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Changes in the electroholographic properties of a paraelectric potassium lithium tantalate niobate crystal by electrostriction

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ABSTRACT

We theoretically studied the diffraction properties of an electroholographic (EH) optical switch made from a $K_{0.95}Li_{0.05}Ta_{0.61}Nb_{0.39}O_3$ crystal, assessing the influence of the Kerr effect and electrostriction effect (ES). Specifically, we studied how the diffraction properties changed with temperature, writing-beam angle and polarization angle, when the ES effect is ignoring or accounting for it. We then analyzed the origin of the influence of ES on the diffraction properties. Our results revealed that ES increased the maximum diffraction efficiency and the specific field. We concluded that ES influenced the diffraction properties by decreasing the Bragg mismatch angle and increasing the effective Kerr coefficient.

1. Introduction

Electroholography (EH) is a beam-steering method based on the reconstruction of volume holograms by using an externally applied electric field [1]. It has gained much interest for several applications such as volume holographic storage, optical filters, and electric-field-controlled optical switches [2–4]. EH is particularly suitable for optical switches because of its rapid response time and tunable properties [5–7].

In recent decades, most EH research on high-speed optical switches has focused on the paraelectric phase of $K_{1-y}Li_yTa_{1-x}Na_x$ (KLTN), advantageous because of its high Kerr coefficient (quadratic electro-optic coefficient) and high diffraction efficiency near its phase-transition temperature (Curie temperature, T_C) [8–10]. It has been observed that applying an external electric field to paraelectric KLTN induces electrostriction (ES). Recently, Tian et al. found that KLTN exhibited a high ES coefficient of $8.8\times10^{-16}\,m^2\,V^{-2}$ near its Curie temperature [11]. Similar to how the piezoelectric effect influences the behavior of optical switches made from in crystalline $LiNbO_3$ based on the line electro-optic effect [12], the deformation induced by ES would affect the diffraction efficiency of linear gratings, impacting the diffraction properties of EH optical switches made from paraelectric crystalline KLTN. However, previous studies have not often discussed how ES affects the diffraction properties of EH devices [4–6].

To investigate the diffraction properties of EH devices, in this paper we chose a $K_{0.95}Li_{0.05}Ta_{0.61}Nb_{0.39}O_3$ crystal, which is in its paraelectric phase near room temperature. We studied its diffraction properties in two contexts, ignoring ES or accounting for it, to assess how ES influenced the specific field E_s and the diffraction efficiency η. We then analyzed the origin of the influence of ES on the diffraction properties.

2. Influence of the Kerr effect on the diffraction properties of EH optical switches

2.1. Principle of EH optical switching in crystalline paraelectric KLTN

Fig. 1(a–c) shows diagrams that describe the principle of the EH optical switch, operating based on Kerr effect, fabricated from a paraelectric KLTN crystal. Fig. 1(a) shows the recording process for a sinusoidal—space–charge grating, accomplished by the interference of two writing beams with the wavelength λ_1; writing-beam angle between the two beams is defined as θ, with one beam incident along the x axis. The space–charge field over real space can be defined as

$$E_{sc}(x)=E_{sc}\cos\left(\frac{2\pi}{\Lambda}x\right)=E_{sc}\cos(\vec{k_G}\times\vec{x}),\tag{1}$$

where Λ is the grating period, E_{sc} is the amplitude of the field, $\vec{k_G}$ is the grating vector, and ϕ is the angle between the grating vector and the z axis.

Fig. 1(b) shows the process of reading a switch without an applied field. In this process, a plane wave with a wavelength λ_1 or λ_2 (λ_2 is a random wavelength, different from λ_1) impinges on the crystal. Because of the quadratic electro-optic effect (Kerr effect) in the paraelectric KLTN crystal, there is only quadratic index phase

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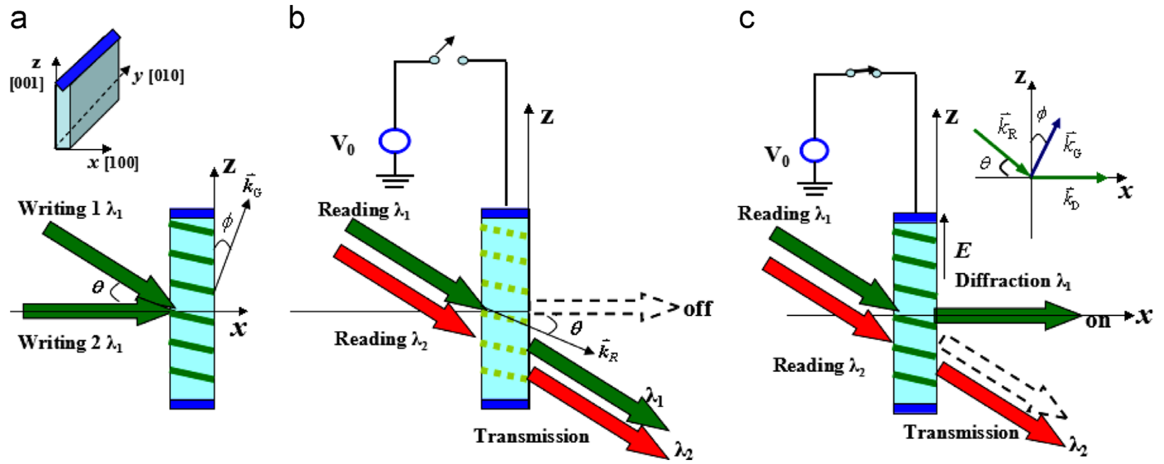

Fig. 1. Schematic of the transmission EH switch: (a) Writing the grating, (b) reading without field and (c) reading with field.

grating $2\vec{k}_G$ and no linear index phase grating $\vec{k}_G$. In this case the Bragg condition is not fulfilled, causing the reading beam to pass through the crystal with no effect: the optical switch is in the "off" state for the reading beams with wavelengths λ_1 and λ_2.

When an external electric field E_0 is applied to the crystal along the crystallographic [0 0 1] direction (along z axis) ($V_0 \neq 0$), the refractive index changes can be expressed as

$$\Delta n_1 = -\tfrac{1}{2} n_0^3 s_{\text{eff}} [E_{\text{sc}}^2(\vec{k}_G \times \vec{x}) + E_0^2 + 2E_0 E_{\text{sc}}(\vec{k}_G \times \vec{x})], \tag{2}$$

where n_0 is the refractive index for wavelength λ_1 and s_{eff} is the effective Kerr polarization-optic coefficient, whose value depends on the polarization of readout beam and temperature of sample. For the two-wave mixing configuration shown as Fig. 1(a), the effective quadratic polarization-optic coefficient s_{eff} (effective Kerr coefficient) is

$$s_{\text{eff}} = s_{11} \cos^2 \Phi + s_{12} \sin^2 \Phi \tag{3}$$

where, the Kerr coefficients s_{11} and s_{12} are defined according to the direction of the external field and the crystallographic directions. The polarization angle Φ is defined as the angle between the polarization direction of readout beam and the z axis direction, which is equal to the angle θ.

Thus, the induced birefringence consists of three terms: a uniform term (induced by E_0^2), a $\vec{k}_G$ grating (induced by $E_0 E_{\text{sc}}$), and a $2\vec{k}_G$ grating (induced by E_{sc}^2). In this case, the readout beam with wavelength λ_1 satisfies the Bragg condition $2n_0\Lambda \cos(\phi-\theta) = \lambda_1$, causing it to be diffracted along the x axis by the $\vec{k}_G$ grating, as shown in Fig. 1(c). The beam with wavelength λ_2 remains unaffected because it does not fulfill the Bragg condition for the $\vec{k}_G$ grating. In this case, the optical switch was in the "on" state for λ_1 and the "off" state for λ_2. Thus, the properties of the EH optical switch depend on the diffraction efficiency of the $\vec{k}_G$ grating and the external field.

2.2. Factors affecting the diffraction properties of the EH optical switch

According to Kogelnik's coupled-wave theory, the diffraction efficiency of a beam diffracted by a $\vec{k}_G$ grating can be written as

$$\eta = \frac{\sin^2(\nu^2+\xi^2)^{1/2}}{1+(\xi/\nu)^2}, \tag{4}$$

where $\nu = \pi d \Delta n / \lambda \left[\cos\theta(\cos\theta - (k_G/k_l)\sin\phi)\right]^{1/2}$, k_l is the propagation vector of the diffracted beam, d is the depth of the grating, Δn is the change of the refractive index along the x axis, described by $\Delta n = -n_0^3 s_{\text{eff}} E_0 E_{\text{sc}}$, and $\xi = \Gamma d / 2(\cos\theta - (k_G/k_l n_0))\sin\phi$, where $\Gamma = \Delta\Theta k_G d \cos(\phi+\theta) - (\Delta\lambda k_G^2 / 4\pi n_0)$ is the Bragg mismatch caused by the mismatch angle $\Delta\Theta$ and the deviation wavelength $\Delta\lambda$ between the reading beam and the writing beam. When only considering the Kerr effect and that the reading beam is the same as the writing beams, $\Delta\lambda = 0$ and $\Delta\Theta = \Delta\Theta_k = -\cot(\theta-\phi)\frac{\Delta n}{n_0} = s_{\text{eff}} n_0^2 E_0 E_{\text{sc}} \cot(\theta-\phi) > 0$.

when applying the field E_0 to the crystal along the z axis. Based on these analyses, the Kerr effects will have a positive Bragg mismatch angle.

To analyze the diffraction properties of the EH optical switch, we chose the paraelectric phase of a $K_{0.95}Li_{0.05}Ta_{0.61}Nb_{0.39}O_3$ crystal with a Curie temperature of T_c=9.5 °C. During writing, the angle between the two writing beams was $\theta = 15^\circ$ and the angle between the propagation vector k_G and the z axis was $\phi = 7.5^\circ$, as shown in Fig. 1(b). We measured the Kerr coefficient using a Mach–Zehnder interferometer, as described in Ref. [8], at 12.5 °C, finding $s_{11} = 4.9 \times 10^{-16}\ \text{m}^2\,\text{V}^{-2}$ and $s_{12} = -0.8 \times 10^{-16}\ \text{m}^2\,\text{V}^{-2}$. The wavelength of both the reading and writing beams was $\lambda_1 = 632.8$ nm, the refractive index was $n_0 = 2.271$, and the depth of the grating was $d = 2$ mm. For writing, we chose a grating period of $\Lambda = 2.4\ \mu m$ and a space–charge field of $E_{\text{sc}} = 15\ \text{kV m}^{-1}$. In Fig. 2, the solid line shows the periodic oscillation of diffraction efficiency η versus the external applied field, revealing a maximum diffraction efficiency of $\eta_{\max} = 89\%$ at an applied field of $E_s = 365\ \text{V mm}^{-1}$. We defined the applied field E_s as the specific field, which we used to obtain the maximum diffraction efficiency of the reading beam. The specific field E_s is determined by the period of diffraction efficiency.

We chose the working voltage V_0 and extinction ratio (ER) to evaluate diffraction properties of the EH optical switch. The working voltage depends on the specific field as follows: $V_0 = E_s/d$. The extinction ratio is defined as the ratio of the transmission intensities of the reading beam λ_1 when the switch is in the "on" state versus the "off" state ($ER = 10 \lg \eta$). So the ER increases as the maximum diffraction efficiency $\eta_{\max}$ increases. Improving properties of the EH optical switch meant lowering the working voltage and increasing the extinction ratio, so we attempted to increase the diffraction efficiency $\eta_{\max}$ and to reduce the specific field. We studied how the specific field and maximum diffraction efficiency were affected by temperature, the writing-beam angle θ, and the polarization angle Φ; these results are shown in Fig. 3.

The relationship between the effective Kerr coefficient s_{eff} and the temperature is $s_{\text{eff}} \propto 1/(T-T_C)^2$, showing that the temperature greatly affects the diffraction properties of the EH optical switch. We studied how the Kerr coefficient s_{eff} changed with temperature by using a Mach–Zehnder interferometer. We used self-made equipment to control the temperature of the sample: dry-ice