Wide band enhancement of transverse magneto-optic Kerr effect in magnetite

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Abstract. Transverse magneto-optical Kerr effect (TMOKE) is known to be an effective tool for external magnetic field control of optical properties of magnetoplasmonic crystals. In some applications there is a demand for the pronounced TMOKE in the wide wavelength range. In this work we experimentally and theoretically demonstrate that a magnetite based magnetoplasmonic crystal exhibit a multiple wide band enhancement of TMOKE response in transmission compared to a plain magnetite film without metal. Our RCWA calculations are in good agreement with experimental results.

1. Introduction

Transverse magneto-optical Kerr effect attracts great deal of attention from researchers 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 using of surface plasmon polaritons in magnetoplasmonic crystals [1] and magneto-plasmonic nanoantennas [2]. Yttrium Iron Garnet (YIG) is most often used as magnetic material for theoretical and experimental studied of TMOKE. Apart from a relatively large amplitude of TMOKE at resonant frequencies in such structures, the frequency range of enhanced TMOKE response turns out to be narrow. At the same time, in some applications there is a demand for the pronounced TMOKE in a relatively wide wavelength range. It is quite obvious that the amplitude and width of the enhancement peaks in the TMOKE signal are directly determined by the Q-factor of the resonances in magnetic structures. The high Q-factor resonances can give a sharp features in the TMOKE spectra, while the low Q-factor can yield in a wide band TMOKE of lower amplitude. This leads us to the need in a ferromagnetic dielectric with internal losses intensity which ensure wide band TMOKE enhancement of reasonable amplitude.

In this work we show that the well known since ancient times Fe$_3$O$_4$ (magnetite) is one of such dielectrics. We use this material as a compound of a magnetoplasmonic crystal with gold nanostripes array and study theoretically and experimentally the TMOKE in it. To the
best of our knowledge, there are no publications describing the TMOKE properties of such systems. Great interest in magnetite TMOKE properties is also due to the large number of its 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 both from practical and fundamental viewpoints.

2. Experimental details

The magnetic films containing nanoparticle (Fe₃O₄/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/cm³, respectively. These values are considerably higher than the corresponding parameters of polycrystalline Fe₃O₄ 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 by the photolithographic method. Then 600 nm thick negative e-beam resist 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.

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 temperatures of 300 K using a tungsten halogen lamp, which illuminates 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 alangular 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]. 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

$$\hat{\varepsilon} = \begin{bmatrix} \varepsilon & 0 & ig \\ 0 & \varepsilon & -ig \\ -ig & ig & \varepsilon \end{bmatrix}$$ (1)

where $\varepsilon$ 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.

4. Results and discussions

Theoretical predictions of the transmission and TMOKE spectra for the magnetoplasmonic crystal are shown in Fig. 2. The spectral features are attributed to excitation of surface plasmon polaritons and the guided resonance modes. One can see that the TMOKE response reaches the value of $\sim 5 \times 10^{-3}$ which is one order of magnitude higher than in the case of a bare magnetite film.

![Theory and Experiment Spectra](image)

Figure 2: (Color online) Experimental (a, b) and theoretical (c, d) transmission and TMOKE spectra as a function of photon energy and wavevector.
5. Conclusion
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. Our experimental data are in agreement with RCWA theoretical calculations.

Acknowledgements
Authors thank the RFBR (Project No. 15-52-12011) and the Deutsche Forschungsgemeinschaft (DFG) within the framework of the International Collaborative Research Centre (ICRC) TRR 160.

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