Nonlinear generation of a neat semi-Gaussian laser beam with a transversely varying periodically-poled $LiTaO_3$ crystal

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Abstract: We experimentally demonstrate a compact, all-solid-state 532nm semi-Gaussian laser beam (SGB) source based on a 1064nm laser and a transversely varying periodically-poled $LiTaO_3$ (TPPLT) crystal as the laser beam shaper as well as the nonlinear frequency converter. We have used the designed TPPLT crystal to obtain a neat 532nm SGB with the quality of Q_{SGB}=1:17.5 by a single-pass second harmonic generation. The dependence of the generated SGB quality on the designed TPPLT parameter and the potential applications of the neat SGB are also discussed.

OCIS codes: (140.3300) Laser beam shaping; (130.7405) Wavelength conversion devices; (220.0220) Optical design and fabrication.

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1. Introduction

Laser beams with different intensity profiles have attracted much more attention of the scientists as they can be widely used in the fields of both research and application since the birth of lasers in 1960s [1, 2]. So far, the researchers have generated laser beams with various intensity profiles, such as hollow laser beam [3-5], flat-topped laser beam [6-9], semi-Gaussian laser beam [10-12], Airy laser beam [13] and so on. Among of them, a neat semi-Gaussian laser beam (SGB) with no diffraction fringes is what we are most interested in, whose cross section has an intensity distribution of a half Gaussian profile in one transverse direction and a Gaussian profile in the orthogonal transverse direction. The SGB, especially neat SGB, has some potential applications in modern optics and atomic (molecular) physics. For example, the self-bending of the SGB in the nonlinear refractive material can be used in the nonlinear refractive index measurement of materials [14]. Theoretical investigations concerning molecular deceleration or reflection by the neat SGB in conjunction with the optical dipole force have been reported [15,16]. Usually, the SGB is simply generated by using a sharp blade to block half profile of the TEM_{00} Gaussian laser beam, but includes many oscillating diffraction fringes (i.e. diffraction by the straight edge) [10]. In 2008, we proposed a scheme to generate a neat SGB with no diffraction fringes using the combination of a spatial light modulator and a sharp blade and performed the theoretical study [12]. Up to now, the experiment on the generation of a neat SGB with no diffraction fringes hasn't been reported. So it would be interesting and worthwhile to propose, demonstrate this kind of neat SGB. In this paper, we describe a special method, based on the use of a transversely nonuniform quasi-phase-matching (QPM) grating to convert a Gaussian pump beam to a SGB. We have designed and fabricated a transversely varying periodically-poled $LiTaO_3$ (TPPLT) crystal. Using this TPPLT crystal, we experimentally obtain a neat 532nm SGB from a 1064nm Gaussian pump beam.

QPM materials have been extensively used in the nonlinear optical processes (such as second harmonic generation (SHG), optical parametric amplification (OPA) and optical parametric oscillation (OPO)) due to the large effective nonlinear coefficient and the possibility that they provide extra degrees of freedom in engineering the nonlinear properties of the medium. What's more, the transverse pattern of QPM grating is able to be designed to satisfy the beam shaping processes. QPM gratings have been successfully used to generate a flat-topped second harmonic (SH) Gaussian beam from a Gaussian pump beam by using of a QPM periodically-poled lithium niobate (PPLN) grating with transversely varying nonlinear interaction length [9]. Besides, the Fraunhofer diffraction, the focusing of SH beam and non-diffracting Airy beam by three-wave mixing processes have been already demonstrated by taking advantage of transversely engineered QPM materials, respectively [13, 17, 18]. Also, with the gratings patterned into and out of the waveguide, the overlap of the waveguide mode and the nonlinearity of the periodically-poled material is modulated and the sidelobes of the frequency tuning curves are suppressed by 13 dB or more, compared with a uniform grating [19]. The generation of a neat SGB using the QPM grating in this paper opens up new possibilities to manipulate SGB properties.

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2. Design and fabrication of the TPPLT crystal sample

The key point of our idea is to introduce transversely nonuniformity into the structure of the QPM grating (see Fig. 1). We take a SH nonlinear process of the transversely varying periodically-poled $LiTaO_3$ (TPPLT) crystal for example. The general phase-matching condition for this nonlinear interaction in the QPM material can be written as [20-22]

$$\vec{k}_{2\omega} = 2\vec{k}_{\omega} + \vec{G}, \tag{1}$$

where $\vec{k}_{2\omega}$ is the wave vector of the SH light, $\vec{k}_{\omega}$ is the wave vector of the pump laser and $\vec{G}$ is the reciprocal vector provided by the TPPLT crystal. The advantage of using TPPLT as the nonlinear frequency converter lies in the fact that QPM allows the use of the highest nonlinear coefficient d_{33} [23]. The TPPLT sample used in our experiment is designed to be a periodic structure with a period of 7.505μm, which carries out the SHG process of 1064 nm to achieve green light at 532nm by using its first-order QPM. The temperature is designed at 200°C to avoid photorefractive effect.

The amplitude of a wave generated in a QPM mixing process depends on the length of the QPM grating, QPM with a transversely varying grating length can be used to engineer a desirable conversion profile, such as the flat-topped laser beam [9] and SGB. The pump laser is propagating along the *x* direction. In the low conversion efficiency limit, the relationship between the light intensities of the pump beam $I_{\omega}(y,z)$ and SH beam $I_{2\omega}(y,z)$ on the output surface can be described as [9,20]

$$I_{2\omega}(y,z) = C^2 I_{\omega}^2(y,z) L^2(y), \tag{2}$$

where $L(y)$ is the interaction length distribution of the QPM grating and independent of z, C^2 is the material constant [9,20]. Equation (2) shows that $I_{2\omega}(y,z)$ profile can be engineered by modulating $L(y)$ profile. We deduce that the interaction length $L(y)$ can be described as

$$L(y) = \sqrt{I_{2\omega}(y,z) / C^2 I_{\omega}^2(y,z)}. \tag{3}$$

In this paper, we want to obtain a neat SH SGB in the following form

$$I_{2\omega}(y,z) = Ae^{-\frac{2z^2}{w_0^2}} \begin{cases} e^{-\frac{2y^2}{w_B^2}} & y < 0 \\ e^{-\frac{2y^2}{w_0^2}} & y \geq 0 \end{cases}, \tag{4}$$

where A is the amplitude of the SH SGB, w_B is the designed border width of the generated SGB and defined as a width at $1/e^2$ of the maximum intensity of the sharp border in the SGB [12], w_0 is the waist radius of the SGB and defined as a width at $1/e^2$ of the maximum intensity of the semi-Gaussian part in the SGB [12] and equals to $1/\sqrt{2}$ of the pump Gaussian beam waist radius [9]. We define a parameter $Q_{SGB}=w_B/w_0$ to describe the quality of the generated SGB. The lower value of Q_{SGB}, the SGB border is steeper, i.e. the higher quality of the SGB. Equation (4) shows that the transverse light intensity distribution $I_{2\omega}(y,z)$ of the SH SGB depends on the border width w_B and the waist radius of the pump Gaussian beam. In an extreme case, the border width of the SGB is $w_B=0$ which will be discussed later. In the actual case, the border width of the SGB satisfies $0< w_B < w_0$. Combining Eqs. (3) and (4), when $I_{\omega}(y,z)$ is a Gaussian one, the interaction length $L(y)$ of the TPPLT grating should be

$$L(y) = L_0 \begin{cases} e^{(\frac{y^2}{w_0^2} - \frac{y^2}{w_B^2})} & y < 0 \\ 1 & y \geq 0 \end{cases} \approx L_0 \begin{cases} e^{-\frac{y^2}{w_B^2}} & y < 0 \\ 1 & y \geq 0 \end{cases} \quad (w_B << w_0), \tag{5}$$

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where L_0 is the physical length of the TPPLT grating.

In order to elucidate the above idea, we consider a SHG process in a transversely varying periodically-poled $LiTaO_3$ (TPPLT) crystal. The designed parameter of the TPPLT is w_B=w_d=24μm. The TPPLT sample with a period of 7.505μm is 5mm in length (*x* direction), 2.5mm in width (*y* direction), 0.5mm in thickness (*z* direction), cut from a *z*-cut congruent $LiTaO_3$ wafer. Based on the above design algorithm (Eq. (5)), the TPPLT sample with lithographically defined patterned QPM gratings is successfully fabricated by pulse electric field poling technique at room temperature [24]. After poling, the TPPLT sample is etched in HF acid for several hours to reveal the domain patterns. Figure 1 shows a portion of the TPPLT domain edge of the +C surface using an optical microscope. We can see that the 7.505μm-period domains have been successfully fabricated with high quality and the duty cycle is close to 1:1. The TPPLT domain edge is the exponential function distribution according to Eq. (5) and works like a nonlinear grating to cut the fundamental Gaussian pump laser beam into half. The end faces of the TPPLT sample are polished but not coated with optical antireflective film on the light pass surfaces.

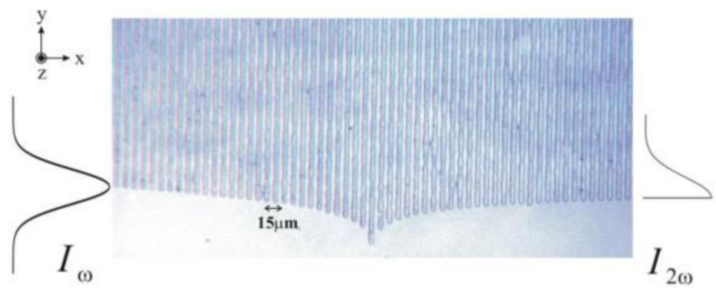

Fig. 1. Structure on +*C* surface of domain-inverted periods in a portion of the TPPLT sample

3. Experimental setup

The experimental setup is shown in Fig. 2. The fundamental pump beam is produced by a commercial OPO laser which gives the output wavelength of 1064 nm with a repetition rate of 10Hz and pulse duration of 5ns. The pump laser is incident along the *x*-axis and collimated by two lenses L_1=150mm and L_2=200mm. The pump laser is e-polarized along the *z*-axis of the TPPLT. As illustrated in Fig. 2, it is worth noted here that the collimated pump 1064nm laser is focused into the TPPLT by a cylindrical lens L_3=300mm which shapes an elliptical spot at the focus plane to match the sample's shape which is a thin wafer. The beam waists inside the crystal are about 3.2mm in the long-axis and 0.17mm in the short-axis. In this experiment, in order to keep working temperature constant and avoid photorefractive effect, the TPPLT is placed in an oven with a temperature controller and heated to the phase-matching temperature with an accuracy of 0.1°C. Behind the TPPLT, we put a 1064nm optical high reflecting mirror (HR@1064nm) and an optical filter F to block the 1064nm pump laser. The generated neat 532nm SGB is imaged by a lens L_4=350mm onto a CCD camera.

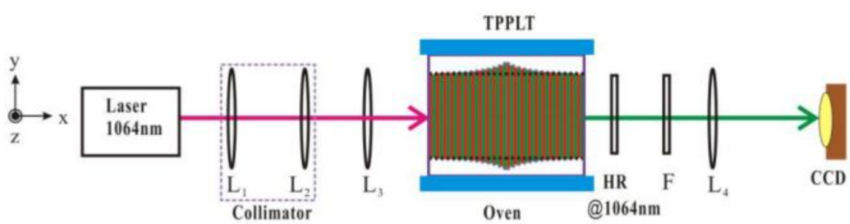

Fig. 2. Schematic of the experimental setup for the SGB generation. L, HR and F represent lens, 1064nm optical high reflecting mirror and the optical filter, respectively.

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4. Experimental results and discussion

The experimental measured phase-matching temperature of our TPPLT crystal is 188.5°C. This actual phase-matching temperature is deviated from the theoretical design 200°C, and it might result from thermal expansion which induces the deviation between actual grating period and theoretical calculation. Figure 3(a) and 3(c) show the 3D light intensity distributions of the 1064nm pump Gaussian laser and the generated 532nm SGB taken by a CCD camera, respectively. Figure 3(b) and 3(d) show the light intensity profiles of the Gaussian pump laser and the generated SGB which is obtained from a single line of pixels along the *y*-axis at the CCD camera, respectively. It can be seen from Fig. 3 that our TPPLT crystal has successfully converted a 1064nm Gaussian pump beam into a neat 532nm SGB with a sharp border and no significant diffraction fringes. By analyzing Fig. 3(d), we find that the generated SGB has a Q_{SGB}=1:17.5 with w_B=61.2μm and w_0=1.07mm, which shows that the border width is very sharp and very small comparing with the width of the semi-Gaussian part. Here, the detected SGB border width w_B is larger than the designed parameter w_d. It is caused by the poling fluctuation of the domain edge and the divergence of the generated SGB for the focused pump beam. The detected 532nm SGB has energy of 6.5μJ while the incident 1064nm pump laser is 320μJ, and the corresponding conversion efficiency is about 2%.

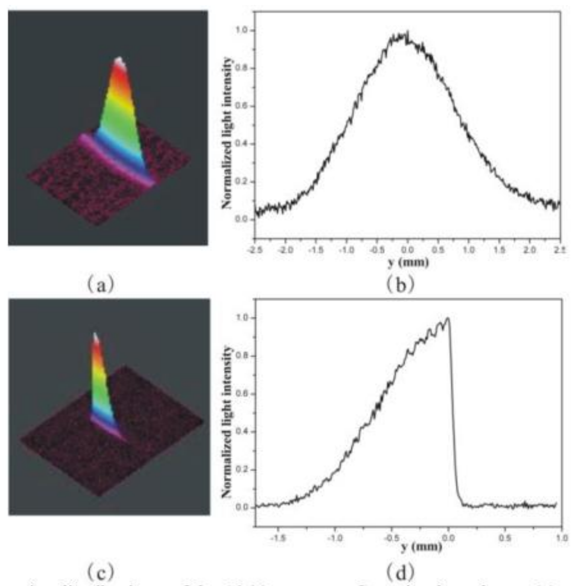

Fig. 3. The 3D light intensity distributions of the 1064nm pump Gaussian laser beam (a) and the generated 532nm SGB (c); The light intensity profiles of the 1064nm pump Gaussian laser beam (b) and the generated 532nm SGB along the x-axis (d).

We have also studied the generated SGB propagation in the free space. In the experiment, we image the generated SGB in the output face of the TPPLT to CCD camera by a lens L_4. We detect the light intensity profiles in different planes vertical to the *x*-axis by moving CCD camera near the image plane along the propagation direction. The SGB intensity distributions in the *yz* plane behind the image plane correspond to the SGB propagating from the back face of the TPPLT. We find that the Q_{SGB} of the generated SGB is the smallest in the image plane, and increases with the increasing of the distance away from the image plane. When Q_{SGB}>1:10, the border width of SGB is broad, so we regard the border width of SGB is not sharp and the quality of SGB becomes worse. We define the distance that the Q_{SGB} equals to 1:10 is the effective propagation distance of the SGB and it is ~3.0mm in our experiment. After a certain propagation distance of ~10mm, the neat SGB transfers to a SGB with diffraction fringes according to the Huygens-Fresnel principle.

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According to Eq. (5), the appropriate form of the TPPLT grating length *L(y)* is mostly related to the border width w_B of the generated SGB. So a particular TPPLT design is appropriate only for a series of SGBs that have the same border width. We have theoretically studied the generated SGB intensity profiles in the cases of different designed parameter w_B for the same incident pump Gaussian laser beam, and the results are shown in Fig. 4(a). Figure 4(a) indicates that the border of the generated SGB becomes broader when the designed parameter w_B of the TPPLT is larger, and the Q_{SGB} value of the generated SGB is larger, i.e. the SGB quality becomes worse. When w_B increases to the SH Gaussian beam waist radius, i.e. $w_B=w_0$, the generated SGB becomes a Gaussian one. So, we deduce that a high quality SGB in the experiment can be obtained when w_B is very small. However, w_B cannot be decreased to $w_B=0$. In this case, the domain edge is straight and works like a nonlinear knife that cut the Gaussian laser beam into a SH SGB with diffraction fringes, which is similar to the straight edge diffraction in the classical optics [18]. Figure 4(b) shows the experimental SH laser beam when we use the straight domain edge (corresponding to $w_B=0$) of a conventional PPLT. It is evident that the generated SGB has many significant diffraction fringes, which agrees well with the theoretical prediction.

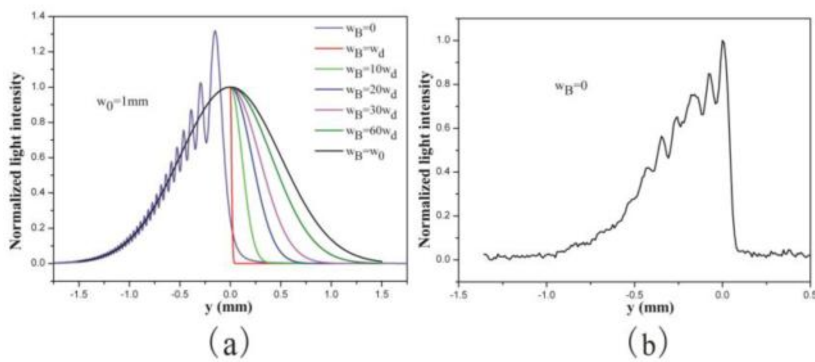

Fig. 4. The generated SGB intensity distribution profiles in the cases of different design parameter w_B of the TPPLT: (a) theoretical calculated results and (b) experimental result in the case of $w_B=0$.

5. Conclusions

In conclusion, we have designed and fabricated a 0.5mm-thick, 2.5mm-wide and 5mm-long TPPLT crystal in this paper. We use this TPPLT crystal to obtain a 532nm neat SGB with the quality of Q_{SGB}=1:17.5 by single-pass SHG for a 1064nm pump laser. Based on the QPM theory, for this TPPLT crystal, we can also obtain a 1064nm or a tunable wavelength SGB by a parametric down conversion process with a 532nm Gaussian pump laser. The experimental results above indicate that this scheme is of practical value and an attractive way to construct compact, all-solid-state SGB generator. For further development, this SGB generation scheme can be extended to work in quasiperiodic, aperiodic, or dual-periodic structures to obtain SGBs with multi-wavelength. This nonlinear generation process opens up new possibilities for all-optical switching and manipulation of SGB that cannot be achieved using linear optics. The generated neat SGB has potential applications in the optical data storage that demands diffraction-limited performance, the atomic and molecular micro-manipulation, the nonlinear refraction index measurement of the materials, etc.

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