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COLLINEAR ACOUSTOOPTICAL COUPLING IN MULTIMODE FIBER-OPTIC WAVEGUIDES

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Studies of acoustooptical (AO) coupling in fiber-optic waveguides (FOW) is of significant interest for optoelectronics in view of the development of fiber-optic sensors, mode filters, and light modulators [1, 2]. AO coupling in the multimode FOW has not been adequately investigated, although intense studies are now being carried out aimed at the development of fiber-optic waveguides based on different materials, including uniaxial $LiNbO_3$ crystal, sillenite cubic gyrotropic crystals (BGO, BSO, BTO). In [3], characteristics of the AO coupling with the flexural and torsional ultrasonic modes of a cylindrical waveguide from cubic crystal were studied theoretically.

In this paper we consider specific features of the collinear AO coupling of the linearly polarized LP_{mn} modes in uniaxial and cubic crystals, including gyrotropic one in multimode FOW using constitutive equations for a gyrotropic dielectric [3] and a method of slowly varying amplitudes. We study in detail different cases of the AO coupling between the fourfold-degenerate ($m \neq 0$) modes of the FOW, with its symmetry axis directed along the optical axis of the uniaxial gyrotropic crystal, and the lowest elastic modes of a cylindrical waveguide: longitudinal, flexural, and torsional.

We assume in what follows that the optical fiber is weakly guiding. Then, the parameters of the profile height $\Delta = 1 - n_1 / n_2$ (n_1 and n_2 are the refractive indices of the core and the cladding, respectively) and phase velocities of the longitudinal $\upsilon_1^l \left(\upsilon_2^I\right)$ and shear υ_1^s (υ_2^s) ultrasonic waves in the core (cladding) satisfy the relations: $\Delta << 1$, $\upsilon_2^l = \upsilon_1^l$, and $\upsilon_2^s = \upsilon_1^s$.

As shown in [7], the inclusion of gyrotropy of a weakly guiding fiber slightly disturbs the permittivity tensor of the core and cladding and breaks down the waves into approximately linearly polarized *LP* modes. The dispersion equations and spatial distributions of electric fields of the *LP* modes of the FOW are presented in [2].

We will seek the solution of wave equation as a sum of two coupled waves (modes) with slowly varying amplitudes. The fiber mode LP_{mn} with the effective refractive index N_{mn} is assumed to diffract into the fiber mode $LP_{m'n'}$ with the refractive index $N_{m'n'}$.

The AO coupling constants (κ_{ij}^{kl}) of the coupled modes were calculated using known expressions for components of the elastic wave displacement vectors in the cylindrical coordinate system [3]. For the longitudinal and flexural ultrasonic waves, one has to take into account only the components of the strain tensor S_{zz} and for the torsional waves, only those of $S_{r\theta}$ [1].

As can be easily shown, in the general case of diffraction of the fourfold degenerate waves LP_{mn} ($m \neq 0$) by a longitudinal ultrasonic wave with the axial distribution of elastic displacements, the overlap integrals F_{ij}^{kl} vanish. For the collinear AO diffraction by the flexural ultrasonic mode F_{2q} and torsional ultrasonic mode, the overlap integrals are nonzero for $m' = m + 2$. In the general case of the flexural ultrasonic mode F_{pq} ($p > 1$), the overlap integrals are nonzero for $m' = m + p$, with any combinations of signs being valid for $m' > 0$. These features of the AO coupling are related to azimuthal distribution of the light and ultrasonic fields over the cross section of the round FOW.

The coupled-wave equation may be presented in the form of matrix-vector equation [3]:

$$\frac{d\mathbf{E}_0}{dz} = P\mathbf{E}_0 + i\left(\frac{\bar{\varepsilon}_0}{\bar{\varepsilon}_1}\right)Q\mathbf{E}_1, \frac{d\mathbf{E}_1}{dz} = \tilde{P}\mathbf{E}_1 + i\left(\frac{\bar{\varepsilon}_1}{\bar{\varepsilon}_0}\right)\tilde{Q}\mathbf{E}_0, \qquad (1)$$

where $\mathbf{E}_0 = (A_0^o, B_0^o, A_0^e, A_0^e)^\tau, \mathbf{E}_1 = (A_1^o, B_1^o, A_1^e, A_1^e)^\tau$ (τ is the transposition sign),

$$P = \begin{pmatrix} 0 & 0 & 0 & -(\rho_0 + id_e) \\ 0 & 0 & -(\rho_0 + iq_e) & 0 \\ 0 & -(\rho_0 + id_e) & 0 & 0 \\ -(\rho_0 + iq_e) & 0 & 0 & 0 \end{pmatrix}, \quad Q = \begin{pmatrix} \kappa_{xx}^{aa} & \kappa_{xx}^{ab} & \kappa_{yx}^{aa} & \kappa_{xy}^{ab} \\ \kappa_{xx}^{ba} & \kappa_{xx}^{bb} & \kappa_{yx}^{ba} & \kappa_{xy}^{bb} \\ \kappa_{xx}^{aa} & \kappa_{yx}^{ab} & \kappa_{yy}^{aa} & \kappa_{yy}^{ab} \\ \kappa_{yx}^{ba} & \kappa_{yx}^{bb} & \kappa_{yy}^{ba} & \kappa_{yy}^{bb} \end{pmatrix}$$

The tilde in expression for $\tilde{P}$ designates the substitution of ρ_1 for ρ_0, while $\rho_0 = q_0(\hat{G}\mathbf{e}_z), \rho_1 = q_1(\hat{G}\mathbf{e}_z)$ ($q_0 = \omega/2c\sqrt{\bar{\varepsilon}_0}, q_1 = \omega/2c\sqrt{\bar{\varepsilon}_1}, \bar{\varepsilon}_0 = Sp(\hat{\varepsilon}_0)/3, \bar{\varepsilon}_0 = Sp(\hat{\varepsilon}_1)/3$). The quantities κ_{ij}^{kl} are expressed through the convolutions of perturbation dielectric tensor $\Delta\hat{\varepsilon}_0$ with unit vectors $\mathbf{e}_x$ and $\mathbf{e}_y$, and $\kappa_{ij}^{kl} = F_{ij}^{kl}(e_i \Delta\hat{\varepsilon}^0 e_j)$, where $i, j = x, y$; $k, l = a, b$; and ω is the optical frequency, $\omega_1 = \omega \pm \Omega$ (Ω is acoustic angl frecuensy). The coupling constants $d_{o,e}$ and $q_{o,e}$ of FOW degenerate modes have a rather cumbersome form and are presented in [2]. The tilde in the expression for $\tilde{Q}$ designates the substitution of $\Delta\hat{\varepsilon}^0$ for $\Delta\hat{\varepsilon}^1$ in the expressions for elements of the matrix Q, and the subscript “1” for subscript “0” in the denominators of the expressions for overlap integral F_{ij}^{kl}.

Expression (1) shows that the intensity profile of the diffracted light at the output boundary $z = l$ of the fiber is determined by the effective photoelastic constant, ultrasonic wave intensity, and gyrotropy of the acoustic-line material. The polarization of the diffracted light differs, in the general case, from that of the incident light. This is related to the anisotropy of the photoelastic scattering and to the complex distribution of the light fields in the fiber. As the specific rotation $\rho \approx \rho_0 \approx \rho_1$ increases, the diffracted wave amplitude decreases. A considerable decrease in the relative intensity of the diffracted wave in FOW made of the sillenite crystals is caused by strong rotation of the light polarization plane in these crystals. It is shown that the efficiency of acoustooptical diffraction on the torsional acoustical modes in uniaxial gurotropic crystal is higher then on the flexural; diffraction of fiber-optic modes on the longitudinal acoustical modes is absent.

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