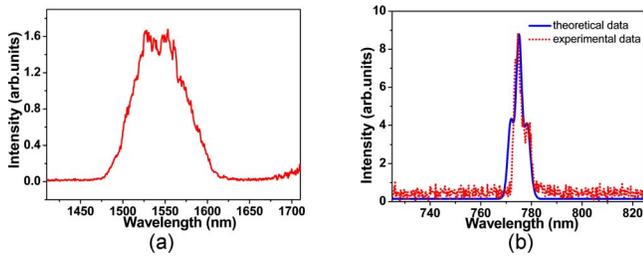


Fig. 3. (Color online) (a) Input spectrum, (b) SH spectrum of experimental (dotted curve) and theoretical (solid curve) results.

length is only about 0.1 mm, while the SHG interaction length is 1 cm. In addition to the main peak, two pronounced spectral dips appear on both sides of the spectrum. Moreover, the asymmetry of the two dips in experimental spectrum is more obvious than that of the calculated spectrum. The asymmetry of the spectrum may be caused by strong nonlinear effects owing to such high-peak power of femtosecond pulse, or a nonuniform temperature distribution in the temperature-controlling oven [10]. The near-field mode profile of SH pulses is shown in Fig. 4. The NA of the waveguide calculated from an estimated refractive index change of $\Delta n \approx 3 \times 10^{-3}$ is about 0.166.

Figure 5 shows the experimental data of SH power with the input power. In the experiment, SH power increases almost linearly as the input power increases. In our simulation, the curve fitting shows the trend will be quadratic as the input power is enhanced. Therefore, we estimate if the input power is increased to a higher range, the curve would follow a quadratic trend. At an incident average power of 26.8 mW, the maximum conversion efficiency of 18.2% is obtained. According to $\bar{\eta} = P_{2\omega} / P_{\omega}^2 L^2$ (L is the length of PPLN waveguide), we get the normalized efficiency of $12.6 \% \text{ W}^{-1} \text{ cm}^{-2}$, which is almost twice of the best published results [5].

In summary, we have investigated the tuning characteristics of ultrashort pulses, and we have demonstrated by experiments on frequency doubling of 40 fs pulses in a 10-mm-long double-line-written PPLN waveguide.

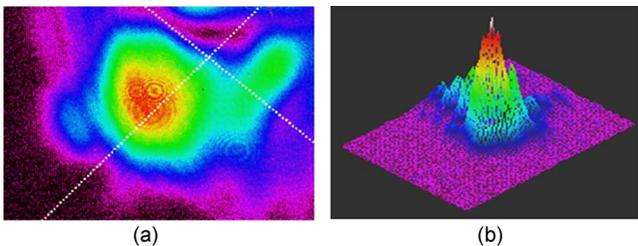


Fig. 4. (Color online) (a) 2D image of near field mode at SH wavelength, (b) corresponding 3D image.

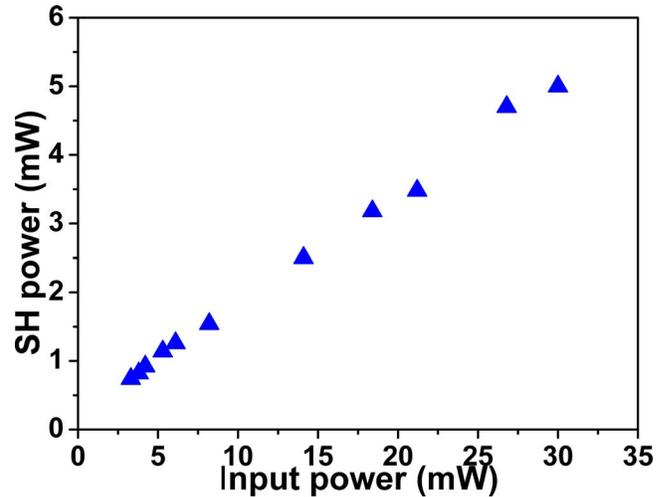


Fig. 5. (Color online) SH power versus fundamental power.

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