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Journal of Magnetism and Magnetic Materials 282 (2004) 256–259
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Enhanced Faraday and nonlinear magneto-optical Kerr effects in magnetophotonic crystals

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Available online 4 May 2004

Abstract

The fabrication of magnetophotonic crystals (MPC) composed from Bi-substituted yttrium-iron-garnet films separated by silicon oxide layers is presented. The enhancements of the Faraday rotation, second-harmonic generation and nonlinear magneto-optical Kerr effect are observed at the photonic band gap edge. These demonstrate strong light-matter magnetic coupling in MPC and provide the prospects of the new magneto-optical materials for applications.

PACS: 78.20.Ls; 42.70.Qs; 42.65. – k

Keywords: Photonic crystals; Magneto-optics; Nonlinear optics; Second-harmonic generation; Magnetic garnets

1. Introduction

Photonic crystals are dielectric microstructures with periodic modulation of refractive index in one or several directions with a period comparable with optical wavelength. The key feature of photonic crystals is the photonic band gap (PBG) representing the prohibition of the light propagation with the certain wave vectors inside photonic crystals [1]. PBG manifests itself in reflection and transmittance spectra as the spectral region with full reflection and strongly suppressed transmittance. Many spectacular effects associated with the specific light propagation are observed in photonic crystals. These include spatial localization of light and anomalous dispersion properties at the PBG edge [2], enhanced second [3] and third-harmonic [4] generation and bistability [5]. One of the important issues regarding the application of PBG materials is the development of magnetophotonic crystals (MPC), that are photonic crystals formed from magnetic materials. MPC open up prospects for new spintronic devices utilizing magneto-optical effects. For example, the enhancement of linear (Faraday) [6] and nonlinear-optical effects [7,8] is observed in one-dimensional MPC with magnetic defect layer and nonmagnetic Bragg reflectors. One of the difficulties of fabrication of magnetic Bragg reflectors is the magnetic film thickness control critical for the Bragg reflector quality. Another problem is the

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0304-8853/$ - see front matter
doi:10.1016/j.jmmm.2004.04.058

magnetic material transparency essential for the PBG formation. Bi-substituted yttrium-iron-garnet (Bi:YIG) is very convenient material for the MPC fabrication [9] due to low absorption in red and infrared regions, large magneto-optical response and small saturation magnetic fields. In this paper, the fabrication of magnetophotonic crystals formed from Bi-substituted yttrium-iron-garnet layers is reported. Enhancement of the nonlinear magneto-optical Kerr effect (NOMOKE) in second-harmonic generation (SHG) accompanied by the Faraday rotation enhancement is studied.

2. Experimental

The MPC are fabricated from four repeats of $3\lambda_{MC}/4$-thick layers of Bi-substituted yttrium-iron-garnet, $Bi_{1.0}Y_{2.5}Fe_5O_x$, and $\lambda_{MC}/4$-thick SiO_2 layers, where λ_{MC} denotes the PBG center at the normal incidence. Studied samples of MPC have $\lambda_{MC} \simeq 950$ nm. The MPC are grown by the RF sputtering of corresponding targets in Ar^+ atmosphere on a fused quartz substrate. After evaporation of each successive Bi:YIG layer, the sample is removed from the sputtering chamber and annealed in air at 700°C for 20 min for residual oxidation and crystallization of the Bi:YIG films. Fig. 1 shows the characteristic hysteresis loops measured for the tangential and normal application of magnetic field. Coercivity of MPC is approximately 30 Oe for both configurations. Saturating magnetic field is slightly above 100 Oe for the tangential field application and close to 2 kOe for the normal field configuration. This indicates the easy-magnetization axis aligned in the plane of the MPC as it is expected for thin ferromagnetic films.

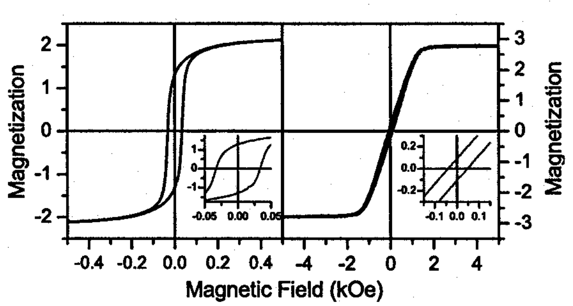

Fig. 1. Hysteresis loops measured by vibrating sample magnetometer in the tangential and normal application of magnetic field, left and right panels, respectively. Insets show the central parts of loops.

The linearity polarized output of a tunable optical parametric generator with wavelength from 730 to 1150 nm is used for NOMOKE studies. The pulse duration is 2 ns and energy is below 5 mJ/pulse. The fundamental radiation is directed on MPC at the 28°-angle of incidence. The second-harmonic (SH) radiation reflected from the MPC is selected by a series of glass filters and detected by a photomultiplier tube and a boxcar. Saturating DC-magnetic field is applied to MPC using a permanent FeNdB magnet.

3. Results and discussion

Transmittance spectrum of MPC is shown in Fig. 2. Spectral region from 850 to 1100 nm with a small transmittance indicates the photonic band gap with the smallest transmittance value of 0.12 reached at 965 nm. Outside the PBG, the spectrum represents interference fringes, where transmittance is increased up to 0.9. Transmittance becomes smaller at shorter wavelengths and tends to zero at approximately 550 nm that correlates with the edge of the Bi:YIG absorption band. The spectrum of the Faraday rotation angle is also

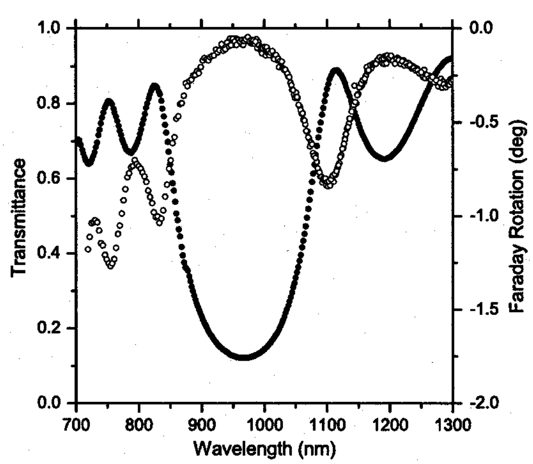

Fig. 2. Optical (filled circles) and magneto-optical (open circles) spectra of MPC at the normal incidence.

shown in Fig. 2. The Faraday rotation angle is strongly suppressed in the PBG and increased at the long-wavelength PBG edge at 1100 nm, where it is enhanced up to $-0.8°$. It corresponds to an effective value of $-0.75° \mu m^{-1}$ that is approximately 8 times larger than the Faraday rotation angle for the single Bi:YIG film of the same composition at this wavelength. Peaks observed at 750 and 830 nm correlate with the transmittance maxima and ride on the monotonous increase of the Faraday angle with the wavelength decrease that is associated with the Faraday rotation spectrum of the Bi:YIG film.

In magnetic materials with broken inversion symmetry quadratic polarization $\mathbf{P}^{(2)}_{2\omega}$ oscillating with the doubled frequency of the fundamental radiation $\mathbf{E}_\omega$ can be written in the electric-dipole approximation as the sum of two terms, $\mathbf{P}^{(2)}_{2\omega} = \chi^{(2,0)} : \mathbf{E}_\omega \mathbf{E}_\omega + \chi^{(2,1)} \vdots \mathbf{E}_\omega \mathbf{E}_\omega \mathbf{M}_0$. The first term is independent on the magnetization vector $\mathbf{M}_0$ and describes the nonmagnetic crystallographic SHG contribution governed by the tensor $\chi^{(2,0)}$. The second component is linear in magnetization and governed by the pseudotensor $\chi^{(2,1)}$. Due to the symmetry properties of magnetic garnet films isotropic in its plane, magnetization-induced SHG component is equal to zero for the p-in,p-out polarization combination and the longitudinal configuration of the DC-magnetic field application [10]. Fig. 3 shows the SH intensity spectrum measured in the longitudinal NOMOKE configuration. The spectrum demonstrates the resonant enhancement at the fundamental wavelength of 1055 nm. The spectral position of the SHG peak correlates with the long-wavelength PBG edge, which is blue-shifted in comparison with the PBG edge at the normal incidence due to oblique angles of incidence. The enhancement of the SH intensity is interpreted as a result of the phase matching at the PBG edge. The phase-matching conditions, which are essentially for the efficient SHG, can be fulfilled at the PBG edge due to the anomalous small optical dispersion. This leads to the increase of the SHG gain. Another reason of the observed enhancement is the spatial localization of the fundamental radiation inside MPC as the wavelength is tuned across the PBG edge. Nonlinear dependence of the SH field on the fundamental radiation amplitude leads to an additional enhancement of the SHG response. In the case of the transversal NOMOKE configuration, the nonmagnetic SH field interferes with the magnetization-induced SH field [10]. Depending on the relative phase between these SHG components, additional enhancement of the SH intensity can be observed for one of the directions of the magnetic field. Fig. 3 shows by circles the SHG spectrum measured in the transversal NOMOKE configuration. The SH intensity is enhanced by a factor of four in comparison with the longitudinal configuration and peaked in the vicinity of 1050 nm corresponding to the SHG phase matching at the long-wavelength PBG edge of MPC for both nonmagnetic and magnetization-induced SHG components.

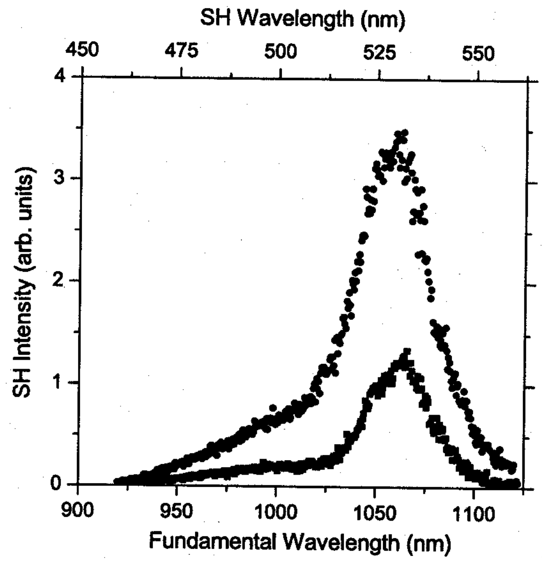

Fig. 3. SH intensity spectra of the longitudinal and transversal magneto-optical Kerr effect, squares and circles, respectively, measured in the p-in, p-out polarization combination.

4. Conclusions

In conclusion, the Faraday rotation angle and intensity of magnetization-induced second-harmonic generation reveal enhancement by a factor of approximately 10 and 10^2, respectively, if the fundamental radiation is tuned across the photonic band gap edge of 1D magnetophotonic crystals consisted of a stack of magnetic garnet layers. The enhancement is a manifestation of multiple interference in MPC and the SHG phase matching fulfilled at the PBG edge of MPC.

The work is supported by the Grant-In-Aid from the Ministry of Education, Science, Culture and Sport of Japan (Nos. 14205045 and 14655119) and the Russian Foundation for Basic Research.

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