Acousto-optic tunable second-harmonic Talbot effect based on periodically poled LiNbO₃ crystals

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Based on nonlinear Talbot effect, we propose an acousto-optic tunable second-harmonic (SH) array in a one-dimensional periodically poled LiNbO₃ (PPLN) crystal. The SH array is the self-imaging of $\chi^{(3)}$ in the PPLN crystal. By applying an acoustic wave, we can tune the period, the distribution, and even the dimension of the array. Such a phenomenon has potential applications in tunable high-resolution Talbot illuminators, beam shapers, and image processing. © 2012 Optical Society of America


1. INTRODUCTION

In 1836, Talbot self-imaging was first observed as H. F. Talbot illuminated a periodic object using a white light source. Such a phenomenon can be well understood by Fresnel’s diffraction theory [1]. One important application of the Talbot effect is to make a Talbot illuminator (TI), which is an optical element capable of converting a uniform plane wave into a periodic intensity pattern. Such components can be used in multiple imaging, optical communications, optical computing, and optical testing [2–4]. The conventional method to fabricate a TI is the spatially selective etching or depositing. In this way, the illuminator is usually fixed for a specific wavelength. The tunable array can be realized with spatial light modulators (SLM) based on, for example, liquid crystals. However, the commercial SLM usually has a relative big pixel (~10 μm), which limits its further applications.

Because of excellent nonlinear optical performances, periodically poled LiNbO₃, LiTaO₃, and KTiOPO₄ crystals, i.e., PPLN, PPLT, and PPKTP, have been widely studied for frequency conversion and quantum information processing [5–8]. Also, big electro-optic (EO), acousto-optic (AO), and piezoelectric coefficients make these crystals suitable for tunable TIs. For example, M. Paturzo et al. proposed an EO tunable phase array in a PPLN crystal [9]. The phase step can be continuously modulated from 0 to $2\pi$ by applying a variable voltage. As a benefit from the recent development of poling techniques, PPKTP crystal with a period of a few hundred nanometers can be easily fabricated [10]. Therefore, it is possible to reduce the pixel of the tunable TI based on periodically poled crystals down to submicron.

Recently, we reported the second-harmonic (SH) Talbot effect in periodically poled crystals [11–13]. The SH self-imaging results from the generated SH waves, which present a periodic pattern at the output face of the crystal because of the periodic distribution of $\chi^{(3)}$ in the crystal. In comparison with the fundamental pump case, the most important advantage is the improved spatial resolution due to frequency-doubling, which makes it a better candidate for making high-density arrays. In this letter, we theoretically propose an AO tunable TI based on SH Talbot self-imaging in a one-dimensional (1D) PPLN crystal. The acoustic wave can be either self-generated in PPLN crystals driven by a radio-frequency (RF) field, or introduced from an external transducer. Our simulations show that the phase, the period, and even the dimension of the SH array can be further tuned.

2. THEORETICAL ANALYSIS AND SIMULATIONS

The sample is a 1D PPLN crystal, which is fabricated through an electric-field poling technique at room temperature. The sample size is $4 \text{mm}(L_x) \times 5 \text{mm}(L_y) \times 0.5 \text{mm}(L_z)$. The period ($d_1$) of the PPLN crystal is 40 μm. The experimental setup is shown in Fig. 1. An 800 nm (λ), z-polarized laser beam propagates along the $y$ axis of the crystal. After filtering out fundamental waves, the “object,” a periodic SH array, is presented at the end face of the crystal [see Fig. 2(a)], which fulfills the necessary condition to realize the nonlinear Talbot self-imaging [11]. Here, the involved nonlinear coefficients is $\chi^{(3)}$. Its sign is modulated in the PPLN crystal (i.e., $+\chi^{(3)}$ in positive domains and $-\chi^{(3)}$ in negative domains). Therefore, the SH waves generated in the neighbored domains have the same intensities but with different phases. The dark fringes in Fig. 2(a) correspond to the domain walls. The domain wall in a PPLN crystal usually has a width of 100 nm to few micrometers [14]. Here, we assume the width is 1 μm. In simulations, the "object" is a grating ($G_1$) defined by

$$t_1(x) = \sum_{n=-\infty}^{\infty} c_n \exp \left(i2\pi n \frac{x}{d_1}\right),$$  \hspace{1cm} (1)

where $c_n$ is the Fourier coefficient,
The maximal amplitude of the standing wave locates at the center of the domain. Therefore, the refractive index in PPLN is periodically modulated by the acoustic wave. So is the phase of the light travelling through the crystal. In our simulations, the standing wave is considered as a phase grating \( G_2 \) parallel to \( G_1 \) and its period \( (d_2) \) is equal to \( d_1 \) (Fig. 1). We need to point out that the surface acoustic wave is ignored because it has no appreciable effect on the phase of the light in our setup.

Next, we deduce the expression of \( G_2 \). The phase shift caused by the acoustic waves is defined by \( \Delta \phi = (2\pi/\lambda)L_\gamma \Delta n \). In our case, \( \Delta n = \frac{1}{2} n_0^2 P_{21} S_1 \) is the change of the refractive index, \( n_0 \) is the refractive index of the PPLN, \( P_{21} \) is the involved photo-elastic coefficients, and \( S_1 \) is the strain due to the acoustic wave along the \( x \) axis. Starting from the above equations and using the Raman-Nath’s theory, the maximal amplitude of \( \Delta \phi \) is \([18, 19]\)

\[
\Delta \phi_m = \frac{\pi}{\lambda} \sqrt{\frac{M_2}{L_\gamma}} \sqrt{\frac{2P_{21}L_\gamma}{L_z}}.
\]

Here, \( M_2 \) is the AO figure of merit of the crystal. The power of the acoustic wave \( P_s \) is related to the electromechanical coupling coefficient of the PPLN crystal \([15]\). Hence, the phase grating \( G_2 \) can be expressed as

\[
t_2(x) = \exp \left[ i \Delta \phi \sin \left( \frac{2\pi x}{d_2} \right) \right] \text{rect} \left( \frac{x}{L_x} \right)
= \sum_{m=0}^{\infty} J_m(\Delta \phi) \exp \left[ i2\pi m \frac{x}{d_2} \right] \text{rect} \left( \frac{x}{L_x} \right).
\]

where \( J_m \) is the Bessel function of the first kind. The “object” taking into account the acoustic waves can be represented by the form \( t(x) = t_1(x) + t_2(x) \). According to the diffraction
theory [20], the Fresnel field at a distance of $Z_t$ away from the sample can be written as

$$U(x) = \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} T_1\left(\frac{n}{d_1}\right) T_2\left(\frac{m}{d_2}\right) \exp\left[-i\pi \left(\frac{n}{d_1} + \frac{m}{d_2}\right)^2 Z_t\right]$$

$$\times \exp\left[i2\pi x\left(\frac{n}{d_1} + \frac{m}{d_2}\right)\right],$$

where $T_1(n/d_1)$ and $T_2(m/d_2)$ are the amplitudes of the Fourier series of the grating $G_1$ and $G_2$, respectively.

The parameters used in our simulations are $\lambda = 800$ nm, $d_1 = d_2 = 40$ μm, $v = 6190$ m/s, and $M_2 = 4.6$. Figure 3 shows the simulated intensity distributions of the SH waves at $Z_t = 8$ mm under different acoustic powers. A weak acoustic wave has no obvious influence on the SH pattern [Fig. 3(a)]. When increasing the acoustic power [see Figs. 3(b) and 3(c)], the phases of the SH waves are modulated, and a series of gaps (i.e., the inverse-Gauss shape with steep edges and downing of intensity in the center) appear within each period of the patterns along the $x$ axis. The intensity and the width of the gap can be tuned by applying variable acoustic power. If choosing appropriate parameters, the intensities of the gaps can be suppressed down to zero and the period of the pattern reduces to a half of the original one. When $P_s$ reaches 1.38 W [Fig. 3(d)], the SH wave is focused, which results in a series of narrow lines with high intensities. With a high input power, the acoustic standing wave can work as a group of microlenses. Stronger focusing happens with higher acoustic power. One can find that at the center of a period (arrows in Fig. 3), the SH intensity experiences an oscillation as increasing the acoustic power. Mathematically, it originates from the oscillation of the Bessel function. It should be mentioned that the acoustic standing wave oscillates at a frequency of $f$, and this results in the blinking of the observed SH patterns. In PPLN crystals, $f$ is usually a few hundred MHz [15–17], which makes it difficult to distinguish the blinking by the naked eye.

Fig. 3. (Color online) SH pattern modulated by the acoustic waves generated in the PPLN crystal. The acoustic power is 0.10 (a), 0.54 (b), 0.64 (c), and 1.38 W (d), respectively.
Besides generating acoustic waves in the PPLN crystal, we can also induce an external acoustic wave from a transducer. In this case, it is more convenient to tune the SH array. For example, let us assume that an acoustic standing wave is introduced along the $x$ axis. Its frequency is 413 MHz and the power is 0.34 W. The period of the equivalent phase grating is 15 $\mu$m. Using Eqs. (3), (4), and (5), we simulate the SH patterns with such an input acoustic power [Fig. 4(a)]. A complicated 1D pattern with a period of 60 $\mu$m exhibits at the first Talbot plane.

If we apply an acoustic standing wave along $z$ axis, the form of the phase grating now becomes

$$t_2(z) = \exp \left[ i\Delta\phi \sin \left( \frac{2\pi z}{d_0} \right) \right] \left[ \frac{z}{L_z} \right] \text{rect} \left( \frac{z}{L_z} \right).$$

(6)

Hence, the object can be written as $t(x, z) = t_1(x) + t_2(z)$, and the SH pattern at $Z = 8$ mm can be evaluated with given parameters. Figure 4(b) illustrates one example in which by applying a 155 MHz, 1.0 W acoustic wave, the 1D diffraction patterns as shown in Fig. 2(b) can be tuned to 2D.

3. SUMMARY

We propose an AO-tunable TI based on SH Talbot effect in a 1D PPLN crystal. By controlling the power and the frequency of the acoustic wave, the phase of the SH array can be continuously tuned. Because the resolution is improved due to frequency doubling and the pixel (domain) of the crystal can be nano-size, it has potential applications in various laser technologies. For example, depending on the input acoustic power, the PPLN crystal can be used as a beam-shaper to provide various beam profiles (Gaussian or inverse-Gaussian). The flexibility is very useful in wave-packet transformation and image processing, as well as in making an optimum intensity distribution for a special application. Another possible application is to build a two-grating interferometer for observing the defects in the PPLN domain structure without damaging the crystal.

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