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Enhancement of Faraday rotation at photonic-band-gap edge in garnet-based magnetophotonic crystals

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Abstract

Spectral dependences of Faraday rotation angle in one-dimensional garnet-based magnetophotonic crystals are considered. The enhancement of Faraday angle is demonstrated at the photonic band gap (PBG) edge both theoretically and experimentally. It is shown to be associated with the optical field localization in the magnetic layers of the structure. The advantages of magnetophotonic crystals in comparison with traditional magnetic microcavities are discussed. The specially designed microcavity structures optimized for the Faraday effect enhancement at the PBG edge are suggested.

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Keywords: Photonic crystals; Magneto-optics; Faraday effect enhancement; Magnetic garnets

1. Introduction

Photonic crystals have been attracting much of attention recently due to the opportunity of development of various compact optical devices they provide. Photonic crystals give an effective way to control the propagation of light utilizing effect of the photonic band gap (PBG) resulted in prohibition of light propagation with a certain wavelength through a photonic crystal [1]. One of the most intriguing applications of PBG materials is the development of magnetophotonic crystals (MPC), i.e. photonic crystals, formed from magnetic materials. MPC open up prospects for new photonic devices utilizing magneto-optical effects [2]. The drastic enhancement of Faraday effect is expected in multilayered structures in the course of multiple reflection interference due to nonreciprocal character of Faraday effect. Optical field amplitude is a quantitative attribute of multiple reflection interference, in these terms optical field localization indicates constructive interference leading to the Faraday effect enhancement.

The enhancement of the Faraday effect was first observed in magnetic microcavities (MMC), that are multilayered structures consisting of two dielectric photonic crystals and one magnetic $\lambda/2$- or λ-thick layer between them with λ denoting the wavelength corresponding to the microcavity mode at the normal incidence [3–5]. The enhancement of Faraday rotation at the microcavity mode in such structures is obtained due to high Q-factor leading to the strong field localization in the cavity spacer. However, the further increase of Faraday angle is limited by accuracy of magnetic spacer thickness control, restricted by fabrication procedure.

In this paper, MPC consisting of alternating $\lambda/4$-thick magnetic and nonmagnetic dielectric layers are considered. MPC possess many magnetic layers and provide field localization in each of them. The enhancement of Faraday effect at the wavelength corresponding to the PBG edge is shown to be obtained by combination of constructive multiple interference and the increase of magnetic material thickness. Specially designed $3\lambda/4$-MMC structures optimized for the Faraday effect enhancement at the PBG edge

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are also considered. A $3\lambda/4$-thick microcavity spacer almost degenerates the microcavity mode into the PBG edge. It leads to additional field localization in all magnetic layers in comparison with MPC and consequently to the stronger Faraday effect.

The PBG structures based on bismuth-substituted yttrium–iron–garnet (Bi:YIG) are considered because Bi:YIG turns out to be one of the most attractive materials for practical applications due to low absorption in red and infrared regions, large magneto-optical response and small saturation magnetic fields [8].

2. Numerical results

2.1. Method

The four-by-four matrix technique is utilized for Faraday effect calculation. The optical field inside each layer is given as a sum of four normal modes: right and left circular polarized waves propagating in both directions along the MPC normal. Then a set of four-by-four matrices is calculated: each matrix corresponds to each layer of the structure and determines the values of optical field on the layer boundaries. Multiplying all the matrices one can obtain the matrix characterizing reflectance and transmittance of the whole structure. Among the reflectance and transmittance, Faraday angle and spatial optical field distribution in the structure are calculated. The details of the method can be found in Ref. [6].

2.2. Faraday effect and transmittance spectra

The MPC considered consist of 10.5 pairs of alternating $\lambda/4$-thick magnetic Bi:YIG and nonmagnetic SiO_2 layers. The refractive indices are supposed to be $n_{\mathrm{Bi:YIG}} = 2.6$ and $n_{\mathrm{SiO_2}} = 1.45$. The gyration vector is assumed to be $g_{\mathrm{Bi:YIG}} = 0.0054$ which is close to experimental values [8]. Optical thickness of the central Bi:YIG layer, Λ, is varied from $\lambda/4$ to $3\lambda/4$. The $\lambda/4$-thick central layer corresponds to the common Bragg reflector. The $\lambda/2$-thick cavity spacer corresponds to the MMC with microcavity mode at wavelength λ coinciding with PBG center. For $\Lambda = 3\lambda/4$, microcavity mode is almost degenerated into the long-wavelength PBG edge, such structure is called here and after $3\lambda/4$-MMC. The transmittance (a) and Faraday angle (b) spectral dependences as functions of the central magnetic layer are shown in Fig. 1 in the patterned plot. Right plots in Fig. 1 represent optical (a) and magneto-optical (b) spectra for $\lambda/4$-MPC and $3\lambda/4$-MMC with $\lambda \simeq 1000$ nm, labeled as MPC and MMC, respectively.

White areas in the patterned plot in Fig. 1a correspond to the maxima of transmittance. Black area in the patterned plot in Fig. 1a from 800 to 1200 nm corresponds to the PBG, white curve across PBG shows the thickness dependence of the microcavity mode, white areas at the PBG edges reveal the transmittance maxima. White area in the patterned plot in Fig. 1b shows a strong suppression of Faraday effect at the wavelengths corresponding to the PBG. Faraday angle Θ_F is enhanced drastically at the

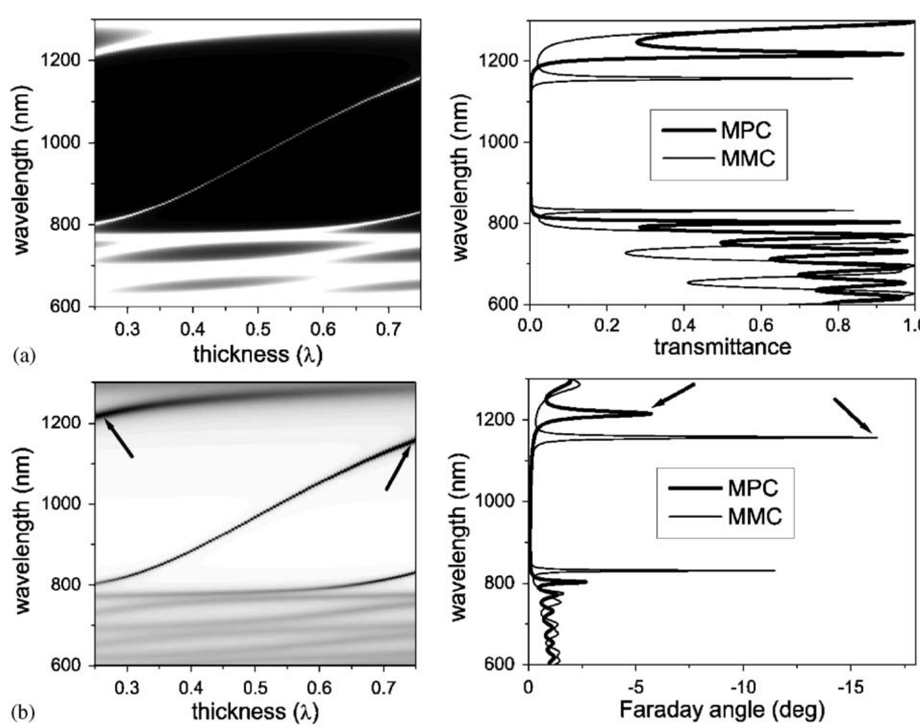

Fig. 1. Set of optical (a) and magneto-optical (b) spectra vs thickness of the cavity spacer. Transmittance and Faraday angle are shown by grey scale on the patterned plot. Right plots show optical (a) and magneto-optical (b) spectra for $\lambda/4$-MPC and $3\lambda/4$-MMC structures.

microcavity mode. For $\Lambda = \lambda/4$ and $\Lambda = 3\lambda/4$, Θ_F is enhanced at the PBG edges, especially at the long wavelength one at 1200 and 1150 nm, respectively. It is indicated by black arrows.

The Θ_F enhancement in the $3\lambda/4$-MMC is nearly 3 times higher than the same in the MPC and reaches the values up to -16° at the wavelength of 1150 nm corresponding to the long-wavelength PBG-edge. Faraday angle maxima are correlated in spectrum with transmittance maxima. The calculations show the absence of the ellipticity of transmitted light polarization at the maximum of Θ_F. It means that MPC and $3\lambda/4$-MMC give an opportunity to rotate efficiently the polarization plane without distortion and weakening the transmitted light.

2.3. Optical field distribution

The enhancement of Faraday effect in multilayered structures is obtained due to constructive multiple reflection interference which can be quantitatively characterized by spatial optical field distribution. Spectral dependences of spatial optical field distribution in the sample for the $\lambda/4$-MPC (a) and the $3\lambda/4$-MMC (b) are given in Fig. 2. In the case of the $\lambda/4$-MPC, the field is localized in all magnetic layers at the long-wavelength PBG edge at approximately 1200 nm and the field amplitude in the central layer is 2.7 times higher than that of the incident light. The $3\lambda/4$-MMC provides the better field localization in all magnetic layers in comparison with the $\lambda/4$-MPC, the field amplitude in the microcavity spacer at the wavelength of 1150 nm is almost 2 times higher than that in the $\lambda/4$-MPC sample. The field localization in magnetic layers indicates the constructive interference resulted in the Faraday effect enhancement and vividly explains the Θ_F enhancement at the PBG edge of $\lambda/4$-MPC and $3\lambda/4$-MMC.

The increase of number of layers in MPC leads to the enhancement of Faraday rotation at the PBG edge by the combined effect of field localization and the increase of magnetic material thickness. The enhancement up to $\Theta_F = 45^\circ$ is expected in $3\lambda/4$-MMC consisting of about 20 pairs of layers.

3. Experiment

MPC are fabricated from alternating $\lambda/4$-thick magnetic Bi:YIG, $Bi_{1.0}Y_{2.0}Fe_5O_x$, and nonmagnetic SiO_2 layers with thicknesses of $d_M \simeq 93$ nm and $d_N \simeq 143$ nm, respectively. Studied MPC samples have $\lambda \simeq 900$ nm. MPC are grown by RF sputtering of corresponding targets on a fused quartz substrate and high-temperature annealing of each successive Bi:YIG layer [7].

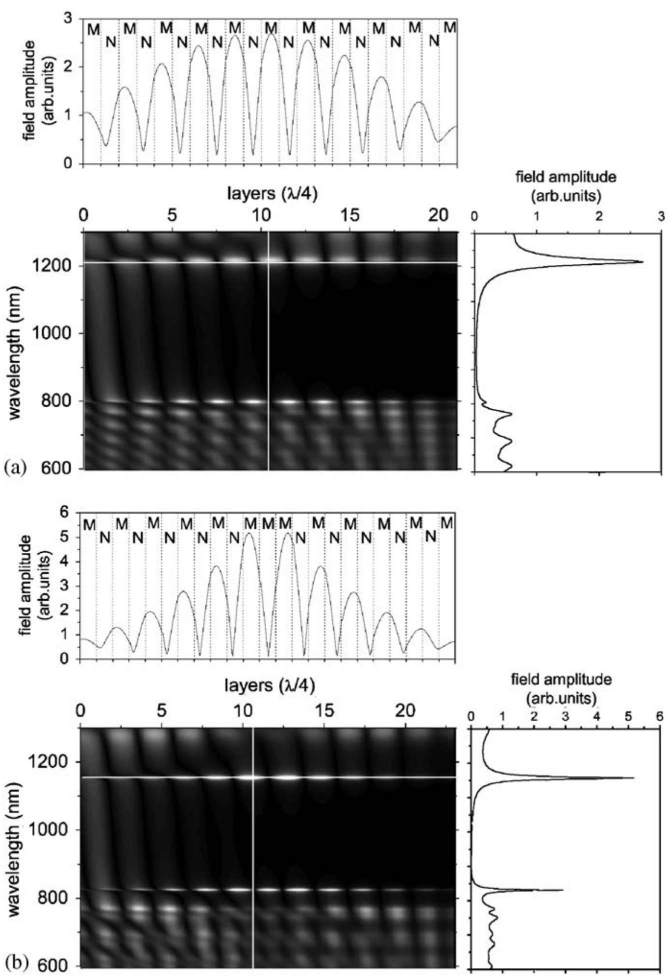

Fig. 2. Spectral dependence of spatial optical field distribution in $\lambda/4$-MPC (a) and $3\lambda/4$-MMC (b). Field amplitude is shown by grey scale on the patterned plot. White color corresponds to the maxima of the field amplitude. Upper and right plots at each panel represent spatial field distribution at the PBG edge and its spectrum in the central layer taken at cross sections marked by white lines. Magnetic layers are labeled as M and nonmagnetic as N.

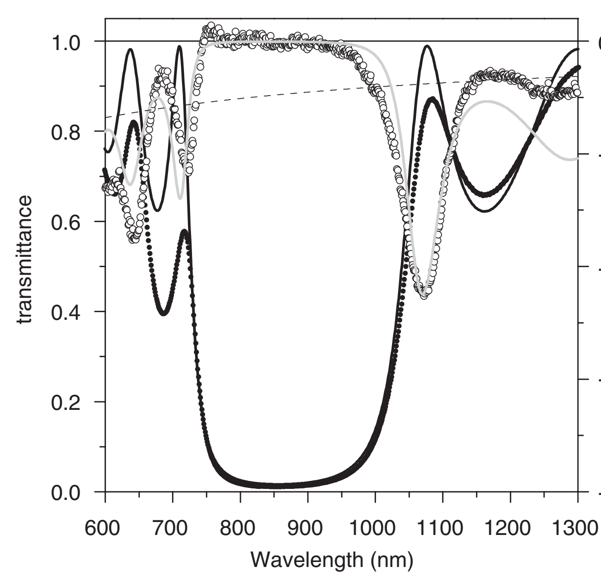

Fig. 3. Optical (filled circles) and magneto-optical (open circles) spectra of MPC measured at the normal incidence and their 4×4 matrix technique approximations, black and grey lines, respectively. Dashed line shows magneto-optical spectrum in the case of single Bi:YIG layer with the same thickness of the magnetic material.

Optical and magneto-optical spectra are shown in Fig. 3. Faraday effect is suppressed in PBG and enhanced at the PBG edges. The largest Θ_F enhancement is achieved at the long-wavelength PBG edge at 1060 nm, where it reaches 1.2°, which is 6.5 times higher in comparison with single Bi:YIG layer with the thickness equal to the total thickness of the magnetic material in MPC. Experimental results are in good agreement with theoretical calculations.

4. Conclusion

A new approach of Faraday effect enhancement in one-dimensional magnetic PBG structures utilizing the spatial localization of light with wavelength corresponding to the PBG edge is suggested. In this case optical field is localized in all magnetic layers and the Faraday angle is enhanced by combined effect of the field localization and the magnetic material thickness increase, that is an advantage of suggested structures in comparison with traditional MMC with the single magnetic layer.

The MMC with $3\lambda/4$-thick magnetic spacer is suggested as an optimal structure for the Faraday effect enhancement at the PBG edge. The better optical field localization in comparison with MPC at the wavelength corresponding to the microcavity mode degenerated into the long-wavelength PBG edge results in 3 times higher Faraday angle. Maximum values of the effect in Bi:YIG samples normalized on the total sample thickness reach $2.4^\circ/\mu m$ for MPC consisting of 21 layers and $5.7^\circ/\mu m$ for $3\lambda/4$-MMC with the same number of layers. The maximum values of Faraday angles reach -6° and -16°, respectively.

The results of theoretical predictions are proved experimentally in garnet-based MPC. The results of numerical calculations performed using the four-by-four matrix technique are in good agreement with experimental data.

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