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Theory study of domain visibility optimization in single rotating compensator Kerr microscopy

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ABSTRACT

In this work, an optical elements azimuth optimization method in single rotating compensator domain imaging system was provided to improve the domain image visibility. After that, simulations were performed on 200 nm permalloy films and results displayed that the Kerr rotations exhibited a periodic increase-maximum-decrease tendency with the compensator rotating in one period. The Kerr effect enhancement can be achieved by collecting the light intensity at four compensator azimuths in a rotating period of the compensator. Furthermore, simulation results indicated that this method could effectively enhance the domain image contrast and signal-to-noise ratio of the permalloy film by setting the polarizer and analyzer at the optimal azimuth. What's more, to confirm the validity of this method, simulations were performed on 200 nm optically anisotropic cobalt film. The 2D image contrast figure indicated that unlike the isotropic permalloy film, there existed two large image contrast regions which are corresponding well to the extraordinary and ordinary light vector of the reflected light.

1. Introduction

Magnetic materials are widely used in magnetic data storage and spintronic devices. Magnetic domains and their substructures build a bridge between the basic microscopic physical properties and the macroscopic characteristics [1–3]. So the domain behavior and imaging techniques are quite important in domain research. Magneto-optical Kerr effect (MOKE) is widely used to probe the domain structure especially for the ultrathin film based on its high spatial, temporal resolution and external magnetic compatibility [4,5]. The Kerr microscopy obtains the domain images by detecting the magneto-optical response of the magnetic materials versus different inner magnetizations. However, the magneto-optical response and reflected light intensities can be affected by the polarizer and analyzer azimuth. Thus, the image quality directly depends on the configuration of the optical elements and the signal detection. So optimization of system configurations in Kerr microscopy can effectively improve the detecting sensitivity and domain image contrast.

Generalized magneto-optical ellipsometry (GME) combines MOKE and the traditional ellipsometry, which can obtain the magneto-optical and optical properties of the magnetic film in one single experiment [6–9]. In our previous reports, using GME, we investigated the optimization of polarizer and analyzer azimuth in Kerr imaging system to enhance the image contrast and signal to noise ratio (S/N) on a 200 nm permalloy film [10,11]. Results showed that the image contrast and S/N could be effectively enhanced by setting the polarizer and analyzer at the optimal azimuth. However, for materials with a large elliptical component in the reflected Kerr light, the reflected elliptically polarized light could not be easily extincted after passing the analyzer, which would decrease the Kerr rotations. Thus, a rotatable quarter wave plate was needed to compensate the ellipticity.

In this work, we gave a detailed description of the domain imaging theory based on a single rotating compensator (a quarter wave plate) Kerr microscopy. After that, the GME experimental data were used to investigate the optimal compensator azimuth to improve the magneto-optical response. Then, simulations were performed on 200 nm permalloy films to study the optimizations of polarizer and analyzer azimuth to enhance the domain image contrast and the S/N. Furthermore, the domain image contrast of the optically anisotropic cobalt film was investigated and results confirmed the validity of this method. Additionally, in this work, a two-dimensional coordinate system with axes parallel (index p) and perpendicular (index s) to the plane of incidence was used. All the polarizer and analyzer azimuths were relative to the s-direction.

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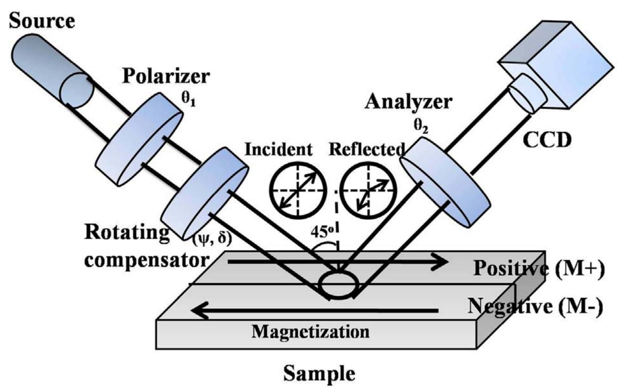

Fig. 1. Schematic of single-rotating compensator Kerr imaging system.

2. Theory

Magneto-optical phenomena are classified according to the orientation of the electromagnetic wave vector of light emission relative to the magnetic field [3]. As is shown in Fig. 1, when the light is reflected from the domain surface, the polarizations are manipulated by the positive and negative magnetizations, respectively, leading to a polarization difference of the reflected light. When the reflected light passes through an analyzer, the polarization difference will be transformed to the light intensity difference, leading to the fact that one domain appears "dark" and the adjacent one appears "bright". By detecting the local distribution of the "light" and "dark" light, the domain image of the magnetic material can be obtained [12].

As is described above, the polarization change occurs in the reflection process. When the incident light vector is reflected from the material surface, the electric field received by the detector can be determined as [7]

$$E_D = A{\cdot}R{\cdot}C{\cdot}P{\cdot}E_I, \tag{1}$$

where E_I, P, A and C are the Jones matrices of the incident polarized light, polarizer, analyzer and compensator, respectively and R is the Fresnel reflection matrix.

The polarizer and analyzer Jones matrices P and A can be defined as

$$A = \begin{pmatrix} \cos^2(\theta_2) & \sin\theta_2\cos\theta_2 \\ \sin\theta_2\cos\theta_2 & \sin^2(\theta_2) \end{pmatrix} \tag{2}$$

and

$$P{\cdot}E_I = \begin{pmatrix} \cos\theta_1 \\ \sin\theta_1 \end{pmatrix}, \tag{3}$$

where θ_1 and θ_2 refer to the polarizer and analyzer azimuth relative to the s orientation (as shown in Fig. 1). The characteristic Jones matrix of an oblique retarder whose fast axis makes an angle φ with the s-axis can be given as

$$C(\delta,\varphi) = \begin{bmatrix} \cos\frac{\delta}{2} + i\sin\frac{\delta}{2}\cos 2\varphi & i\sin\frac{\delta}{2}\sin 2\varphi \\ i\sin\frac{\delta}{2}\sin 2\varphi & \cos\frac{\delta}{2} - i\sin\frac{\delta}{2}\cos 2\varphi \end{bmatrix}, \tag{4}$$

where δ is the phase difference introduced by the retarder. The Fresnel reflective matrix R can be written as

$$R = \begin{pmatrix} r_{ss} & r_{sp} \\ r_{ps} & r_{pp} \end{pmatrix}, \tag{5}$$

where r_{ss}, r_{sp}, r_{ps} and r_{pp} are the Fresnel reflection coefficients which are determined by the incident angle, light wavelength and the optical and magnetic parameters of the material [13]. r_{ss} and r_{pp} are the conventional optical reflective coefficients. While, r_{sp} and r_{ps} are the inner magnetization induced reflective coefficients. So, for nonmagnetic case, the Fresnel reflective matrix can be obtained as

$$R_1 = \begin{bmatrix} r_{ss} & \\ & r_{pp} \end{bmatrix}. \tag{6}$$

As a consequence, for magnetic film, the received light intensity under positive magnetization can be obtained as [9]

$$I(M+) = E_D{\cdot}E_D^*. \tag{7}$$

By taking Eqs. (1)–(5) into Eq. (7), the received intensity can be calculated as

$$I(M+) = I_0(1 + \alpha\cos(2\varphi) + \beta\sin(2\varphi)), \tag{8}$$

where α and β are the combination of the Fresnel reflective matrix coefficients. However, for nonmagnetic film, the light intensity can be given as.

$E_{D1} = A \cdot R_1 \cdot C \cdot P \cdot E_I$, and

$$I(M=0) = E_{D1}{\cdot}E_{D1}{}^*. \tag{9}$$

Then the Kerr signal can be calculated as [14]

$$\delta I = I(M_+) - I(M_-) = 2(I(M+) - I(M=0)). \tag{10}$$

In this equation, $I(M_+)$ and $I(M_-)$ are the intensities of the reflected light under positive and negative magnetizations, respectively.

3. Simulations and discussions

GME is a widely used technique in detecting the magneto-optical properties of the magnetic materials. Through GME, the Fresnel reflective matrix coefficients in Eq. (5) can be obtained. In Berger's work [7], the GME experiment was performed on a 200 nm permalloy film with the incident angle and wavelength of 45° and 632.8 nm, respectively. In this work, using the data in Berger's work, simulations were performed to investigate the enhancement of domain image visibility of 200 nm Permalloy film in this single-rotating compensator Kerr imaging system.

As shown in Fig. 1, for two domains with opposite magnetization directions, the Kerr amplitudes differ only in sign. Thus, the Kerr rotation can be calculated as

$$\theta_k = 2{\cdot}\eta{\cdot}\frac{I(M+) - I(M=0)}{I(M=0)}, \tag{11}$$

where η is the angle of the analyzer deviated from the extinction place. As shown in Eqs. (8)–(11), the Kerr rotation can be affected by the compensator azimuth. So the Kerr rotation enhancement can be obtained by setting the compensator at the optimal azimuth.

Fig. 2 shows the Kerr rotations as a function of the compensator azimuth with setting η equals 1. The Kerr rotation sign just represents the polarization directions. As is revealed in this figure, with the compensator azimuth increasing from 0°–360°, the Kerr rotation exhibits a periodic tendency. In the first period, the Kerr rotation shows an "increase-maximum-decrease" tendency. The maximum Kerr rotation (− 0.4376) can be obtained at the compensator azimuth of 89.2°.

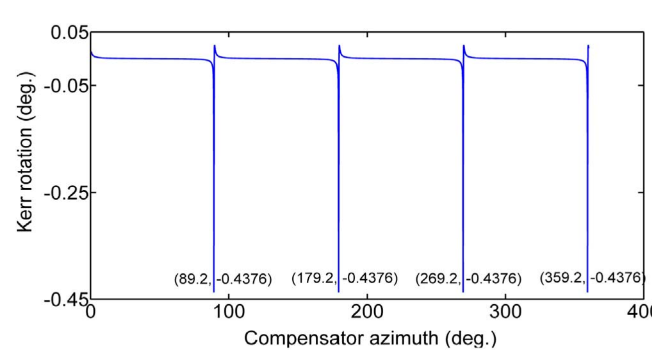

Fig. 2. The Kerr rotations as a function of the compensator azimuth with the polarizer and analyzer set at (0°, 90°).

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