Extraordinary Magneto-Optical Effects and Transmission through Metal-Dielectric Plasmonic Systems

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We predict theoretically a significant enhancement of the magneto-optical Faraday and Kerr effects in the bilayer systems of a metallic film perforated with subwavelength hole arrays and a uniform dielectric film magnetized perpendicular to its plane. Calculations, based on a rigorous coupled-wave analysis of Maxwell's equations, demonstrate that in such structures the Faraday effect spectrum has several resonance peaks in the near-infrared range, some of them coinciding with transmittance peaks, providing simultaneous large Faraday rotation enhanced by an order of magnitude and high transmittance of about 35%.

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Presently, magneto-optical (MO) Faraday and Kerr effects arising in gyrotropic media attract much attention due to their possible applications for control of light at a submicronic scale [1,2]. In the last several decades the urge towards efficient MO media was mainly concentrated on the chemistry. At the same time, substantial MO effect enhancement can be achieved in some nanostructured materials owing to the special design of their geometry. This was shown recently by observation of the giant Faraday effect in magnetic photonic crystals [3–5].

The giant Faraday effect can also be achieved in some other materials. In this respect metallic films perforated with the periodical arrays of subwavelength holes or grooves can be of prime interest. Such systems have been extensively studied due to the phenomenon of the extraordinary optical transmission (EOT) found in them [6,7]. It was claimed in most of the theoretical papers devoted to the EOT that the surface plasmon polaritons (SPPs) (see, e.g., Ref. [8]) play a crucial role in the EOT. Though the precise involvement of the SPPs is still being debated, it is undoubted that they contribute in the EOT phenomenon allowing described structures to be referred to as plasmonic systems. Along with SPPs, some other types of slow waves can be involved into the EOT, e.g., guided waves or surface waves supported by arrays of holes [9].

Some plasmonic aspects of magneto-optics have also been considered ([10–14]; see also [2]). However, most of the studies were devoted to the bulk crystals or the smooth multilayered metal/dielectric structures with either metallic or dielectric component magnetized. In the papers [15,16] the MO Kerr effect enhancement was claimed but it was usually accompanied by the decrease in the detected signal. Magnetized plasmonic systems with perforation have been examined in several works so far [15–18]. In Ref. [17] the optical transmission through a perforated metallic film in the presence of an external magnetic field applied in the film plane was studied and a strong dependence of the EOT-peak position on both the magnitude and direction of the in-plane magnetic field was found. Recently, experiments on perforated Co films have also been conducted [15]. In that study, the MO Kerr effect in the spectral range of the anomalous transmission band was found to be about one order smaller than that in uniform Co films of the same thickness. As it will be demonstrated further, for aquiring the enhancement of the MO effects several specific conditions must be satisfied.

In the present Letter we study the MO effects in the bilayer heterostructure consisting of a nonmagnetic metallic plate, periodically perforated with hole arrays, which is deposited on a thin uniform magnetic dielectric layer of thickness h. Holes constitute a square lattice of period d. The size of each hole is r [see inset in Fig. 1(a)]. We show that the Faraday and Kerr effects in this case can be enhanced significantly.

The thin magnetic dielectric layer here plays a twofold role. On the one hand the thin magnetic layer engenders the MO effects because of its magnetization; i.e., it produces TM-TE-mode conversion, and, on the other hand, it makes the TE-mode localized or, in other words, guided. At the same time, periodic nanostructuring of the metal layer serves for effective excitation of the SPPs and additionally provides the EOT effect.

The mechanism of the EOT and enhanced magneto-optics can be explained qualitatively as follows. The incident light excites the SPP on the upper surface of the metallic film. Because of the periodicity in the perforation

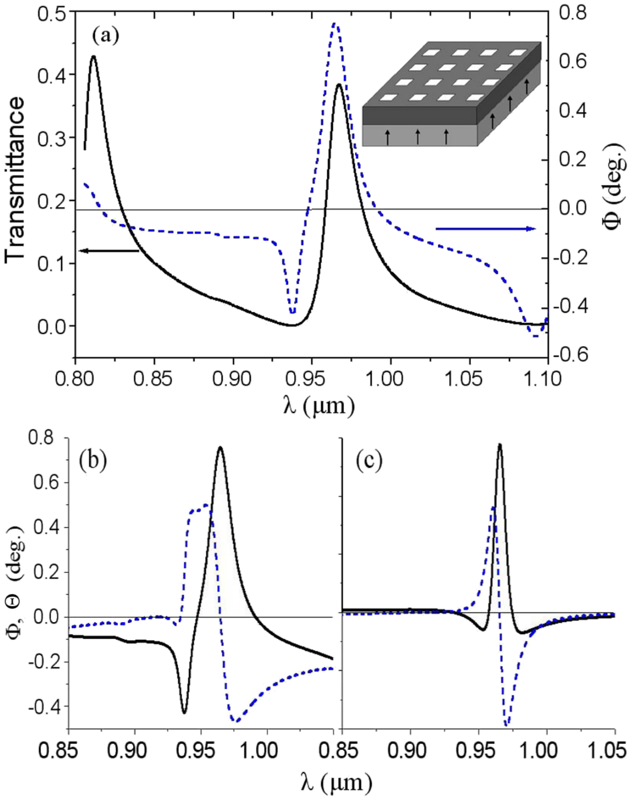

FIG. 1 (color online). Spectra of the optical transmittance [solid line in (a)], Faraday rotation [dashed line in (a) and solid line in (b)], and ellipticity [dashed line in (b)], Kerr rotation [solid line in (c)] and ellipticity [dashed line on (c)] of the bilayer system of perforated Au-film of thickness 68 nm and uniform Bi:YIG film of thickness 118 nm; $d = 750$ nm, $r = 395$ nm.

the SPP is described by the Bloch waves propagating along the metal surface, tunneling through the film and exciting the Bloch wave guided waves into the dielectric layer. By obvious analogy the considered heterostructure can be called 2D plasmonic crystal (see, e.g., [19]). The electromagnetic waves in the dielectric layer scatter at the holes and partially radiates in the far optical field. The presence of the magnetic field leads to the TM-TE-mode conversion, i.e., to the Faraday rotation. It is well known that the effective conversion demands equal phase velocities of the TM and TE modes. Thus, the enhanced Faraday effect along with high optical transmittance arises when the edges of the photonic band gaps for both considered principal modes coincide, i.e., $\omega_{n0}^{\mathrm{TM}} = \omega_{m0}^{\mathrm{TE}}$. This can be reached by the appropriate choice of the dielectric film thickness.

In order to get the dispersion laws for the TE and TM modes for the smooth metallic film with attached dielectric layer of thickness h, we found the following transcendent equation:

$$i \tan(k_{z2}h) = \alpha_2(\alpha_1 + \alpha_3)/(\alpha_2^2 + \alpha_1\alpha_3), \tag{1}$$

where $\alpha_i = k_{zi}/\varepsilon_i$ for the TM mode, $\alpha_i = k_{zi}$ for the TE mode; $k_{zi} = \sqrt{\varepsilon_i(\omega/c)^2 - \mathbf{k}_\perp^2}$, $i = 1, 2, 3$; ε_i are the dielectric functions of the metal ($i = 1$), dielectric layer ($i = 2$), and surrounding medium ($i = 3$); $\mathbf{k}_\perp$ is the in-plane component of the wave vector. It can be shown that bands of the $\omega_n^{\mathrm{TM}}(k_\perp)$ and $\omega_m^{\mathrm{TE}}(k_\perp)$ overlap. Therefore, in the presence of the periodicity, the TE and TM dispersion curves should intersect and the condition of $\omega_{n0}^{\mathrm{TM}} = \omega_{m0}^{\mathrm{TE}}$ would be satisfied for some $\mathbf{k}_\perp$ lying in the first Brillouin zone. By changing the value of the thickness h it is possible to control photonic bands of the TM and TE modes and arrange the appropriate conditions for the EOT and the Faraday effect enhancement. The aforementioned discussion is proved by the comprehensive numerical modeling.

Assuming $\mu = 1$ it is straightforward to obtain from Maxwell equations the following eigenvalue problem for the magnetic heterostructure described by the dielectric function $\varepsilon(\mathbf{r})$ and gyrotropy $g(\mathbf{r})$:

$$(\hat{H} + \hat{V} - k_0^2)\mathbf{\Psi}(\mathbf{r}) = 0, \tag{2}$$

where $\mathbf{\Psi}(\mathbf{r}) = [\varepsilon(\mathbf{r})]^{-1/2}\mathbf{E}(\mathbf{r})$ [20], $\mathbf{E}(\mathbf{r})$ is the electric field amplitude, $k_0 = \omega/c$, $\hat{H}\mathbf{\Psi}(\mathbf{r}) = [\varepsilon(\mathbf{r})]^{-1/2}\nabla \times \{\nabla \times [\varepsilon(\mathbf{r})]^{-1/2}\mathbf{\Psi}(\mathbf{r})\}$; $\hat{V}\mathbf{\Psi}(\mathbf{r}) = -ik_0^2 g(\mathbf{r}) \cdot \mathbf{m} \times \mathbf{\Psi}(\mathbf{r})$, $\mathbf{m}$ is the unit vector of the medium magnetization. Eigenfunctions of $\hat{H}$ are vectorial Bloch functions

$$\mathbf{\Psi}_{n\mathbf{k}}(\mathbf{r}) = \mathbf{u}_{n\mathbf{k}}(\mathbf{r})e^{i\mathbf{k}\cdot\mathbf{r}}, \tag{3}$$

where $\mathbf{k}$ is the quasimomentum and n is a number of the given photonic band; $\mathbf{u}_{n\mathbf{k}}(\mathbf{r}_{||}) = \mathbf{u}_{n\mathbf{k}}(\mathbf{r}_{||} + \mathbf{a})$, $\mathbf{r}_{||}$ is a radius vector in the XY plane, and $\mathbf{a}$ is the lattice vector of the holes grating.

To solve the eigenvalue problem (2) a rigorous coupled-wave analysis (RCWA) was used [21,22]. In the RCWA technique the electromagnetic fields in each grating layer are determined by projecting of Eq. (2) on the $(2N_1 + 1) \times (2N_2 + 1)$-dimensional Hilbert subspace of the harmonic modes:

$$\mathbf{\Psi}_{n\mathbf{k}}(\mathbf{r}) = \sum_{n_1=-N_1}^{N_1}\sum_{n_2=-N_2}^{N_2}\mathbf{C}_{n_1n_2}^{n} \times \exp\left[i\left(\frac{2\pi n_1}{d_1}x + \frac{2\pi n_2}{d_2}y + k_z z\right)\right], \tag{4}$$

where N_1 and N_2 are chosen by the convergence conditions.

In the bilayer system we consider the magnetic layer uniformly magnetized perpendicularly to its plane. For the optical frequency range it is described by the dielectric tensor $\hat{\varepsilon}^{(m)}$ having the following nonzero components: $\varepsilon_{11} = \varepsilon_{22} = \varepsilon_{33} = \varepsilon_2$, $\varepsilon_{12} = -ig$, $\varepsilon_{21} = ig$, where g is the value of medium's gyration [2]. Here we assume the case when the magnetic medium is optically isotropic and second-order MO effects are negligible. In the numerical modeling parameters of Bi-substituted yttrium, iron garnet magnetic film were used: $\varepsilon_2 = 5.5 + i0.0025$, $g = (1 - i0.15) \times 10^{-2}$ [2]. The metallic material is characterized by the dielectric function ε_1 with the Drude model $\varepsilon_1 = \varepsilon_\infty - \omega_p^2/(\omega^2 + i\gamma\omega)$ for the frequency dependence. At the analysis the metal film was assumed to be made of gold, for which we set $\varepsilon_\infty = 7.9$, $\omega_p = 8.77$ eV, and $\gamma = 1.13 \times 10^{14}$ c^{-1} to fit the empirical data [23] for the Au film over the wavelength range of interest.

The results of the calculations of transmittance and MO effects in the considered system are shown in Fig. 1. The Faraday and Kerr effects are described by the angles $\mathbf{\Phi}_F$ and $\mathbf{\Phi}_K$, which stand for the Faraday and Kerr rotation of light polarization, and angles $\mathbf{\Theta}_F$ and $\mathbf{\Theta}_K$ denoting the Faraday and Kerr ellipticity of light polarization, respectively [24].

The transmittance spectrum of the Au/Bi: YIG bilayer has several EOT resonances, which are related to the light coupling with surface waves in the films. At the same time, at the vicinity of some transmittance peaks a pronounced enhancement of the MO effects is found. Namely, at $\lambda_{\max} = 963$ nm where the transmittance reaches 35%, the Faraday and Kerr rotations get positive values of $\mathbf{\Phi}_F = 0.78°$ and $\mathbf{\Phi}_K = 0.63°$, respectively. This corresponds to their enhancement by 9 times in comparison with the case of the same single magnetic layer surrounded by optically matched medium. The ellipticity of transmitted/reflected light polarization gets increased as well, but their positive and negative extrema happen at slightly different wavelengths and the ellipticity is almost zero at the resonance of the MO rotation. Consequently, transmitted and reflected electromagnetic waves at $\lambda_{\max} = 963$ nm are linearly polarized.

Optical and MO spectra presented in Fig. 1 correspond to the magnetic film thickness $h = 118$ nm. Under change of the thickness h all spectra substantially modify, which is demonstrated in Fig. 2, where the optical transmittance and the Faraday rotation at $\lambda = 963$ nm versus thickness h are shown. It is vivid that for the given wavelength the optimal value of h is close to 118 nm. Positive and negative resonances in the Faraday rotation also happen for some other thicknesses but all of them correspond to smaller enhancement level. At some other incident wavelength the shape of the thickness dependences would modify and the optimization would take place for different h.

It should be noted here that, as it follows from Fig. 2, the resonances of the transmittance and Faraday rotation do not fully correlate and their matching appears only for narrow interval of the film thickness values. In the framework of the qualitative analysis discussed above it is explained by the difference in the conditions necessary for getting high transmitted optical power and light polarization rotation. Indeed, for the former incident light frequency must correlate with the band gap for SPP and quasi-wave-guided modes, while for the latter phase velocities of TM and TE modes at the incident frequency have to be equal. The phenomenon of the simultaneously high transmittance and the Faraday rotation will take place only when both requirements are met.

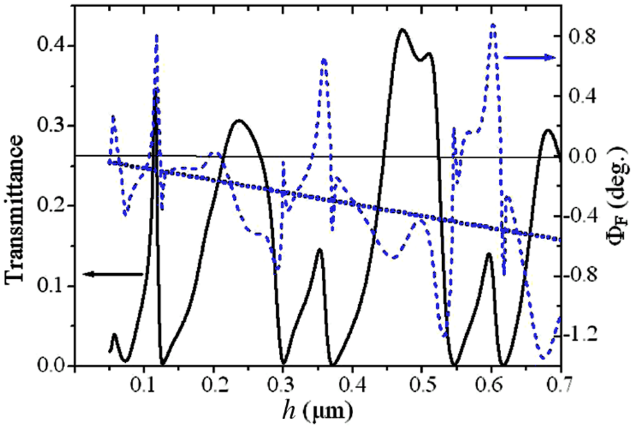

FIG. 2 (color online). Faraday rotation (dashed line) and transmittance (solid line) versus the thickness h of the magnetic layer. Geometrical parameters of the Au-BiYIG film are the same as in Fig. 1; $\lambda = 963$ nm. Dotted line represents the Faraday rotation for the same single magnetic layer placed in optically matched surrounding medium.

To get further physical insight into the enhancement of the Faraday effect let us apply two-coupled-wave approach developed in [5] for the MPCs and based on the Eqs. (2) and (3) and get the following expression for the specific Faraday rotation angle $\mathbf{\Phi}_{F0}$ measured by the difference Δk_z between the longitudinal wave numbers of two quasi-circular-polarized modes (k_z^+ and k_z^-) in the heterostructure:

$$\mathbf{\Phi}_{F0} = \Delta k_z/2 = \frac{\langle Q\rangle\omega}{2\beta}\left(\frac{1-(\omega_0/\omega)^2}{\beta}\right)^{-1/2}, \tag{5}$$

where $\beta = \beta^{\mathrm{TE}} = \beta^{\mathrm{TM}}$; $\beta^{\mathrm{TE/TM}} = c^2\langle u_{n\mathbf{k}}^{\mathrm{TE/TM}}|\varepsilon^{-1}|u_{n\mathbf{k}}^{\mathrm{TE/TM}}\rangle$, $\langle Q\rangle = \langle u_{n\mathbf{k}}^{\mathrm{TE}}|g/\varepsilon|u_{n\mathbf{k}}^{\mathrm{TM}}\rangle$, and the matrix elements are calculated in the volume of the single lattice cell of the system. It is assumed here that for the given photonic band $[1-(\omega_0/\omega)^2]/\beta > 0$ and edges of the photonic band gaps for both principal modes coincide: $\omega_{n0}^{\mathrm{TM}} = \omega_{m0}^{\mathrm{TE}} = \omega_0$. In Ref. [5] it was emphasized that the Faraday rotation in the periodic systems is strongly related with the group velocity V_g and gets its maximum values at the vanishing V_g. In the case of the considered heterostructure this dependence can be written by $\mathbf{\Phi}_{F0} = \langle Q\rangle\omega/2V_g$, where $V_g = \beta\sqrt{[1-(\omega_0/\omega)^2]/\beta}$, which demonstrates the enhancement of the Faraday rotation and correlates with an intuitive view on mechanism of the effect.

It is interesting that at some resonance wavelengths the Faraday rotation angle $\mathbf{\Phi}_F$ is positive, i.e., it is of the opposite sign being compared to the Faraday angle in the single uniform magnetic medium of the same gyrotropy [see Figs. 1(b) and 2]. This can be explained in terms of Eq. (5) by the fact that at such wavelengths (e.g., $\lambda = 963$ nm, for Fig. 1) the photonic band curvature β is negative and, consequently, the angle $\mathbf{\Phi}_F$ has sign opposite to the sign of the MO parameter $\langle Q \rangle$, which determines the Faraday rotation in the uniform magnetic media. Note that at this wavelength the ratio of the phase and group velocities is negative. At the same time, some other Faraday rotation peaks are negative (e.g., at $\lambda = 941$ nm, for Fig. 1), corresponding to the positive values of the curvature β and positive phase to the group velocities ratio.

Thus, for the considered heterostructure, there appears a new situation when the value and the sign of the MO effects is determined not only by the medium MO properties but also by its geometry.

To demonstrate that SPPs are important for extraordinary MO effects we also modeled influence of SPPs damping on the transmittance and MO spectra. The characteristic parameter here is ω/γ, where ω is the resonance frequency and γ is the rate of electron collisions in the metal. It was found that when $\omega/\gamma \gg 1$ transmittance and the Faraday effect are high and resonance width is relatively small. However, when the parameter ω/γ approaches unity the EOT and Faraday rotation resonance peaks broaden, and get much smaller, completely vanishing for $\omega/\gamma \leq 1$, when the damping distance of the SPPs is about the lattice period. Such behavior of extraordinary MO effects and transmittance spectra approves that the SPPs play a crucial role here.

To conclude, we have studied optical properties of the bilayer metal/dielectric heterostructure, the metallic plate being perforated with the periodic hole arrays and the dielectric plate being magnetized in polar geometry perpendicularly to its plane. As test media for the metal and dielectric Au and BiYIG are used, respectively. Numerical modeling was performed on the basis of the RCWA approach extended for the case of MO media. The effect of simultaneous enhancement of transmittance and MO Faraday and Kerr effect is found. It is shown that the proper choice of the gyrotropic nanostructure geometry allows acquiring the EOT and extraordinary Faraday rotation for the wavelengths of the near-infrared range where the SPPs can be excited efficiently. Though the problem of light interaction with perforated metal-dielectric systems is very complex, qualitative explanations for the revealed phenomena are given, suggesting SPPs coupling with quasiguided waves in the thin dielectric layer being in its roots. Such interpretation and the significance of the SPPs excitation, in particular, are proved by the modeling of all-dielectric perforated films, where the phenomenon of simultaneously high polarization rotation and transmittance is shown to be no longer present.

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