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RESEARCH ARTICLE

Contribution of interference to the magneto-optical transverse Kerr effect in white light

Igor V. Gladyshev,
Alexey N. Yurasov,
Maxim M. Yashin @

MIREA – Russian Technological University, Moscow, 119454 Russia
@ Corresponding author, e-mail: yashin@mirea.ru

Abstract
Objectives. When measuring the transverse Kerr effect on thin-film structures, interference effects have a great influence on the result obtained. In conference presentations, some researchers have reported on the use of white light in experiments. In their opinion, despite the thickness of the studied layers being much less than the wavelength of light, white light can help avoid interference effects and/or resonant excitation of plasmon waves. The aim of the present work is to verify the validity of such statements using simulation.
Methods. In order to solve this problem, the method of computer simulation was used. A numerical solution of equations was compiled for a model structure for various thicknesses and materials of layers.
Results. The simulation results show that interference effects in different parts of the spectrum when using white light sources do not neutralize each other. The magnitude of the effect is affected not only by the thickness of the structure layers, but also by the shape of the source emission spectrum, as well as the sensitivity curve of the photodetector. In this case, the output of the measured value of the effect to a plateau at relatively large thicknesses of the magneto-optical film is due to the light being absorbed in the thickness of the magneto-optical film and is negligibility of the back reflection of light from the substrate.
Conclusions. The presented technique takes into account the influence of interference effects when measuring the equatorial Kerr effect in white light or using other sources having a wide spectral range, thus improving the interpretation of experimental results. The results are relevant to the development and research of the physical foundations for creating new and improving existing devices in micro-, nano-, and solid-state electronics, as well as quantum devices, including optoelectronic devices and converters of physical quantities.

Keywords: magneto-optical transverse Kerr effect, dielectric constant tensor, interference, reflection coefficient, thin films

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НАУЧНАЯ СТАТЬЯ

Вклад интерференции в магнитооптический экваториальный эффект Керра в белом свете

И.В. Гладышев,
А.Н. Юрасов,
М.М. Яшин @

МИРЭА – Российский технологический университет, Москва, 119454 Россия
@ Автор для переписки, e-mail: yashin@mirea.ru

Резюме
Цели. При измерении экваториального эффекта Керра в тонкопленочных структурах большое влияние на полученный результат оказывают интерференционные эффекты. В выступлениях на конференциях некоторые исследователи сообщали об использовании белого света в экспериментах. На их взгляд, хотя толщина исследуемых слоев была много меньше длины волны света, белый свет может помочь избежать интерференционных эффектов и/или резонансного возбуждения плазмонных волн. Цель статьи – путем моделирования проверить обоснованность таких утверждений.
Методы. Для решения обозначенной задачи применялся метод компьютерного моделирования – численного решения уравнений, составленных для модельной структуры при различных толщине и материалах слоев.
Результаты. Результаты моделирования показывают, что интерференционные эффекты в разных частях спектра при использовании источников белого света не нейтрализуют друг друга, и на величину эффекта влияет не только толщина слоев структуры, но и форма спектра излучения источника, а также кривая чувствительности фотоприемника. При этом выход измеряемой величины эффекта на плато при относительно большой толщине магнитооптической пленки обуславливается тем, что при этом свет поглощается в толще магнитооптической пленки и обратное отражение света от подложки пренебрежимо мало.
Выводы. Представленная методика позволяет учитывать влияние интерференционных эффектов при измерении экваториального эффекта Керра в белом свете или с использованием других источников с широким спектральным диапазоном и более качественно интерпретировать экспериментальные результаты, что может быть весьма полезным для разработки и исследования физических основ создания новых и совершенствования существующих приборов, изделий микро- и наноэлектроники, твердотельной электроники, а также квантовых устройств, включая оптоэлектронные приборы и преобразователи физических величин.

Ключевые слова: магнитооптический экваториальный эффект Керра, тензор диэлектрической проницаемости, интерференция, коэффициент отражения, тонкие пленки

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INTRODUCTION

The transverse magneto-optical Kerr effect (TMOKE) involves a change in the intensity of light reflected from a sample when it is remagnetized in the direction perpendicular to the plane of light incidence. As such, TMOKE represents an important and very effective method for studying the magnetic microstructure of homogeneous and inhomogeneous magnetics. By measuring the EEC value as a function of the radiation wavelength, the magneto-optical transitions reflecting the electronic, crystalline, and magnetic structures of a given local section of the sample can be evaluated. Magneto-optical thin-film systems are also widely studied for use in optical data storage devices, in which data are recorded using thermomagnetic processes, but read by measuring the change in polarization upon reflection using the polar magneto-optical Kerr effect. Researchers have been very active in applying this principle (see, for example, [1–8]), including for ultrathin [9] and multilayer (ferromagnetic material and thin film coating [10]) structures. In this case, TMOKE measurement is generally carried out using a source having a narrow, almost monochromatic spectrum. However, at the 8th Euro-Asian Symposium "Trends in MAGnetism" held in 2022 in Kazan, Skidanov [11] report the use of white light in conducting experiments on the influence on the magnitude of the magneto-optical effect of thin films of nonmagnetic metals deposited on top of a ferromagnetic layer. Hypothesizing that this would significantly reduce the influence of interference effects, the researcher concluded that the observed change in the Kerr effect was due to more fundamental physical processes. However, such an interpretation does not seem entirely convincing, since almost all quantities affecting the magnitude of the effect have a nonlinear dependence on the frequency of incident light. Although the report has not yet been published in full, the very fact of raising the question led us to the necessity of a more detailed consideration of the degree of influence of interference effects on TMOKE parameter in white light.

MATHEMATICAL MODEL AND CALCULATION METHODOLOGY

As already mentioned, TMOKE consists in changing the intensity of light reflected from the sample when an external magnetic field is applied to the sample in the direction perpendicular to the plane of light incidence. Accordingly, it is necessary to calculate the intensity of light reflected from the sample both with and without the application of a magnetic field. The geometry of the model structure is shown in Fig. 1. Here, the vector of magnetic field strength lies in the plane of the film perpendicular to the plane of light incidence.

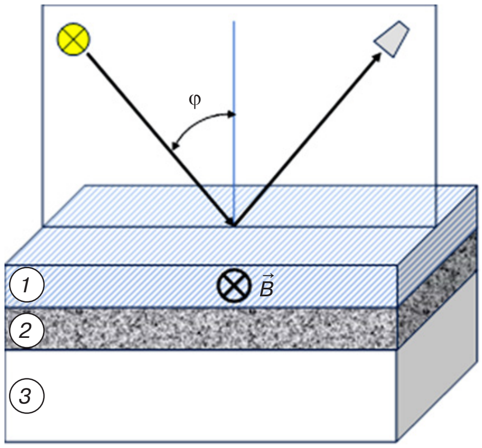

Fig. 1. Model structure geometry:
(*1*) protective film (if any);
(*2*) material with magneto-optical properties;
(*3*) substrate, where φ is an angle of incidence of light,
$\vec{B}$ is the magnetic field induction vector

The relation between the amplitudes of reflected R_j and incident A_j light can be expressed through their s- and p-components as in [12]:

$$\begin{pmatrix} R_s \\ R_p \end{pmatrix} = \begin{pmatrix} r_{ss} & r_{sp} \\ r_{ps} & r_{pp} \end{pmatrix} \begin{pmatrix} A_s \\ A_p \end{pmatrix}.$$

For an isotropic material, $r_{sp} = r_{ps} = 0$. While the application of an external magnetic field generally breaks the symmetry, in the geometry used in this work and shown in Fig. 1, i.e., when a non-zero magnetic field is applied to the magneto-optical material in the film plane perpendicular to the plane of light incidence, we also have $r_{sp} = r_{ps} = 0$. Therefore, in our case, the matrix of reflection coefficients has an invariant form:

$$\hat{r} = \begin{pmatrix} r_{ss} & 0 \\ 0 & r_{pp} \end{pmatrix}.$$

Then:

$$\begin{cases} R_s = r_{ss} A_s, \\ R_p = r_{pp} A_p. \end{cases} \quad (1)$$

During simulation, the spectral dependence of the source radiation intensity was taken into account. The model considered "natural" or circularly polarized light. In this case, the matrix of components of the incident light amplitude can be represented in the following form:

$$\begin{pmatrix} A_s \\ A_p \end{pmatrix} = |A| \begin{pmatrix} e^{i(\alpha+\pi/2)} \\ e^{i\alpha} \end{pmatrix},$$

where the initial phase α changes either arbitrarily ("natural" light) or cyclically at a given frequency (circularly polarized light); accordingly,

$$\begin{cases} R_s = |R_s| e^{i\chi}, \\ R_p = |R_p| e^{i\xi}. \end{cases}$$

Here $\chi = \alpha + \pi/2 + \Delta_s$ and $\xi = \alpha + \Delta_p$, and Δ_s and Δ_p are the phase run-ups as a result of light reflection from the investigated structure for s- and p-components, respectively. Due to the time-varying initial phase α, the resulting phases χ and ξ change in the same way.

Then the intensity of light falling on the photodiode will be equal to:

$$I = \left[|R_s|^2 \cos^2\chi + |R_p|^2 \cos^2\xi \right] \sin^2\omega t,$$

where ω is the frequency of radiation; t is time.

Due to the inertia of the photodetector, the signal is averaged over time and, taking into account also the constant change of the initial phase α and, as a consequence, of the resulting χ and ξ, we obtain $\overline{\cos\chi} = \overline{\cos\xi} = \overline{\sin\omega t} = 0$ and

$$\overline{I} = \frac{|R_s|^2 + |R_p|^2}{4}. \quad (2)$$

As already noted, practically all quantities influencing the magnitude of the effect have a nonlinear dependence on the frequency of incident light. Therefore, the method of calculations in a wide spectral range was as follows. The spectral range was divided into small sections, within which the values of the used quantities were considered to be independent of frequency and corresponding to the value in the middle of this section. Figure 2 depicts an example of such partitioning for the relative spectrum of one of the radiation sources. The partition sections for all values simultaneously used in the calculation were taken to be identical; in case of insufficient experimental data, linear approximation was used. For nonlinear dependencies, the error of this method is smaller the narrower the partition section, leading to an increase in computation time. In the present work, the frequency partitioning into sections of $1 \cdot 10^{-3} - 3 \cdot 10^{-3}$ eV (240–720 GHz). For each partitioning section, the average intensity of radiation detected by the photodetector is determined by Eq. (2) taking into account its spectral sensitivity S_ω. Then, the total signal value is determined by summing over all partition areas:

$$\overline{I_\Sigma} = \sum_\omega S_\omega \overline{I}_\omega, \quad (3)$$

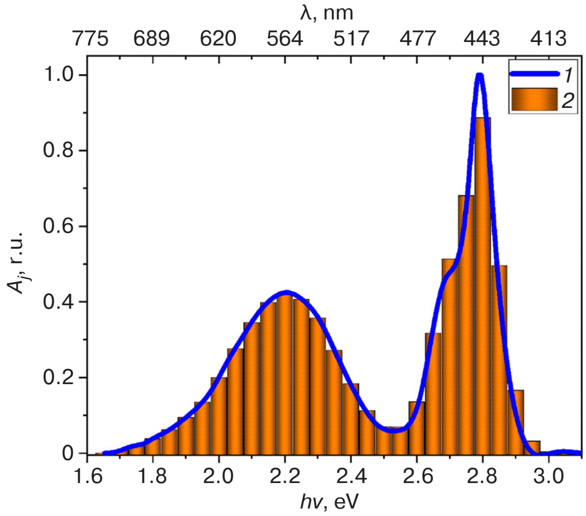

Fig. 2. Emission spectrum of white LED with color temperature T_c = 6500 K: (*1*) data taken from [13], (*2*) representation of the spectrum as a piecewise constant function. λ is the wavelength of light in a vacuum, which corresponds to a quantum of energy *hv*

The total signal magnitude is determined both in the absence of a magnetic field $\overline{I_\Sigma^0}$ and in its presence $\overline{I_\Sigma^M}$. Then the magnitude of the transverse magneto-optical effect δ is calculated:

$$\delta = \frac{\overline{I_\Sigma^M} - \overline{I_\Sigma^0}}{\overline{I_\Sigma^0}}. \quad (4)$$

In order to determine the amplitudes of the reflected signal (1), it is necessary to calculate the light reflection coefficients from the investigated structure in the absence of the magnetic field (r_{ss}^0, r_{pp}^0) and when it is switched on (r_{ss}^M, r_{pp}^M). This calculation was based on the well-known paper by V.M. Maevskiy "Theory of magneto-optical effects in multilayer systems with arbitrary magnetization orientation" [12], where the magneto-optical parameter $Q = i\varepsilon_{xy}\varepsilon_{xx}^{-1}$ linear in magnetization is considered as a small value ($|Q| << 1$). Here ε_{xx}, ε_{yy}, etc. are the elements of the dielectric tensor $\hat{\varepsilon}$, which for isotropic materials in our case can be represented as:

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon & -i\varepsilon Q & 0 \\ i\varepsilon Q & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{pmatrix} = \varepsilon \begin{pmatrix} 1 & -iQ & 0 \\ iQ & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

Taking into account that the magnetic permeability for the optical range $\mu \approx 1$, we can assume $n^2 \approx \varepsilon$. Here n is the refractive index of the substance. All the mentioned quantities are complex in the general case. Then, for the reflection coefficients of s- and p-polarized wave at the boundary of media, j and k can be written as follows:

$$r_{jk}^{\mathrm{s}} = \frac{g_j - g_k}{g_j + g_k},\ r_{jk}^{\mathrm{p}} = \frac{g_j\varepsilon_k - g_k\varepsilon_j}{g_j\varepsilon_k + g_k\varepsilon_j}. \quad (5)$$

Here

$$g_j = \sqrt{\varepsilon_j - \sin^2\varphi}, \quad (6)$$

φ is the angle of incidence of light on the structure under study. Light falls from air, $\varepsilon_{\mathrm{air}} \approx 1$.

The following recurrence formulas can be used for the reflection coefficients of multilayer structures [12, 14]:

$$r_{jkl}^{\mathrm{s(p)}} = \frac{r_{jk}^{\mathrm{s(p)}} + F_k^2 r_{kl}^{\mathrm{s(p)}}}{1 + F_k^2 r_{jk}^{\mathrm{s(p)}} r_{kl}^{\mathrm{s(p)}}},\ r_{jklm}^{\mathrm{s(p)}} = \frac{r_{jk}^{\mathrm{s(p)}} + F_k^2 r_{klm}^{\mathrm{s(p)}}}{1 + F_k^2 r_{jk}^{\mathrm{s(p)}} r_{klm}^{\mathrm{s(p)}}}, \quad (7)$$

etc., where j, k, l, m are the numbers of layers (media), and the values F_k determine the phase run-up and amplitude attenuation at the thickness of the kth layer:

$$F_k = \mathrm{e}^{-2\pi g_k \frac{d_k}{\lambda}}. \quad (8)$$

Here d_k is the thickness of the layer, λ is the wavelength of light in vacuum, g_k is determined by the Eq. (6).

While these expressions are valid for coherent radiation, in the case of white-light measurements, the thickness of some layers (e.g., the substrate) may exceed it due to the small size of the coherence length. Since coherent and incoherent calculations are not generally mixed within the same model, the substrate could be excluded by treating it as a semi-infinite space. However, when conducting an experiment with illumination of the ferromagnetic film from the substrate side, it becomes impossible to take into account the influence of the thickness and absorption spectrum of the weakly absorbing substrate. Therefore, taking into account the inertia of the photodetector and the fact that the absorption practically does not change between two interference maxima for weakly absorbing materials, we averaged the coefficients (7) for a layer thickness much larger than the coherence length to "fix" the phase of the reflected light and ignore the influence of absorption. Thus, Eq. (7) for one layer can be written in the following form:

$$r_{jkl}^{\mathrm{s(p)}} = r_{jk}^{\mathrm{s(p)}} \left(\frac{1 + F_k^2 \dfrac{r_{kl}^{\mathrm{s(p)}}}{r_{jk}^{\mathrm{s(p)}}}}{1 + F_k^2 r_{jk}^{\mathrm{s(p)}} r_{kl}^{\mathrm{s(p)}}} \right). \quad (9)$$

Since any complex quantity can be represented as $Y\mathrm{e}^{i\alpha}$, where Y and α are real numbers, the numerator and denominator of formula (9) contain expressions of the following form:

$$Y_1\mathrm{e}^{i\alpha_1} + Y_2\mathrm{e}^{i\alpha_2} = Z\mathrm{e}^{i\beta},$$

where Y_1, Y_2, and $Z \geq 0$ are the modules of the complex numbers, and α_1, α_2, and β are their arguments.

Let us assume that $\gamma = \alpha_2 - \alpha_1$, then the resulting amplitude is

$$Z = \sqrt{Y_1^2 + Y_2^2 + 2Y_1Y_2\cos\gamma},$$

and for the argument β we can write:

$$\beta = \alpha_1 + \frac{\sin\gamma}{|\sin\gamma|}\arccos\left(\frac{Y_1 + Y_2\cos\gamma}{Z}\right). \quad (10)$$

The second summand in (10) is periodic and antisymmetric; when averaging over the phase difference, it can be easily shown that γ it converges to zero. Then:

$$\overline{Z} = \sqrt{Y_1^2 + Y_2^2},\ \overline{\beta} = \alpha_1.$$

In our case $\alpha_1 = 0$, since $1 = 1 \cdot \mathrm{e}^{i0}$. And then for the case when the thickness of the kth layer is much larger than the coherence length, Eq. (9) can be written as follows:

$$r_{jkl}^{\mathrm{s(p)}} = r_{jk}^{\mathrm{s(p)}} \sqrt{\frac{1 + |F_k^2 r_{kl}^{\mathrm{s(p)}} / r_{jk}^{\mathrm{s(p)}}|^2}{1 + |F_k^2 r_{jk}^{\mathrm{s(p)}} r_{kl}^{\mathrm{s(p)}}|^2}}. \quad (11)$$

Correspondingly,

$$r_{jklm}^{\mathrm{s(p)}} = r_{jk}^{\mathrm{s(p)}} \sqrt{\frac{1 + |F_k^2 r_{klm}^{\mathrm{s(p)}} / r_{jk}^{\mathrm{s(p)}}|^2}{1 + |F_k^2 r_{jk}^{\mathrm{s(p)}} r_{klm}^{\mathrm{s(p)}}|^2}},\ \text{etc.}$$

In order to demonstrate the advantages of such averaging over the use of expressions for coherent light for the substrate while the coherence condition is not fulfilled, Fig. 3 shows the results of calculations using the method considered for an absorbing substrate at a change of its thickness, performed using Eqs. (7) and (11).

Let us consider the structure shown in Fig. 1 surrounded by air. Then the reflection coefficients in the absence of magnetic field r_{ss}^0 and r_{pp}^0 can be calculated by Eqs. (5)–(8), (11) as follows:

$$r_{\mathrm{ss}}^0 = r_{\mathrm{a123a}}^{\mathrm{s}},\ r_{\mathrm{pp}}^0 = r_{\mathrm{a123a}}^{\mathrm{p}}. \quad (12)$$

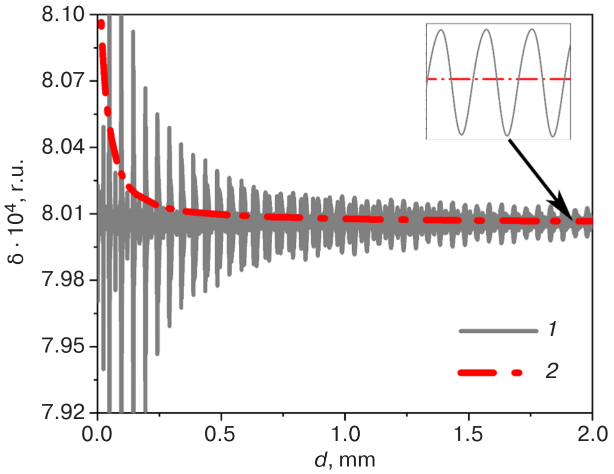

Fig. 3. Dependence of the effect value on the silicon substrate thickness for uncoated ferromagnetic film. The reflection coefficient from the substrate was calculated: (*1*) by Eq. (7), (*2*) by Eq. (11)

Here, index 'a' corresponds to air and the rest corresponds to the layer numbers in Fig. 1.

When taking into account the magneto-optical effect, reflection coefficients r_{ss}^{M} and r_{pp}^{M} can be expressed as follows:

$$r_{ss}^{M} = r_{ss}^{0}, \quad r_{pp}^{M} = r_{pp}^{0} W(1+\rho_p). \tag{13}$$

We define the multipliers W and ρ_p following [12], taking into account the geometry (Fig. 1) and the incidence of light on the structure from air. Then:

$$\rho_p = i(1-F_2^2)\times$$
$$\times\left[\frac{r_{23a}^{p} - r_{21a}^{inv}}{1 - F_2^2 r_{21a}^{inv} r_{23a}^{p}} - \frac{r_{23a}^{p} - r_{21a}^{p}}{1 - F_2^2 r_{21a}^{p} r_{23a}^{p}}\right]\frac{Q\sin\varphi}{2g_2}, \tag{14}$$

where

$$r_{21a}^{inv} = \frac{r_{21}^{p} r_{1a}^{p} + F_1^2}{r_{1a}^{p} + F_1^2 r_{21}^{p}}. \tag{15}$$

For thin films, we can assume $W \approx 1$. Considering arbitrary thicknesses, following [12]:

$$W = \frac{1 - F_2^2 a_p \sin^2\vartheta}{1 + F_2^2 a_0 \sin^2\vartheta}, \tag{16}$$

where

$$\vartheta = \frac{\pi d_2 n_2 Q}{\lambda},$$

$$a_p = \frac{(r_{23a}^{p} - r_{23a}^{s})(1 - r_{21a}^{inv} r_{21a}^{s})}{(r_{21a}^{inv} - F_2^2 r_{23a}^{p})(1 - F_2^2 r_{21a}^{s} r_{23a}^{s})},$$

$$a_0 = \frac{(r_{23a}^{p} - r_{23a}^{s})(r_{21a}^{p} - r_{21a}^{s})}{(1 - F_2^2 r_{21a}^{s} r_{23a}^{s})(1 - F_2^2 r_{21a}^{p} r_{23a}^{p})}.$$

Considering Eqs. (1)–(4), we can write down:

$$\delta = \frac{\sum_\omega S_\omega(|r_{ss_\omega}^{M} A_{s_\omega}|^2 + |r_{pp_\omega}^{M} A_{p_\omega}|^2)}{\sum_\omega S_\omega(|r_{ss_\omega}^{0} A_{s_\omega}|^2 + |r_{pp_\omega}^{0} A_{p_\omega}|^2)} - \frac{\sum_\omega S_\omega(|r_{ss_\omega}^{0} A_{s_\omega}|^2 + |r_{pp_\omega}^{0} A_{p_\omega}|^2)}{\sum_\omega S_\omega(|r_{ss_\omega}^{0} A_{s_\omega}|^2 + |r_{pp_\omega}^{0} A_{p_\omega}|^2)}. \tag{17}$$

SIMULATION RESULTS

Since we were primarily interested in the presence or absence of the influence of interference effects, standard materials possessing magneto-optical properties were chosen: cobalt and a protective film of polyvinyl acetate (PVA). Two-layer (magneto-optical film on a substrate) and three-layer (a protective layer was applied to the film) structures were studied. Assuming the coherence length of radiation to be 500 nm, we took for calculations either thicknesses smaller (for the film and the protective layer) or much larger (for the substrate, the thickness of which was assumed to be 500 μm), which is close to the thicknesses of silicon wafers used in microelectronic production. White light was considered to be "natural" (circularly polarized), with the induction direction of the external magnetic field lying in the plane of the film perpendicular to the plane of light incidence (Fig. 1). As a photodetector, a silicon photodiode whose sensitivity curve was "averaged" according to the data [15, 16] was considered.

According to the performed numerical simulations, the assumption that interference effects in different parts of the spectrum when using white light sources do not neutralize each other was confirmed; here, the magnitude of the measured effect can strongly depend on the film thickness of the magneto-optical material up to the change of the effect sign (see, for example, curve *1* in Fig. 4). The measured value is also markedly affected by the shape of the emission spectrum of the source, which is also clearly visible in Fig. 4. The plateau of the measured value of the effect at relatively large thicknesses of the magneto-optical film is apparently caused by the absorption of light in the thickness of the magneto-optical film, while the back reflection of light from the substrate is negligible. This is confirmed by the fact that the substrate material does not play a role at such film thicknesses (Fig. 5).

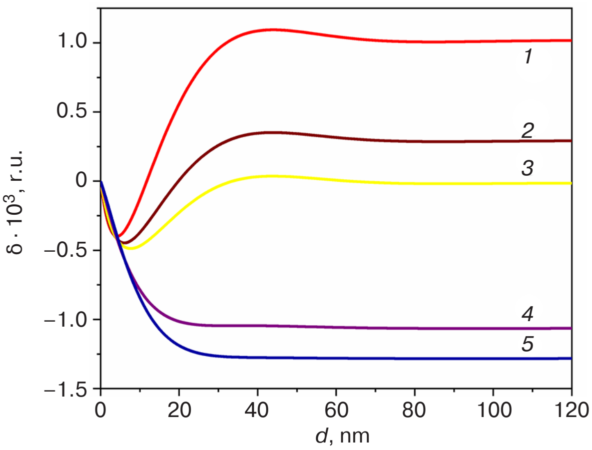

Fig. 4. Dependence of the effect size on the thickness of uncoated ferromagnetic film (light incidence angle 75°, silicon photodiode) for different white light sources:
(*1*) 'A' type source (absolutely black body (ABB) with $T = 2856$ K),
(*2*) 'B' type source (ABB with $T = 4874$ K),
(*3*) 'sunlight' (ABB with $T = 6000$ K),
(*4*) white LED with color temperature $T_c = 3000$ K,
(*5*) white LED with color temperature $T_c = 6500$ K

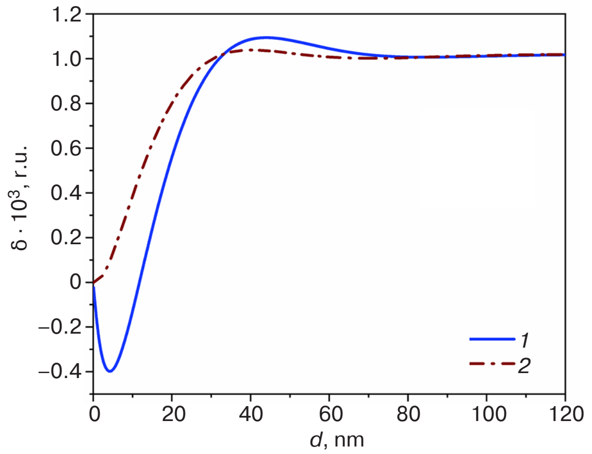

Fig. 5. Dependence of the effect value on the thickness of uncoated ferromagnetic film on SiO_2 (*1*) and Si (*2*) quartz substrates (light incidence angle 75°, 'A' type source, silicon photodiode)

If a protective film is applied on top of the structure, it will further complicate the observed picture. To verify this assumption, we performed calculations in which PVA was considered as a protective material. Since in this case the effect of changing the thickness of the magneto-optical film turned out to be much stronger than the effect of changing the thickness of the transparent film, Fig. 6 demonstrates the dependencies of the effect magnitude on the thickness of the protective film normalized to the effect magnitude in the absence of such a coating. An SiO_2 substrate was used, having a light incidence angle of 75°, an 'A' type source, and a silicon photodiode.

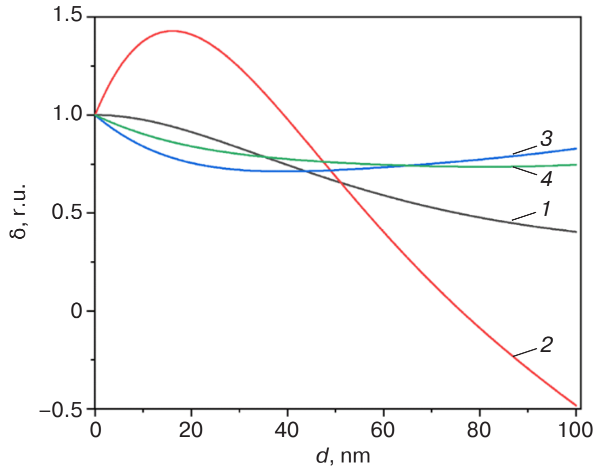

Fig. 6. Dependencies of the effect size on the thickness of the PVA protective layer on ferromagnetic films of different thickness, normalized to the effect size in the absence of such a layer:
(*1*) 10 nm, (*2*) 20 nm, (*3*) 30 nm, (*4*) 60 nm

The curves in Fig. 7, which are in agreement with the theory of metallooptics (e.g., [17]), show that in order to obtain the maximum value of the measured effect, it is better to work in the geometry when light falls on the structure at an angle of around 70°–75°. The lack of dependence of the effect value on the thickness of the magneto-optical material at angles of incidence close to 90° (slip angle) is due to the fact that in this case light practically does not penetrate into the film and only the surface effect is registered. At the same time, we can see a clear influence of interference effects, which decreases with increasing thickness of the ferromagnetic film. This decrease is due to the absorption of light in the thickness of the ferromagnetic material and consequent decrease in the influence of light reflected from the interface with the substrate. An SiO_2 substrate was used having an 'A' type source and a silicon photodiode.

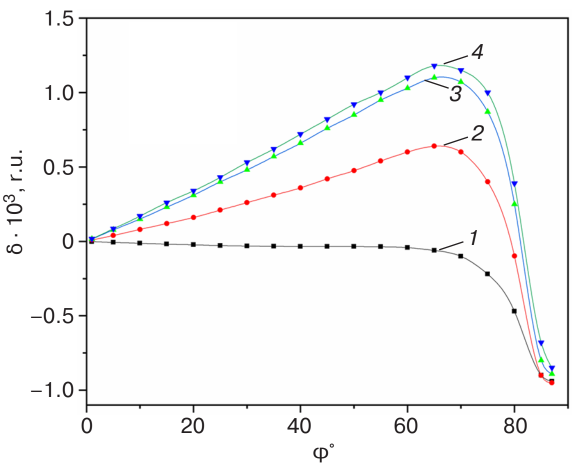

Fig. 7. Dependencies of the TMOKE value on the angle of incidence of light on ferromagnetic films of different thicknesses without a "protective layer":
(*1*) 15 nm, (*2*) 30 nm, (*3*) 45 nm, (*4*) 60 nm

CONCLUSIONS

The performed calculations demonstrate the necessity of taking into account the influence of the spectral sensitivity of the photodetector when interpreting the obtained results on TMOKE measurement using white light sources. Here, it is also important to consider interference at small thicknesses of ferromagnetic and/or "protective" film. The developed technique allows us to take into account the influence of interference effects when measuring TMOKE in white light—or, using other sources, across a wide spectral range—and to interpret the experimental results more precisely.

Authors' contributions

I.V. Gladyshev—model proposal and development, calculation methodology development, creating a computer program, computer simulation, discussion of results, writing the text of the article.

A.N. Yurasov—computer simulation, discussion of results, writing and editing the text of the article.

M.M. Yashin—processing the literary sources, computer simulation, discussion of results, writing the text if the article.

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About the authors

Igor V. Gladyshev, Cand. Sci. (Phys.–Math.), Associate Professor, Department of Nanoelectronics, Institute for Advanced Technologies and Industrial Programming, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: i_gladyshev@mirea.ru. ResearcherID N-1535-2016, Scopus Author ID 6701612553, RSCI SPIN-code 6735-1887, https://orcid.org/0000-0002-7627-4978

Alexey N. Yurasov, Dr. Sci. (Phys.-Math.), Professor, Department of Nanoelectronics, Institute for Advanced Technologies and Industrial Programming, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: alexey_yurasov@mail.ru, ResearcherID M-3113-2016, Scopus Author ID 6602974416, RSCI SPIN-code 4259-8885, https://orcid.org/0000-0002-9104-3529

Maxim M. Yashin, Cand. Sci. (Phys.-Math.), Associate Professor, Department of Nanoelectronics, Institute for Advanced Technologies and Industrial Programming, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: ihkamax@mail.ru. ResearcherID G-6809-2017, Scopus Author ID 57210607470, RSCI SPIN-code 2438-6135, https://orcid.org/0000-0001-8022-9355

Об авторах

Гладышев Игорь Васильевич, к.ф.-м.н., доцент, кафедра наноэлектроники, Институт перспективных технологий и индустриального программирования, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: i_gladyshev@mirea.ru. ResearcherID N-1535-2016, Scopus Author ID 6701612553, SPIN-код РИНЦ 6735-1887, https://orcid.org/0000-0002-7627-4978

Юрасов Алексей Николаевич, д.ф.-м.н., профессор, кафедра наноэлектроники, Институт перспективных технологий и индустриального программирования, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: alexey_yurasov@mail.ru. ResearcherID M-3113-2016, Scopus Author ID 6602974416, SPIN-код РИНЦ 4259-8885, https://orcid.org/0000-0002-9104-3529

Яшин Максим Михайлович, к.ф.-м.н., доцент, кафедра наноэлектроники, Институт перспективных технологий и индустриального программирования, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: ihkamax@mail.ru. ResearcherID G-6809-2017, Scopus Author ID 57210607470, SPIN-код РИНЦ 2438-6135, https://orcid.org/0000-0001-8022-9355

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