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RESEARCH ARTICLE

Magneto-optical transverse Kerr effect in $Co_x(CoO)_{1-x}$ nanocomposites

Maxim M. Yashin @,
Vitaly E. Ryabukhin,
Alexey N. Yurasov

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

Abstract
Objectives. The aim of this paper is to attain and investigate the spectra of the magneto-optical transverse Kerr effect (TKE) in $Co_x(CoO)_{1-x}$ nanocomposites, to compare the obtained results with experimental data, and identify their specific features. Magneto-optical spectroscopy is a method for non-destructive testing and research of a wide class of nanostructures with promising and interesting properties, and such studies are essential in terms of both fundamental and practical aspects.
Methods. Computer modeling is used as part of the promising effective medium method. This is in the form of the Bruggeman approximation, according to which the structure under study is replaced by a medium with effective properties.
Results. TKE experimental spectra were studied and Kerr effect spectra in the range of 1.5–3.0 eV were obtained by computer modeling. In this case, the modeling is performed by means of two methods, ignoring and considering the quasiclassical size effect. The final result is the comparison of the model and experimental Kerr effect spectra, in which the influence of size effects on the appearance of the TKE spectra is shown. The reliability of methods is well confirmed by comparing the results obtained with empirical data. The value of the results obtained stems from the fact that all the calculated parameters of the nanocomposite under study and the shape of TKE spectral dependencies are in good agreement with the observation results.
Conclusions. The optimal parameters of the sample under study are established as part of computer modeling: form factor, average granule size, and the anomalous Hall effect coefficient. The described approach allows the magneto-optical properties of promising nanomaterials to be studied in a non-contact and non-destructive manner. These results are useful for creating new types of devices as well as electronics and nanoelectronics elements.

Keywords: nanocomposites, effective medium approach, transverse Kerr effect, cobalt oxide, size effects

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НАУЧНАЯ СТАТЬЯ

Магнитооптический экваториальный эффект Керра в нанокомпозитах $Co_x(CoO)_{1-x}$

М.М. Яшин @,
В.Е. Рябухин,
А.Н. Юрасов

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

Резюме

Цели. Целью работы является получение и исследование спектров магнитооптического экваториального эффекта Керра (ЭЭК) в нанокомпозитах $Co_x(CoO)_{1-x}$, сравнение полученных результатов с экспериментальными данными, выявление их особенностей. Подобные исследования являются, безусловно, важными, как с фундаментальной точки зрения, так и с практической, т.к. магнитооптическая спектроскопия – метод неразрушающего контроля и исследования широкого класса наноструктур с перспективными и интересными свойствами.

Методы. Для достижения поставленной цели применялось компьютерное моделирование в рамках перспективного метода эффективной среды – приближения Бруггемана, согласно которому исследуемая структура заменяется средой с эффективными свойствами.

Результаты. Изучены экспериментальные спектры ЭЭК и в рамках компьютерного моделирования получены спектры эффекта Керра в диапазоне 1.5–3.0 эВ. При этом моделирование проводилось двумя способами: без учета и с учетом квазиклассического размерного эффекта. Конечным результатом стало сопоставление модельных и экспериментальных спектров эффекта Керра, где было показано влияние размерных эффектов на вид спектров ЭЭК. Достоверность методик хорошо подтверждается сравнением полученных результатов с эмпирическими данными, а ценность полученных результатов обусловлена тем, что все рассчитанные параметры обсуждаемого нанокомпозита и форма спектральных зависимостей ЭЭК хорошо согласуются с результатами наблюдений.

Выводы. В рамках компьютерного моделирования установлены оптимальные параметры исследуемого образца: форм-фактор, средний размер гранул, коэффициент аномального эффекта Холла. Описанный подход позволяет бесконтактным и неразрушимым способом изучать магнитооптические свойства перспективных наноматериалов, а полученные результаты являются важными при создании новых типов устройств, а также элементов электроники и наноэлектроники.

Ключевые слова: нанокомпозиты, теория эффективной среды, экваториальный эффект Керра, оксид кобальта, размерные эффекты

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INTRODUCTION

Achievements in magneto-optics are being actively applied today in the modern electronic industry. Magneto-optics is a branch of physics which studies the phenomena resulting from interactions of electromagnetic radiation (of the optical range in the infrared (IR), visible, and near-ultraviolet regions of the spectrum) with magnetized matter. The transverse Kerr effect (TKE) described in Fig. 1 is one of the magneto-optical effects.

TKE is actively used in studying nanostructures, magnetic reading, and recording data from magnetic disks. Current trends in the development of information storage devices are driving the search for new materials in the field of magnetic granular alloys and nanocomposites.

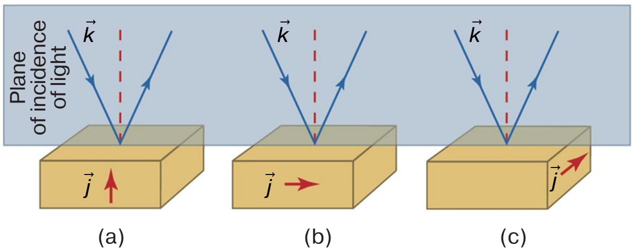

Fig. 1. Kerr effect in polar (a), meridional (b), and equatorial (c) geometries. $\vec{k}$ is wave vector; $\vec{j}$ is magnetization

Thus research into the properties of promising nanostructures represent an important research task. This is particularly relevant to the possibility of significantly enhancing important practical effects such as magnetoresistance, quantum Hall effects, magnetorefractive effect, and many others [1–3]. Co–CoO-based nanocomposite is an interesting example of a nanostructure, while modeling the observed optical and magneto-optical effects enables various characteristic parameters of the investigated samples to be assessed in a non-contact manner [4–7].

The experiment described in [8, 9] established the spectral dependencies of the TKE parameter (δ) in the equatorial geometry of $Co_x(CoO)_{1-x}$ nanocomposite at different values of the cobalt volume fraction X (Fig. 2).

MATHEMATICAL MODEL AND CALCULATION METHODOLOGY

The phenomenological theory of magneto-optical effects requires Maxwell's equations to be resolved with allowance for the dielectric permittivity in matrix (tensor) form; $\hat{\varepsilon}$ is the dielectric permittivity tensor (DPT):

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon & i\gamma & 0 \\ -i\gamma & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{pmatrix}. \quad (1)$$

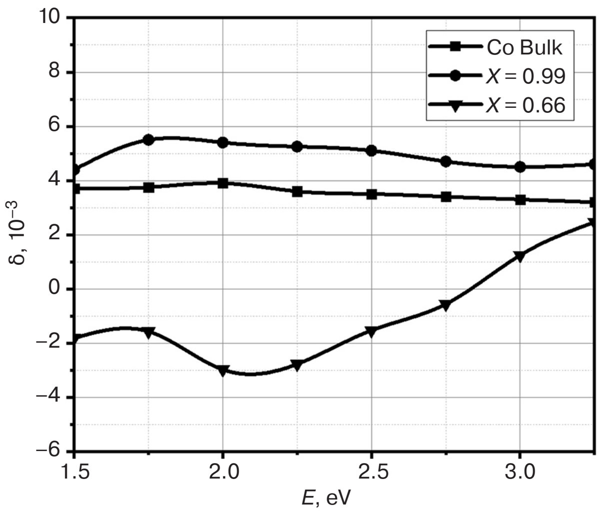

Fig. 2. Experimental TKE spectra of $Co_x(CoO)_{1-x}$ nanocomposite. E is the electromagnetic wave energy [8, 9]

The magnetic induction vector is directed along the z-axis while the ε and γ components of DPT have the following form:

$$\gamma = \gamma_1 - i\gamma_2, \quad \varepsilon = \varepsilon_1 - i\varepsilon_2, \quad (2)$$

wherein ε and γ are complex quantities. In this case, ε_1 and γ_1 are the real part of diagonal and nondiagonal DTP components, while ε_2 and γ_2 are the imaginary part of DTP components, respectively.

Any magneto-optical effect can be unambiguously expressed through DTP components. Magneto-optical effects enable the contribution of left and right spin subzones to be separated, whereas studying frequency dependencies of imaginary parts of diagonal and nondiagonal DTP components provides comprehensive information on the zone structure of the investigated medium.

Furthermore, magneto-optical effects allow the domain structure to be visualized. It is thus one of the most important tools in studying magnetic nano- and micro-objects, including the working zone of magnetic heads and domain boundaries [1–6].

The global advantage of magneto-optical Kerr spectroscopy is the ability to determine non-diagonal components of tensors using TKE, and, in practical terms, to “screen out” noise and interference in the experimental setup. At the same time, the Kerr effect parameter δ can be measured experimentally on the p-component only. This is due to the fact that the δ_s-effect on the s-component in metallic ferromagnets is 2–3 times smaller than δ [9]:

$$\delta = (A\gamma_1 + B\gamma_2) + \frac{2\sin 2\varphi}{A^2 + B^2}, \quad (3)$$

wherein $A = \varepsilon_2(2\varepsilon_1 \cos^2\varphi - 1)$, $B = \cos^2\varphi(\varepsilon_2^2 - \varepsilon_1^2 + 1) + \varepsilon_1 - 1$, φ is the light incidence angle.

The effective medium theory is optimal in describing spectral dependencies of nanostructures and nanocomposites in particular [10]. In the IR spectral region, the significant influence of the quasi-classical size effect due to intraband transitions should be taken into account when using this theory [11]. The size effects are accounted for by varying the form factors of particles L and by adding the ferromagnetic component of the nanocomposite to the diagonal and nondiagonal DTP components, due to the electron scattering on granule surfaces. Finally, when allowing for the contribution of dimensional effects to the permittivity tensor, according to the Drude–Lorentz model, DTP components are represented in the following form [11]:

$$\varepsilon_{\text{mod}} = \varepsilon_{\text{Co}} + \frac{\omega_p^2}{\omega(\omega + i/\tau_{\text{bulk}})} - \frac{\omega_p^2}{\omega(\omega + i/\tau_{\text{part}})},$$
$$\gamma_{\text{mod}} = \gamma_{\text{Co}} - \frac{4\pi\sigma_{xy}^{\text{bulk}}/\tau_{\text{bulk}}^2}{\omega(\omega + i/\tau_{\text{bulk}})^2} + \frac{4\pi\sigma_{xy}^{\text{gr}}/\tau_{\text{part}}^2}{\omega(\omega + i/\tau_{\text{part}})^2}, \quad (4)$$

wherein ε_{Co} and γ_{Co} are the diagonal and non-diagonal DTP components of the ferromagnet (cobalt in this case); ω is the frequency of the incident electromagnetic wave; ω_p is the plasma frequency; τ_{bulk} and τ_{part} are the average electron path times in bulk samples and granules, respectively; $\sigma_{xy}^{\text{bulk}} = 4\pi M_s R_{\text{bulk}} / \rho_{\text{bulk}}^2$; $\sigma_{xy}^{\text{gr}} = 4\pi M_s R_{\text{gr}} / \rho_{\text{gr}}^2$; M_s is the saturation magnetization of the ferromagnet; R_{gr} and R_{bulk} are coefficients of the anomalous Hall effect (AHE) for granules and bulk sample, respectively; ρ_{bulk} is the bulk sample resistivity; and ρ_{gr} is the granule resistivity. The size effect is evident both in the AHE parameter and in the resistivity, as follows:

$$R_{\text{gr}} = R_{\text{bulk}} + 0.2R\frac{l}{r_0}\left(1 + \frac{l}{r_0}\right), \quad (5)$$

$$\rho_{\text{gr}} = \rho_{\text{bulk}}\left(1 + \frac{l}{r_0}\right), \quad (6)$$

wherein R is the AHE parameter value of the granule surface material, r_0 is the nanocomposite particle size, and l is the free path length.

Further expressions (4), (5) are substituted into effective medium formulas (e.g., see [6]) and finally into (3).

MODELING RESULTS

The values of the TKE parameter are obtained using formulas (1)–(3) within the framework of the Bruggeman approximation [12] as a promising effective medium method. Differences in the form of particles L (form factor) are allowed for while ignoring the size effect. They are compared with the experimental data obtained by the research laboratory at the Department of Magnetism, Faculty of Physics, Lomonosov Moscow State University [12] (Fig. 3). The nanocomposite with the cobalt volume fraction $X = 0.66$ is chosen as a comparative sample.

It can be seen in Fig. 3 that the best agreement is observed at $L = 0.3$. For more precise TKE description, we consider the influence of the quasiclassical size effect (formulas (4) and (5)) (Fig. 4).

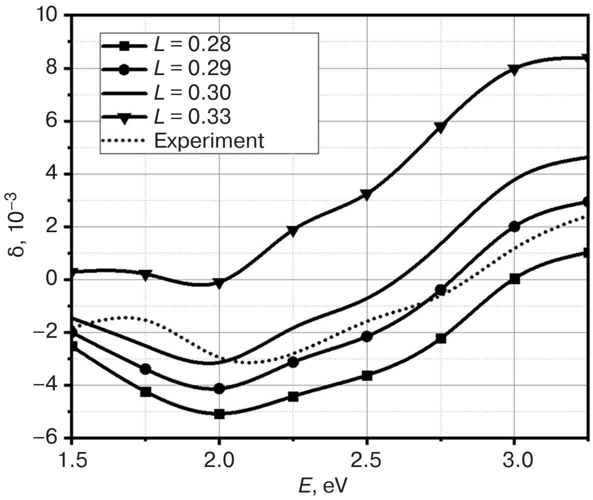

Fig. 3. Model TKE spectra of the $Co_x(CoO)_{1-x}$ nanocomposite ignoring the size effect at different values of the particle form factor

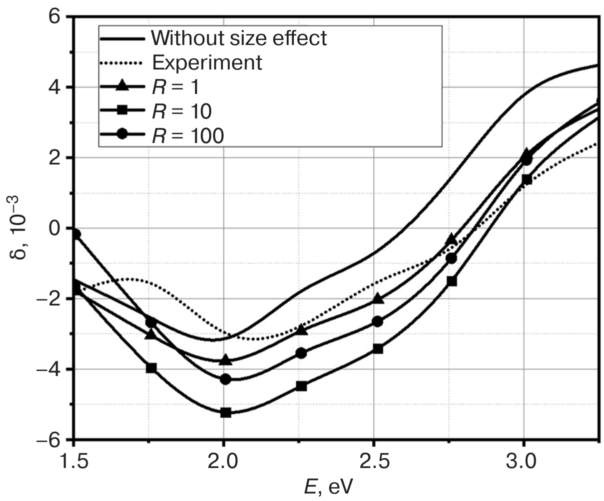

Fig. 4. Model TKE spectra of the $Co_x(CoO)_{1-x}$ nanocomposite ignoring and considering the size effect at different values of AHE parameter R

Figure 4 shows that considering the quasiclassical size effect allows the TKE change in the near-IR region of the spectrum to be described in a better way. The best coincidence of the model and experimental curves is observed at $R = 1$. The average size of the Co_xCoO_{1-x} nanocomposite granules is found to be $r_0 = 2.5$ nm. These results are useful in creating new types of devices, as well as elements of electronics and nanoelectronics [13–15].

CONCLUSIONS

As a result of the study, TKE model spectra in the $Co_x(CoO)_{1-x}$ nanocomposite were obtained and compared with experimental data.

The study also showed the significance of considering the contribution of the particle form factor, as well as the quasi-classical size effect on the TKE spectral dependencies. By means of computer modeling, the optimal parameters of the sample investigated, such as form-factor, average granule size, and AEC coefficient were established.

Thus, the above approach enables the magneto-optical properties of promising nanomaterials to be studied in a noncontact and nondestructive manner.

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Authors' contributions

M.M. Yashin—computer simulation, discussion of results, and writing and editing the text of the article.

V.E. Ryabukhin—processing of literary sources, computer simulation, discussion of results, and writing the text of the article.

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

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About the authors

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: yashin@mirea.ru. ResearcherID G-6809-2017, Scopus Author ID 57210607470, RSCI SPIN-code 2438-6135, https://orcid.org/0000-0001-8022-9355

Vitaly E. Ryabukhin, Student, Institute for Advanced Technologies and Industrial Programming, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: vitas900@gmail.com. https://orcid.org/0009-0001-0421-4845

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

Об авторах

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: yashin@mirea.ru. ResearcherID G-6809-2017, Scopus Author ID 57210607470, SPIN-код РИНЦ 2438-6135, https://orcid.org/0000-0001-8022-9355

Рябухин Виталий Евгеньевич, магистрант, Институт перспективных технологий и индустриального программирования, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: vitas900@gmail.com. https://orcid.org/0009-0001-0421-4845

Юрасов Алексей Николаевич, д.ф.-м.н., профессор, профессор кафедры 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

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