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ACOUSTO-OPTIC TeO_2 DEVICES USING REGULAR DOMAIN STRUCTURE TRANSDUCERS[1]

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Some results on investigation of anisotropic light scattering by a scanning sound field in an uniaxial crystal are presented. Scanning acoustic waves are generated by means of a transducer with a regular domain structure. The principal possibility to create an acousto-optical tunable filter operating in a wide tuning spectral range and at the same time in a relatively narrow ultrasonic frequency band is demonstrated. An anisotropic acoustooptical deflector using a regular domain structure transducer is considered in the paper as well. Experimental data of light diffraction by the scanning sound field in TeO_2 single crystal are also presented.

1. Introduction

Methods of laser beam control based on acousto-optical interaction in a solid medium find wide applications in optics, optical engineering and laser technology. The design principles of acousto-optic devices: deflectors, modulators, tunable filters are well known [1,2]. As a rule, an acousto-optical Bragg cell uses a uniform piezotransducer with rectangular sound field distribution. If parameters of a Bragg device are to be improved by expanding of the operation range of sound frequencies, then position of the sound beam in space must be controlled. Many authors [3,4,5] have studied in details a beam-steering deflector systems which uses a grating consisting of phased transducers. However, this approach was limited by a case of an isotropic light diffraction only.

First results on a principal possibility to use a grating of phased transducers in anisotropic acousto-optical devices on base of paratellurite was presented in paper [6]. It was shown that there exists a possibility to create an acousto-optical tunable filter with a very wide tuning spectral band. In reference [7], the problem of light diffraction in anisotropic media by application of a scanning sound field found further development.

This presented research is devoted to a general theoretical and experimental investigation of anisotropic light scattering in a paratellurite single crystal with a scanning sound field. In all the examined practical cases, the scanning acoustic waves were generated by means of Lithium Niobate single crystal piezoelectric transducers with a regular domain structure.

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2. General consideration

We examine a transducer consisting of a grating with N elements of length d, each of them launching a sound wave with a phase shift 180° relative to an adjacent element. It is stated that the total length of the transducer is equal to $L = Nd$. Acoustic energy distribution in the far zone has two peaks, each possessing an angular distribution corresponding to a uniform transducer with a length L. These two peaks are positioned symmetrically relative to a normal to the transducer plane at angles $\alpha_1 = \pm V/fd$, where V is the sound phase velocity and f is the sound frequency.

The wave-vector diagram of the anisotropic light scattering in paratellurite single crystal is shown in Fig. 1. Here $\vec{K}_+$ and $\vec{K}_-$ are the wave vectors of sound, corresponding to the two peaks, respectively, while $\vec{k}_i$, $\vec{k}_{d+}$ and $\vec{k}_{d-}$ are the wave vectors of incident and diffracted light, φ is the Bragg angle of incidence and α the angle between normal to the transducer plane and **[110]** axis of the paratellurite single crystal. Let us suppose that optical activity of the crystal in a spectral interval of acoustoptic interaction is negligible. In the general case, a relationship between acoustic frequency f, providing scattering of light, the Bragg angle φ and orientation angle of the paratellurite prism relative to crystalline axes α is determined by the equations [6]:

$$f = \left(\frac{V}{\lambda_0}\right)\left\{(n_0 + R)\cos\left(\varphi + \alpha \pm \frac{V}{fd}\right) \pm \left[n_0^2 - (n_0 + R)^2 \sin^2\left(\varphi + \alpha \pm \frac{V}{fd}\right)\right]^{1/2}\right\}, \tag{1}$$

where

$$R = n_0 n_e \left(n_0^2 \cos^2\varphi + n_e^2 \sin^2\varphi\right)^{-1/2} - n_0. \tag{2}$$

Here n_0 and n_e are the refraction indexes for ordinary and extraordinary optical waves and λ_0 is the optical wavelength in vacuum.

A dispersion of the refraction indexes n_0 and n_e is determined by empirical equations

$$n_0^2 = 1 + 2.5844\lambda_0^2/\left(\lambda_0^2 - 0.0180\right) + 1.557\lambda_0^2/\left(\lambda_0^2 - 0.0696\right), \tag{3}$$

$$n_e^2 = 1 + 2.8525\lambda_0^2/\left(\lambda_0^2 - 0.0180\right) + 1.5441\lambda_0^2/\left(\lambda_0^2 - 0.0696\right), \tag{4}$$

where λ is expressed in μm.

Phase velocity V of sound as a function of the crystal orientation α is given by the equation

$$V = 0.617 \times 10^5 \left(1 + 10.62 \sin^2\alpha\right)^{1/2} \text{cm/sec}. \tag{5}$$

The presented equations (1–5) determine Bragg angle φ dependence upon the sound frequency value f for an anisotropic interaction. Obviously, only one lobe of the sound field ($\vec{K}_+$ or $\vec{K}_-$) can be used for light scattering. In case of a uniform transducer ($d = \infty$) solution of equations (1–6) $f = f(\varphi)$ describes all types of the acoustooptic TeO$_2$ devices fabricated so far. For example, in the low frequency region of the solution where $\partial f/\partial\varphi = 0$, one can observe acoustooptic interaction with a large angular aperture commonly used in tunable filters [8]. The region of the solutions, where $\partial f/\partial\varphi = \infty$ determines well-known high frequency bands of the acoustooptical interaction widely used in the anisotropic deflectors [1,2].

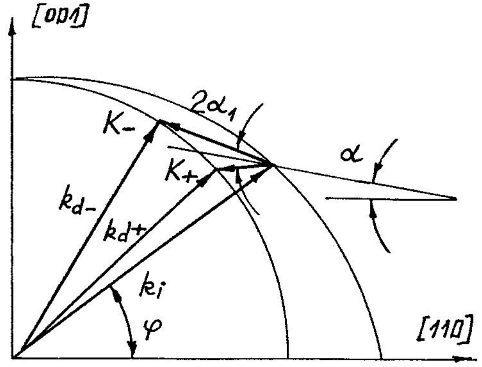

Fig. 1. Wave vector diagram of anisotropic light by scanning ultrasound waves.

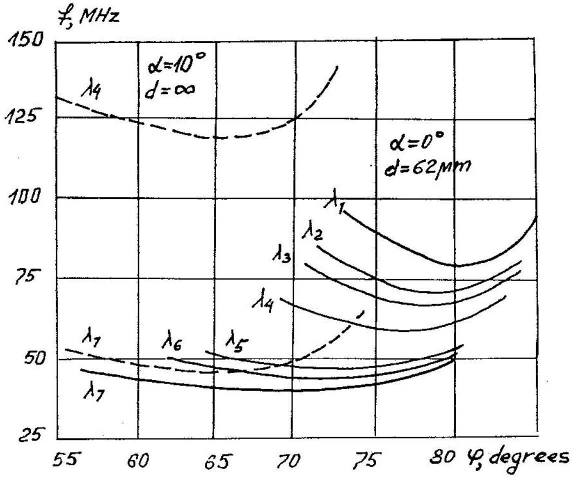

Fig. 2. Solution of equations (1–5) for a tunable filter case with a uniform transducer (dashed curves $\hat{a} = \infty$, $\alpha = 10°$) and with a grating of phased transducers (solid curves). $\lambda_1 = 0.4047$ μm, $\lambda_2 = 0.488$ μm, $\lambda_3 = 0.515$ μm, $\lambda_4 = 0.6328$ μm, $\lambda_5 = 1.0$ μm, $\lambda_6 = 1.2$ μm, $\lambda_7 = 1.5$ μm; $d = 62$ μm; $\alpha = 0$.

Now we consider the solution of equations (1–5) in the presence of the scanning sound field ($d \neq \infty$) in the region, with $\partial f/\partial\varphi = 0$ corresponding to a non-collinear acoustooptical tunable filter. These solutions for a paratellurite single crystal and $\vec{K}_+$ scanning lobe (the sign plus in equation (1)) are plotted in Fig. 2 for various wavelengths λ. The dashed curves correspond to a well-known acoustooptical tunable filter with the uniform transducer ($d = \infty$, $\alpha = 10°$) [8].

Fig. 3 shows how the wavelength λ_0 to which the filter is tuned depends on the

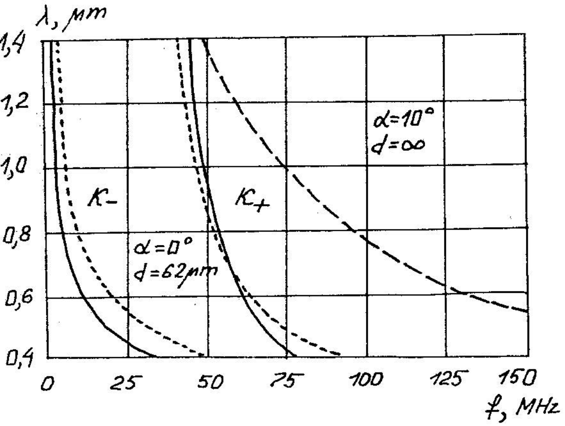

Fig. 3. Wavelength value to which the filter is tuned vs sound frequency. Solid curves $d_1 = 62$ μm, $\alpha = 0$, $\varphi_0 = 78°$; point curves $d_2 = 62$ μm, $\alpha = 0$, $\varphi_0 = 75°$; dashed curve – for a uniform transducer $d_2 = \infty$, $\alpha = 10°$, $\varphi_0 = 69°$.

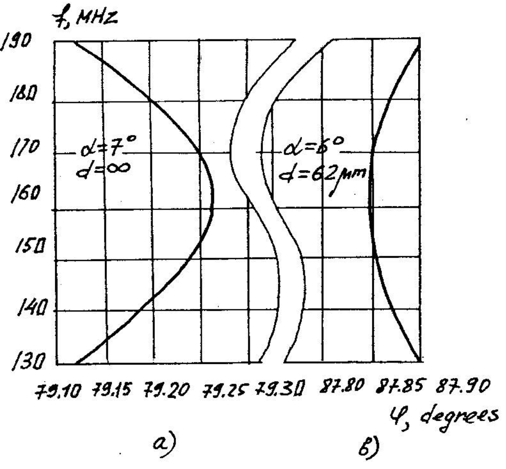

Fig. 4. Solution of equations (1–5) for the deflector case a) with a uniform transducer, b) with a grating of phased transducers $\lambda = 0.6328$ μm.

sound frequency f.

Typical acoustooptic tunable filters [8] have the disadvantage of a narrow tuning spectral range, which is usually no greater than an octave (dashed curve in Fig. 3). The results shown in Fig. 2 and Fig. 3 definitely demonstrate a significant expanding of tuning spectral range, if an appropriate lobe of the sound scanning field ($\vec{K}_+$) is used. In the case of $d = 62$ μm and $\alpha = 0$, the tuning spectral range is about twice the octave.

Now we consider the influence of a phased transducers grating on basic parameters

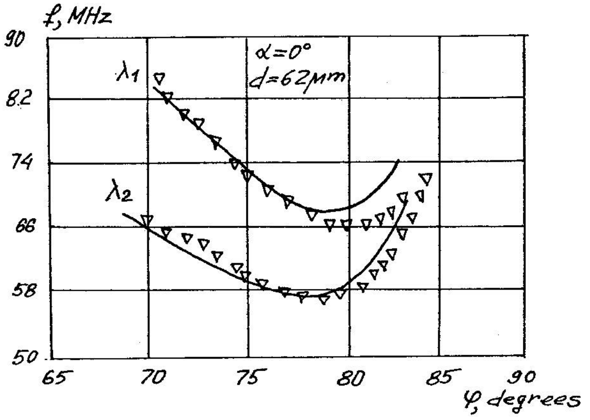

Fig. 5. The interaction frequency vs incident Bragg angle. $\lambda_1 = 0.488$ μm, $\lambda_2 = 0.6328$ μm.

of the anisotropic deflector. The solutions of equations (1–5) for paratellurite single crystal corresponding to the appropriate region $\partial f/\partial\varphi = \infty$ are plotted in Fig. 4. The solution shown in Fig. 4a illustrates a high frequency band of diffraction (the sign plus in (1)) for an ordinary deflector with a uniform transducer ($d = \infty$, $\alpha = 7°$). The curve in Fig. 4b corresponds to the low frequency band (the sign minus in (1)) for a deflector using a grating of phased transducers ($d = 62$ μm, $\alpha = 6°$). Fig. 4b shows that divergence of sound in paratellurite may be about 3 times smaller and according to the length of the transducer it may be about 3 times larger. Unfortunately, this scanning system has the disadvantage that only one of two lobes in the sound field is used to deflect light. Therefore, only $4/\pi^2 = 0.4$ of the acoustic power is used to advantage.

3. Experimental results

Shear acoustic waves were generated in TeO$_2$ by 163°YZ-cut LiNbO$_3$ piezoelectric transducer with a regular domain structure formed by the thermoelectric method described in papers [9,10,11]. Thermoelectric treatment of the crystal after its growth had created regular domain structure containing oppositely polarized domain regions of approximately equal thickness. During this treatment process Lithium Niobate was influenced by a temperature gradient near Curie point and by an interchangeable electric field which determined the sign of a spontaneous polarization. A rectangular specimen of Lithium Niobate single-crystal oriented along XYZ axes was placed in a tubular furnace with a temperature gradient along a vertical axis and was heating above Curie point. The specimen was shifted to the region of a lower temperature with a given velocity in the presence of the interchangeable electric field. Oppositely polarized domains regions launch sound waves 180° out of phase with that launched by the adjacent region.

The Lithium Niobate transducer was bonded to a surface of TeO$_2$ prism by indium cold welding method in vacuum. Combination of deposited one by one films of Aurum and Indium is mostly preferable for a transducer fabrication in acoustooptic devices. Interdiffusion of Aurum and Indium in the film even at a room temperature stimulates formation of binary intermetallic compounds such as AuIn, $AuIn_2$, etc. Type of compound to be formed depends on the Au:In ratio in the layers and on the diffusion time. The resulting compound is formed in accordance with a Au–In equilibrium diagram.

Orientation of the experimental TeO_2 filter cell for the filter operation was along the **[110]**, **[1$\bar{1}$0]** and **[001]** crystalline axes. The $LiNbO_3$ transducer was placed on **(110)** facet of paratellurite prism ($\alpha = 0$). The dimensions of the transducer were 2×2 mm. The diffraction efficiency reached 50% at 0.5W of driving RF power. The period of the transducer regular domain structure $2d$ was about 120 μm. Electrical impedance of the transducer was matched with the driver in a frequency band 50–90 MHz with VSWR 3:1. The experiment was carried out in visible light at two wavelengths 0.488 μm and 0.6328 μm.

Interaction sound frequency dependence on incident Bragg angle was investigated during this experiment. The experimental results are presented in Fig. 5. The solid curve in the figure was calculated on base of equations (1–5).

4. Conclusion

Theoretical analysis of anisotropic light diffraction by scanning acoustic field has been carried out. The analysis was limited to a wave-vector diagram formalism. A new method for expanding of a tuning spectral range of a TeO_2 acousto-optical filter is presented. TeO_2 acousto-optical deflector is considered in the paper as well. In all the examined cases, the acoustic waves were generated by means of a transducer with a regular domain structure. Experimental results of the investigation are in good agreement with the results of a calculation.

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