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Calculation of the Faraday Signal of a Magneto-Optical Memory in the Presence of Magnetic Circular Dichroism

The polarization of a light field after passing through a circularly birefringent material is calculated, and the results are used to investigate the readout problem in magneto-optical memories. It is shown that the circular dichroism has no effect on the readout efficiency in three different readout configuration possibilities.

1. Introduction

The utilization of the magneto-optical effects for reading out information stored in magnetic thin films in a bit-by-bit manner has been considered by several authors [1–3].

In the case of a transparent medium the Faraday effect is preferable. The Faraday rotation of a magnetic medium may be considered as circular birefringence because the refractive indices for right- and left circularly polarized light are different [4]. In an absorbent material there is also another a occuring simultaneously effect namely, that of magnetic circular dichroism due to the complex refractive index. The Faraday effect brings about a phase change between the opposite circularly polarized waves (it causes the rotation of the plane of polarization of the incident linearly polarized light), while an amplitude difference between the waves, and thus ellipticity is due to the circular dichroism. This paper discusses the effect of ellipticity on the readout performance of a magneto-optical memory (using present detection techniques) and shows that the readout efficiency does not depend on the ellipticity caused by circular dichroism.

2. Circular birefringence and dichroism

A linearly polarized wave can always be resolved into two circularly polarized waves, the right- (RCP), and the left circularly polarized one (LCP). A circularly polarized wave, propagating in the z direction is represented by [4]:

RPC

$$\boldsymbol{E} = \tfrac{1}{2}E_0(\hat{\boldsymbol{e}}_x + i\hat{\boldsymbol{e}}_y)\exp[i(\omega t - kz)] + \mathrm{cc},$$

LCP

$$\boldsymbol{E} = \tfrac{1}{2}E_0(\hat{\boldsymbol{e}}_x - i\hat{\boldsymbol{e}}_y)\exp[i(\omega t - kz)] + \mathrm{cc}.$$

where $\boldsymbol{E}$ is the electrical field, $\hat{\boldsymbol{e}}_x$ and $\hat{\boldsymbol{e}}_y$ are the unit vectors along the x and y axes, respectively, and cc stands for complex conjugate. An elliptically polarized wave is:

$$\boldsymbol{E} = \tfrac{1}{2}E_0\ (\hat{\boldsymbol{e}}_x + \exp(i\delta)\hat{\boldsymbol{e}}_y)\exp[i(\omega t - kz)] + \mathrm{cc},$$

where δ is the phase difference between the x and y components of $\boldsymbol{E}$.

In a magnetic material the refractive indices for RCP and LCP are different:

$$n_{\pm} = N_{\pm} - iK_{\pm}.$$

If a plane electromagnetic wave — linearly polarized along the x axis at the $z = 0$ point — propagates in the medium toward positive z, the electrical field is given by:

$$\boldsymbol{E} = \mathrm{Re}\{\tfrac{1}{2}E_0\exp(i\omega t)[(\hat{\boldsymbol{e}}_x + i\hat{\boldsymbol{e}}_y)\times \times\exp(-i\frac{2\pi}{\lambda}n_+z) + +(e_x - ie_y)\exp(-i\frac{2\pi}{\lambda}n_-z)]\}.$$

The wave has been resolved into two circular components. This can be rewritten in a more convenient form:

$$\boldsymbol{E} = \mathrm{Re}\{E_0\exp[i(\omega t - \frac{2\pi}{\lambda}\overline{n}z)]\big(\hat{\boldsymbol{e}}_x\cos(\delta/2) + +\hat{\boldsymbol{e}}_y\sin(\delta/2)\big)\},$$

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where the following equations have been used:

$$\exp(-i\frac{2\pi}{\lambda}n_{\pm}z)$$

$$=\exp\left[-i\frac{2\pi}{\lambda}\frac{n_{\pm}+\bar{n}}{2}z\right]\exp\left[-i\frac{2\pi}{\lambda}\frac{n_{\pm}-\bar{n}}{2}z\right],$$

$$\frac{\delta}{2}=\frac{2\pi}{\lambda}\frac{n_{+}-n_{-}}{2}z=\frac{2\pi}{\lambda}\left[\frac{\Delta N}{2}-i\frac{\Delta K}{2}\right]z$$
$$=Fz-i\Delta az,$$

$$\bar{n}=\frac{n_{+}+n_{+}}{2}=\bar{N}-i\bar{K};\frac{2\pi}{\lambda}\bar{K}=\frac{a}{2}.$$

Using the identities:

$$\cos(a-ib)=\cos a ch b+i\sin a sh b,$$
$$\sin(a-ib)=\sin a ch b-i\cos a sh b$$

we can find the following form for the field:

$$E=E_0\exp\left(-\frac{az}{2}\right)\{\hat{e}_x[\cos(\omega t-$$
$$-\frac{2\pi}{\lambda}\bar{N}z)\cos(Fz)ch(\Delta az)-\sin(\omega t-\frac{2\pi}{\lambda}\bar{N}z)\times$$
$$\times\sin(Fz)sh(\Delta az)]+\hat{e}_y[\cos(\omega t-$$
$$-\frac{2\pi}{\lambda}\bar{N}z)\sin(Fz)ch(\Delta az)-\sin(\omega t-\frac{2\pi}{\lambda}\bar{N}z)\times$$
$$\times\cos(Fz)sh(\Delta az)]\}.$$

This is the equation of a rotated ellipse with the parameters:

Half major axis: $a=ch(\Delta az)$,
Half minor axis: $b=sh(\Delta az)$,
The angle of rotation: $\theta=Fz$,
Ellipticity: $E=\frac{b}{a}=\mathrm{tgh}(\Delta az)$.

3. Application to the readout problem

In this section we calculate the readout efficiencies of a magneto-optical memory material in three different readout configurations, taking into account the ellipticity caused by the circular dichroism.

Consider a linearly polarized beam of intensity incident on a magnetic film; the magnetization of the film is perpendicular to the film plane. The output light will be elliptically polarized; the major axis of the ellipse is rotated with respect to the input polarization direction. The angle of rotation is either $+Fz$ or $-Fz$ depending whether the direction of the magnetization of the illuminated area is parallel or antiparallel to the light propagation vector. The two magnetization states with Fz and $-Fz$ rotation are called "0" state and "1" state, respectively. Magnetic information can be read by analyzing the exit light in three different ways:

1. The detector is placed after an analyzer, its the extinction direction makes an angle Fz with the original direction of polarization [2]. In the two magnetic states the detector currents are:

$$I_{\text{“0”}}=\tfrac{1}{2}I_0b^2\exp(-az)$$

and

$$I_{\text{“1”}}=\tfrac{1}{2}I_0\exp(-az)[a^2\sin^2(2Fz)+$$
$$+b^2\cos^2(2Fz)].$$

The readout efficiency [5] is:

$$\eta^{(a)}=\frac{I_{\text{“0”}}-I_{\text{“1”}}}{I_0}=\tfrac{1}{2}\exp(-az)\sin^2(2Fz).$$

If the rotation angle is small (this is true of materials used in practice) the optimum thickness $z=\frac{2}{a}$, and the maximized efficiency:

$$\eta^{(a)}_{\max}=\left(\frac{2F}{a}\right)^2\cdot 0.54.$$

2. In a more general case the extinction direction of the analyzer makes an angle φ with the input polarization direction. In this case the readout efficiency can be written as:

$$\eta^{(b)}=\tfrac{1}{2}\exp(-az)\sin(2Fz)\sin(2\varphi).$$

It is optimized at the thickness $z=\frac{1}{a}$ and at $\varphi=\frac{\pi}{4}$. The value of $\eta^{(b)}_{\max}=\left(\frac{F}{a}\right)\cdot 0.37.$

3. In the third case (this appears to be the most suitable for a working memory) a polarizing beam-splitter and two detectors are placed behind the film [5]. The detector signals are fed to a differential amplifier. The optical axis of the beam-splitter makes and angle φ with the input polarization direction. The two detector currents in the $\{{}^{\text{“0”}}_{\text{“1”}}\}$ state are:

$$I_{\prime}\{{}^{\text{“1”}}_{\text{“1”}}=\tfrac{1}{2}I_0\exp(-az)[a^2\cos^2(\varphi\mp Fz)+$$
$$+b^2\sin^2(\varphi\mp Fz)],$$
$$I_{\prime\prime}\{{}^{\text{“0”}}_{\text{“1”}}=\tfrac{1}{2}I_0\exp(-az)[a^2\sin^2(\varphi\mp Fz)+$$
$$+b^2\cos^2(\varphi\mp Fz)].$$

The amplifier output are:

$$\Delta I_{\text{“}0\text{”}} = I_{,\text{“}0\text{”}} - I_{,,\text{“}0\text{”}} = \tfrac{1}{2} I_0 \exp(-az) \times \times \cos(2\varphi - 2Fz),$$

$$\Delta I_{\text{“}1\text{”}} = I_{,\text{“}1\text{”}} - I_{,,\text{“}1\text{”}} = \tfrac{1}{2} I_0 \exp(-az) \times \times \cos(2\varphi + 2Fz).$$

The readout efficiency:

$$\eta^{(c)} = \frac{\Delta I_{\text{“}0\text{”}} - \Delta I_{\text{“}1\text{”}}}{I_0} = \exp(-az) \sin 2\varphi \sin\, 2Fz.$$

The optimal conditions: $\varphi = 4/\pi,$: $z = 1/a$; and the maximized efficiency: $\eta^{(c)}_{\max} = \left(\frac{F}{a}\right) \cdot 0.74.$

4. Remarks

The explicit form of the light wave in the case of an absorbent circularly birefringent material has been calculated, and the results have been applied to the problem of readout in magneto-optical memories. We state – in contrast with reference [1] – that circular dichroism is of no importance in determining readout efficiency. Furthermore, the third detection method (using the polarizing beam-splitter and differential detection) has two main advantages: firstly, the surface noises of the material are eliminated, and secondly, the readout efficiency increases by twice.

Calcul de mémoire magnéto-optique du signal de Faraday dans la présence du dichroisme magnétique circulaire

On a calculé la polarisation du champ lumineux après sa transition par un matériau biréfringent qui polarise circulairement. Les résultats ont été utilisés dans l'analyse d'un problème de lecture des mémoires magnéto-optiques. On a démontré que le dichroisme circulaire n'a aucune influence sur l'efficacité de lecture pour les trois configurations de lecture possibles.

Расчет магнитооптической памяти сигнала фарадея при наличии кругового магнитного дихроизма

Рассчитана поляризация светового поля после перехода сквозь материал с круговой поляризацией. Результаты были применены при исследовании проблемы отсчета в магнитооптических запоминающих устройствах. Показано, что круговой дихроизм не оказывает влияния на эффективность отсчета для трех различных конфигураций отсчета.

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