Magneto-optical microcavity with Au plasmonic layer

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Abstract. Optical and Faraday rotation spectra of magneto-optical microcavity coated with Au plasmonic layer of gradient thickness were investigated theoretically and experimentally. It was shown that the Tamm plasmon-polaritons mode forms near the long-wavelength edge of photonic band gap. The presence of Au coating of thickness of 90.4 nm increase the Faraday rotation at Tamm plasmon-polaritons and cavity resonances in 1.3 and 7 times, respectively. By transfer matrix method it were found that the incorporation of SiO₂ buffer layer with a thickness in the range from 155 to 180 nm between microcavity and Au coating leads to the strong coupling between cavity mode and Tamm plasmon-polaritons. In this case, one or two resonances arise in the vicinity of the cavity mode depending on the thickness of plasmonic layer. The Faraday rotation for coupled mode in twice less than the value of rotation for single cavity mode.

1. Introduction
Microcavity (MC) is the most common element of modern optoelectronic devices. Cavity structure allows to enhance the different optical effects exhibited of embedded materials. One of the first proposed structures in magnetophotonics was the structure of MC based on nonmagnetic dielectric Bragg mirrors and a layer of bismuth-substituted iron garnet [1, 2]. In such structure the increasing of Faraday and Kerr rotation angles of the polarization plane is achieved most effectively. Later, the photonic and magnetophotonic crystals with localized Tamm surface states were investigated [3-11]. The excitation of optical Tamm state also leads to an amplification of magneto-optical (MO) effects. One of the effective methods for exciting optical Tamm states is to use the structure of a photonic crystal with a plasmonic coating or layer [4, 6, 8-11]. In this case, the optical Tamm state or Tamm plasmon-polaritons (TPP) can effectively be combined with resonances of another nature. For example, in the work [10] the hybrid state of Tamm and surface plasmon-polaritons were observed. The coupling of TPP and cavity modes occurs in MC with metal layers [8, 11]. In this paper, we propose to consider the influence of TPP excitation on properties of MO MC in Faraday effect geometry.

2. Experimental technique and modelling
The investigated MO MC consists of symmetrically dielectric Bragg mirrors of titanium and silicon oxides, between which the double garnet layer is placed. Two following configurations, schematic shown in Figure 1, are considered

GGG / [TiO₂/SiO₂]₄ / Bi₁₁₀Y₀₅Gd₁₅Fe₄₂Al₀₈O₁₂ / Bi₂₈Y₀₂Fe₅O₁₂ / [SiO₂/TiO₂]₄ / Au (No. 1) and GGG / [TiO₂/SiO₂]₄ / Bi₁₁₀Y₀₅Gd₁₅Fe₄₂Al₀₈O₁₂ / Bi₂₈Y₀₂Fe₅O₁₂ / [SiO₂/TiO₂]₄ / SiO₂ / Au (No. 2).

There GGG is substrate of gadolinium gallium garnet with crystallographic orientation of (111). The MC No. 1 were synthesized and investigated experimentally and theoretically. Synthesis of MO MC performed according to the technology described in [12, 13]. Iron garnet layers were fabricated by reactive ion beam sputtering of corresponding ceramic targets in argon-oxygen mixture and crystallized
in the annealing process at the air. TiO$_2$ and SiO$_2$ layers were synthesized by electron beam evaporation. Plasmonic Au coating with a gradient of thickness along the chosen direction on the sample surface, was deposited by thermal evaporation in vacuum [14, 15]. Using a unique technique of coating synthesis allowed in the experiment to choose different surface areas along a thickness gradient in order to reveal dimensional effects on the properties of structures. As a result, it became possible to compare the theoretical and experimental data obtained for different parameters of the layers of the structure. The MO MC No. 2 were considered only theoretically to investigate the capabilities of modes control.

The layers thicknesses of the synthesized structure determined by fitting the transmission and Faraday rotation (FR) spectra were $h_{M1} = 66$ nm for garnet layer of composition Bi$_{1.0}$Y$_{0.5}$Gd$_{1.5}$Fe$_{4.2}$Al$_{0.8}$O$_{12}$, $h_{M2} = 161$ nm for garnet layer of composition Bi$_{2.8}$Y$_{0.2}$Fe$_{5}$O$_{12}$, $h_{SO2} = 117$ nm and $h_{TiO2} = 79$ nm for SiO$_2$ and TiO$_2$ layers of Bragg mirrors, respectively. The 4×4 transfer matrix method [16] was used for numerical solution of Maxwell’s equations in modelling of light propagation. The components of layers permittivity tensors, taken into account, are given in the publication [13].

To measure the thickness of the deposited Au coating, a microinterferometer MII-4 with a digital data processing complex were used. The thickness of the wedge of Au coating from one edge of the sample to other varied from 0 to 100 nm. Investigation of transmittance was carried out in the wavelength range from 400 to 980 nm using an automated spectrophotometer KFK-3. Measurements of MO FR in the wavelength range from 400 to 750 nm was performed using hand-made computer-control spectropolarimeter by compensation method. The range of variation of the constant magnetic field was from 0 to 5 kOe. The sample was placed in a saturated field for Faraday effect measuring. Buffer SiO$_2$ layer of thickness from 110 to 330 nm was incorporated in model configuration No. 2 between MO MC with the same layer parameters as in the structure No. 1 and Au coating of a certain thickness (only 10 and 40 nm are considered).

The comparison of calculated and experimental optical and FR spectra for structure No. 1 are given in the subsection 3.1. The results of modeling of the properties of structure No. 2 are given in the subsection 3.2.

3. Results and discussion

3.1. Microcavity with Au plasmonic layer of gradient thickness (No. 1)

Measured and calculated transmittance and FR spectra of MO MC with Au thickness $h_{Au}$ from 6.7 to 90.4 nm are shown in Figure 2. The experiment is in a good agreement with the theoretical model. The
center of photonic band gap (PBG) of the structure is placed at 690 nm. Wavelength of cavity mode is 653.5 nm. While the thickness of Au layer increases, the TPP mode forms near the long-wavelength edge of PBG in the vicinity of the wavelengths from 770 to 790 nm. TPP resonance is not observed at thicknesses $h_{\text{Au}} < 25$ nm and has a maximum optical figure of merit at $h_{\text{Au}} = 65.8$ nm in experimental spectra. Theoretical spectra show that TPP mode is clearly separated from PBG edge at the thickness of $h_{\text{Au}} = 65.8$ nm.

![Figure 2](image)

**Figure 2 (a, b, c, d).** Measured (a, b) and calculated (c, d) transmittance and FR spectra of synthesized MO MC No. 1 as a function of thickness of Au coating $h_{\text{Au}}$.

TPP resonance is more clearly expressed in theoretical transmittance spectra, since a higher absorption of Au coating that was used in calculation was realized in the experiment. The amplitudes of cavity and TPP resonances are compared in Figure 3 (a). TPP peak has amplitude higher than the amplitude of cavity peak for thickness of Au layer $h_{\text{Au}} > 35$ nm. Calculations shown that enhancement of FR at TPP mode for MO MC with $h_{\text{Au}} = 90.4$ nm is 7 times in comparison with the value for MO MC without Au layer. For cavity mode, the resonant value of transmittance decreases sharply at increasing of $h_{\text{Au}}$ to 90.4 nm. Simultaneously, FR of cavity mode increases only by 1° in theory and 1.5° in experiment (Figure 2). These values correspond to enhancement factors of 1.15 and 1.3 times, respectively. According to the calculated spectra, blue shift of resonant modes takes place with increasing thickness $h_{\text{Au}}$. Shifting of TPP is more pronounced. Nevertheless, the red shift of resonant modes is observed in the experimental spectra. A possible reason for the difference in modes shift in the experimental and theoretical spectra is the structural changes in Au coating with increase of its thickness, which leads to a change of optical properties of coating. So, the corrections of the components of the permittivity tensor of Au layer for each thickness are needed. In the calculation presented in Figure 2, the same values of the components for different thicknesses $h_{\text{Au}}$ were used [13].
Figure 3 (b, c, d) shows calculated spatial distributions of electric field intensity in MO MC No. 1 with Au coating of thickness $h_{Au} = 43.9$ nm and without Au coating for resonance modes. The distribution presented in Figure 3 (b) is classical for TPP mode. The maximum intensity is observed in the layer adjacent to the plasmonic coating, and an exponential decay of the electromagnetic field is formed inside the structure. Minor localization in the vicinity of the MO layer is present. Distribution for cavity mode is characterized by asymmetric localization in the vicinity of the boundaries of the MO layer (Figure 3, c, d). The intensity values are smaller for a configuration with an absorbing Au coating (Figure 3, c). Figure 3 (a, b, c, d). Calculated and measured amplitudes of TPP and cavity resonances in transmittance spectra of MO MC No. 1 (a). Calculated spatial distributions of electric field intensity in MO MC No. 1 with Au coating of thickness $h_{Au} = 43.9$ nm for TPP (b) and cavity (c) modes and without Au coating $h_{Au} = 0$ nm for cavity mode (d); the incident electric field has unit amplitude, coming from the left.

3.2. Microcavity with buffer SiO$_2$ layer of gradient thickness and Au coating (No. 2)

As next step we investigated the configuration No. 2, in which the strong coupling between cavity mode and Tamm plasmon-polaritons occurs. Figure 4 shows image plots of the calculated transmittance and FR spectra for MO MC No. 2 with Au coating thicknesses $h_{Au} = 10$ nm and $h_{Au} = 40$ nm. The shift of TPP mode within the PBG is caused by varying thickness of buffer SiO$_2$ layer $h_{SiO2}$ from 110 to 330 nm. The shift of cavity mode is caused by the coupling to the TPP mode. Positions of modes and region of coupled mode are illustrated in the Figure 4 (a). The strong coupling between modes occurs at thicknesses $h_{SiO2} = 155$ nm for $h_{Au} = 10$ nm and $h_{SiO2} = 180$ nm for $h_{Au} = 40$ nm. The thickness of the Au coating strongly affects the characteristics of the coupled mode. Evidence of this coupling is formation of two nearly symmetric resonances with an increase of the thickness $h_{Au}$ above 20 nm. The splitting of resonances is 17 nm for $h_{Au} = 40$ nm and $h_{SiO2} = 180$ nm. The coupled mode has higher values of transmittance and almost in two times smaller values of the Faraday rotation angle.
4. Conclusions
Optical and Faraday rotation spectra of magneto-optical microcavity with structure of \([\text{TiO}_2/\text{SiO}_2]_4/\text{Bi}_{0.8}\text{Y}_{0.5}\text{Gd}_{1.5}\text{Fe}_{1.2}\text{Al}_{0.5}\text{O}_{12}/\text{Bi}_{2.8}\text{Y}_{0.2}\text{Fe}_{4.2}\text{O}_{12}/[\text{SiO}_2/\text{TiO}_2]_4\) on GGG substrate, coated with Au plasmonic layer of gradient thickness, were investigated theoretically and experimentally. It was shown that the Tamm plasmon-polaritons mode forms near the long-wavelength edge of photonic band gap. The presence of Au coating of thickness of 90.4 nm increase the Faraday rotation at Tamm plasmon-polaritons and cavity resonances in 1.2 and 7 times, respectively. The configuration of structure with SiO\(_2\) buffer layer between microcavity and Au coating, in which the strong coupling between cavity mode and Tamm plasmon-polaritons arises, are investigated theoretically. In this case, one or two resonances arise in the vicinity of the cavity mode depending on the thickness of plasmonic layer. The Faraday rotation for coupled mode in twice less than the value of rotation for single cavity mode.

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Figure 4 (a, b, c, d). Image plots of the calculated transmittance and Faraday rotation (FR) spectra for MO MC No. 2 with Au coating thickness \(h_{\text{Au}} = 10\) nm (a and b, respectively) and \(h_{\text{Au}} = 40\) nm (c and d, respectively) as a function of thickness of buffer SiO\(_2\) layer \(h_{\text{SiO}_2}\). The upper graphs show the spectra corresponding to the cross sections in the plots.
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