Acousto-Optics and Applications

Quasi-Collinear Acousto-Optic Interaction in Inhomogeneous Acoustic Field

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In studying characteristics of quasi-collinear acousto-optic tunable filters, we observed a new effect not explained by existing theories. As found, at high levels of driving power corresponding to high diffraction efficiency, a transition of energy from a diffracted light beam to a non-diffracted one vanished. In addition, the increase of the acoustic power was accompanied by a significant broadening of the filter frequency bandwidth. This effect could not be described in terms of the traditional consideration of acousto-optic diffraction based on a plane wave approximation and a model of a homogeneous acoustic column. The goal of this research was to develop a mathematical model capable of a correct description of the new effects. The paper examines a case of the quasi-collinear acousto-optic diffraction taking into account the two-dimensional spatial structure of the acoustic field. We gave a theoretical description of the effect of diffracted light beam intensity saturation at high level of acoustic driving power. It was shown that this effect was caused by the diffraction distortion of the acoustic field phase fronts in the plane of the acousto-optic interaction.

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1. Introduction

Acousto-optics (AO) deals with the interaction of sound and light in a dielectric material. The fundamental operation principle of AO devices is as follows: a high frequency electrical signal is converted into an ultrasonic wave by a piezoelectric oscillator bonded to AO medium; the sound wave travels through the medium and diffracts light in a certain direction [1]. One of modifications of AO devices, which are widely used in modern optoelectronic and laser physics, is related to the acousto-optic tunable filters (AOTFs). In particular, the devices of practical interest are the AOTFs with a quasi-collinear geometry of AO interaction based on paratellurite single crystal (TeO_2). The quasi-collinear filters based on TeO_2 were for the first time proposed in Moscow University [2]. The main feature of such devices is that they operate in the Bragg regime of light and sound interaction while the wave vector of the incident light is sent in AO cell collinearly with the group velocity vector of ultrasound. As a result, application of the diffraction geometry provides longer lengths of AO interaction and narrower frequency bandwidths of filtering.

In experimental study of the quasi-collinear AOTF, we observed an unusual effect [3]. As found, at high levels of driving power corresponding to high diffraction efficiency, a transition of energy from a diffracted light beam to a non-diffracted one vanished (Fig. 1). In addition, the increase of the acoustic power was accompanied by a significant broadening of the frequency bandwidth of the device. This effect could not be described in terms of the traditional consideration of AO diffraction.

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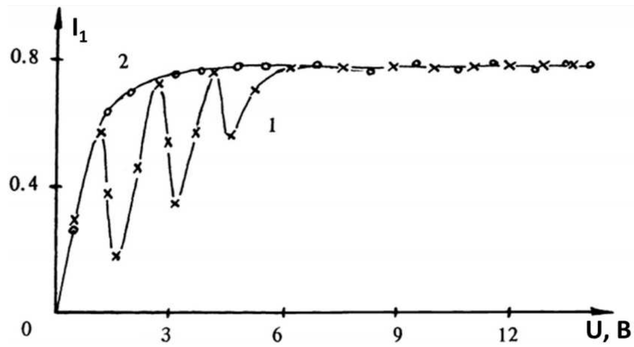

Fig. 1. Dependence of the diffracted light beam intensity on the driving voltage. Diameter of the incident light beam is equal to (1) 0.1 cm, (2) 0.4 cm.

The traditional consideration of AO diffraction is based on plane wave approximation and a model of a homogeneous acoustic column. The classical model [1] assumes a periodic exchange of energy between the diffraction orders with the increasing acoustic power. Therefore, the goal of this research was to develop a mathematical model capable of a correct description of the new effects.

2. Analysis of quasi-collinear acousto-optic interaction in presence of inhomogeneous acoustic field

2.1. Acoustic field of rectangular transducer

The effect of backscattering absence from the first to zeroth diffraction order was considered earlier for the simpler case: light beam was sent in AO cell not collinearly but orthogonally to the acoustic column [4]. As it was shown in the paper [5] in order to correctly describe the phenomenon of light diffraction by ultrasound, it is necessary to consider inhomogeneity of the real acoustic field structure generated by the transducer. It was also shown that it is necessary to consider not only the acoustic field amplitude distribution in the crystal but also the distortion of the phase fronts of the sound field, including as a result of diffraction effects. Further examination is devoted to consideration of the spatial acoustic field structure generated by a rectangular transducer in terms of the mathematical model described in [6].

It is known that the field of elastic displacement of the medium particles in monochromatic wave, generated by piezoelectric transducer placed in the plane $x = 0$, is described by the following equation [6]:

$$S(x, y, z, t) = \Re S_0 H_y(x, y) H_z(x, z - x\tan\psi) \times \exp\left(-\mathrm{i}\,\Omega\left(t - x/V_s\right)\right), \quad (1)$$

where S_0 — acoustic amplitude near the transducer, V_s — phase velocity of the central acoustic wave, Ω — its frequency, ψ — acoustic energy walk off angle in the plane zx, H_y and H_z — complex profiles of the acoustic field which describe its spatial structure.

If transducer occupies the area $-0.5l_y \le y \le 0.5l_y$ and $-0.5l_z \le z \le 0.5l_z$ in the plane yz, where l_y, l_z — dimensions of transducer along the corresponding coordinates, complex profiles in normalized coordinates X_y and X_z have the following identical form:

$$H_y(x, y) = H\left(X_y, y/l_y\right), X_y = \Lambda B_y x/\pi l_y^2,$$

$$H_z(x, z) = H\left(X_z, z/l_z\right), X_z = \Lambda B_z x/\pi l_z^2,$$

$$H(\alpha, \beta) = 0.5\mathrm{erf}\left(\left(\beta + 0.5\right)/\sqrt{\mathrm{i}\alpha}\right) - \mathrm{erf}\left(\left(\beta - 0.5\right)/\sqrt{\mathrm{i}\alpha}\right). \quad (2)$$

In Eq. (2), Λ — wavelength of acoustic wave, erf(ξ) — error function, α and β — parameters related to spatial coordinates x, y, z, B_z, B_y — quadratic anisotropy factors of crystal. General view of amplitude and phase distribution is shown in Figs. 2, 3 in case of walk off angle equal to zero. The figure shows that in the near-field, phase of the acoustic field is practically uniform, and phase fronts are gradually distorted with increasing distance from the transducer. It turned out that this fact significantly influences on the characteristics of acousto-optic diffraction.

2.2. Two-dimensional coupled wave equation

For solving the problem of light beam diffraction in the inhomogeneous acoustic field, it is necessary to extend the well-known one-dimensional coupled-wave equation over the two-dimensional case. For the first time this procedure was considered in the following paper [7].

We considered practically interesting regime of the Bragg diffraction from the first to the zeroth diffraction order. There is the only mismatch vector $\eta_0 = \{\eta_x, 0, \eta_z\}$ in this case, and the coupled wave equation system takes the following form:

$$\frac{\partial C_0}{\partial x}\cos\gamma_0 + \frac{\partial C_0}{\partial z}\sin\gamma_1 = -0.5q^* C_1 \exp\left(\mathrm{i}\left(\eta_x x + \eta_z z\right)\right),$$
$$\frac{\partial C_1}{\partial x}\cos\gamma_1 + \frac{\partial C_1}{\partial z}\sin\gamma_1 = 0.5qC_0 \exp\left(-\mathrm{i}\left(\eta_x x + \eta_z z\right)\right). \quad (3)$$

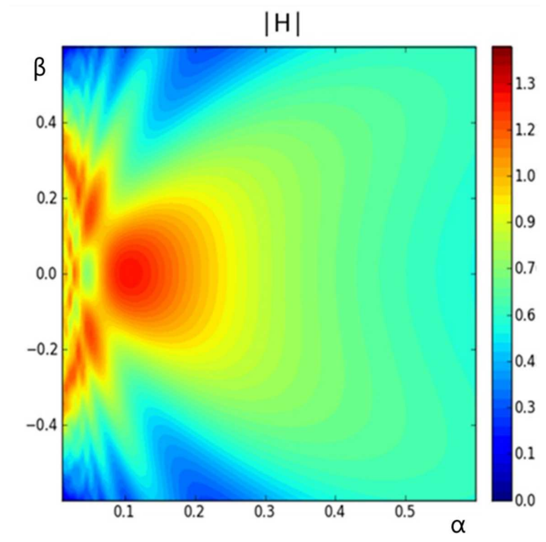

Fig. 2. General view of amplitude distribution presented by the function $H(\alpha, \beta)$ without energy walk-off.

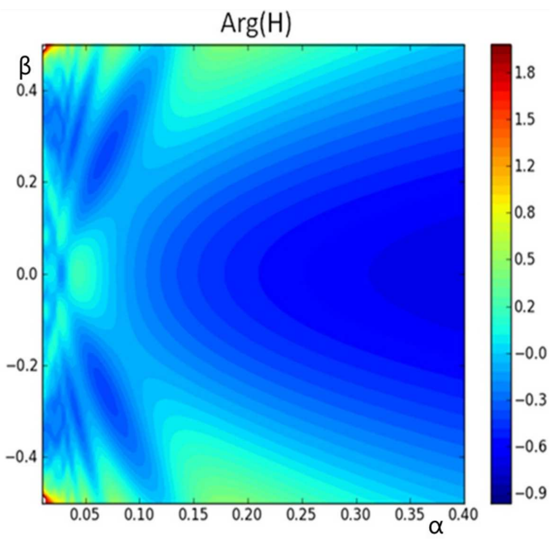

Fig. 3. General view of phase distribution presented by the function $H(\alpha, \beta)$ without energy walk-off.

In Eq. (3), all the parameters with the index 1 correspond to diffracted light, parameters with the index 0 describe transmitted light, q^* — complex conjugate coupling parameter.

3. Calculation of characteristics of quasi-collinear acousto-optic filter

From the general consideration of 2D acousto-optic interaction, we can go to analysis of the quasi-collinear AO diffraction. We suppose that a monochromatic light beam with a Gaussian amplitude distribution is incident by the Bragg angle on the central acoustic wave in the diffraction plane xz. Scheme of the considered AO interaction geometry is shown in Fig. 4 where $\boldsymbol{G}$ — the Pointing vector of acoustic wave, vectors $\boldsymbol{E}_1$, $\boldsymbol{E}_0$ correspond to optical field amplitudes of the first and zeroth

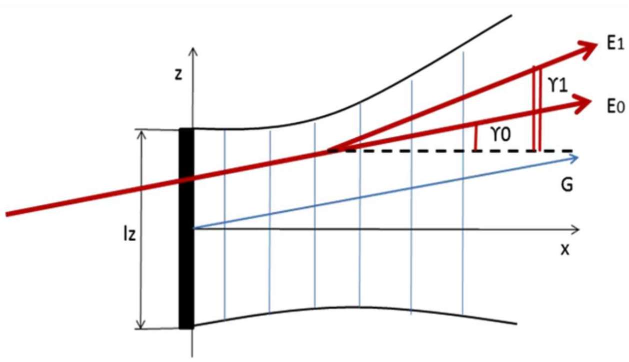

Fig. 4. General scheme of quasi-collinear AO interaction geometry.

diffraction orders, $\gamma_{0,1}$ — angles between wave vectors of light beams and x-axis, l_z — transducer dimension along z-axis.

For the Bragg diffraction in case of matching, Eq. (3) transforms in the following way:

$$\frac{\partial C_0}{\partial x}\cos\gamma_0 + \frac{\partial C_0}{\partial z}\sin\gamma_1 = -0.5q^* C_1,$$
$$\frac{\partial C_1}{\partial x}\cos\gamma_1 + \frac{\partial C_1}{\partial z}\sin\gamma_1 = 0.5qC_0. \quad (4)$$

Further consideration was carried out under the following assumptions:

1. We can neglect diffraction of light beam on its aperture over the length of AO interaction;
2. Limitations of the AO matching bandwidth can be neglected;
3. The incident and diffracted light beams are spatially overlapping.

The numerical calculation allows to obtain the dependence of the diffraction orders intensities on the control power level. The dependence takes the following form (Fig. 5). The character of this dependence is in qualitative agreement with the experimental results.

In order to find it out how the transmission bandwidth of the filter changes with variation of the driving power corresponding to constant diffraction efficiency, we consider the coupled-waved equation in the case of nonzero mismatch parameter.

Numerical calculation of this system gives the 2D dependences of the diffraction efficiency on the mismatch parameter at fixed levels of the driving power. The transmission bandwidth of the quasi-collinear filter is broadening with the growth of the driving power. This trend is confirmed experimentally.

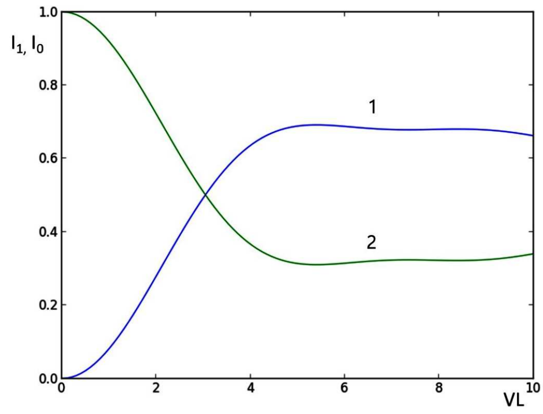

Fig. 5. Dependence of diffraction efficiency on Raman–Nath parameter (1 — first diffraction order; 2 — zeroth diffraction order).

4. Conclusion

The presented results make it possible to concede a general possibility to design principally new of AO filters, in which control of the transmission bandwidth may be provided by changes of the driving power applied to the transducer. We develop a mathematical model capable of a correct description of the quasi-collinear diffraction in a real acoustic field. A theoretical verification was given for the effect of saturation of the diffracted light beam intensity at high level of the acoustic driving power. It was shown that this effect is caused by the diffraction distortion of the acoustic field fronts in the plane of the AO interaction.

Acknowledgments

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