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Quasicollinear acoustooptic tunable filters based on KDP single crystal

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The paper is devoted to the theoretical and experimental investigation of acousto-optical tunable filters based on quasicollinear light-sound interaction in KDP single crystal. The filter geometry uses the effect of acoustic anisotropy in KDP and features of acoustic wave reflection from the input optical facet. The simple and effective approach to define optical, electrical and constructive parameters of the filter was developed. Experimental acousto-optical cell was designed and tested. Spectral resolution of 1,0 nm and diffraction efficiency exceeding 30% at driving power of 1,0 W were measured at wavelength 532 nm. The experimental data is in good agreement with calculated data.

1 Introduction

Collinear acousto-optical interaction based on collinear both phase and group light and sound velocities firstly was demonstrated in crystal quartz and calcium molibdate single crystals [1,2]. Another type of collinear interaction utilizing collinear phase light and group sound velocities but noncollinear phase velocities was proposed in paper [3]. In that paper the properties of an acoustic anisotropy in crystal quartz and reflection of acoustic wave from the input facet of the crystal was used. The quasicollinear interaction in paratellurite single crystal was the subject of numerous papers [4-9]. That interaction was studied in the cases when input light wave was reflected from the transducers plane as well as in the cases when sound column was reflected from the optical input face of the crystal.

The preliminary investigation of quasicollinear acousto-optical properties for KDP crystal was performed in only one paper recently [10], while noncollinear interaction was studied in details [11-13]. KDP single crystal has relatively low figure of merit M_2 and nevertheless it is one of the best material for UV radiation with wavelength value up to 200nm. Our own experience shows that the typical spectral resolution of acousto-optical non-collinear filters at the sound column length of 26 mm is about 2,5 nm at –3 dB level at wavelength 440 nm [14]. According to [10] the filter resolution in quasicollinear version is much higher: about 0,15 nm at 410 nm at the length of interaction of 72 mm. But that article didn't solve the main design problem: how to align input light beam and sound column for practical performance. The acoustic anisotropy in KDP single crystal is less comparing with high anisotropic materials such as paratellurite. Due to that limitation it must be another approach to KDP devices design. The present paper is devoted to the simple mathematical approach to practical filter development and design. The peculiarities of quasicollinear geometry and acousto-optical interaction in KDP based filters are also investigated.

2 Theoretical consideration

KDP single crystal belongs to the point group symmetry $\bar{4}2$ m. It is characterized by rather high acoustical, optical and photoelastic anisotropy. The slowness curves for propagation in XY-plane resulting from Christoffel equation solution [15] are shown in Fig1.

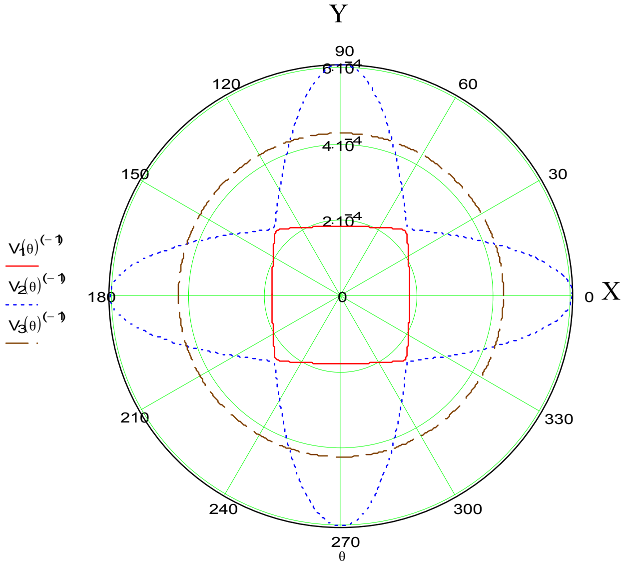

Fig. 1 Slowness curves in XY-plane for KDP crystal.

The analysis is carried out for the XZ-plane of KDP usually used in the acousto-optical devices. The corresponding slowness curves are presented in Fig 2.

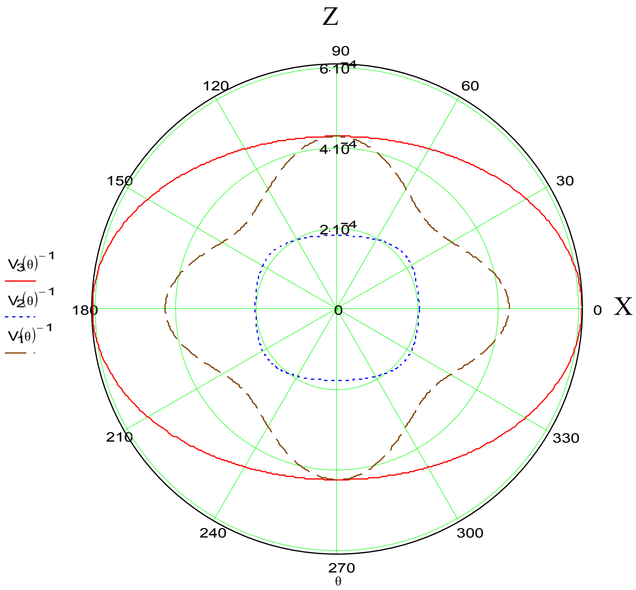

Fig. 2 Slowness curves in XZ-plane for KDP crystal.

Here $V_3(\theta)$ is pure shear acoustic mode (solid curve), $V_1(\theta)$ and $V_2(\theta)$ are quasishear and quasilongitudinal acoustic waves (dashed and dotted lines). The well-known wave-vector diagram formalism for uniaxial crystal is used. That formalism defines the relations between frequency of Bragg synchronism and the angles of light and sound propagation relative crystallographic axis in a plane wave approximation [16]. These relations are necessary conditions for light sound interaction. The driving power value is determined by the effective photoelastic constant. We explore quasicollinear acousto-optical interaction, therefore the wave vector k_i of incident light propagating at the angle φ must be collinear to acoustic group velocity V_{g1} defined in the same coordinate system (Fig.3) 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; ψ_1 - walk-off angle between phase and group velocity of sound. We define the angle α_1 as the angle between acoustic phase velocity V_{p1} reflected from the input facet of the crystal and [100] axis of the crystal.

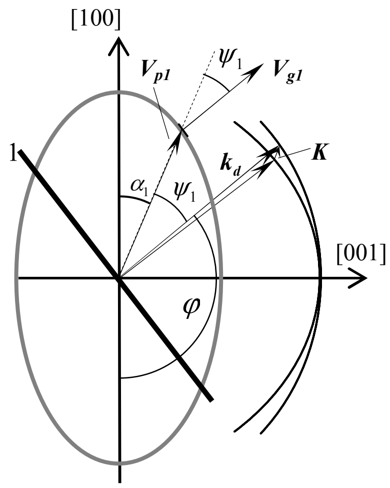

Fig. 3 One-to-one correspondence of wave vector diagram and slowness curve for pure shear mode in KDP single crystal. 1 is the optical facet.

We assume the input facet of the crystal is orthogonal to the wave vector of the light (Fig.3). We consider pure shear acoustic mode propagating in KDP in the plane (XZ) with polarization vector orthogonal to that plane. The solution for phase velocity V_{p1} described by the formula:

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

here ρ – crystal density, c_{11}, c_{12} and c_{44} –elastic constants.

The walk-off angle ψ_1 between acoustic phase and group velocities is defined by equation:

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

Corresponding dependence is presented in Fig 4. The walk – off angle reaches extreme value of 19.8° at α_1=35°.

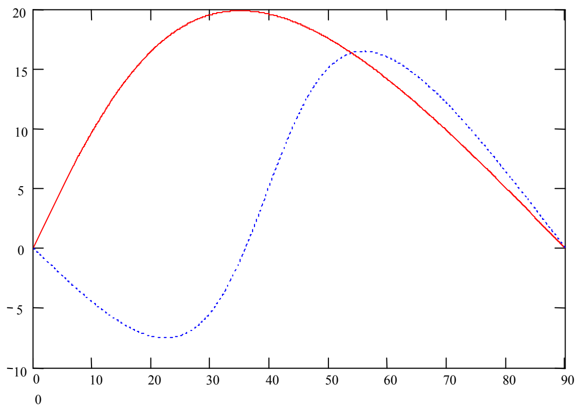

Fig. 4 The walk-off angle between pure shear phase and group velocities (solid line) and quazilongitudinal one (dotted line) versus α_1 value.

3 Quasicollinear KDP filter design.

We assume 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 π/2 - (α_1 + ψ_1) between facet plane and [100] axis of the crystal. In order to determine the transducer's facet orientation relative crystallographic axis we consider drawing presented in Fig.5.

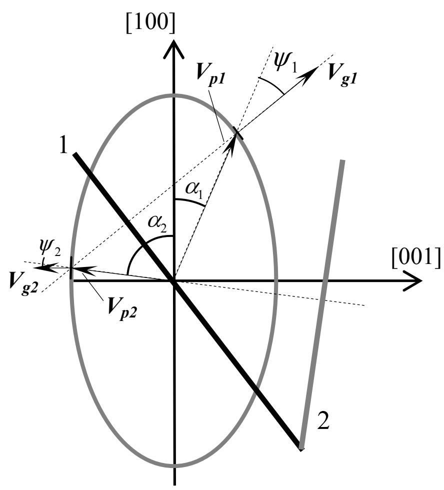

Fig. 5 Orientation of acoustical facet 2 is determined by refection conditions. The optical facet 1 is orthogonal to the light beam.

According to wave motion's law acoustic wave vectors of incident and reflected sound columns have to satisfy to the requirement of equal projection in the crystal. That requirement can be written in the following form:

$$\frac{1}{V_{p1}(\alpha_1)}\sin\psi_1 = \frac{1}{V_{p2}(\alpha_2)}\sin(\alpha_1+\psi_1+\alpha_2), \qquad (3);$$

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

The orientation of the transducer or acoustical facet is defined by the angle $\pi/2$-α_2 between facet plane and [100] axis of the crystal. The angle α_2 value can be determined as a function of α_1 from equations (1)-(3).

The equation (3) doesn't have any analytical solution and was solved by numerical methods.

As it was mentioned above, the main parameter defining optical and acoustical configuration of quasicollinear filter relative to crystalline axes is the angle α_1.

The calculations of optical and acoustical facets orientation versus angle α_1 demonstrate the following features. When α_1 increases from 0º to 90º the angle between optical and acoustical facets raises up to extreme value 24,7º at α_1=32º. If a_1>32° than the angle between facets decreases. The typical design of quasicollinear KDP based filter utilizing orthogonal input optical facet for incoming light beam is shown in Fig 6.

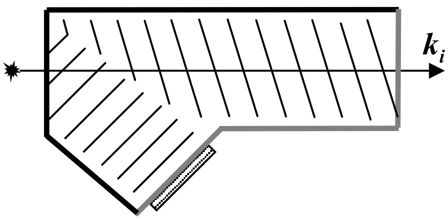

Fig. 6 The construction of KDP based filter utilizing orthogonal input facet.

The following constants taken at a room temperature were used for calculations: c_{11}=7.219x 10^{10} dynes · cm^2, c_{12}=-0.972x 10^{10} dynes · cm^2, c_{44}=1.291 x 10^{10} dynes · cm^2, ρ =2.38 g/cm^3 [17]. We must mention that there are variations for c_{ij} values in the literature.

The optimum value of angle α_1 should be defined from the system requirements.
The figure of merit M_2 corresponding to an angle α_1 is described by well-known formula [10]

$$M_2 = \frac{n_o^3 n_e^3(\alpha_1)\; p^2(\alpha_1)}{\rho V_{p1}{}^3(\alpha_1)}, \qquad (4);$$

here:
n_o, n_e – ordinary and extraordinary indexes of refraction.

$$p(\alpha_1) = p_{66}\cdot\cos\alpha_1\sin(\alpha_1+\psi_1(\alpha_1)) + p_{44}\sin\alpha_1\cos(\alpha_1+\psi_1(\alpha_1)) \qquad (5);$$

$$n_e(\alpha_1) = \frac{n_o n_e}{\sqrt{n_o^2\cos^2(\alpha_1+\psi_1(\alpha_1)) + n_e^2\sin^2(\alpha_1+\psi_1(\alpha_1))}} \qquad (6)$$

The following photoelastic constants were used for calculations: p_{66}=-0.068; p_{44}=-0.034 [12]. We must mention that there are significant variations for p_{44} value in the literature too. The dependence of M_2 calculated for λ=532 nm versus angle α_1 is presented in Fig 7. The M_2 value reaches the maximum equal to 1.7 relative fused quartz at an angle α_1 equal to 30º. (The reference value of M_2 for fused quartz is 1.51 x10^{-15}sec^3/kg).

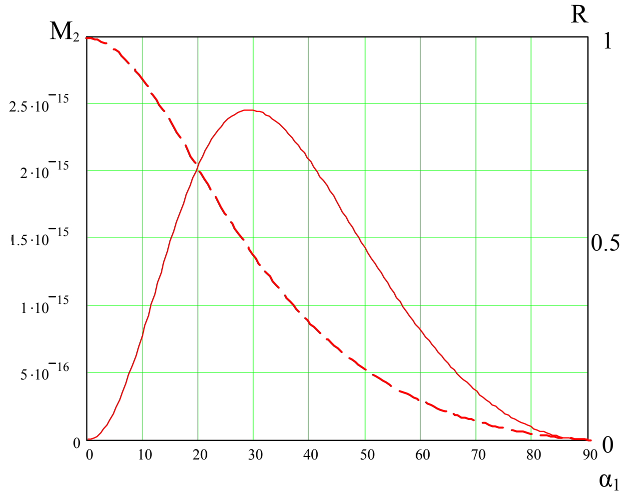

Fig. 7 Acousto-optical figure of merit M_2 (solid curve) and normalized spectral resolution R (dashed curve) versus angle α_1.

The width of spectral transmission function $\delta\lambda$ of the filter at -3gb level is defined as:

$$\delta\lambda = \frac{0.8\lambda^2}{L\cdot(n_o - n_e)\cdot\cos^2(\alpha_1+\psi_1(\alpha_1))} \qquad (7);$$

here L –is the length of acoustic column.

The normalized dependence of filter spectral resolution R, defined as $\lambda/\delta\lambda$, from α_1 value is presented in Fig7 too. Fig 7 demonstrates clearly, that like in the paratellurite case [9] it's impossible to create quasicollinear KDP based filter with both high resolution and low driving RF power.

4 Experimental results

Experimental quasicollinear filter was fabricated according to design approach developed in this paper. The filter was intended for UV-visible region of spectra. Calculation of walk-off angle ψ_2 between the group and phase velocities of acoustic wave, generated by transducer from formulas (1)-(2) allows to define exactly the transducer size and its placement on the acoustical facet.

The α_1 value corresponded to extreme walk-off angle value and was equal to 35º.

The crystal length of the experimental acousto-optical cell was rather small: about 21 mm. The optical aperture (the crossection of acoustic column) was 3x3 mm. The X-cut $LiNbO_3$ transducer was bonded to acoustic facet by indium cold welding vacuum technology. The central working frequency, corresponding to Bragg synchronism conditions at wavelength 532 nm was 52.6 MHz. The four-element LC-circuit matches the complex impedance of the transducer with the standard 50-Ohm output to cover spectral band 250-440 nm. The VSWR ratio at 52 MHz region was out of matching band and was equal to 3.6:1.

The measurements were performed using solid-state single frequency diode-pumped laser operating at wavelength 532 nm. The laser radiation was linearly polarized orthogonal to the diffraction plane. The measured diffraction efficiency was about 32% at 1,0 W driving power. The experimental cell demonstrated excellent spectral resolution at 532 nm. The transmission function bandwidth was about 1,0 nm at -3 dB level. The intrinsic angular aperture of the filter was measured at -3 dB level from the maximum of spectral transmission function. The corresponding date was ±2 angular minutes. All experimental data is in good agreement with calculated parameters. The corresponding recalculation also showed that experimental data correlates with previously published data.

5 Conclusion

Simple and effective algorithm for KDP based quasicollinear acousto-optical filter design was proposed in that work. Generally speaking that algorithm is valid for crystals with different types of symmetry. Experimental device was designed and fabricated. The experimental data demonstrate a good agreement with calculated data. The performed investigations clearly demonstrated that quasicollinear approach to acousto-optical interaction in KDP single is very promising for creating acousto-optical filter having extremely high spectral resolution in UV region. That approach is very useful also to design adaptive acousto-optical delay lines intended to femtosecond laser pulse shaping.

Acknowledgements

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