Acousto-optic devices using acoustic waves refraction

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Abstract. The methods of acousto-optics provide multiple techniques for controlling optical beam. The technical parameters of corresponding acousto-optic devices are largely determined by the efficiency of acoustic waves generation. In present work we examine the features of elastic waves generation in materials used in acousto-optics. In most of practical applications the elastic wave generation process is implemented through the refraction of elastic waves at the boundary between two anisotropic media. We present a detailed study of the refraction of elastic waves in strongly anisotropic media. We report new refractive effects such as “extraordinary” refraction. In the latter case the change in the direction of the incident acoustic wave does not influence the direction of the energy flow propagation for refracted elastic waves. The configuration of an acousto-optic device using the geometry of unusual refraction in an anisotropic medium is discussed.

1. Introduction

Science and technology extensively use acoustic waves transformation at the interface of two media. This work is motivated by acousto-optics applications. The acousto-optics studies the phenomenon of the light waves interaction with diffraction gratings generated by the periodic elastic deformations [1–18]. The refractive indices of transparent crystal are disturbed by acoustic wave propagation in the material. The ultrasound with the velocity V effectively transforms the material into the phase diffraction grating with respect to optical waves. After light-sound interaction one may see a specific diffraction pattern. Therefore, the questions of the ultrasound propagation and transformation are central in the discussions of the acousto-optic interaction. Only a complete understanding of sound waves propagation process and their transformation at the interface between two media open possibilities for optimization of acousto-optic interaction and allow to make it effective. To do this, it is necessary to determine the number of elastic waves, their direction of propagation, as well as the main characteristics, such as: phase velocity, group velocity and polarization vector orientation. In this way, one is obliged to solve the acoustic problem in order to have a clear understanding of the sound generation mechanism in a crystal. In most of the applications, a piezoelectric transducer bonded to the crystal is used to generate ultrasound in a crystalline medium. It is important to note that both the properties of the piezoelectric transducer and the crystal itself, in which the sound waves are excited, determine the main characteristics of generated waves and their number. Significant elastic anisotropy requires detailed calculations of acoustic waves characteristics. Since crystalline media are investigated and their properties depend on the direction of wave propagation, the detailed calculations of the properties of waves in each investigated direction are required.
The development of acousto-optics is associated with the development of new materials. They have unusual physical properties, in particular, optic and acoustic properties. These materials include both a well-known paratellurite crystal and little-used mercury compounds such as calomel (Hg₂Cl₂), mercury bromide (Hg₂Br₂), mercury iodide (Hg₂I₂) and others [3, 4]. The latter manifests itself in many observable properties, for example, in the dependence of the phase velocity of ultrasound on the direction of propagation in the crystal. It turned out that the unusual physical processes and phenomena exist in these new materials that are not observed in isotropic and weakly anisotropic media. The calculations of the acousto-optic interaction are more complex due the anisotropy of the physical properties. Optical and acoustic anisotropy of the used materials allows to observe new effects thereby increasing the efficiency of acousto-optical devices.

In this work, we study the features of the wave’s behavior during their excitation in a crystal. The paratellurite crystal is chosen for the analysis as the one which is used most in the acousto-optic devices. The extremely strong anisotropy of this crystal physical properties is of special interest to it. This leads to the fact that, in contrast to an isotropic medium, fundamentally new effects can be observed in it. We consider a sound emitter made of lithium niobate as a transducer. It is known that crystal of lithium niobate possesses a strong piezoelectric effect. Therefore, it is an efficient media for excitation of the ultrasound. Lithium niobate is widely used in various devices, which involve generation of ultrasound [12]. An important task fulfilled in this work is to study the excitation of elastic waves in a paratellurite crystal using a transducer made of a lithium niobate crystal. The calculations are performed in the approximation of the elastic wave propagation through the surface between two semi-infinite anisotropic media lithium niobate – paratellurite, see figure 1. Here, the lithium niobate plate is effectively replaced by a semi-infinite medium. In other words, waves are studied in a paratellurite crystal after their refraction at the lithium niobate-paratellurite interface. During consideration, the following parameters are found: the number of waves, the directions of their propagation, as well as the magnitudes of the phase and group velocities.

2. Acoustic waves refraction at the boundary of lithium niobate - paratellurite

Figure 1 shows the boundary of two semi-infinite crystals of lithium niobate and paratellurite. The lithium niobate crystal is considered in the (100) plane, while the paratellurite crystal is considered in the (001) plane. For each material, the surface of the inverse velocities is shown in the selected planes.

\[ \begin{align*}
\theta_i & \text{ – is the angle between the wave vector of the incident wave and the normal to the boundary, } \\
\psi & \text{ – the angle between the direction of the phase velocity and the normal to the boundary, } \\
\chi & \text{ – is the angle between the energy flux and the normal to the boundary.}
\end{align*} \]

In figure 1 the angle of incidence \( \theta_i \) is the angle between the wave vector of the incident wave and the normal to the boundary, the angle of refraction \( \psi \) is the angle between the wave vector of the refracted wave and the normal to the boundary, the angle of refraction \( \chi \) is the angle between the direction of the energy flux and the normal to the boundary. The properties of refracted waves are calculated for the incident waves with the angle of incidence in range \(-90^\circ < \theta_i < 90^\circ\).

The plot in figure 1 shows three surfaces of inverse velocities for each of the two crystals. This means that three waves can propagate simultaneously in the crystal on each side. The polarization of the shear wave in lithium niobate, shown in red, as well as the polarization of the shear wave in the paratellurite...
crystal, shown in blue, have an orientation of the polarization vector orthogonal to the plane in which refraction takes place. The polarizations are orthogonal to the plane of incidence and refraction of figure 1, i.e. these waves are pure transverse modes. The polarizations of the other waves are localized in the plane and do not have components orthogonal to the plane. This means that for transverse waves, polarization vector does not have a component lying in the plane. This fact indicates that transverse wave in lithium niobate excites in paratellurite only a transverse wave with the same polarization.

Likewise, a wave in lithium niobate, whose polarization lies in the incidence plane, can only generate a mode with a polarization vector vibrating inside the plane. That is why one may focus the study on the waves polarized in the plane and exclude from consideration wave with the polarization vector directed orthogonally to the refractive plane [4].

In the cases of sound propagation in anisotropic medium, the direction of the wave vector of sound does not coincide with the direction of energy flow, the so-called group velocity vector. Therefore, a calculation should be performed in order to estimate the direction of energy flow for refracted and reflected waves. It is believed that the initial wave is excited in a lithium niobate crystal. After refraction, the mutual orientation of the energy flows is found. The dependences of the refraction angles on the angle of incidence $\theta$ are presented in figure 2.

Figure 2. Surface separating lithium niobate and paratellurite crystals. The crystallographic axes of the paratellurite crystal forms 45 degrees with the boundary (a); dependences of the refraction angle $\psi$ for the phase velocity on the incidence angle $\theta_i$ for Y crystal cut of lithium niobate: purple curve corresponds to the quasi-longitudinal wave, blue curve corresponds to a fast quasi-shear wave, orange curve corresponds to a slow quasi-shear wave (b); dependences of the refraction angle $\chi$ for the group velocity on the incidence angle $\theta_i$ for Y crystal cut of lithium niobate: purple curve corresponds to the quasi-longitudinal wave, blue curve corresponds to a fast quasi-shear wave, orange curve corresponds to a slow quasi-shear wave (c).
3. Quasi-longitudinal acoustic wave generation at the lithium niobate - paratellurite boundary

In this part the refraction at the boundary between lithium niobate and paratellurite in the case of quasi-longitudinal acoustic wave generation is considered. Figure 2(a) shows that Y axis of a lithium niobate crystal is directed along the surface while Z axis is oriented orthogonally to the boundary. The paratellurite crystal forms 45 degrees angle with respect to the crystallographic axes. Fast quasi-longitudinal wave is excited in a lithium niobate crystal at different angles. There are 2 waves propagating in the paratellurite crystal after refraction: quasi-longitudinal and quasi-shear waves. Figure 2(b) shows the dependences of the angle of refraction \( \psi \) for the phase velocity on the incidence angle \( \theta_i \). One may observe the traditional refraction behavior similar to the refraction of waves in isotropic medium. On the contrary refraction for the group velocities manifests itself in a very bright manner. Dependences of the refraction angles \( \chi \) on the incidence angle \( \theta_i \) shown in figure 2(c), demonstrate very interesting peculiarities.

Figure 2(c) demonstrates that group velocity dependences for fast quasi-transverse refracted wave does not depend on the incidence angle, while a slow quasi-transverse wave shows sharply change orientation of refraction energy flow versus incidence angle. Moreover, in figure 2(c) it can be seen that there exist incidence angles providing refraction angle \( \chi \) close to 80\(^\circ\). Therefore, wave propagates practically along the boundary (figure 3(a)). On the other hand, the direction of the incident wave can be varied in a wide range without changing the direction of the refracted wave’s energy flux. This simplifies the design of the acousto-optic devices which require generation of the certain wave.

On the other hand, the dependences for the fast quasi-longitudinal wave shown in figure 2(c) demonstrate another interesting peculiarity. It may be seen that the refraction angle for a fast wave does not depend on the incident angle.

Moreover, refraction angle is close to zero for all directions of the incident wave. It means that in spite of different orientations of the initial wave, the refracted mode is oriented normally with respect to the boundary i.e. quasi-longitudinal refracted wave remain fixed for all angles of incidence and the system is insensitive to the direction in which the incident wave propagates. The diagrams in figures 3(a)–(i) illustrate the above. The dotted line shows the different directions of the incident wave, while the solid line corresponds to the direction of the group velocities of the refracted waves. The figures show the mutual orientation of the waves for different incident angles. Several unusual phenomena mentioned above may be observed in these schemes.

The quasi-longitudinal refracted wave does not change orientation and lies orthogonally to the boundary. A slow quasi-shear wave can have both a negative angle (third quadrant) and positive one (fourth quadrant).

In the other words, a change in the direction of the incident wave in a lithium niobate crystal in the range of angles of incidence \(-180^\circ < \theta_i < 180^\circ\) does not affect the direction of energy flux propagation for the refracted quasi-longitudinal wave. It means that an error in the transducer cut does not influence the direction of generated waves propagation. This is an important advantage in technology of acousto-optic devices manufacturing [19–24].

Using the effects mentioned above, it is possible to propose the multichannel device using several waves simultaneously. These waves supposed to be generated in the initial crystal at different angles. After the refraction, they are transformed into quasi-longitudinal wave oriented normally to the boundary. Each of these waves is an independent diffraction grating that provides diffraction in specific spectral range [17].
4. Conclusions

The paper demonstrates the results of the analysis of the elastic wave reflection at the lithium niobate – paratellurite boundary. It is shown that significant change in the direction of the incident wave propagation in lithium niobate crystal does not influence on the direction of propagation of the energy flows of the refracted waves in paratellurite. Therefore, one may conclude that during the transducer manufacturing, an error in the cut angle of several degrees is permissible, which substantially simplifies manufacturing. The features of the “extraordinary” wave refraction at the boundary between the two...
media examined in the work may be employed when creating new acoustic and acousto-optic devices. Possibility to create a multichannel device for controlling light beams is shown.

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References
[1] Auld B 1990 Acoustic Waves and Fields in Solids (New York: Robert Krieger)
[2] Voloshinov V B, Polikarpova N V and Mozhaev V G 2006 Acoust. Physics. 52(3) 245–51
[3] Burov V A, Voloshinov V B, Dmitriev K V and Polikarpova N V 2011 Phys. Usp. 54 1165–70
[4] Voloshinov V B and Polikarpova N V 2009 J. Acoust. Soc. Am. 125(2) 772–9
[5] Voloshinov V B and Polikarpova N V 2009 Applied Optics 48 C55–C66
[6] Voloshinov V B, Gupta N, Knyazev G A and Polikarpova N V 2011 Journal of Optics 13(1) 015706–14
[7] D’yakonov E A, Voloshinov V B and Polikarpova N V 2012 Acoust. Physics 58(1) 107–16
[8] Polikarpova N V and Malneva P V 2012 Bulletin of the Russian Academy of Sciences Physics 76(12) 1269–72
[9] Polikarpova N V, Mal’neva P V and Voloshinov V B 2013 Acoustical Physics 59(3) 291–6
[10] Polikarpova N V and Malneva P V 2014 Acta Acustica United with Acutica 100(3) 427–433
[11] Balakshy V I, Kuznetsov. Yu I, Mantsevich S N and Polikarpova N V 2014 Optics & Laser Technology 62 89–94
[12] Polikarpova N V, Voloshinov V B and Reznikov A M 2015 Physics of Wave Phenomena 23(1) 52–7
[13] Voloshinov V B and Polikarpova N V 2015 Physics proccedia 70 749–53
[14] Polikarpova N V and Voloshinov V B 2015 Bulletin of the Russian Academy of Sciences Physics 79(10) 1274–7
[15] Dyakonov E A, Voloshinov V B and Polikarpova N V 2015 Optics and Spectroscopy 118(1) 166–74
[16] Voloshinov V B and Polikarpova N V 2018 Phys. Lett. A 382(33) 2226–9
[17] Voloshinov V B, Polikarpova N V, Ivanova P A and Khorkin 2018 V S Applied Optics 57(10) C19–C25
[18] Polikarpova N V, Voloshinov V B and Ivanova P A 2019 Acoustical Physics 65(6) 740–50
[19] Machikhin A S, Batshev V I, Pozhar V Ed, Naumov A A and Gorevoy A V 2018 Optics Letters 43(5) 1087–90
[20] Machikhin A S and Pozhar V Ed 2014 Technical Physics Letters 40(9) 803–6
[21] Machikhin A S, Batshev V I and Pozhar V Ed 2017 JOSA A 34(7) 1109–13
[22] Machikhin A S, Batshev V I, Pozhar V Ed, Naumov A A and Gorevoy A V Optics Letters 43(5) 1087–90
[23] Machikhin A S and Pozhar V Ed 2014 Technical Physics Letters 40(9) 803–6
[24] Machikhin A S, Batshev V I and Pozhar V Ed 2017 JOSA A 34(7) 1109–13