# **Quasi-phase-matched second-harmonic Talbot** self-imaging in a 2D periodically-poled LiTaO<sub>3</sub> crystal

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Abstract: We demonstrate the improved second-harmonic Talbot selfimaging through the quasi-phase-matching technique in a 2D periodicallypoled LiTaO<sub>3</sub> crystal. The domain structure not only composes a nonlinear optical grating which is necessary to realize nonlinear Talbot self-imaging, but also provides reciprocal vectors to satisfy the phase-matching condition for second-harmonic generation. Our experimental results show that quasiphase-matching can improve the intensity of the second-harmonic Talbot self-imaging by a factor of 21.

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### **References and links**

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## 1. Introduction

The Talbot effect, i.e. a self-imaging phenomenon of a periodic structure in the Fresnel nearfield, holds various applications in imaging process and synthesis, photolithography, optical testing, as well as Talbot illuminator [1, 2]. The origin of this effect can be attributed to the interference of diffracted beams. It usually requires a periodic object to realize the selfimaging. Up to now, the related fundamental researches have been extended to plasmonics, waveguide arrays, Bose-Einstein condensates, and quantum optics [2]. Discrete Talbot effect [3], second-order Talbot effect [4], and other novel Talbot effects have been experimentally demonstrated. Particularly, Talbot interferometer becomes very useful in X-ray imaging due to the lack of efficient lenses for X-ray [5]. Recently, we reported nonlinear Talbot effect in periodically-poled LiTaO<sub>3</sub> (PPLT) crystals [6–8]. Unlike other Talbot effects, there is no real grating required. The prerequisite condition to realize self-imaging is fulfilled by the periodic distribution of the second-order nonlinear coefficients ( $\chi^{(2)}$ ) in the PPLT crystal rather than the refractive index (n). Potential applications of such nonlinear Talbot effect include noninvasive imaging of domain structures and high-resolution lithography. However, in our previous experiments, quasi-phase-matching (OPM) does not work because the incident laser propagates along the z-axis of the PPLT crystal (the domains are arranged in the x-y planes). Therefore, the produced nonlinear Talbot image has a low intensity due to phasemismatching, which impedes the further applications of such interesting phenomenon.

The QPM technique in periodically-poled nonlinear optical crystals has been widely studied because it can efficiently realize laser frequency conversion by introducing a reciprocal vector to compensate the mismatch between the wave vectors [9, 10]. Now, all-solid-state lasers based on the QPM method have been developed to generate high-power red, green, and blue lights, which have been applied in laser projector and display [9, 10]. Moreover, the concept of nonlinear photonic crystals [11] (i.e. 2D periodically-poled crystals) inspires the discoveries of many interesting nonlinear optical effects, such as broadband second-harmonic generation (SHG) [12], nonlinear Cerenkov radiations [13], and nonlinear Airy beams [14]. QPM not only enhances these nonlinear effects, but also provides an efficient way to modulate them.

In this article, we demonstrate, both in theory and experiment, the improved secondharmonic (SH) Talbot self-imaging through the QPM technique in a squarely-poled  $LiTaO_3$ crystal. The periodic SH pattern generated at the output face of the crystal composes a nonlinear optical "grating", which is necessary to realize the Talbot self-imaging [6]. Meanwhile, the domain structure provides reciprocal vectors to satisfy the phase-matching condition for SHG [9], which can greatly enhance the intensity and quality of the SH selfimages.

## 2. Experimental setup and theory

The sample is a squarely-poled LiTaO<sub>3</sub> crystal with a size of 10 mm (x) × 5 mm (y) × 0.5 mm (z), which was fabricated through an electric-field poling process. The period of the domain structure is  $\Lambda = 5.5 \ \mu$ m and the duty cycle is ~35%. The experimental setup is shown in Fig. 1(a). A tunable Ti:Sapphire femtosecond laser serves as the input fundamental field. The pulse width is about 140 fs and the repetition rate is 80 MHz. The wavelength can be continuously tuned from 690 nm to 1050 nm. The polarization of the laser is parallel to the z-axis of the crystal. The fundamental wave was first reshaped to produce a near-parallel beam with a spot size of ~100  $\mu$ m in diameter and was then directed into the PPLT slice along the y-axis of the crystal. Before collecting the SH patterns, a filter was used to filter out the fundamental beam. Under this experimental configuration, the involved nonlinear optical coefficient is d<sub>33</sub> [15], which is periodically modulated in the PPLT crystal.



Fig. 1. (a) Experimental setup. The fundamental beam propagates along the y-axis of the crystal. The near-field images are collected by a CCD camera and the far-field images are projected on a screen. (b) The schematic diagram of QPM SH Talbot self-images. At the end face of the LiTaO<sub>3</sub> crystal, the fundamental lights that travel through the negative domains (dashed arrows in red) produce bright SH stripes while the fundamental waves that do not pass the inverted domains (dashed arrow in black) generate dark stripes. In the far-field, five SH spots (A, B<sub>1</sub>, B<sub>1</sub>', B<sub>2</sub>, and B<sub>2</sub>') are generated due to QPM. The collinear (c) and noncollinear (d) phase-matching schemes in the 2D PPLT crystal are also shown.

The phase-matching condition in a 2D PPLT crystal can be written as [11]

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

where  $k_{\omega}$  and  $k_{2\omega}$  are the wave vectors of the fundamental and second-harmonic waves, respectively.  $G_{m,n} = \frac{2\pi\sqrt{m^2 + n^2}}{\Lambda}$  is the reciprocal vector of the 2D domain structure with the subscripts *m* and *n* representing the orders of the reciprocal vectors [16]. Both collinear and noncollinear QPM SHG can be realized in such a 2D PPLT crystal. Figure 1(b) presents the far-field SH pattern projected on a screen 26 cm away from the end face of the sample. The SH pattern was excited by a fundamental input with  $\lambda = 958$  nm. Five SH spots can be clearly observed. The spot A at the center results from the collinear SHG with the participation of the reciprocal vector G<sub>01</sub> [Fig. 1(c)]. It is brightest because the collinear SHG processes [Fig. 1(d)]. B<sub>1</sub> and B<sub>1</sub>' involve noncollinear reciprocal vectors G<sub>11</sub> and G<sub>-11</sub>, respectively. The corresponding emit angle is 0.092 radian, which agrees well with the calculated 0.086 radian from Eq. (1). B<sub>2</sub> and B<sub>2</sub>' correspond to G<sub>21</sub> and G<sub>-21</sub>, respectively. Their emit angle is measured to be 0.18 radian while the calculated value is 0.17 radian. The intensities of the four noncollinear SH spots are much weaker than spot A (i.e. I<sub>A</sub>:I<sub>B1</sub>:I<sub>B2</sub> =

1:0.18:0.85) because their corresponding effective nonlinear coefficients are smaller and their phase-matching conditions are not totally fulfilled at this wavelength [11].

The near-field SH imaging was magnified by a 100x objective lens with N.A. = 0.7 and was then recorded through a CCD camera. Different imaging planes were selected by moving the objective lens along the propagation direction of the SH waves. The SH Talbot length can be calculated by  $Z_T = 4\Lambda^2/\lambda$ , where  $\lambda$  is the wavelength of the fundamental beam [6]. To realize nonlinear Talbot effect, it is necessary to achieve a periodic SH pattern, which can be easily satisfied under our experimental configuration. As the fundamental beam propagates along the y-axis of the crystal, it can be split into two groups. One group travels through the periodically inverted domains [see the dashed arrows in red in Fig. 1(b)] and the generated nonlinear polarization waves are modulated, i.e. QPM works. In this case, the phase mismatch in SHG is totally or partially compensated, depending on the incident wavelength, and the bright SH stripes are produced. The other group of the fundamental beam experiences no inverted domains [see the dashed arrow in black in Fig. 1(b)], which results in the dark stripes because no reciprocal vectors get involved. Hence, a SH amplitude "grating", having a structure determined by the domain structure along the x-axis of the crystal, exhibits at the end face of the crystal and produces the SH Talbot self-images at the Talbot planes [6].

#### 3. Experimental results and discussions

As expected, we observed SH Talbot self-images at the first Talbot plane in our experiments (Fig. 2), which result from the periodic SH patterns at the output face of the crystal. The structure period of 5.5  $\mu$ m in the SH self-image is the same as the period of the domains in the PPLT sample. To achieve the maximum intensity of the SH self-images, we tuned the input wavelength to fit the QPM condition. The fundamental power was kept at 60 mW for all the wavelengths. As shown in Figs. 2(a)-2(e), the intensity of the SH pattern at the first Talbot plane dramatically changes when modulating the incident wavelengths. The brightest SH selfimage appears with an incident fundamental beam of  $\lambda = 958$  nm [Fig. 2(c)] because SHG is totally phase-matched and the conversion efficiency reaches maximum at this wavelength. The wavelength of the generated SH waves is 479 nm. Considering that the reciprocal vector  $G_{01}$  participates, the theoretical QPM wavelength can be easily calculated from Eq. (1) to be 963 nm. The small deviation may result from that the dispersion relation of the PPLT crystal used in the calculations [17] does not perfectly fit our sample. The corresponding SH Talbot length is calculated to be 124 µm which is well consistent with the measured Talbot length of  $126 \mu m$ . In the experiments, the intensity of the SH stripes became weaker as the incident wavelength was tuned away from 958 nm. For example, the SH intensities of the self-images at excitation wavelengths of 958 nm, 952 nm, and 946 nm are 170 a.u., 119 a.u., and 8 a.u., respectively. This is because the QPM condition is partially satisfied at  $\lambda = 952$  nm and QPM is negligible at  $\lambda = 946$  nm. The SH self-images at  $\lambda = 946$  nm is not shown here because it is too weak to be clearly observed. By comparing the SH intensity at  $\lambda = 958$  nm and  $\lambda = 946$ nm, an improvement by a factor of 21 can be achieved through the introduction of QPM to nonlinear Talbot effect.





We also recorded the far-field images of the collinear SHG [Fig. 3(a)]. The results show that the collinear SHG is phase-matched at an input fundamental wavelength of  $\lambda = 958$  nm, which shares the same QPM condition as the near-field SH imaging in the PPLT crystal. Figure 3(b) shows the dependence of the SH intensity on the fundamental wavelength. The bandwidth of the phase-matching is measured to be 12 nm, which can be attributed to the wide linewidth of the femtosecond laser.



Fig. 3. (a) The far-field SH spot of the collinear SHG with different input wavelengths. (b) The dependence of the SH intensity on the incident wavelength. The SH intensity is normalized to the peak intensity.

The QPM SH Talbot self-imaging at the integer and fractional Talbot planes was then experimentally investigated by setting the fundamental wavelength at 958 nm. The measured Talbot length is 126  $\mu$ m. The input power was reduced to 37 mW to avoid saturation in the CCD camera. The "object" is the periodic SH pattern at the output face of the PPLT crystal as shown in Fig. 4(a). The period is not uniform because of the non-perfect domain structures in the PPLT crystal. We carefully measured the SH images at different distances from the sample [Figs. 4(b)-4(f)]. Because of the enhanced SH intensity, it is easier to observe the details in the self-images. For example, one can easily find a defect in the object [see the marked area in Fig. 4(a)], which is totally recovered in the first and second Talbot planes as shown in Figs. 4(b) and 4(c), respectively. However, in the fractional Talbot plane at a distance of 29.1  $\mu$ m away from the sample, the defect becomes a fine structure as the marked area in Fig. 4(d), which was not observed in our previous experiments.

It is obvious that the duty cycle of the SH pattern in the fractional image changes. For instance, the duty cycle in Fig. 4(d) is ~80% while it is ~50% in Fig. 4(a). Interestingly, in comparison with the traditional Talbot effect [1,2], there is no obvious period change and lateral shift in the SH pattern as we move the imaging plane in our experiment. A possible explanation is that the wave-front of the SH wave is engineered by the domain structure in the PPLT crystal. We are performing further experiments and simulations to understand this interesting phenomenon.



Fig. 4. Integer and fractional QPM SH Talbot self-imaging. (a) is the SH pattern at the end face of the sample. The marked area is a defect in the sample. (b) and (c) are the SH self-images at the first and second Talbot planes, respectively. The marked areas corresponds to the same position of the defects in (a). (d)-(f) are the fractional SH self-image at a distance of 29.1um, 63um, and 84um away from the sample, respectively. The marked area in (d) present a fine structure due to the defect in (a).

## 4. Conclusion

In conclusion, we have experimentally demonstrated the QPM SH Talbot effect in a squarelypoled LiTaO<sub>3</sub> crystal. The collinear SHG is phase-matched with the use of a reciprocal vector in the domain structure. Also, the SHG process produces a periodic SH pattern at the end face of the crystal, which originates from the periodic domain structure along the lateral direction in the crystal. The QPM SH Talbot effect can be then observed in the Fresnel near-field. The introduction of QPM can efficiently convert the fundamental wave into the SH wave. As a result, the intensity of the SH Talbot self-imaging are enhanced by a factor of 21 through the QPM technique. These improvements make it more practical to apply nonlinear Talbot selfimaging in lithography, array illuminator and imaging process.

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