RELATIONSHIP BETWEEN THE TRANSITION METAL MAGNETIZATION DIRECTION AND THE SIGN OF THE FARADAY AND KERR ROTATIONS IN RARE-EARTH TRANSITION METAL ALLOYS FOR MO RECORDING

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Abstract: In magneto-optical technology, the interest for magnetic coupled layers has increased in the last decade with the development of new methods like the Magnetic Super Resolution (MSR) and the Magnetic Amplification of Magneto-Optical System (MAMMOS), allowing improvement in recording density. In this framework, hysteresis loops of a GdFeCo/TbFeCo bilayered structure are studied. For the rare-earth transition metal (RE-TM) alloys in the infrared and visible light wavelength, the Kerr and Faraday rotations are predominantly due to the transition metal magnetization. Experimental results show that the relation between the sign of the rotation and the transition metal (TM) magnetization direction is not so obvious but depends on several parameters like the material thicknesses and the optical and magneto-optical constants. The experimental investigation of the structure is complemented by optical simulations where great variations on the rotation order of magnitude and rotation sign are also obtained. The analytical model of the system shows that these variations are due to the interferences occurring in the layered structure.

Key words: magneto-optical recording, Kerr and Faraday rotations, rare-earth transition metal alloys, hysteresis loops, optical simulations, magnetic coupling.

1. Introduction

To overcome the density limit of optical recording devices in magneto-optical technology, an alternative is the use of multilayered structures. Techniques such as Magnetic Super Resolution (MSR) or Magnetic AMplification of Magneto-Optical Systems (MAMMOS) allow the increase of the recording density. The principles of such techniques are based on magnetic coupling between the storage and the readout layers. Studies of magnetic coupling can be realized by analyzing the Kerr and Faraday hysteresis loops. This gives indications on the magnetization rotation of each layer when subjected to an external magnetic field. The rare-earth transition metal alloys (RE-TM) magnetization is composed of two subnetworks, the rare-earth and the transition metal subnetworks whose magnetizations ($M_{\text{RE}}$ and $M_{\text{TM}}$) point in opposite directions. The resultant magnetization $M (= M_{\text{RE}} + M_{\text{TM}})$ is parallel to the dominant subnetwork magnetization. In the infrared and visible light wavelength, the Kerr and Faraday rotations are predominantly due to the transition metal magnetization. In order to understand the magnetic coupling phenomena, it is necessary to determine the directions and orientations of the resultant magnetizations and also those of the TM magnetizations. Considering a double magneto-optical (MO) layered structure, this paper deals with the relationship between the TM magnetization direction and the Kerr and Faraday rotations sign. First of all, based on a study of experimental data, we point out that this relationship is not straightforward. In the second part of the paper, a theoretical approach is developed to analyze the dependence of the Kerr and Faraday rotations. This includes an analytical model and optical simulations.

2. Experiment

2.1 Film structure

The film structure consists of two MO layers, which exhibit perpendicular anisotropy. A 25 nm TbFeCo layer is deposited on top of a 10 nm GdFeCo layer. The two alloys have their compensation temperature below room temperature, so they are both transition metal dominant and the TM and resultant magnetizations point in the same direction. The MO layers are deposited on a glass substrate, overcoated by Si$_3$N$_4$ layers to protect them against oxidation. The structure is presented on Fig. 1. Hysteresis loops are measured by Faraday and Kerr (polar configuration) effects using a 633 nm wavelength in a field up to 6.5 kOe.

![Fig. 1 Film structure](image)

2.2 Results

The results are presented on Fig. 2. On each hysteresis loops the total magnetization and the transition metal magnetization are indicated by the arrows. We can see in
the Faraday and the Kerr loops the switching of the two magnetic layers but the loops have different shapes. With Faraday measurement, the contributions from each layer are additive. For the Kerr configuration, the contributions have opposite signs. This shows that the MO rotations signs (Kerr and Faraday) are not directly related to the TM magnetization direction. So, if the compensation temperatures of the alloys are unknown, the interpretation of the experimental results can be wrong if we just take into account the hysteresis loop shape. A theoretical study is then necessary to point out the parameters that give rise to the effective MO rotation.

3. Theory

The MO effects originate from the interaction between light and material. Intrinsically, they are related to the electronic structure and the material response can be represented by the complex dielectric tensor from which the MO effects are evaluated. When measuring the MO rotation of a stack, multiple reflections that take place inside the sample have significant influence on the measurements. As a consequence, the effect of the optical constants and the layers thicknesses has to be taken into account. We propose to give the analytical expression of the complex Kerr rotation in the simplified case of a bilayered structure. We also use a matrix formalism to illustrate these parameters effects and to validate the experimental results.

3.1 Analytical model

When a linearly polarized light interacts with a magneto-optical material, the reflected wave is elliptically polarized due to the circular magnetic birefringence and dichroism of the RE-TM alloys. A convenient mathematical approach considers the left and right circular polarizations separately. These two polarizations propagate in the MO layers with different complex optical indices $N'$ and $N''$ given by:

$$N'' = n + i \kappa = (n + \Delta n) - i (k + \Delta k)$$

$$N' = n - i \kappa = (n - \Delta n) - i (k - \Delta k)$$

where the complex optical index of the magneto-optical layer is $N = n - ik$.

The corresponding reflection and transmission coefficients $R^+$ and $T^+$ allow then to calculate the Kerr and Faraday rotations respectively. For the analytical model, we limit our analysis to a bilayered structure which consists of two MO layers. The corresponding air/MO1/MO2/air configuration is drawn on Fig. 3. The MO layers thicknesses are sufficiently small (Cf. experimental structure on Fig. 1) to consider that the perpendicular incident light beam is reflected by the three interfaces noted N0/N1, N1/N2, and N2/N0 with respective reflection coefficients $R_{01}, R_{12}$ and $R_{20}$. For the right and left circular polarized lights, these coefficients are

$$R^+ = \frac{N'^+ - N''^+}{N'^+ + N''^+} = \frac{R_{01}^+ + R_{12}^+ e^{-2i\beta_1^+}}{1 + R_{01}^+ R_{12}^+ e^{-2i\beta_1^+}}$$

$$R^- = \frac{N'^- - N''^-}{N'^- + N''^-} = \frac{R_{20}^+ + R_{12}^- e^{-2i\beta_2^-}}{1 + R_{20}^+ R_{12}^- e^{-2i\beta_2^-}}$$

where $\beta_1^+ = 2\pi N^+ d_s / \lambda$ are the propagation constants of light of the MO layer $s$ with thickness $d_s$.

We define the complex Kerr rotation as

$$\phi_K = \theta_K + i \kappa_K$$

with

$$\theta_K = \frac{(\theta_R - \theta_L)}{2}$$

For thin films, $\theta_K$ and $\kappa_K \ll 1$, then

$$\frac{R^-}{R^+} = \exp\left(i \left(\theta_K - \theta_K^*\right)\right) = 1 + 2i\phi_K$$

Fig. 3: Schematic illustration of the reflected beam in the air/MO1/MO2/air configuration

From Eq. (4), if we neglect the second order in $\phi_K$, the apparent complex Kerr rotation for the air/MO1/MO2/air configuration can be expressed as follows:

$$\phi_K = a \phi_{K0} + e^{-2i\beta_1} \left|b \phi_{K1} + c \phi_{K2} + d \phi_{P1}\right|$$

$$\phi_{K0} = \frac{D1* D2}{D1 + D2}$$


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where
\[
a = 2R_{01}R_{12}R_{20}e^{-2i\beta_2} (1-e^{-4i\beta_1}) + R_{01}R_{20}^2 e^{-4i\beta_2} (R_{12}^2 e^{-4i\beta_1}) + R_{01} (1-R_{12}^2 e^{-4i\beta_1}) \\
b = R_{12} (1-R_{20} e^{-4i\beta_1}) \\
c = R_{20} e^{-2i\beta_2} (1-R_{12}^2) \\
d = e^{-2i\beta_1} (1-R_{01}^2) (R_{12} + R_{20} e^{-2i\beta_2}) + (R_{01} + R_{12} e^{-2i\beta_2}) R_{20} e^{-2i\beta_2} \\
D_1 = (R_{01} + R_{12} e^{-2i\beta_2}) + (R_{01} + R_{12} e^{-2i\beta_2}) R_{20} e^{-2i\beta_2} \\
D_2 = (1 + R_{01} R_{12} e^{-2i\beta_2}) + (R_{12} + R_{01} e^{-2i\beta_2}) R_{20} e^{-2i\beta_2} \\
\phi_{k0}, \phi_{k1}, \phi_{k2} \text{ are the complex Kerr rotations at the air/MO1, MO1/MO2 and MO2/air interfaces respectively.} \phi_{FS} \text{ is the eigenvalue of the Faraday rotation in the MO layer noted } s \left( \phi_{FS} = \pi d_s \left( N_s^+ - N_s^- \right) / \lambda \right)
\]

From Eq. (7) we can see that the effective Kerr rotation of the bilayered structure MO1/MO2 is a combination of the Kerr rotations induced at the three interfaces and the Faraday rotations of the MO layers. Depending on the layers thicknesses, the first reflected beam B0 will interfere destructively or constructively with the other ones B1, B2, B3, ... As the thickness increases, the apparent Kerr rotation will exhibit alternatively maximum and minimum values which can be either positive or negative. Equation 7 shows that these values are function of the layers thickness but also of the optical constants.

The Kerr rotation that occurs after the reflection on the MO layer is usually very small (a few tenths of degrees). The interference effect can then be used to enhance the apparent Kerr rotation of the film with proper layers thicknesses and material coated on the MO layer surface with adequate refractive index.

The experimental hysteresis loops on Fig. 2 have different shapes due to the different MO contributions. But we can also notice the top and bottom rounding on the Kerr loop that is absent on the Faraday one. Indeed, the magnetization profile in the bilayered structure combined with the fact that for the Kerr and Faraday measurements the resulting lights don’t come from the same reflected and transmitted beams can explain this effect.

This analytical model gives qualitative results of the parameters influence and allows to emphasize the MO contribution from each interface when the light undergoes multiple reflections. But when the layers number exceeds two, it becomes rapidly complicated and a matrix formalism is preferred.

### 3.2 Matrix formalism

We only consider the case of normal incidence. The wavelength is 633 nm. The optical simulations are based on Abélys formalism \(^7\) where each layer \(j\) is represented by a matrix \(M_j\), expressed by Eq. (8), and characterized by its thickness, optical (\(n\) and \(k\)) and magneto-optical constants (\(\Delta n\) and \(\Delta k\)) related to the dielectric tensor elements.

\[
M_j = \begin{pmatrix}
\cos(\beta_j) & iN_j \sin(\beta_j) \\
iN_j \sin(\beta_j) & \cos(\beta_j)
\end{pmatrix}
\]

The constants used in the calculation are given on Fig. 1. The optical constants \(n\) and \(k\) are experimental values whereas the magneto-optical constants represented by \(\Delta n\) and \(\Delta k\) are taken in Ref. 8. The Kerr and Faraday rotations are then respectively expressed by:

\[
\theta_k = \text{Im} \frac{R^+ - R^-}{R^+ + R^-} \quad \text{and} \quad \theta_f = \text{Im} \frac{T^+ - T^-}{T^+ + T^-}
\]

\(R^\pm\) and \(T^\pm\) are the reflection and transmission coefficients of the film for the right and left circular polarizations. They are defined by the elements of the film matrix \(M = \Sigma M_j\) and the substrate refractive index.

The calculation consists then in the determination of the relative sign of the two MO contributions as a function of one or two parameters.

### 3.3 Interpretation of the experimental results

The results of the simulation program are presented on the following cartographies (cf. Fig. 4,5 and 6). The black area corresponds to additive contributions of the two MO layers and the grey area represents contributions of opposite sign. By considering first of all the optical and MO constants as fixed (see the values reported on Fig. 1), we calculate the rotation contributions of the two MO layers as a function of the first and second \(Si_3N_4\) layers thickness noted respectively \(D_1\) and \(D_2\). Figure 4 shows that for the proposed film structure, the hysteresis Faraday loop shape can change depending on the dielectric layers

![Fig. 4 Relative Kerr and Faraday contributions sign as a function of the dielectric layers thicknesses](image-url)
thickness. Meanwhile, for the Kerr configuration, the two contributions always have opposite signs. For D1 equals to 20 nm and D2 equals to 30 nm, the simulation results agree with the experimental data, as it is indicated by the white and black dots on Fig. 4.

As already mentioned, the MO rotations depend not only on the layers thickness but also on the materials (the dielectric and the MO materials) and the wavelength through the optical constants. The results of the simulation at 633 nm, with fixed materials thicknesses and refractive indices but with the absorption coefficient k of the GdFeCo and TbFeCo layers varying from 2 to 4, are plotted on Fig. 5 for the Faraday configuration. In this case, we also obtain variations on the relative MO contributions sign and we still verify the experimental data.

The last point we focus on, concerns the influence of the substrate. Its refractive index N_substrate acts on the reflection coefficient at the top of the sample and this reflection contributes to the effective MO rotation. Figure 6 illustrates the N_substrate effect for the Faraday configuration. The simulation is again performed with dielectric layers thickness varying from 0 to 100 nm and increasing substrate refractive index. We can see that as N_substrate increases from 1.0 to 1.53, the grey area decreases. This observation is important for experimental interpretations if comparisons are made between multilayered structures deposited on different substrates.

4. Conclusion

In this article, we have studied experimentally and theoretically a magneto-optical bilayered structure. The corresponding Kerr and Faraday hysteresis loops clearly show that the MO rotation sign is not only defined by the transition metal magnetization direction. The theoretical analysis indicates that the rotations are influenced by the film structure through the layers thicknesses, the optical and magneto-optical constants and the substrate properties. We have shown that these parameters not only affect the MO rotation sign but also its magnitude. The observed variations in the MO rotation sign and magnitude are due to the interference effect caused by the multireflections of the light induced in the multilayered structure. This can lead to wrong interpretations of the experimental results. A careful analysis is then necessary. Nonetheless, the values of all these parameters can be judiciously adjusted to optimize the MO rotation, and consequently the readout signal.

References