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# Quasi-collinear tunable acousto-optic paratellurite crystal filters for wavelength division multiplexing and optical channel selection

V.Ya. Molchanov, V.B. Voloshinov, O.Yu. Makarov

***Abstract*. Quasi-collinear acousto-optic interaction is studied in acoustically and optically anisotropic paratellurite crystals. The possible applications of this interaction in acousto-optic tunable filters with a high spectral resolution are discussed. Different modifications of devices are compared and variants of devices intended for processing light beams and selection of light signals in fibreoptic communication systems with wavelength division multiplexing (WDM) at $\lambda \simeq 1550$ nm are considered.**

***Keywords***: *acoustooptics, fibreoptic communication systems, WDM systems, acoustic and optic anisotropy, quasi-collinear interaction, tunable acousto-optic filters, spectral resolution, paratellurite.*

## 1. Introduction

Low light loss and relatively wide optical transmission bands of single-mode fibres allow one to form a number of independent spectral data transmission channels. The transmission capacity of fibreoptic communication lines can be increased by several hundred times by using wavelength-division multiplexing (WDM) for data transmission [1]. The most important elements of WDM communication systems are spectral signal selectors selecting light beams at specified wavelengths and directing light beams to one or another fibreoptic channels.

It is known that tunable acousto-optic (AO) filters can operate as selectors of optical signals [2, 3]. Moreover, the AO interaction and AO devices are extremely promising for applications in multispectral information channels of fibreoptic communication systems and in switches of telecommunication networks [1 – 3] because tunable AO devices have low optical loss, provide many independently controlled spectral channels and high operation speed. These devices offer the advantage of the direct light – light conversion, rather than the indirect light – electric signal – electric signal – light conversion.

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Tunable AO filters are unique electron-controlled devices which can simultaneously and independently control a significant number of closely spaced spectral channels and direct optical signals transmitted in these channels into one of two output ports. It is obvious that when filtering devices are used in multichannel fibreoptic communication networks, stringent requirements are placed on the parameters of these devices. In particular, the insertion losses, driving power and interchannel crosstalk noise of filters should be low. For applications in telecommunication networks with a considerable number of spectral channels and spectral division of 50 – 200-GHz carrier laser frequencies, devices should have a high spectral resolving power $R = \lambda/\Delta\lambda \simeq 10^3 - 10^4$, where $\lambda$ is the wavelength and $\Delta\lambda$ is the filter passband.

## 2. Acousto-optic paratellurite crystal filters

In principle, different regimes of light diffraction by ultrasound can be used in AO filters [2, 3]. However, at present the collinear and quasi-collinear geometry of AO interaction seems optimal for realisation of the above problems [4 – 18].

The aim of this paper is to study the quasi-collinear geometry of AO interaction in a paratellurite ($TeO_2$) crystal. This crystal is characterised by strongly pronounced anisotropy of optical and acousto-optic properties. For this reason, the development of spectral tunable AO filters based on a $TeO_2$ crystal is an important applied problem. In the theoretical part of this paper, we give the main consideration to the specific schemes of quasi-collinear interaction in paratellurite by using the phenomenon of acoustic wave reflection from the input optical face of the filter.

The diffraction in a $TeO_2$ single-crystal on a slow shear wave propagating in the $(1\bar{1}0)$ plane and polarised orthogonally to this plane is chosen for the analysis. The light interacts with the shear sound wave in the $(1\bar{1}0)$ plane more efficiently compared to other interaction schemes in paratellurite. The high interaction efficiency is especially important when the filter is used in the multichannel regime in the IR range, where the driving powers are very high.

The collinear interaction with collinear phase and group velocities of light and sound were first observed in lithium niobate and calcium molybdate single-crystals [3 – 5]. Another type of collinear interaction with collinear group velocities of light and sound and non-collinear phase velocities was considered in detail in [6 – 8]. Authors of these papers used the acoustic anisotropy of the $SiO_2$ crystal and employed the reflection of the acoustic wave from the input optical face of the crystal, which provided rather simple coupling of a light beam into the sound column collinearly with the group velocity of sound. Later, several modifications of collinear filters were fabricated, which found wide applications in AO spectrometers [9, 10].

Unfortunately, because of limitations imposed by the material symmetry, the collinear interaction with the coinciding directions of phase or group velocities of beams cannot be realised in the highly-effective paratellurite crystal. However, quasi-collinear interaction of light and sound was realised in this material [11 – 18], this interaction being observed both in the case when an incident light wave was reflected from the piezoelectric transducer plane and when the direction of light propagation in the cell was unchanged, while the reflection of a sound wave from the input optical face of the crystal was realised.

Known data on quasi-collinear interaction in paratellurite can be divided into two major groups. The first one includes papers considering the practical development of filters [14 – 16, 18]. The second group of papers is devoted to the study of the quasi-collinear interaction properties as a function of anisotropic optical and acoustic properties of the paratellurite crystal [11 – 13, 17]. However, these investigations were not confirmed by the proper experiments.

Another aim of this paper was to fabricate a family of quasi-collinear AO filters with perfect optical and electric parameters. The main task was to optimise the design of the devices taking into account the requirements imposed on WDM communication systems. The proposed method for the analysis of the filter parameters is universal and simple, the efficiency of this method being confirmed experimentally by the example of fabricated samples of AO filters.

## 3. Theoretical description

The first stage in designing AO filters is the drawing of vector diagrams establishing the relationship between wave vectors of interacting beams in the approximation of plane light and sound waves [3]. From these diagrams, one can find the relationship between the angles of incidence of light and sound with respect to the crystallographic axes of the material as well as the ultrasound frequency providing diffraction. This relation is a necessary condition for the efficient interaction of light and sound; however, diffraction can be absent if the effective photoelastic constant of the crystal in the specified direction of interaction is zero.

In quasi-collinear interaction the angle of light incidence obtained from vector diagrams should determine the orientation angle of the group velocity of the sound wave propagating in the crystal along the light beam. Crystals are acoustically anisotropic media, which implies that the directions of the phase and group velocities of the acoustic wave do not coincide in the general case. It is known that acoustic velocities are determined from the slowness surface whose general shape is specified by the specific group symmetry of the crystal and the elasticity coefficients of the material [19]. Thus, in a crystal of any symmetry group, an unambiguous correspondence can be established between the angle of light incidence and the group velocity direction of the sound wave, at which the quasi-collinear interaction is realised. It is obvious that the degree of this interaction is determined by the effective photoelastic constant acting in the direction of light propagation and by other parameters, for example, refractive indices of the incident and diffracted waves, sound speed and material density.

Because AO filters in WDM communication systems operate with multispectral laser signals, the input optical face of the filter is selected orthogonal to incident light to eliminate the undesirable dispersion effect of the crystal refractive indices on the filter parameters. This condition determines the orientation of the crystal input face with respect to the material crystallographic axes.

To realise quasi-collinear interaction in the crystal, it is necessary to produce an extended acoustic column of small cross section. It is also important to couple light into the acoustic column without losses. In this paper, the sound field is produced by reflecting the acoustic wave from the input optical face of the crystal. This method for the sound column formation is the most successful and promising [8, 12, 15, 16].

At this stage of consideration, the orientation of the acoustic wave vector in the sound column and the orientation of the input optical face of the crystal with respect to the crystallographic axes are unambiguously determined. At the second stage, the propagation direction of the acoustic wave incident on the input face of the AO cell is found. This acoustic wave is generated by a piezoelectric transducer and after reflection from the crystal input face is transformed into a sound wave providing quasi-collinear interaction [14 – 21]. To determine the direction of the initial acoustic wave, it is necessary to use the known laws of reflection of acoustic waves from the interface [22]. The direction of the phase velocity of the initial acoustic wave unambiguously determines the orientation of the crystal face on which the piezoelectric transducer is mounted.

The problem can be solved by simultaneously drawing the vector diagram of AO interaction in the selected diffraction plane and the acoustic slowness surfaces of the crystal so that to orient them mutually with respect to the crystallographic axes. In the paratellurite crystal under study, the slow shear acoustic wave propagates in the $(1\bar{1}0)$ plane and is polarised orthogonally to this plane. If the angle $\alpha$ is measured between the phase velocity $\boldsymbol{V}_{\mathrm{ph}}$ of sound and the [110] axis, the expression for the phase velocity of the sound wave in paratellurite has the form [22]

$$V_{\mathrm{ph}}(\alpha) = \left[\frac{1}{\rho}\left(c_{44}\sin^2\alpha + \frac{c_{11}-c_{12}}{2}\cos^2\alpha\right)\right]^{1/2}, \qquad (1)$$

where $\rho$ is the material density and $c_{ij}$ are elastic coefficients. The analysis shows that the walk-off angle $\psi$ of the acoustic wave, i.e. the angle between the phase $\boldsymbol{V}_{\mathrm{ph}}$ and group $\boldsymbol{V}_{\mathrm{g}}$ velocities of ultrasound, is defined by the expression:

$$\psi(\alpha) = \arctan\left[\frac{(2c_{44}-c_{11}+c_{12})\tan\alpha}{c_{11}-c_{12}+2c_{44}\tan^2\alpha}\right]. \qquad (2)$$

By definition, during quasi-collinear interaction the wave vector $\boldsymbol{k}_{\mathrm{i}}$ of incident light is collinear to the group velocity vector $\boldsymbol{V}_{\mathrm{g1}}$ of the acoustic wave. Figure 1 presents the scheme determining the directions of the light and sound waves and the orientation of the input optical face of the crystal with respect to the crystallographic axes. The sound wave is reflected from the crystal input face. The scheme uses standard acousto-optic notations: $\boldsymbol{k}_{\mathrm{d}}$ и $\boldsymbol{K}$ are the vectors of diffracted light and sound, respectively. The angle $\varphi$ in the vector diagram determines the AO interaction frequency. Figure 1 also shows the input optical face of the

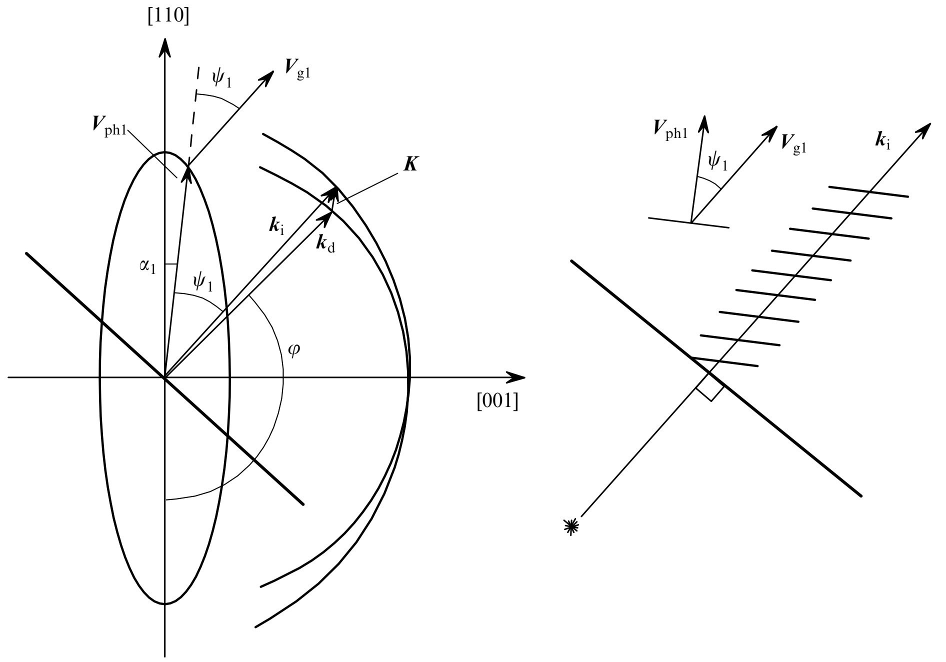



**Figure 1.** Use of the vector diagram and acoustic slowness surface of the paratellurite crystal for the analysis of the quasi-collinear interaction geometry.

crystal onto which extraordinary polarised laser multispectral radiation is incident at a right angle.

One can see from Fig. 1 that the orientation of the input optical face of the crystal is determined by the angle $\pi/2 - (\alpha_1 + \psi_1)$ measured from the [110] axis. In the latter relation, the angle $\alpha_1$ is the angle between the direction of the phase velocity $\boldsymbol{V}_{ph1}$ of sound and the [110] axis and the angle $\psi_1$ is measured between the phase $\boldsymbol{V}_{ph1}$ and group $\boldsymbol{V}_{g1}$ velocities of the ultrasound wave. After reflection from the input optical face, the acoustic wave with the phase $\boldsymbol{V}_{ph2}$ and group $\boldsymbol{V}_{g2}$ velocities transforms into a sound wave with the phase $\boldsymbol{V}_{ph1}$ and group $\boldsymbol{V}_{g1}$ velocities. It is obvious that the light beam is diffracted by the ultrasound wave. The geometric plot illustrating acoustic reflection from the crystal input face is presented in Fig. 2. It follows from this figure that the angle $\alpha_2$ lies between the phase velocity $\boldsymbol{V}_{ph2}$ of sound and the [110] axis and the angle $\psi_2$ lies between the phase $\boldsymbol{V}_{ph2}$ and group $\boldsymbol{V}_{g2}$ velocities of the acoustic wave generated by the piezoelectric transducer.

The condition for the sound wave reflection from the interface is determined by the known equality rule of the projections of the inverse velocities of the incident and

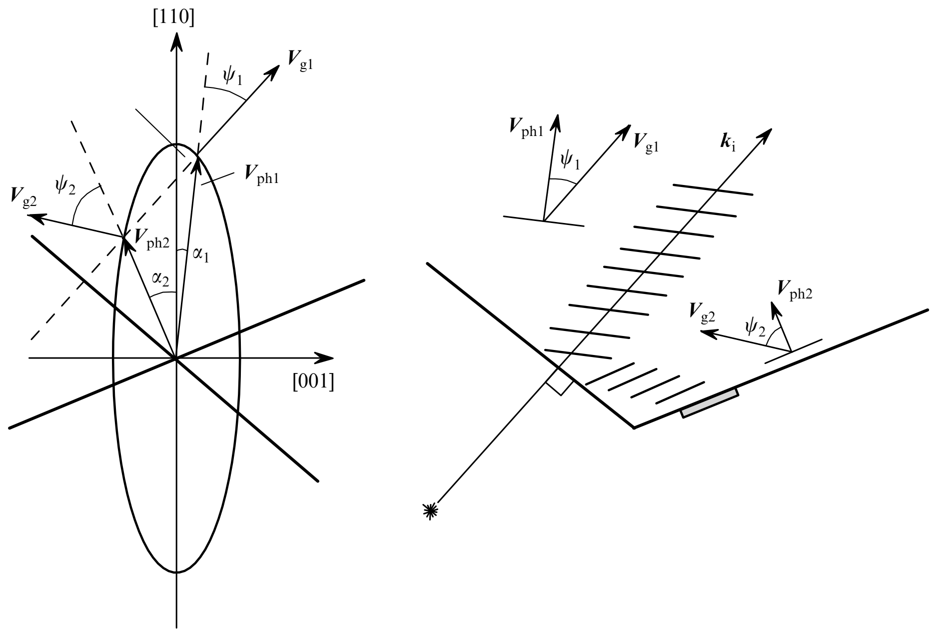



**Figure 2.** Analysis of the sound wave reflection from the input optical face of the crystal with the use of the acoustic slowness surface of the paratellurite crystal.

reflected waves on the interface [22] and in this case is written in the form

$$\frac{1}{V_{\text{ph1}}(\alpha_1)}\sin\psi_1 = \frac{1}{V_{\text{ph2}}(\alpha_2)}\sin(\alpha_1+\psi_1+\alpha_2). \qquad (3)$$

One can see from Fig. 2 that the orientation of the crystal face on which the piezoelectric transducer is mounted, with respect to crystallographic axes is determined by the angle $\pi/2-\alpha_2$. The angle $\alpha_2$ is formed by the [110] axis and the plane of the piezoelectric cell and can be found from the equality condition for projection of inverse velocities (3). It turned out that equation (3) does not have an analytic solution; hence, it was solved numerically during the analysis. It follows from (3) that there exist two non-zero solutions, one of which is trivial ($\alpha_2=-\alpha_1$) and corresponds to the collinear direction of group velocity vectors $\boldsymbol{V}_{g1}$ and $\boldsymbol{V}_{g2}$ of sound waves. It is obvious that the trivial solution corresponds to the filter configuration improper for the realisation of collinear interaction. Therefore, in this paper we used the second solution for the angle $\alpha_2$.

## 4. Design of quasi-collinear filters for laser communication systems

As follows from theoretical considerations, the initial parameter determining the optical and acoustic configuration of the AO filter with respect to the crystallographic axes is the angle $\alpha_1$, which specifies the orientation of the sound wave vector. The angle $\alpha_1$ is selected taking into account optical, energy and design considerations. As is known, stringent requirements for the width of the spectral passband are placed on filters for their application in WDM communication systems. In addition, the driving power of the filter should be minimal, which is especially important in the multichannel operation regime of the device [1].

The design features of the filters are caused by different variants of orientation of crystal faces with respect to crystallographic axes. The calculation of the angles determining the orientation of cell faces shows that depending on the quantity of the angle $\alpha_1$ there exist several possible configurations of cells (shown in Fig. 3). Thus, when $\alpha_1$ is increased from 0 to 1.78° the angle between the input optical face of the filter and the face on which the piezoelectric transducer is mounted is acute. If $\alpha_1$ lies in the range $1.78° < \alpha_1 < 13.31°$, the angle between the input face and the face of the piezoelectric transducer is obtuse, and at $\alpha_1 > 13.31°$ this angle becomes acute again. Two configurations of the cells at which the filter faces are orthogonal, correspond to two values of the angle $\alpha_1$ (1.78° and 13.31°). In this case, the orientation of the crystallographic axes is different for each of these cells.

Figure 3a corresponds to the variant when the phase velocity $\boldsymbol{V}_{\text{ph2}}$ of sound is directed to the side of the optical face of the filter. The direction of light incident on the crystal is specified by the wave vector $\boldsymbol{k}_i$. It is shown in Fig. 3b that the direction of the phase velocity $\boldsymbol{V}_{\text{ph2}}$ is parallel to the optical face, which corresponds to the grazing incidence of the acoustic beam on the face [20]. Finally, Fig. 3c shows that the phase velocity $\boldsymbol{V}_{\text{ph2}}$ is directed opposite to the input optical face. In the two latter modifications of the filters, the acoustic wave excited by the piezoelectric transducer is incident on the input optical face due to the acoustic anisotropy of the paratellurite crystal.

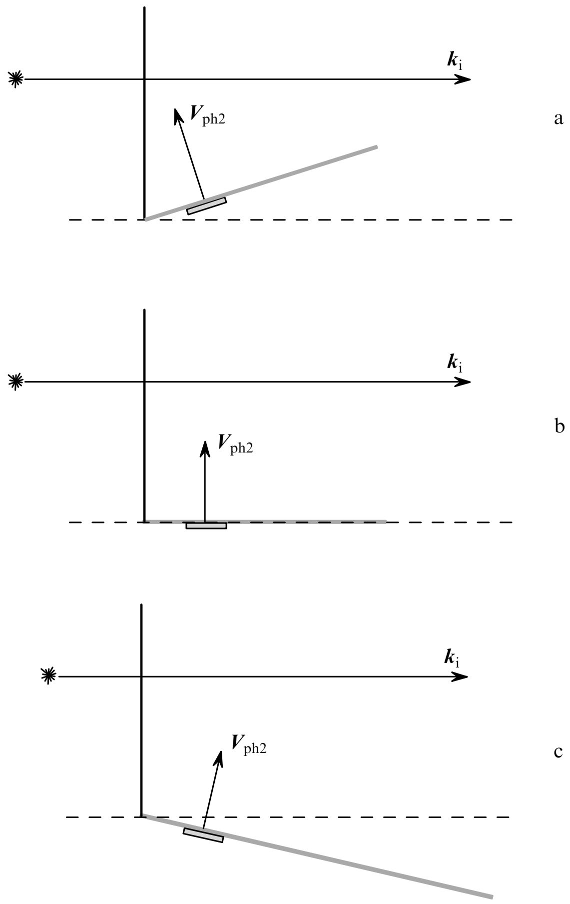



**Figure 3.** Different variants of mutual orientation of the filter faces: at $0 < \alpha_1 < 1.77°$ and $\alpha_1 > 13.31°$ the angle between the filter faces is acute (a), at $\alpha_1 = 1.77°$ and $\alpha_1 = 13.31°$ the filter faces are perpendicular to each other (b), at $1.77° < \alpha_1 < 13.31°$ the angle between the filter faces is obtuse (c).

In calculations of the acoustic wave velocity in the crystal, we used the following values of the elastic constant of the material corresponding to temperature 20 °C [23]: $c_{11} = (5.612 \pm 0.020)\times 10^{10}$ dyne cm$^{-2}$, $c_{12} = (5.155 \pm 0.025)\times 10^{10}$ dyne cm$^{-2}$, $c_{13} = (2.303 \pm 0.030)\times 10^{10}$ dyne cm$^{-2}$, $c_{33} = (10.571 \pm 0.025)\times 10^{10}$ dyne cm$^{-2}$, $c_{44} = (2.668 \pm 0.005)\times 10^{10}$ dyne cm$^{-2}$ and $c_{66} = (6.614 \pm 0.015)\times 10^{10}$ dyne cm$^{-2}$. The paratellurite density was taken equal to 6.00 g cm$^{-3}$.

It is known that the fabrication of filters with a high resolution requires the growth of large $TeO_2$ single-crystals, which is a rather complex problem in crystal physics. From this point of view, the case, when the acousto-optic filter faces are perpendicular to each other is preferable because the crystal material is used more efficiently. In the case, when the obtuse angle between the optical and acoustic faces is large (at a maximum it exceeds 120°), the advantages of the proposed quasi-collinear geometry of AO interaction already become unobvious. The conventional scheme for light coupling in/out can prove simpler and more efficient when light is reflected from the piezoelectric transducer face [1, 11].

The optimal value of the angle $\alpha_1$ is selected taking into account the system requirements to energy and optical parameters of the AO filter. These parameters can be estimated by using data of Figs 4 and 5, which show the dependence of acousto-optic figure of merit $M_2$ of the paratellurite crystal on the angle $\alpha_1$ and the normalised dependence of the filter resolution $R$ on the angle $\alpha_1$ [11]. It follows from Figs 4 and 5 that it is impossible to fabricate an optical quasi-collinear paratellurite filter, which simultaneously has the maximum resolution parameters and the minimum driving power. Therefore, the choice of the angle $\alpha_1$ is determined by the specific system requirements to the filter.

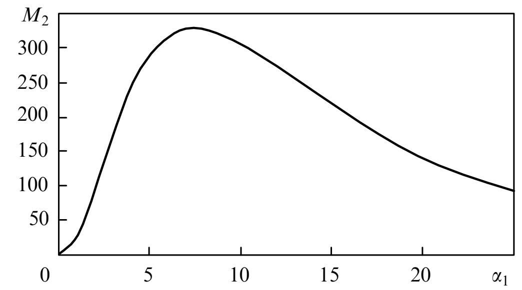



**Figure 4.** Dependence of the acousto-optic figure of merit of paratellurite on the angle $\alpha_1$.

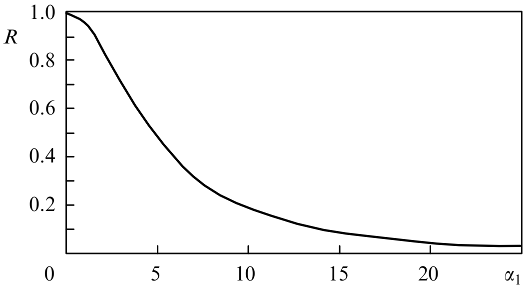



**Figure 5.** Dependence of the normalised resolution of the filter on the angle $\alpha_1$.

## 5. Experimental study of filters

We fabricated a family of quasi-collinear AO filters corresponding to three main configurations of cells presented in Fig. 3. Figure 6a shows the scheme of the filter with the angle $\alpha_1 = 1.58°$ and orientation of the faces of the AO cell with respect to the crystallographic axes. The peculiar feature of the device is the fact the acoustic waves propagate in the crystal strictly along the [001] angle, when the walk-off angle of the acoustic wave generated by the transducer is $\psi_2 = 0$. The photograph of the filter is presented in Fig. 6b. Two other typical configurations of the AO filters are shown in Fig. 7. To eliminate the standing acoustic wave we used an indium absorber in the filters.

Based on the calculations of orientation of the filter faces with respect to the crystallographic axes and walk-off angles $\psi_2$ of the acoustic waves generated by the piezoelectric transducer, we determined the filter dimensions as well as the geometric dimensions of the piezoelectric transducer and its position on the acoustic face of the crystal depending on the requirements to the optical aperture of the device.

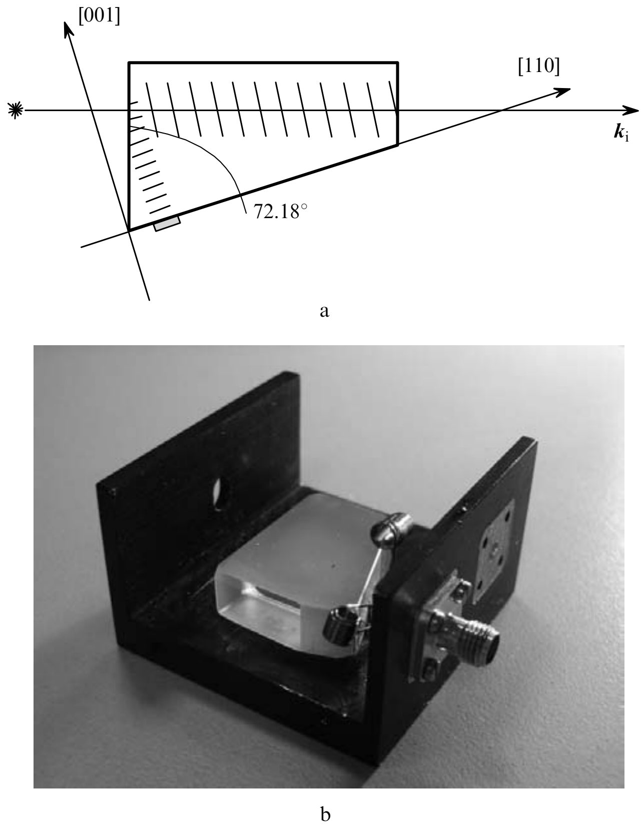



**Figure 6.** A quasi-collinear filter with the angle $\alpha_1 = 1.58°$: orientation of the faces with respect to the crystallographic axes (a) and the view of the device with a removed cover (b).

According to the data of Figs 4 and 5, one should expect that the filter presented in Fig. 7a will have a high spectral resolution but not the optimal value of the control electric power. On the other hand, the filter in Fig. 7b can have the value of the driving power that is close to the minimal one; however, other conditions being the same, it will have a worse spectral resolution. It is obvious that the maximum spectral resolution of the filter is realised theoretically for the angle $\alpha_1 = 0$, when the acoustic wave propagates strictly along the [110] axis. However, the corresponding effective photoelastic constant and the acousto-optic figure of merit in paratellurite are equal to zero [1, 2].

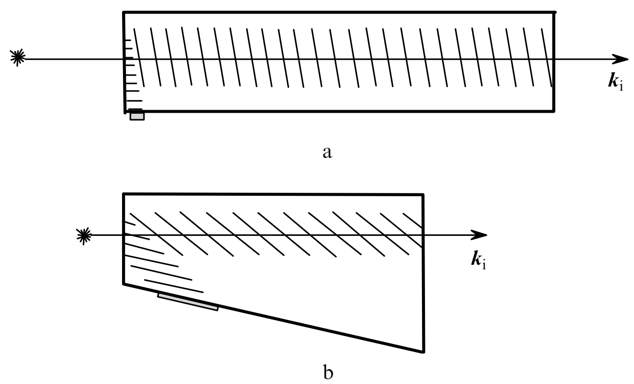



**Figure 7.** Schemes of quasi-collinear AO filters: optimised with respect to the spectral resolution (a) and optimised with respect to the driving power (b).

The fabricated AO filters were studied experimentally under conditions which are maximally close to real operating conditions of WDM communication systems. Radiation with a continuous spectrum in the range from 1400 to 1600 nm or radiation from a 1550-nm laser was coupled into the single-mode fibre with the core diameter 9 μm. After the fibre, radiation was directed with the help of the collimator to the AO filter under study. The receiving collimator at the filter output was tuned either to the propagated radiation (zero diffraction order) or to the filtered radiation ($-1$ diffraction order), after that the optical signal was fed to the spectrum analyser input.

Figure 8 presents the transmission spectrum of the filter shown in Fig. 6. The spectrum was obtained by using a source of a continuous optical spectrum, whose radiation was linearly polarised in the plane perpendicular to the diffraction plane. The width of the filter passband estimated at the 0.5 level was 0.48 nm. The light diffraction efficiency of 90 % at 1550 nm was achieved for the driving power of 90 mW. The length of the acoustic column in the cell was 28 mm and its transverse cross section was $3.5 \times 3.5$ mm. The AO interaction frequency was 54.9 MHz when the phase-matching condition was fulfilled at $\lambda = 1550.7$ nm.

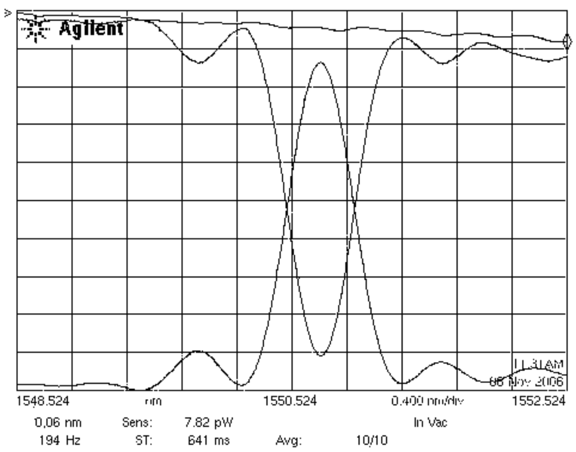



**Figure 8.** Spectral transmission function of a quasi-collinear AO filter with the angle $\alpha_1 = 1.58°$.

The spectral transmission function of the quasi-collinear AO filter with the angle $\alpha_1 = 1.78°$, whose scheme is presented in Fig. 7a, is given in Fig. 9. The length of the acoustic column was 67 mm, which provided an extremely narrow transmission band of the device: 0.24 nm at the 0.5 level. The diffraction efficiency till 90 % at $\lambda = 1537$ nm was provided for the driving power of 60 mW. The transverse cross section of the acoustic column was $3.5 \times 3.5$ mm and the diffraction frequency was 52.2 MHz. The driving power proved somewhat higher than the calculated one, which is explained by the inhomogeneity of the acoustic field in such a long crystal.

Figure 10 demonstrates the possibility of operation of this device in WDM communication systems. The collimator at the filter output in these experiments was placed in the zero diffraction order. The radiation source was a 1550-nm laser. The emission spectrum of the laser shown in Fig. 10 represented a typical spectrum of a mutifrequency laser with equidistantly spaced lines corresponding to a large number of longitudinal modes. The intermode distance in the laser

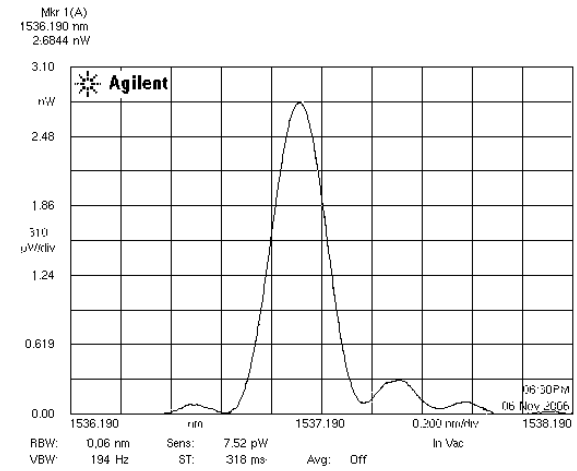



**Figure 9.** Spectral transmission function of a quasi-collinear AO filter with the angle $\alpha_1 = 1.78°$.

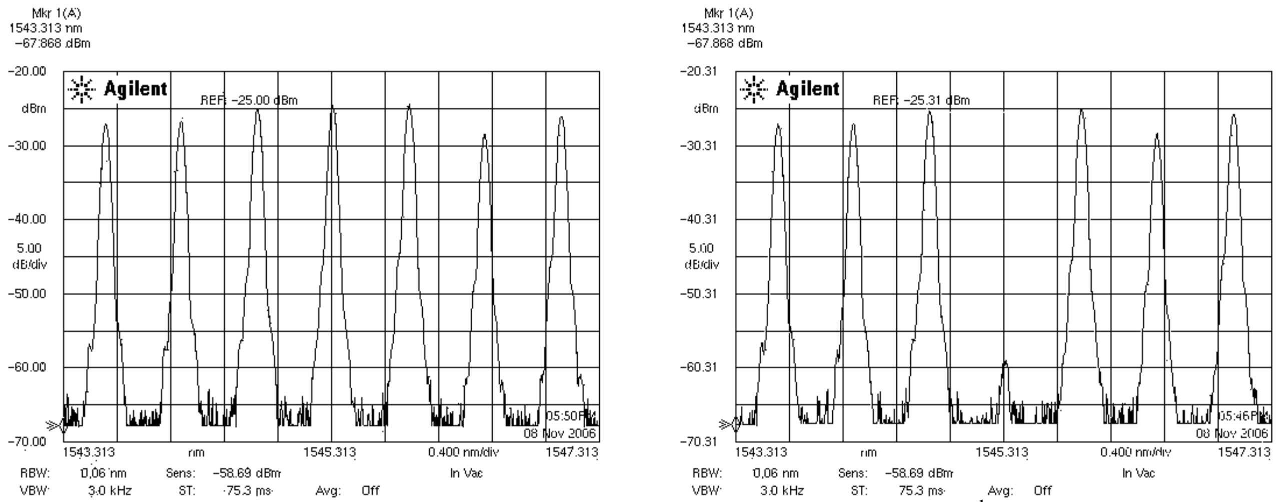
spectrum was 0.55 nm, which slightly exceeded the standard division interval (0.4-nm) of carrier frequencies in the 50-GHz WDM communication system but was smaller than the spectral interval of 0.8 nm of a typical 100-GHz fibreoptic WDM system. The filter was tuned to the frequency of one of the longitudinal modes of the laser, and the driving power was selected to provide the maximum diffraction efficiency. Figure 10b demonstrates the suppression of one of the spectral components of the initial signal to the level above $-30$ dB by the filter in the zero diffraction order and its transfer to the $-1$ order, the influence of the AO filter on adjacent spectral components being no more than 1 dB. The experiments show that the fabricated devices can be efficiently used for operation in WDM communication systems with the spectral division of signal frequencies of 100 GHz and higher.

The experiments with the filter presented in Fig. 7b showed that, as was expected, the filter has a moderate spectral resolution. However, the operating power of control signals of this device proves rather low, which is crucial for a number of applications. For example, in a device with the angle $\alpha_1 = 5°$ and the 21-mm-long crystal the driving power corresponding to the diffraction efficiency of 90 % was 63 mW, which well agrees with the calculations. The width of the filter transmission band did not exceed 1.4 nm in this case.

The main factors, which determine the transmission band $\delta\lambda$ of the filter, are the divergence of light and sound waves and the spectral broadening of the acoustic train of waves filling the crystal of limited dimensions. In practice, the estimation relation [1, 11]

$$\delta\lambda = \sqrt{\delta\lambda_\varphi^2 + \delta\lambda_\alpha^2 + \delta\lambda_L^2} \tag{4}$$

is usually used, where $\delta\lambda_\varphi$, $\delta\lambda_\alpha$, $\delta\lambda_L$ are the spectral transmission bands caused by the divergences of the light ($\delta\varphi$) and acoustic ($\delta\alpha$) beams and the spectral broadening of the acoustic train filling the crystal of length $L$ [11]. The estimates presented for the filter design parameters with $\alpha = 1.78°$ showed that the contribution $\delta\lambda_\alpha$ to the passband $\delta\lambda$ can be neglected due to the weak dependence of the angle-frequency parameter of the filter on $\alpha$ [11]. For a collimated laser beam with a 2-mm waist, the effect of its




a b

**Figure 10.** Suppression of the spectral component of a multifrequency laser with the intermode distance 0.55 nm by the AO filter: the spectrum in the absence of the RF power (a) and the spectrum at the switched-on RF power (b).

diffraction divergence is significant: $\delta\lambda_\varphi = 0.17$ nm because of the linear dependence of the acoustic frequency on the angle of light incidence [1–3]. Finally, the value $\delta\lambda$ determined for the collinear case by the expression $\delta\lambda_L = 0.8\lambda V_{\rm ph}/(Lf\cos\psi)$, where $f$ is the AO interaction frequency, is 0.24 nm [11].

Thus, using expression (4) it is easy to find the spectral transmission band of the quasi-collinear filter with the angle $\alpha = 1.78°$: $\delta\lambda = 0.29$ nm. A slight discrepancy of this quantity with the experimental estimate of 0.24 nm is caused by the fact that the receiving collimator serves as a spatial-frequency filter, which leads to narrowing of the transmission function width in this experiment.

Note in conclusion a very important property in operation of the fabricated quasi-collinear filters based on a paratellurite crystal. In experiments with filters we used collimated optical beams with a relatively large diameter (1.5–2.0 mm), while the typical cross section of the sound column in AO devices is $3.5 \times 3.5$ mm. In the general case, diffracted light propagates in cells not strictly collinear to the incident light and the flow of the sound energy. Nevertheless, AO interaction in the fabricated filters occurred along the entire length of the acoustic column even when the longest crystal was used.

The main reason for localisation of the diffracted light beam within the sound column is explained as follows. The angle between the wave vectors of incident and diffracted light beams due to AO interaction in the filters under study was 2.0°–3.5°. However, this angle was partially compensated for by the 1.5°–2.3° deviation of the extraordinary polarised light beam diffracted in the backward direction due to the strong optical anisotropy of paratellurite. As a result, energy fluxes of incident and diffracted light beams in filters were virtually parallel to each other and to the energy flux of the sound wave. The latter circumstance proves the possibility of successful realisation of AO interaction regime close to collinear in practical filter designs.

## 6. Conclusions

The developed method for determining the optical, energy and design parameters of quasi-collinear AO filters based on paratellurite is efficient, universal and easy-to-realise in practice. We have calculated and fabricated a number of AO filters with different optical and design features. We have studied experimentally the fabricated devices in the spectral range 1550 nm. The record spectral resolution has been achieved for these devices, i.e. 0.24 nm at the 0.5 level at the wavelength 1537 nm. The transmission coefficient in the filter transparency window for the linear polarisation of input radiation is 90 % for the driving power of 60 mW. A high degree of correspondence between the calculated and experimental parameters has been established. We have performed a number of experiments with the AO filters under conditions imitating their operation in multispectral WDM communication systems. The results of the experiments show that the fabricated filters are modern electron-controlled instruments for the wavelength division multiplexing of laser signals in fibreoptic communication networks with the spectral multiplexing of channels 100 GHz and small crosstalk noise. The developed filters allow for the further improvement of their parameters, for example, when using double-crystal [24] and multipass filtration schemes [25].

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