THE INTERMEDIATE REGIME OF LIGHT DIFFRACTION BY ULTRASOUND IN PLANAR GYROTROPIC OPTICAL WAVEGUIDES IN AN EXTERNAL ELECTRIC FIELD

G. V. Kulak and S. N. Kovchur

A theoretical investigation is carried out for an intermediate regime of optoacoustic interaction, close to the Bragg one, by ultrasonic Rayleigh surface waves in gyrotropic planar waveguides in an external electric field. A system of equations of associated waves is presented which describes the planar optoacoustic interaction in intermediate, Raman–Nath, and Bragg regimes of diffraction by ultrasonic surface waves in gyrotropic crystals with electrically induced anisotropy. It is shown that the intermediate (transition) regime of optoacoustic interaction, which is characterized by an angular selectivity and by the presence of several diffraction maxima, is the basic regime of diffraction. In this case diffracted light is generally elliptically polarized with an ellipticity and polarization azimuth that depend on the external electric field intensity.

Key words: optoacoustic interaction, ultrasonic wave, gyrotropy, cubic crystal, optical waveguide, electrically induced anisotropy.

Investigation of light diffraction by ultrasonic (US) waves in planar gyrotropic optical waveguides in an external electric field is of scientific and practical interest [1], since a number of crystals with the structure of sillenite (Bi$_2$GeO$_2$O$_{20}$, Bi$_2$SiO$_2$O$_{20}$, Bi$_2$TiO$_2$O$_{20}$, etc.), being promising for optoelectronics, have a high specific rotation of the polarization plane of a light wave and simultaneously an electro-optical effect. The waveguide properties of planar structures based on crystals with a sillenite structure are investigated in [2, 3]. In [4], the waveguide properties are considered for multilayer planar structures based on uniaxial gyrotropic crystals of quartz (SiO$_2$) and paratellurite (TeO$_2$).

It is well known [5, 6] that in uniaxial and biaxial crystals gyrotropy is manifested only for directions of light propagation that are close to the optical axes, while in an isotropic medium and in a cubic crystal, gyrotropy should be taken into account for any geometry of interaction between light and ultrasound. The specific features of planar Bragg optoacoustic (OA) interaction in gyrotropic cubic crystals in an external electric field are studied in [7]. In [8], the peculiarities of the Raman–Nath OA diffraction in gyrotropic crystals with electrically induced anisotropy are considered and it is shown that the gyrotropy and the electrically induced anisotropy of a crystal in an external electric field change substantially the polarization and energy responses of diffracted light.

In the present work, using a method of slowly varying amplitudes, we consider the specific features of the intermediate (transition) regime of OA diffraction in planar gyrotropic optical waveguides in an external electric field.

Suppose that a planar optical waveguide occupies a space between planes $z = 0$ and $z = h$. Here we denote the refractive indices for the coating, waveguide film, and substrate by $n_c$, $n_f$, and $n_s$, respectively. It is shown in [9] that in a gyrotropic optical waveguide there are hybrid waves (modes) that can be divided into TE- and TM-similar ones. Moreover, for low-mode optical waveguides made on the basis of known OA crystals, optical gyrotropy leads to a small perturbation of the dielectric permeability tensor and, as a consequence, to approximate

---

division into TE- and TM-modes. The vector-functions that account for the spatial distribution of electric fields in the regions of the coating, film, and substrate are given in [9, 10].

Let us assume that a surface acoustic wave (SAW) of Rayleigh polarization propagates along the OY axis, which coincides with the crystallographic axis or with the direction (110) of the gyrotropic cubic crystal. In the case of a waveguide film prepared of an optically uniaxial crystal, a two-part SAW should propagate across the optical axis. It is a known fact that along with exponential damping the change in the normal component of the US-wave shift amplitude has an oscillating character [11]. We will write the deformation tensor components of the SAW in the form [12]:

\[ U_{q2} = B_{q2} V_{q2} \left( z \right) \exp \left[ i \left( Kr - \Omega t \right) \right], \quad q = 1, 2, 3, \]

where \( B_{q2} \) is the amplitude of deformations; \( V_{q2} \) is the function of the transverse distribution in the film and substrate; \( |K| = \Omega / v_r \), where \( \Omega \) and \( v_r \) are the angular frequency and velocity of the SAW.

When light propagates near the optical axis of an anisotropic crystal, just as for a cubic crystal, the regime of OA diffraction is determined by the parameter \( Q = \lambda_0 l / (N_0 \Lambda^2) \), where \( N_0 \) is the effective refractive index for the guiding mode of incident light; \( \lambda_0 \) is the length of the light wave in vacuum; \( \Lambda \) is the sound wavelength; \( l \) is the length of the OA interaction region [13]. The Bragg regime of OA diffraction is observed with \( Q \to \infty \), and the Raman–Nath regime, with \( Q \to 0 \) [14]. For the case of a light wave incident at the Bragg angle \( \varphi_B = \lambda_0 / (2 \Lambda N_0) \) and at not very high levels of US power, we can restrict ourselves to four diffraction orders (instead of two diffraction orders for the Bragg regime of diffraction) [13, 14].

A three-layer structure consisting of a coating, a waveguide film, and a substrate possesses uniaxial optical anisotropy. Moreover, the effective tensors of the unperturbed dielectric permeability \( \epsilon^m \) (\( m = 0, \pm 1, \pm 2, \ldots \)) for the waveguide modes of TE(TM)-polarization with effective refraction indices \( N_a^m \) (\( N_b^m \)) have nonzero components \( \epsilon_{11}^m = (N_a^m)^2 \), \( \epsilon_{22}^m = \epsilon_{33}^m = (N_b^m)^2 \).

For each of the waveguide modes of the periodic lattice the effect of ultrasound leads to the formation of dielectric permeability of the form

\[ \epsilon^m_{ij} = \epsilon^m_{ij} + \Delta \epsilon_{ij}^m + \Delta \epsilon_{ij} \cos \left( Kr - \Omega t \right), \]

where \( (\Delta \epsilon_{ij}^m)_{ij} = -\epsilon_{ij}^m P_{ijkl} U_{jk} \); \( P_{ijkl} \) are the tensor components of the photoelastic constants; \( U_{jk} \) are the deformation tensor components; \( (\Delta \epsilon_{ij}^m)_{ij} = -\epsilon_{ij}^m r_{ijkl} E_k \); \( r_{ijkl} \) are the tensor components of the electro-optical constants, \( E_k \) are the vector components of the external electric field intensity.

Maxwell equations yield a wave equation of the form

\[ \nabla^2 E - \nabla (VE) - \frac{1}{c^2} \frac{\partial^2 D}{\partial t^2} = 0, \quad (1) \]

where \( E \) and \( D \) are the vectors of intensity and induction of the electric field of the light wave, respectively; \( c \) is the speed of light in vacuum.

The solution of wave equation (1) is sought in the form

\[ D = \sum_{m=-\infty}^{\infty} D_m \exp \left[ i \left( k_m r - \omega_m t \right) \right], \quad (2) \]

\[ E = \sum_{m=-\infty}^{\infty} \left[ \epsilon_{ij}^{-1} D_m \frac{1}{\epsilon_m} \left( \hat{g} m_n, D_m \right) \right] \exp \left[ i \left( k_m r - \omega_m t \right) \right], \quad (3) \]

where