Hybrid states of Tamm plasmon polaritons in nanostructures with Bi-substituted iron garnets

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Abstract. The work presents the results of investigation of hybrid states of Tamm plasmon polaritons (TPP) in magnetoplasmonic nanostructures (MPNS) based on Bi-substituted iron garnet (Bi:IG) and Au layers and nanoparticles. To study the interaction of resonances, two MPNS were synthesized with gold-coated dielectric layer of gradient thickness. It was shown the difference in properties of model MPNS with hybrid state of TPP – Fabry-Perot and a single TPP excitation. It was suggested to use the hybrid state to increase the sensitivity of optical sensors.

1. Introduction
One-dimensional magnetophotonic crystals with metallic layers and nanoparticles (NP) are promising magnetoplasmonic nanostructures (MPNS) to design optical sensors and devices for transmission and display of information [1-4]. Depending on the geometry and parameters of MPNS elements, it is possible to create resonances corresponding to volume excitations, excitation of propagating surface electromagnetic waves, non-propagating surface states, localized surface plasmons (LSP) and their various hybrid states in the spectral characteristics. The presence of hybridization allows the additional possibilities to control the spectral position and resonant amplitude of modes.

One of the non-propagating surface states that can be realized in magnetoplasmonic nanostructures on the basis of photonic (PC) and magnetophotonic (MPC) crystals are optical Tamm state (OTS). PC and MPC with OTS were first investigated in works [5-12]. OTS were demonstrated in PC with plasmonic coating or structure with adjacent two PC that differ in parameters of layers. As has been shown, the excitation of OTS in structures with magnetooptical (MO) layers leads to an amplification of MO effects. In addition, the term “Tamm plasmon-polaritons” (TPP) in the case of excitation of OTS on the boundary with plasmon metallic layer are used [6]. TPP can be effectively combined with resonances of another nature. For example, in the work [11, 14] the hybrid state of TPP and surface plasmon-polaritons (SPP) were observed. The coupling of TPP and cavity modes occurs in microcavities with metal layers [10, 13]. Simultaneous formation of TPP and localized state similar to the defect mode inside the dielectric nanocomposite layer with metallic NP was demonstrated also in [15].

In our previous works [16, 17] new original TPP structures with Bi-substituted iron garnet (Bi:IG) and Au plasmonic layers were proposed, synthesized and investigated. The structures with single and double garnet layers [TiO2/SiO2]/M1/SiO2/Au and [TiO2/SiO2]/M1/M2/SiO2/Au, respectively, were
modelled to form a TPP mode at the center of photonic band gap and the features of TPP resonances as a function of the thickness of metal coating were found [16]. M1 and M2 in the formulas are Bi:IG of compositions of Bi$_{1.0}$Y$_{0.5}$Gd$_{1.5}$Fe$_{4.2}$Al$_{0.8}$O$_{12}$ and Bi$_{1.5}$Gd$_{1.5}$Fe$_{4.5}$Al$_{0.5}$O$_{12}$, respectively. Subsequently we suggested the MO microcavities [TiO$_2$/SiO$_2$]$^m$/M1/M3/[SiO$_2$/TiO$_2$]$^m$/SiO$_2$/Au of layer of Au of gradient thickness and coated with bilayer SiO$_2$/Au with gradient SiO$_2$-thickness and Au-thickness of 40 nm. M3-layer has composition of Bi$_{2.8}$Y$_{0.2}$Fe$_5$O$_{12}$.

The work presents the results of investigation of properties of hybrid states of Tamm plasmon polaritons (TPP) in MPNS based on Bi:IG and Au layers and NP. The hybrid states of TPP – Fabry-Perot and TPP – LSP were considered. Spectra and structure functionality were investigated for MPNS with hybrid state of TPP – Fabry-Perot using numerical methods.

2. Modelling and experimental technique

MPNS with hybrid states of TPP were designed using conventional 4×4 transfer matrix method. We considered in the calculations next nanostructures:

No.1 – M1/[SiO$_2$/M1]$^m$/SiO$_2$/Au;  
No.2 – [TiO$_2$/SiO$_2$]$^m$/M1/M3/[SiO$_2$/TiO$_2$]$^m$/SiO$_2$/Au;  
No.3 – [SiO$_2$/TiO$_2$]$^m$/SiO$_2$/[TiO$_2$/SiO$_2$]$^m$/M1/M3/SiO$_2$/Au;  
No.4 – [SiO$_2$/TiO$_2$]$^m$/[SiO$_2$/M1]/[TiO$_2$/SiO$_2$]$^m$/M1/M3/SiO$_2$/Au.

There $m$ is the repetition number of layers pairs. Substrate of gadolinium gallium garnet (GGG) with crystallographic orientation of (111) and the spectral dependence of components of permittivity tensors of layers were taken into account [4]. Components of permittivity tensors of layers were defined using the experimental data of single films and synthesized MPC. We considered that TM polarized light falls on the structure.

MPNS No.1 was designed to synthesize the nanostructure with hybrid state of TPP – LSP:  
No.5 – (Au NP)/M1/[SiO$_2$/M1]$^3$/SiO$_2$/Au,

where (Au NP) is array of Au particles on GGG surface. The thicknesses of layers in MPNS No.1 were chosen in such a way that the TPP resonance overlapped spectrally with the LSP resonance of NP embedded in the matrix of M1-layer.

For this MPNS No.6 (Au NP)/M1 was created before modeling and we measured its resonant wavelength $\lambda_{\text{LSP}} = 700$ nm. The array of Au NP was synthesized by thermal evaporation of a 2 nm-layer and subsequent annealing at temperature of 950°C for 10 minutes. The thickness of the first M1-layer that coats GGG or NP in MPNS No.1, 5 and 6 was chosen equal to $h_{M1} = 125$ nm.

The thicknesses of layers of MPC [SiO$_2$/M1]$^m$ in MPNS No.1 and 5 were $h_{SiO2} = 120$ nm and $h_{M1} = 70$ nm. The thickness of buffer SiO$_2$ layer $h_{SiO2}$ that placed under the Au coating varied in the range from 150 to 290 nm in order to shift the TPP resonance inside the photonic band gap (PBG). Optimal number of layers pairs $m = 3$ and the thickness of Au-layer of $h_{Au} = 30$ nm for MPNS No.5 were chosen based on the optimization of MO quality factor $Q$ defined as [2]

$$Q = -2 \cdot |\Theta_f|/\ln T[^\circ].$$

There $\Theta_f$ is angle of Faraday rotation, $T$ is transmittance.

MPNS No.2 was modelled based on the parameters of already synthesized MPC with the number of layers pairs $m = 4$, the thicknesses of layers of Bragg mirrors $h_{BMiO2} = 73$ nm and $h_{BMSiO2} = 115$ nm and the thicknesses of cavity MO layers $h_{CM1} = 66$ nm and $h_{CM3} = 166$ nm. The properties of MPNS No.2 were simulated by varying $h_{SiO2}$ from 110 to 320 nm and $h_{Au}$ from 0 to 70 nm. As the most optically effective TPP resonance was predicted by simulations for MPNS with the thickness $h_{Au} = 40$ nm, we synthesized this configuration of the structure.

Thus, in the work we experimentally realized and investigated MPNS No.2 with the hybrid state of TPP – Fabry-Perot and No.5 with the hybrid state of TPP – LSP. MPNS are shown schematically in figure 1. Both MPNS were realized with the gradient of $h_{SiO2}$ to investigate the interaction of resonances.
Dielectric Bragg mirrors of MPNS No.2 \([\text{TiO}_2/\text{SiO}_2]_5\) and \([\text{SiO}_2/\text{TiO}_2]_5\) were synthesized by electron beam evaporation on hot (400 °C) substrate. The thicknesses of layers were optically controlled during deposition.

Bi:IG layers of MPNS were fabricated by reactive ion beam sputtering of corresponding ceramic targets in argon-oxygen mixture and crystallized in the annealing process at the air [3, 16, 17]. Au thin films were deposited by thermal evaporation in vacuum [16, 17]. The buffer layers of SiO₂ placed between MPC and Au-layer were formed with gradient of thickness by reactive ion-beam sputtering. The gradient of \(h_{\text{SiO}_2}\) were 11.7 and 9.2 nm/mm for MPNS No.5 and 2, respectively.

All SiO₂-layers in MPNS No.5 were synthesized by reactive ion beam sputtering.

Thicknesses of layers were determined by MII-4 microinterferometer. Investigation of transmittance was carried out using an automated spectrophotometer KFK-3. Measurements of Faraday rotation were performed using hand-made computer-control spectropolarimeter by compensation method in saturation fields. The beam aperture along the gradient of layers thickness in the measurement process was 0.1 mm.

The properties of MPNS No.3 and 4 were considered only in model calculation to study the difference in properties of hybrid state of TPP – Fabry-Perot from a single TPP excitation. The configurations were chosen in such a way that they can be successfully synthesized (figure 2).

The resonant wavelength \(\lambda_{\text{res}}\) was chosen about 700 nm at a normal incidence of light for two structures. The thicknesses of layers \(h_{\text{M1TiO}_2}\) and \(h_{\text{M1SiO}_2}\) for two structures were 77 and 120 nm, respectively. The thickness of \(h_{\text{M1}}\) was 70 nm. The thickness of \(h_{\text{M3}}\) was \(h_{\text{M1}} = 84\) nm. The layer of SiO₂ with thickness of \(h_{\text{SiO}_2} = 30\) nm was taken into account as its application allows to use the technology of closed crystallization of garnet. The technic allows to reduce the roughness of interfaces during synthesis [18]. The thickness \(h_{\text{Au}}\) and number \(m\) varied in the ranges from 0 to 50 nm and from 1 to 10, respectively, to determine the optimal configuration. The calculations of \(Q\) were carried out to assess the perspectivity of structures for practical implementation and subsequent applications [10, 11]. The case of total internal reflection in the Kretschmann geometry with GGG prism was considered in order to excite the surface plasmon-polaritons (SPP).

### 3. Results and discussion

#### 3.1. Hybrid state of TPP – Fabry-Perot

Hybrid state of TPP – Fabry-Perot manifests itself in the form of two resonances, which have anticrossing behavior and cannot be combined at the same wavelength at \(h_{\text{Au}} > 20\) nm. Figures 3 and 4 show measured (symbols) and simulated (lines) spectra of transmittance and Faraday rotation angle of
synthesized MPNS, respectively. The transmittance values for calculated spectra are reduced by 6 times.

Figure 3. Optical spectra of synthesized MPNS No.2 at different $h_{\text{BSiO}_2}$.

Figure 4. MO spectra of synthesized MPNS No.2 at different $h_{\text{BSiO}_2}$.

Spectral shift of Fabry-Perot resonance when changing $h_{\text{BSiO}_2}$ are caused of hybridization. The value of repulsion of resonances are 20 nm for $h_{\text{BSiO}_2} = 185$ nm. This thickness is characterized by the strongest hybridization, in which Fabry-Perot resonance has almost half of $\Theta_F$ with respect to Faraday rotation values with a small degree of hybridization or in the absence of such. Calculations show that the decrease in $\Theta_F$ will be observed for any thickness of Au coating. Table 1 presents the calculated resonance values $T$, $\Theta_F$ and $Q$ depending on the thickness $h_{\text{BSiO}_2}$ and $h_{\text{Au}}$. The strongest hybridization of states will be observed for the presented configurations.

Table 1. Resonance values $T$, $\Theta_F$ and $Q$ of TPP and Fabry-Perot (FP) mode of different configurations of MPNS No.2.

| $h_{\text{BSiO}_2}$, nm | $h_{\text{Au}}$, nm | $T$, % | $\Theta_F$, $^\circ$ | $Q$, $^\circ$ |
|-----------------------|------------------|-------|-----------------|--------|
|                       |                  | TPP   | FP              | TPP   | FP         |
| 0                     | 0                | -     | 27             | -     | 10.3      | 15.7   |
| 155                   | 10               | 45    | -               | -5.9  | 2.4       | 14.8   |
| 170                   | 20               | 34    | -3.5            | -5.2  | 6.5       |        |
| 180                   | 30               | 21    | -1.9            | -1.9  | 4.9       | 5.1    |
| 180                   | 70               | 6.6   | -6.7            | -6.7  | -6.9      |        |

Factors $Q$ of synthesized MPNS No.2 with $h_{\text{BSiO}_2} = 185$ nm are 0.93$^\circ$ and 2.67$^\circ$ for TPP and Fabry-Perot mode, respectively.

Among simulated configurations of MPNS No.3 and 4 the following optimal configurations should be highlighted:
- with average values $Q = 6.9^\circ$ for two resonances $m = 4$ and $h_{\text{Au}} = 40$ nm;
- with $Q = 7.3^\circ$, $m = 2$ and $h_{\text{Au}} = 40$ nm.

MO parameters of proposed structures with hybrid state of TPP – Fabry-Perot significantly exceed MO parameters of known structure [SiO$_2$ / Bi:IG]$^5$/Au ($\Theta_F = -0.4^\circ$, $T = 25\%$, $Q = 0.6^\circ$) [1].

Comparison of optical and MO spectra of MPNS No.3 and 4 with identical parameters of layers $m = 4$ and $h_{\text{Au}} = 40$ nm is shown in figure 5. The value of $\Theta_F$ for single TPP resonance divided equally
for two resonances of TPP – Fabry-Perot hybrid state. Non-zero value of $\Theta_F$ for Fabry-Perot resonance presents in the spectra although the defect in resonator is not MO active.

![Figure 5](image1.png)  
**Figure 5.** Optical (a) and MO (b) spectra of modelled MPNS No.3 (black line) and 4 (light red line).

![Figure 6](image2.png)  
**Figure 6.** Reflectance spectra of modelled MPNS No.3 (a) and 4 (b).

Spectra of reflectance of MPNS No.3 and 4 in Kretschmann geometry for angle of light incidence 33° and refractive index of the medium adjacent to the gold layer of 1.00 (black line) and 1.01 (orange line) are presented in figure 6. The parameters of structures are $m = 5$ and $h_{Au} = 50$ nm. Changes in reflectance in the vicinity of OTS wavelength for structures No.3 and 4 are 6.6% and 5.6%, respectively. Thus, the hybrid state can be used to increase the sensitivity of optical sensors.

### 3.2. Hybrid state of TPP – LSP

The Faraday rotation of initial MPNS No.6 (Au NP)/$\text{M}_1$, demonstrated LSP resonance at $\lambda_{LSP} = 700$ nm, are shown in figure 7. According to atomic force microscopy and electron scanning microscopy measurements [19, 20], synthesized NP have a shape close to a semi-ellipsoid of rotation with average aspect ratio (ratio of height to diameter of the particle) of 0.5. NP have variation in lateral size range up to 100 nm. The average particle size is about 55 nm. MO spectra of MPNS No.1 with different $h_{bSiO_2}$, which were modelled for synthesis of MPNS with hybrid state of TPP – LSP No.5, are also shown in figure 7. It is evident that the maximum value of Faraday effect in modelled MPNS No.1 is achieved for the configuration with $h_{bSiO_2} = 208$ nm. Chosen MPNS No.1 among different configurations of such nanostructure have the highest value of $Q = 1.2^\circ$. We synthesized a sample of structure No.1 with this configuration and demonstrated $\Theta_F = -0.04^\circ$, $T = 2\%$, $Q = 0.02^\circ$ at resonant wavelength $\lambda_{res} = 700$ nm of TPP. Non-ideality of MPNS characteristics is connected with the changes of parameters of synthesized garnet from model value.

Figure 8 shows Faraday rotation spectra of synthesized MPNS No.5 with maximum of Faraday rotation that evident for $\lambda = 700$ nm. The configuration has $T = 0.05\%$ and $Q = 0.1^\circ$. The interaction of TPP and LSP leads to an increase in Faraday effect by 5 times compared with initial structure No.6 (only LSP resonance) and by 8.5 times compared with initial structure No.1 (only TPP resonance). For MPNS No.5 the anticrossing behaviour of resonances is not observed.
4. Conclusions

In the work we experimentally realized and investigated MPNS with hybrid states of TPP – Fabry-Perot and TPP – LSP. Both MPNS were realized with the gradient of thickness of layer adjacent to the plasmon layer to investigate the interaction of resonances.

MO quality factor of synthesized MPNS with TPP – Fabry-Perot hybrid state is 0.93° and 2.67° for TPP and Fabry-Perot mode, respectively. TPP – Fabry-Perot hybrid state manifests itself in the form of two resonances, which have anticrossing behaviour.

MO quality factor of synthesized MPNS with hybrid state of TPP – LSP is 0.1°. Hybridization of TPP – LSP gives enhancement of Faraday effect of initial resonances in 5 – 8 times.

Model MPNS were considered also to study the difference in properties of hybrid state of TPP – Fabry-Perot from a single TPP excitation. It was shown that the hybrid state can be used to increase the sensitivity of optical sensors.

Acknowledgments

The authors acknowledge support by the RF Ministry of Science and Higher Education in the framework of the state task (project no. 3.7126.2017/8.9) and V. I. Vernadsky Crimean Federal University (Grants no. ВГ 13/2018 and ВГ 22/2018).

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