Optic, acoustic and acousto-optic properties of tellurium in close-to-axis regime of diffraction

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Abstract
We examined the optic, acoustic, photoelastic and acousto-optic (AO) properties of single crystal tellurium. We also determined the Bragg angle dependences on the acoustic frequency at 10.6 μm. The phenomenon of optical activity and its influence on the Bragg matching condition during anisotropic diffraction near the optic axis of the crystal are discussed in detail. Based on the results of our calculations, we designed, fabricated and characterized an AO cell to determine parameters of the anisotropic interaction with longitudinal acoustic waves propagating along the X axis in the crystal. In our experiments, we also measured the value of one of the important photoelastic coefficient in tellurium, \( p_{41} = 0.14 \pm 0.01 \) and demonstrated that this coefficient determines the efficiency of the anisotropic diffraction in the employed geometry.

1. Introduction

The acousto-optic (AO) effect is widely used to control the parameters of electromagnetic radiation. The AO devices such as filters, modulators and deflectors are used in optics, laser technology, spectroscopy, telecommunication systems and optical information processing [1–4]. These no-moving-parts devices provide high speed operation with relatively low applied power and optical loss. Such AO devices have been widely used in many spectral regions including the ultraviolet, visible and near and middle infrared (IR). At present, single crystal tellurium dioxide (TeO₂) is the most widely used crystal in these devices because of its high AO figure of merit, \( M_2 = 1200 \times 10^{-15} \text{s} \text{kg}^{-1} \) [1–3]. Such a high value of \( M_2 \) in paratellurite has spurred the development of a variety of AO devices that require a low driving power [1, 2]. Since paratellurite crystal is not transparent at wavelengths longer than 4.5 μm it cannot be used in the devices operating at such wavelengths, i.e., in the longer IR region.

IR AO devices can be designed and fabricated in both optically isotropic and anisotropic materials. The optically isotropic crystals germanium (Ge) and KRS-5 have been used in the IR AO [1–3]. However, it is well known that efficient AO devices can only be developed using birefringent crystals, such as crystalline tellurium (Te) as well as chemical compounds of thallium and mercury. Tl₃AsSe₅, calomel (Hg₂Cl₂), mercursic bromide (Hg₄Br₂) and iodide (Hg₂I₂), have been used in modulators, deflectors and filters [4–10]. In the AO literature, the acoustic, optic and AO properties of Te have been examined in detail since the material was considered as one of the most promising for applications in the longer IR wavelengths [11–22]. In particular, we published a few papers in which we summarized results of our theoretical and experimental investigation of the anisotropic diffraction regime in Te crystal [17–22]. These results showed that an extremely high value of \( M_2 \) in Te may only be obtained if the optical radiation propagates in the far-off-axis direction in the material. However, the crystal is not transparent to the extraordinary polarized light propagating at wide angles relative to the optic axis [19]; therefore, this AO interaction geometry is not suitable in designing AO devices despite its extremely high \( M_2 \). This drawback may be overcome by the use of efficient Te-based glasses [23].
Using an AO interaction geometry in Te where light propagates close to the Z axis or at narrow angles with respect to the optic axis, avoids the low transparency scenario [20–22]. In this interaction geometry, the photoelastic coefficient \( p_{41} \) is a key factor. In the literature, the value of this coefficient, \( p_{41} \), was listed as 0.28, which is 1.5–2 times larger than the values for the other photoelastic constants in the crystal [13–16]. Therefore, use of a diffraction geometry dependent on the coefficient \( p_{41} \) looked promising. Based on this conclusion, an imaging AO tunable filter (AOTF) was designed, fabricated and characterized [20]. The filter demonstrated quite reasonable performance in the longwave IR spectral region. However, experimental investigation of the imaging device highlighted a significant drawback in the material: the value of \( p_{41} \) is 0.14, which results in a four times lower diffraction efficiency as compared to the efficiency value predicted using \( p_{41} = 0.28 \) from the literature [14, 20].

It is worth noting that in that paper [20], the photoelastic constant \( p_{41} \) was measured at tilted direction to the propagation of the shear elastic wave with respect to crystal axes in a Te sample. Thus, the measurement cannot be considered completely reliable because the coefficient itself was not directly measured, but rather as a combination of the three photoelastic coefficients \( p_{41}, p_{14} \) and \( p_{66} \). The value of \( p_{41} \) was extracted using calculations which assumed correctness of the values of \( p_{66} = 0.013 \) and \( p_{14} = -0.04 \) [14] were correct. Unfortunately, the result obtained in that paper [20] was quite different from literature [14]. It is evident that this discrepancy makes it difficult to reliably predict the operational parameters of AO devices which restricts designs of such devices.

In the investigation discussed in this paper, we used a much simpler AO interaction geometry to determine the value \( p_{41} \) directly. A longitudinal acoustic wave was sent along the crystalline X axis of Te, while the AO interaction plane included the X and Z axes. Optical radiation was propagating in the crystal at a Bragg angle, \( \theta_i = 11^\circ \) relative to the optic axis (Z axis), thus satisfying the requirement for a close-to-optic axis propagation of light. Therefore, one of the main objectives of our investigation is to carry out direct measurement of the photoelastic coefficient \( p_{41} \). The second goal of our research is to observe the anisotropic diffraction in the wide angle AO interaction regime in Te, as this interaction regime is considered the most optimal for application in the design of imaging AOTFs. We also examined the phenomenon of optical activity [3] in Te and its influence on the interaction between light and sound.

2. Theoretical investigation of the problem

2.1. AO properties of single crystal tellurium

Single crystal Te is a single axis crystalline material belonging to the crystallographic class 32 of the trigonal syngony [1–3]. The material is transparent from 4 to 23 \( \mu m \) and its indices of refraction at 10.6 \( \mu m \) for ordinary and extraordinary polarized light are \( n_o = 4.8 \) and \( n_e = 6.25 \), respectively [11, 19]. The crystal is optically active; therefore, rotatory power in the crystal may influence AO interaction when radiation is propagating near the Z axis. This is discussed in the following sections.

We know from the theory of AO interaction that the efficiency of anisotropic diffraction, i.e., the diffraction accompanied by the change of optical modes from an ordinary to an extraordinary and vice versa, is determined by the ratio \( I_d/I_o \) of the diffracted and incident light intensities [1–3]. The AO efficiency is given by the following expression

\[
\frac{I_d}{I_o} = \sin^2 \left( \frac{\pi}{\lambda \cos \theta_i} \sqrt{\frac{M_2 P I}{2d}} \right)
\]

\[
M_2 = \frac{P_{eff}^2 n_i^2 n_d^3}{\rho V^3}
\]

where \( P_r \) is the applied acoustic power, \( P_{eff} \) is the effective photoelastic constant, \( n_i \) and \( n_d \) are the refractive indices corresponding to the incident and diffracted light, \( \rho \) and \( V \) are the density and phase velocity in the crystal, respectively, \( \theta_i \) is Bragg angle of light incidence, and \( l \) and \( d \) are the length and width of the AO column in the crystal, respectively [1–3]. According to equation (1), the diffraction efficiency depends on the value of the effective photoelastic coefficient. This effective coefficient depends on a chosen AO interaction geometry. Consequently, one must properly choose the optimal interaction geometry to specify the value of the photoelastic coefficient \( p_{41} \).

To evaluate the value of \( p_{41} \), we chose an AO interaction geometry in the XZ plane of Te with a longitudinal acoustic mode propagating along the X axis. It should be mentioned that as many as three acoustic waves propagate in the crystal in this direction: the pure longitudinal wave \( L \), and the fast FS and slow shear SS waves. All the waves are pure modes and propagate at velocities given by \( V_L = 2450 \text{ m s}^{-1} \), \( V_{FS} = 2600 \text{ m s}^{-1} \) and \( V_{SS} = 1050 \text{ m s}^{-1} \) [17, 18]. Here, we use the longitudinal wave, which is most easily launched in the crystal by means of a traditional transducer. Since the wave is a pure mode, it only induces the elastic deformation \( S_L \). This
choice of wave simplifies our experimental investigation of the diffraction because all the acoustic energy is concentrated in the longitudinal mode, providing direct evaluation of the photoelastic effect. In our previous paper [20], we could not take advantage of this kind of direct measurement.

Propagation of the longitudinal acoustic wave along the X axis induces the following changes in the optical indicatrix [1–3]:

\[
x^2 \left( \frac{1}{n_x^2} + p_{11} S_1 \right) + y^2 \left( \frac{1}{n_y^2} + p_{12} S_1 \right) + z^2 \left( \frac{1}{n_z^2} + p_{31} S_1 \right) + 2 y z p_{41} S_1 = 1,
\]

where \( p_{ij} \) are the photoelastic coefficients of Te.

As seen in equation (2), the longitudinal acoustic mode allows us to observe in the XZ plane of Te the isotropic as well as anisotropic light diffraction, because the first three terms in equation (2) correspond to the isotropic diffraction while the fourth term is responsible for the anisotropic interaction. Using equation (2), we found that the value of the effective photoelastic coefficient in the anisotropic diffraction geometry is described by the following expression [1, 2]:

\[
P_{\text{eff}} = p_{41} \sin \theta_i.
\]

The above expression shows that the anisotropic interaction is the most efficient if light propagates along the X axis when \( \theta_i = 90^\circ \), while the isotropic diffraction is the most efficient at close to the axis light propagation. In the latter case, the effective photoelastic coefficients are \( p_{11} \cos \theta_i \) and \( p_{12} \cos \theta_i \). On the other hand, data in [19] showed that strong absorption of light propagating far away from the Z axis makes this interaction geometry ineffective for AO applications. Moreover, equation (3) demonstrates that anisotropic interaction does not exist if light propagates strictly along the Z axis at \( \theta_i = 0^\circ \). That is why we want to examine the anisotropic diffraction when the optical propagation is at relatively small angles, \( \theta_i = 4^\circ – 11^\circ \), with respect to the optic axis.

A wave vector diagram of the anisotropic diffraction in the XZ plane of Te illustrating known vector relation \( k_i + K = k_d \) is shown in figure 1, where \( k_i, k_d \) and \( K \) are the wave vectors for the incident light, diffracted light and the ultrasound wave, respectively [1, 21, 22]. This is the AO interaction geometry examined theoretically and experimentally in this paper.

2.2. Influence of optic activity on parameters of diffraction in tellurium

We note that analysis of dependence of the Bragg angle on the acoustic frequency for optical wave propagation for \( \theta_i < 5^\circ \) should be carried out by taking into consideration the optical activity. The optical activity is the phenomenon of polarization rotation if an optic beam is propagating in a liquid or a crystalline medium [3]. The magnitude of the optical activity, i.e., rotatory power \( P_R \) characterizes the angle of rotation of the polarization.
plane per unit length of the optical path in a material. With single crystal Te, the value of the rotatory power along the Z axis at 10.6 μm is 16° mm−1 [3].

Next, we present the results of our analysis related to the optical activity in Te and its influence on acoustic frequency dependence of the Bragg angles. Since the effect in the crystal is local and very small, its influence on the absolute values of the indices of refraction is not large. Thus, we examine the optical activity in Te crystal in comparison with a hypothetical Te material which is without the rotatory power. Based on the vector diagram in figure 1, we calculated the acoustic frequency dependence of the Bragg angle, θ(f), for the case of ordinary polarized light in the hypothetical crystal. The corresponding dependence illustrating the case without the optical activity is shown in figure 2 by line 1 which shows that zero acoustic frequency, f = 0, corresponds to the AO interaction along the Z axis at θ = 0. This result is due to the fact that the wave surfaces in figure 2 for the ordinary and extraordinary polarized light coincide.

The presence of optical activity indicates that the linearly polarized light propagating along the Z axis is split into two circularly polarized eigenmodes propagating with different phase velocities [3]. Thus, we have two indices of refraction for the eigenmodes along the optic axis. The difference in the indices

\[ n_d = n_r - n_l \]

is given by the expression,

\[ n_r - n_l = \left( \frac{\lambda}{2\pi} \right)^2 \left( \frac{x^2}{n_o^2} + \frac{z^2}{n_e^2} \right) \]

Since the optical activity excludes the spatial coincidence by separating the two wave surfaces and the two indices of refraction along the Z axis, we can approximate the above expressions by the following equations:

\[ \frac{x^2}{n_o^2} + \frac{z^2}{n_e^2} = \left( \frac{\lambda}{2\pi} \right)^2 \]

\[ \frac{x^2}{n_o^2} + \frac{z^2}{(n_o + \delta n)^2} = \left( \frac{\lambda}{2\pi} \right)^2 \]

In this way, we can evaluate the optical activity and take into account the rotatory power of Te in any arbitrary direction in the XZ plane of the crystal. Based on this approach, we obtained the frequency dependence of the Bragg angle on ultrasound given by curve 2 in figure 2.
The second approach is more complicated but more correct from the point of view of fundamental optics [3]. The consideration is based on the fact that the optical activity changes the tensor of the dielectric permittivity of a material \( \varepsilon_{ij} \). In particular, the activity induces, in the tensor, the gyration \( G_{ij} \) component such that \( \varepsilon_{ij}^a = \varepsilon_{ij} + iG_{ij} \) [3]. The modified dielectric permittivity tensor may then be used as the initial value to solve the Fresnel equation. Solving the Fresnel equation provides information on the indices of refraction as well as the polarization of optical waves propagating in the material along a given direction:

\[
\det \left[ \mu^2 \delta_{ik} - n_i n_k - \varepsilon_{ik}^a \right] = 0,
\]

where \( n_i \) is \( i \)-component of the refractive index along a given propagation direction and \( \delta_{ik} \) is the Kronecker delta function. In the case of optical activity along the \( Z \) axis, the gyration tensor component \( G_{12} \) is nonzero and given by \( G_{ij} = P_{jk} \lambda n_{\text{e}} / \pi \) [3], where \( n_{\text{e}} \) is the refractive index of the medium in the absence of activity. Based on the Fresnel approach, we calculated curve 3 for the Bragg angle dependence on the acoustic frequency in Te as shown in figure 2.

As seen in figure 2, the two approaches when applied to optical activity in Te have quite similar effects on the AO interaction. At small Bragg angles, \( \theta_1 \approx 1.4^\circ \), and relatively low frequencies of ultrasound, \( f < 20 \text{ MHz} \), we predict the existence of a regime of wide angle AO anisotropic interaction in the crystal [1–3, 20, 21]. This interaction is characterized by a zero derivative, \( d\phi / d\theta_1 = 0 \), common for curves 2 and 3. It means that the AO interaction may be recommended for application in the design of imaging AOTFs [20]. However, the two theoretical approaches did result in different acoustic frequencies for the wide angle Bragg matching, \( f = 18 \text{ MHz} \) and \( f = 13 \text{ MHz} \), respectively. It is necessary to note that according to the data presented in figure 2, the simplified method of analysis leads to significant errors when determining the frequencies of Bragg matching in Te. On the other hand, at \( \theta_1 > 5^\circ \), this type of analysis may be carried out without consideration of the optical activity, as shown by curves 3 and 1, which are close to each other for \( \theta_1 > 5^\circ \).

Since our analysis showed that calculating the parameters of AO interaction depends on which method of analysis is used, we experimentally tested both methods using a single crystal of TeO$_2$. As discussed in [3], this crystalline material has a very strong rotatory power, \( P_{\text{R}} = 87^\circ \text{ mm}^{-1} \), in the visible region at \( \lambda = 0.63 \text{ m} \). Our experiments in paratellurite at \( \lambda = 0.63 \text{ m} \) showed that the parameters obtained using the Fresnel equation are correct; they were quite close to those measured in the crystal. Thus, the evaluation of the diffraction parameters in this paper was carried out using the precise Fresnel approach instead of the simplified approach.

### 2.3. Choice of AO cell configuration

To examine efficiency of anisotropic diffraction in the material, we designed and fabricated an AO cell in single crystal Te. In section 2.1, we showed that the diffraction efficiency in the XZ plane of the crystal increases with the propagation angle \( \theta_1 \). We also found that the isotropic diffraction provided by the effective photoelastic coefficients \( p_{11} \cos \theta_1 \) and \( p_{12} \cos \theta_1 \) is very strong at close to zero angle propagation [18]. Consequently, we expected difficulties in observing a relatively weak anisotropic diffraction at \( \theta_1 \leq 5^\circ \) due to contribution from a strong isotropic interaction. Based on these considerations, we realized that to observe anisotropic diffraction light should propagate at an angle varying from a few to a dozen degree with respect to the optic axis in the crystal.

In a previous investigation, we fabricated an AO cell using a rectangular prism cut along the crystal’s X, Y and Z axes [22]. As mentioned earlier, the ordinary index of refraction in Te is extremely high, \( n_0 = 4.8 \); therefore, to send light at an angle of \( \theta_1 \geq 5^\circ \), we had to increase the angle of light incidence on the prism in air to more than \( 45^\circ \). This way, the condition of far-off-axis propagation of light in the experiment was satisfied [22]. However, Te has a very strong Fresnel reflection loss at the crystal–air boundary. The calculated dependence of the two reflection coefficients on the angle of incidence for the two orthogonal polarizations—parallel (denoted by \( || \)) and perpendicular (denoted by \( \perp \))—are shown in figure 3. This figure clearly shows that the two reflection coefficients strongly depend on the incidence angle [11], the value of the Brewster angle is \( 11.8^\circ \) corresponding to \( R || = 0 \), the angle for unity coefficient for either polarization is close to \( 12.02^\circ \), and at \( 10^\circ \) incidence \( R \perp = 0.62 \). The incidence angle \( \theta_1 \) is the angle between the direction of light propagation and the normal to the optical facet. These facts were not properly taken into account in our previous paper [22].

Based on the above observations, we cut a new AO cell with optical facets tilted with respect to the Z axis at an angle \( \sim 11^\circ \). The chosen configuration of the cell provided a normal incidence of light on the input facet of the crystal with light propagating at \( 11^\circ \) relative to the acoustic wave front. In this case, the reflection coefficients in the cell were \( R || = 0.42 \) for the extraordinary and \( R \perp = 0.44 \) for the ordinary polarized incident light as shown in figure 3. This means that the reflection coefficients for both optical modes were nearly equal to each other.
3. Experimental investigation of the anisotropic diffraction

The experimental setup used in our research consisted of a 10.6 μm CO₂ laser; an AO cell controlled by a signal from an RF generator and a liquid-nitrogen-cooled germanium (Ge):gold (Au) optical detector. The output signal of the detector was observed on an oscilloscope. The fabricated AO cell in Te in the form of a tilted prism is shown in figure 4(a). The crystal was cut in such a manner that its input and output optical facets were tilted in the XZ plane at an angle of 11° relative to the Z axis. This ensured off-axis propagation of the optical radiation with respect to the Z axis while minimizing the Fresnel losses at the crystal facet. Moreover, the input and output optical facets were slightly rotated at the angle \( \alpha = 3.3^\circ \) around the X axis which increased the frequency of the wide angle anisotropic interaction from 13 MHz (as shown by curve 3 in figure 2) to 39 MHz. This made it easier to carry out an experimental investigation of diffraction in the wide angle and some other AO interaction regimes with a single piezoelectric transducer.

A piezoelectric transducer fabricated of \((Y + 36^\circ)\)-cut lithium niobate crystal was attached to one of the Te facets orthogonal to the X axis. The dimensions of the transducer plate were \( l = 0.8 \text{ cm} \) and \( d = 0.3 \text{ cm} \). The transducer launched a pure longitudinal acoustic wave in the crystal along the X axis. An electric impedance matching network was used to increase the conversion efficiency of the electric energy into the acoustic wave.

![Figure 3. Incidence angle dependence of reflection coefficient at the crystal–air interface.](image)

![Figure 4. Photograph of AO cell based on Te, (a) single crystal Te and (b) the crystal with the impedance matching network.](image)
energy. The impedance matching covered the frequency range from 39 to 56 MHz. Figure 4(b) shows a photograph of the AO cell including the Te crystal and the matching network.

In the experiments, we observed the acoustic frequency dependence of Bragg angle $\theta_i$ which is shown in figure 5 by dots. In particular, we observed light in both $+1$ and $-1$ diffraction orders. Deflection of light into a $-1$ diffraction order is due to the incidence of an extraordinary polarized light beam and it is theoretical dependence is shown by curve 1 in the figure 5. Similarly, curve 2 corresponds to the ordinary polarized incident light that gets deflected into a $+1$ diffraction order. Angle $\theta_i(f)$ was measured from $4^\circ$ to $11^\circ$ over a frequency range from 39 to 56 MHz.

The frequency dependence of the Bragg angle shown in figure 5 includes data from a few different AO interaction regimes of special interest. The first interaction regime corresponds to the intersection point for the two theoretical $\theta_i(f)$ curves 1 and 2 where a simultaneous diffraction of light into a $+1$ and $-1$ diffraction order takes place. This interaction was observed at $\theta_i = 3.9^\circ$ and at $f = 40$ MHz. This regime was characterized by equal intensities of light in each of the two diffraction orders. This implies that the cell could be used as a modulator of arbitrary polarized radiation at 10.6 $\mu$m [24]. The second interaction regime observed at $\theta_i = 3.9^\circ$ and $f = 39$ MHz corresponds to a wide angle diffraction suitable for application in an imaging AOTF.
Finally, in the interaction regime corresponding to $\theta_i = 10.9^\circ$ and $f = 48.5$ MHz, we observed the maximum anisotropic diffraction efficiency for the transducer in the designed AO cell. In this interaction geometry, we also measured the acoustic power dependence of the diffraction efficiency as shown in figure 6 by dots and error bars with the measurement accuracy $\pm0.1\%$. This figure shows that the diffraction efficiency $I_d/I_0 \approx 1.1\%$ at 1.0 W acoustic power corresponding to the longitudinal acoustic mode propagation along the X axis. This result was a few times lower compared to that of our earlier paper [20]. Using equation (1), we calculated the dependence (figure 6, solid line) using the following parameters: $n_i = 4.83$, $n_\perp = 4.8$, $\rho = 6.25$ g cm$^{-2}$, $V = 2450$ m s$^{-1}$, $\theta_i = 11^\circ$, $l = 0.8$ cm and $d = 0.3$ cm. It should be noted that the best agreement between theory and experiment was obtained when the value of $p_{41}$ was found to be $0.14 \pm 0.01$. Consequently, we predict that the correct value of the photoelastic coefficient $p_{41}$ is most likely smaller than the 0.28, the value listed in the literature [14]. We also evaluated $M_2$ in the crystal using equation (1) and found it to be $\approx 100 \times 10^{-18}$ s$^3$ g$^{-1}$ which is lower than expected. We would like to highlight the two possible reasons for the lower observed value of $M_2$: a moderate value of the photoelastic coefficient, $p_{41} = 0.14$ and a small value of the Bragg angle, $\theta_i = 11^\circ$. Both these factors cause a decrease in the value of the effective photoelastic coefficient in the crystal.

4. Conclusion

We presented results of both the theoretical and experimental investigations of the AO interaction in the single crystal Te. The interaction in the XZ plane of the crystal was examined theoretically including the effect of optical activity along the optic axis of the material. Based on our theoretical analysis, we designed and fabricated an AO cell in Te and used it to experimentally investigate the anisotropic diffraction from it. We were able to realize a polarization insensitive regime of diffraction in the cell that may be of interest in the future designs of AO modulators and imaging filters. The absolute value of the photoelastic coefficient responsible for diffraction in the XZ plane was determined experimentally and this value was used to evaluate the corresponding figure of merit $M_2$ for the crystal. The calculated value of $M_2$ was quite low, which is a clear indication that that a Te AO cell using an XZ cut of the crystal with the longitudinal acoustic waves propagating along the X axis is not useful for a practical application.

In summary, we found that the anisotropic regime of interaction in the XZ plane of Te with a longitudinal acoustic wave propagation is characterized by a relatively low diffraction efficiency. In this respect, this anisotropic diffraction regime is completely different from the isotropic diffraction regime also provided by the longitudinal acoustic waves in this crystal plane. To improve the figure of merit value by at least one order of magnitude, the Bragg angle of light incidence needs to be increased by a factor of 2.5–3. However, this change in the interaction geometry leads to an increase in the value of the acoustic frequency which has the drawback of high acoustic attenuation in the crystal. Moreover, propagation of light far away from the optic axis inevitably decreases the optical transparency of the Te crystal for the extraordinary polarized light. This means that some kind of tradeoff between the crystal transparency and the diffraction efficiency should be considered while designing new Te based AO devices. Selection of other crystal cuts of Te and other AO interaction geometries may be able to overcome the disadvantages discussed in this paper.

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References

[1] Xu J and Stroud R 1992 Acousto–Optic Devices (New York: Wiley)
[2] Goutzoulis A and Pape D 1994 Design and Fabrication of Acousto–Optic Devices (New York: Dekker)
[3] Yariv A and Yeh P 1984 Optical Waves in Crystals (New York: Wiley)
[4] Feichtner J D, Gottlieb M and Conroy J J 1979 Tl3AsSe3 noncollinear acousto-optic J. Cryst. Growth 225 124–8
[5] Gottlieb M, Goutzoulis A and Singh N 1992 High-performance acousto-optic materials: Hg2Cl2 and PbBr2, Opt. Eng. 31 2110–7
[6] Singh N B, Suhre D, Gupta N, Rosch W and Gottlieb M 2001 Performance of TAS crystal for AOTF imaging J. Cryst. Growth 225 124–8
[7] Suhre D, Taylor L and Melamed N 1992 Spatial resolution of imaging noncollinear acousto-optic tunable filters Opt. Eng. 31 2118–23
[8] Krztonen D J, Singh N B, Gottlieb M, Suhre D and Gupta N 2007 Crystal growth, fabrication and design of mercurocyan bromide acousto-optic tunable filters Opt. Eng. 46 064001
[10] Kim J, Trivedi S B, Soos J, Gupta N and Palosz W 2008 Growth of Hg$_2$Cl$_2$ and Hg$_2$Br$_2$ single crystals by physical vapor transport J. Cryst. Growth 310 2457–63
[11] Fukuda S, Shiosaki T and Kawabata A 1979 Acousto-optic properties of tellurium at 10.6 μm J. Appl. Phys. 50 3899–906
[12] D’yakonov A M, Ilisavskii Y V and Yakhind E Z 1981 Investigation of acousto-optic interaction of IR radiation with sound in tellurium Sov. Tech. Phys. J. 51 1494–502
[13] Oliveira J and Adler E 1987 Analysis of off-axis anisotropic diffraction in tellurium at 10.6 μm IEEE Trans. Ultrason. Ferroelectr. Freq. Control 34 86–94
[14] Souilhac D, Billerey D and Gundjian A 1989 A photoelastic tensor of tellurium Appl. Opt. 28 3993–6
[15] Souilhac D, Billerey D and Gundjian A 1990 A infrared two-dimensional acousto-optic deflector using a tellurium crystal Appl. Opt. 29 1798–804
[16] Souilhac D and Billerey D 1993 TeO$_2$ and Te spectrometer imaging system Proc. SPIE 2312 212–50
[17] Voloshinov V B, Balakshy V I, Kulakova I A and Gupta N 2008 Acousto-optic properties of tellurium that are useful in anisotropic diffraction J. Opt. A: Pure Appl. Opt. 10 095002
[18] Voloshinov V B, Gupta N, Knyazev G A and Polikarpova N V 2011 An acousto-optic X–Y deflector based on close-to-axis propagation of light in the single crystal tellurium J. Opt. 13 015706
[19] Gupta N, Voloshinov V B, Knyazev G A and Kulakova I A 2011 Optical transmission of single crystal tellurium for application in acousto-optic cells J. Opt. 13 035702
[20] Gupta N, Voloshinov V B, Knyazev G A and Kulakova I A 2011 Tunable wide angle acousto-optic filter applying single crystal tellurium J. Opt. 14 035502
[21] Voloshinov V B, Knyazev G A, Kulakova I A and Gupta N 2013 Acousto-optic control of light beams in the infrared range Phys. Wave Phenom. 21 134–8
[22] Knyazev G A, Voloshinov V B, Vorob’ev E S and Khitrin N V 2013 Anisotropic acousto-optic diffraction in tellurium in the presence of optical activity Phys. Wave Phenom. 21 261–3
[23] Voloshinov V B, Gupta N, Kulakova I A, Khorkin V S, Melikh B T and Knyazev G A 2016 Investigation of acousto-optic properties of tellurium-based glasses for infrared applications J. Opt. 18 025402
[24] Voloshinov V B and Molchanov V Y 1995 Acousto-optic modulator of radiation with arbitrary polarization direction Opt. Laser Technol. 27 307–13