TMOKE enhancement in structured all-dielectric iron-garnet films with waveguide modes

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Abstract. The idea of using nanostructured all-dielectric structures to enhance magneto-optical effects instead of plasmonic ones is attracting much interest. The use of dielectric materials allows one to avoid significant energy losses that are present in metals. In this paper, an experimental research of TMOKE effect in 1D dielectric magnetic structures was performed. Experimental results demonstrate a significant enhancement of TMOKE, as well as a high transparency and high Q-factor of the obtained resonances, which opens up broad opportunities for the use of such structures as light modulators.

1. Introduction

Transverse magnetooptical Kerr effect (TMOKE) is a promising perspective for light modulation since it allows laser beam intensity control via external magnetic field that could be switched at GHz frequencies [1]. Magnetoplasmonic crystals were shown to enhance TMOKE due to excitation of surface plasmon polaritons which propagation constant is sensitive to structure magnetization [2,3]. However, plasmonic structures have big absorption due to the presence of metal layers. Nowadays there is a growing interest to another type of structures with significantly higher quality factor – hybrid metal-dielectric and all-dielectric structures – which possess lower absorption and could be used for efficient light localization and control [4]. But in dielectric gratings, the surface plasmon-polariton will not be excited anymore. Instead of surface plasmon polaritons, waveguide or Mie modes could be excited to increase the light-matter interaction in these structures. We concentrate our attention on all-dielectric gratings where guided modes with narrow resonances are known to be excited [5].
Excitation of the waveguide modes is responsible for enhancement of the magnetooptical effects with simultaneous increase of the resonance Q-factors demonstrated experimentally in Kretschmann in smooth magnetic films [6]. At the same time, numerical simulations show that the use of all-dielectric magnetic gratings leads to a significant increase of both intensity [7,10] and polarization effects [8,9].

We present an experimental study of TMOKE effect in 1D all-dielectric gratings etched in ferromagnetic iron-garnet film and show that TMOKE effect experience multifold increase due to the excitation of the waveguide modes.

2. Waveguide modes in all-dielectric iron-garnet gratings
To enhance the magneto-optical effects, we use a 1D all-dielectric grating made of bismuth-substituted iron garnet film perforated with ion beam etching deposited on gadolinium gallium garnet substrate. The width of the air gap of our grating is 200 nm, and the period of the grating is 400 nm. The height of the grating is 225 nm, and the smooth iron-garnet sublayer of 75-nm thickness is left below the grating.

In such a grating, the waveguide modes propagating perpendicular to the slits are excited under the following excitation condition:

\[ k_{\text{inc}} \cdot \sin(\theta) + m \cdot G = \pm \beta_0, \]

where \( k_{\text{inc}} = \frac{2\pi}{\lambda} \) is the propagation constant of the incident light, \( \lambda \) is the wavelength in free space, \( m \) is the diffraction order (integer number), \( G \) – reciprocal lattice vector value, \( \beta_0 = \frac{2\pi}{\lambda} n_{\text{eff}} \) – propagation constant of the waveguide mode, \( n_{\text{eff}} \) – the effective refractive index of the mode. Light is incident from the air. The process is shown schematically in figure 1. The excitation of waveguide modes leads to a significant enhancement of the local field in the iron-garnet layer (see figure 2).

3. TMOKE enhancement in all-dielectric iron-garnet gratings
The main object of our research is the intensity transversal magneto-optic Kerr effect. In smooth magnetic films, this effect arises from boundary conditions affected by the external magnetic field in transversal configuration. When waveguide modes are excited, the propagation constant \( \beta \) acquires a linear on gyration coefficient \( \Delta \beta \), depending on the direction of magnetization [1].

\[ \beta = \beta_0 + \Delta \beta(\vec{H}). \]

As a consequence of the appearance of this additive term, TMOKE arises, which is determined by the relative change in the intensity of the transmitted light during the magnetization reversal of the
material. Usually, TMOKE is observed in absorbing media with oblique incidence of light polarized in the plane of incidence (p-polarization) and is characterized by the parameter $\delta$:

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

where $I(+M)$ or $I(-M)$ is the intensity of the transmitted light in the magnetized in two opposite directions. It is worth noting that TMOKE is usually measured for reflected light, but in the case of transparent structures, the effect can also be investigated in transmitted light. In our case, the transmittance of the sample $T$ reaches 50% for the resonance conditions (see figure 3).

The measurements were carried out using a white-light setup with focused light beam allowing for simultaneous measurements of the wide angle range (from -10 degrees to 10 degrees).

Experimental results presented in figure 4 show a significant enhancement of TMOKE in all-dielectric structures up to $\delta=0.5\%$ with high simultaneously high transmission $T=50\%$. For a comparison, the smooth iron-garnet film of the same width provides the TMOKE about $\delta=0.004\%$. At the same time, TMOKE resonances in grating structures also have high Q-factor and a width of about 5 nm, which is a significant advantage over plasmonic structures.

![Figure 3. Transmission measurements on a 1D all-dielectric grating with p-polarized light](image)

![Figure 4. TMOKE measurements on a 1D all-dielectric grating with p-polarized light](image)

4. Conclusions

TMOKE effect in 1D all-dielectric structures with iron-garnet was investigated. The theoretically predicted multifold enhancement of TMOKE in such structures was confirmed experimentally. The resonances in 1D gratings accompanied by the TMOKE enhancement are characterized by the high transmission and high Q-factors making 1D iron-garnet gratings perspective for light modulation applications.

Acknowledgments

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