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Giant Faraday Rotation in One-Dimensional Photonic Crystal with Magnetic Defect

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Abstract—The effect of a substantial increase of the Faraday rotation angle has been investigated in a symmetrical resonator structure, which is represented by a one-dimensional photonic crystal with dielectric Bragg mirrors and a magnetically active layer placed between mirrors. In the numerical analysis, the parameters of a pure yttrium iron garnet at two wavelengths $-1.15\,\mu$m and $1.3\,\mu$m have been used. The increase in the Faraday rotation angle is caused by not only an increase of the magnetic layer thickness, but also a symmetrical increase in the number of Bragg mirrors periods.

1. INTRODUCTION

Increased in the recent years, the interest of researchers in the magnetically active photonic crystal (PC) structure is explained by not only the presence of photonic band gaps in its frequency spectrum, but also the ability to effectively manage their optical characteristics [1–15]. Among a wide range of tape structures, particular interest should be paid to the structure of the Fabry-Perot resonator type, which is a magnetic dielectric layer interposed between the nonmagnetic dielectric photonic crystal (PC) mirrors [9–11, 13, 14]. In such a PS-structure, the magnetic layer acts as an optical microcavity, which can be located as the light wave field at a defect of the periodic structure [7, 8, 12], resulting in significantly enhanced different magneto-optical effects. In particular, a substantial increase of the Faraday and Kerr effects should be expected in the polar geometry of the magnetic layer magnetization (towards the incident wave) [4, 5, 12]. In this paper, we investigate the transmission spectra and rotation angle of the polarization plane (Faraday rotation), as manifested in one-dimensional magnetically active photonic-crystal structure of a resonator type with a linearly polarized wave passing through it. This structure is manifested in a defect-free PC-structure formed on the basis of two transparent (as for the investigated frequency range) dielectrics with creation of a double defect-inversion and implementation [16]. In this case, the implementation layer (magnetic layer) is between two symmetrical Bragg PC-mirrors. Investigation of the Faraday effects features in magnetically active PC structures was carried out in a number of papers [1, 7–9, 12–15]. However, these works are devoted mainly to the non resonator-type structures, which contain a lot of magnetic layers [7, 8, 12]. Another particularity of this work consists in application as a magnetically active layer of a widely used in practice pure yttrium iron garnet (non-doped bismuth or lutetium with high MO characteristics, but also with a greater absorption). In this paper, we compare the ability of the considered PC-structure to rotate the polarization plane at two wavelengths in the infrared transparent window. The obtained theoretical result shows the possibility to achieve very high values of the rotation angle as compared both to the same monolayer thickness (even at its high MO quality factor) and to other PC-type structures.

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2. BASIC RELATIONSHIPS

We are considering a one-dimensional PC structure, which consists of a finite number of alternating layers of nonmagnetic isotropic dielectric with permittivities (DP) ε_j and thicknesses d_j $(j = 1, 2)$. Let us consider their permeabilities at optical frequencies equal to unity. The OZ-axis is directed perpendicular to the layer interface. The external magnetic field $\mathbf{H}_0$, saturating magnetically active layer, is oriented along this direction, where eigen circularly polarized waves with the components of the electric $E^{\pm} = E_x \pm iE_y$ and magnetic $H^{\pm} = H_x \pm iH_y$ fields are also propagated. The time dependences of the wave fields components are proportional to the factor $\exp(i\omega t)$.

In the case of a binary periodic structure, the transfer matrix of one period $\hat{N}^{\pm}$ that connects wave field amplitude at the beginning and the end of k-th period is usually introduced: $E_1^{\pm} = \hat{N}^{\pm} E_2^{\pm}(z_k + d_1 + d_2)$, where $d_1 + d_2$ is the period of structure. If the layers are not absorbing, the matrix of period $\hat{N}^{\pm} = \hat{N}_1^{\pm} \hat{N}_2^{\pm}$ is unimodular, and its determinant is equal to unity. The relationship between the wave fields in planes spaced from each other by an integer number of periods p is determined by the transfer matrix $(\hat{N}^{\pm})^p$ [17]. The non-inverted PC structure with a finite number of periods $2a$ is defect-free and is characterized by the transmission matrix $\hat{S} = (\hat{N}_1 \hat{N}_2)^{2a}$. The symmetrical magnetoactive resonator structure is intended to include a magnetic layer between the side dielectric PC-mirrors, which are inverted to each other: if the input mirror layers are formed in the order $1-2-1-2\ldots$, in the output mirror, the order of layers is changed, i.e., $2-1-2-1\ldots$. From the defect viewpoint, such structure has an inversion defect and a magnetic interstitial defect. The inversion defect consists in the change of order of sequence layers in one of two parts of the structure and is defined by the formula $\hat{S} = (\hat{N}_1 \hat{N}_2)^a (\hat{N}_2 \hat{N}_1)^a$. The inverted period corresponds to the transfer matrix, whose elements are associated with the elements of the normal period matrix: $\overline{N}^{\pm}_{\alpha\beta} = N^{\pm}_{3-\beta,3-\alpha}$, where $\alpha, \beta = 1, 2$. Together with the inversion defect, the resonator structure contains a magnetically active layer which is embedded between the PC-mirrors $(\hat{N}_1 \hat{N}_2)^a$ and $(\hat{N}_2 \hat{N}_1)^a$. The longitudinal external magnetic field saturates the magnetic layer with its magnetic moment oriented along the axis of the structure (see Fig. 1 geometry of the problem). In this case, the transmission matrix of the structure has the form $\hat{S}^{\pm} = (\hat{N}_1 \hat{N}_2)^a \hat{M}^{\pm} (\hat{N}_2 \hat{N}_1)^a$, where the signs "$\pm$" belong to the eigen waves with right and left circular polarization.

The DP tensor of the magnetically active layer magnetized to saturation along the axis OZ has the following nonzero components

$$\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon = \varepsilon' + i\varepsilon'', \quad \varepsilon_{zz} = \varepsilon_0, \quad \varepsilon_{xy} = -\varepsilon_{yx} = ig. \tag{1}$$

The transfer matrix for this layer for each of eigen circularly polarized waves propagating along the magnetization can be written as:

$$\hat{M}^{\pm} = \begin{pmatrix} \cos(k_{\pm} d) & \pm(k_0/k_{\pm}) \sin(k_{\pm} d) \\ \mp(k_{\pm}/k_0) \sin(k_{\pm} d) & \cos(k_{\pm} d) \end{pmatrix}, \tag{2}$$

where d is layer thickness, $k_{\pm} = k_0\sqrt{\varepsilon \pm g}$, $k_0 = \omega/c$, and ω and c are the wave frequency and the velocity of light in vacuum. The amplitude and energy transmission coefficients are determined by the

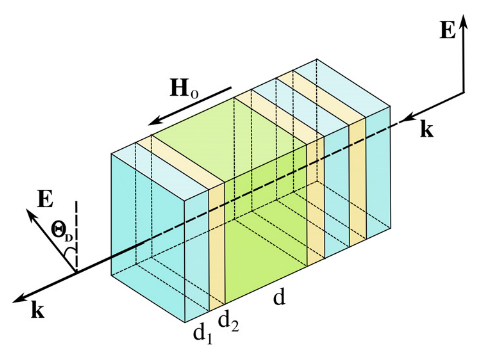

Figure 1. Finite magneto active symmetrical microcavity.

matrix elements $S^{\pm} = (N_1N_2)^a M^{\pm}(N_2N_1)^a$ for PC- structure in vacuum with inversion and interstitial defects:

$$t^{\pm} = \frac{E_t^{\pm}}{E_0^{\pm}} = \frac{2}{S_{11}^{\pm} + S_{12}^{\pm} + S_{21}^{\pm} + S_{22}^{\pm}} = |t^{\pm}| \exp(i\varphi_t^{\pm}), \quad T^{\pm} = |t^{\pm}|^2. \tag{3}$$

In the case of an incidence on a similar PC-structure of the linearly polarized wave, the transmitted wave, in general, suffers the polarization plane rotation (the Faraday effect) and ellipticity. The full rotation angle and the ellipticity of the transmitted wave in this case is determined by the expressions:

$$\Theta = (\varphi_t^- - \varphi_t^+)/2, \quad E = (|t^+| - |t^-|)/(|t^+| + |t^-|). \tag{4}$$

where $\varphi_t^{\pm}$ and $|t^{\pm}|$ are the phases and the amplitudes of the complex amplitude transmission coefficients of right and left waves of circular polarization $t^{\pm} = |t^{\pm}| \exp(i\varphi_t^{\pm})$. In the absence of circular dichroism $|t^-| = |t^+|$, the ellipticity $E = 0$ and, therefore, the wave passed through the PC structure is linearly polarized.

The thicknesses of the layers in the dielectric mirrors were selected equal to quarter wavelength in each layer: $d_1 = \lambda_0/4n_1$ and $d_2 = \lambda_0/4n_2$ in the numerical analysis. It is with this thickness of layers when the reflection from PC-mirrors is maximum. The thickness of the magnetic layer is chosen equal to $d = \xi d_0$, where $d_0 = \lambda_0/2n$. Here, the refractive indices (RI) of dielectric layers $n_{1,2} = \sqrt{\varepsilon_{1,2}}$. For the magnetic layer in geometry of the longitudinal propagation, the RI for two natural waves are $n^{\pm} = \sqrt{\varepsilon \pm g}$. Since the magnitude ε is complex, so, the corresponding RI are complex, i.e.,

$$n^{\pm} = (n' - in'')^{\pm} = \sqrt{(\varepsilon' \pm g) + i\varepsilon''}. \tag{5}$$

In view of Eq. (5), for the real and imaginary parts of RI, we obtain:

$$(n')^{\pm} = \frac{1}{\sqrt{2}}\left[\sqrt{(\varepsilon' \pm g)^2 + (\varepsilon'')^2} + (\varepsilon' \pm g)\right]^{1/2}, \quad (n'')^{\pm} = \frac{1}{\sqrt{2}}\left[\sqrt{(\varepsilon' \pm g)^2 + (\varepsilon'')^2} - (\varepsilon' \pm g)\right]^{1/2}. \tag{6}$$

Since the difference between the values $(n')^+$ and $(n')^-$ is small, we will continue to take the following magnitude as the RI of the magnetic layer:

$$n = \frac{1}{2}\left[(n')^+ + (n')^-\right]. \tag{7}$$

The imaginary part of RI is associated with an absorption coefficient

$$\alpha_f = 2k_0 \frac{(n'')^+ + (n'')^-}{2} = \frac{2\pi}{\lambda_0}\left[(n')^+ + (n')^-\right]. \tag{8}$$

Next, the transmission spectra and Faraday rotation of the polarization plane of the transmitted through the PC structure radiation are numerically analyzed. As shown by analysis, the symmetrical resonator structure with defects of inversion and interstitial: $S^{\pm} = (N_1N_2)^a M^{\pm}(N_2N_1)^a$ is a preferred one to achieve large rotation angles of the polarization plane and more efficient management of the dynamics of wave propagation. Thus, a larger rotation angle of the polarization plane passing through the PC-structure radiation can be achieved in the case where the magnetic layer is in contact with dielectric layers with a lower refractive index [16].

3. NUMERICAL ANALYSIS

We have examined the structures with the PC-mirror made from two materials — $Gd_3Ga_5O_{12}$ with $\varepsilon_1 = 3.71$ at $\lambda = 1.15\,\mu m$ and $\varepsilon_1 = 3.748$ at $\lambda = 1.3\,\mu m$ (the layers N_1), and SiO_2 with $\varepsilon_2 = 2.098$ at $\lambda = 1.15\,\mu m$ and $\varepsilon_2 = 2.094$ at $\lambda = 1.3\,\mu m$ (the layers N_2). The material of magnetic defect (the layer M) is yttrium iron garnet ($Y_3Fe_5O_{12}$), for which the diagonal and off-diagonal components of the permittivity tensor have the form: $\varepsilon = \varepsilon' + i\varepsilon''$, $\pm ig$. Parameters of the individual magnetic layers at two wavelengths are shown in the following Table 1 [18, 19].

Fig. 2 for the structure $(N_1N_2)^a M(N_2N_1)^a$ with the parameter $a = 10$ shows the frequency dependences of the modulus of the amplitude transmission coefficient obtained by varying the thickness of the magnetically defective layer in the first photonic band gap with a center frequency $\omega_0 = 1.638 \cdot 10^{15}\,s^{-1}$ corresponding to the wavelength $\lambda_0 = 2\pi c/\omega_0 = 1.15\,\mu m$. In the absence of a defect

Table 1. Parameters of the individual magnetic layers at two wavelengths.

λ_0, μm	ε'	ε''	g	θ_F^0, deg/cm	α_f, 1/cm
1.15	4.65	$3.95 \cdot 10^{-6}$	$3.38 \cdot 10^{-4}$	245	0.1
1.3	4.84	$1.37 \cdot 10^{-5}$	$3.34 \cdot 10^{-4}$	210	0.3

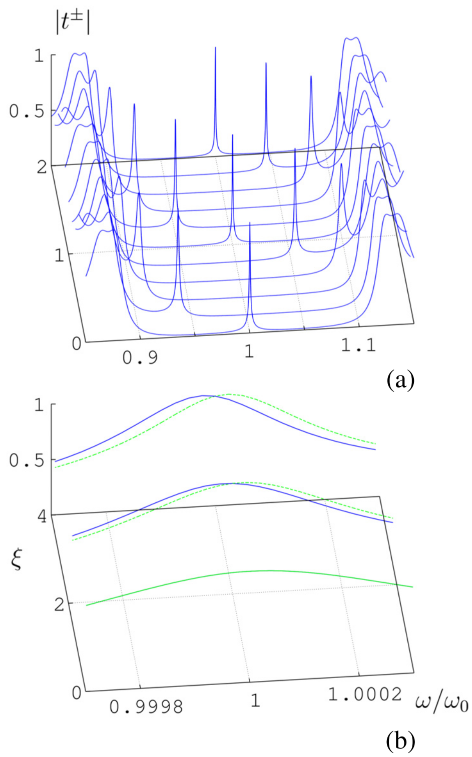

Figure 2. The frequency dependence of the modulus of the amplitude waves transmission coefficient at different thicknesses of the magnetic defect ξ. The wavelength of radiation $\lambda_0 = 1.15\,\mu$m, for the structure $(N_1N_2)^a M(N_2N_1)^a$ where $a = 10$. For the whole first photonic band gap (a), for larger frequency scale (b).

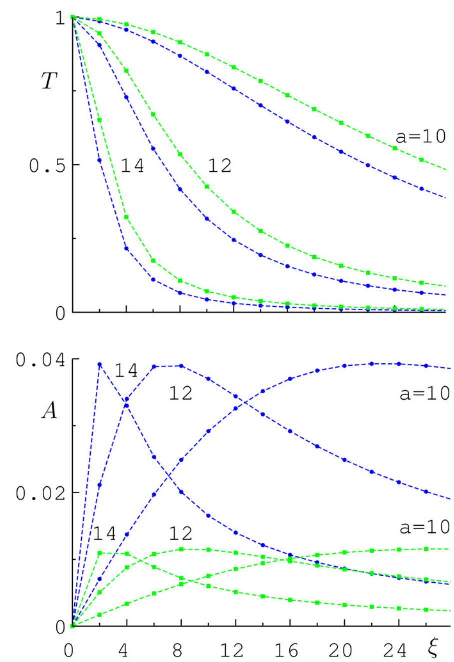

Figure 3. Dependencies of the maximum value of the transmission and absorption coefficients at the frequency of the defect mode $\omega_0 = 2\pi c/\lambda_0$ of the magnetic defect thickness at the emission wavelength $\lambda_0 = (1.15, 1.3)\,\mu$m (squares and circles or green and blue, respectively), for the structure $(N_1N_2)^a M(N_2N_1)^a$ where $a = 10, 12, 14$.

magnetic layer (at $\xi = 0$), the spectra for right- and left-polarized waves coincide, and a degenerate defective mode is located strictly in the center of the zone. With the introduction of the magnetic layer and increase of parameter ξ, the degeneracy is lifted, leading to the separation of the spectral lines of eigen waves $|t^{\pm}|$. In the selected scale, the separation of spectral lines is within the graphical accuracy and this division is not visible in the figure. Let us note, that at the wavelength $\lambda_0 = 1.15\,\mu$m (in the transparency window), the absorption for pure $Y_3Fe_5O_{12}$ is very small ($\alpha = 0.1\,\text{cm}^{-1}$, for comparison, when at $\lambda_0 = 0.63\,\mu$m the damping parameter is $\alpha = 6.2 \cdot 10^3\,\text{cm}^{-1}$), so by increasing the thickness of the defect layer with a repetition period $2d_0$ we get almost a periodic variation of the spectrum shape. Fig. 2(b) shows dependences of the quantities $|t^{\pm}(\omega)|$ built on an enlarged scale in frequency. The spectral lines of the eigen modes are located strictly symmetrical to the center of forbidden band gaps when the defect layer thickness is arbitrary. The increase of this layer thickness leads to an increase of the frequency interval between the spectral lines of the right- and left-polarized defect modes. However,

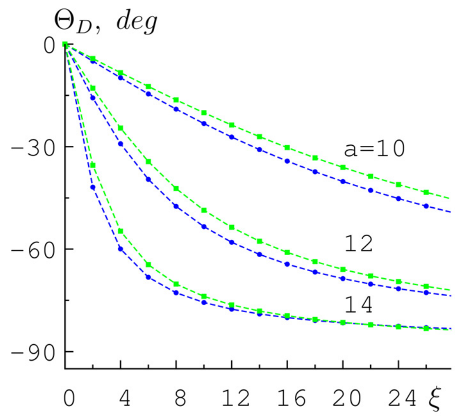

Figure 4. Dependence of the Faraday rotation angle Θ_D on the magnetic defect thickness at the emission wavelength $\lambda_0 = (1.15, 1.3)$ µm (squares and circles or green and blue, respectively), for the structure $(N_1N_2)^a M(N_2N_1)^a$ where $a = 10, 12, 14$.

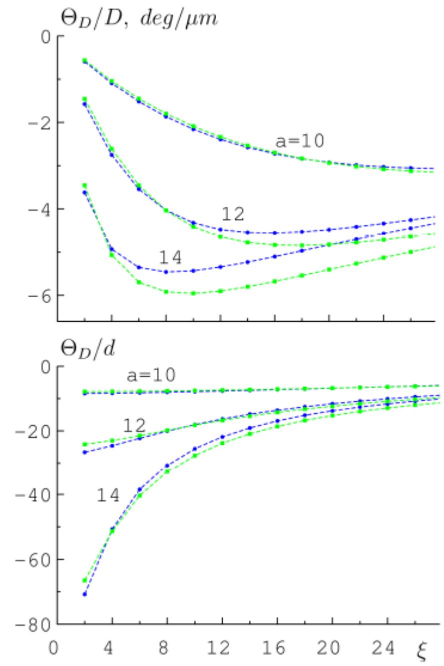

Figure 5. Dependences of the two types Faraday rotation angle on the magnetic defect thickness: assigned to the thickness of the whole structure $\theta_D = \Theta_D/D$, and assigned to the thickness of the defect $\theta_d = \Theta_D/d$. Dependencies are obtained at the wavelength $\lambda_0 = (1.15, 1.3)$ µm (squares and circles or green and blue) for the structure with $a = 10, 12, 14$.

the distance between the peaks of the spectral line of eigen mode even with $d = 4d_0$ is $\Delta\omega_\pm \approx 10^{-3}\omega_0$.

Fig. 3 shows the dependence of the transmission $T = (T^+ + T^-)/2$ and absorption $A = (A^+ + A^-)/2$ energy coefficients on the thickness of the magnetoactive layer for the considered PC-structure with the number of periods in the Bragg mirrors $a = 10, 12, 14$. The dependencies are presented for two wavelengths $\lambda_0 = (1.15, 1.3)$ µm (squares and circles, respectively). It can be seen that with the increase in the number of periods in PC mirrors (parameter a), the transmission coefficient is reduced at this thickness of the magnetic layer. The analysis shows that the presence of Bragg mirrors leads to multiple reflections at Bragg mirrors and creation of a standing wave inside of the magnetoactive resonator. At the selected refractive index distribution in the structure, the field distribution maximums are being formed at the resonator boundaries with Bragg mirrors. The height of these peaks, as well as the field amplitude at the output surface of the structure, depends on the thickness of the defect layer, which is associated with the presence of the absorption in the material layer. For each wavelength and number of periods in the PC-mirrors, the absorption in the structure $A = 1 - R - T$ reaches its maximum at a certain value parameter ξ. At the wavelength $\lambda_0 = 1.15$ µm, maximum absorption is $A \simeq 0.011$, at the wavelength $\lambda_0 = 1.3$ µm, maximum absorption is $A \simeq 0.04$. With increasing number of periods in PC mirrors, the magnetic layer thickness, where the maximum absorption is observed, is also growing. However, even when $\xi = 24$ (i.e., at $d = 6.5$ µm) the absorption coefficient does not exceed $A \simeq 0.04$.

The possibility to make multiple reflections at Bragg mirrors leads to a large optical waves path in a magnetoactive layer, resulting in the possibility to obtain high values of rotation angle for the polarization plane coming out of the wave structure. Fig. 4 shows the dependence of the total rotation angle of the polarization plane Θ_D transmitted through the investigated structure of a linearly polarized wave of the magnetically active layer thickness $d = \xi d_0$, where the parameter ξ takes discrete values

$\xi = 0, 2, 4, \ldots$. Dependencies are built for the wavelength $\lambda_0 = (1.15, 1.3)\,\mu\text{m}$ when the number of periods in the Bragg mirrors $a = 10, 12, 14$.

These dependences prove that the rotation angle of the polarization plane Θ_D increases while increasing both the magnetic layer thickness and the number of periods in the PC-mirrors. It can be seen that the resonator PC-structure allows obtaining the rotation angle of the polarization plane, which is much higher than its value in a single passage of an isolated magnetic layer. Thus, when the magnetic layer thickness equals to $d = 16d_0 \simeq 4.27\,\mu\text{m}$, the Faraday angle of the resonator scheme at $a = 12$ is equal to $\Theta_D \simeq 60\,\text{deg}$. For an isolated magnetic layer, the angle of Faraday rotation is given by

$$\Theta_d = \frac{\omega_0}{2c}(n^+ - n^-)d = \frac{\pi}{\lambda_0}\frac{g}{n}d. \tag{9}$$

At the layer thickness $d \simeq 4.27\,\mu\text{m}$, we get $\Theta_d \simeq 0.1\,\text{deg}$ which is much smaller (more than by two orders) than the corresponding values for the resonator structure. This inequality $\Theta_D \gg \Theta_d$ allows us to consider the rotation angle of the polarization plane in the considered resonator PC-structure to be giant.

Fig. 5 shows the dependence of the specific Faraday rotation, i.e., the angle, related to the thickness of the whole structure $\theta_D = \Theta_D/D$, where $D = 2a(d_1 + d_2) + d$ (the same parameters as in the previous figures) on the magnetic defect thickness. It is seen that the dependence $\theta_D(\xi)$ is nonmonotonic. First, with an increase of the parameter ξ, the module of the angle θ_D increases, reaches the maximum and then decreases slowly. The parameter value ξ, at which the maximum value $|\theta_D|$ is reached, shifts with the increasing number of periods in the PC-mirrors to the region of the magnetic layer large thickness.

In this paper, we consider the case when the defect mode lies strictly in the band gap center. For the parameter values $\xi \neq 0, 2, 4, \ldots$, the defect mode position is shifted from the band center resulting in the reduction of the transmission coefficient value at the wavelengths corresponding to the band center. In order to achieve maximum values for the transmission coefficients and magneto-optical effects, the wave frequency has to be adjusted to the defect mode frequency.

4. CONCLUSION

The analysis made in this paper shows that the use of the inverted PC-structure with a single magnetic defect and symmetrical dielectric Bragg mirrors allows obtaining large Faraday rotation angles of the polarization plane of the transmitted radiation, significantly exceeding the corresponding values for a single magnetic layer of the same thickness. It is shown that the large rotation angles can be achieved by using a magnetoactive layer of the pure (undoped) yttrium iron garnet. The magneto-optical quality factor of a single layer of such material is lower than that of the doped one, but the absorption is also much lower. The resonator PC-structure allows increasing the angle of Faraday rotation by more than two orders. To this effect, the frequency of the wave propagating in the photonic-crystal structure has to coincide with the frequency of the defect mode. If the defect layer thickness is equal to the integer number of half wavelengths in the magnetic material layer, the defect mode is formed in the middle of the photonic bandgap.

The increase of the Faraday rotation is also caused by the increase of the magnetic layer thickness in structure, the symmetrical increase of the periods number in dielectric PC-mirrors, the sequence order of layers with higher and lower refractive index in the mirrors. To achieve the greatest angle of Faraday rotation, it is necessary to form a magnetic defect so that it had contact with the layers of dielectric with a lower dielectric constant.

It should be noted that the dispersion of the material parameters of pure YIG in the investigated frequency range (near IR) is negligible, so the parameters α_f and θ_F^0 can be assumed to be constant in the wavelength range $\lambda_0 \pm \Delta\lambda$, where $\Delta\lambda \simeq 0.05\,\mu\text{m}$. Thus, the material dispersion does not affect the position of the defect mode in the PBG. The role of the external magnetic field $\mathbf{H_0}$ is to bring the magnetic layer to the magnetization direction of the field state. For YIG, the saturation field of thin layer perpendicular to its surface should be $\mathbf{H_0} \geq 4\pi M_0 \simeq 1760\,\text{Oe}$, and a further increase of the field does not change the magnetic state of the layer. Therefore, in the optical region, the magnetic field at its further increase does not change the magneto-optical characteristics of the layer (in contrast to the microwave region). A significant influence on the working range of the devices using this effect can be caused by a structural dispersion which is sensitive to the geometric parameters (in particular, to the thicknesses of the layers). If the size of all layers and values of the material parameters are observed, as well as when the wavelength of the incident radiation is set strictly on a defective mode, the effect of large angles of rotation of the polarization plane should appear.

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