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Anisotropy of Acoustooptical Properties of Lithium Niobate Crystals

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Abstract: Anisotropy of acoustooptical properties of lithium niobate crystals has been studied, when the direction of the light wave vector changes in the plane perpendicular to the direction of propagation of the acoustic wave. The values of components of the photoelastic tensor were determined by the Dixon method. It is shown that for the main geometries of Bragg diffraction of light, when acoustic waves propagate along the crystallographic axes, the acousto-optical quality factor is approximately the same for both longitudinal and transverse acoustic waves. The results obtained on the anisotropy of acousto-optical interaction in lithium niobate crystals can be useful for their application in acousto-optical devices for measuring the frequency of acoustic waves based on the phenomenon of acoustical activity.

Keywords: Acousto-optical quality factor, Photoelastic constants, Acoustic waves, $LiNbO_3$ crystals, Dixon method.

1. Introduction

The study of the anisotropy of acoustooptical properties of crystals is quite important for determining the most effective crystal cuts used as working media and optimizing the parameters of acousto-optic devices.

As shown in [1], even within the Pockels model, finding the extreme directions in a crystal that provide the maximum value of the effective photoelastic constant requires solving a system of 21 nonlinear fourth, third, and second order equations with high rank tensors. In this regard, the photoelastic properties of crystals are usually considered for specific geometries of acousto-optic interaction and for certain cuts of the crystal [2].

In the literature, as a rule, most works are devoted to determining the acousto-optical quality factor M_2, which was introduced by Dixon [3] as a characteristic of the efficiency of Bragg diffraction at acoustic waves and determines the intensity of diffracted light in a given material, regardless of the size of the piezoelectric transducer and the power of the acoustic wave:

$$M_2 = \frac{n_1^3 n_2^3 p_{эфф}^2}{\rho V^3}, \qquad (1)$$

where n_1 and n_2 are the refractive indices of the incident and diffracted light, respectively, ρ is the density, V is the velocity of the acoustic wave.

The effective photoelastic constant, p_{eff} in relation (1) is the convolution of the values of components of the photoelastic tensor p_{ijkl} of the crystal with respect to the normalized polarization vectors, respectively, of the diffracted and incident light α and β, and the direction and polarization of the acoustic wave κ and γ [1, 3]:

$$p_{эфф} = p_{ijkl}\alpha_i\beta_j\gamma_k\kappa_l \qquad (2)$$

Thus, the coefficient M_2 depends on the geometry of the diffraction of light by sound and makes it possible to assess the acousto-optic properties of materials. By changing the direction of the polarization of the incident light relative to the wave vector and the polarization of the acoustic wave, one can influence the value of the effective photoelastic constant and, ultimately, control the efficiency of Bragg diffraction of light in this crystal. Such experiments also make it possible to identify the most optimal geometries of Bragg diffraction for obtaining the highest intensity of diffracted light.

In the present work, the anisotropy of effective photoelastic constants and the acousto-optical quality factor M_2 in lithium niobate crystals, which are widely used in different acousto-optic devices [3], has been investigated. Despite the fact that the components of the photoelastic tensor of these crystals have been determined in many works, the anisotropy of the effective photoelastic constants has not been fully investigated, and there are also inaccuracies in the available works [5–8].

2. Samples and Experimental Technics

Cylindrical lithium niobate samples with a length of about 15 mm and a diameter of 6 mm were oriented along the directions [100], [010] and [00]) with an accuracy of no worse than 1 degree. The surfaces of the samples were processed and polished with optical precision.

The measurements were carried out by the Bragg light diffraction method [1, 3]. Piezoelectric quartz plates (X or Y-cut) were used to excite longitudinal or transverse acoustic waves with frequencies of 400–1200 MHz. The helium-neon laser with a wavelength of 632.8 nm was used as a light source. The intensities of diffracted light were measured with the help of photoelectric multiplier.

To determine the effective photoelastic constants, a modified Dixon-Cohen method was used, in which acoustic waves are excited both from the side of the standard specimen and from the side of the studied sample [7]. Upon excitation of acoustic waves from the side of the standard specimen, the values of the intensity of light diffracted in the standard specimen I_{1st} and the studied sample I_{1x} were measured.

Then, acoustic waves were excited from the side of the studied sample, and the light intensities in the sample I_{2x} and the standard specimen I_{2st} were measured again. A sample of fused silica was used as the standard specimen. The acoustic contact of the sample with the samples was carried out using epoxy resin.

The values of the effective photoelastic constants for different geometries of the Bragg diffraction of light were determined from the relation:

$$\left[\frac{p_{eff}^2 n^6}{\rho V^3}\frac{n^2}{(n+1)^4}\right]_x = \left[\frac{p_{eff}^2 n^6}{\rho V^3}\frac{n^2}{(n+1)^4}\right]_{st}\left(\frac{I_{1x} I_{2x}}{I_{1st} I_{2st}}\right)^{\frac{1}{2}}, \qquad (3)$$

where ρ is the density of the crystal; n is the refractive index of light; V is the velocity of the acoustic wave.

The values of the velocity of acoustic waves required for the calculation were determined from the angle of Bragg diffraction of light at these waves with an accuracy of about 0.2%. The values of the remaining quantities required for the calculation were taken from [8, 9]. The accuracy of determining the effective photoelastic constants was approximately 15 %.

3. Results and Discussion

One of the universal methods for studying the elastic and photoelastic properties of materials, including piezoelectric and ferroelectric crystals, are acousto-optic methods based on the Bragg diffraction of light by acoustic waves [1, 4]. In this case, the intensity of the diffracted light is determined by the effective photoelastic constant p_{eff}, the value of which can be obtained using the transformation formulas for the components of the fourth-rank tensor [1, 2]. Using simple transformations, one can obtain an expression for determining the effective photoelastic constants in the form:

$$p^2_{\text{эфф}} = (\chi_1 P_2 - \chi_2 P_1)^2 + (\chi_1 P_3 - \chi_3 P_1)^2 + (\chi_2 P_3 - \chi_3 P_2)^2 \qquad (4)$$

where χ_j are the direction cosines of the wave vector of the diffracted light, P_i are the values of the light polarization components, which are calculated by the formula:

$$P_i = p_{iklm} \cdot \beta_k \cdot \gamma_l \cdot \kappa_m, \qquad (5)$$

where p_{iklm} are the components of the photoelastic tensor, β_k are the direction cosines of the polarization of the incident light, γ_l and κ_m are the direction cosines of the polarization and the wave vector of the acoustic wave respectively.

The experimentally obtained values of the effective photoelastic constants were used to determine the components of the photoelastic tensor in lithium niobate crystals using relations (3) and (4). The expressions for the effective photoelastic constants (in terms of the components of the photoelastic tensor p_{ijkl}) for some geometries of Bragg light diffraction in lithium niobate crystals are presented in Table 1. In this table $\boldsymbol{q}$ is the wave vector of acoustic wave, $\boldsymbol{\gamma}$ is the polarization of the acoustic wave, $\boldsymbol{k}$ is the wave vector of the light and $\boldsymbol{\beta}$ is the unit vector of polarization of the light incident on the sample.

It can be seen that for many geometries of Bragg diffraction, the effective photoelastic constant is equal to one of the components of the photoelastic tensor, that facilitates their determination.

As a result the next absolute values of photoelastic constants have been obtained:
p_{11}=0.031, p_{33}=0.086, p_{44}=0.046, p_{66}=0,024, p_{12}=0.081, p_{13}=0.090. p_{14}=0.075, p_{31}=0.175, p_{41}=0.156.

The accuracy of determining these constants of the photoelasticity tensor was approximately 15 %. It is worth noting the relatively high value of the photoelastic constant p_{44} that allows one to expect a high intensity of light diffracted on the transverse acoustic waves in lithium niobate crystals.

Table 1. Expressions p_{eff} for some geometries of Bragg light diffraction in lithium niobate crystals.

q	γ	k	β	$P_{eff.}$
[001]	Z	arbitr.	∥ q	p_{33}
			⊥ q	p_{13}
	X	X	arbitr	0
		Y	arbitr	p_{44}
		k^X=α	∥ q	$p_{44}\mathrm{Sin}\alpha$
			⊥ q	$(p_{14}^2\sin^2 2\alpha + p_{44}^2\sin^2\alpha)^{1/2}$
[100]	X	Z	⊥ q	p_{12}
		Y	⊥ q	p_{31}
		k^Z=α	⊥ q	$p_{12}\cos^2\alpha+p_{31}\sin^2\alpha + p_{41}\sin 2\alpha$
	γ^Z =φ	Z	arbitr	$p_{14}\cos\varphi+p_{66}\sin\varphi$
		Y	arbitr	$P_{41}\sin\varphi+P_{44}\cos\varphi$

Based on the values of the components of the photoelastic tensor determined by the Dixon method, the anisotropy of the effective photoelastic constants p_{eff} in these crystals has been studied for the case of propagation of longitudinal acoustic waves along the [100] direction and transverse acoustic waves along the [001] direction, when the light is incident and diffracted in the crystallographic plane perpendicular (accurate to the Bragg angle) to the wave vector q of the acoustic wave under an arbitrary angle.

The cross section of the surface of the square of the effective photoelastic constant by the (100) plane for Bragg light diffraction on the transverse acoustic waves in $LiNbO_3$ crystals is presented at Fig. 1. The direction of the light polarization is perpendicular to the direction of propagation of acoustic wave. It is seen that for transverse waves along the [001] direction, the effective photoelastic constant varies from zero to the maximum value when the wave vector of light is directed approximately along the [110] axis.

The calculations according to the expression from Table 1 showed that the square of the effective photoelastic constant for light Bragg diffraction by transverse waves propagating along the 001 axis reaches its maximum value (0.0066 10^{-15} s^3/kg) when the light is incident at an angle of 47 degrees to the [100] axis in the (001) plane. This direction is the most effective for acousto-optical interaction of light with transverse acoustic waves along the [001] axis.

Similar anisotropy was investigated for isotropic diffraction of light by longitudinal acoustic waves along the [100] direction, when the diffraction occurs without rotation of the plane of the light polarization.

The geometry of this Bragg diffraction is described by the equation:

$$p_{eff}=p_{12}\cos^2\alpha+p_{31}\sin^2\alpha \quad (6)$$

The direction of the incident light was changed in the (100) plane. The results of calculation are shown in Fig. 2.

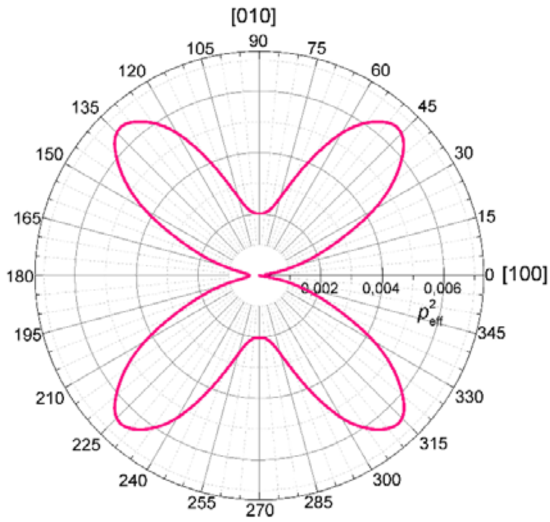

Fig. 1. Anisotropy of the square of the effective photoelastic constant in $LiNbO_3$ crystals for transverse waves along [001] at different orientation of the light wave vector in the plane (001).

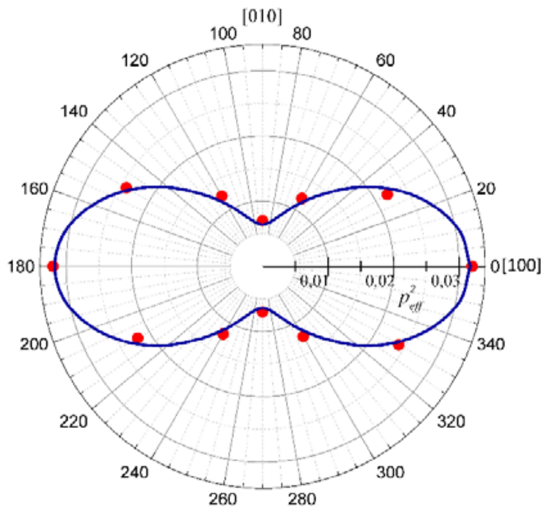

Fig. 2. Anisotropy of the square of the effective photoelastic constant in $LiNbO_3$ crystals for longitudinal waves along [100] at different orientation of the light wave vector in the plane (100). Points are results of the experiment.

Simultaneously, measurements were carried out to determine the intensity of the diffracted light, which, as is known, is proportional to the square of the effective photoelastic constant. The direction of the wave vector of light incident perpendicularly (accurate to the Bragg angle) on the lateral surface of the sample was changed by rotating the sample around the direction of propagation of the longitudinal acoustic wave with a step of 30 degrees. The direction of polarization of the light incident on the sample, relative to the wave vector and the polarization of the acoustic wave was determined using a polarization analyzer.

The results of the measurements (in the form of points) are also shown in Fig. 2. Intensity values are given in relative units. The maximum value was taken to be the intensity of the light diffracted along the [010] direction. It is seen that the experimental results are in good agreement with the calculated dependence.

It should be noted that, in the general case, the effective photoelastic constant for anisotropic Bragg diffraction by longitudinal acoustic waves propagating along the [100] axis is described by a more complex dependence, the expression of which is given in Table 1.

In this case, the maximum intensity of diffracted light in the specified geometry of Bragg diffraction will be observed when the light propagates at a certain angle to the [010] axis in the (100) plane. This angle can be determined by the photoelastic constants p_{12}, p_{31}, and p_{41}.

The calculations of the acousto-optical quality factor were carried out for some of the most commonly used light diffraction geometries, which are given by the directions, respectively, of the wave vectors of sound $\boldsymbol{q}$ and light $\boldsymbol{k}$, and the polarization of sound γ and incident light β. Cases were considered when longitudinal and transverse acoustic waves propagate along the [100] and [001] directions.

The calculation results are shown in Table 2, in which the values of the attenuation coefficient of these waves at a frequency of 1 GHz are also given [11].

It can be seen that for the considered geometries of Bragg diffraction of light, the acousto-optical quality coefficient is approximately the same for both longitudinal and transverse acoustic waves. Thus, the geometry of acousto-optic interaction shown in Fig. 1 can be successfully applied to study the acoustic activity in lithium niobate crystals [10].

Table 2. Acousto-optical quality factor M_2 for some geometries of Bragg light diffraction in lithium niobate crystals.

q	γ	β	**k**	α, dB/μs	M_2, 10^{-15} s^3/kg
[001]	[001]	[010]	[100]	0.12	6.6
[001]	[001]	[001]	[100]	0.12	4.5
[001]	⊥[001]	[001]	[110]	0.25	4.7
[100]	[100]	[010]	[001]	0.28	5.4
[100]	⊥[001]	[100]	[001]	0.24	1.6

It should be noted that some of the obtained values of the coefficient M_2 are in good agreement with the results in [1, 2].

4. Conc1usions

The calculation results were shown that the square of the effective photoelastic constant in lithium niobate crystals for longitudinal waves along the [100] axis has a relatively large value of ~ 0.03. At the same time, as can be seen from the results of this study, this constant for transverse waves is an order of magnitude lower than for longitudinal waves.

The results obtained on the anisotropy of acousto-optical interaction in lithium niobate crystals can be useful for their application in acousto-optical devices for measuring the frequency of acoustic waves based on the phenomenon of acoustical activity. In particular, one can choose the most optimal geometry of Bragg diffraction of light by transverse acoustic waves in lithium niobate crystals.

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