Quasicollinear acoustooptic filters using strong acoustic anisotropy in tellurium dioxide crystal

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Abstract. The paper is devoted to the theoretical and experimental investigation of acoustooptical tunable filters, based on quasicollinear geometry of light-sound interaction in tellurium dioxide (paratellurite) single crystal. This configuration uses the effect of strong acoustic anisotropy in paratellurite as well as peculiarities of acoustic wave reflections from the free boundary of the crystal. The mathematical approach for determination of optical, electrical and constructional parameters of the filters was developed. Several experimental acoustooptical filters intended for dense WDM networks operating in S, C and L-bands were designed and tested. The experimental data is in good agreement with theoretical ones.

1. Introduction
The wavelength division-multiplexing (WDM) concept for telecommunications was developed to increase the information capacity of the single optical fiber. The input signal in WDM systems consists of several independent laser’s spectral carriers or spectral channels separated by reference equidistant spectral intervals. Electronically tunable acoustooptical filters are almost the ideal devices for independent and simultaneous controlling of laser’s spectral channels in WDM telecommunication networks. These filters are high performance optoelectronic devices with low insertion loses, high spectral resolution, high interchannel crosstalk, low driving power. Acoustooptical filter provides direct “light-to-light” conversion and can support more than 10 simultaneously operating channels in S (1491.69-1529.55 nm), C (1529.75-1569.59 nm) and L (1569.80-1611.79 nm) communication bands.

The acoustooptical tunable filter operates on the principle of light diffraction by ultrasound waves in a birefringent crystal. The most interesting material for tunable filters is paratellurite single crystal. It has unique combination of physical properties and constants and, particularly, very large figure of acoustooptical merit $M_2$. Paratellurite belongs to 422 crystal class and is characterized by very high acoustical, optical and photoelastic anisotropy. The walk-off angle between the acoustic wave vector and the Poynting vector in paratellurite may exceed dozen of degrees. Quasicollinear acoustooptic interaction is the most interesting configuration of light-sound interaction in order to minimize driving power as well as spectral bandwidth [1,2]. According to recent papers [3,5] we define quasicollinear interaction as a configuration when phase velocity of light is collinear to group velocity of sound. The main problem is how to align the laser beam and acoustic column. Typical technical solution is to use acoustic reflection from the input optical crystal facet. Last years several different types of paratellurite based acoustooptical filters for multispectral operation were investigated [1-5].
Nevertheless variety of problems relating to optimal quasicollinear design remain unclarified until now.

The present paper is devoted to the simple mathematical approach of development and design as well as determination filter’s optical, electrical and constructional characteristics. Several experimental acousto-optical filters were designed and fabricated according to that concept. A very good agreement between theory and experiment was obtained to all data presented here.

2. Theoretical consideration
The analysis is carried out for the plane (1-10) of paratellurite commonly used in the acousto-optic devices. The well-known wave-vector diagram formalism for uniaxial crystal is used in this consideration. This formalism defines the relationship between frequency of Bragg synchronism and the angles of light and sound propagation relative crystallographic axis in a plane wave approximation. The driving power is determined by the effective photoelastic constant. We consider quasicollinear acousto-optical interaction, therefore the wave vector $k_i$ of incident light propagating at the angle $\phi$ should be collinear to acoustic group velocity $V_{g1}$ defined in the same coordinate system (Fig.1) after reflection from the input facet of crystal. Here: $k_d$ and $K$ – wave vectors of the diffracted light and sound, $n_o$ and $n_e$ – ordinary and extraordinary indexes of refraction; $\psi_1$ - walk-off angle between phase and group velocity of sound; $\alpha_1$ - the angle between acoustic phase velocity $V_{p1}$ reflected from the input facet of the crystal and [110] axis of the crystal.

![Figure 1. Geometry of acoustooptical interaction defined from wave vector diagram and slowness curve for pure shear mode](image1)

![Figure 2. Orientation of transducer facet defined from reflection conditions. The optical facet is orthogonal to the light beam](image2)

We assume the input facet of the crystal is orthogonal to the wave vector of the light (Fig.1). We consider pure shear acoustic mode propagating in paratellurite in the plane (1-10) with polarization vector orthogonal to that plane and corresponding to very high figure of merit $M_2$. The solution for phase velocity $V_{p1}$ resulting from Christoffel equation [5] is given by the formula:

$$V_{p1}(\alpha_1) = \frac{1}{\rho^{1/2}} \left( c_{44} \sin^2 \alpha_1 + \frac{c_{11} - c_{12}}{2} \cos^2 \alpha_1 \right)^{1/2},$$

(1)

here $\rho$ - crystal density, $c_{11}$, $c_{12}$ and $c_{44}$ – elastic constants.

The walk-off angle $\psi_1$ between acoustic phase and group velocities is defined by equation:

$$\psi_1(\alpha_1) = \arctg \left[ \frac{2c_{44} - c_{11} + c_{12}}{c_{11} - c_{12} + 2c_{44} \tan^2 \alpha_1} \right],$$

(2)

The quasicollinear interaction takes place within sound column reflected from the input optical facet of the filter. The orientation of input optical facet is defined by the angle $\pi/2 - (\alpha_1 + \psi_1)$ between facet plane and [110] axis of the crystal. The drawing that helps to determine the transducer’s
facet orientation is presented in Fig.2. According to wave motion’s law acoustic wave vectors of incident and reflected sound columns have to satisfy in the crystal to the requirement of equal projection. That requirement can be written in the following form:

$$\frac{1}{V_{p1}(\alpha_1)} \sin \psi_1 = \frac{1}{V_{p2}(\alpha_2)} \sin(\alpha_1 + \psi_1 + \alpha_2),$$

where $V_{p1}$ and $V_{p2}$ are the phase velocities of incident and reflected acoustic waves.

The orientation of the transducer facet or acoustical facet is defined by the angle $\pi/2 - \alpha_2$ between facet plane and [110] axis of the crystal. The angle $\alpha_2$ value can be determined as a function of $\alpha_1$ from equations (1)-(3).

3. Quasicollinear filter design

As it was mentioned above, the main parameter defining optical and acoustical configuration of quasicollinear filter relative to crystalline axes is the angle $\alpha_1$. The calculations of optical and acoustical facets orientation versus angle $\alpha_1$ demonstrate the following features. When $\alpha_1$ is increased from 0° to 1.775° the angle between optical and acoustical facets raises up to 90°. If 1.775°< $\alpha_1$<13.31° than angle between these two facets exceeds 90° and it’s extremum value is slightly more than 120°. If $\alpha_1$>13.31° than angle between facets decreases. There are two particular values $\alpha_1$=1.775° and $\alpha_1$=13.31° when optical and acoustical facets are orthogonal. It should be pointed, that in these cases the crystal orientations are different. The following constants taken for room temperature were used for calculations: $c_{11}=5.612 \times 10^{10}$ dynes×cm², $c_{12}=5.155 \times 10^{10}$ dynes×cm², $c_{44}=2.668 \times 10^{10}$ dynes×cm², $\rho=6.00$ g/cm³.

System requirements should be taken into account to select the optimum value of angle $\alpha_1$. The normalized dependences of acoustooptical figure of merit $M_2$ (solid line), as well as spectral resolution $\lambda/\Delta \lambda$ (dashed line) from $\alpha_1$ value [5] are presented in Fig.3. Here $\lambda$ - optical wavelength, $\Delta \lambda$ - spectral bandwidth of the filter. Fig.3 demonstrates clearly, that it’s impossible to create quasicollinear filter having both high resolution and low driving RF power.

![Figure 3. Acoustooptical figure of merit $M_2$ (solid curve) and resolution $\lambda/\Delta \lambda$ (dashed curve) versus angle $\alpha_1$](image)

![Figure 4. General view of experimental quasicollinear acoustooptical filter](image)

4. Experimental results

Several experimental types of quasicollinear filters were designed using mathematical approach developed in the paper. The filters are intended for 1550 nm telecommunication wavelength window. Calculation of walk-off angle $\psi_2$ between the group and phase velocities of acoustic wave, generated by transducer allows to define the transducer size and its placement on the acoustical facet.
The general view of experimental acoustooptical quasicollinear filter corresponding to parameter $\alpha = 1.775^\circ$ is presented in Fig.4. The crystal size is $10 \times 12 \times 68$ mm, the optical aperture is $4 \times 4$ mm. The optical input facet and acoustical one are orthogonal. The X-cut LiNbO$_3$ transducer is bonded to acoustic facet by the indium cold welding method in vacuum. The central working RF frequency, corresponding to 1550 nm is 52.2 MHz. The two-element LC-circuit matches the complex impedance of the transducer with the output of 50-Ohm driver to cover S, C and L telecommunications bands. All experiments were performed using collimating laser beam 2.0 mm in diameter. The spectral bandwidth is 0.24 nm at -3dB level at wavelength 1536 nm. The RF power, required for 90% diffraction efficiency level, is about 60 mW. Driving power is extremely low that permit to control up to 16 independent optical channels simultaneously.

![Figure 5. Laser longitudinal modes transmitted through the acoustooptical filter. RF power off.](image)

![Figure 6. Laser longitudinal modes transmitted through the acoustooptical filter. RF power on.](image)

WDM applications of the experimental device in C-band are demonstrated in Fig.6. The laser source operating in C-band radiates typical spectrum of numerous longitudinal modes separated by interval 0.55 nm. The receiving collimator was placed at the zero-order laser beam. This spectral interval exceeds slightly typical data 0.4 nm corresponding to standard 50 GHz WDM. Fig.5b corresponds to maximum diffraction efficiency when fine tuning to one of the longitudinal modes was performed. The spectral channel rejection is about -30 dB.

5. Conclusion
Simple and effective mathematical algorithm for quasicollinear acoustooptical filter geometry determination was proposed in this work. This algorithm is valid for crystals with different types of symmetry. Several experimental devices were designed and fabricated. The experiments performed demonstrate that these devices can be useful for add-drop applications in 100 GHz WDM networks.

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