PARTICULATE FILMS FOR MAGNETO-OPTICAL RECORDING
I. THEORY OF THE MAGNETO-OPTICAL EFFECT

M. ABE and M. GOMI
Tokyo Institute of Technology, Okayama, Meguro-ku, Tokyo 152, Japan

Abstract—For magneto-optical (MO) recording media we propose particulate films with magnetic fine particles dispersed in binders. Using effective dielectric tensor Faraday rotation $\hat{\theta}_F$ and absorption coefficient $\hat{\alpha}$ are calculated for the particulate films containing Bi–substituted YIG and Co fine particles. The MO figure of merit $\hat{\theta}_F/\hat{\alpha}$ of the particulate films exceeds that of continuous magnetic films. This enhancement is prominent for Co (or metal in general) compared to Bi–YIG (or oxide in general).

KEY WORDS: PARTICULATE FILMS, MAGNETO-OPTICAL RECORDING, EFFECTIVE DIELECTRIC TENSOR

INTRODUCTION

For magneto-optical (MO) recording media we propose particulate films in which magnetic fine particles are dispersed in matrices or binders, as Fig.1 shows. The magnetization is aligned perpendicular to plane of the film (z axis). Such particulate films will enable us to use magnetic materials of strong MO effect which we can easily fabricate as fine particles but hardly as films.

In this paper we introduce an "effective dielectric tensor" for composite particulate films, with which we calculate the MO and optical properties of the films containing garnet and Co particles. It will be shown that the MO figure of merit of the particulate films exceeds that of continuous magnetic films.

EFFECTIVE DIELECTRIC TENSOR

When the size of the particles and structure of the composite film (average separation between the particles) are much smaller than wavelength of light, the light can propagate in the film without being scattered by the particles. The composite film behaves as a continuous medium against the light, and we can describe the light propagation in terms of an effective dielectric tensor. Its off–diagonal terms, which are responsible for the MO effect, have been derived by the authors[1]. The diagonal and off–diagonal terms of the effective tensor of the composite films in Fig.1 are expressed as follows;

$$\hat{\epsilon}_{xx}=\epsilon_x+f(\epsilon_x-\epsilon_y)\left[1+(1-f)(\epsilon_2-\epsilon_1)\epsilon_x^{-1}N_x\right]$$ (1a)

$$\hat{\epsilon}_{xy}=f\epsilon_{xy}\left[1+(1-f)(\epsilon_2-\epsilon_1)\epsilon_y^{-1}N_y\right]$$ (1b)

Here, $f$ is the volume fraction of the particles,

$$\epsilon_x(=\epsilon_x'+i\epsilon_x'')$$ the dielectric constant of the matrix, and

$$\epsilon_2(=\epsilon_2'+i\epsilon_2'')$$ and

$$\epsilon_{xy}(=\epsilon_{xy}'+i\epsilon_{xy}'')$$ the diagonal and off-diagonal terms of the dielectric tensor of the magnetic materials, respectively. $N_x$ and $N_y$ are depolarization factors of the particles along the x and y directions, which takes values of,

$$N_x=N_y=1/3$$ for spheres (Fig.1(a)),

$$N_x=N_y=0$$ for discs with infinite aspect ratio (Fig.1(b)),

and

$$N_x=N_y=1/2$$ for cylinders with infinite aspect ratio (Fig.2(c)).

For the spheres garnet or spinel ferrites are fitted, while for the discs and cylinders hexaferrites and acicular $\gamma$-Fe$_2$O$_3$ are fitted, respectively.

In terms of the effective tensor the Faraday rotation $\hat{\theta}_F$ and the absorption coefficient $\hat{\alpha}$ of the composite particulate film at wavelength $\lambda$ are written as follows (assuming $|\epsilon_{xy}|<<1$ which holds in general),

$$\hat{\theta}_F=(\pi\lambda)\text{Im}[\hat{\epsilon}_{xy}/\epsilon_{xx}^{1/2}]$$ (2)

$$\hat{\alpha}=(2\pi\lambda)\text{Im}[\epsilon_{xx}^{1/2}].$$ (3)

Using eqs.(2) and (3) we have successfully explained MO and optical properties of alumite composite films of ano-
Abe and Gomi: PARTICULATE FILMS FOR MAGNETO-OPTICAL RECORDING I. THEORY OF THE MAGNETO-OPTICAL

Table I Dielectric constants, $\varepsilon_{1}=\varepsilon_{1}'+i\varepsilon_{1}''$ of matrix and $\varepsilon_{2}=\varepsilon_{2}'+i\varepsilon_{2}''$ and $\varepsilon_{xy}=\varepsilon_{xy}'+i\varepsilon_{xy}''$ of magnetic materials at $\lambda=633$ nm.

<table>
<thead>
<tr>
<th></th>
<th>Diagonal Term</th>
<th>Off Diagonal Term</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\varepsilon_{1}'$</td>
<td>$\varepsilon_{1}''$</td>
</tr>
<tr>
<td>Matrix</td>
<td>2.25</td>
<td>0</td>
</tr>
<tr>
<td>Bi$<em>{125}$Y$</em>{1.75}$Fe$<em>{5}$O$</em>{12}$</td>
<td>6.35</td>
<td>0.054</td>
</tr>
<tr>
<td>Co</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In deriving the effective tensor we[1] used an approximate solution of a potential boundary problem of a magnetic ellipsoid embedded in a nonmagnetic matrix on which an external electric field is applied. Furthermore, we assumed that such magnetic ellipsoids are dispersed sparsely (i.e., $f<<1$) and therefore the electric dipole interaction between the ellipsoids is weak.

However, we[3] recently found that when the magnetic particles are spherical the potential boundary problem can be solved rigorously and that the dipole interaction is intrinsically weak when the magnetic fine particles are distributed in a completely random way. Therefore the effective dielectric tensor are applicable even when $f$ is not small.

It should be noted that when the magnetic particles are of metal with a strong light absorption the effective tensor is applicable only when the size of the particles is much smaller than penetration depth (typical value is 10 nm) of the light in the metal. This is because the effective tensor is calculated assuming that a uniform electric field is induced in the particles.

**MO EFFECT AND FIGURE OF MERIT OF PARTICULATE FILMS**

Using eqs.(1)–(3) we have calculated at $\lambda=633$nm $\hat{\Theta}_{p}$ and MO figure of merit $\Theta_{p}/\alpha$ for composite films with spherical particles of Co and Bi–substituted YIG (Bi$_{125}$Y$_{1.75}$Fe$_{5}$O$_{12}$) dispersed in a hypothetical matrix. We assumed that the matrix has a refractive index (n) typical for organic compounds ($\varepsilon_{r}''$=2.25), and an absorption coefficient or $\varepsilon_{1}''$ is 0, 1/1000, 1/100 or 1/20 times as large as that of Bi–YIG (Table I).

Figure 2 and 3 show normalized values of $\hat{\Theta}_{p}/\theta_{p}$ and $\hat{\alpha}/\alpha$ , ($\theta_{p}$ and $\alpha$: values of continuous films) plotted as a function of $f$ for Co and Bi–YIG. For both materials $\hat{\Theta}_{p}$ calculated for the various values of $\varepsilon_{1}''$ converges to a single curve. For Bi–YIG a relation

$$\hat{\Theta}_{p}/\theta_{p}=f$$

holds very accurately (deviation <1.5%), while for Co $\hat{\Theta}_{p}/\theta_{p}$ deviates from $f$ appreciably. This is because for the garnet (or oxide in general) with a weak absorption we have a relation

$$0<\varepsilon_{2}''<<\varepsilon_{2}$$

and $1/[1+(1-f)(\varepsilon_{2}''-\varepsilon_{2}''')\varepsilon_{1}^{-1}N_{x}]$, which appears in the right side of eq.(1), is nearly equal to 1. While in Co (or metal in general) with a strong absorption we have

$$\varepsilon_{2}'<0, 1<\varepsilon_{2}'<\varepsilon_{2}$$

and $1/[1+(1-f)(\varepsilon_{2}''-\varepsilon_{2}''')\varepsilon_{1}^{-1}N_{x}]$ deviates from 1. Then, eq.(1a) tells us that in the metals the relation

$$\hat{\epsilon}_{xy}/\varepsilon_{xy}=f$$

has been assumed previously in order to analyze the MO effect in fine metal particles dispersed in dielectric substance does not hold.

The normalized absorption coefficient $\hat{\alpha}/\alpha$ depends on $\varepsilon_{1}'$, and exceeds 1 ($\hat{\Theta}_{p}>\alpha$) when $\varepsilon_{2}''$ approaches to $\varepsilon_{2}'$, as shown for Bi–YIG in Fig. 2. In Fig.3 for Co $\hat{\alpha}/\alpha$ does not exceed $\alpha$, which is because even the maximum values of $\varepsilon_{2}''$ (=0.05) which we gave for the matrix is much smaller than $\varepsilon_{2}''$=18.4 of Co.

Figure 4 shows $g=\hat{\Theta}_{p}/\theta_{p}$, an enhancement factor of the MO figure of merit for Co and Bi–YIG. When $\varepsilon_{2}''=0$, as $f$ increases from 0, $g$ for Co increases rapidly from 0 to a maximum value (which is as large as 4.5 when $\varepsilon_{2}''=0.05$) and then it decreases to 1 at $f=1$. For Co $\hat{\Theta}_{p}$ exceeds $\theta_{p}$ for all values of $\varepsilon_{2}''$ and $f$ (except $f$ is close to 0), while $\hat{\Theta}_{p}$ for Bi–YIG exceeds $\theta_{p}$ only when $\varepsilon_{2}''<0.001$. Thus the MO figure of merit of metal enhances much when the particles are dispersed in a matrix whose absorption is much weaker than in the metal.
CONCLUSION

The MO effect and the MO figure of merit of particulate films can be described by an effective dielectric tensor. The figure of merit is enhanced in the particulate films especially when the magnetic particles are metals.

REFERENCES