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INFLUENCE OF NEAR-SURFACE MEDIUM INHOMOGENEITY ON POLARIZATION EFFECTS IN LIGHT REFLECTION

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It was shown that, contrary to some authors opinion, the polarization effects observed recently in low-intensity light interaction with $\bar{4}3m$-class crystals (GaAs, InSb) did not point to any violation of the symmetry principle for kinetic coefficients in these crystals, since these effects are mainly caused by near-surface nonuniformity of their optical properties. Polarization effects were indicated which, if observed, would actually confirm the symmetry principle violation of these crystals kinetic coefficients.

Recent experimental works [1–3] present interesting observations of polarization effects occurring under normal reflection of low-intensity light by the [001] surface of the $\bar{4}3m$-class crystals (GaAs, InSb) and under light travel along these crystals optical axes. The observed effects are attributed to the nonvanishing part of the tensor γ_{ijk} symmetrical with respect to permutation of first two indices. The tensor describes the medium nonlocal optical response in the Landau–Lifshits approach,

$$D_i = \varepsilon_{ij} E_j + 4\pi\gamma_{ijk}\nabla_k E_j. \tag{1}$$

The conclusion is drawn that in these crystals the symmetry principle for kinetic coefficients is violated. This points to the presence of weak magnetic structures therein. (In $\bar{4}3m$-class crystals, the part of γ_{ijk} antisymmetric with respect to permutation of first two indices is always zero for the symmetry reasons.) This explanation of the effects observed in [1–3] has already been criticized [4], although, only qualitatively.

The aim of the present communication is to analyze quantitatively the above-mentioned effects and to demonstrate that the experimental results of [1–3] lead to conclusions opposite to those made by their authors. A fundamentally new line of experimental search for manifestations of a possible nonvanishing value of the spatial dispersion tensor γ_{ijk} symmetric part is also revealed.

For the samples studied in [1–3], let us assume that the part of tensor γ_{ijk} symmetric with respect to permutations of first two indices does not vanish due to some reasons, and consider normal light incidence on the $\bar{4}3m$-class crystal surface normal to the [001] axis (X_3-axis). In the absence of surface defects, this surface has three symmetry elements: a rotation symmetry axis of the second order, 2_{X_3}, and two mutually orthogonal symmetry planes $(m_{X_1X_2}, m_{-X_1X_2})$ [5]. In other words, the surface has symmetry class $mm2$, but its crystallographic axes x and y are rotated through 45° to the crystallographic axes X_1 and X_2 of the crystal. In what follows, calculations will be mainly made in the coordinate system x, y, z ($z = X_3$). In this system, the material tensors that characterize the linear optical response of the media in question have the form

$$\varepsilon_{ij} = \varepsilon_1\delta_{ij}; \qquad \gamma_{113} = \gamma_{131} = \gamma_{311} = \gamma_0, \quad \gamma_{223} = \gamma_{232} = \gamma_{322} = -\gamma_0, \tag{2}$$

the remaining tensors $\gamma_{ijk} = 0$. Here $i, j, k = 1, 2, 3$; δ_{ij} is the Kronecker delta, and the subscripts 1, 2, and 3 correspond to the x-, y-, and z-axes, respectively.

Simple substitution into the wave equation

$$k^2\mathbf{E} - \mathbf{k}(\mathbf{kE}) = \frac{\omega^2}{c^2}\mathbf{D} \tag{3}$$

demonstrates that to a first approximation in the spatial dispersion parameter $\mu = \omega|\gamma_0|/c$, the waves $\mathbf{E}^{(+)}(z,t)$ and $\mathbf{E}^{(-)}(z,t)$ traveling in the positive and negative directions along the z-axis, respectively, can be presented as

$$\mathbf{E}^{(+)}(z,t) = \left(E_{1x}e^{-\rho_0 z}\mathbf{e}_x + E_{1y}e^{\rho_0 z}\mathbf{e}_y\right)\exp\left(ik_1 z - i\omega t\right), \tag{4a}$$

$$\mathbf{E}^{(-)}(z,t) = \left(E_{2x}e^{-\rho_0 z}\mathbf{e}_x + E_{2y}e^{\rho_0 z}\mathbf{e}_y\right)\exp\left(-ik_1 z - i\omega t\right), \tag{4b}$$

where $\rho_0 = 2\pi\gamma_0\omega^2/c^2$; $k_1^2 = \omega^2\varepsilon_1/c^2$; $\mathbf{e}_x$ and $\mathbf{e}_y$ are the unit vectors of the x- and y-axes, respectively; ω is the incident light frequency.

To find the reflected and transmitted light characteristics we use the refined boundary conditions that make it possible to consider the influence of the actual medium near-surface inhomogeneity in the sharp boundary model [6, 7]. In the case of normal light incidence, they may be presented as

$$E_{x,y}^{(2)} = E_{x,y}^{(1)}, \qquad \left[\mathbf{n}, \mathbf{B}^{(2)} - \mathbf{B}^{(1)}\right] = \frac{4\pi\hat{\eta}}{c}\frac{\partial\mathbf{S}}{\partial t}, \tag{5}$$

where $\mathbf{n}$ is the unit normal vector directed from medium 1 to medium 2; $\mathbf{B}$ is the wave magnetic field induction; $\mathbf{B}^{(m)}$ and $\mathbf{E}^{(m)}$ are the field values in the medium m ($m = 1, 2$) near the boundary; $\mathbf{S} = \mathbf{E} + (\mathbf{D} - \mathbf{E}, \mathbf{n})\mathbf{n}$; and $\hat{\eta}$ characterizes the reflecting surface dielectric properties. With account of the latter surface symmetry, the tensor $\hat{\eta}$ has a diagonal form [5] irrespective of its internal symmetry.

Experiments [1–3] were carried out with almost normal light incidence (deviations were about 1°). In the calculations, this makes it possible, first, to assume strictly normal light incidence, and, second, to neglect the effects of multiple reflections from the opposite crystal faces. In this approximation, using (4) and (5), we can demonstrate that the amplitudes of the waves reflected $\mathbf{E}^{(r)}$, singly transmitted $\mathbf{E}$, and doubly transmitted $\mathbf{E}_2^{(r)}$ through the medium (there and back after reflection from the mirror placed behind the crystal) are the following functions of the incident wave amplitude $\mathbf{E}^{(i)}$:

$$\begin{gathered}
E_{x,y}^{(r)} = \left(-R + r_{x,y}^{(1)}T_0\right)E_{x,y}^{(i)}, \\
E_{x,y} = T_0T_1\left(1 + r_{x,y}^{(1)}\right)\left(1 + r_{x,y}^{(2)}\right)\exp\left(\mp\rho_0 L\right)E_{x,y}^{(i)}, \\
E_{2x,2y}^{(r)} = -T_0^2T_1^2\left(1 + r_{x,y}^{(1)}\right)^2\left(1 + r_{x,y}^{(2)}\right)^2 E_{x,y}^{(i)},
\end{gathered} \tag{6}$$

where L is the medium length; $R = (k_1 - k_0)/(k_1 + k_0)$; $T_0 = 2k_0/(k_1 + k_0)$; $T_1 = 2k_1/(k_1 + k_0)$; $k_0 = \omega/c$; $r_{x,y}^{(m)} = i\Delta_{x,y}^{(m)}/(k_1 + k_0)$; $\Delta_{x,y}^{(m)} = \Delta_{1,2}^{(m)} \pm (-1)^m\rho_0$; $\Delta_{1,2}^{(m)} = 4\pi\omega^2\eta_{1,2}^{(m)}/c^2$; $\eta_1^{(m)} = \eta_{11}^{(m)}$, $\eta_2^{(m)} = \eta_{22}^{(m)}$, $m = 1, 2$; $\hat{\eta}^{(1)}$ and $\hat{\eta}^{(2)}$ characterize the dielectric properties of the front and back surface, respectively. Relations (6) were obtained to the first approximation in parameters μ and μ_1, where $\mu_1 \propto |\hat{\eta}|/k_1$ characterizes the effect of the crystal near-surface inhomogeneity on light reflection and refraction. In this approximation, the assumption $\rho_0 L \ll 1$ following from smallness of the effects [2] makes it possible to obtain from (6) the following relations for the polarization plane rotation under linearly polarized light incidence on a crystal in the three cases under consideration:

after light reflection,

$$\Delta\beta_r = \mathrm{Im}\left\{\frac{k_0\left(\Delta_2^{(1)} - \Delta_1^{(1)} + 2\rho_0\right)}{k_1^2 - k_0^2}\right\}\cos\left(2\beta_0\right); \tag{7.1}$$

after light single transmission through the crystal,

$$\Delta\beta_t = \left(\mathrm{Re}\{\rho_0 L\} + \mathrm{Im}\{\Delta_s\}\right)\cos\left(2\beta_0\right); \tag{7.2}$$

after light forward and backward transmission through the crystal,

$$\Delta\beta_{2r} = 2\,\mathrm{Im}\{\Delta_s\}\cos(2\beta_0)\,. \tag{7.3}$$

In (7), $\Delta_s = \left(\Delta_1^{(1)} - \Delta_2^{(1)} + \Delta_1^{(2)} - \Delta_2^{(2)}\right)\Big/\left[2(k_1+k_0)\right]$; β_0 is the rotation angle of the plane of polarization of incident light with respect to the crystallographic axis X_1 ([100]) of the crystal (and not to the x-axis which is rotated through 45° about the X_1-axis). For comparison we quote (in our notation) the formulas for $\Delta\beta_r$ and $\Delta\beta_t$ of [2] (there is no formula for $\Delta\beta_{2r}$ in [2]),

$$\tilde{\Delta}\beta_r = \mathrm{Im}\left\{\frac{4k_0\rho_0}{k_1^2 - k_0^2}\right\}\cos(2\beta_0)\,, \tag{8.1}$$

$$\tilde{\Delta}\beta_t = \mathrm{Re}\{\rho_0 L\}\cos(2\beta_0)\,. \tag{8.2}$$

It is easy to notice that (8.1) can be obtained from (7.1) assuming that

$$\Delta_2^{(1)} - \Delta_1^{(1)} = 2\rho_0. \tag{9}$$

However, it should be borne in mind that (8.1) was obtained in [8] subject to the boundary conditions proposed in [9]. The latter conditions were shown to be incorrect [6], as they could lead to the results contradictory to the energy conservation law.

Furthermore, (8.2) follows from (7.2) assuming the weak near-surface inhomogeneity effect on reflection and refraction of light,

$$\mathrm{Im}\{\Delta_s\} \ll \mathrm{Re}\{\rho_0\}L. \tag{10}$$

However the measurement data on $\Delta\beta_{2r}$ and $\Delta\beta_t$ [2] give $\Delta\beta_{2r} \approx 2\Delta\beta_t$. According to (7.2) and (7.3), this means that the main contribution to the change in polarization characteristics of singly and doubly transmitted light is made by the near-surface layer anisotropy. Therefore, assumption (10) made in [2] is unjustified. So, relations (8) cannot be used to interpret the effects of [1–3].

Consider now the results of [1–3] subject to (7). It follows from (7) that $\Delta\beta_{2r} = 2\Delta\beta_t$ if only $\mathrm{Re}\{\rho_0\} = 0$. Therefore, a small *difference* of $\Delta\beta_{2r}$ and $2\Delta\beta_t$ is of particular interest in [2] (contrary to its authors opinion) because it is just this difference that may imply $\mathrm{Re}\{\rho_0\} \neq 0$. However, one should understand that there may be other reasons for this difference, for instance, effects of second order of smallness in μ and/or μ_1. Unfortunately, the authors of [2] did not state clearly that the accuracy of their experiment guaranteed actual difference of $\Delta\beta_{2r}$ and $2\Delta\beta_t$. However, in any case it follows from the experiments [2] that

$$\mathrm{Re}\{\rho_0\}L \ll \mathrm{Im}\{\Delta_s\}. \tag{11}$$

Thus, subject to (11), it follows from (7) that all the linear effects observed in [1–3] are mainly induced by nonuniformity of dielectric properties of the crystal near its surface, and especially by different symmetries of the near-surface layer and the medium bulk.

In [2], a certain difference between the function $\Delta\beta_{2r}(\beta_0)$ and that predicted by (7.3) was reported,

$$\Delta\beta_{2r}^{(\mathrm{exp})} = A\cos\left[2\left(\beta_0\right) + \Delta\beta\right)]\,, \tag{12}$$

where $\Delta\beta = 24°$. Considering that no such discrepancies have been reported for the light reflected by the crystal front face, it can be assumed that distinction between (12) and (7.3) is caused by the crystal lattice small defects in the crystal bulk. However, the results of [2] are inadequate to fully eliminate the possible influence of other reasons on the $\Delta\beta$ appearance, for example, defects of the crystal back face, which modify its symmetry.

Thus, contrary to its authors opinion, the experimental results of [2] demonstrate that the symmetry principle for the kinetic coefficients in GaAs is fulfilled (within the experimental error).

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