Acousto-Optics and Applications

Acousto-Optic Characteristics in Media with Strong Acoustic Anisotropy

A.S. Voloshin and V.I. Balakshy*

Faculty of Physics, Moscow State University, Leninskiye Gory, 119991 Moscow, Russia

Calculations of acousto-optic diffraction spectrum are fulfilled on the basis of modified Raman–Nath equations which take into consideration the acoustic energy walk-off. It is shown that, depending on acousto-optic interaction geometry, the walk-off can change essentially angular and frequency ranges of the interaction. Coefficients of broadening are put in practice as characteristics of the walk-off influence. The calculations are carried out for 5° crystal cut of a paratellurite crystal in wide ranges of ultrasound frequencies and Bragg angles.

DOI: 10.12693/APhysPolA.127.60

PACS: 78.20.hb, 42.79.Jq

1. Introduction

In modern acousto-optics, crystals are employed predominantly as a medium of acousto-optic (AO) interaction. Many of them are distinguished by uniquely strong optical and acoustic anisotropy, such as paratellurite (TeO_2), tellurium (Ňe), calomel (Hg_2Cl_2), etc. Paratellurite is a basic material for fabrication of AO devices for visible and IR spectral ranges. This crystal demonstrates very strong acoustic anisotropy; the acoustic energy walk-off angle reaches 74° [1, 2]. This anisotropy leads to new effects in AO interaction, changing its angular, frequency and spectral characteristics. These effects are not studied in a proper way, although one may expect that they will allow us to reach better characteristics of AO devices. There are only a few papers devoted to this problem [3–5]. The present research is focused on extensive examination of acoustic walk-off influence on AO characteristics in a paratellurite single crystal.

2. Theoretical basis

The problem of the AO interaction in media with strong optic and acoustic anisotropy has been solved as a general problem of light diffraction on a slanted sinusoidal phase grating [5–7]. Modified Raman–Nath equations have been obtained to describe interaction of light and ultrasound in any diffraction regime (Raman–Nath, Bragg or intermediate); they are valid for both isotropic and anisotropic diffraction. These equations were used at numerical calculations of frequency, angular and spectral characteristics of AO interaction for various types of AO light scattering (arbitrary geometry, isotropic and anisotropic diffraction).

In the case of the Bragg diffraction regime, the geometrical interpretation of AO interaction is based on the following vector relationship which results from the Raman–Nath equations:

$$\boldsymbol{k}_1 = \boldsymbol{k}_0 + \boldsymbol{K} + \boldsymbol{\eta}_0, \tag{1}$$

where $\boldsymbol{k}_0$ and $\boldsymbol{k}_1$ are the wave vectors of the incident and diffracted light, $\boldsymbol{K}$ is the sound wave vector and $\boldsymbol{\eta}_0$ is the mismatch vector oriented orthogonally to the boundaries of the acoustic beam. The length of the mismatch vector determines the +1st order diffraction efficiency; the longer this vector, the lower is the scattered light intensity.

3. Peculiarities of AO interaction in paratellurite

Paratellurite was chosen for investigation because of its unique properties and wide applications for fabrication AO devices [8]. Most these devices use crystal cuts with AO interaction plane $(1\bar{1}0)$, when the sound vector $\boldsymbol{K}$ of the slow shear wave forms the angle χ with the (001) crystallographic plane. The cut angle $\chi = 0°$ is characterized by exceptionally high AO quality $M = 1200\times10^{-18}$ c^3/g. However, due to strong acoustic anisotropy, the acoustic field in this case appears to be very non-homogeneous [2]. For eliminating this drawback, skew crystal cuts are usually applied. Then, the acoustic beam proves to be sufficiently homogeneous, but the energy walk-off appears.

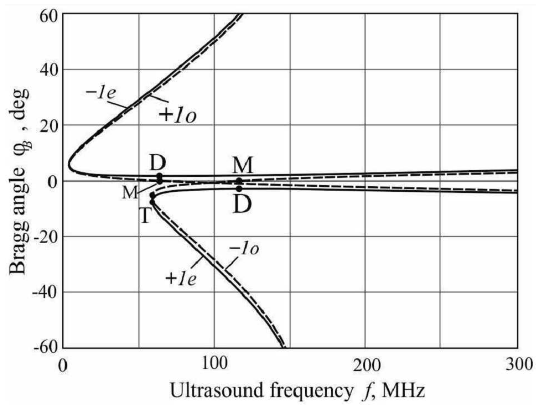

Fig. 1. Frequency dependence of Bragg angles in the case of anisotropic diffraction in paratellurite crystal: +1o — diffraction of an o-wave into +1st order; +1e — diffraction of an e-wave into +1st order; –1o — diffraction of an o-wave into –1st order; –1e — diffraction of an e-wave into –1st order.

*corresponding author; e-mail: balakshy@phys.msu.ru

Below we present calculations of AO anisotropic diffraction for the crystal cut with $\chi = 5°$ characterized by the walk-off angle $\alpha = 40.5°$. The dependence of the Bragg angles ϕ_B on the ultrasound frequency f for the optical wavelength $\lambda = 0.63$ μm is presented in Fig. 1. The calculation is fulfilled for both polarizations of incident light (o and e) and both diffraction orders (the +1st and –1st ones) in the most practically important ranges of angles and frequencies. For example, branch +1e corresponds to the anisotropic scattering of the extraordinary wave into the +1st order. Specific areas are pointed out in the curves: points T correspond to areas of tangential geometry that are used in AO videofilters, points D show areas which are optimal for deflectors and points M provide the best characteristics of modulators [8].

4. Broadening coefficient

One of the main characteristics of AO devices is the frequency characteristic, in other words, the dependence of the diffraction efficiency ς on the ultrasonic frequency f. This dependence defines the operating frequency range of AO devices and, consequently, the operation speed.

For estimating the influence of the acoustic walk-off on the frequency characteristics we introduced the broadening coefficient $B_f = \Delta f_\alpha/\Delta f_0$, where Δf_α and Δf_0 are the frequency bandwidths in the real situation and in the case of walk-off absence, respectively. Figure 2 displays the coefficients B_f as functions of the AO matching frequency f_0, i.e. the frequency for which the chosen incidence angle is the Bragg angle. The ordinate scale is chosen in the reverse direction. The dependences have a complicated character. Acoustic anisotropy can both increase ($B_f > 1$) and decrease ($B_f < 1$) the frequency range. In the calculated region, the maximal broadening has proved to be $B_f \approx 2$ at the Bragg angle $\phi_B = -60°$ for branches +1e and –1o. The narrowing reaches $1/B_f = 7.8$ times for branches –1e and +1o at the Bragg angle $\phi_B = +42°$. With increasing χ the magnitudes of the broadening coefficients also increase. For example, the crystal cut with $\chi = 10.5°$ gives $1/B_f = 17$ times. This effect is caused by joined action of two reasons: (1) change of the mismatch vector $\boldsymbol{\eta}_0$ direction due to the walk-off and (2) change of the optical path length in the slanted acoustic beam.

The value $B_f = 1$ means that the acoustic energy walk-off does not impact the AO interaction bandwidth. This situation is possible only for the +1e and –1o branches. It corresponds to close points: $\phi_B = -22.2°$, $f_0 = 83$ MHz for the +1e branch and $\phi_B = -21.2°$, $f_0 = 85$ MHz for the –1o branch. The peculiarity revealed becomes understandable from the vector diagrams in Fig. 3 constructed according to Eq. (1) for the Bragg angle $\phi_B \approx -20°$. The scheme scale is distorted purposely to make the diagram view more clear. The diagram corresponds to the case when the e-polarized incident wave is scattered into the +1st diffraction order. Here the vector $\boldsymbol{\eta}_0^{(0)}$ represents the mismatch that would be, if the walk-off is absent. The direction of this vector is orthogonal to the wave vector $\boldsymbol{K}$. The mismatch vector $\boldsymbol{\eta}_0^{(\alpha)}$ depicts the real situation with the walk-off angle α. This vector is perpendicular to the boundaries of the acoustic beam and forms the angle α with the vector $\boldsymbol{\eta}_0^{(0)}$. At the angle $\phi_B \approx -20°$ these two vectors have the same length and, in consequence of this feature, the frequency ranges Δf_α and Δf_0 have equal values. Geometry of AO interaction in the paratellurite cell is depicted in Fig. 4. It should be noticed that the points, where the acoustic walk-off does not influence AO characteristics, are determined by the crystal cut and, in more general sense, by acoustic and optical anisotropy of a concrete crystal.

Comparing Figs. 1 and 2, one can note their astonishing similarity despite the fact that the value B_f, that is plotted along the vertical axis, characterizes acoustic

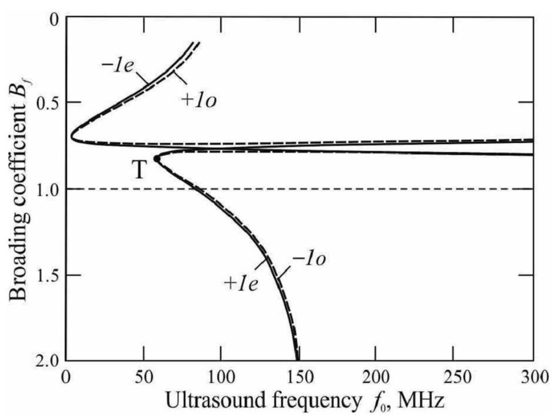

Fig. 2. Broadening coefficients as functions of acoustic frequency: +1o — diffraction of an o-wave into +1st order; +1e — diffraction of an e-wave into +1st order; –1o — diffraction of an o-wave into –1st order; –1e — diffraction of an e-wave into –1st order.

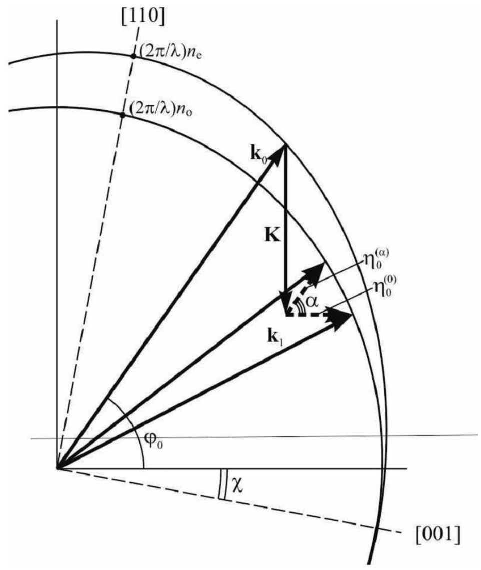

Fig. 3. Wave vector diagram illustrating the case, when the acoustic walk-off does not influence AO characteristics.

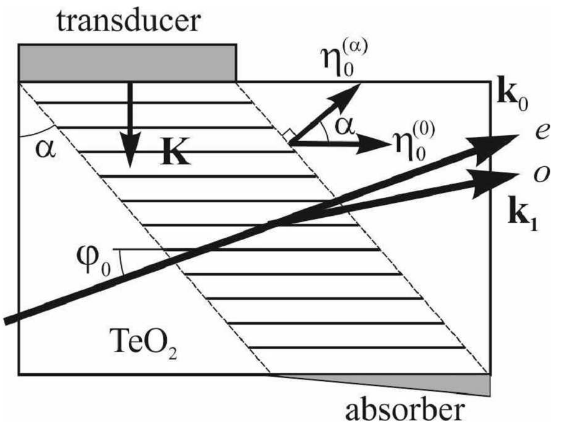

Fig. 4. Geometry of light and sound beams interaction in the paratellurite cell.

anisotropy influence and has no relevance to the Bragg angles. One can suppose that this similarity is caused indirectly by optical anisotropy (shape of the refractive indices surface). At the same time, we see some distinctions. In the tangential regions, the curves for o and e polarizations do not cross; they only touch each other. Besides, they have the inverted location in the region of small Bragg angles in comparison with Fig. 1.

Another interesting and unexpected peculiarity was revealed at calculation of angular characteristics, i.e. the dependence of the diffraction efficiency ς on the incidence angle ϕ_0. It has been established that the dependences $B_\phi(f_0)$ coincide with $B_f(f_0)$ not only qualitatively, but quantitatively as well (within limits of computation accuracy). This is astonishing because the angular and frequency characteristics have substantial differences.

5. Conclusions

In this work, the Bragg diffraction of light on a sinusoidal phase grating induced in an anisotropic medium by an acoustic wave has been studied for the case of a large acoustic energy walk-off. This kind of diffraction is typical for a number of crystals, in particular, for paratellurite which is widely used in modern acousto-optics.

Modified Raman–Nath equations are derived that determine light scattering in cases of both isotropic and anisotropic diffraction. It is shown that the acoustic walk-off can significantly alter characteristics of AO interaction. Broadening coefficients B_f and B_ϕ are introduced which describe the change in the width of frequency and angular ranges.

Calculation of the broadening coefficients has been carried out for 5° cut of a paratellurite single crystal in wide ranges of the Bragg angles and acoustic frequencies for different polarizations of the incident light. Subject to the crystal cut, acoustic frequency and incident light polarization the coefficients B can take values more or less than unity, demonstrating thereby effects of broadening or narrowing the AO interaction ranges. Numerical calculations have shown that the influence of the acoustic walk-off at anisotropic diffraction is not vanishingly small; this effect can change the AO interaction range several times. Thus, our research has shown that the acoustic walk-off should be taken into consideration when designing AO devices.

Acknowledgments

This study was supported by the Russian Scientific Fund, project 14-22-00042.

References

[1] J.-C. Kastelik, M.G. Gazalet, C. Bruneel, E. Bridoux, *J. Appl. Phys.* **74**, 2813 (1993).

[2] V.I. Balakshy, S.N. Mantsevich, *Acoust. Phys.* **58**, 549 (2012).

[3] A.V. Zakharov, V.B. Voloshinov, E. Blomme, *Ultrasonics* **51**, 745 (2011).

[4] J.-C. Kastelik, S. Dupont, K.B. Yushkov, J. Gazalet, *Ultrasonics* **53**, 219 (2013).

[5] V.I. Balakshy, A.S. Voloshin, *Opt. Spectrosc.* **110**, 788 (2011).

[6] H. Kogelnik, *Bell Syst. Techn. J.* **48**, 2909 (1969).

[7] E.N. Glytsis, T.K. Gaylord, *J. Opt. Soc. Am. A* **7**, 1399 (1990).

[8] V.I. Balakshy, V.N. Parygin, L.E. Chirkov, *Physical Principles of Acousto-Optics*, Radio i Svyaz, Moscow 1985 [in Russian].