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Magneto-Optical Effect of One-Dimentional Magnetophotonic Crystal Utilizing the Second Photonic Band Gap

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We fabricated new one-dimensional magnetophotonic crystal (1D-MPC) utilizing the second and third photonic band gaps where localized modes existed. Structure of the 1D-MPC was $(Ta_2O_5/SiO_2)^5$/Bi:YIG/$(SiO_2/Ta_2O_5)^5$ with optical thicknesses of $3\lambda/4$ for Ta_2O_5 and SiO_2 dielectric layers and $\lambda/2$ for Bi:YIG defect layer, where λ is a wavelength of a localized mode in the second photonic band gap. Faraday rotation at the localized mode in the second photonic band gap was enhanced, which was confirmed by calculation using 4×4 matrix method.

Key words : magnetophotonic crystal, MPC, second photonic band gap, Bi:YIG, Faraday rotation

1. Introduction

In recent years, one-dimensional magnetophotonic crystals (1D-MPCs) have attracted much attention due to their unique properties, such as control of propagation of light by applying magnetic field, enhancement of Faraday rotation and high transmittance at a localized mode in the photonic band gap (PBG) [1]. The 1D-MPCs consist of a transparent magnetic film as a defect layer and periodic dielectric films as Bragg mirrors. Linear and nonlinear magneto-optical (MO) properties of the1D-MPCs were investigated for the first PBG [2-5]. However, up to date, high order PBGs of the 1D-MPCs have not been discussed yet.

In this article, we investigated the second and the third PBGs of the 1D-MPC to clarify their optical and magneto-optical properties. In the 1D-MPC, high order PBGs appear in shorter wavelength distance than one between the first and the second PBGs. Adjacent multiple PBGs of the 1D-MPC will be used for applicative devices, such as a photonic band pass filter and so on. Goal of our study is to obtain not only the 1D-MPC but also two- and three-dimensional (2D- and 3D-) MPCs. Idea of utilizing high order MPC may be one of solutions for difficulty of fabrication of 2D- and 3D-MPCs using magneto-optical material like magnetic garnet.

2. Experimental

Structure of the 1D-MPC is $(Ta_2O_5/SiO_2)^5$/Bi:YIG/$(SiO_2/Ta_2O_5)^5$ formed on a fused quartz substrate as shown in Fig. 1. Wavelength λ at a localized mode in the second PBG was designed to be 900 nm. Optical length of Ta_2O_5 and SiO_2 was $3\lambda/4$; that of Bi:YIG was $\lambda/2$. Since refractive index n_{Ta2O5} is 2.05, thickness d_{Ta2O5} is 329 nm; n_{SiO2}=1.45, d_{SiO2}=466 nm; $n_{Bi:YIG}$=2.36, $d_{Bi:YIG}$=191 nm.

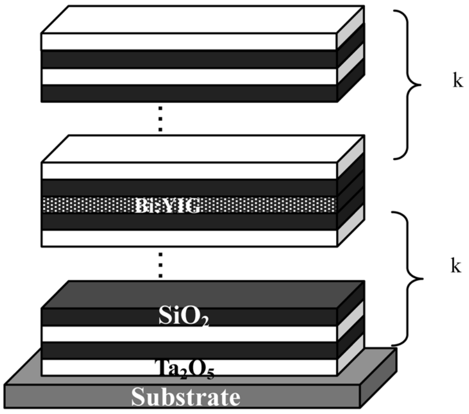

Fig. 1. Structure of 1D-MPC.

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Table 1. Conditions of deposition by RF magnetron sputtering method

	Ta_2O_5	SiO_2	Bi:YIG
Sputtering gas	Ar: 8 ccm O_2: 2 ccm		Ar 6.3 ccm
Pressure	10 mTorr		3 mTorr
Substrate temperature	100 degrees		rees
Sputtering power	150 W	100 W	100 W

First, five pairs of the dielectric layers of Ta_2O_5 and SiO_2, the first Bragg reflector, were deposited on the fused quartz substrate by using RF magnetron sputtering method, whose fabrication conditions of films are shown in Table 1. On the dielectric layers, a Bi:YIG defect layer was also deposited by RF magnetron sputtering method; it was heated in air at 700 °C for 15 minutes for crystallization of the magnetic garnet. Five pairs of dielectric films, the second Bragg reflector, were subsequently deposited. Finally, the 1D-MPC utilizing the second PBG around 900 nm was fabricated.

A field-emission scanning electron microscope (FE-SEM, JSM-6700F, JEOL) was used for observation of the fabricated 1D-MPC. Transmissivity of the 1D-MPC was measured by an ultraviolet-visible-infrared spectrophotometer (UV-3150, Shimadzu). Magnetic properties were measured by a vibration sample magnetometer (VSM, TM-VSM261483HGC, Tamagawa). A homemade magneto-optical measurement system was used for measurements of Faraday rotation angles.

3. Calculation Method

To simulate optical and magneto-optical properties we used 4×4 matrix method of Ref. [1]. This method is generalization of the transfer matrix method [2] on multilayered structures where at least one of the layers represents magneto-optical material. Following Ref. [1], we introduce transfer matrix $\hat{\Phi}_n$, which matches amplitudes of electric and magnetic fields of the EM wave at the boundaries of the n-th layer:

$$\begin{bmatrix} E_x \\ E_y \\ H_x \\ H_y \end{bmatrix}^n = \hat{\Phi}_n \begin{bmatrix} E_x \\ E_y \\ H_x \\ H_y \end{bmatrix}^{n-1} \qquad (1)$$

where E_x (E_y) and H_x (H_y) are amplitudes of the x-(y-) projection of electric and magnetic fields, respectively, and EM wave propagates along z-direction, which coincides with the axis of the layered structure.

In the calculation, structure contains the pair of identical Bragg reflectors of Ta_2O_5 and SiO_2 layers and one defect layer of Bi:YIG. The total transfer matrix for the 1D-MPC, which relates amplitudes at the last boundary of the last layer to amplitudes at the first boundary of the first layer, and therefore completely describes optical and magneto-optical properties of the structure, can be written in the following form:

$$\hat{\Phi} = (\hat{\Phi}^{Ta_2O_5} \hat{\Phi}^{SiO_2})^N \hat{\Phi}^{Bi:YIG} (\hat{\Phi}^{SiO_2} \hat{\Phi}^{Ta_2O_5})^N \qquad (2)$$

where N is the repetition number of the Ta_2O_5-SiO_2 pairs. When amplitudes of the fields are determined from equations (1) and (2), the well-known equation for the Faraday rotation angle can be used as

$$\theta_F = \frac{1}{2}\arctan\left(\frac{2\,\mathrm{Re}(\chi)}{1-|\chi|^2}\right) \qquad (3)$$

where χ is the ratio of the y and x components of the electric or magnetic field at the fixed polarization of the incident wave.

4. Results and Discussion

Fig. 2 shows a cross-section SEM image of the fabricated 1D-MPC having a localized mode inside the second PBG around 900 nm. Film thicknesses measured by FE-SEM were 307 nm for Ta_2O_5 and 454 nm for SiO_2 on averages, and 260 nm for Bi:YIG. Because our RF magnetron sputtering system does not have monitoring system of film thickness during deposition, each film thickness of the 1D-MPC is not exactly equal to designed one. In the fabricated 1D-MPC, the saturation magnetization was about 1.3 kG as shown in Fig. 3; the saturation magnetic

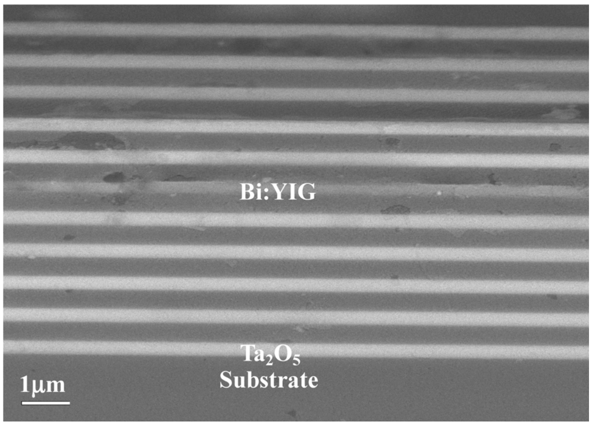

Fig. 2. Cross-section SEM image of the 1D-MPC having a localized mode in the second PBG around 900 nm.

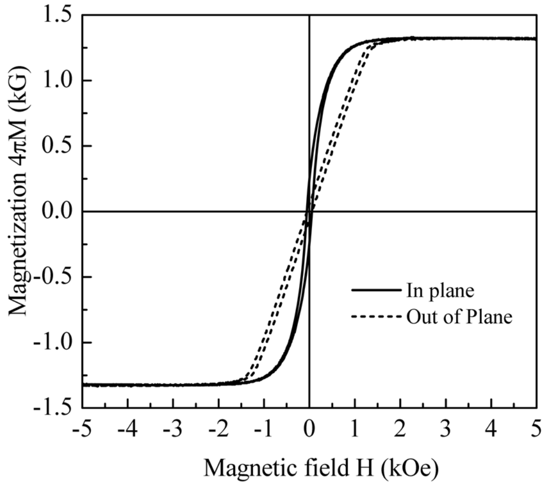

Fig. 3. Magnetization of the 1D-MPC.

field for out-of-plane was 1.5 kOe, which corresponds to Faraday configuration.

Fig. 4 shows transmittance spectrum of the fabricated 1D-MPC having high order PBGs, which there are the first PBG in wavelength from 2200 to 2900 nm, the second PBG from 820 to 930 nm, the third PBG around 550 nm and the localized mode at 894 nm in the second PBG. Since film thicknesses in the 1D-MPC were different from the designed thicknesses as described before, wavelength of the localized mode in the second PBG was shifted from 900 nm to 894 nm, and the center of the second PBG was also shifted from 900 nm to 860 nm. Furthermore, as seen in Fig. 4, the narrow third PBG appeared around 550 nm. However, the transmittance near the edge of the third PBG around 400 nm decreased drastically. This is the reason that the light was absorbed in the Bi:YIG defect layer of the 1D-MPC below 600 nm, which can be understand by transmittance of single B:YIG film as shown in Fig. 5(a).

The Bi:YIG is well known to be a magnetic material with high transparency (Fig. 5(a)); maximum Faraday

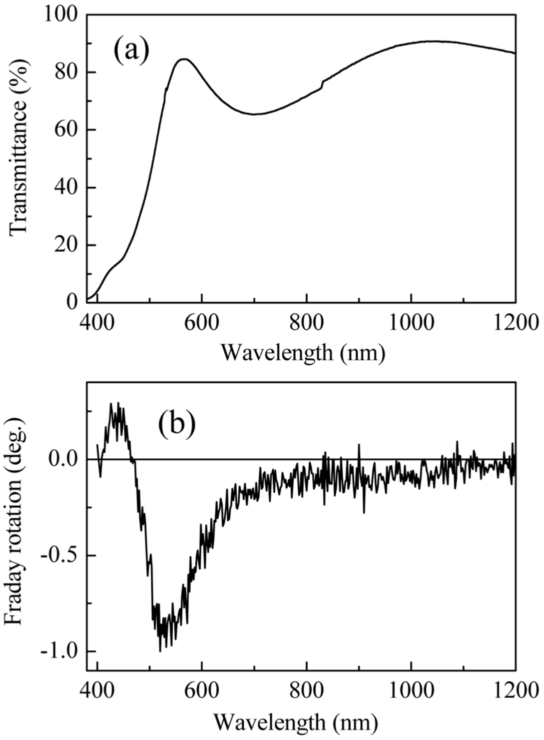

Fig. 5. (a) Transmittance and (b) Faraday rotation spectra of single Bi:YIG thin film with thickness of 250 nm.

rotation occurs in the vicinity of 520 nm (Fig. 5(b)). Using the Bi:YIG as the defect layer of the 1D-MPC, enhancement of the Faraday rotation was obtained at the localized mode in the first PBG [1-3]. In this measurement of Faraday rotation of the 1D-MPC, magnetic field of 3 kOe was applied, which is larger than the saturation magnetic filed of 1.5 kOe (Fig. 3). Fig. 6 shows experimental and calculated spectra of (a) transmittance and (b) Faraday rotation of the 1D-MPC including the second PBG and the third PBG; the calculated spectra were obtained by using film thickness measured by FE-SEM. As seen in Fig. 6, at the localized mode of 900 nm in the second PBG, transmittance of 57% was obtained (Fig.

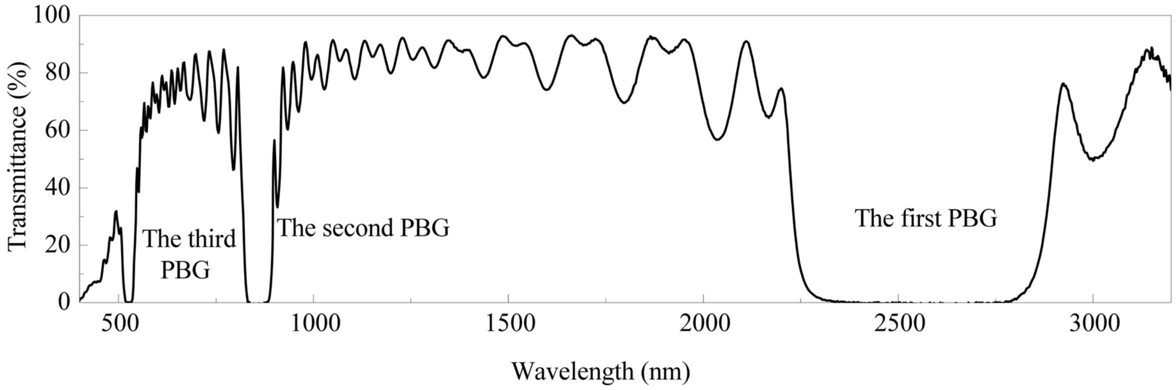

Fig. 4. Transmittance spectrum of the fabricated 1D-MPC having higher order PBGs. Three PBGs exist in the wavelength region.

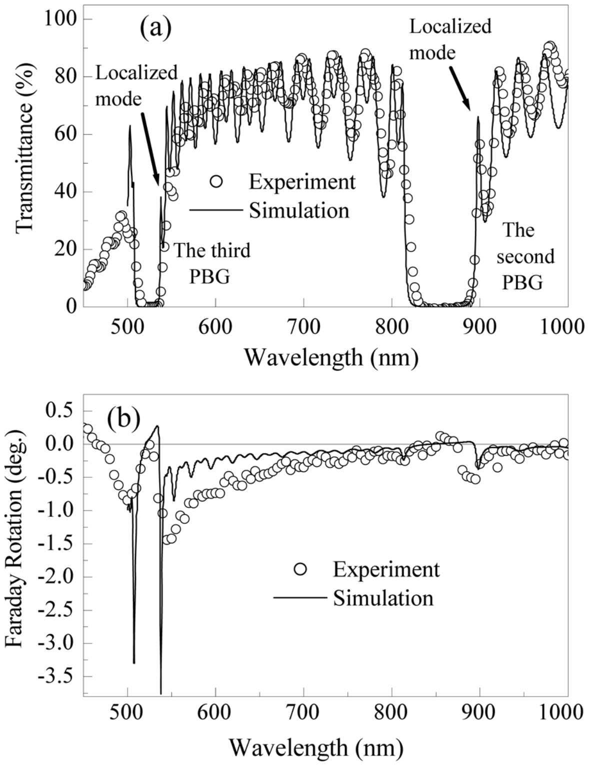

Fig. 6. Magnified spectra for (a) transmittance and (b) Faraday rotation of the 1D-MPC around the second and the third PBGs. Experimental data is denoted by open circle and calculated data is denoted by solid line.

6(a)), and enhancement of Faraday rotation angle of –0.5 degree was observed (Fig. 6(b)). In addition, at a localized mode in the third PBG vicinity of 540 nm, transmittance of about 30% and Faraday rotation angle of –1.5 degree were obtained. These angles are larger than the Faraday rotation of –0.2 degree (900 nm) and –0.8 degree (540 nm) for the single Bi:YIG film. Faraday rotation could be enhanced by increment of effective optical thickness of Bi:YIG, which was induced by reflection effect of light in periodic structure of the 1D-MPC. Feature of experimental spectra of transmittance and Faraday rotation (indicated by open circles) as shown in Fig. 6 is in good agreement with calculated spectra (indicated by solid lines). However, Faraday rotation angles in experiment and calculation were not so large as we expected before. It can be caused by shift of localized mode from center of the second PBG, therefore, accurate periodic structure is of importance for large Faraday rotation in the 1D-MPC

Faraday rotation angle of the 1D-MPC utilizing the second PBG was not so large in comparison with the 1D-MPC utilizing the first PBG as described in ref. [1-3]. In the 1D-MPC having the localized mode at 900 nm in the second PBG, thickness of Bi:YIG defect layer is same to one of the 1D-MPC having the localized mode of the first PBG at 900 nm, however, thickness of dielectric layers of $3\lambda/4$ for the second PBG-MPC is thicker than one of $\lambda/4$ for the first PBG-MPC. Because extinction coefficient of Ta_2O_5 is not small as described in ref [2], absorption of light is large in the second PBG-MPC with thick Ta_2O_5 layers. Therefore, reflection effect and light localization in the Bi:YIG defect layer of the second PBG-MPC would be smaller than one of the first PBG-MPC. If we use a dielectric material with small extinction coefficient, large Faraday rotation might be obtained at the localized mode in the second PGB. Otherwise, thin Ta_2O_5 layers in periodic structure may be effective. This consideration can be generally applied to the MPC with Bragg refractors and defect layer.

5. Conclusion

We investigated the 1D-MPC utilizing high order photonic band gap. The localized modes appeared in the second and the third PBGs; enhancement of the Faraday rotation was observed at each localized mode. Optical and magneto-optical properties of their PBGs were simulated, which were in good agreement with experimentally obtained spectra. Comparing with the single Bi:YIG film, enhancement of Faraday rotation at the localized modes was observed. The guideline for obtaining larger Faraday rotation in the magnetophotonic crystals was examined.

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