Magneto-Optical Spectra of Magnetic Photonic Crystal with Composite (SiO$_2$-Au) Layer

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Abstract. The resonant enhancement of magneto-optical effects due to structure modes arising at the boundary of magnetic photonic crystal [TiO$_2$ / SiO$_2$]$^m$ / iron garnet / SiO$_2$ / (SiO$_2$-Au), in which the upper layer (SiO$_2$-Au) is a composite layer of SiO$_2$ with metallic Au nanoscale inclusions, and iron garnet is a bi-layer of composition Bi$_{1.0}$Lu$_{0.5}$Gd$_{1.5}$Fe$_{4.2}$Al$_{0.8}$O$_{12}$ / Bi$_{2.3}$Dy$_{0.7}$Fe$_{4.2}$Ga$_{0.8}$O$_{12}$, has been considered by modelling of 4×4 transfer matrix method.

1. Introduction
The synthesis and investigation of magnetic photonic crystals (MPC) with one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) structuring attracts the attention of researchers due to the implementation of new effects associated with the propagation of light waves inside such structures [1]. Structuring opens up the possibility of localizing and amplifying the electromagnetic field of a light wave inside magnetic layers of 1D structures or magnetic elements of various shapes of 2D and 3D structures, creating resonance features in optical and magneto-optical (MO) spectra. The use of metal and composite metal-dielectric components allows transformation of properties due to the excitation of propagating surface plasmon-polaritons, localized plasmons and optical Tamm states (OTSs). It should be noted, that the properties of MPCs based on composites have not been considered previously. The authors present the modelled optical and MO spectra of a similar structure – MPC with a composite layer (SiO$_2$-Au).

2. Structure model and methods
The structure under consideration can be represented by the general formula

$$\left[\text{TiO}_2 / \text{SiO}_2\right]^m / \text{G1} / \text{G2} / (\text{SiO}_2 - \text{Au}).$$

There, $\left[\text{TiO}_2 / \text{SiO}_2\right]^m$ is Bragg mirror made of silicon and titanium dioxide layers with repetition number $m = 4$; G1 is bismuth-substituted garnet layer Bi$_{1.0}$Lu$_{0.5}$Gd$_{1.5}$Fe$_{4.2}$Al$_{0.8}$O$_{12}$; G2 is bismuth-substituted garnet layer Bi$_{2.3}$Dy$_{0.7}$Fe$_{4.2}$Ga$_{0.8}$O$_{12}$; SiO$_2$ is a buffer layer of silicon dioxide and (SiO$_2$-Au) is a composite layer with nanoparticles of Au.

As a comparison, we also present the MO spectra of MPC with an upper continuous layer of Au:

$$\left[\text{TiO}_2 / \text{SiO}_2\right]^m / \text{G1} / \text{G2} / \text{SiO}_2 / \text{Au}.$$  

In order to simulate the optical and MO properties of MPC and numerically solve Maxwell's equations, a software algorithm was implemented using the transfer matrix method 4×4. The software
algorithm takes into account the angle of incidence of light on the structure \( \theta \), incident light wave polarization state \( \Psi \), anisotropy and gyration of structure layers [2]. The dielectric constant of composite (SiO\(_2\)–Au) layer was calculated based on the Maxwell-Garnett model [3]. Nanocomposite is an uniaxial crystal. Its effective permittivity is represented by a diagonal tensor with components \( \varepsilon_x = \varepsilon_{||} \) and \( \varepsilon_y = \varepsilon_{\perp} \) (the subscripts \( || \) and \( \perp \) refer to two orientations of electric field vector of electromagnetic wave: parallel and perpendicular to optical axis of metal nanoparticles, respectively). The components can be calculated using the following expression:

\[
\varepsilon_{\perp||} = \varepsilon_m \left( 1 + \frac{f (\varepsilon_p - \varepsilon_m)}{\varepsilon_m + (1 - f)(\varepsilon_p - \varepsilon_m) g_{\perp||}} \right),
\]

where \( \varepsilon_m \) and \( \varepsilon_p \) are dielectric constants of metal inclusions and dielectric matrix, respectively; \( f \) is volume fraction of inclusions; \( g_{\perp||} \) are geometric factors that take into account the effect of nanoparticles shape on the induced dipole moment of nanoparticles. We assumed that \( g_{\perp} = g_{||} = 1/3 \). That is, the nanoparticles are spherical. The sizes of nanoparticles in the matrix should be much less than the wavelength, that is, should not exceed 30 nm.

The structures under consideration are shown schematically in figure 1. The substrate of fused quartz is also take into account. All optical and MO parameters of the layers were determined as a result of measurements and fitting of optical and MO spectra of single layers forming the structures. The procedures are described in more detail in the works [4, 5].

The following general invariant parameters of the layers were chosen. The thicknesses of layers in Bragg mirror are \( h(\text{TiO}_2) = 76 \) nm and \( h(\text{SiO}_2) = 108 \) nm. The iron garnet layers have the thicknesses \( h(G1) = 80 \) nm and \( h(G2) = 250 \) nm, respectively. Normal incidence \( \theta = 0 \) deg of light was taken into account.

3. Spectral dependences of Faraday Effect and transmittance for structural modes

Figure 2 shows the formation of optical and MO spectra and resonances for structure (1) in the case of \( f = 0.2 \). The composite possess only positive \( \varepsilon \) component at these fraction in investigated wavelength region. As a result, all resonances I, II and III should be attributed to resonance defect mode (RM) corresponding of G1 / G2 / SiO\(_2\) / (SiO\(_2\)–Au) layer. A change in the thickness of any layer of upper part of structure leads to a shift in resonant wavelength to longer wavelengths. The greatest enhancement of Faraday Effect for any of configurations will be observed in 600 nm wavelengths range. This region is characterized by the highest values of the components \( \varepsilon \) of the composite.
Figure 2. Optical (a) and magneto-optical (b) spectra for different configuration of structure (1): spectra 1 for a Bragg mirror; 2 for Bragg mirror / G1 / G2; 3 for Bragg mirror / G1 / G2 / SiO₂ with \( h(\text{SiO₂}) = 80 \text{ nm} \); 4 for the whole structure with \( h(\text{SiO₂}) = 80 \text{ nm} \), \( h(\text{SiO₂}-\text{Au}) = 55 \text{ nm} \) and \( f = 0.2 \); 5 for the whole structure with \( h(\text{SiO₂}) = 80 \text{ nm} \), \( h(\text{SiO₂}-\text{Au}) = 120 \text{ nm} \) and \( f = 0.2 \).

Figure 3. Dependences of magneto-optical spectra on the thickness of top layer SiO₂ and fraction \( f \): structure (1) \( f = 0.2 \) (a), structure (1) \( f = 0.4 \) (b), structure (2) or structure (1) \( f = 1 \) (c). The thicknesses of composite and Au layers were fixed \( h(\text{SiO₂}-\text{Au}) = 120 \text{ nm} \) and \( h(\text{Au}) = 55 \text{ nm} \), respectively.

A break in the vicinity of 630-650 nm for the spectral dependences of structure (1) on the thickness of top SiO₂ layer (or with a change in the thickness of any layer of upper part of the structure, G1 or
G2) becomes characteristic with an increase in fraction $f$ above 0.35. This discontinuity is due to the fact that in this region $\varepsilon$ of the composite passes through zero point. On the left (in the region of short wavelengths) $\varepsilon$ has negative values. On the right (in the region of long waves) $\varepsilon$ has positive values.

In this case, the excitation of OTS and RM is possible (figure 3). OTS exists only in a certain area – in the area, where the composite is similar to metal [3]. The discontinuity is most pronounced in the spectra of Faraday rotation angle; therefore, we present here only these spectra. At the same time, we still observe the greatest increase in MO rotation for the short wavelength range, where in this case there already exists a OTS.

It should be noted that the existence of OTS depends only on $\varepsilon$-component of composite and fraction. However, we can create several modes simultaneously by changing the thickness of composite layer $h$(SiO$_2$-Au). Figure 4 shows the formation of RM within (SiO$_2$-Au) layer, which can exist simultaneously with OTS for higher composite concentrations.

![Figure 4.](image)

Figure 4. Dependences of magneto-optical spectra on the thickness of composite layer (SiO$_2$-Au). The thickness of top SiO$_2$ $h$(SiO$_2$) = 80 nm and fraction $f$ = 0.2.

4. Conclusions
As a result of modelling of MO properties of magnetophotonic crystal with a composite layer (SiO$_2$-Au), it was shown that the highest values of Faraday rotation can be achieved in the short spectral region. The results are interesting for shortwave applications: design of multicolor optical filter / green and blue light modulators for displays.

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