1 April 1999

OPTICS COMMUNICATIONS

ELSEVIER

Optics Communications 162 (1999) 64–70

Multilayer films composed of periodic magneto-optical and dielectric layers for use as Faraday rotators

S. Sakaguchi *, N. Sugimoto

NTT Opto-Electronics Laboratories, Tokai, Ibaraki 319-1193, Japan

Received 30 November 1998; received in revised form 3 February 1999; accepted 4 February 1999

Abstract

Since multilayer films composed of periodic magneto-optical (M) and dielectric (G) layers have an enhanced Faraday effect, we investigated the possibility of using them as Faraday rotators for optical isolators. Under a constant magnetic field, the rotation can be adjusted precisely by adding an extra magneto-optical layer in which the rotation is proportional to the thickness. When the magnetic field is assumed to be variable, the rotation can be adjusted through the change in the magnetic induced permittivity of the magneto-optical layer. Since our investigation revealed that the rotation can be adjusted precisely, it is suggested that the use of multiple films with a rotation of half or one-third of 45° would make it possible to assemble low loss isolators.

Keywords: Multilayer film; Faraday rotation; Translation matrix; Optical isolator; Magneto-optical material; Dielectric material

1. Introduction

Periodic multilayer films are employed in such widely used devices as optical filters. Recent investigations have demonstrated theoretically that multilayer films composed of magneto-optical (M) and dielectric (G) materials exhibit extremely large Faraday rotations compared with that observed in the same bulk magneto-optical material [1,2]. This phenomenon can be attributed to the enhanced effect originated from a resonant phenomenon seen specifically in periodic multilayer structures. Such films have the possibility of realizing a rotation of 45° with a thickness of only several micrometers. This thinness makes them useful as Faraday rotators in optical isolators for integrated optical circuits.

The transmission characteristics of these films vary depending on the layer stacking structure. Our previous investigation [3] showed that films with a conventional periodicity, with a cavity layer included in their central part, can realize a rotation close to 45° with a thickness of less than 10 μm, although the transmittance becomes low. We also showed that the transmittance of the films can be improved by multiple stacking the conventional structures without degrading the rotation characteristics. However, the rotation is not always adjusted precisely to the required values for application to isolators. Therefore, it is necessary to clarify methods for adjusting the Faraday rotation when these films are to be considered as Faraday rotators.

Since Faraday rotation is induced by the difference in propagation constants between right and left circularly polarized lights, the rotation is proportional to the optical path length and/or magnetic field intensity when the magnetization is unsaturated [4]. Namely, it seems possible to adjust the rotation by adding an extra layer or by varying the magnetic field intensity. However, the Faraday rotation in multilayer films is not induced by a simple Faraday effect as seen in bulk material, but by an enhanced effect originating from the layer structure [1–3]. Therefore, it is unclear whether or not these methods are suitable.

This report deals with the transmission characteristics of multilayer films composed of periodic M and G layers,

* Corresponding author. E-mail: sakaguti@iba.iecl.ntt.co.jp

0030-4018/99/$ - see front matter
PII: S0030-4018(99)00061-9

to clarify the possibility of employing them as Faraday rotators in optical isolators. The rotation can be adjusted precisely by adding an extra M layer or by varying the magnetic induced permittivity. We also suggest that the use of multiple films with a rotation of half or one-third of 45° would make it possible to assemble low loss isolators.

2. Translation matrix

An example of multilayer film made of alternating layers of M and G materials is shown in Fig. 1, as well as the coordinate system for analysis. This periodic structure, which is described as $[\mathrm{MG}]^n[2\mathrm{M}][\mathrm{GM}]^n$ where n is the repetition number, is often seen in conventional multilayer films such as interference filters. The layer structure is symmetric with respect to its center and the central layer [2M] is called a cavity. The transmission characteristics of such films can be evaluated by the matrix formulation [5]. The translation matrix $\boldsymbol{\Phi}$ for the example film is given by

$$\boldsymbol{\Phi} = [\boldsymbol{\Phi}_{\mathrm{M}}\boldsymbol{\Phi}_{\mathrm{G}}]^n[\boldsymbol{\Phi}_{\mathrm{M}}\boldsymbol{\Phi}_{\mathrm{M}}][\boldsymbol{\Phi}_{\mathrm{G}}\boldsymbol{\Phi}_{\mathrm{M}}]^n \tag{1}$$

where matrices $\boldsymbol{\Phi}_{\mathrm{M}}$ and $\boldsymbol{\Phi}_{\mathrm{G}}$ are for M and G layers, respectively.

According to the formalism presented by Inoue and Fujii [1,2], the state of the light traveling in an M layer is described by the column vector composed of e_x, e_y, h_x and h_y which are components of the electric field vector $\boldsymbol{e}$ $(=\varepsilon_0\boldsymbol{E})$ and the magnetic field vector $\boldsymbol{h}$ $(=\mu_0\boldsymbol{H}/c$, c is the light speed in vacuum) of the light, where ε_0 and μ_0 are the permittivity and permeability of vacuum. When the magnetic field is applied to the film along the $+z$-direction, the magnetic induced components appear in the permittivity tensor $\tilde{\varepsilon}$ of an M layer. Then, the state of light in the M layer is described using forward and backward traveling lights with right and left circular polarization by

$$\begin{pmatrix} e_x \\ e_y \\ h_x \\ h_y \end{pmatrix}_z = \begin{pmatrix} 1 & 1 & 1 & 1 \\ -i & -i & i & i \\ i\sqrt{\varepsilon_{\mathrm{p}}} & -i\sqrt{\varepsilon_{\mathrm{p}}} & -i\sqrt{\varepsilon_{\mathrm{n}}} & i\sqrt{\varepsilon_{\mathrm{p}}} \\ \sqrt{\varepsilon_{\mathrm{p}}} & -\sqrt{\varepsilon_{\mathrm{p}}} & \sqrt{\varepsilon_{\mathrm{n}}} & -\sqrt{\varepsilon_{\mathrm{n}}} \end{pmatrix} \times \begin{pmatrix} A_1 e^{ik_{\mathrm{p}}z} \\ A_2 e^{-ik_{\mathrm{p}}z} \\ A_3 e^{ik_{\mathrm{n}}z} \\ A_4 e^{-ik_{\mathrm{n}}z} \end{pmatrix} \tag{2}$$

where k_{p} and k_{n} are the wavenumbers, ε_{p} and ε_{n} are the permittivity for right and left circular polarization, respectively and A_1–A_4 are coupling coefficients. $\boldsymbol{\Phi}_{\mathrm{M}}$ is obtained from Eq. (2) using the continuity condition at the interfaces for input and output. For simplicity, we suppose that M is isotropic and non-absorbing. Then, the permittivity for right and left circular polarization is given by $\varepsilon_{\mathrm{p}} = \varepsilon_1 + \varepsilon_2$ and $\varepsilon_{\mathrm{n}} = \varepsilon_1 - \varepsilon_2$, respectively, where ε_1 and ε_2 are the principal and induced permittivity, respectively.

The transmission characteristics of the film are given by comparing the states of light incident at $z = z_0$ and output at $z = z_0 + D$. When light with polarization parallel to the x-axis is incident normally to the film surface, the output light is given by

$$\begin{pmatrix} C_3 & 0 & 0 & 0 \\ 0 & 0 & C_4 & 0 \\ 0 & 0 & -C_4 & 0 \\ C_3 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} e^{ik(z-z_0-D)} \\ e^{-ik(z-z_0-D)} \\ e^{ik(z-z_0-D)} \\ e^{-ik(z-z_0-D)} \end{pmatrix}_{z=z_0+D} = \boldsymbol{\Phi} \begin{pmatrix} 1 & C_1 & 0 & 0 \\ 0 & 0 & 0 & C_2 \\ 0 & 0 & 0 & C_2 \\ 1 & -C_1 & 0 & 0 \end{pmatrix} \begin{pmatrix} e^{ik(z-z_0)} \\ e^{-ik(z-z_0)} \\ e^{ik(z-z_0)} \\ e^{-ik(z-z_0)} \end{pmatrix}_{z=z_0} \tag{3}$$

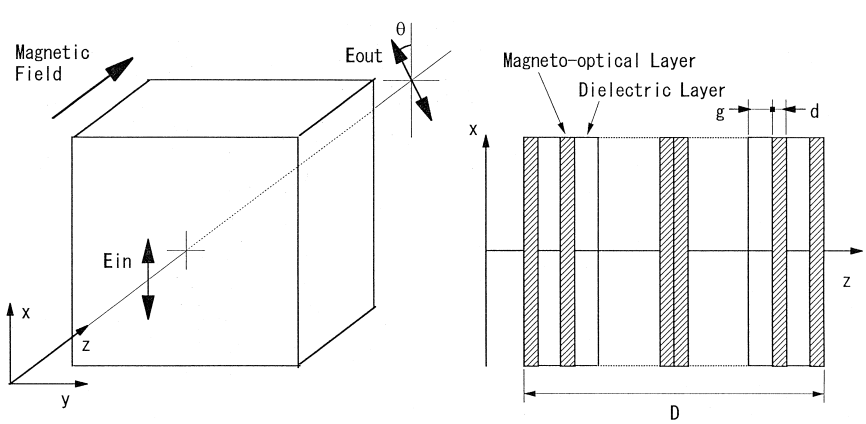

Fig. 1. An example of multilayer film composed of alternating layers of magneto-optical and dielectric materials, coordinate system for analysis (left) and cross-section (right).

where C_1–C_4 are coupling constants. These constants give reflectance R $(=R_x+R_y)$ and transmittance T $(=T_x+T_y)$ as follows;

$$R_x=|C_1|^2,\quad R_y=|C_2|^2,\quad T_x=|C_3|^2,\quad T_y=|C_4|^2, \tag{4}$$

where $T=1-R$. Furthermore, the rotation angle θ and the ellipticity η are given using $\chi=C_4/C_3$ by

$$\theta=\frac{1}{2}\tan^{-1}\left(\frac{2\,\mathrm{Re}(\chi)}{1-|\chi|^2}\right), \tag{5}$$

and

$$\eta=\tan\left(\frac{1}{2}\sin^{-1}\left(-\frac{2\,\mathrm{Im}(\chi)}{1+|\chi|^2}\right)\right), \tag{6}$$

where Re and Im represent the real and imaginary parts of χ, respectively.

3. Film structures

The multilayer films considered are composed of Bi substituted yttrium–iron garnet (Bi-YIG) for the M layer and SiO_2 for the G layer, in which enhanced Faraday rotation was shown by Inoue and Fujii [1,2]. We evaluated the transmission characteristics of films with periodic structures:
1. MGGM: $[MG]^n[GM]^n\cdot[GM]^n[MG]^n$, and
2. M2G2: $[MG]^n[2M][GM]^n\cdot[GM]^n[2G][MG]^n$
under previously reported conditions [1,2,6], i.e., $\varepsilon_1=4.75$,

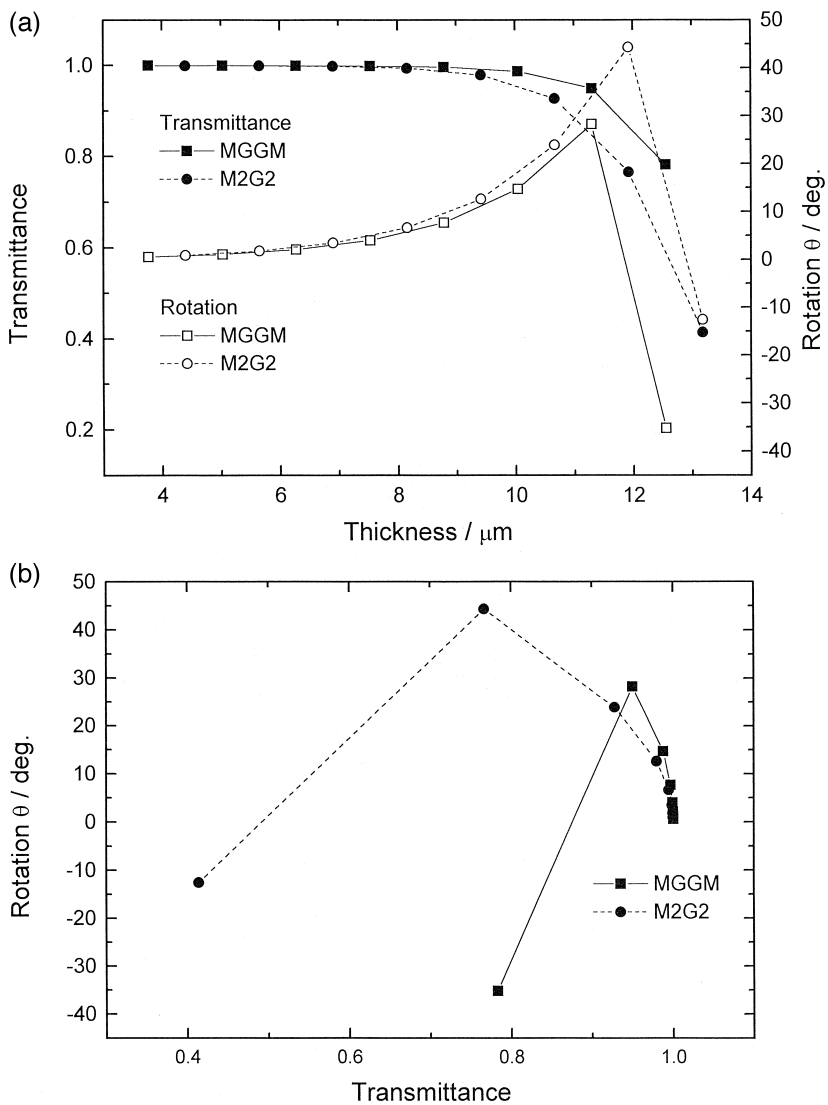

Fig. 2. Transmission characteristics of films with MGGM and M2G2 structures: (a) rotation and transmittance versus film thickness, and (b) rotation versus transmittance.

$\varepsilon_2 = 0.00269$, $\varepsilon_g = 2.5$ (ε_g is the permittivity of SiO_2), at $\lambda = 1.15$ μm (λ is the wavelength in vacuum). The thickness of each layer is set to its optical path length equal to $\lambda/4$. These structures are double stacks of the following conventional structures:

GM: $[GM]^n[MG]^n$,
G2: $[GM]^n[2G][MG]^n$,
MG: $[MG]^n[GM]^n$, and
M2: $[MG]^n[2M][GM]^n$.

Since the double stacked films have an improved transmittance [3], we selected these structures.

Since the Faraday rotation is induced by the difference between the propagation constants of right and left circularly polarized lights, the rotation is proportional to the optical path length and magnetic field intensity below saturated magnetization [4]. We anticipate that, as a first approach, it will be possible to adjust the rotation by adding an extra M layer or by varying the magnetic field. In the former case, the rotation is proportional to the optical path length of the added layer. In the latter case, the rotation varies through the change in magnetic induced permittivity. For an isotropic and non-absorbing M layer, ε_2 is given as

$$\varepsilon_2 = \frac{\lambda\sqrt{\varepsilon_1}}{\pi}\theta_F C \qquad (7)$$

where θ_F is the Faraday rotation per unit length (rad/m), and C is the relative magnetization and a function of the applied magnetic field.

4. Transmission properties

4.1. Films without adjustment

The transmission characteristics of films with MGGM and M2G2 structures are shown in Fig. 2 and numerical values are listed in Table 1.

Table 1
Transmission characteristics of multilayer films with MGGM and M2G2 structures

Structure	n	Rotation (deg)	Transmittance	Thickness (μm)
MGGM	5	2.13	0.999	6.275
	6	4.06	0.999	7.530
	7	7.73	0.997	8.785
	8	14.7	0.987	10.040
	9	28.3	0.950	11.295
	10	−35.2	0.783	12.550
M2G2	5	3.51	0.998	6.902
	6	6.67	0.994	8.157
	7	12.7	0.980	9.412
	8	23.9	0.928	10.667
	9	44.4	0.766	11.922
	10	−12.5	0.414	13.177

Fig. 2a shows plots of the transmittance and rotation θ versus film thickness, and Fig. 2b shows plots of rotation θ versus transmittance. Each data point corresponds to that for repetition number n. The data are discrete because of the discrete value of n. As n increases, the rotation increases. The maximum rotation of the M2G2 structure reaches 44.4° at $n = 9$ with a thickness of 11.922 μm, while that of MGGM remains at 28.3° at $n = 9$ with a thickness of 11.294 μm. Their transmittance at maximum rotation is 0.950 and 0.766 for MGGM and M2G2, respectively.

For the M2G2 structure, a rotation of 44.4° is obtained. This is close to the value of 45° required for the Faraday rotator used in isolators. By contrast, that for the MGGM structure is 28.3° which is not suitable for the rotator. This difference is related to the layer structure of the film. Therefore, the films do not always exhibit the desired rotation.

Although these films have a similar thickness, their rotation and transmittance are very sensitive to the layer structure. It is not clear whether there is a certain systematic relation between their layer structure and transmission characteristics. In other words, we must make many trials for designing films to fit the required transmission characteristics. Therefore, it is necessary to adjust the characteristics to required values other than the structure. The rotation must be adjusted precisely for isolator applications. To this end, we investigated two possible adjustment methods, adding an extra M layer and varying the applied magnetic field.

As listed in Table 1, only M2G2 at $n = 9$ exhibits a rotation close to 45° with a transmittance of 0.766. It is not easy to adjust the rotation to 45° at high transmittance. However, a reasonably careful inspection reveals that MGGM and M2G2 films have rotations close to 15 and 22.5°, which are one-third and half of the required rotation, with high transmittance. MGGM film at $n = 8$ and M2G2 film at $n = 7$ have rotations of less than 15° with transmittances of 0.987 and 0.980, respectively. MGGM film at $n = 9$ and M2G2 film at $n = 8$ have rotations larger than 22.5° with transmittances of 0.950 and 0.928, respectively. We employed additional layer adjustment to the former group, and the variable magnetic field method to the latter group.

4.2. Films with an additional M layer

The rotation adjustment by adding an M layer is confirmed for MGGM film at $n = 8$ and M2G2 film at $n = 7$. Numerical data are listed in Table 2. For the MGGM film, the 14.7° rotation is adjusted to 15° by adding an M layer with a thickness of 1.311 μm. The increase in rotation for this thickness coincides with θ_F used in Eq. (7) for $C = 1$. The 0.987 transmittance is reduced slightly to 0.981. Simi-

Table 2
Multilayer films with rotation adjustment

Structure	Adjustment	Variable	Rotation (deg)	Transmittance
MGGM ($n=8$)	Layer M	1.311 μm	15	0.981
M2G2 ($n=7$)	Layer M	9.755 μm	15	0.968
MGGM ($n=9$)	ε_2	2.15×10^{-3}	22.5	0.969
M2G2 ($n=8$)	ε_2	2.53×10^{-3}	22.5	0.936

larly, the 12.7° rotation for the M2G2 film is adjusted to 15° by adding a layer with a thickness of 9.755 μm. This ratio of rotation to thickness also corresponds to θ_F in Eq. (7). The 0.980 transmittance is reduced to 0.968.

The field intensity in the additional layer in the MGGM film is uniformly distributed in its cycle, as shown in Fig. 3 which shows plots of electric field intensity distributions along the z-axis in the MGGM film. The thickness of 1.311 μm is almost equal to 10 times the quarter wave optical path length of the M layer, i.e., 2.5 times the wavelength. Thus, an additional M layer of this thickness behaves as a bulk rotator. Similarly, an additional M layer with a thickness of 9.755 μm is required for the M2G2 film.

As described above, it is clear that an additional M layer with a suitable thickness can be used to adjust the rotation precisely. The ellipticity is less than 1×10^{-4}.

4.3. Films with varied induced permittivity

If we can assume that the magnetic field intensity applied to the film can be controlled accurately, it seems possible that we can adjust the induced permittivity of an M layer. This is performed on MGGM film at $n=9$ and M2G2 film at $n=8$.

For the MGGM film, the rotation of 28.3° is adjusted to 22.5° by varying ε_2 from 2.69×10^3 to 2.15×10^3. The transmittance of 0.950 is slightly increased to 0.969. Similarly, the rotation of 23.9° for the M2G2 film is adjusted to 22.5° by varying ε_2 from 2.69×10^3 to 2.53×10^3. The transmittance of 0.928 is slightly increased to 0.936. The distribution of the electric field intensity should change after varying ε_2. The distribution of MGGM film at $n=9$, whose induced permittivity is varied, is almost the same as that before the adjustment, as shown in Fig. 4.

The enhanced Faraday rotation observed in periodic multilayer films is fundamentally induced by a localization effect of light specifically seen in multilayer films [1,2,7] and a phase matching of right and left circularly polarized lights with periodicity [1–3]. The localization means multi-reflection of the light, which corresponds to an increase of effective optical path length. Therefore, the enhanced Faraday effect observed in multilayer films is attributable to this multi-reflection effect. However, phase matching conditions for right and left circularly polarized lights differ slightly, because of the slight difference in propagation constants for them. There seems to be the most efficient phase matching condition for both polarized

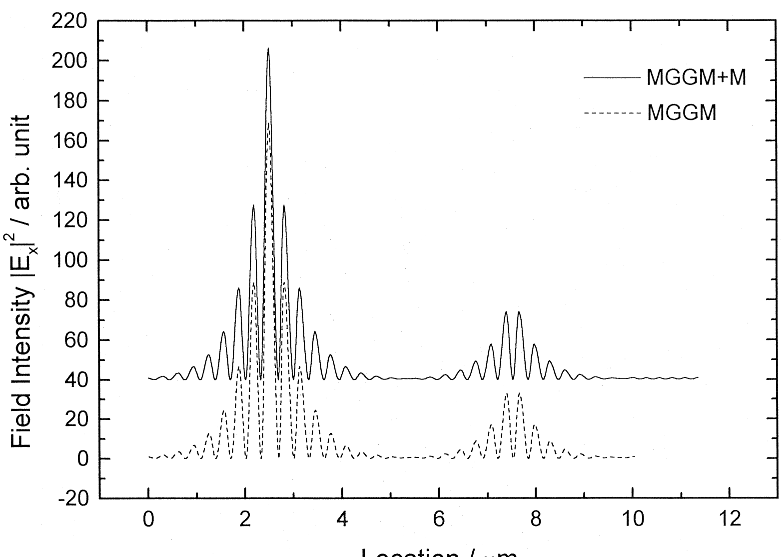

Fig. 3. Electric field intensity distribution in MGGM film at $n=8$ in which the rotation is adjusted to 15° by adding an M layer (represented by '+M').

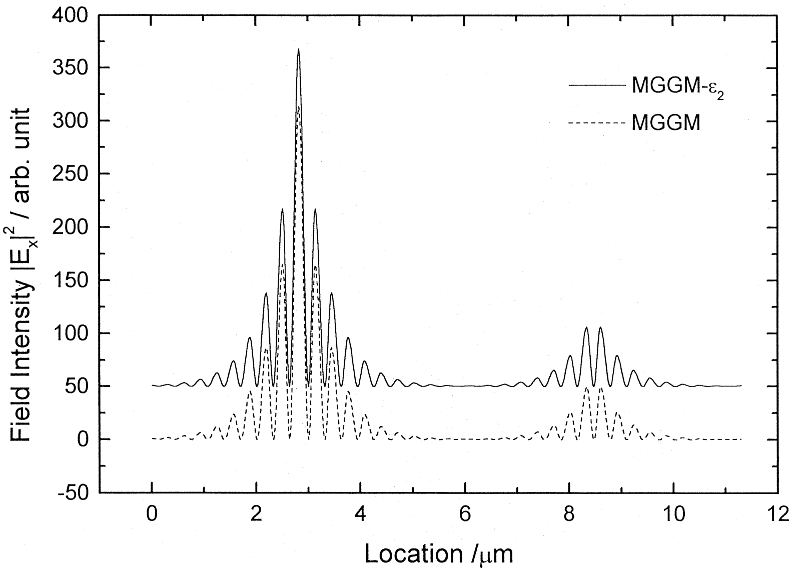

Fig. 4. Electric field intensity distribution in MGGM film at $n = 9$ in which the rotation is adjusted to 22.5° by varying the induced permittivity of the M layer (represented by '$-\varepsilon_2$').

lights with respect to the multilayer structure [8]. Under this condition, the largest Faraday rotation seems to occur. This complex effect gives rise to the enhanced rotation. For this reason, the enhanced effect is very sensitive to the stacking structure.

If these films are to be considered for use as Faraday rotators in isolators, the rotation must be precisely adjusted. When the induced permittivity is constant, the addition of an M layer with a suitable thickness is an effective way of accomplishing this, as shown in Fig. 3. In this case, the magnetization in the M layer is saturated. It is common for isolators to apply a magnetic field larger than that sufficient to saturate the magnetization.

When it is possible to control the magnetization in the M layer by adjusting the magnetic field intensity, the rotation can be adjusted through the induced permittivity as shown in Fig. 4. In this case, the magnetization in the M layer is unsaturated. The induced permittivity must be reversible without hysteresis for the precisely controlled magnetic field. The effect of magnetic hysteresis can be neglected in the type of Bi:YIG used for magnetic field sensors [9]. Thus, it is also possible to use with unsaturated magnetization.

Films whose rotation is adjusted to 15 or 22.5° exhibit a transmittance higher than 0.9, and their thickness is less than 10 μm. If two or three pieces of these films are installed in isolators, it is expected to assemble low loss isolators. For example, three pieces of M2G2 film, each of which having a transmittance of 0.981 and the rotation adjusted to 15°, induce a loss of 0.25 dB, while an M2G2 film at $n = 9$ with a 44.4° rotation induces a loss of 1.1 dB (a transmittance of 0.766). Similarly, two pieces of MGGM film with a transmittance of 0.969 adjusted to 22.5° induce a loss of 0.27 dB. These values are comparable to those of current isolators. Their thinness gives these films a considerable advantage over conventional Faraday rotators. When multiple films are used for a rotator, interference between the constituent films is expected. To avoid this interference effect, it is necessary to assemble the isolator with some consideration, for example, tilting the films.

5. Conclusion

An investigation of the transmission characteristics of multilayer films composed of magneto-optical and dielectric materials suggests that they can be used in isolators as Faraday rotators. It is not always possible to adjust the rotation of films with conventional periodicity to the required value because of the discrete repetition number. The addition of an extra M layer to the films is an effective way to adjust the rotation under a constant magnetic field. It is also possible to adjust the rotation by varying the magnetic field. In addition, we suggest that two or three pieces of film with precisely adjusted rotation make it possible to assemble low loss isolators.

Acknowledgements

The authors thank Drs. Toshihiro Shintaku and Minoru Suzuki for useful discussions.

References

[1] M. Inoue, T. Fujii, J. Appl. Phys. 81 (1997) 5659.
[2] M. Inoue, T. Fujii, J. Magn. Soc. Jpn. 21 (1997) 187, in Japanese.

[3] S. Sakaguchi, N. Sugimoto, to be published.
[4] A. Yarif, Y. Peh, Optical Waves in Crystals, Wiley, New York, 1984.
[5] M. Born, E. Wolf, Principles of Optics, Pergamon, New York, 1970.
[6] P. Hansen, J.-P. Krumme, Thin Solid Films 114 (1984) 69.
[7] T. Hattori, N. Tsurumachi, H. Nakatsuka, J. Opt. Soc. Am. 14 (1997) 348.
[8] M. Inoue, K. Arai, T. Fujii, M. Abe, J. Appl. Phys. 83 (1998) 6768.
[9] N. Itoh, H. Minemoto, D. Ishiko, S. Ishizuka, J. Magn. Soc. Jpn. 19 (1995) 209, in Japanese.