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# Transverse magneto-optical Kerr effect in magnetoplasmonic waveguide structures based on $Fe_3O_4$

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# Transverse magneto-optical Kerr effect in magnetoplasmonic waveguide structures based on $Fe_3O_4$

**S I Pavlov[1], A B Pevtsov[1], S A Dyakov[2], D A Yavsin[1], F Spitzer[3], I Akimov[1,3], S Y Verbin[4], S G Tikhodeev[5], N A Gippius[2], A V Nashchekin[1] and M Bayer[1,3]**

[1] Ioffe Institute, Polytekhnicheskaya Str. 26, St. Petersburg, 194021, Russia
[2] Skolkovo Institute of Science Technology, 143025, Moscow Region, Russia
[3] Experimentelle Physik 2, Technische Universität Dortmund, 44221 Dortmund, Germany
[4] Spin Optics Laboratory, Saint Petersburg State University, 198504, St. Petersburg, Russia
[5] Lomonosov Moscow State University, 119234, Moscow, Russia

e-mail: Pavlov_sergey@mail.ioffe.ru

**Abstract**. In this study transverse magneto-optical Kerr effect in transmission for the magnetite thin film with gold grating on top was examined theoretically and experimentally. The magnetite films with thickness of 200 nm were fabricated by the laser electrodispersion technique. Arrays of gold stripes with 600 nm period and 350 nm and 500 nm stripe widths were created by lift-off e-beam lithography. It was shown experimentally that the TMOKE enhancement in structures with 350 nm width is attributed to SPP excitation on gold-magnetite surface. TMOKE value $\delta$ reaches magnitude of $\pm 5\cdot 10^{-3}$ at the wavelengths 790 nm and 860 nm at light incidence angles of 8-10° and 12-13°, respectively. In case of 500 nm stripe width, SPP excitation is poor, however $\delta$ reaches magnitude of $\pm 6.6\cdot 10^{-3}$ at angles of incidence more than 20°, that can be associated with the quasiguided mode resonance in such structure.

## 1. Introduction

Magneto-optical properties investigation is of great interest for development of novel types of optical and optoelectronic devices. In particular, transverse magneto-optical Kerr effect (TMOKE) is the one, that attracts researchers' attention due to its potential for such applications as data storage, optical filtering, magnetic and bio- sensors.

TMOKE effect describes a change in the intensity of the transmitted/reflected light when changing of magnetization perpendicular to the plane of incidence. The TMOKE value is characterized by the parameter $\delta$, which is a relative change in the intensity of light when the magnetization $M$ of the medium is reversed:

$$\delta = 2\frac{I(M) - I(-M)}{I(M) + I(-M)},$$

where $I$ denotes refection or transmission.

The factor limiting practical application of the Kerr effect is its low magnitude – $\delta$ (of the order of $1\cdot 10^{-3}$) for smooth ferromagnetic films. One of the promising methods for the TMOKE signal enhancement is the surface nanostructuring by noble metal gratings where surface plasmon-polariton

(SPP) can be excited [1-4]. In addition, since the refractive index of magnetite film is larger than that of the substrate, due to the presence of the gold grating, the quasiguided modes can be excited in such structures [5-8]. These modes are the Fano resonances with asymmetric spectral shape [9]. This fact, in turn, provides the high sensitivity of the resonances to the changes of external conditions such as an applied magnetization.

It has been demonstrated that in magnetic films capped by noble metal gratings, the magnitude of TMOKE is enhanced compared to bare magnetic films [3]. In the most studied magnetic materials for magnetoplasmonic crystals, namely Bismuth Iron Garnet (BIG) and Yttrium Iron Garnet (YIG), the TMOKE can reach relatively large magnitudes, although in a narrow wavelength range which is attributed to the low optical losses in BIG and YIG. At the same time, in some applications it can be useful to get TMOKE in relatively wide range of light wavelength and incidence angles. It can be achieved by using magnetic materials with internal losses, but with reasonable TMOKE amplitude. Magnetite ($Fe_3O_4$) which is well-known ferrimagnetic, is promising material from this point of view.

In this paper we study theoretically and experimentally the TMOKE in magnetite ($Fe_3O_4$) thin films with plasmonic grating with different metallic stripe widths.

## 2. Methods

### 2.1. Sample preparation

The magnetic films with thickness of 200 nm were deposited on quartz substrate by the laser electrodispersion technique. After the annealing in vacuum at 300°C magnetic films containing nanoparticle ($Fe_3O_4$/α-Fe) complexes have been formed [10]. X-ray phase analysis of the films demonstrated a set of peaks typical for crystalline magnetite ($Fe_3O_4$).

200x200 μm arrays of gold stripes were created by lift-off e-beam lithography as follows. 300nm thick positive e-beam resist PMMA 950K (Allresist, Gmbh) was spin-coated on the substrate and electron beam lithography was carried out using SEM JSM 7001F (JEOL, Japan) equipped with EBL-system 'Nanomaker' (Interface Ltd, Russia). After developing of the e-beam pattern, 40nm gold with 5 nm titanium adhesive layer were deposited by thermal evaporation and lift-off process was performed forming gold stripes. Structures with two different gold stripe widths $w$=350 and 500 nm were created in our study. Grating period was $a$=600 nm.

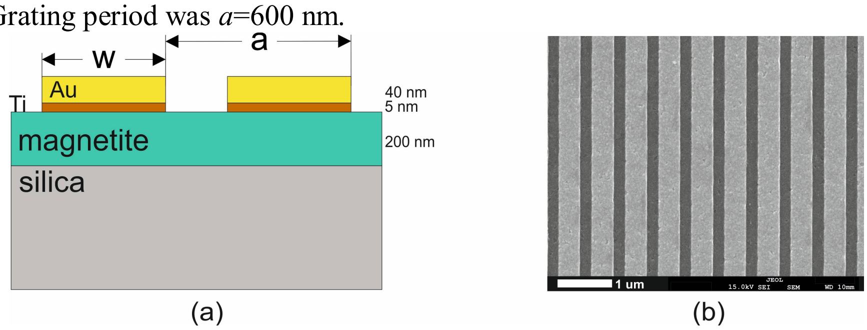


**Figure 1.** (a) Sketch of samples: magnetite films covered with periodic array of gold nanostripes, (b) SEM image of the sample with $w$=400 nm.

### 2.2. Measurements

TMOKE measurements have been performed using a Fourier imaging spectroscopy setup. The samples are positioned between ferrite cores of an electromagnet, with the external magnetic field up to 0.6 T oriented in-plane of the magnetic film perpendicular to the incidence plane. For measured samples in-plane magnetization saturation was achieved at magnetic field 0.1 T. Angular and wavelength resolved transmission spectra were measured at room temperature using a tungsten halogen lamp, which illuminates the sample with p-polarized light. The transmitted light is collimated onto spectrometer slit and CCD detector using a microscope objective with N.A. of 0.4, resulting in the experiment al angular range of -23 to +23°. Sensitivity of the method is of the order of $10^{-4}$.

### *2.3. Calculations*

To calculate the transmission spectra we used a rigorous coupled wave analysis (RCWA) in the scattering matrix form [6]. This method is based on splitting a structure into elementary planar layers, homogeneous in the Z direction and 2D periodic in the X and Y directions. The solutions of Maxwell's equations for each layer are found by expansion of the electric and magnetic fields into Floquet-Fourier modes. The exact solution can be presented as an infinite series over these modes. In numerical simulations, the scattering matrices are determined by truncating the Fourier series on a finite number of plane waves. In the described form, our RCWA implementation is capable to simulate both homogeneous and periodic gyrotropic materials.

The impact of the magnetic field on the optical transmission spectra is accounted for by means of non-diagonal dielectric tensor given by

$$\hat{\varepsilon} = \begin{bmatrix} \varepsilon_0 & -ig & 0 \\ ig & \varepsilon_0 & 0 \\ 0 & 0 & \varepsilon_0 \end{bmatrix},$$

where $\varepsilon_0$ is the dielectric permittivity of the non-magnetized film, $g$ is the value of the gyration. Spectral dependencies for the $\varepsilon_0$ and $g$ for magnetite was taken from [11]. Titanium layer was not taken into account in calculations. However, since it is not a continuous layer, but only discrete layers under gold stripes, with thickness of only about 5 nm it doesn't make a significant changes in optical losses and TMOKE signal.

## 3. Results

Experimental and theoretical spectra of transmission and TMOKE magnitude $\delta$ for structure with 350 nm gold stripe widths are shown in figure 2. Transmission spectra are normalized to the transmission of the magnetite film without grating. Besides of that, the transmission spectra have been corrected by the spectral functions of the lamp and CCD camera.

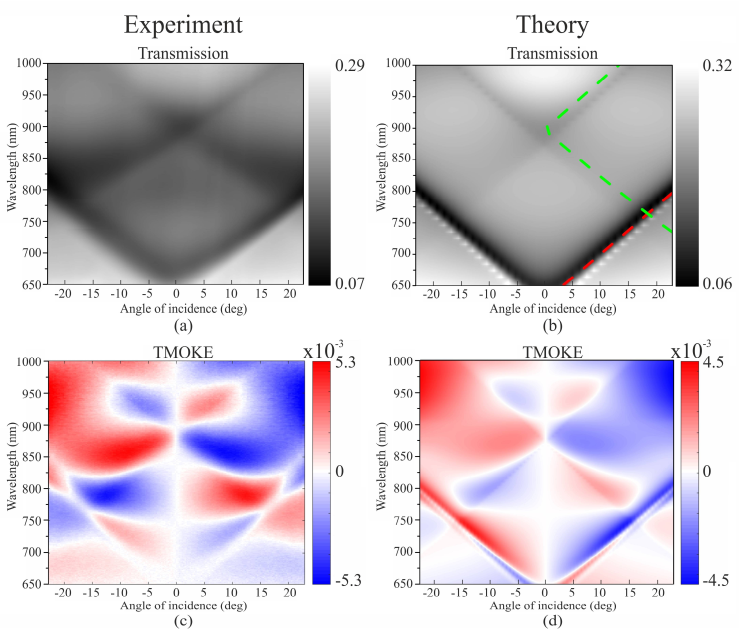


**Figure 2.** Experimental (a, c) and theoretical (b, d) transmission and TMOKE spectra for 350 nm stripe structure. In panel (b), the red and green lines highlight the gold-air SPP and gold-quartz SPP-respectively.

Comparison between theoretical and experimental spectra reveals that the spectral features of transmission and TMOKE are associated with the presence of gold grating. It can be shown that the resonances in transmission (dark regions) and TMOKE (white regions) are attributed to excitation of SPP on the gold-air and gold-substrate surfaces. Due to the small thickness of magnetite film SPP field penetrates to quartz substrate and thus resonance near the gold-quartz SPP line is observed. Gold-quartz SPP has less pronounced shape compare to gold-air one because of absorption in magnetite.

The TMOKE spectra appear to be more informative. Indeed, the white lines correspond to zero magnitude of $\delta$, except for the zero-degree line, related to the fact that $\delta$ is proportional to the transmission derivative in some resonance modes [3]. Thus, the TMOKE spectra can reveal the resonance modes, such as quasiguided modes, that are poorly visible in transmission spectra. However, it is clearly seen that $\delta$ reaches three maxima around gold-magnetite SPP. There are two peaks with $\delta$ magnitude of $\pm 5\cdot 10^{-3}$ at wavelength around $\lambda$=790 nm and 860 nm. The 790 nm peak has maximum at angle of incidence $\theta$=12-13°, and 860 nm at $\theta$=8-10°, respectively. There is another peak along gold-magnetite SPP at higher wavelength around 930 nm, but its magnitude is only $2.5\cdot 10^{-3}$.

In figure 3 the transmission and TMOKE spectra at $\theta$=12° are presented. Features which are attributed to SPP are marked by arrows. The FWHM of the corresponding TMOKE peaks is 40 nm.

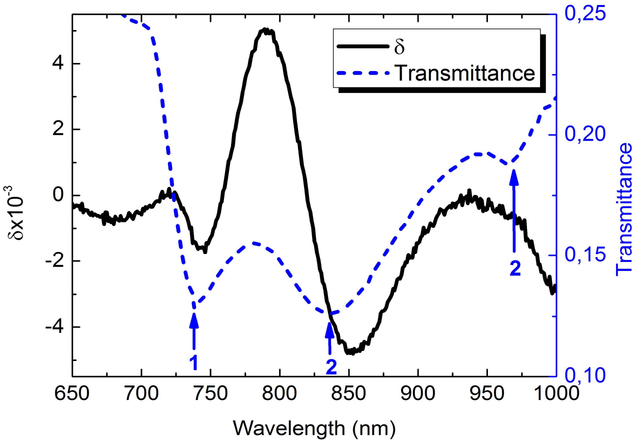


**Figure 3.** Transmission and TMOKE spectra at $\theta$=12°. Arrows marked by 1 and 2 highlight gold-air and gold-quartz SPPs respectively.

In figure 4 the transmission and TMOKE spectra for 500 nm gold stripe widths structure are shown. The SPP lines as well as the TMOKE is less pronounced than in previously described case of 350 nm gold stripes, and $\delta$ reaches only $2.5\cdot 10^{-3}$ along SPP line. However, the TMOKE magnitude reaches $6.6\cdot 10^{-3}$ for the $\lambda$=870 nm and $\theta$ above 20°. The FWHM for this maximum is 70 nm. It can be shown that this maximum is associated with the quasiguided modes.

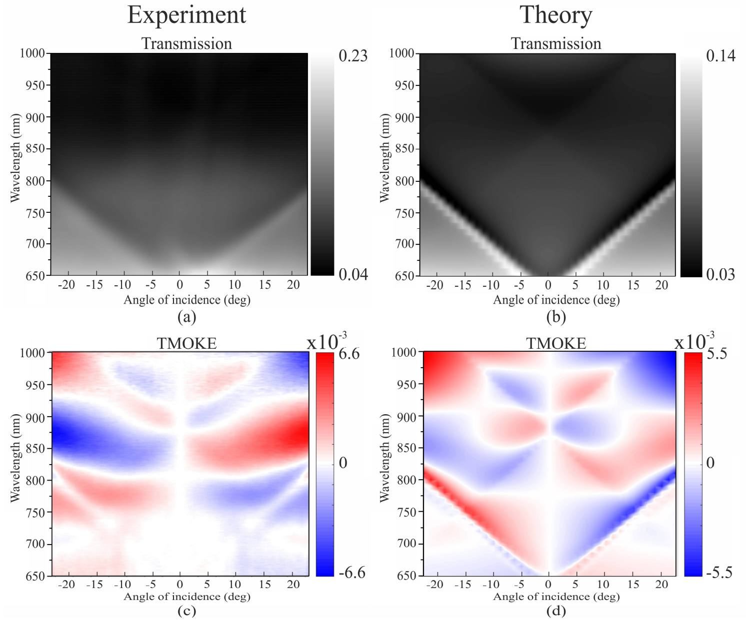


**Figure 4.** Experimental (a, c) and theoretical (b, d) transmission and TMOKE spectra for 500 nm stripes structure.

Experimental results slightly differ from the results of theoretical calculations. It can be explained by the fact that in our calculation we use the dielectric permittivity of pure $Fe_3O_4$ taken from [11], whereas our magnetite film contains $Fe_3O_4$/α-Fe nanoparticles that requires addition characterization.

## 4. Conclusions

In this paper, we study the transverse magneto-optical Kerr effect in transmission for structures with magnetite thin films and periodic array of gold stripes. Transmission and TMOKE spectra for the gold grating structures with 600 nm period and different stripe widths were calculated theoretically and measured experimentally. It was shown that in case of 350 nm stripes the TMOKE has maximal values up to $\pm 5\cdot 10^{-3}$ (at $\lambda$=790 nm and $\theta$=12-13° or at $\lambda$=860 nm and $\theta$=8-10°) close to SPP modes on gold-magnetite reaching. In case of 500 nm stripes structure the SPP peaks are not pronounced, however $\delta$ reaches value of $\pm 6.6\cdot 10^{-3}$ at $\theta$ more than 20°, that can be associated with the quasiguided mode resonance in such structure.

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