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Review

Control of defect mode in magnetophotonic crystals in the magnetic resonance region

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ABSTRACT

The influence of magnetic field on the reflection spectra of one-dimensional magneto-photonic crystals of two types has been investigated. The first type is a periodically layered defect-free magnetic-dielectric structure, the second one is a magnetically active defect placed between dielectric photonic crystal mirrors. If the frequency of magnetic resonance is close to the central frequency of one of the photonic band gaps or to the frequency of the defect mode, it creates a significant reconstruction of the spectrum in the mentioned frequency domain. Namely, it can bring the suppression of the oscillation spectrum and the defect mode, which makes it possible to effectively control the spectrum of such a structure by an external magnetic field.

1. Introduction

One-dimensional photonic-crystal (PC) structures and layered periodic structures made of various materials have gained much attention of researchers over the last years. Owing to periodic modulation of the refractive index, the photonic spectrum of these structures possesses the forbidden band gaps in which the incident radiation is reflected almost completely [1–4]. This property is important for various applications of PC structures, in particular, for controlling the optical radiation in laser engineering and data transmission systems. These structures functionality can be significantly extended by controlling their spectral characteristics via the variation of the geometrical or physical parameters of the structure. In particular, the photon spectrum of the structure can be modified by introducing the active magnetic layers into the structure, as a result the spectrum can be controlled by the external magnetic field [5–8]. A significant spectrum reconstruction can also be caused by a local breaking of the structures periodicity that can lead to a defective transmission miniband in the forbidden band gap [9–12]. The structure, which has a defect layer placed between two Bragg photonic crystal mirrors (Fabry–Perrot microcavity), is of special interest. This layer in such a structure plays the role of an optical microcavity, where the light wave field can be localized, thus greatly enhancing many effects of the light matter interaction [8–10]. In such a structure, this layer plays the role of the optical microcavity where the light wave field can be localized and various effects of interaction of radiation with media can be significantly increased [13–15]. An effective control over the photonic spectrum, by using the external magnetic field, is also possible in microcavity structures with a magnetic defect. The resonance response of the magnetic permeability of the defect to the high frequency field of the propagating wave in the region of magnetic resonance can substantially modify the spectral line of the defect mode to its complete suppression. In this work, we investigate the modification of reflection spectra of a magnetic-dielectric defect-free PC structure and microcavity structure with a magnetic defect in the external magnetic field in the domain of magnetic resonance, as well as the possibility of suppression of the oscillation spectrum and the defect mode of the spectra concerned.

2. Material parameters of layers

Let us consider two types of one-dimensional magnetoactive PC structures (Fig. 1). The first type is the finite defect-free periodically layered structure consisting of alternating magnetic and dielectric layers. The second structure type is a symmetrical magnetoactive microcavity, in which the magnetic layer is placed between the dielectric PC mirrors.

The structures of the first type include non-magnetic dielectric layers, which will be characterized by the thickness L_d and scalar permittivity and permeability (DP and MP) ε_d and μ_d. Layers of two different dielectrics with thicknesses $L_{1,2}$, permittivities $\varepsilon_{1,2}$ and permeabilities $\mu_{1,2}$ are used in the structures of the second type. In the structures of both types the layers of uniformly magnetized magnetic are characterized by thickness L_m and are described by the scalar DP and tensor MP in the high frequency range:

$$\hat{\mu}_m = \begin{pmatrix} \mu_0 & 0 & 0 \\ 0 & \mu & -i\mu_a \\ 0 & i\mu_a & \mu \end{pmatrix}. \quad (1)$$

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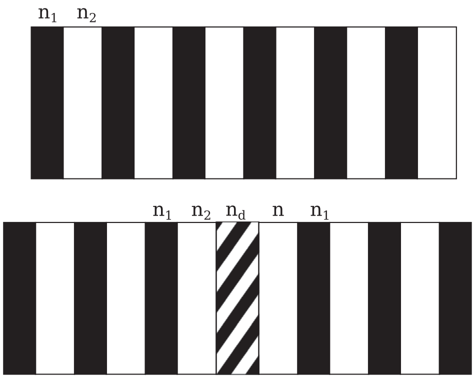

Fig. 1. Finite defect-free layer-periodic structure and magneto active symmetrical microcavity.

We assume that the external static magnetic field H_0 is oriented along the OX-axis. Tensor components $\hat{\mu}_m$ are the following: $\mu_0 \simeq 1$,

$$\mu = 1 + \frac{\omega_M(\omega_H + i\alpha\omega)}{(\omega_H + i\alpha\omega)^2 - \omega^2}, \quad \mu_a = \frac{\omega_M \omega}{(\omega_H + i\alpha\omega)^2 - \omega^2}, \tag{2}$$

where we introduce the parameters $\omega_H = \gamma H_0$, $\omega_M = 4\pi\gamma M_0$, M_0 is the saturation magnetization, γ is the gyromagnetic ratio, $\alpha = \Delta H / H_0$ is the parameter of the magnetic damping, ΔH is the resonance line width [16].

We assume that the waves propagate in the structure along its periodicity axis (the OY axis), and the field H_0 is oriented perpendicular to this axis, i.e. lies in the layers plane. The solution of the Maxwells equations, taking into account the propagation direction and the orientation of the bias field, yields two eigenmodes of the structure, the TE and TM modes. Only TE wave with the components of wave field (E_x, H_y, H_z) is controlled by an external magnetic field. TM-type wave with (H_x, E_y, E_z) components practically does not react to changes in the external magnetic field.

Solutions of wave equations for each component in j-th layer can be represented as a superposition of the forward and backward waves

$$F_{\alpha,j}(y) = F^1_{\alpha,j} \exp\,[i(\omega t - k_j y)] + F^2_{\alpha,j} \exp\,[i(\omega t + k_j y)], \tag{3}$$

where $k_j = k_0\sqrt{\varepsilon_j \mu_j}$ are the wave numbers in each of the layers, $k_0 = \omega/c$, c is the light speed in vacuum. For dielectric layers $\varepsilon_j = \varepsilon_d$, $\mu_j = \mu_d$. For the magnetic layers in the case of TM wave $\varepsilon_j = \varepsilon_m$, $\mu_j = \mu_0$, and in the case of TE wave

$$\mu_j = \mu_\perp = \mu - \frac{\mu_a^2}{\mu} = \frac{(\omega_a + i\alpha\omega)^2 - \omega^2}{\omega_r^2 - \omega^2 + i\alpha\omega(\omega_a + \omega_H)}, \tag{4}$$

where we introduce the magnetic resonance frequency $\omega_r = \sqrt{\omega_H \omega_a}$ and antiresonance frequency $\omega_a = \omega_H + \omega_M$ [16]. The frequency and field dependences of $\mu_\perp(\omega, H_0)$ determine in many ways, the characteristics of TE wave interaction with the magnetoactive PC structure.

Fig. 2 shows the dependence of the real part of the effective magnetic permeability on frequency and values of the magnetizing field. The dependence on the frequency is obtained for the field values $H_0 = (400, 600)$ Oe (curves 1 and 2), and for the frequency values $\omega = (1.5; 2.0) \times 10^{10}\ \mathrm{s}^{-1}$ (curves 1 an 2). The calculations were performed for a magnetic with the parameters $4\pi M_0 = 1780$ G, $\alpha = 0.05$. The dashed line shows the relevant curves in the absence of magnetic damping. The presence of damping leads to limitation of the effective permeability values of the magnetic material in the resonance region. It is also evident that each value of resonance frequency corresponds to its own value of the magnetizing field, and resonance value of the magnetic field corresponds to its frequency value. The increase of the field leads to a shift of the resonance line to higher frequencies, and the increase in the frequency to the region of high fields. Let us consider the frequency region $\omega_r < \omega < \omega_a$, where the real part of the effective permittivity $\mu_\perp$ is negative (here we introduced the frequency antiresonance $\omega_a = \omega_H + \omega_M$). By changing the magnetic field, these features of the functions $\mu_\perp(\omega, H_0)$ allow to provide proximity magnetic resonance frequency or region of negative effective MP to the center frequency of the photonic band gap, or to the frequency of the defect mode. This, in turn, should lead to a substantial restructuring of the photon spectrum of a magnetophotonic crystal.

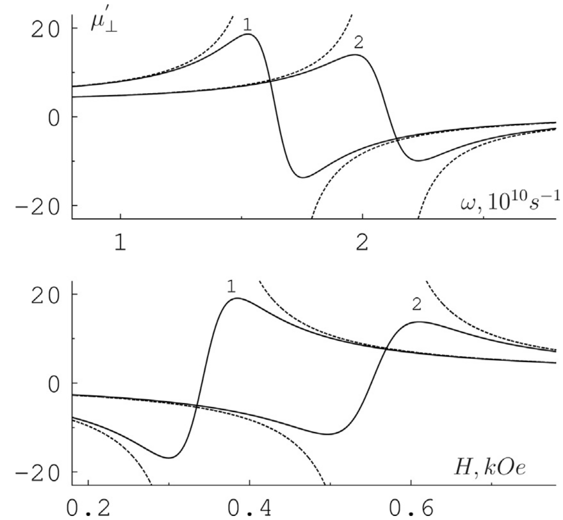

Fig. 2. Frequency dependences of the real part of the effective magnetic permeability for the values of the field $H_0 = (0.4; 0.6)$ kOe (solid curves 1 and 2) as well as the value of the magnetizing field for values of the frequencies $\omega = (1.5; 2.0) \times 10^{10}\ \mathrm{s}^{-1}$ (solid curves 1 and 2); the absence of magnetic damping (dashed curves).

3. Transfer matrices and the reflection and transmission coefficients

Using the boundary conditions for wave fields and the periodicity, we can get the connection of wave fields in planes separated by an arbitrary number of layers. In the case of defect-free periodic structure containing a finite number of periods, this relationship is a matrix $\hat{G} = (\hat{M})^n$, which is the n-th degree of the matrix of one period. In its turn, the transfer matrix of one period is the product of the transfer matrices of the layers that make up the period, i.e. $\hat{M} = \hat{N}_1 \hat{N}_2$. In this case, the transfer matrices of each layer are as follows:

$$\hat{N}_j = \begin{pmatrix} C_j & \dfrac{k_0\mu_j}{ik_j} S_j \\ -\dfrac{ik_j}{k_0\mu_j} S_j & C_j \end{pmatrix}, \tag{5}$$

where we introduced the notation $C_j = \cos(k_j L_j)$ and $S_j = \sin(k_j L_j)$. Using (5) the transfer matrix of one period has the following matrix elements:

$$M_{11} = C_1 C_2 - \frac{\mu_1 k_2}{\mu_2 k_1} S_1 S_2,$$

$$M_{12} = -\frac{k_0 \mu_2}{ik_2} C_1 S_2 - \frac{k_0 \mu_1}{ik_1} S_1 C_2,$$

$$M_{21} = \frac{ik_2}{k_0 \mu_2} C_1 S_2 + \frac{ik_1}{k_0 \mu_1} S_1 C_2,$$