Influence of Paratellurite Anisotropy at the Characteristics of Acousto-optic Interaction

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Abstract

The results of paratellurite acoustic and acousto-optic anisotropy influence on the characteristics of acousto-optic diffraction. The examination was carried for the (110) crystallographic plane. The distribution of acousto-optic figure of merit was calculated. Also the structure of acoustic beams aroused by the transducers of various sizes at different frequencies was simulated. It is shown that media anisotropy influences the acousto-optic device transfer functions significantly.

Keywords: Acousto-optic interaction, anisotropy, transfer functions, acoustic field structure

1. Introduction

Acousto-optic devices characteristics usually don’t match with those obtained by solving the acousto-optic (AO) diffraction problem in classical approach, as interaction of plane light and acoustic waves. The fact that AO interaction occurs between wave beams is the reason of such discrepancy. Inhomogeneity of interacting beams affects mostly the AO diffraction efficiency.

To date large part of AO devices is being fabricated from paratellurite crystal. It is well known that TeO₂ crystal has extremely great anisotropy of acoustic and acousto-optic properties [1-3]. The highest difference in paratellurite acoustic properties is observed in XY crystallographic plane [1]. However this plane is not used in acousto-optics.
Different cuts in \((1\bar{1}0)\) plane are applied for AO devices fabrication most frequently. In this case acoustic anisotropy is not so great but achieves substantial value.

The examination of light diffraction by an inhomogeneous acoustic field is a very complicated problem. In [4] the calculations were carried considering that acoustic beam has Gaussian profile. Media acoustic anisotropy was ignored. The collinear and quasiorthogonal light diffraction in inhomogeneous acoustic field for acousticallyotropic and anisotropic media was examined in [3].

Another type of AO interaction, namely quasicollinear geometry in paratellurite, was examined in [5]. Recently, quasicollinear AO devices became widely used in laser techniques [6,7]. Parameters of these devices are determined by the anisotropy of elastic properties of crystals. The asymmetry of transmission function because of acoustic anisotropy in quasicollinear AO filters was studied fragmentary. The transmission function asymmetry may be also caused by the peculiarities of AO filter transfer function transformation caused by AO figure of merit properties [8]. We examine the influence of paratellurite anisotropy on the characteristics of quasicollinear AO diffraction.

2. \(\text{TeO}_2\) crystal acoustic anisotropy

Paratellurite crystal \((1\bar{1}0)\) plane is widely used in acousto-optics. It is well known that \(\text{TeO}_2\) has high anisotropy of acoustic properties in this plane producing in particular huge acoustic energy walk-off. We will determine the magnitude of crystal anisotropy in the given direction by introducing the coefficient \(\kappa\) defined as a ratio of acoustic beam divergence in presence \(\Delta\) and in absence \(\delta\) of media acoustic anisotropy [3]:

\[
\kappa = \frac{\Delta}{\delta}
\]

where \(\delta = 2\Lambda/l = 2V/lf\), \(\delta = 2\Lambda(l=2Vfl)\), \(\Lambda\) is the acoustic wavelength, \(l\) – piezoelectric transducer length, \(V\) – acoustic wave velocity, \(f\) – ultrasound frequency. Fig. 1 presents the dependences of \(\kappa\) coefficient and acoustic walk-off angle \(\psi\) on the polar angle \(\theta_0\) in \((\bar{1}10)\) paratellurite crystal plane calculated for \(l=4\)mm and \(f=40\)MHz.

Angle \(\theta_0\) defines the acoustic beam spatial spectrum central component propagation direction and is counted from the crystallographic axis Z. Curve 1 shows the alteration of walk-off angle in \((1\bar{1}0)\) plane. Curve 2 – anisotropy coefficient in \((1\bar{1}0)\) and curve 3 – anisotropy coefficient in the planes orthogonal to the \((1\bar{1}0)\) plane. Acoustic anisotropy appearance causes the distortion of acoustic beam amplitude and phase in crystal. Such distortion affects the Bragg interaction conditions and therefore the shape of AO device transmission function [9,10]. There are several manifestations of transmission function shape distortion. First – pass band widening, caused by acoustic field phase inhomogeneity. Phase distribution affects the phase matching conditions for separate spectral components of interacting acoustic and light beams. The widening may be also accompanied with pass band shift. Second – the reduction of AO interaction diffraction efficiency. This effect is caused by acoustic energy spatial repartition in ultrasound beam. The third factor is the appearance of transmission function asymmetry and function.

![Fig. 1. The dependences of \(\kappa\) coefficient and acoustic walk-off angle \(\psi\) on the polar angle \(\theta_0\) in \((\bar{1}10)\) paratellurite crystal plane.](image-url)
side lobes growth. The last effect has negative consequences for the application of AO devices in spectral analysis as side lobes allows the undesirable spectral components to pass through the AO filter.

\[ a(x, z) = \left( \frac{\Omega}{2\pi} \right)^2 \int_{-\pi}^{\pi} A_n(\phi) \times \left[ S^2 + S\left( \phi \frac{\partial S}{\partial \phi} \right) \right] \times \exp \left\{ -j\Omega \left[ \phi z + \left( 1 - \frac{\phi^2}{2} \right) x \right] \right\} d\phi \]  

(2)

here \( \phi \) is the small angle being measured from the acoustic beam spatial spectrum axial component in \((1\bar{1}0)\) plane, \( A_n(\phi S) \) – acoustic disturbance angular spectrum on the media input, \( \Omega = 2\pi f \) - ultrasound frequency, \( S(\phi) \) - acoustic slowness.

Acoustic beams amplitude and phase structure for various transducer dimensions, ultrasound frequencies and crystal cut off angles were simulated using equation (3). The simulation is illustrated by Fig. 2. The acoustic beam propagating in \((1\bar{1}0)\) plane amplitude structure is presented in Fig.4a. Here the 1mm transducer is located in the left corner of the picture; acoustic wave magnitude is displayed by colour. Acoustic field structure is simulated in the 1x2 cm area, ultrasound frequency \( f = 20\text{MHz} \), cut angle \( \alpha = 2^\circ \). In this case acoustic walk-off \( \psi = 20.2^\circ \) and anisotropy coefficient \( \kappa = 10 \). With these parameters far-field diffraction is observed at the small distances from the transducer.

Fig. 2b shows the beam amplitude structure in cross sections disposed at various distances from piezoelectric transducer. The dependences 1-3 match to the lines 1-3 in Fig. 2a. All curves correspond to the acoustic beam far-field diffraction. Also it is possible to notice the asymmetry for cross sections 2 and 3. This effect is produced by specific asymmetric shape of slowness surface for the slow acoustic mode in \((1\bar{1}0)\) plane and large derivative \( d\psi/d\theta \). In the presented case various components of acoustic beam spatial spectrum propagate at significantly different angles, deforming the acoustic beam.

![Fig. 2. a – acoustic beam amplitude structure for 1mm transducer \( f = 20\text{MHz}, \alpha = 2^\circ \); b – acoustic beam amplitude cross sections corresponding to the 1-3 lines in Fig.2a](image1)

3. Quasicollinear acousto-optic interaction

One of important problems modern acousto-optics face with is the creation of the devices high spectral resolution. This means that the pass band of such devices should be as narrow as possible. The primary method of pass band reduction is the increase of AO interaction length. It is possible to realize this variant in paratellurite by using quasicollinear geometry of AO interaction [7-9] with small crystal cut angles \( \alpha \). But as follows from the fig.1 the smaller is the \( \alpha \) angle the higher is the acoustic anisotropy, consequently the stronger is the influence of media acoustic anisotropy influence at the transmission function shape.

Fig. 3 presents the wave vector diagram corresponding to Fig.2 geometry when AO interaction phase matching condition is fulfilled. Here \( n_o \) and \( n_e \) are the refraction indexes for ordinary and extraordinary light waves, \( K \) - ultrasound wave vector, \( k_i \) and \( k_d \) – incident and diffracted light wave vectors correspondingly.
The phase mismatch $\eta$ appearing when AO phase matching conditions are violated is directed along $k_d$ and defined by the following equation (3). Hereinafter we use dimensionless mismatch $R = \eta l$.

$$\eta = K \cos \psi - k_i + \sqrt{k_i^2 - K^2 \left(1 - \cos^2 \psi \right)}$$

(3)

4. Conclusions

In this paper, we have analyzed peculiarities of quasico-linear light diffraction in paratellurite crystal in an inhomogeneous acoustic field of a piezoelectric transducer. The evaluations were based on the solution of acoustic beams propagation problem for anisotropic media (2). It was shown that paratellurite acoustic anisotropy in $\{1\overline{1}0\}$ plane causes the acoustic beam magnitude distribution asymmetry appearance in the cross section due to the shape of acoustic slowness surface shape in this plane. Acoustic field inhomogeneous structure influences significantly the quasico-linear AO filter transmission functions. In acts on the diffraction efficiency in the first place making impossible to reach 100% efficiency. Moreover the higher acoustic power is needed to reach maximal possible efficiency when acoustic field has complicated structure. Acoustic field inhomogeneity may also slightly affect the filter pass band broadening and phase matching conditions shift. In general it is possible to conclude that acoustic anisotropy influence on the AO diffraction characteristics for quasico-linear geometry is stronger than for collinear but weaker than for quasiorthogonal AO interaction

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References