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Polarization effects at collinear acousto-optic interaction

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ABSTRACT

Collinear acousto-optic diffraction of an arbitrarily polarized optical radiation is studied theoretically and experimentally. It is shown that in the general case the diffracted light spectrum at the acousto-optic cell output consists of four components with different frequencies and polarizations. Beatings of these components lead to intensity modulation of the light passed through an output analyzer. Dependences of output intensity components on ultrasound frequency and acoustic power are examined for different orientations of the polarizer and the analyzer. Experimental investigations are carried out with a collinear acousto-optic cell fabricated with calcium molybdate single crystal.

1. Introduction

Nowadays, crystals and glasses are used mostly for fabrication of acousto-optic (AO) devices. Crystals primordially possess anisotropy of acoustic and optical properties. When arbitrarily polarized light passes through the optically anisotropic crystal, it splits into two orthogonally polarized components, which diffract in the acoustic field independently. In the case of optically isotropic media (cubic crystals or glasses), the acoustic wave induces optical anisotropy. Thus, the anisotropy axes that determine polarization of optical eigenmodes are either predetermined by crystal symmetry (in anisotropic media) or induced by ultrasound (in isotropic media). AO effect strongly depends on the optical radiation polarization; the polarization affects AO diffraction efficiency and all other characteristics of AO devices [1–3]. Conventional recommendations consist in the following: in an anisotropic medium the incident radiation should have the polarization of one of the medium normal modes, whereas in an isotropic medium the polarization vector should be directed along one of the sound-induced anisotropy axes. However AO interaction of arbitrarily polarized or unpolarized light is undoubtedly of theoretical and practical interest.

In an isotropic medium, two variants of AO interaction, namely, light diffraction on longitudinal or shear acoustic waves are possible. In the case of a longitudinal wave, the AO cell can be considered as a superposition of two phase diffraction gratings. These gratings have the same period, but different amplitudes of refractive index change Δn because of difference in elasto-optic coefficients p_{11} and p_{12}. Each optical mode diffracts on its own grating independently. At the AO cell output the diffracted modes are put together, forming the wave with changed polarization. This effect was first examined in [4,5] for the Raman–Nath diffraction regime. It has been shown that the radiation remains linearly polarized in all diffraction maxima in the case of arbitrary linear polarization of incident light, but the polarization plane can turn by an angle depending on the acoustic power. The situation becomes more complicated in the Bragg diffraction regime and especially in the intermediate one because of the additional phase shift effect appearing in the diffraction maxima [6–9]. Due to this effect the polarization of light at the output of the AO interaction region turns out to be elliptical in the general case. The orientation of the polarization ellipse and its form (ellipticity coefficient) can vary from linear to circular depending on the acoustic power and the ratio of the coefficients p_{11} and p_{12} [10].

In the case of light diffraction by a shear acoustic wave, the polarization vectors of eigenmodes are oriented at the angle 45° with respect to the ultrasound direction. The diffraction gratings induced by ultrasound have the same amplitudes of the refractive index change Δn defined by the elasto-optic coefficient $p_{44}=(p_{11}-p_{12})/2$. However these gratings are shifted with respect to each other by the acoustic half-wavelength. The shift has no effect on the 0th diffraction order, whereas in the first one it gives a phase shift by π between the normal modes. As a result, the output radiation polarization does not depend on AO interaction parameters, however the polarization in the first order is inverted specularly. For example, if the incident light is linearly polarized at an angle α with respect to the ultrasound direction, the diffracted radiation will be polarized at an angle $90^\circ-\alpha$. In the case of circular polarization of incident light, the diffracted wave will have circular polarization with the opposite direction of rotation [10].

Polarization effects in optically anisotropic media have a number of peculiarities [11]. (1) The natural birefringence produces a phase

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shift between eigenmodes. This shift does not depend on the acoustic power, but it changes at varying the acoustic frequency or the optical angle of incidence. (2) The difference in Bragg angles for the eigenmodes can be so great that only one mode will be diffracted. In this case, the AO cell operates as a polarizer oriented along one of the anisotropy axes. (3) The polarization state can depend on the orientation of the cell input face. (4) Polarization effects show themselves differently at isotropic (without optical eigenmodes conversion) and anisotropic (with conversion of the modes) diffractions.

There is another side of the subject matter. In applied physics, the problem of unpolarized optical radiation control appears fairly often. It is obvious that this problem can be solved by setting a polarizer at the input of the optical system. But this way results in the loss of half optical power that is inadmissible in many cases. In acousto-optics, there is no general and effective solution of this problem. Sometimes, two AO cells arranged one by one or in parallel are used [12,13]. In this case AO devices become complicated in design and difficult in adjustment.

In all articles cited, only quasi-orthogonal geometry of AO interaction was examined, which takes place when the optical wave propagates almost perpendicularly to the acoustic beam. In the case of collinear AO diffraction, polarization effects have quite other features. This problem was first analyzed in our work [14]. The given paper presents detailed theoretical and experimental investigations of polarization effects at collinear AO interaction. The experiments were carried out with a collinear AO cell fabricated of a calcium molybdate ($CaMoO_4$) single crystal.

2. Basic relations

The main peculiarity of collinear AO interaction is that incident and diffracted optical waves as well as an acoustic wave propagate along the same direction [1,3]. Fig. 1 shows the scheme of collinear diffraction implementation in a calcium molybdate cell [15,16]. An acoustic wave is first excited by a transducer along the crystallographic axis Z (optical axis of the crystal) in the form of a longitudinal acoustic mode. After reflection from the input optical face of the AO cell, this mode is transformed into a shear mode propagating along the X axis. The progressive wave regime is ensured by an acoustic absorber placed at the output end of the cell. A laser beam passes through the cell along the X axis and diffracts in the acoustic field with change in polarization (anisotropic diffraction [1,3]). Two prisms are employed to compensate refraction of light at the input and output faces of the $CaMoO_4$ cell.

Generally, collinear AO cells are used as spectral filters [15]. In this case, a polarizer specifies the input optical polarization along the Y or Z axes (ordinary or extraordinary polarization), whereas an analyzer is oriented perpendicularly to the polarizer. Such geometry makes it possible to separate the diffracted wave from the incident one. Contrary to this conventional situation, in this work we examine the case of arbitrary polarization of the incident light.

Let us suppose that a plane acoustic wave with the frequency Ω and the wave vector $\mathbf{K}$ propagates along the X axis. Due to the

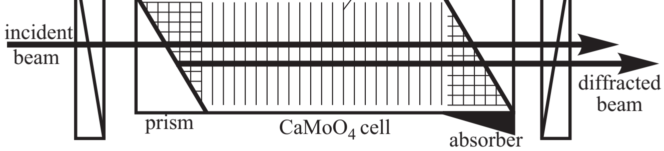

Fig. 1. Schematic plot of collinear AO interaction in a $CaMoO_4$ cell.

elasto-optic effect this wave changes the refractive index as [1,3]

$$n(x,t) = n + \Delta n \sin(\Omega t - Kx), \quad (1)$$

where n is the static index of refraction and Δn is its amplitude variation under the action of the acoustic wave. An incident optical wave with the amplitude E_i, the frequency ω_0 and the wave vector $\mathbf{k}_0$, passing through the acoustic field, is split into a set of waves:

$$\mathbf{E}(x,t) = E_i \sum_{p=-\infty}^{\infty} \mathbf{e}_p C_p \exp[j(\omega_p t - \mathbf{k}_p \mathbf{r})] \quad (2)$$

where $\mathbf{e}_p$ are the unit vectors of polarization of the diffracted waves with relative amplitudes C_p. Substituting this expression into the wave relationship:

$$\nabla^2 \mathbf{E} = \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\left\{\left[n^2 + 2n\Delta n \sin(\Omega t - Kx)\right]\mathbf{E}\right\}, \quad (3)$$

we derive the following set of coupled-wave equations:

$$\frac{\mathrm{d}C_p}{\mathrm{d}x} = \frac{q_p}{2}\left[C_{p+1}\exp(\mathrm{j}\eta_p x) - C_{p-1}\exp(-\mathrm{j}\eta_{p-1}x)\right]. \quad (4)$$

here $q_p = k_p \Delta n / n\cos\theta_p$ are the AO coupling coefficients and θ_p are the angles measured from the X axis, which define the direction of the diffracted waves. Eq. (4) have the same form as for the case of the quasi-orthogonal AO interaction [1,2], but the phase mismatch parameters η_p are determined as

$$\eta_p = k_p \cos\theta_p - k_{p+1}\cos\theta_{p+1} + K. \quad (5)$$

In a real experimental situation the mismatches η_p are too great for all diffraction transitions with the exception of the first ones. Therefore, high diffraction orders are entirely absent and the collinear AO interaction is always realized in the form of Bragg diffraction. Calcium molybdate belongs to the group of positive crystals; its refractive index for the extraordinary light polarization (n_e) is greater than that for the ordinary polarization (n_o). Consequently, if the incident radiation has the ordinary polarization, then it is scattered into the $+1$st diffraction order. In the case of the extraordinary polarization the scattering occurs into the -1st order. The diffraction process is accompanied by changing polarization (anisotropic diffraction) and frequency (due to the Doppler effect), so that $\omega_{\pm 1} = \omega_0 \pm \Omega$. With taking into account these peculiarities one can write down eq. (4) separately for both the optical eigenmodes:

$$\begin{cases} \frac{\mathrm{d}C_0^{(o)}}{\mathrm{d}x} = \frac{q_0}{2}C_1^{(e)}\exp(\mathrm{j}\eta_0 x) \\ \frac{\mathrm{d}C_1^{(e)}}{\mathrm{d}x} = -\frac{q_1}{2}C_0^{(o)}\exp(-\mathrm{j}\eta_0 x) \end{cases}, \quad \begin{cases} \frac{\mathrm{d}C_0^{(e)}}{\mathrm{d}x} = -\frac{q_0}{2}C_{-1}^{(o)}\exp(-\mathrm{j}\eta_{-1} x) \\ \frac{\mathrm{d}C_{-1}^{(o)}}{\mathrm{d}x} = \frac{q_{-1}}{2}C_0^{(e)}\exp(\mathrm{j}\eta_{-1} x) \end{cases} \quad (6)$$

Now we can perceive the situation, which takes place when the incident optical wave propagating exactly along the X axis ($\theta_p = 0$) has linear polarization at the angle α to the Y axis (Fig. 2). Entering the crystal, the wave is split into two waves with amplitudes E_i^Y (ordinary mode) and E_i^Z (extraordinary mode), which are polarized along the axes Y and Z. These waves diffract in the acoustic field independently. The ordinary wave E_i^Y diffracts into the $+1$st diffraction order, forming the waves E_0^Y (the 0th order with ordinary polarization) and E_{+1}^Z (the $+1$st order with extraordinary polarization). The extraordinary optical wave E_i^Z diffracts in a similar manner in -1st order, forming the waves E_0^Z and E_{-1}^Y. The optical waves of the 0th order E_0^Y and E_0^Z have the frequency ω_0 equal to the frequency of the incident light, whereas the waves E_{+1}^Z and E_{-1}^Y have frequencies $\omega_0 + \Omega$ and $\omega_0 - \Omega$, correspondingly. Solving Eq. (6), one can obtain the following expressions for the components of the optical beam at the AO cell output:

$$E_0^Y = E_i \cos\alpha \cdot \left(\cos\frac{K}{2} - \mathrm{j}\frac{R}{2}\,\mathrm{sinc}\,\frac{K}{2\pi}\right)\exp\left[\mathrm{j}\left(\omega_0 t - k_o l + \frac{R}{2}\right)\right], \quad (7)$$