2023 Wave Electronics and its Application in Information and Telecommunication Systems (WECONF) | 979-8-3503-4829-3/23/$31.00 ©2023 IEEE | DOI: 10.1109/WECONF57201.2023.10147922

Transforming Acoustic Waves to Create Acousto-optic Devices

N.V. Polikarpova
Faculty of Physics
M.V. Lomonosov Moscow State University
Moscow, Russia
e-mail: polikarpnv@yandex.ru

Abstract— **This study focuses on the issue of acoustic mode conversion at the interface between a crystal and vacuum. The significance of this problem stems from the application of this excitation method for generating a shear elastic wave in wide aperture acousto-optical filters. Utilizing the fundamental laws of reflection for arbitrary media, this research examines a specific case of transforming a longitudinal elastic wave into a slow shear wave at the boundary of a paratellurite crystal, which is commonly employed in filter design. The outcomes of a numerical assessment of the amplitude and energy reflection coefficients for all acoustic modes are reported.**

Keywords*— *Acousto-optics; acoustic waves reflection; anisotropy; tellurium dioxide

I. Introduction

The existing literature discusses a vast array of acousto-optic devices and tools that vary in function, structure, and operating principle. Nevertheless, despite their diversity, these devices share many similarities, as they all rely on an acousto-optic cell - a transparent crystal sample in which an acoustic wave is generated using a piezoelectric transducer. As light passes through the cell, it scatters on the sound column. The diffracted beam conveys information about both the incident optical wave and the electrical signal [1]. These acousto-optic cells serve as the foundation for contemporary filters, modulators, deflectors, and optical information processing devices.

Paratellurite, also known as TeO_2, is a crystal widely used as the interaction medium in modern acousto-optics. This uniaxial crystal has unique elastic and photoelastic properties, making it a popular choice. In certain directions, the speed of ultrasound is extremely low, leading to an exceptionally strong acousto-optic effect [2]. However, achieving record high acousto-optical quality in a crystal requires special configurations of the interaction of light and sound. To do this, a polarized acoustic mode must be used in a specific way, which can present technical challenges during direct excitation.

Currently, the production of TeO_2 crystals has reached an industrial scale, with the technology allowing for the growth of single-domain samples that meet the optical quality requirements of applied optics and have dimensions of several centimeters. This, coupled with paratellurite's transparency in the visible and near-infrared ranges, enables the efficient design of various acousto-optic devices with technical characteristics that eliminate the need for powerful cooling systems.

One of the most promising devices in the realm of acousto-optics is the tunable acousto-optic filter. This ingenious contraption is specifically designed to extract a narrow spectral range from a light beam that boasts an impressively wide spectrum. The filter's central wavelength of the transmission range can be tuned in accordance with a control signal, rendering it exceptionally versatile. To achieve this, the filter utilizes the selectivity of anisotropic Bragg light scattering on an acoustic wave - the selectivity of diffraction in terms of the angle of incidence or wavelength of light at a high frequency of ultrasound. When a light flux with a continuous spectrum falls on an acousto-optic cell, only light that satisfies the Bragg condition at a given acoustic frequency is scattered by ultrasound. As the frequency of ultrasound varies, the device is restructured, since the Bragg condition becomes valid for optical beams with a different wavelength, resulting in an optimal filtering effect.

In general, any periodic phase structure possesses filtering properties. However, the use of a sound column as a diffractive element offers several advantages, including high periodization accuracy resulting from the stability of the ultrasound generator and uniformity of the elastic medium. Additionally, the period of the resulting structure can be easily modified. The key characteristics of filters, such as bandwidth and resolution, are determined by the number of periods of the phase structure over the length of the interaction between light and ultrasound [3]. Therefore, high-resolution acousto-optic filters often use collinear or nearly collinear diffraction, where optical and acoustic waves propagate in the same direction. This geometry provides the narrowest bandwidths.

Despite their advantages, collinear filters are not suitable for image processing, as the optical beam incident on the acousto-optic cell has a wide angular aperture of up to ten degrees, which is unacceptable for collinear filters. To address this issue, noncollinear acousto-optical interaction can be used. Non-collinear filters have wider bandwidths and are less sensitive to the angle of incidence of light. They are also structurally easier to implement than collinear filters, and the range of materials suitable for use is significantly expanded [1].

However, exciting this acoustic mode presents significant challenges. Creating a reliable acoustic contact between the paratellurite crystal and the piezoelectric transducer is problematic, as is dealing with the difference in acoustic impedances between the transducer and sound duct, as well as the difference in electrical parameters between the control oscillator and piezoelectric plate. One effective method for exciting a shear elastic wave in wide-aperture acousto-optic filters is to generate a longitudinal elastic wave in paratellurite and convert it into a shear wave via internal reflection from the free crystal face at the crystal-vacuum interface. This study focuses on this specific method of generating shear acoustic waves.

II. Acoustic Modes Generation

Three decades ago, researchers proposed a configuration for an acousto-optic device that relied on a calcium molybdate crystal and used acoustic reflection from the optical face of a filter [1]. However, the creation of such devices presented a challenge as it was necessary to solve the problem of acoustic reflection in this specific material. Later on, with the synthesis of the paratellurite crystal, researchers faced a similar issue with reflection of acoustic waves in this acousto-optic material. Elastic waves come in many different forms, such as Rayleigh, Gulyaev-Bluestein, and Lamb waves, depending on the conditions of propagation in the crystals [4-6]. However, for the purposes of this problem, only two main types of bulk acoustic waves in solids are considered: longitudinal and transverse acoustic waves.

Longitudinal waves, also known as compression waves, are characterized by the displacement of particles parallel to the direction of propagation, with the polarization of the wave being parallel to the wave vector. As a plane longitudinal wave propagates, it changes the distance between parallel planes containing particles, which subsequently changes the volume per given number of particles.

In contrast, transverse or shear waves result in particles being displaced perpendicular to the wave vector. While the sliding of parallel planes does not lead to a change in volume, it is important to consider these types of waves when dealing with the reflection of acoustic waves in materials like calcium molybdate and paratellurite crystals.

In crystalline structures, there are typically three waves that can propagate in a given direction. However, in some cases, none of these waves are purely longitudinal or purely transverse. When this happens, the wave with the smallest angle between the polarization vector and the direction of propagation is referred to as a quasi-longitudinal wave, while the other two are called quasi-transverse waves [4, 5]. The absolute value of the velocity is what differentiates the quasi-transverse waves.

The three modes - quasi-longitudinal (QL), fast quasi-transverse (QFS), and slow quasi-transverse (QSS) - always have mutually perpendicular polarizations. The energy flux vectors that dictate the direction of energy transfer for each wave generally form different angles with the wave vectors. However, there are certain directions, such as symmetry axes, along which pure modes can propagate [4]. In these cases, the energy flux vector and the wave vector are parallel, similar to an isotropic solid.

In paratellurite, a transverse elastic wave propagating along the [110] direction or close to it is of great interest for acousto-optics. This direction achieves a very low sound speed of V = 616 m/s for modern photoelastic materials. The efficiency of the interaction between light and an elastic wave is determined by the coefficient of acousto-optical quality M_2, which is greater when the speed of the sound wave is lower [1]. However, there are certain technical difficulties associated with efficient and broadband excitation of shear acoustic waves along the direction of the paratellurite crystal [7, 8]. The frequency of the resonant transducer is determined by the thickness of the piezoelectric plate, which is $d = V / 2f$, where V is the speed of sound and f is its frequency. As a result, the transducer must be made thinner with higher ultrasound frequencies, leading to a greater static capacitance $c = \varepsilon S/4\pi d$ (where ε is the dielectric constant of the piezoelectric and S is the transducer area). This makes matching the electrical parameters of the piezoelectric transducer and the generator of high-frequency oscillations a complex technical problem. In addition, creating filters presents difficulties due to the difference in the acoustic impedances of the transducer material and the TeO_2 crystal. Establishing a reliable acoustic contact between the piezoelectric plate and the crystal is also challenging. For example, the acoustic impedances of materials like $LiNbO_3$ and TeO_2 differ by a factor of 5, which impedes efficient transmission of acoustic waves through gluing [9]. To overcome these challenges, longitudinal acoustic waves can be excited in paratellurite and then transformed from the longitudinal mode L to the shear mode S upon reflection of the longitudinal ultrasound wave from the free crystal-vacuum interface. This approach largely addresses the difficulties associated with exciting shear acoustic waves directly.

Figure 1 provides a general view of an acousto-optic cell that relies on a paratellurite crystal to convert a longitudinal ultrasound wave L into a shear wave S. After reflection from the sample face, three waves are observed. However, part of the energy from the incident longitudinal acoustic wave L is reflected in the form of parasitic waves, including the fast acoustic mode QL and the fast quasi-transverse mode QFS. As a result, the energy fraction in the slow shear acoustic mode is reduced.

III. Transformation of Acoustic Modes upon Reflection at the Boundary

When a monochromatic elastic wave passes through the boundary between two crystalline media, three waves can arise on each side of the interface. This includes an incident quasi-longitudinal wave that can generate quasi-longitudinal and quasi-transverse (slow and fast) reflected waves in the first crystal, and quasi-longitudinal and quasi-transverse transmitted (refracted) waves in the second crystal. To determine the propagation direction, amplitude, and polarization of these waves, one must solve propagation equations for each medium while considering the boundary conditions for the continuity of displacements and mechanical stresses at the interface. However, analytical solutions are only possible for specific cases of reflection.

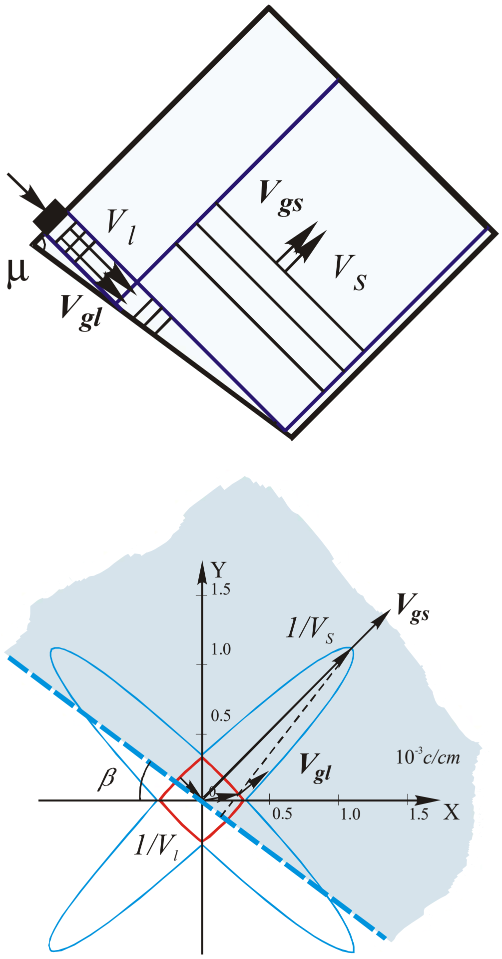

Fig. 1. Acoustic reflection from the boundary between a paratellurite crystal and vacuum involves a transformation of modes, which can be illustrated by a scheme that depicts the process.

In this paper, we explore a particular method for transforming an incident longitudinal ultrasound wave into a slow quasi-transverse mode, which is significant for acousto-optics. This method involves the propagation of a reflected quasi-shear wave at an angle α to the [110] axis (as shown in Fig. 2). The longitudinal ultrasound wave L is generated in the sample along this axis, due to the crystal's symmetry with respect to this direction, where pure acoustic modes propagate in paratellurite without loss of elastic energy. In this case, the longitudinal wave is generated using a thicker transducer with a greater thickness d and lower static capacitance *c*. By selecting the correct angle of inclination of the reflecting face of the sample with respect to the axes and [001], an effective transformation of the longitudinal acoustic wave into a quasi-shear QSS can be achieved. This transformation efficiency is of particular interest, as is identifying the cut angle of the crystal that provides the required transformation of elastic energy [11, 12].

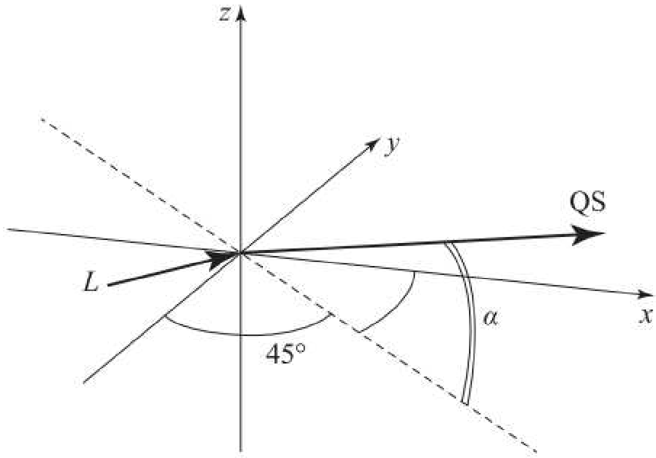

Fig. 2. The conversion of a longitudinal acoustic wave L, propagating outside the principal plane, into a slow quasi-transverse QSS wave.

When dealing with the free surface of a solid body, no elastic waves can pass into vacuum. The only boundary condition in this case is the absence of mechanical stresses at every point of the free boundary surface. However, when analyzing the propagation of elastic waves through an interface, solving a system of linear equations is necessary [9-11]. The solution of this system of equations provides the ratio of the amplitudes of the reflected waves to the amplitude of the incident wave, known as the amplitude reflection coefficients.

Energy reflection coefficients may be more practical for certain applications [13]. These coefficients can be obtained by converting the acoustic amplitude into the Poynting vector value for each of the waves under consideration.

The Poynting vector, which governs energy transfer, aligns with the group velocity and can differ from the direction of the phase velocity in anisotropic media [14]. It's important to note that the incident and reflected acoustic beams may have different widths (as shown in Fig. 1), which affects the ratios of the normal components of the Poynting vectors to the interface, rather than their absolute values.

Creating an acousto-optic device requires addressing the issue of sound reflection outside the principal plane of a paratellurite crystal (as shown in Fig. 2). This results in not one, but three reflected waves. Specifically, after reflection, a quasi-longitudinal wave and two quasi-transverse waves (slow and fast) are observed. As a result, some of the energy from the incident longitudinal acoustic wave L is reflected in the form of a fast acoustic mode QL and a fast quasi-transverse mode QFS. These waves are generally not utilized in acousto-optic cells and are therefore considered spurious modes in this case.

In Figure 3, the energy reflection coefficients for all three acoustic modes are presented. These coefficients were numerically calculated based on the angle α between the direction [110] of the axis and the wave vector of the slow shear acoustic mode in the plane (110). The graph clearly shows that the efficiency of energy transfer from the generated longitudinal wave to the shear one increases as the angle α increases, with a maximum possible efficiency of 100% at 90 degrees. However, in reality, the experimentally measured reflection coefficient will always be less than 100% due to various factors such as the dissipation of acoustic power on a non-ideal crystal face, the absorption of ultrasound in the material itself, the partial passage of the wave into a medium other than the model vacuum, the divergence of acoustic energy flows, and other reasons.

It is possible to calculate the energy reflection coefficients for all three acoustic modes based on the angle α between the direction [110] of the axis and the wave vector of the slow shear acoustic mode in the plane (110). Figure 3 shows the results of these calculations. As the angle α increases, the efficiency of energy transfer from the generated longitudinal wave to the shear one increases, with a maximum efficiency of 100% at 90 degrees. However, in practice, the experimentally measured reflection coefficient will always be less than 100% due to various factors such as non-ideal crystal faces, ultrasound absorption in the material, and the divergence of acoustic energy flows. Additionally, parasitic waves can reduce the energy fraction in the slow shear acoustic mode. These challenges must be carefully considered when designing experiments to excite shear acoustic waves in paratellurite crystals.

In the context of applied acousto-optics, the range of sound propagation angles used in existing filter modifications is the only practical interest. From the perspective of acousto-optic interaction, these angles correspond to diffraction regimes in which the efficiency of diffracted light is relatively insensitive to changes in the angle of incidence of light on the acoustic column. When the angle α between the front of the ultrasonic wave and the optical axis of the crystal is not too large [1, 7], such a wide-aperture interaction can occur. For paratellurite, this angle is calculated to be 19 degrees. Interestingly, calculations show that at the boundary of the specified range of propagation angles, the energy reflection coefficient for the slow quasi-transverse mode in paratellurite can reach up to 93%. This finding has important implications for the design and optimization of acousto-optic devices based on paratellurite crystals.

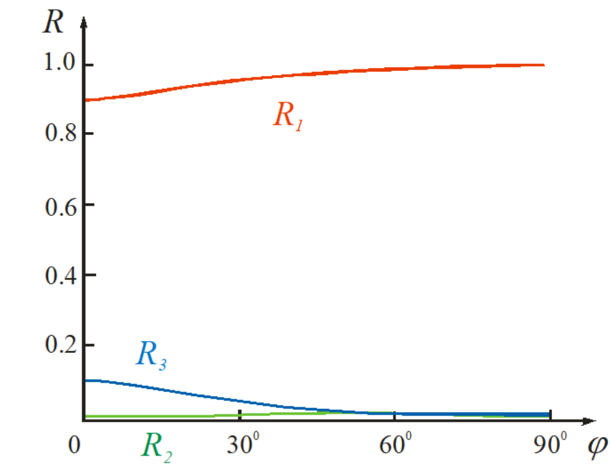

Fig. 3. The energy reflection coefficients in the crystal plane depending on the angle α.

The graph clearly shows that the fast quasi-transverse mode has a relatively small influence, becoming significant only at angles of approximately 50°. Therefore, in practical acousto-optic devices, this wave should not significantly affect the formation of the acoustic field. Instead, the main energy losses during reflection and mode conversion are associated with the excitation of a parasitic quasi-longitudinal wave. Calculations indicate that the efficiency of energy transfer to this mode does not exceed 10%. This finding underscores the importance of carefully considering the excitation method when designing acousto-optic devices based on paratellurite crystals. Based on the results of the calculations, it is justified to use the sound excitation method with reflection and acoustic mode conversion in such devices.

IV. Exploring Acoustic Mode Transformations in Paratellurite

To verify the correctness of theoretical conclusions and experimentally determine the value of the reflection coefficient of an elastic wave, the ratio of the powers of the incident and reflected ultrasonic beams was measured using an acousto-optic method for visualizing sound beams [2, 11, 15-17]. An acousto-optic cell was created based on a paratellurite crystal (Figure 4). The crystal is shown in the figure, with its upper surface sloping at a slight angle. The longitudinal sound travels horizontally from the upper part of the crystal on the left to the right. The transducer is located on the left side of the crystal in its upper part. The slope of the upper surface is small due to the large difference in velocities between longitudinal and shear acoustic modes. The longitudinal wave is reflected from the upper surface, converted into a slow shear mode, and travels vertically downward through the crystal. The elements of the system for matching the parameters of the piezoelectric transducer with the generator of electrical signals are visible on the left side of the crystal, including an inductance coil.

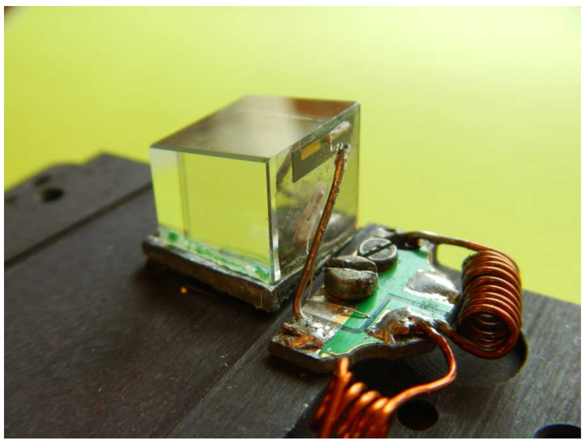

Fig. 4. An acousto-optic device that utilizes a paratellurite crystal as its core component.

An acousto-optic cell was fabricated based on precise calculations to ensure that the ultrasound wave vector after reflection would form an angle 7 degrees with the [110] direction in the crystal plane, thereby efficiently transforming the incident longitudinal wave into a slow quasi-transverse wave. Using acousto-optic methods, the intensity of diffracted light was measured at an ultrasound frequency of $f = 92$ MHz for two reflected acoustic modes: the quasi-longitudinal (QL) mode and the slow quasi-transverse (QSS) mode. This allowed for an estimation of the proportion of energy transferred to each mode. The experimental ratio of the acoustic powers of the reflected slow quasi-transverse (QSS) and quasi-longitudinal (QL) waves was measured to be PQS/PQL = 6.7 + 1.0, while the theoretical prediction was PQS/PQL = 9.0. No fast quasi-transverse acoustic wave was observed in the experiment. The agreement between the experimental and theoretical data confirms the calculated reflection coefficient for the working wave and demonstrates the effectiveness of exciting the slow quasi-transverse acoustic wave during mode transformation. This result has implications for the development of new acousto-optic devices [13,17].

V. Conclusion

Paratellurite crystals can efficiently convert longitudinal ultrasound waves into slow shear elastic waves, especially when the sound propagates along or near the [110] direction. This mode transformation results in a steadily increasing energy reflection coefficient from 90% to 100% as the sound propagation direction changes from the [110] axis to the [001] axis. However, parasitic modes can lead to energy losses during wave conversion, with the quasi-longitudinal acoustic mode absorbing up to 10% of the energy. The fast quasi-transverse mode has a minimal impact on the formation of the acoustic field. Experimental results have confirmed the theoretical predictions of the effectiveness of this method for generating ultrasound in paratellurite crystals, which can be used in the development of advanced acousto-optic devices such as modulators, deflectors, and filters.

Acknowledgment

This work has been supported in part by the Russian Science Foundation (RSF), project N 19-12-00072.

References

[1] B. Auld, Acoustic Waves and Fields in Solids. New York: Robert Krieger, 1990.

[2] V.B. Voloshinov, N.V. Polikarpova and V.G. Mozhaev, "Nearly backward reflection of bulk acoustic waves at grazing incidence in a TeO2 crystal", *Acoust. Physics*., vol. 52(3), pp. 245-251, 2006.

[3] V.A. Burov, V.B. Voloshinov, K.V. Dmitriev and N.V. Polikarpova, "Acoustic waves in metamaterials, crystals, and anomalously refracting structures", *Phys. Usp*., vol. 54, pp. 1165-1170, 2011.

[4] V.B. Voloshinov and N.V. Polikarpova, "Reflection of plane elastic waves in tetragonal crystals with strong anisotropy", *J. Acoust. Soc. Am*., vol. 125(2), pp. 772-779, 2009.

[5] V.B. Voloshinov and N.V. Polikarpova, "Acousto-optic investigation of propagation and reflection of acoustic waves in paratellurite crystal", *Applied Optics*, vol. 48. pp. C55-C66. 2009.

[6] V.B. Voloshinov, N. Gupta, G.A. Knyazev and N.V. Polikarpova, "An acousto-optic X-Y deflector based on close-to-axis propagation of light in single crystal Te", *Journal of Optics*, vol. 13(1), pp. 015706- 015714, 2011.

[7] E.A. D'yakonov, V.B. Voloshinov and N.V. Polikarpova, "Acousto┐ optic study of the unusual cases of reflection of bulk elastic waves in a paratellurite crystal", *Acoust. Physics*, vol. 58(1), pp. 107-116, 2012.

[8] N.V. Polikarpova. and P.V. Malneva, "Polarization of elastic waves in tellurium single crystal", Bulletin of the Russian Academy of Sciences. *Physics*, vol. 76(12), pp. 1269-1272, 2012.

[9] N.V. Polikarpova, P.V. Mal'neva and V.B. Voloshinov, "The anisotropy of elastic waves in a tellurium crystal", *Acoustical Physics*, vol. 59(3), pp. 291-296, 2013.

[10] N.V. Polikarpova and P.V. Malneva, "Polarization characteristics of bulk ultrasonic waves in acousto-optic paratellurite crystal", *Acta Acustica United with Acutica*, vol. 100(3), pp. 427-433, 2014.

[11] V.I. Balakshy, Yu.I Kuznetsov, S.N. Mantsevich and N.V. Polikarpova, "Dynamic processes in an acousto-optic laser beam intensity stabilization system", *Optics & Laser Technology*, vol. 62, pp. 89-94, 2014.

[12] V.B. Voloshinov and N.V. Polikarpova, "Phase and group velocities of bulk optic and acoustic waves in crystals and artificial periodically structured media", *Physics procedia*, vol. 70, pp. 749-753, 2015.

[13] N.V. Polikarpova and V.B. Voloshinov, "Transformation of Acoustic Modes in Acousto-Optical Devices", Bulletin of the Russian Academy of Sciences, *Physics,* vol. 79(10), pp. 1274-1277, 2015.

[14] E.A. Dyakonov, V.B. Voloshinov and N.V. "Polikarpova, Semicollinear diffraction of light by ultrasound in a medium with strong elastic anisotropy", *Optics and Spectroscopy*, vol. 118(1), pp. 166-174, 2015.

[15] V.B. Voloshinov and N.V. Polikarpova, "Opto-mechanic oscillatory system based on birefingent crystal", *Phys. Lett. A*, vol. V. 382(33), pp. 2226-2229, 2018.

[16] V.B. Voloshinov, N.V. Polikarpova, P.A. Ivanova and V.S. Khorkin, "Acousto-optic control of internal acoustic reflection in tellurium dioxide crystal in case of strong elastic energy walkoff", *Applied Optics*, vol. 57(10), pp. C19-C25, 2018.

[17] N.V. Polikarpova, V.B. Voloshinov and P.A. Ivanova, "Acoustic waves reflection during inclined incidence on the boundary of paratellurite crystal", *Acoustical Physics*, vol. 65(6), pp. 740-750, 2019.