Contribution of magnetic linear birefringence of light to odd magneto-optical reflection effects

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It is shown that due to the Dzyaloshinskii interaction magneto-optical reflection effects, owing to magnetic linear birefringence of light, which are specific to magnetically ordered media and are odd with respect to the magnetic field, appear. Methods are indicated for distinguishing them from the usual magneto-optical effects and for determining experimentally both the real and imaginary parts of the symmetrical and odd, with respect to the magnetic field, components of the dielectric permeability tensor.

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Dzyaloshinskiĭ's analysis[1] of the interaction, owing to mixed invariants of the type $l_i m_j$, explained not only the appearance of weak ferromagnetism but also predicted a number of new physical effects in magnetically ordered crystals with given symmetry. Examples are piezomagnetism[2] and its thermodynamic inverse, linear magnetostriction.[3]

The optical effect analogous to linear magnetostriction, namely, the appearance of symmetric and odd, with respect to the magnetic field or magnetization, components in the dielectric permeability tensor, was examined by Zvezdin and Kotov[4] and was recently discovered experimentally in light transmitted through CoF_2 and $DyFeO_3$ crystals by

Eremenko and Kharchenko and their co-workers[5,6] and in hematite crystals by Rudashevskii and co-workers.[7]

In this paper, we examine for the first time the appearance of magneto-optical effects, due to odd magnetic linear birefringence of light (OMLB), in reflected light. As will be evident from what follows, these effects are interesting for the following reasons: 1) in reflected light, it is easy to determine independently the symmetrical ϵ^s and antisymmetrical ϵ^{as} components of the tensor ϵ, linear with respect to the magnetic field, which involves well-known difficulties in transmitted light; 2) it turns out to be possible to find both the real and the imaginary parts of ϵ^s; 3) the effect of the natural birefringence of the crystal on the results of measurements is eliminated; 4) it turns out to be possible to determine ϵ^s not only in regions of transparency of the crystal but also in regions of intense optical transitions, where the values of ϵ^s must increase sharply.

We shall analyze the reflection of light from an DMLB medium for the example of a $DyFeO_3$ crystal at $T < T_m$. As usual, we shall determine the magnitude of the magneto-optical effect δ from the equation $\delta = [J(+H) - J(-H)]/2J(0)$, where J is the intensity of the reflected light. In the temperature range being examined, the following tensor components differ from zero $(H \| z)^6$: $\epsilon_{xx} = \epsilon_a$, $\epsilon_{yy} = \epsilon_b$, $\epsilon_{zz} = \epsilon_c$, $\epsilon^s_{xy} = \epsilon^s_{yx} = a^s H$, and $\epsilon^{as}_{xy} = -\epsilon^{as}_{yx} = i a^{as} H$.

We shall first examine the case of equatorial magnetization, when the external field H is perpendicular to the plane of incidence of light (Fig. 1a). We shall show that the contribution of the symmetrical component of the tensor $a^s H$ to the magnitude of the effect in this case is equal to zero. Indeed, if φ is the angle of incidence of the light and E' and E'' are the amplitudes of the incident and reflected waves, then for p polarization, the following equality is satisfied:

$$(E'_p - E''_p)/(E'_p + E''_p) = \cos\varphi\,(\epsilon_c n_p + \epsilon^s \sin\varphi - i\epsilon^{as}\sin\varphi)/(\epsilon_c - \sin^2\varphi), \quad (1)$$

which is obtained from the solution of the boundary value problem. Substituting into (1) the value of the index of refraction obtained from the solution of Maxwell's equations

$$n_p = -\epsilon^s \sin\varphi/\epsilon_c + \sqrt{\epsilon_b(\epsilon_c - \sin^2\varphi)/\epsilon_c + O[(\epsilon^s)^2, (\epsilon^{as})^2]}, \quad (2)$$

we see that the terms linear in ϵ^s cancel out and the entire effect stems only from the antisymmetrical components of the tensor ϵ^{as}.

We shall now show that for a different orientation of the magnetic field and the crystallographic axes, a magneto-optical effect, linear with respect to H and owing to OMLB, arises in reflection. We shall orient the field along the C axis perpendicular to the surface of the crystal (Fig. 1b). For the generalized Fresnel coefficients, defined by the equalities

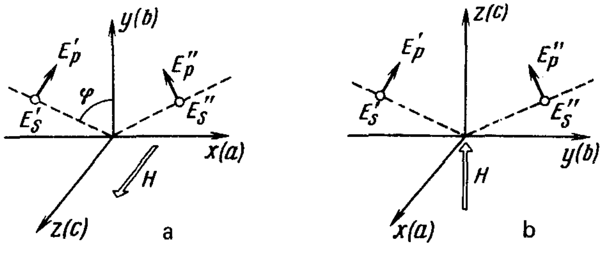

FIG. 1

$$E_p'' = r_{pp} E_p' + r_{ps} E_s' ; \quad E_s'' = r_{sp} E_p' + r_{ss} E_s' \tag{3}$$

and from the solution of Maxwell's equations and the boundary conditions, we obtain the following expressions:

$$r_{pp} = \frac{\sqrt{u\mathrm{v}}\cos\varphi - 1}{\sqrt{u\mathrm{v}}\cos\varphi + 1} ; \quad r_{\left\{\substack{ps \\ sp}\right\}} = \frac{2(\pm a^s - i a^{as})\cos\varphi H}{(\sqrt{u/\mathrm{v}} + \sqrt{w})(1 + \sqrt{u\mathrm{v}}\cos\varphi)(\sqrt{w} + \cos\varphi)}$$

$$r_{ss} = \frac{\cos\varphi - \sqrt{w}}{\cos\varphi + \sqrt{w}}, \text{ where } u = \epsilon_b , \; \mathrm{v} = \epsilon_c / (\epsilon_c - \sin^2\varphi), \; w = \epsilon_a - \sin^2\varphi . \tag{4}$$

In absorbing media, the components of the tensor ϵ entering into (4) are complex and the magnitude of the effect will be determined not only by OMLB but also by the odd magnetic linear dichroism. As follows from (4), the magnitude of the effect δ depends linearly both on the symmetrical and the antisymmetrical components of the tensor ϵ. $a^s = a_r^s + i a_i^s$ can be determined independently from the normal incidence of light ($\varphi = 0$). Introducing the average index of refraction $\tilde{n} = (n_a + n_b)/2$ and neglecting the terms[1] $(n_a - n_b)\epsilon^s$ and $(n_a - n_b)\epsilon^{as}$ compared to ϵ^s and ϵ^{as}, taking into account the explicit form of the generalized Fresnel coefficients (4), we obtain the magnitude of the relative change in the intensity of linearly polarized light reflected from the crystal

$$\delta_1 = 2\,\mathrm{Re}\,[(a_r^s + i a_i^s)/(\tilde{n}^3 - \tilde{n})]\,H \sin 2\theta . \tag{5}$$

Here, θ is the angle between E' and the b axis of the crystal and $\tilde{n} = n + ik$ is the complex index of refraction. The magnitude of the effect δ for normal incidence of light is determined only by the symmetrical part of the tensor $a^s = a_r^s + i a_i^s$. A measurement of δ with a circular analyzer at the output can serve as an independent means for determining a_r^s and a_i^s. In this case,

$$\delta_2 = 2\,\mathrm{Re}\left(\frac{a^{as}}{\tilde{n}^3 - \tilde{n}}\right) H + 2\,\mathrm{Im}\left(\frac{a^s}{\tilde{n}^3 - \tilde{n}}\right) H (\sin 2\theta + \cos 2\theta) . \tag{6}$$

Separating out of (6) the part anisotropic with respect to θ and using the experimental value of δ_1, it is possible to determine a_r^s and a_i^s from (5) and (6). We emphasize that as follows from the analysis carried out above, measurment of δ in the presence of equatorial magnetization allows us to determine a_r^{as} and a_i^{as}. We shall estimate the quantity δ_1 with $\lambda = 0.59$ μm for dysprosium orthoferrite using the data from Ref. 6. Substituting into (5), $\tilde{n} = 2.5$, $H = 1$ kOe, $a^s = 2.5 \times 10^{-7}$ Oe^{-1}, we obtain $\delta_1 = 0.38 \times 10^{-4}$, which is easily recorded with the help of a modulation technique. The effect indicated must increase considerably in a region of intense optical transitions in the Fe^{3+} ions.

[1] For DyFeO$_3$, $\Delta n \sim 0.03$,[6] $\epsilon^{s,as}\Delta n$ is two orders of magnitude less than ϵ^s and ϵ^{as}, which justifies our approximation.

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