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Acousto-Optic Cell Based on Paratellurite Crystal with Surface Excitation of Acoustic Waves

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Abstract—An acousto-optic cell based on a paratellurite (TeO_2) crystal, in which bulk acoustic waves are excited directly from the surface due to an intrinsic piezoelectric effect in the material, has been studied. The bulk shear acoustic waves with a frequency of 50 MHz propagate along the [001] and [110] axes with a polarization along the $[\bar{1}10]$ axis. The ultrasound has been excited by a simple system of two electrodes formed on one face of the crystal. Characteristics of the acousto-optic cell have been determined and the parameters of acoustic waves have been measured at 633 nm by optical beam diffraction on the acoustic diffraction grating.

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Acousto-optic devices are now widely used in the schemes of beam control in both basic science and technology, in particular, in optics, spectroscopy, optoelectronics, optical data processing, laser technology, etc. [1–3]. Using acousto-optic modulators and deflectors, it is possible to control the amplitude, frequency, phase, polarization, and direction of beam propagation. The acousto-optic control devices are distinguished by high reliability, possibility of using fast-response electronic switches, low power of control signals, and the absence of mechanical moving units [1–4].

Presently, most of acousto-optic devices are based on paratellurite (tellurium dioxide, TeO_2) crystals, which are characterized by a very high acousto-optic efficiency that is determined by the acousto-optic figure of merit that reaches a maximum value of $M_2 = 1200 \times 10^{-15}$ s^3/kg in a circularly polarized light and decreases to $M_2 = 790 \times 10^{-15}$ s^3/kg in a linearly polarized light [1–3]. The acousto-optic deflectors and filters employ slow shear acoustic waves running on the $(1\bar{1}0)$ plane with a polarization along the $[1\bar{1}0]$ axis, for which record high M values are characteristic.

One of the main disadvantages of acousto-optic devices is a high cost that restricts their increasing application in science and technology. The high cost is related to significant expenditures for manufacturing piezoelectric transducers and difficulties encountered in ensuring a broadband acoustic contact between the transducer plate and a crystal [2, 3]. In particular, the creation of high-frequency transducers involves a stage of manual mechanical polishing that cannot be automated and is accompanied by high percentage of rejects, which strongly increases the cost of acousto-optic devices.

This Letter describes an acousto-optic cell based on a TeO_2 crystal, in which no traditional piezoelectric transducer is employed and the acoustic waves are excited directly in the crystal by means of an intrinsic (reverse) piezoelectric effect in paratellurite. The study was aimed at generating and characterizing a slow shear acoustic wave that propagates along the [110] axis with a polarization along the $[\bar{1}10]$ axis. Acoustic waves on this and close types are frequently employed in acousto-optic devices [1–3].

An advantage of the proposed acousto-optic cell is simplicity of the manufacturing technology. First, a parallelepiped of required orientation is cut out of the initial paratellurite crystal and one face is cut at a preset angle φ (Fig. 1a) to provide for a desired transformation of acoustic modes. Then, metal electrodes are applied onto another face of the crystal. Evidently, the cost of manufacturing this cell is several dozen times lower compared to those of the traditional cells with traditional piezoelectric transducers in the form of thin crystalline plates.

Paratellurite crystals belong to the tetragonal system of crystallographic class 422 [1–5]. In addition to significant photoelasticity, crystals of this class also exhibit electro-optic as well as direct and reverse piezoelectric effects [4]. Unfortunately, the piezoelectric effect in paratellurite crystals is weaker than, e.g., in lithium niobate crystals [5]. Nevertheless, it was suggested [6] that bulk acoustic waves can be excited from the surface of a paratellurite crystal. Zadorin et al. [7] reported on the generation of ultrasound by a surface interdigital transducer in a direction close to

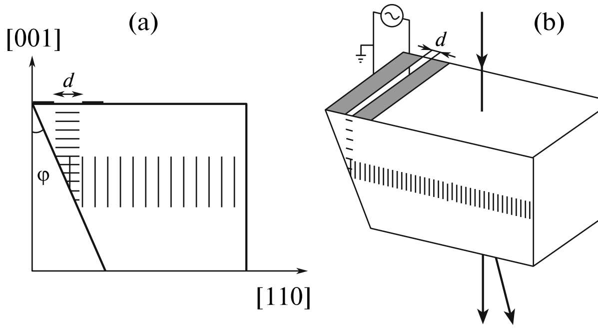

Fig. 1. Acousto-optic cell based on a paratellurite crystal with metal electrodes for ultrasound excitation: (a) scheme of sound propagation and reflection; (b) scheme of electric control and light rays diffracted on acoustic waves.

[110] axis of the crystal. Previously, we observed [8] piezoelectric resonances during acousto-optic variation of Bragg synchronism frequency in an acousto-optic filter based on a paratellurite crystal. All those investigations proved the principal possibility of exciting bulk ultrasonic waves from the surface by means of an intrinsic (reverse) piezoelectric effect. The present experimental study demonstrated the surface excitation of bulk ultrasonic waves in a paratellurite crystal with the aid of a simple system of two electrodes. Figure 1b shows a scheme of the proposed cell and the arrangement of electrodes. This cell can be used as an acousto-optic deflector or tunable filter.

The matrix of piezoelectric moduli d_{ij} of a paratellurite crystal contains two nonzero elements, d_{14} and d_{25}. Accordingly, the application of an arbitrary electric field $\mathbf{E} = (E_1, E_2, E_3)$ to the crystal gives rise to a dimensionless elastic deformation with components $S_4 = d_{14}E_1$ and $S_5 = -d_{14}S_2$. As s known, these deformations correspond to shear acoustic wave modes [1–4].

Calculations show that the application of an alternating electric field to a paratellurite crystal in the [110] direction leads to the appearance of two waves that propagate along the Z axis with mutually orthogonal polarizations along the Y and X axes. Since the Z axis in crystals of the tetragonal system is the fourth-order symmetry axis and, hence, an acoustic axis, it can be expected that of the two waves propagating in the crystal with identical velocities and frequencies would generate a resultant wave polarized along the $[\bar{1}10]$ axis.

It should be noted that a $[\bar{1}10]$-polarized shear acoustic wave that propagates in paratellurite along the Z axis at a velocity of V_{001} =2103 m/s is not used in acousto-optic cells because of a low acousto-optic figure of merit of this material. However, using oblique incidence and subsequent reflection of this wave from a crystal face, it is possible to covert this wave without losses into a slow shear acoustic wave that propagates

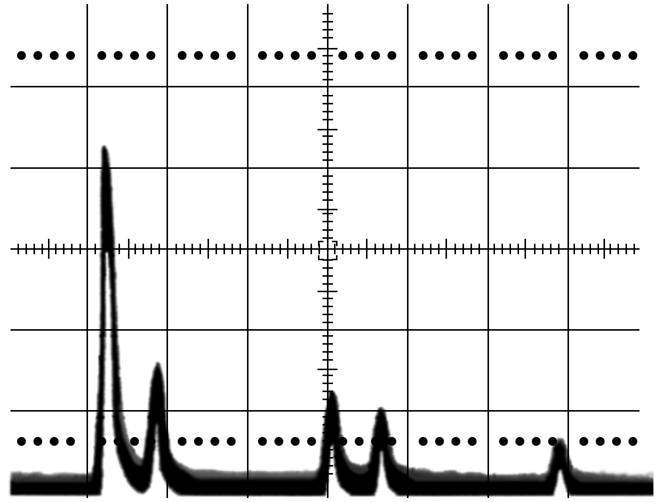

Fig. 2. Typical pattern of acoustic pulses in a paratellurite crystal monitored at a wavelength of 633 nm (abscissa scale, 15 μs/div).

along the [110] axis at a velocity of $V_{110} = 616$ m/s and is polarized along the $[\bar{1}10]$ axis. Note that the diffraction of light on this acoustic mode corresponds to the maximum acousto-optic figure of merit of paratellurite. The angle φ of the crystal face slope that ensures propagation of the reflected wave along the [110] axis is determined from the following relation:

$$\varphi = \arctan(V_{110}/V_{001}) = \arctan 0.293 = 16°20'. \quad (1)$$

Figure 1 shows an acousto-optic cell that was manufactured from a paratellurite crystal in accordance with the above theoretical considerations. The cell appears as a cube with an edge length of about 1.0 cm, with one face cut at an angle of φ, and two metal electrodes deposited onto a face perpendicular to the Z axis. The electrodes had a width of l = 0.6 cm, a spacing of d = 0.03 cm, and a preset orientation in the (001) plane.

The cell was excited by an alternating electric field with a frequency of f = 50 MHz that was applied using the electrodes on the paratellurite crystal face. In order to increase the efficiency of acoustic wave excitation, the electrical parameters of the acousto-optic cell were matched with the output of a high-frequency voltage generator. An equivalent electric scheme of the system of sound excitation in the crystal represents parallel-connected effective capacitor and resistor. The reactive component of the impedance was compensated and the active resistance was converted using an autotransformer scheme of signal transfer from the generator to load.

The metal electrodes were oriented on the crystal face so that the electric field would be directed along the [110] axis. According to the above theoretical considerations, a shear acoustic wave is excited in the interelectrode gap on the crystal surface and propagates along the Z axis with a polarization along the $[\bar{1}10]$ axis. The wave is incident onto the side face of the crystal, which is oriented at an angle of $\varphi = 16°16'$ relative to the Z axis (Fig. 1a). The reflection of the wave from this face was not accompanied by any loss of the acoustic power and did not change the acoustic mode polarization direction. Accordingly, the wave vector of the reflected sound was oriented in the $(1\bar{1}0)$ plane close to the [110] axis.

Radiation of a He–Ne laser with a wavelength of $\lambda = 633$ nm was incident onto the surface of the acousto-optic cell at the Bragg angle (i.e., approximately parallel to the Z axis) as depicted in Fig. 1b. A diffraction pattern observed at the cell output consisted of the interference maxima of the +1 and –1 diffraction orders. At a control electric signal power of $P = 1.0$ W, the diffraction efficiency was about 1%. A complexity of the acoustic wave field in the crystal hindered exact determination of the efficiency of the electric to acoustic power conversion in the system. However, approximate evaluation showed that this conversion coefficient was on an order of 1%. Using the angle of deviation of the diffracted laser radiation, the acoustic wave velocity was evaluated at $V_2 = 623 \pm 5$ m/s. A relatively low experimental value of the acoustic wave velocity shows evidence that the excited wave represents a slow acoustic mode propagating in a direction that is close to the [110] axis. It should be also noted that the estimated velocity almost coincides (to within the experimental error) with the anticipated value of $V_2 = 616$ m/s.

Figure 2 shows the general pattern of acoustic pulses as monitored in the first diffraction order by an oscilloscope at a photodetector output. The oscilloscope sweep scale was 15 μs per division. the laser beam passed through the crystal at a distance of 0.4 cm from the inclined crystal face. An analysis of the observe pattern and evaluation of the delay times between pulses convincingly confirm the fact that the acoustic waves were excited in the crystal in accordance with the theoretical predictions. The obtained experimental value of the acoustic wave velocity shows that the angle of deviation of the acoustic wave vector in the $(1\bar{1}0)$ plane does not exceed $\alpha = 2.5°$. this implies that the proposed cell can be used as a prototype of the acousto-optic deflector or filter [1–4, 9, 10].

Thus, the results of our theoretical analysis and experimental investigation show that slow shear bulk acoustic waves in a direction close to the [110] axis can be generated from the surface of a paratellurite crystal using a system of two closely spaced electrodes. Evidently, by merely varying the sample crystal cut angle (i.e., by controlling the angle of inclination of the side crystal face), it is possible to ensure the excitation of ultrasonic weave in the $(\bar{1}10)$ plane at small angles relative to the [110] direction [1–4]. These acoustic waves are most interesting for use in acousto-optic devices such as deflectors and tunable filters.

REFERENCES

1. V. I. Balakshii, V. N. Parygin, and L. E. Chirkov, *Physical Principles of Acoustooptics* (Radio i Svyaz', Moscow, 1985) [in Russian].
2. J. Xu and R. Stroud, *Acousto-Optic Devices* (Wiley, New York, 1992).
3. A. Goutzoulis and D. Pape, *Design and Fabrication of Acousto-Optic Devices* (Marcel Dekker, New York, 1994).
4. A. Yariv and P. Yeh, *Optical Waves in Crystals* (Wiley, New York, 1984.)
5. *Acoustic Crystals*, Ed. by M. P. Shaskol'skaya (Nauka, Moscow, 1992) [in Russian].
6. V. A. Krakovskii, Izv. Vyssh. Ucheb. Zaved., Fiz., No. 1, 8 (1997) [Russ. Phys. J. **40**, 6 (1997)].
7. A. S. Zadorin, L. Ya. Serebrennikov, and S. N. Sharangovich, Avtometriya, No. 1, 13 (1991).
8. V. B. Voloshinov, D. B. Skripkin, and N. Gupta, Opt. Spektrosk. **85**, 833 (1998).
9. V. B. Voloshinov and N. V. Polikarpova, Appl. Opt. **48** (7), C55 (2009).
10. V. Ya. Molchanov, V. B. Voloshinov, and O. Yu. Makarov, Kvantovaya Elektron. (Moscow) **39**, 353 (2009) [Quant. Electron. **39**, 353 (2009)].

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