Magneto-optical effects in the reflection and transmission of light for the case of an equatorially magnetized plate

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Abstract. Currently, expanding the elemental memory of computers and creating new generations of elemental bases for telecommunication systems are among the most important tasks for the national economy. However, further development of all these directions requires solving problems of a fundamental nature, such as achieving the superparamagnetic limit (which limits recording density), a relatively slow change in the magnetic state under the influence of magnetic field pulses (limiting recording speed), and a small magnitude of magneto-optical effects (limiting their use in integrated photonics). To solve these problems, the development and creation of new hybrid magnetic nanostructures that combine magnetic and non-magnetic materials - dielectrics, semiconductors, and metals - in various combinations is of particular relevance. In such structures, a significant enhancement of non-reciprocal linear and nonlinear optical and magneto-optical phenomena is possible, as well as the manifestation of new effects (for example, the effects of magneto-optical spatial dispersion). This article explores the reflection and transmission of light from a magnetic layer on a transparent (glass) substrate. As a result, formulas were obtained for the equatorial Kerr effect in reflected and transmitted light. These results are necessary for interpreting experimental data on the equatorial Kerr effect.

1 Introduction

At present, researchers are paying close attention to the development and research of computer memory elements and a new generation of element bases for telecommunication systems. It is known that these elements are mainly created on the basis of magnetic materials. Therefore, the study of magnetic structures is an urgent task, since computer memory elements are created on the basis of these materials, and they are also used in the element bases of telecommunication systems.

Many important physical results have been obtained using magneto-optical methods. For example, the role of the Faraday and Zeeman effects in creating Maxwell's theory and deciphering the structure of the atom is well known. The study of magneto-optical effects (MOE) and magneto-optical properties of matter is still an important area in solid state physics and in the physics of magnetic phenomena, which is of great scientific and applied

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importance. The manifestations of magneto-optical properties are specific for different substances and in different spectral ranges of radiation. A special group consists of MOE in ferromagnets observed in the optical frequency range. At optical frequencies, ferromagnets have abnormal magneto-optical properties compared to “non-magnetic” substances due to the presence of spontaneous magnetization. For example, the Verde and Kerr constants for iron, cobalt and nickel are several orders of magnitude higher than for “non-magnetic” metals. The features of the magneto-optical properties of ferromagnets make it possible to use magneto-optical measurement data to study the details of the electronic structure of magnetic metals and semiconductors. On the other hand, they open up opportunities for a wide practical application of MOE, for example, in the study of domain structures of magnetic materials, for modulating research, as well as in devices for recording and reading information.

A special situation arises when the sample is magnetized perpendicular to the plane of incidence of light (equatorial magnetization). In this case, there is no birefringence in the linear magnetization approximation, and odd effects occur solely due to corrections proportional to magnetization to the polarization vectors of electric and magnetic waves excited in a ferromagnet. With P-polarization of the incident wave, only one mode is excited, the electric field intensity vector of which is elliptically polarized in the plane of incidence. Therefore, there should be no polarization change effects in both reflected and transmitted light. At the same time, the presence of a longitudinal correction for this mode leads to a strange change in light intensity in terms of magnetization.

We previously examined the passage of light through a two-layer magnetic structure and a three-layer structure, the middle layer of which is a magnetic material deposited on a semiconductor base. Article [1] presents generalized Fresnel formulas for the reflection and transmission of light for the case of a ferromagnetic plate.

2 Research methodology

In recent years, the equatorial optical effect has become known and is widely used in the study of magneto-optical properties of ferromagnetic materials - the effect of linear magnetization changes in the intensity of reflected light polarized in the plane of incidence. Similarly, with S - polarization of incident light, one mode of magnetic field strength is excited, containing a correction proportional to the magnetization. In this case, an optical effect occurs - the effect of changing the intensity of reflected light, which was observed on massive iron samples.

The polar and meridional effects of Kerr and Faraday, as well as the equatorial effects of changes in the intensity of reflected light, are well known. But when studying equatorial effects, when light passes through an equatorially magnetized film or plate, such effects have not yet been observed.

The existence of unusual magnetization effects associated with changes in the intensity and polarization of a light wave as it passes through an equatorially magnetized ferromagnetic layer has been predicted within the framework of phenomenological theory. The features of these effects were also established there, the main one of which is that they differ from zero only if the optical properties of the medium bordering the magnetic layer are different. Among the new effects, the most interesting are the changes in the intensity of the transmitted light, respectively, at the P - and S - polarizations of the incident wave. The first of them is gyroelectric, i.e. it is proportional to the non-diagonal component of the ƐXY dielectric constant tensor. The second one has a purely gyromagnetic origin, i.e. it is uniquely determined by the magnitude of the μ xy - the non-diagonal component of the magnetic permeability tensor.

Recently, the issue of determining the value of high-frequency magnetic permeability and interpreting the physical meaning of this value in the optical frequency range has attracted attention.

If the direction of magnetization of the sample is normal to the plane of incidence of light, then such magnetization develops equatorially. It is known that with equatorial magnetization of a bigyrotron ferromagnetic mirror, the hydroelectric and gyromagnetic properties of the ferromagnet are separated by the observed effects of changes in the intensity of reflected light [2].

It can be expected that similar effects will occur in the case of interaction of light with a transparent magnetized plate. In magneto-optical effects, when light passes through a plate, as well as when reflected from it, specific phenomena associated with the presence of two interfaces and the interference of light waves should be observed. It should be noted that experimental studies on multilayer magnetic materials are being carried out by quite a lot of scientists [3-7].

3 Results and discussion

In this article we will consider magneto-optical effects during equatorial magnetization. Let us restrict ourselves to an approximation linear in magnetization. For the reflection and transmission matrices we obtain, following [3]. With equatorial magnetization, the phases for forward and backward waves are related by the relation

$$f_j^1 = f_j^{-1} \tag{1}$$

At equatorial, as a result of the identical equality to zero of a number of amplitude coefficients, the main determinant in [2] breaks down into the product of two determinants of a smaller order

$$\Delta(a,b,\dots) = \Delta_1(a, f\bar{u}) \cdot \Delta_2(b, f\bar{u}, c, fc) \tag{2}$$

where

$$\Delta_1 = \begin{vmatrix} a_1 & a_1^{'} \\ f_1\bar{u}_1 & f_1^{'}\bar{u}^{'}_1 \end{vmatrix}$$

$$\Delta_2 = \begin{bmatrix} b_2 & b_2^{'} & b_3 & b_3^{'} \\ f_2\overline{v_2} & f_2^{'}\bar{v}_2^{'} & f_3\overline{v_3} & f_3^{'}\bar{v}_3^{'} \\ c_2 & c_2^{'} & c_3 & c_3^{'} \\ f_2c_2 & f_2^{'}c_2^{'} & f_3c_3 & f_3^{'}c_3^{'} \end{bmatrix} \tag{3}$$

$$a_1 = g_1 + g_{12}(\mu - \alpha_0) - i\psi\xi\mu_1$$
$$\bar{a}_1 = g_1 - g_{12}(\mu - \alpha_0) + i\psi\xi\mu_1$$
$$b_2 = -(\mu_0^{-1}g_1n_{22}^2 + n_1^2g_{22} - \alpha g_1g_{22}^2) + i\psi\xi[n_1^2\Lambda_2 + \alpha g_1g_{22}(L - \Lambda_2)] - \alpha g_1g_{22}^2L\Lambda_2$$
$$\bar{b}_2 = -(\mu_0^{-1}g_1n_{22}^2 - n_1^2g_{22} - \alpha g_1g_{22}^2) - i\psi\xi[n_1^2\Lambda_2 - \alpha g_1g_{22}(L - \Lambda_2)] - \alpha g_1g_{22}^2L\Lambda_2$$
$$b_3 = \xi(\alpha g_1g_{23} - n_1^2 + \alpha g_1g_{23}L\Lambda_3) + i\psi[(\mu_0^{-1}g_1n_{23}^2 + n_1^2g_{23} - \alpha g_1g_{23}^2)\Lambda_3 - \alpha g_1g_{23}^2L]$$
$$\bar{b}_3 = \xi(\alpha g_1g_{23} + n_1^2 + \alpha g_1g_{23}L\Lambda_3) + i\psi[(\mu_0^{-1}g_1n_{23}^2 - g_{23} - \alpha g_1g_{23}^2)\Lambda_3 - \alpha g_1g_{23}^2L]$$
$$c_2 = -\alpha g_{22}[\xi - i\psi g_{22}(L - \Lambda_2) - \xi L\Lambda_2]$$
$$c_3 = \alpha g_{22}[g_{22} + i\psi\xi(L + \Lambda_3) - g_{23}L\Lambda_3]$$
$$a_2 = \bar{a}_2 = a_3 = \bar{a}_3 = b_1 = \bar{b}_1 = c_1 = 0$$

Hence, according to [4], the scalar amplitudes of direct refracted waves in the plate are equal

$$E_1 = \frac{2g_1f_1^{'}\overrightarrow{u_1^{'}}}{\Delta_1(a, fu)}A_s$$

$$E_2 = -\frac{2g_1n_1D_{b_z}}{\Delta_2(b, f\bar{v}, \dots)}A_p$$

$$E_3 = -\frac{2g_1 n_1 D_{b_3}}{\Delta_2(b, f\bar{v}, \dots)} A_p \quad (4)$$

where D_{b_2} and D_{b_3} are the algebraic complements of the elements b_2 and b_3 in the determinant $\Delta_2(b, f\bar{\vartheta}, \dots)$. The amplitudes E_j^1 of backward refracted waves are found from (4) by replacing all non-primed values (related to direct waves) with the corresponding primed values, and vice versa. From formulas (4) it follows that a special wave with polarization vector $\bar{e}$, (4) is excited in the image by the S-component of the incident light wave, and ordinary waves (the second and third) are excited by the P-component. Amplitude coefficients a_2, a_3, b_1,, c_1 etc. are given in the appendix.

It is easy to establish that with equatorial magnetization, the plates and off-diagonal elements of the reflection and transmission matrices are equal to zero [1], and the diagonal elements are given by the expressions

$$r_{ss} = \frac{\Delta_1(\bar{a}, f\bar{u})}{\Delta_1(a, f\bar{u})} = r_{ss}^{(0)}(1 + i\rho_s)$$

$$r_{pp} = \frac{\Delta_2(\bar{b}, f\bar{\vartheta}, \dots)}{\Delta_2(b, f\bar{\vartheta}, \dots)} = r_{pp}^{(0)}(1 + i\rho_p)$$

$$t_{ss} = \frac{g_1 \Delta_1(fu, f\bar{u})}{g_3 \Delta_1(a, f\bar{u})} = t_{ss}^0(1 + i\tau_s)$$

$$t_{pp} = \frac{g_1 n_1 \Delta(fu, f\bar{v}, \dots)}{g_3 n_3 \Delta(b, f\bar{v}, \dots)} = t_{pp}^0(1 + i\tau_p) \quad (5)$$

The determinants in the numerators of expressions (5) are found from the determinants (3) by replacing the first line in them with lines composed of the elements $\bar{a}_v, \bar{b}_v, f_v u_v$ and $f_v u_v$, where $r_{ss}^{(0)}$, $r_{pp}^{(0)}$, $t_{ss}^{(0)}$ and $t_{pp}^{(0)}$ are the reflection and transmittance coefficients of the plate in the absence of magnetization.

Amendments to elements r_{ss} and t_{ss} are in the form

$$\rho_s = \frac{n_1^2(1 - r_{12}^s)[1 - f_0^2(r_{32}^3)^2](1 - f_0^2)}{4g_0^2(1 - f_0^2 r_{12}^s r_{32}^s)(r_{12}^s - f_0^2 r_{32}^s)}\left(1 - \frac{n_0^2}{n_e^2}\right)\mu M sin2\varphi cos\gamma$$

$$\tau_s = \frac{n_1(1 - r_{12}^S)(1 - f_0^2)}{4g_0(1 - f_0^2 r_{12}^S r_{32}^S)}\left(1 - \frac{n_0^2}{n_e^2}\right) M sin2\varphi cos\gamma \quad (6)$$

where r_{12}^s and $t_{32}^{(s)}$ are the reflection coefficients at the interfaces of dielectrics with refractive indices n_1 and n_3 and a non-magnetized medium. f_0 - phase factor of the transverse wave in the plate: $cos\gamma = \pm 1$

When longitudinal waves are taken into account, corrections linear in magnetization to the elements r_{pp} and t_{pp} have, in the general case, an extremely cumbersome form. Therefore, we limit ourselves here to presenting the results in two limiting cases (see Appendix).

Let's move on to expressions for magneto-optical effects. With equatorial magnetization of the plate, the relative measurements of the intensity of reflected and transmitted light are equal

$$\delta' = \frac{2I_m\left(|r_{ss}^0 A_s|^2 \rho_s + \left|r_{pp}^{(0)} A_p\right|^2 \rho_p\right)}{\left|r_{ss}^{(0)} A_s\right|^2 + \left|r_{pp}^{(0)} A_p\right|^2}$$

$$\delta'' = \frac{2I_m\left(\left|t_{ss}^{(0)} A_s\right|^2 \tau_s + \left|t_{pp}^{(0)} A_p\right|^2 \tau_p\right)}{\left|t_{ss}^{(0)} A_s\right|^2 + \left|t_{pp}^{(0)} A_p\right|^2} \quad (7)$$

where $\rho_{s(p)}$ and $r_{s(p)}$ are corrections linear in magnetization, found according to formulas ((6) and appendix) using the relations

$$tg\theta_0' = \frac{r_{pp}^{(0)}}{r_{ss}^{(0)}} tg\theta\ , \quad tg\theta_0'' = \frac{t_{pp}^{(0)}}{t_{ss}^{(0)}} tg\theta\ , \quad tg\theta = \frac{A_p}{A_s} \quad (8)$$

Let us introduce the polarization angles of reflected ($\theta_0^{'}$) and transmitted ($\theta_0^{''}$) waves in the absence of magnetization. Then changes in the polarization angles of reflected and transmitted light with equatorial magnetization of the plate are given by the expressions

$$\Delta\theta^{'} = \frac{1}{2} i(\rho_p - \rho_s) sin2\theta_0^{'}$$
$$\theta^{''} = \frac{1}{2} i(\tau_p - \tau_s) sin2\theta_0^{''} \qquad (9)$$

where

$$\rho_p = \frac{g_e^4 (1 - r_{12}^p)^2}{4n_e^4 g_0^2 r_{12}^p} \varepsilon J_2 sin2\varphi cos\gamma$$
$$\tau_p = \frac{n_1 g_e^3 (r_{32}^p - r_{12}^p)}{2g_0 (g_e^3 + n_1^2 g_0 sin^2\varphi)} J_2 sin2\varphi cos\gamma$$
$$\rho_p = \frac{(1 - r_{12}^p)^2 \left[1 - f_0^2 (r_{32}^p)^2\right] (1 - f_0^2)}{4g_0^2 (r_{12}^p - f_0^2 r_{32}^p)(1 - f_0^2 r_{12}^p r_{32}^p)} \varepsilon Q sin2\varphi cos\gamma$$
$$\tau_p = \frac{n_1 (r_{32}^p - r_{12}^p)(1 - f_0^2)}{2g_0 (1 - f_0^2 r_{12}^p r_{32}^p)} Q sin2\varphi cos\gamma$$

In the case of linear S- or P-polarization of the incident wave, changes in the intensity of the reflected and transmitted light depend only on the corresponding corrections to the diagonal elements of the reflection and transmission matrices:

$$\delta_s^{'} = -2I_m \rho_s \qquad \delta_p^{'} = -2I_m \rho_p \quad \delta_s^{''} = -2I_m \tau_s \qquad \delta_p^{''} = -2I_m \tau_p \qquad (10)$$

and changes in polarization angles (9) are equal to zero.

As can be seen from expressions (6), corrections $r_s(r)_p$ odd in magnetization are nonzero provided that the differences in reflection coefficients $r_{32}^{s(p)}$-$r_{12}^{s(p)}$ on lower and upper borders of the plate. Like the corresponding light, they are of a borderline nature. Their occurrence is associated not with birefringence, which is absent in this geometry, but with the fact that corrections proportional to the magnetization to the polarization vectors of the waves excited at the upper and lower boundaries of the ferromagnetic plate have opposite signs.

$$\sigma_s^{(1231)} = I_m \left[\frac{(r_{231}^{(s)} - r_{21}^{(s)})(1 - f_2^2)}{1 - f_2^2 r_{21}^s r_{231}^s} \frac{n_1 M sin\varphi}{g_1}\right]$$
$$\sigma_p^{(1231)} = I_m \left[\frac{(r_{231}^p - r_{21}^p)(1 - f_2^2)}{1 - f_2^2 r_{21}^p r_{231}^p} \frac{n_1 Q sin\varphi}{g_2}\right] \qquad (11)$$

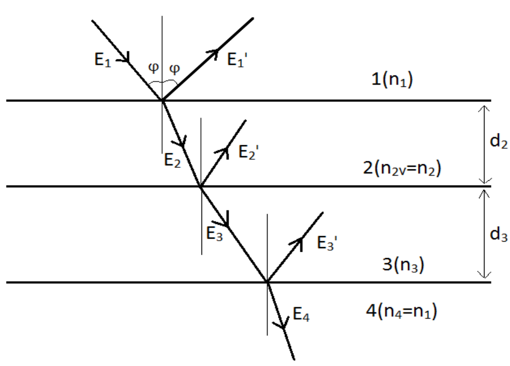

Fig. 1. The effect of the beam path collapse.

In formulas (11), the following designations are used: n_1, n_2 and n_3, respectively, the refractive indices of the external environment (usually $n_1 = 1$), the magnetic layer and the substrate; $r_{ij}^{s(\mathrm{p})}$ - optical reflection coefficients at the boundary of the i-th, j-th media, determined by the expressions

$$\tau_{ij}^{s} = \frac{g_i - g_j}{g_i + g_j}$$

$$\tau_{ij}^{s} = \frac{g_i n_j^2 - g_j n_i^2}{g_i n_j^2 + g_j n_i^2} \quad (12)$$

where $g_i = \sqrt{n_j^2 - n_i^2 sin\varphi}$ - the reflection coefficient is found by the formula

$$r_{231}^{s(p)} = \frac{r_{23}^{s(p)} + f_3^2 r_{31}^{s(p)}}{1 + f_3^2 r_{23}^{s(p)} r_{31}^{s(p)}} \quad (13)$$

$f_j = \exp\left(-i\frac{\omega}{c} g_j \alpha_j\right)$- phase factors of the magnetic layer and substrate, having thicknesses d_2 and d_3 respectively.

From formulas (11) it is not difficult to establish another interesting feature of equatorial effects in transmitted light: a change in the sign of the effect when the beam path collapses.

4 Conclusion

In magneto-optical effects, when light passes through a plate, as well as when reflected from it, specific phenomena are observed related to the presence of two interfaces and the interference of light waves. We examined in this article the magneto-optical effect during equatorial magnetization. In this case, we were limited to an approximation linear in magnetization.

Thus, we obtained formulas (7 and 11) for the first time. equatorial Kerr effect in reflected and transmitted light. Since the growing interest in multilayer magnetic materials, especially their optical and magneto-optical properties, requires interpretation of the experimental results obtained. Therefore, the formulas we obtained are also useful for interpreting experimental results obtained by other authors. This opens up new possibilities for expanding the elemental memory of a computer and creating new generations of elemental bases for telecommunication systems.

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