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PLASMONICS

Transverse Magneto-Optical Kerr Effect in Magnetite Covered by Array of Gold Nanostripes[1]

S. A. Dyakov[a,*], F. Spitzer[b], I. Akimov[b,c], D. A. Yavsin[c], S. I. Pavlov[c], S. Y. Verbin[d], S. G. Tikhodeev[e], N. A. Gippius[a], A. B. Pevtsov[c], and M. Bayer[b,c]

[a] *Skolkovo Institute of Science and Technology, Moscow, 143025 Russia*
[b] *Experimentelle Physik 2, Technische Universitat Dortmund, Dortmund, 44221 Germany*
[c] *Ioffe Institute, St. Petersburg, 194021 Russia*
[d] *Spin Optics Laboratory, St. Petersburg State University, St. Petersburg, 198504 Russia*
[e] *Moscow State University, Moscow, 119234 Russia*
**e-mail: s.dyakov@skoltech.ru*

Abstract—We study theoretically and experimentally a magneto-optical Kerr effect (TMOKE) in magnetite film covered by sub-wavelength grating consisting of gold nanostripes. Our rigorous coupled wave analysis (RCWA) simulations of optical reflection and transmission coefficients of the structure under study predict a multiple enhancement of TMOKE response in transmission as compared with a plain magnetite film without gold nanostripes. We demonstrate that due to the high absorption losses in magnetite film, the quality factors of the optical resonances in our sample are low which results in wide areas on the dispersion diagram where the TMOKE can be observed.

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1. INTRODUCTION

Transverse magneto-optical Kerr effect (TMOKE) attracted attention of researchers in past decade due to its potential in data storage, optical isolation systems, biosensing, optical filtering and other applications. In the case of planar samples consisting of conventional magnetic materials, the TMOKE has values less 10^{-3} which substantially limits its applicability. It was shown that the TMOKE can be enhanced by the Wood's anomalies originated from the surface plasmon polaritons in magnetoplasmonic crystals [1, 2] or quasiwaveguided modes in dielectric photonic crystal slabs [8]. Yttrium Iron Garnet (YIG) is most often used as magnetic material for theoretical and experimental studied of TMOKE.

In this work we theoretically and experimentally study the TMOKE in the dielectric magnetic waveguide layer which is covered by the plasmonic crystal consisting of gold nanostripes array. The geometrical parameters of the grating were optimized to ensure that it supports the surface plasmon polaritons in the spectral range of our experimental setup. As a magnetic material we use Fe_3O_4 (magnetite). To the best of our knowledge, there are no publications describing the TMOKE properties of such systems with magnetite. At the same time, magnetite is used in a variety of applications, from biomedical to environmental. Moreover, it is the most magnetic of all the naturally-occurring minerals on Earth. Therefore, we believe that this study can be interesting from the viewpoint of potential applications.

2. EXPERIMENTAL

The magnetic films containing nanoparticle (Fe_3O_4/a-Fe) complexes were synthesised with the laser electrodispersion technique on quartz substrate with subsequent annealing at 300°C [3]. X-ray diffraction and electron microscopy studies showed that the average size of magnetic nanoparticles in films was 6–10 nm. The coercive force and the saturation magnetization of the synthesized nanostructured films were as large as ~660 Oe and ~520 emu/cm^3, respectively. These values are considerably higher than the corresponding parameters of polycrystalline Fe_3O_4 films.

Array of gold strips was created by e-beam lithography on a thin magnetite film deposited on a quartz substrate by laser electrodispersion technique. First, a thin layer (<100 nm) of polymethylglutarimide (PMGI) was deposited on a magnetite film followed by 15 nm thick Au layer. Au served as a spacer layer between the photo- and the e-beam resists to prevent their mixing and as well as for charge leakage. After this, PMGI and Au were removed in the windows 500 × 500 μm^2 by the photolithographic method. Then 600 nm thick negative e-beam resist

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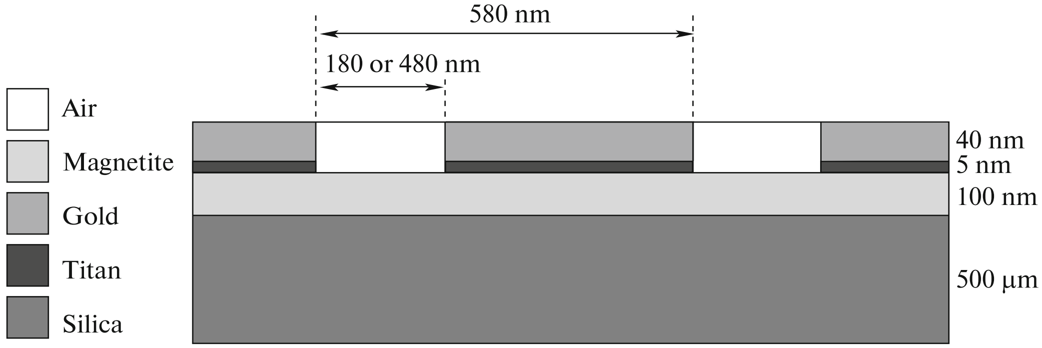

Fig. 1. (Color online) Schematic of magnetoplasmonic system consisting of magnetite film covered by periodic array of gold nanostripes.

AR-N 7520 (Allresist, Germany) was spin-coated on the substrate. 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, 40 nm Au with 5 nm Ti adhesive layer were deposited on substrate. Au strips were performed by lift-off process followed by PMGI/Au mask total remove to clear the substrate. The sketch of the fabricated sample is shown in Fig. 1.

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 varying from 0 up to 0.6 T oriented in-plane of the magnetic film perpendicular to the incidence plane. Angular and wavelength resolved reflectivity were measured at a temperature of 300 K using a tungsten halogen lamp, which illuminated the sample with *p*-polarized light. The reflected light is collimated using a microscope objective with N.A. of 0.4, resulting in the experiment angular range of –23° to +23°. A telescope consisting of two achromatic doublets maps the collimated light onto the imaging spectrometer slit and CCD behind, providing a spectral resolution of 0.6 nm and an angular resolution of about 0.4°.

3. THEORETICAL METHOD

To calculate the reflection and transmission spectra we used a rigorous coupled wave analysis (RCWA) in the scattering matrix form [4]. 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 order to improve the convergence, we implemented Li's factorization rules [5]. In the described form, our RCWA implementation is capable to simulate both homogeneous and periodic gyrotropic materials. As a result, we used 31 plane waves. This approach was previously used for calculation of optical properties of periodic structures with high contrast of refractive index and found a good correspondence with experimental results [6, 7].

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

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

where ε is the dielectric permittivity of the non-magnetized film, g is the value of the gyration. Finally, the TMOKE value is calculated as $\delta = (X(M) - X(-M))/(X(M) + X(-M))$, where symbol X denotes reflection or transmission.

3. RESULTS AND DISCUSSIONS

Theoretical predictions for the TMOKE response in reflection and transmission for the magnetoplasmonic crystal and bare magnetite film are shown in Fig. 2. One can see that the TMOKE response of the bare magnetite film is much stronger pronounced in the transmission mode. At the same time, for the magnetoplasmonic crystal, the TMOKE reaches the value of $\sim 5 \times 10^{-3}$ in both reflection and transmission.

The reflection and TMOKE coefficients are shown in Fig. 3 as functions of the angle of light incidence and the wavelength. Almost linear dependence of the reflection peak spectral position on the incident angle (see Fig. 3a) is attributed to the surface plasmon polaritons on the metal/air interface. Due to the grating periodicity, the surface plasmon polaritons become visible from the far field as Wood's anomalies in the spectra (Fig. 3b). When the external magnetic field is applied perpendicular to the gold nanowires, the

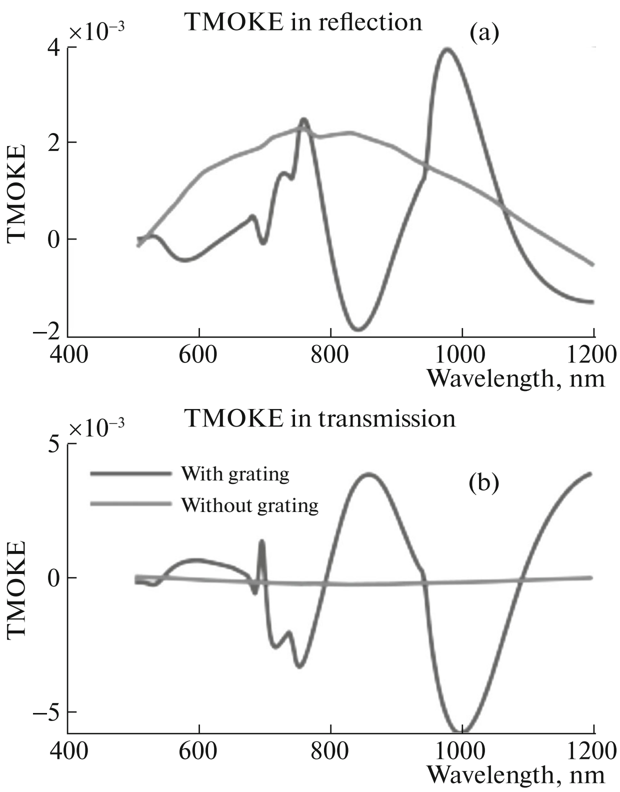

Fig. 2. (Color online) Theoretical prediction for TMOKE in (a) reflection and (b) transmission geometry of magnetoplasmonic crystal with magnetite as well as for bare magnetite film calculate for 10° incident angle.

Wood's anomalies energy appear to be one of the spectral ranges where the TMOKE is observed. Another range with high TMOKE is spectrally located at longer wavelengths (λ > 740 nm). This spectral range is characterized by wide resonances and, as a consequence, larges areas of high TMOKE. This is in contrast to [1, 8] where the high quality factor Wood's anomalies (surface plasmon polaritons in [1] and quasi-waveguided modes in [8]) exhibited narrow and pronounced TMOKE peaks. Contrary to [1, 8], our sample consists of both the plasmonic gold grating and the waveguide layer of magnetite; the interplay between these resonances along with the high extinction coefficient of magnetite ($n = 2.23 + 0.44i$) yields in the dispersion diagrams presented in Fig. 3.

The experimental reflection and TMOKE dependences on the wavelength and incident angle are shown in Figs. 3c, 3d. One can see a good correspondence between theory and experiment.

4. CONCLUSIONS

In conclusion, we have studied the TMOKE effect in magnetoplasmonic crystal consisting of magnetite film covered by periodic array of gold nanostripes. We have demonstrated the multiple enhancement of the TMOKE in transmission for the magnetoplasmonic system in comparison to the bare magnetite film. Due to the high absorption losses in magnetite film, the quality factors of the optical resonances in our sample

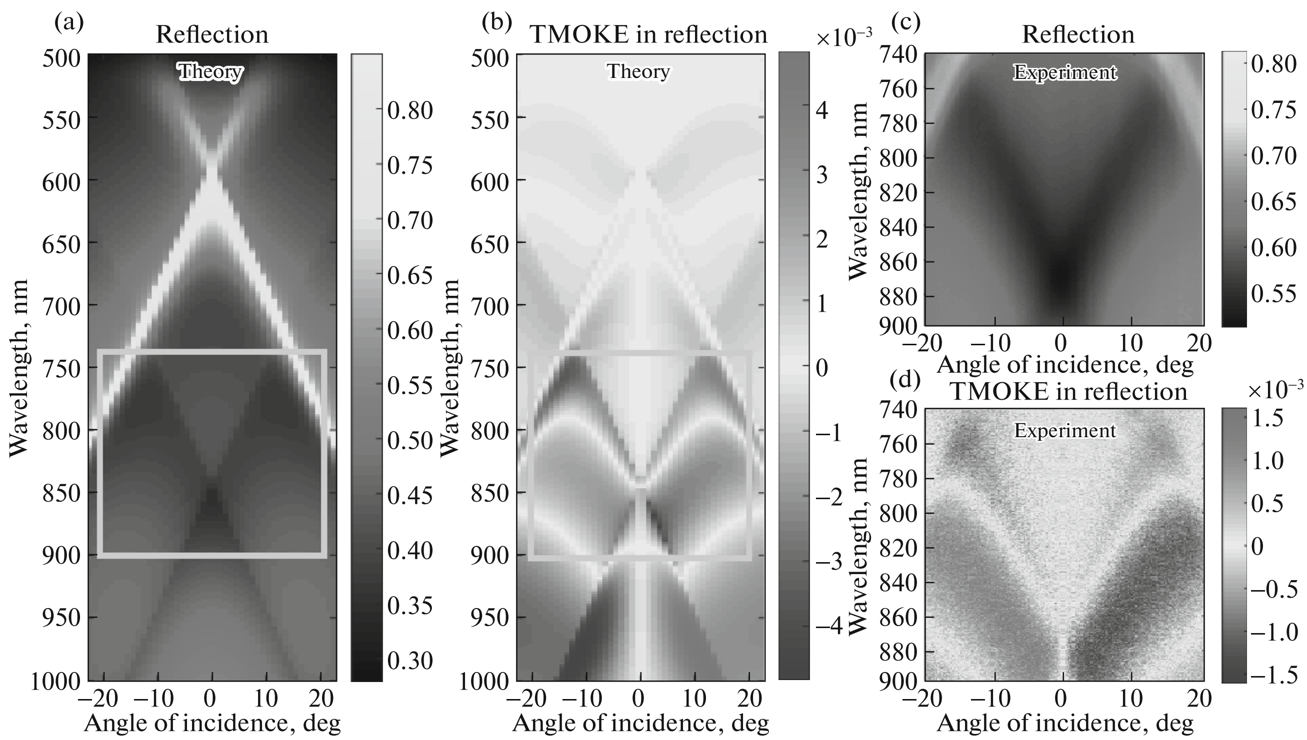

Fig. 3. (Color online) The reflection coefficient (a) and TMOKE in reflection (b) as functions of the angle of light incidence and the wavelength. Experimental data for the reflection (c) and the TMOKE in reflection (d) of magnetoplasmonic crystal with magnetite as function of wavelength and incident angle.

are low which results in wide areas on the dispersion diagram where the TMOKE can be observed. Our experimental data are in agreement with RCWA theoretical calculations.

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