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Hybrid state of Fabry–Perot and Tamm plasmon-polariton modes in structures with different plasmon layers

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Abstract. The paper presents the investigation of magnetophotonic crystals with different metal layers for the formation of a Tamm plasmon polariton. It was revealed that the structure with the Ag layer has the resonance with a higher optical quality factor. It is shown how a change in the symmetry of the structure affects the properties of the hybrid state of Fabry—Perot and Tamm plasmon polariton modes. The effect of oblique incidence and polarization of incident light on the localization of light in the layers of the structure is demonstrated.

Keywords: Tamm plasmon polariton, magnetophotonic crystals, magneto-optics

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Гибридное состояние мод Фабри – Перо и таммовского плазмон-поляритона в структурах с различными плазмонными слоями

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Аннотация. В статье представлено исследование магнитофотонных кристаллов с различными металлическими слоями для формирования таммовского плазмон-поляритона. Было обнаружено, что структура со слоем Ag обладает наиболее добротным резонансом. Показано, как изменение симметрии структуры влияет на свойства гибридного состояния мод Фабри — Перо и таммовского плазмон-поляритона. Продемонстрировано влияние наклона и поляризации падающего излучения на локализацию света в слоях структуры.

Ключевые слова: Таммовский плазмон-поляритон, магнитофотонные кристаллы, магнитооптика

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Introduction

In magnetophotonic crystals (MPCs) based on iron garnet with a single Fabry–Perot mode, as well as in the structures with formation of optical Tamm plasmon-polariton mode (TPP), an increase in magneto-optical effects (MO) at resonant wavelengths arises [1, 2]. In previous works, the simulations of such structures were given and the amplification of MO effects by 20–50 times was shown. Then it was proposed to investigate not only structures with single modes, but also their hybrid state [3]. The presence of the hybrid state in such structures is due to the coincidence of the resonance conditions of the optical modes of Fabry–Perot and TPP: the selection of the thickness of the structure layers — the cavity layer of MPC and the layer adjacent to the metal plasmon layer. In this work, it is proposed to investigate how the hybrid state behaves if we change the symmetry of a microcavity MPC and the metal layer (Ag, Au, Cu) in cases of normal and oblique incidence.

Materials and Methods

The simulations were carried out using the 4×4 transfer matrix method, which uses the approach of Berreman et al. [3] to form transfer matrices of layers and the entire structure. MPCs with a next general formula are considered as the structures with hybrid state of Fabry–Perot and TPP modes:

$$GGG/[TiO_2/SiO_2]^{m1}/D1/[SiO_2/TiO_2]^{m2}/D2/Me, \quad (1)$$

where TiO_2 is the layer of TiO_2; SiO_2 is the layer of SiO_2; Me is the metal layer (Ag, Au or Cu); m_1 and m_2 are the numbers of layer pairs in Bragg mirrors; D1 and D2 are the layers on which the formation of Fabry–Perot and TPP modes depends, respectively. Double-layer film of composition $Gd_3Sc_2Ga_3O_{12}/Bi_{2.8}Y_{0.2}Fe_5O_{12}$ was selected as D1-layer. D2-layer was SiO_2. The thickness of D1-layer was selected to create the Fabry–Perot mode in the center of photonic band gap in the vicinity of 700 nm at normal incidence. To create hybrid state, the thickness of D2-layer sets the resonant wavelength of TPP at the vicinity of 700 nm also.

Assuming that it is possible to achieve a change in the hybrid state for asymmetric microcavity MPCs, we changed the number of layer pairs m1 and m2 in the calculations, actually transforming the localization of light inside D1- and D2-layers. Three configurations were considered for comparison: (2) $m_1 = 2$; $m_2 = 6$; (3) $m_1 = 4$; $m_2 = 4$; (4) $m_1 = 6$; $m_2 = 2$.

The interaction of light is described for each layer by a dielectric constant tensor of the form listed in publication [2]. Dielectric constants at a wavelength of 700 nm are as follows: for the iron-garnet layer: $\varepsilon_{xx} = 6.77 + 0.05 \cdot i$, $\varepsilon_{xy} = 0.03$; for Au-layer: $\varepsilon_{xx} = -15.00 + 2.16 \cdot i$; for Cu-layer: $\varepsilon_{xx} = -18.22 + 0.86 \cdot i$; for Ag-layer: $\varepsilon_{xx} = -19.8973 + 0.70 \cdot i$; for layer of TiO_2: $\varepsilon_{xx} = 5.42$; for layer of SiO_2: $\varepsilon_{xx} = 2.19$; for GGG: $\varepsilon_{xx} = 3.90$. The thickness of used layers was: $h(TiO_2) = 76$ nm, $h(SiO_2) = 120$ nm, $h(D1) = 286$ nm, $h(Me) = 30$ nm. To create a hybrid state at normal incidence, it is necessary that the thickness of D2-layer was, depending on the plasmon layer and configuration used, in the range 206–210 nm.

Results and Discussion

First of all, we will find out how the hybrid state of MPCs (2), (3) and (4) manifests itself at normal incidence. As can be seen from the simulated transmittance and Faraday rotation spectra of MPC (3) (Fig. 1), the hybrid state manifests itself in the form of two resonances located apart from each other at a certain spectral interval **Δ** (the splitting of hybrid mode), as it was shown earlier [4]. At the same time, the value of Δ it is weakly dependent on the metal used. Basically, strong changes in the resonance values of the transmittance and Faraday rotation for two modes occur when Au is replaced by Ag. The resonances of modes become more pronounced, and the transmittance increases by 1.3–2 times. The angle of Faraday rotation also increases by 1.2–2 times. The characteristics of MPCs with Ag and Cu layers are very close to each other.

The splitting of hybrid mode Δ can be changed introducing the asymmetry of MPC (1). In the case of MPC (2), we observe the hybrid state in which a single resonance is observed, since the Fabry–Perot mode is weakly pronounced (Fig. 1, *c*). In this regard, we observe also a weak effect on Faraday rotation spectra (Fig. 1, *d*). When the parameters of the structure change, the competition and redistribution of intensity within MPC occurs. As a consequence, for MPC (4) Δ is the maximum, the TPP mode is dominant.

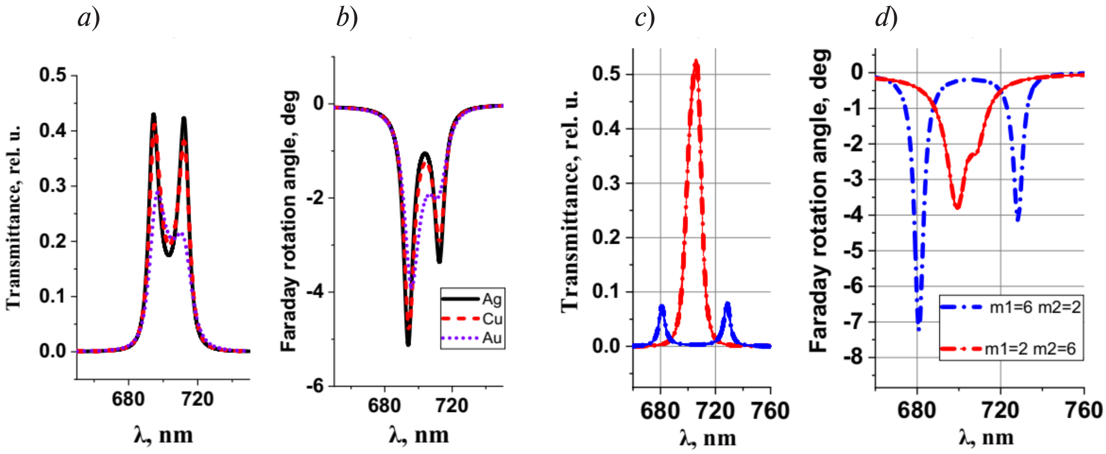

Fig. 1. Transmittance (*a*) and Faraday rotation angle (*b*) spectra of MPC (4) with a different metal layer. The thickness of D2-layer was 206, 209 and 208 nm for Au, Ag and Cu, respectively. Transmittance (*c*) and Faraday rotation angle (*d*) spectra of MPC (2) and (4). The thickness of D2-layer was 210 nm

After that, we simulated the properties of MPCs at oblique incidence of light. As shown earlier in the works [5–7] as the angle of incidence increases, the Fresnel reflection coefficients for *s*- and *p*-polarized waves become different. This results in an increase in *Q*-factors of the optical modes of MPC for s-polarized wave and a decrease for p-polarized wave, which arise with increasing the angle of incidence. As a result, the angle of Faraday rotation increases for s-polarized wave, and decreases for *p*-polarized wave. This is accompanied by the change in the localization of light within the structure when polarization changes (Fig. 2).

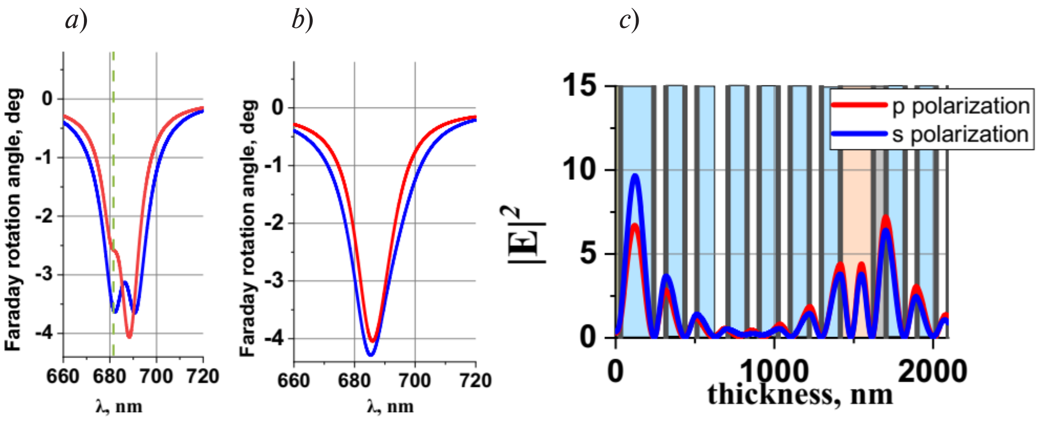

Fig. 2. Faraday rotation spectra of MPC (2) with Ag (*a*) and Au (*b*) layer with thickness of 30 nm at incidence angle of 25° for *s*- and *p*-polarization. Distribution of square of amplitude of electric field of light in MPC (2) with Ag-layer at wavelength of 681 nm (*c*)

For example, for MPC (2) at an angle of 25°, at which a hybrid state with equal amplitudes of Fabry—Perot and TPP resonances is observed for s-polarization in Faraday rotation spectrum, it is possible to achieve a change in the spectra by transition to p-polarization. TPP resonance located at 681 nm weakens, but Fabry—Perot resonance remains virtually unchanged (Fig. 2, *a*, *b*). By actually changing the polarization, we achieve a redistribution of light intensity exclusively in the vicinity of Ag-layer (Fig. 2, *c*). It is worth noting that for the other metal, Au, this effect will be absent.

Conclusion

The paper considers structures with a hybrid state of Fabry Perot and TPP modes. It is determined that the splitting of hybrid mode Δ can be controlled by changing the symmetry of MPC with cavity structure. It is determined that the use of different metals as a plasmon layer makes it possible to change the *Q*-factor of resonances of Fabry—Perot and TPP modes. It is indicated that the most pronounced resonance of TPP mode is possessed by MPC with Ag-layer. It has been revealed that in asymmetric structures at oblique incidence, we can controllably change the localization of light in the layers by polarization.

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