Analyzing the Magnetic Influence on Magneto-optical Interactions

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Abstract
Here, we study the magneto-optical interactions in magnetic structures considering the dependence of the interactions with the magnetic field. We perform numerical simulations in a structure of magnetic nanowires, considering them as one chain of strongly interacting single-domain particles. Robustly, we obtained a quantitative value for the interactions, which allows us to classify them in two magneto-optical states: when the predominant magneto-optical interactions are demagnetizing (PMOID), or when the predominant magneto-optical interactions are magnetizing (PMOIM).

Keywords Magneto-optical · Magnetic states · Interacting system · Energy balance

1 Introduction

The recent interest of the scientific community in magneto-optical interactions has opened the possibility of a global understanding of characteristics not yet dazzled in nanomaterials [1–6]. Minimizing the bit size in one magneto-optical system for data recording is a challenge for optoelectronics and spintronics applications [3–14]. Such reduction produces an increase in the interactions between components of the structure. The scientific interest actual is the quantification (codification) of these interactions. One of the systems that have a high particle distribution density is the arrays of magnetic nanowires electrodeposited in alumina membranes [6, 8–14]. This type of system can present different magnetization reversal modes with a predominant coherent configuration [2, 8–20]. Such systems can be strongly influenced by magneto-optical interactions [2–21]. The influence is mainly detected during the magnetization process with the incidence of light. A striking feature of the magnetization process is that it is not possible to separate the parts of its hysteresis without losing information due to changes in the magnetic energies of the structure, which causes the magneto-optical interactions to be studied together with the purely magnetic interactions. Thus, the study of magneto-optical interactions can be performed using the remanent state obtained during the magnetization process [2].

In a particular system, the well-established normalized $\Delta m$ curves ($\Delta m_N$) produce results of the interaction effects, such curves are comparisons between isothermal remanent magnetization (IRM($H$)) and direct current demagnetization (DCD($H$)) curves, which define other physical quantities such as $m_r(H) = DCD(H)/IRM(H_{Max})$ and $m_p(H) = IRM(H)/IRM(H_{Max})$ that are normalized considering the value obtained with maximum magnetic field [2, 17, 18, 22–27]. In this paper, we present a numerical study on the predominant magneto-optical interactions in structures, for that, we perform numerical simulations in a system of magnetic nanowires, considering them as one chain of strongly interacting single-domain particles. After analyzing magneto-optical interactions, we observe two types of magneto-optical states, i.e., PMOID, and PMOIM, which reveal the main characteristics of magneto-optical energies. Our approach seeks to describe the light-matter interaction with the application of a magnetic field, where the light (in the case, white light) only serves to excite the magneto-optical effects, that is, all results are obtained considering the dependence of the magneto-optical interactions together with the purely magnetic interactions under the magnetic field.

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2 Continuous Approach

The effects of the magnetic interactions in structures have been studied by using \( \Delta m \) curves [17, 18, 22–29] or discrete models without analyzing the dependence directly on the magnetic field and light [2]. The \( \Delta m \) curves are obtained through the relationships between the \( m_d(H) \) and \( m_r(H) \) curves, where the initial magnetic state of the structure differentiates them. The model proposed by Stoner Wohlfarth [17, 27] reveals an intrinsic relationship between \( m_d(H) \) and \( m_r(H) \) for non-interacting structures. Based on this fact, we propose here that the magneto-optical interactions together with the purely magnetic interactions for non-interacting particles have one associated intensity that can be written as

\[
I_{N-1} = \left| \int_{H_i}^{H_f} \left( \frac{\eta_{N-1}}{\Delta H} \right) dH \right|, \tag{1}
\]

where \( H_f > H_i \), and \( \eta_{N-1} = [1 - 2m_r(H)] - m_d(H) \). The magnetic fields \( H_f \) and \( H_i \) represent the maximum and minimum fields in the interval \( \Delta H = H_f - H_i \), respectively. In most experimental systems, the minimum magnetic field \( H_i \) is zero. To better describe real systems, Henkel postulated that the difference in this behavior in a simple design was due to the interactions between the part of the structure. Usually, in experimental measurements, the data are far from the curve obtained with Eq. (1) [17, 18, 22–29]. Thus, Eq. (1) considers that the magnetization and demagnetization processes are the same. Qualitatively, the type of interaction was defined by inserting a term \( \Delta m \) in Eq. (1). Based on this, we propose here that the intensity of the magneto-optical interactions together with the purely magnetic interactions for interacting particles can be written as

\[
I_i = \left| \int_{H_i}^{H_f} \left( \frac{\eta_i}{\Delta H} \right) dH \right|, \tag{2}
\]

where \( \eta_i = \Delta m_N + [1 - 2m_r(H)] - m_d(H) \). The indices \( N-1 \) and \( i \) in Eqs. (1) and (2) are associated with \( \eta \) for systems without and with interactions. The methodology presented here for the calculation from the magneto-optical interactions together with the purely magnetic interactions uses Eqs. (1) and (2) resulting in a numerical value for the magneto-optical interactions of the structure. When the predominant magneto-optical interactions are demagnetizing (PMOID), \( \Delta m_N < 0 \); and when the predominant magneto-optical interactions are magnetizing (PMOIM), \( \Delta m_N > 0 \). Hence, the intensity value from the magneto-optical interactions is obtained through Eqs. (1) and (2) by

\[
I = \left| \int_{H_i}^{H_f} \left( \frac{\Delta m_N}{\Delta H} \right) dH \right|. \tag{3}
\]

Equation (3) represents both PMOID and PMOIM interactions so that we can rewrite it as

\[
i_k = \left| \int_{H_i}^{H_f} \left( \frac{\Delta m_N}{\Delta H} \right) dH \right| \rightarrow \begin{cases} \Delta m_N = \Delta m^p / |\Delta m^p_{Max}| < 0 \text{ for PMOID,} \\ \Delta m_N = \Delta m^m / |\Delta m^m_{Max}| > 0 \text{ for PMOIM.} \end{cases} \tag{4}
\]

where \( k = \text{PMOID} (\Delta m_N < 0) \) or \( \text{PMOIM} (\Delta m_N > 0) \).

3 Results and Discussion

Our results were obtained considering a nanowire as one chain of interacting ellipsoidal grains according to Fig. 1.

Experimentally, the length of the grains is on the order of 20 to 100 nm, as in single-domain particles [3–14]. Demagnetizing interactions are obtained frequently in experimental measurements [17, 18, 22–29], this is due to, in most cases, the magnetic response of structures being contrary to the applied magnetic field \( H \), leaving the system in a global demagnetized state. The dependence of \( \Delta m_N \) in terms of the magnetic field \( H \) on systems involving PMOID can be written as \( \Delta m^p / |\Delta m^p_{Max}| \).
where $\Delta m^D = -(H_D^C)^2 / [(H - H_D^C)^2 + (\Delta J_D^C)^2]$. $H_D^C$ is the critical demagnetizing field for $|\Delta m^D|$ maximum, i.e., for $|\Delta m^D_{\text{Max}}|$ and $\Delta J_D$ is the magneto-optical linewidth. For all our calculations, we considered $\Delta J_D = 1\% H_D^C$. The narrow magneto-optical linewidth condense the energy balance of the interactions so that they would produce a kind of avalanche similar to the magnetic skyrmion bubbles [30, 31].

Figure 2 shows the interactions (Regions I) considering the $\Delta m_N$ curves obtained with $H_D^C = 0.75$ kOe (Fig. 2(a)), $H_D^C = 2.5$ Oke (Fig. 2(b)), $H_D^C = 5.0$ kOe (Fig. 2(c)) and $H_D^C = 7.5$ kOe (Fig. 2(d)).

which are defined as interaction maps. The intensities values of the interactions were numerically calculated using Eq. (4), which are $I_{\text{PMOID}} = 0.26$ and $0.32$, $0.25$, and $0.21$, for Fig. 2(a)–(d), respectively. In this system, the magneto-optical behavior can often create magneto-optical effects due to the light-matter interaction, which are extremely important for the excitation or detection of spin waves using light [30–41]. Such magneto-optical interactions cause propagation of domain walls by light (see inset of Fig. 3(a)).

To analyze PMOIM, we consider the effects of demagnetization and magnetization on magneto-optical interactions as

$$\Delta m_{\text{Total}} = \Delta m^D / |\Delta m^D_{\text{Max}}| + \Delta m^M / |\Delta m^M_{\text{Max}}|$$

where $\Delta m^D = -(H_D^C)^2 / [(H - H_D^C)^2 + (\Delta J_D^C)^2]$ and $\Delta m^M = (H_M^C)^2 / [(H - H_D^C)^2 + (\Delta J_M^C)^2]$, which can also describe very well experimental measurements obtained in the laboratory [17, 18, 22–29]. Here, $\Delta J_M$ is the magneto-optical linewidth, in which we consider $\Delta J_M = 1\% H_M^C$ for all calculations. Figure 3(a)–(d) show the PMOID (Regions I) for the different $\Delta m^D / |\Delta m^D_{\text{Max}}|$ curves obtained with critical magnetic fields of $H_D^C = 0.75$ kOe, $H_D^C = 1.5$ kOe, $H_D^C = 3.0$ kOe, and $H_D^C = 6.0$ kOe, respectively. The same Fig. 3(a)–(d) also show the PMOIM (Regions II) for the different $\Delta m^M / |\Delta m^M_{\text{Max}}|$ curves obtained with critical fields of $H_D^C = 1.5$ kOe, $H_D^C = 3.0$ kOe, $H_D^C = 6.0$ kOe, and $H_D^C = 12$ kOe, respectively. As results obtained with the calculation of PMOID and PMOIM interaction maps of Fig. 3 using Eq. (4), we bring the values, $I_{\text{PMOID}} = 0.12$, 0.01, 0.21, and 0.12 for PMOIM behaviors, and $I_{\text{PMOIM}} = 0.35$, 0.21, 0.27, and 0.35 for PMOIM behaviors, which are shown in Table 1.

![Fig. 2](Image 78x180 to 284x330) (Color online) Interaction maps calculated from the magneto-optical interactions in terms of the applied magnetic field to different critical demagnetizing field $H_D^C$. a $H_D^C = 0.75$ kOe, b $H_D^C = 2.5$ Oke, c $H_D^C = 5.0$ kOe and d $H_D^C = 7.5$ kOe. The interaction maps were results obtained with Eqs. (1) and (2), and the intensities were calculated using Eq. (4), which are $I_{\text{PMOID}} = 0.26$ (item a), $I_{\text{PMOID}} = 0.32$ (item b), $I_{\text{PMOID}} = 0.25$ (item c), and $I_{\text{PMOID}} = 0.21$ (item d).

![Fig. 3](Image 331x676 to 422x730) (Color online) Interaction maps calculated from the magnetic interactions in terms of the magnetic field $H$ to different critical fields demagnetizing $H_D^C$ and magnetizing $H_M^C$. a $H_D^C = 0.75$ kOe and $H_M^C = 1.5$ kOe, b $H_D^C = 1.5$ kOe and $H_M^C = 3.0$ kOe, c $H_D^C = 3.0$ kOe and $H_M^C = 6.0$ kOe, and d $H_D^C = 6.0$ kOe and $H_M^C = 12$ kOe. The interaction maps were results determined with Eqs. (1) and (2), and the intensities were calculated using Eq. (4), which are for the PMOID interactions, $I_{\text{PMOID}} = 0.12$ (item a), $I_{\text{PMOID}} = 0.01$ (item b), $I_{\text{PMOID}} = 0.21$ (item c), and $I_{\text{PMOID}} = 0.12$ (item d) and for PMOIM interactions, $I_{\text{PMOIM}} = 0.35$ (item a), $I_{\text{PMOIM}} = 0.21$ (item b), $I_{\text{PMOIM}} = 0.27$ (item c), and $I_{\text{PMOIM}} = 0.35$ (item d).

The angular behavior of magneto-optical interactions in a strongly interacting system, we present in Fig. 4, the angular dependence from the interactions.

| $H_D^C$ (kOe) | $H_M^C$ (kOe) | $I_{\text{PMOID}}$ | $I_{\text{PMOIM}}$ |
|--------------|---------------|-------------------|-------------------|
| 0.75         | 1.5           | 0.12              | 0.35              |
| 1.5          | 3.0           | 0.01              | 0.21              |
| 3.0          | 6.0           | 0.21              | 0.27              |
| 6.0          | 12            | 0.12              | 0.35              |
considering the relation \( \Delta m_{\text{Total}} = (\Delta m_D^P/|\Delta m_{\text{Max}}^D| + \Delta m_M^M/|\Delta m_{\text{Max}}^M|)\cos(\theta_H) \) similar to the case of a system without application of light \([2, 8, 13, 16, 29]\) to \( H_D^D = 3 \) kOe and \( H_C^D = 6 \) kOe. This approach describes in detail the behavior of magneto-optical interactions in a magnetic nanowire modeled as a chain of interacting ellipsoidal grains \([8, 25–28]\). Such dependence shows that for a magnetic field applied parallel to the wire axis, the PMOID and PMOIM behaviors are maximum and decrease with increasing angle \( \theta_H \). This behavior is the result of the decrease in interactions between the grains as the magnetic field becomes perpendicular to the wire axis. In Fig. 5 we show the general variation of the intensity values from the magneto-optical interactions \( I_{\text{PMOID}} \) and \( I_{\text{PMOIM}} \) as a function of the angle \( \theta_H \), where we use \( \Delta m_{\text{Total}} = (\Delta m_D^P/|\Delta m_{\text{Max}}^D| + \Delta m_M^M/|\Delta m_{\text{Max}}^M|)\cos(\theta_H) \) with \( H_D^D = 3 \) kOe, \( \Delta J_D = 1\%H_C^D \), \( H_C^D = 6 \) kOe and \( \Delta J_M = 1\%H_C^D \). We define for any wavelength (white light range, assuming an output power of approximately 0.5 W \([38, 40, 41]\)), the best conditions to observe the maximum number of magneto-optical interactions, which are when the PMOID and PMOIM have similar intensities.

### 4 Conclusion

The behavior of magneto-optical interactions in magnetic structures revealed two types of predominant magneto-optical states, i.e., PMOID, and PMOIM. Understanding how each state arises due to the different effects produced during the magnetization process makes its study of fundamental importance for applications of devices in areas such as quantum computing and engineering. Our results also represent an efficient way to describe the behavior of magneto-optical interactions by directly considering the angular dependence of the interactions and the magnetic field during the magnetization process. Furthermore, the obtained results show that the effects that cause global magnetic states (demagnetized and magnetized) influence the excitation of spin waves using a conventional method or the light-matter interaction. In terms of fundamentals, the results show a significant advance in understanding the behavior of fundamental interactions in magnetic structures.

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