Bulk wave excitation from the surface of a LiNbO₃ crystal by a system of planar electrodes

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Abstract. Ultrasound generation using planar electrodes deposited on the surface of a lithium niobate crystal is investigated. The analysis is carried out in an acousto-optic device based on the XY cut of a lithium niobate crystal and in an acousto-optic cell designed as a prototype of a modulator of non-polarized radiation. The experimental investigation is conducted at different frequencies of the driving electrical signal. The generated acoustic field is visualized by the acousto-optic method at different polarizations of the incident optical beam in case of slow shear and longitudinal acoustic modes. A relation between diffraction efficiencies for ordinary and extraordinary polarized optical radiation is analyzed. The obtained experimental results on the diffraction efficiencies are compared to the theoretically predicted values. It is demonstrated that the polarization characteristics of the devices differ from the conventional characteristics by the dependence on the structure of the acoustic beam.

1. Introduction

Acousto-optic (AO) devices are widely used in signal processing, laser beam control, frequency shifting, spectral filtering, etc. [1]. Improvement of optoelectronic technology stimulated a more detailed analysis of the AO device characteristics [2]. One of the desired requirements for these devices is related to simplicity of manufacturing. The most difficult part in fabrication of AO devices is transducer bonding: low-loss attachment of a piezoelectric transducer plate to a crystal. In order to make the AO devices cheaper and easier for fabrication, we use the method of bulk wave excitation without application of the piezoelectric transducer plate. The acoustic wave is generated from the surface of a piezoelectric crystal due to its inherent piezoelectric effect [3].

It is known that the efficiency of the AO interaction is primarily determined by the velocity of sound and photo-elastic constants [1–2]. A paratellurite crystal exhibits good AO characteristics [1–2] and can be used in AO devices with surface generation of bulk acoustic waves [9–12]. The efficiency of surface excitation of ultrasound is determined by piezoelectric properties of the crystal [1–3], therefore, in our further investigations we use a lithium niobate crystal because of its strong piezoelectric effect [1–3,5]. There has been a considerable interest in the excitation of bulk acoustic waves in the lithium niobate cells using interdigital transducers [5–7]. The study was predominantly aimed at the conversion of electric energy into acoustic energy [6]. The AO interaction was employed to study acoustic fields. A significant difference in the diffraction efficiencies for optical beams with different polarizations was demonstrated in [7]. In this paper, we define an incident optical beam with the polarization direction collinear with the polarization direction of an “ordinary” intrinsic mode of a
crystal as an ordinary polarized optical beam. Similarly, if the polarization direction of the incident optical beam is collinear with the polarization direction of the “extraordinary” intrinsic mode of a crystal, we call this optical beam extraordinary polarized. The polarization sensitivity is one of the key problems of optoelectronic devices [8–16]. The aim of the research is to investigate polarization characteristics of the AO interaction in the devices with surface generation of bulk acoustic waves in a lithium niobate crystal and their dependence on the acoustic field structure.

2. Theoretical model

The intensity of the diffracted light depends on acoustic driving power and the AO figure of merit (AOFM) $M_2$ [1–2]. In a crystalline media, AOFM is determined by the expression [1,11]:

$$M_2 = \frac{1}{4n_0n_1\rho V^3} \left[ d_{ij}^{(1)} e_{il} d_{l}^{(0)} p_{ijmn} (r_m n_r + r_n m_r) \right]^2$$  

(1)

where $n_0$ and $n_1$ – refractive indices of the incident and diffracted plane optical waves, respectively, $e_{il}$ – components of dielectric permittivity tensor, $d_{l}^{(0)}$ and $d_{ij}^{(1)}$ – corresponding components of a unit electric displacement field vector, $p_{ijmn}$ – components of photoelastic tensor, $r_m$ and $m_r$ – components of acoustic polarization and wave normal vectors, $\rho$ – medium density and $V$ – phase velocity of ultrasound.

A geometry of the AO interaction and a choice of a crystal cut have a great impact on the diffraction efficiency of an optical beam [1–2]. In order to decrease the polarization sensitivity of AO devices, we found a crystal cut of lithium niobate where the diffraction efficiencies for the optical beams with ordinary and extraordinary polarizations were close to each other [11]. In this optimal geometry of the AO interaction, an acoustic wave propagates at an angle of 13° relative to the $Z$ axis in the $YZ$ plane of lithium niobate while the optical beam propagates in the $YZ$ plane orthogonally to the wave vector of ultrasound. AOFM for ordinary and extraordinary polarized optical beams are $M_o = 5.73 \cdot 10^{-18} s^3/g$ and $M_e = 2.99 \cdot 10^{-18} s^3/g$, respectively, i.e. the ratio of intensities for the diffracted ordinary and extraordinary polarized optical beams is $I_e/I_o = M_o^{(o)}/M_e^{(e)} = 1.92$.

3. Experiment

3.1. Investigation of an AO cell based on the XY cut of a lithium niobate crystal

First, we study a prototype of the AO device based on the simple $XY$ cut of a lithium niobate crystal. The facets of the crystal are parallel to the principal crystallographic planes. Three metal electrodes that are parallel to the optical axis $Z$ are deposited on the upper facet of the sample that is orthogonal to the $X$ axis as shown in figure 1. The driving electric signal is applied to the central electrode while the two side electrodes are grounded.

![Figure 1](image-url) (a) - view of the upper facet of the crystal with electrodes. The gap between the central and side electrodes is 0.3 mm.; 
(b) - the AO cell with orientation of crystalline axes. The width of the crystal in $X$ direction is 10 mm.
The scheme of the experiment is shown in figure 2. The output signal of a pulsed oscillator (1) controls a high-frequency (HF) oscillator (2), whose output signal is fed to the central electrode of the AO cell (3) via a network providing matching of electric parameters. The side electrodes are connected with the ground. The waveform of the HF signal can be monitored using an oscilloscope (4). An oscilloscope (5) is used for observation of the time dependence of the diffracted intensity. It is seen that the output linear polarized beam of a laser (6) with the wavelength $\lambda = 532$ nm passes through the cell (3). A semiconductor detector (7) interfaced with an oscilloscope (5) is used to detect the diffracted optical beam intensity. The circuit allows the operation of the cell in a frequency band of 7.0 MHz in the vicinity of the central frequency of 200 MHz. The fraction of the electric power that is reflected from the transducer is about 5%.

Three acoustic modes (longitudinal, fast quasi-shear and slow quasi-shear) are simultaneously generated in the interelectrode gap and propagate in the bulk of lithium niobate along the $X$ crystal axis. The optical radiation is diffracted by the acoustic field that is excited from the crystal surface. In this paper, we are investigating the isotropic AO interaction when the polarization of the incident optical beam coincides with the polarization of the diffracted optical beam [1]. Figure 3 shows the measured diffracted intensity for several positions of the laser beam probing. The optical wave is directed orthogonally to the $XY$ plane of the crystal. Equation (1) shows that the efficiency of the AO interaction and AOFM $M_2$ depend on the velocity of sound $V$ as $M_2 \sim V^{-3}$. The measured characteristics prove this dependence.

![Figure 2. Block scheme of the experimental setup to study the surface excitation of the bulk acoustic waves: (1) – pulsed oscillator, (2) – HF oscillator, (3) – AO cell, (4) – oscilloscope for monitoring of the control voltage, (5) – oscilloscope for monitoring the diffracted intensity, (6) – laser, and (7) – photodetector.](image)

![Figure 3. Intensity distribution of the radiation that is diffracted by the acoustic field excited from the surface of the $XY$ cut of a lithium niobate crystal: (1) – slow quasi-shear acoustic mode, (2) – fast quasi-shear mode, and (3) – longitudinal mode. The dashed line in the vicinity of the abscissa axis shows the electrodes, and the inset shows the result of the AO visualization of the acoustic beam in the $XY$ plane of the crystal.](image)
3.2. Investigation of a AO cell based on the \((Y-13^\circ)\) cut of a lithium niobate crystal

In the second stage, we study an AO cell based on a lithium niobate crystal having a cut in accordance with the theoretical analysis [11,17,18]. The direction of the sound phase velocity must be oriented in the \(YZ\) plane at an angle of 13° relative to the \(Z\) optical axis. The analysis is carried out for two directions of optical radiation: along the \(X\) ([100]) crystal axis and at the angle of 13° with respect to the \(Y\) crystal axis in the \(YZ\) plane (almost along the [010] axis). The scheme of an AO cell based on the lithium niobate crystal of \((Y-13^\circ)\) cut is shown in figure 4. The size of each electrode is 1.9×7mm. The bottom facet of the crystal is tilted to the upper facet preventing appearance of a standing wave. It was shown that the polarization characteristics of the AO interaction are dependent on the acoustic field structure [19]. In the mentioned work, the ultrasound is generated from the surface of a lithium niobate crystal by using an interdigital transducer while the geometry of the AO interaction is the same as mentioned above. Therefore, the diffraction efficiency of the optical beam is dependent on whether the optical beam propagates along the electrodes or in the orthogonal direction. In order to investigate the AO interaction in both cases, two similar systems of planar golden electrodes were deposited on top of the lithium niobate crystal as shown in figure 1.

![Figure 4. Orientation of crystalline axes in the AO cell based on a lithium niobate crystal having a \((Y-13^\circ)\) cut.](image)

We investigated the relation between diffraction efficiencies for the ordinary and the extraordinary polarized optical radiation at different directions of the incident light propagation [19, 20]. In this paper, we measure these diffraction efficiencies in case of different acoustic beam apertures matching the AO cell circuit at different frequencies of ultrasound.

The scheme of the experiment is the same as shown in figure 2 with addition of a polarizer in front of the AO cell and an analyzer behind the cell. The intensity of the diffracted light is measured by a detector (7) and the magnitude of the intensity is displayed on an oscilloscope (5). Every measured intensity value is normalized to the intensity of incident optical beam.

Experimental investigation of polarization characteristics of the AO interaction is carried out in case of the slow quasi-shear mode with the velocity \(V_s = 3590 \text{ m/s}\) at different driving electric frequencies. At the acoustic frequency \(f = 54 \text{ MHz}\), the ratio between intensities of diffracted extraordinary and the incident ordinary polarized radiation propagating along the \(X\) crystal axis equals to \(I_{e[100]}/I_{o[100]} = 16\). For the radiation propagating in the \(YZ\) crystal plane at 13° to the \(Y\) axis (i.e. approximately along the \(Y\) crystalline axis [010]), the relation is equal to \(I_{e[010]}/I_{o[010]} = 0\). At the driving electric frequency \(f = 83 \text{ MHz}\), the ratios for the different directions of the incident radiation propagation are equal to \(I_{e[100]}/I_{o[100]} = 5.42\) and \(I_{e[010]}/I_{o[010]} = 0.45\), respectively. We also carried out
the calculations and a comparison of the experimental data with the theory. The theoretical values do not depend on the structure of the acoustic beam and are equal to the following values: $I_{e[100]}/I_{o[100]} = 0.37$ and $I_{e[010]}/I_{o[010]} = 1.7$. The registered discrepancy between the obtained experimental and theoretical results shows that the acoustic field structure generated in the crystal affects the AO polarization characteristics.

In order to investigate the acoustic field structure generated by the system of planar electrodes, we carried out a series of experiments where the incident laser beam is sent normally on an input facet of the crystal [21]. This optical radiation diffracts on the generated acoustic beam along its propagation direction. The efficiency of the diffracted light is registered during this laser probing of the acoustic field. Data in figure 5 show that the slow quasi-shear mode is generated between the electrodes while the fast longitudinal acoustic mode is concentrated under the electrodes. The optical radiation having elliptical and linear states of polarization was diffracted by different parts of the generated acoustic beams.

Figure 5. AO visualization of acoustic field structure generated by a system of planar electrodes: 2(a), 2(c), 2(e) – components of the acoustic field for the slow quasi-shear mode interacting with the elliptically polarized, extraordinary and ordinary polarized incident light, respectively; 2(b), 2(d), 2(f) – components of the acoustic field for the fast longitudinal mode ($V_l = 7300$ m/s) interacting with the elliptically polarized, extraordinary and ordinary incident radiation, respectively.

4. Conclusion
The surface generation of bulk acoustic waves using a system of planar electrodes deposited on the top facet of a lithium niobate crystal is analyzed in case of the $XY$ and $(Y-13^\circ)$ crystal cuts. The polarization characteristics of the AO interaction are obtained for the elliptically, ordinary and extraordinary polarized radiation diffracted by the slow quasi-shear and the fast longitudinal acoustic waves. The experiment is conducted at different frequencies of ultrasound. It is shown that the structure of the generated acoustic field has a noticeable impact on the ratio of the diffraction efficiencies for the ordinary and the extraordinary polarized radiation.
Acknowledgements
The research is supported by a grant of Russian Science Foundation (grant N 14-22-00042).

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