Behavior of Large Faraday Rotation in Magnetophotonic Crystals with Single-Cavity Structures

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We fabricated one-dimensional magnetophotonic crystals (1-D MPCs, hereafter) with single-cavity structures of (Ta2O5/SiO2)k/Bi:YIG/(SiO2/Ta2O5)k (k=2, 6). Their fundamental optical and magneto-optical fundamental properties were investigated in detail. We obtained experimental results that were in good agreement with the theoretical predictions: the Faraday rotation angle of the medium was more than 100 times larger than that of a Bi:YIG single-layer film. In addition, we performed numerical calculations by taking the optical dissipation effect into account, and the experimental results were examined. The optical dissipation was found to be a key parameter in determining the performance of 1-D MPCs.

Key words: magnetophotonic crystal, magneto-optical, Faraday rotation

1. Introduction

1-D MPCs using magnetic garnet thin film show high transmittance and large Faraday rotation 1)-5). These unique properties arise from the localization effect of light as a result of the multiple interference of light within the magnetic layer. Application of these properties to various magneto-optical devices (eg optical isolators and circulators) is expected. On the other hand, the Faraday rotation angle of magnetic garnet material itself is small at light wavelengths more than 1 µm, i.e. the region of wavelength used for optical communication. Therefore, for application to an optical isolator, bulk-like garnet that reaches several 100 µm is required. This is undesirable for miniaturization of a device 2). However, it is thought that MPCs could be used effectively in this respect. Consequently, we fabricated 1-D MPCs to study their basic characteristics.

In this article, the optical and magneto-optical properties of 1-D MPCs were investigated both experimentally and theoretically.

2. Experimental

We fabricated a 1-D MPC of fabricated a 1-D MPC of (Ta2O5/SiO2)k/Bi:YIG/(SiO2/Ta2O5)k/Glass, where k is the repetition number. (Fig. 1) These films were deposited on corning 1737 (30 mm × 0.8 mm) or BK7 (30 mm × 1.5 mm). The magnetic layer (Bi:YIG film) of the 1-D MPC was formed by using an RF magnetron sputtering apparatus. The dielectric layers were formed by using an ND-controlled EB evaporation apparatus. The Bi:YIG and dielectric films were deposited under the preparation conditions shown in Tables 1 and 2. The design wavelength was 720 nm. Optical and magneto-optical properties of the prepared 1-D MPCs were calculated theoretically by solving Maxwell’s equations with the biaxotropic dielectric tensor for the magnetic layers under the electromagnetic boundary conditions imposed at all discontinuous planes. This is usually rather tedious, but is easily achieved by means of the matrix approach. 1)

Fig. 1 Film structure of a one-dimensional magnetophotonic crystal.

![Fig. 1](image_url)

Table 1 Film preparation conditions (RF sputtering).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Sputtering gas</td>
<td>Ar</td>
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<tr>
<td>Sputtering pressure</td>
<td>7 mTorr</td>
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<tr>
<td>Substrate temperature</td>
<td>Room temperature</td>
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<tr>
<td>Sputtering power</td>
<td>150 W</td>
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<td>Refractive index</td>
<td>2.38</td>
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Table 2 Film preparation conditions (EB evaporation).

<table>
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<tr>
<td>Gas</td>
<td>O2</td>
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<tr>
<td>Pressure</td>
<td>0.18 mTorr</td>
</tr>
<tr>
<td>Substrate temperature</td>
<td>250 °C</td>
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<tr>
<td>Refractive index</td>
<td>2.18</td>
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</table>
3. Results and Discussion

3.1 Thermal annealing in an electric furnace

We employed thermal annealing at 700 °C so as to obtain Bi:YIG single-layer films with smooth surfaces and good magneto-optical properties. However, this annealing condition is not practically applicable for forming the 1-D MPC with a Bi:YIG film sandwiched between two dielectric multilayer films. This is simply because such dielectric multilayer films are unable to withstand annealing at such a high temperature. It is thought that the improvement of surface roughness is important. In order to overcome this problem, we investigated surface roughness of dielectric multilayer films.

Fig. 2 shows the change in surface roughness of dielectric multilayer films \((\text{SiO}_2/\text{Ta}_2\text{O}_5)^7/1737\) on the #1737 substrate versus the thermal annealing temperature (annealing time 20 minutes). Remarkable surface roughness did not appear in the formed dielectric multilayer films on the #1737 substrate with thermal annealing temperatures up to 750 °C. We also investigated the change in surface roughness of dielectric multilayer films on BK7 substrate versus the thermal annealing temperature. We observed significant surface roughness (>600 nm) at 700 °C. The #1737 substrate probably achieved such good results because it is high heat resistance glass. Therefore, it is thought that these Bi:YIG films on multilayer films exhibited excellent magneto-optical properties. Next, we investigated the crystallization temperature and time of the Bi:YIG film on the #1737 substrate. The crystalline Bi:YIG films were formed by thermal annealing in an electric furnace at 700 °C in air. Bi:YIG film on the dielectric layers was finely fabricated by taking into account the characteristics of the glass substrate, and was not damaged at the thermal annealing temperature of about 700 °C. Therefore, when the magnetic characteristics of Bi:YIG on dielectric multilayer films and on the glass substrate were compared, it was found that the magnetization of Bi:YIG film on both these substrates was almost identical. At this time, the Bi:YIG film composition was identified as \(\text{Bi}_{0.7}\text{Y}_{2.3}\text{Fe}_5\text{O}_{12}\).

![Fig.2](image-url) Change in surface roughness of dielectric multilayer films versus annealing temperature.

3.2 Performance of single-cavity structure

First, we fabricated a simple 1-D MPC of \((\text{Ta}_{2}\text{O}_5/\text{SiO}_2)^k/\text{Bi:YIG}/(\text{SiO}_2/\text{Ta}_2\text{O}_5)^k/1737\) \((k=2, 6)\). The design wavelength \(\lambda\) was 720 nm. The thickness of each dielectric layer was set so that its optical pathlength was equal to \(\lambda/4\). (The physical thickness was \(\lambda/4n\), where \(n\) is the refractive index.) The thickness of the Bi:YIG layer was set so that its optical path length was equal to \(\lambda/2, 3\lambda/4, \text{or } \lambda\). (The physical thickness was \(\lambda/2n, 3\lambda/4n, \text{or } \lambda/n\).) The photonic band structure of the sample with \((\text{Ta}_{2}\text{O}_5/\text{SiO}_2)^2/\text{Bi:YIG}/(\text{SiO}_2/\text{Ta}_2\text{O}_5)^2/1737\) is shown in Fig. 3. In Fig. 3(a), the localization wavelength was designated to be 720 nm, so that the sample exhibited a photonic bandgap between 600 nm and 900 nm and a resonant transmission due to the light localization appeared at 720 nm. As clearly seen in the figure, the sample shows a Faraday rotation of \(\theta_{F}=-0.1^\circ\) and a transmittance of \(T=85\%\) at \(\lambda=720\) nm. (Figure of Merit (FOM) was 0.092 \(^\circ\).) This result shows a typical feature of 1-D MPCs, that high transmittance and large Faraday rotation appear simultaneously. The Faraday rotation of the multilayer structure achieves more than 6 times that of a Bi:YIG single-layer film. The localization wavelength of the 1-D MPC with a thickness of 3\(\lambda/4\) shifts to the long wavelength side, as shown in Fig. 3(b).

Furthermore, in Fig. 3(c), the localization wavelength of 1-D MPC with thickness \(\lambda\) returns to the original localization wavelength of the 1-D MPC with a thickness \(\lambda/2\). Also, the single-cavity structure with a thickness \(\lambda\) of the Bi:YIG film exhibits a Faraday rotation of \(\theta_{F}=-0.6^\circ\) and a transmittance of \(T=80\%\) for \(k=2\). (FOM was 0.536 \(^\circ\).) Therefore, the Faraday rotation increases by increasing the film thickness of Bi:YIG film for the same repetition number. These are features of a 1-D MPC.

Next, we fabricated a sample with a \((\text{Ta}_{2}\text{O}_5/\text{SiO}_2)^k/\text{Bi:YIG}/(\text{SiO}_2/\text{Ta}_2\text{O}_5)^k/1737\) structure in order to increase the repetition number \(k\), as shown in Fig. 4. In Fig. 4(a), single-cavity structures with Bi:YIG film of thickness \(\lambda/2\) exhibits a Faraday rotation of \(\theta_{F}=-3.0^\circ\) and a transmittance of \(T=80\%\) for \(k=4\). (FOM was 1.16 \(^\circ\).) However, the increase in repetition number leads to an increase in the optical path length, which leads to a decrease in transmittance. In Fig. 4(b), a single-cavity structure with Bi:YIG film of thickness \(\lambda/4\) exhibits a Faraday rotation of \(\theta_{F}=-2.0^\circ\) and a transmittance of \(T=85\%\) for \(k=6\). (FOM was 1.16 \(^\circ\).) A typical feature of 1-D MPC is that the Faraday rotation increases with an increase in the repetition number of the dielectric multilayer. This is a much larger value than that of a single Bi:YIG film. A comparison of the performance of the 1-D MPC with \(k=2\) (Fig. 3) with that of the 1-D MPC with \(k=6\) (Fig. 4), showed that the latter has better performance. However, FOM has not been improved too much.

3.3 Optical dissipation of films

The Faraday rotation of the fabricated 1-D MPC is very large. However, the decrease in transmittance of the fabricated 1-D MPC is also large. It is thought that the
optical constant of the film is the main cause for this. The spectra of refractive index $n$ and extinction coefficient $\kappa$ (optical dissipation) of the SiO$_2$, Ta$_2$O$_5$ and Bi:YIG film were measured, and the results are presented in Fig. 5. These results suggest that the dispersion of the refractive index of each film and the optical dissipation of Bi:YIG and Ta$_2$O$_5$ film are the main influences on the short wavelength side. Optical dissipation of Ta$_2$O$_5$ film in $k=6$ multilayer becomes relatively important at longer wavelengths, since dissipation of Bi:YIG becomes negligibly small above 800 nm. We performed numerical calculations using the dispersion of the refractive index $n$ of each film and the optical dissipation of Ta$_2$O$_5$ and Bi:YIG films. The theoretical calculations and the measured values were almost identical, regardless of the differences in the repetition number of the element structure, as shown in Figs. 3 and 4. The optical dissipation of Ta$_2$O$_5$ and Bi:YIG films seems to be the main factor causing the decrease in transmittance at the localization wavelength. Therefore, it is important to fabricate film having low optical dissipation.

**Fig. 3** Transmittance and Faraday rotation of 1-D MPCs with a (Ta$_2$O$_5$/SiO$_2$)$_2$/Bi:YIG/(SiO$_2$/Ta$_2$O$_5$)$_2$/1737 structure for various thickness of the Bi:YIG layer. (a) $\lambda/2$ (b) $3\lambda/4$ (c) $\lambda$.

**Fig. 4** Transmittance and Faraday rotation of 1-D MPCs with a (Ta$_2$O$_5$/SiO$_2$)$_6$/Bi:YIG/(SiO$_2$/Ta$_2$O$_5$)$_6$/1737 structure for various thickness of the Bi:YIG layer. (a) $\lambda/2$ (b) $3\lambda/4$ (c) $\lambda$. 

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4. Conclusion

The optical and magneto-optical properties of 1-D MPCs were demonstrated experimentally. In the 1-D MPC utilizing the magnetic layer, Faraday rotation is enhanced. The Faraday rotation of the multilayer structure reaches more than 100 times ($k=6$) that of a Bi:YIG single-layer film. Also, the localization wavelength of 1-D MPC of thickness $3\lambda/4$ (Bi:YIG film) is shifted to the long wavelength side. Furthermore, the localization wavelength of 1-D MPC with thickness $\lambda$ (Bi:YIG film) is returned to the original localization wavelength of 1-D MPC with thickness $\lambda/2$ (Bi:YIG film). In this case, the Faraday rotation increases as film thickness increases, even if the repetition number is the same. We could also confirm the 1-D MPC feature, that the Faraday rotation (magneto-optical effect) increases with an increase in the repetition number. Our experimental results were in agreement with our theoretical predictions. However, the disadvantage of the 1-D MPC fabricated for magneto-optical applications is that the large Faraday rotation enhancement is always accompanied by a large reduction in the transmittance. It is thought that this is mainly caused by the optical constants of the films. We measured refractive index and extinction coefficient (optical dissipation) spectra of the SiO$_2$, Ta$_2$O$_5$ and Bi:YIG films. It seemed that the optical dissipation of Ta$_2$O$_5$ and Bi:YIG films influenced the localization wavelength. Therefore, it is important to fabricate film having low dissipation in order to produce practical magneto-optical devices. Furthermore, it is thought that the improvement of the multilayer film structure is necessary.

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References

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