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## Measurement of Kerr rotation and ellipticity in magnetic thin films by MOKE magnetometry 🕫

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#### ABSTRACT

When polarized light is incident on a magnetic material, the magneto-optical Kerr effect (MOKE) rotates the polarization and induces ellipticity in the reflected light, which allows the magnetization direction to be probed optically. The Kerr rotation and ellipticity determine the magnitude of the effect and are usually measured using dedicated ellipsometers. Here, we demonstrate a simple method for extracting Kerr rotation and ellipticity in magnetic thin films using a conventional MOKE magnetometer consisting of two polarizers and a quarter waveplate. Using this technique, we report the longitudinal Kerr angle of BiYIG, GdCo, and TbCo. We additionally observe a linear decrease in polar complex Kerr angle magnitude in 3 nm GdCo films as the atomic fraction of Gd is increased.

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#### **I. INTRODUCTION**

The magneto-optical Kerr effect (MOKE) describes the change in polarization orientation and ellipticity that occurs when linearly polarized incident light is reflected from a magnetic surface, proportional to the magnetization, M. MOKE magnetometry takes advantage of this effect by casting the polarization change into a detectable intensity change via a quarter waveplate and analyzer. MOKE magnetometry is ubiquitous as a high-speed magnetic characterization technique with uses ranging over determination of coercive or exchange bias fields,<sup>1,2</sup> dominant sublattice in ferrimagnets,<sup>3</sup> domain wall velocity,<sup>6–9</sup> and ultrafast magnetization dynamics.<sup>10,11</sup>

The strength of the MOKE-induced polarization change is characterized by the complex Kerr angle,  $\Phi_k = \theta_k + i\epsilon_k$ . Here,  $\theta_k$ is the Kerr rotation angle, which describes the rotation of the polarization axis, and  $\epsilon_k$  is the Kerr ellipticity angle. The magnitude of  $\Phi_k$  determines the MOKE signal strength, and the relative contributions of  $\theta_k$  and  $\epsilon_k$  determine the optimal configuration for a MOKE polarimeter.  $\Phi_k$  plays a similar role in other magneto-optic measurement techniques such as in Brillouin light scattering (BLS) for detection of magnons.<sup>12,13</sup> Consequently, a simple technique for quantitative measurement of the complex Kerr angle is of considerable practical utility.

Conventional techniques for measuring the real and imaginary components of  $\Phi_k$  typically rely on specialized ellipsometers containing photoelastic modulators<sup>14,15</sup> or require precise knowledge of the Fresnel reflection coefficients of the optical components in the setup.<sup>16</sup> In this paper, we establish a simple technique for measuring the Kerr rotation and ellipticity angles using a standard MOKE magnetometer or MOKE microscope in polar and longitudinal geometries. In Sec. II, we outline the measurement technique, and we then apply it to characterize several exemplary magnetic films in Sec. III.

#### **II. NORMALIZED MOKE SIGNAL ANALYTICAL EXPRESSION**

#### A. Quarter waveplate fast axis parallel to incident polarization

MOKE magnetometry is typically carried out in one of the three geometries: polar, where M and the light path are perpendicular to the sample surface; longitudinal, where M is parallel to the plane of reflection; and transverse, where M is perpendicular to the plane of reflection.<sup>17</sup> In the polar and longitudinal geometries, MOKE results in a transformation of incident linearly polarized light to elliptical, rotated light upon reflection from a magnetized sample, proportional to M.<sup>18</sup> The subsequent analysis applies to these two geometries.

A schematic of a longitudinal MOKE magnetometer is shown in Fig. 1(a). The light is initially s-polarized by the input polarizer



**FIG. 1.** Longitudinal MOKE magnetometer and normalized MOKE signal model. (a) Schematic of a longitudinal MOKE magnetometer showing the initial polarizer, P; quarter waveplate, W; analyzer, A; and photodetector, PD. The black double-headed arrows signify the optical axes of the polarizers. The red double-headed arrow is the fast axis of W. (b) MOKE hysteresis loop of 25 nm Gd<sub>0.33</sub>Co<sub>0.67</sub> showing the definitions of  $\overline{I}$  and  $\Delta I$ . (c) Predicted normalized MOKE intensity for a magnetic material with  $\theta_k = \epsilon_k = 0.1^{\circ}$  and  $\gamma_D = 4 \times 10^{-4}$ .

(P), reflects off the magnetic sample, proceeds through a quarter waveplate (W) and analyzer (A), and finally reaches the photodetector. This setup can be adapted to a polar geometry by reducing the incidence angle and adding a non-polarizing beamsplitter after P.

The polarization of a ray of light can be represented by a Jones vector  $\boldsymbol{E} = \begin{pmatrix} E_x \\ E_y \end{pmatrix}$ , where  $E_x$  and  $E_y$  are the complex amplitudes of the electric field components of the ray of light in the horizontal and vertical directions, respectively. For the longitudinal geometry shown in Fig. 1(a), the horizontal and vertical components are taken to be *s*- and *p*-polarized light, respectively. If the incident light is *s*-polarized, the reflected light is described by

$$E_{sample} = \frac{1}{\sqrt{1+b^2}} \begin{pmatrix} 1\\ be^{i\delta} \end{pmatrix},\tag{1}$$

with  $b = \frac{E_y}{E_x}$  and  $\delta = \delta_y - \delta_x$ , the phase difference between orthogonal components. The quantities *b* and  $\delta$  are related to the orientation angle,  $\theta$ , and ellipticity angle,  $\epsilon$ , by<sup>19,20</sup>

$$\tan 2\theta = \frac{2b\cos\delta}{1-b^2}, \ \sin 2\epsilon = \frac{2b\sin\delta}{1+b^2}.$$
 (2)

For small  $\theta$  and  $\epsilon$ , this reduces to

$$b = \sqrt{\theta^2 + \epsilon^2}, \quad \delta = \arctan \frac{\epsilon}{\theta}.$$
 (3)

The Jones vector of the light after passing through W and A is given by the product of the Jones matrices,

$$\begin{aligned} \mathbf{E}_{out} &= \begin{pmatrix} E_{out,x} \\ E_{out,y} \end{pmatrix} = R^{-1}(\phi_{A,abs}) P_y R(\phi_{A,abs}) R^{-1}(\phi_{W,f,abs}) W_x R(\phi_{W,f,abs}) \mathbf{E}_{sample} \\ R(\phi) &= \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix}, P_y = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, W_x = \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}. \end{aligned}$$
(4)

ough W

Here,  $R(\phi)$  is the counterclockwise (CCW) rotation matrix,  $P_y$  is a vertically oriented polarizer, and  $W_x$  is a quarter waveplate with a horizontal fast axis, parallel to the incident polarization.  $\phi_{A,abs}$  and  $\phi_{W,f,abs}$  are the CCW angles of the analyzer from vertical (*p*-axis) and the quarter waveplate fast axis from horizontal (*s*-axis) as indicated in Fig. 1(a). The intensity at the photodetector is then  $I = E_{out,x}E_{out,x}^* + E_{out,y}E_{out,y}^*$ <sup>19</sup> which takes the form

$$I = \frac{1}{4} \left[ (\theta^{2} + \epsilon^{2} - 1) \cos 2\phi_{A,abs} + (\theta^{2} + \epsilon^{2} - 1) \cos \left( 2(\phi_{A,abs} - 2\phi_{W,f,abs}) \right) + 2(1 + \theta^{2} + \epsilon^{2}) + 2\epsilon \sin \left( 2(\phi_{A,abs} - \phi_{W,f,abs}) \right) -2\theta \cos \left( 2(\phi_{A,abs} - \phi_{W,f,abs}) \right) \sin 2\phi_{W,f,abs} \right].$$
(5)

Applying a small-angle approximation for  $\phi_A$  and  $\phi_{W,f}$  (since MOKE magnetometers operate near extinction) and keeping terms through second order gives

$$I(\theta, \epsilon) \approx \theta^{2} + \epsilon^{2} + 2\epsilon \phi_{A,abs} - 2(\theta + \epsilon + \phi_{A,abs}) + \phi_{A,abs}^{2} + 2\phi_{W,f,abs}^{2} + \gamma_{D}.$$
(6)

Here, we have added a phenomenological depolarization factor,  $\gamma_D$ , to account for the limitations of physical optical components, following Ref. 18. The depolarization factor is a measure of the quality of the optical system and is equivalent to the reciprocal of the extinction ratio.  $\theta$  and  $\epsilon$  describe the total rotation and ellipticity imparted to light reflected off the sample and can be separated into a Kerr component,  $\theta_k$  or  $\epsilon_k$ , and non-Kerr component,  $\theta_0$  or  $\epsilon_0$ ,

$$\theta = \theta_k + \theta_0, \quad \boldsymbol{\epsilon} = \boldsymbol{\epsilon}_k + \boldsymbol{\epsilon}_0.$$
 (7)

Only the Kerr components,  $\theta_k$  and  $\epsilon_k$ , change sign under a reversal in M, resulting in the MOKE signal,  $\Delta I$ ,

$$\Delta I = I_{M^+} - I_{M^-} = I(\theta_k + \theta_0, \epsilon_k + \epsilon_0) - I(-\theta_k + \theta_0, -\epsilon_k + \epsilon_0),$$
(8a)

$$\Delta I = 4(\theta_0 \theta_k + \boldsymbol{\epsilon}_k (\boldsymbol{\epsilon}_0 + \boldsymbol{\phi}_{A,abs}) - (\boldsymbol{\epsilon}_k + \theta_k) \ \boldsymbol{\phi}_{W,f,abs}).$$
 (8b)

The average intensity,  $\overline{I}$ , is

$$\bar{I} = \frac{1}{2}(I_{M^+} + I_{M^-}) = \frac{1}{2} \left[ I(\theta_k + \theta_0, \boldsymbol{\epsilon}_k + \boldsymbol{\epsilon}_0) - I(-\theta_k + \theta_0, -\boldsymbol{\epsilon}_k + \boldsymbol{\epsilon}_0) \right].$$
(9a)

$$\bar{I} = \theta_k^2 + \epsilon_k^2 + \theta_0^2 + (\epsilon_0 + \phi_{A,abs})^2 -2(\theta_0 + \epsilon_0 + \phi_{A,abs})\phi_{Wf,abs} + 2\phi_{Wf,abs}^2 + \gamma_D.$$
(9b)

A MOKE hysteresis loop defining  $\Delta I$  and  $\overline{I}$  is shown in Fig. 1(b). Precisely aligning optical axes of the two polarizers and waveplate requires removing those components from the magnetometer and is experimentally tedious as a result. In a MOKE magnetometer, it is generally more convenient to locate extinction while a magnetic sample is inserted. Using Eq. (9b), the analyzer and waveplate extinction angles are  $\phi_{A,ext} = \theta_0 - \epsilon_0$  and  $\phi_{W,f,ext} = \theta_0$ . Thus, the non-Kerr rotation and ellipticity only add an offset to the analyzer and waveplate angles. Defining angles relative to extinction,  $\phi_A = \phi_{A,abs} - \phi_{A,ext}$  and  $\phi_{W,f} = \phi_{W,f,abs} - \phi_{W,f,ext}$ , and combining Eqs. (8b) and (9b) give the normalized MOKE signal,  $\frac{\Delta I}{I}$ ,

$$\frac{\Delta I}{\bar{I}} = \frac{4(\boldsymbol{\epsilon}_k \phi_A - (\boldsymbol{\epsilon}_k + \theta_k) \phi_{Wf})}{\theta_k^2 + \boldsymbol{\epsilon}_k^2 - 2\phi_A \phi_{Wf} + \phi_A^2 + 2\phi_{Wf}^2 + \gamma_D}.$$
 (10)

Figure 1(c) shows the normalized MOKE intensity near extinction for  $\theta_k = \epsilon_k = 0.1^\circ$  and  $\gamma_D = 4 \times 10^{-4}$ . The extrema straddle extinction ( $\phi_A = \phi_{W_f} = 0$ ) and change polarity across extinction. The magnitude of the extrema and their corresponding locations are given by

$$\left(\frac{\Delta I}{\overline{I}}\right)_{crit} = \begin{cases} \pm \frac{2|\Phi_k|}{\sqrt{\gamma_D}}, \ \theta_k > \epsilon_k \text{ or } \theta_k = \epsilon_k < 0\\ \mp \frac{2|\Phi_k|}{\sqrt{\gamma_D}}, \ \theta_k < \epsilon_k \text{ or } \theta_k = \epsilon_k > 0 \end{cases}, \quad (11a)$$

$$\phi_{A,f,crit} = \mp |\boldsymbol{\epsilon}_{k} - \boldsymbol{\theta}_{k}| \frac{\sqrt{\gamma_{D}}}{|\boldsymbol{\Phi}_{k}|} , \quad \phi_{W,f,crit} = \pm sgn(\boldsymbol{\epsilon}_{k} - \boldsymbol{\theta}_{k}) \ \boldsymbol{\theta}_{k} \frac{\sqrt{\gamma_{D}}}{|\boldsymbol{\Phi}_{k}|}.$$
(11b)

From Eq. (11a), the magnitude of the normalized MOKE  $\overline{\Phi}_{R}$  signal peak is directly proportional to  $|\Phi_k|$  and inversely proportional to the depolarization. In general, the signal-to-noise ratio (SNR) of MOKE magnetometry can be expressed as

$$SNR = \frac{\Delta I}{g_1 \overline{I} + g_2}, \qquad (12) \quad \overset{\overline{Q}}{\underset{\overline{Q}}{\overline{I}}}$$

where  $g_1$  is an optical noise coefficient, which incorporates intensitydependent noise contributions such as shot noise and laser noise, and  $g_2$  incorporates intensity-independent noise.<sup>18,21,22</sup> In wide-field MOKE microscopy, typically a number of images N is averaged to reduce the noise by a factor  $N^{1/2}$ . In the high N limit, the dominant noise contribution is the variation in pixel-to-pixel responsivity of the detecting camera sensor, known as the photoresponse non-uniformity (PRNU) of the sensor, and Eq. (12) reduces to

$$(SNR)_{max} = \frac{\Delta I}{\overline{I}g_{PRNU}},$$
 (13)

with  $g_{PRNU}$  quantifying the PRNU of the sensor (typically expressed as a percentage). Since the PRNU is a fixed property of the sensor, maximizing SNR requires maximizing the normalized MOKE signal,  $\Delta I/\bar{I}$ . As a result, locating the  $\Delta I/\bar{I}$  extrema (by adjusting  $\phi_A$ and  $\phi_{Wf}$ ) and minimizing depolarization are critical to imaging samples with low Kerr angles via MOKE microscopy.

Figures 2(a)–2(c) show the normalized MOKE signal with  $|\Phi_k| = 0.1^{\circ}$  and  $\gamma_D = 4 \times 10^{-4}$  for various combinations of Kerr rotation and ellipticity. Without Kerr ellipticity ( $\epsilon_k = 0$ ), the  $\Delta I/\bar{I}$ 

peaks occur along a +45° line with the  $\phi_A$  axis, meaning equal rotations of waveplate and analyzer from extinction are required for the maximum signal. However, without Kerr rotation ( $\theta_k$ ), the extrema fall along the  $\phi_A$  axis. When both Kerr rotation and ellipticity equally contribute, the extrema straddle the  $\phi_A$  axis. Defining  $\psi_f$  as the angle of the extrema with the  $\phi_A$  axis,

$$\tan \psi_f = \frac{\phi_{W,f,crit}}{\phi_{A,f,crit}} = \frac{-\theta_k}{\epsilon_k - \theta_k}.$$
(14)

From Eq. (14), the angle of the  $\Delta I/\bar{I}$  extrema determines the ratio of  $\theta_k$  to  $\epsilon_k$ . Combining this result with the magnitude of the  $\Delta I/\bar{I}$  peak, given in Eqs. (11a) and (11b), allows for the unique determination of magnitude and sign of  $\theta_k$  and  $\epsilon_k$ .

### B. Quarter waveplate slow axis parallel to incident polarization

The average intensity,  $\overline{I}$ , relative to extinction is identical for a quarter waveplate regardless of whether the fast or slow axis is parallel to the incident polarization direction. As a result, the fast and slow axes can easily be mistaken for one another. However, this mistake will result in an inverted sign for  $\epsilon_k$ . The fast axis can be verified using the same components as a MOKE magnetometer, following Ref. 23. Following the same methods as described in Sec. II A, the normalized MOKE intensity with a waveplate slow axis parallel to incident polarization is (relative to extinction),

$$\frac{\Delta I}{\bar{I}} = \frac{-4(\boldsymbol{\epsilon}_k \phi_A + (\theta_k - \boldsymbol{\epsilon}_k) \phi_{W,s})}{\theta_k^2 + \boldsymbol{\epsilon}_k^2 - 2\phi_A \phi_{W,s} + \phi_A^2 + 2\phi_{W,s}^2 + \gamma_D}.$$
(15)

The extrema are

$$\left(\frac{\Delta I}{\bar{I}}\right)_{crit} = \pm \frac{2|\Phi_k|}{\sqrt{\gamma_D}} sgn(\epsilon_k + \theta_k), \qquad (16a)$$



FIG. 2. Normalized MOKE signal for different Kerr rotation and ellipticity values. (a)–(c) Normalized MOKE signal with waveplate fast axis parallel to incident polarization. (d)–(f) Normalized MOKE signal with waveplate slow axis parallel to incident polarization.



FIG. 3. Normalized MOKE signal for (a) 50 nm BiYIG, (b) 25 nm Gd<sub>0.33</sub>Co<sub>0.67</sub>, and (c) 6 nm Tb<sub>0.12</sub>Co<sub>0.88</sub> with quarter waveplate slow axis parallel to incident polarization. Contour lines show the fitted function.

$$\phi_{A,s,crit} = \mp |\boldsymbol{\epsilon}_{k} + \theta_{k}| \frac{\sqrt{\gamma_{D}}}{|\Phi_{k}|}, \quad \phi_{W,s,crit} = \mp sgn(\boldsymbol{\epsilon}_{k} + \theta_{k}) \ \theta_{k} \frac{\sqrt{\gamma_{D}}}{|\Phi_{k}|},$$
(16b)

and the angle with the  $\phi_A$  axis is

$$\tan \psi_s = \frac{\phi_{W,s,crit}}{\phi_{A,s,crit}} = \frac{\theta_k}{\epsilon_k + \theta_k}.$$
 (17)

The differences between the two waveplate orientations are shown in Fig. 2. With no Kerr ellipticity, the normalized MOKE signal is independent of waveplate orientation [Figs. 2(a) and 2(d)], whereas with no Kerr rotation, the two orientations result in opposite MOKE signal polarities [Figs. 2(b) and 2(e)]. Finally, mixed contributions to the Kerr angle result in qualitatively different plots for each orientation [Figs. 2(c) and 2(f)]. Despite these qualitative differences, however, mistaking the waveplate optical axes only results in an inverted Kerr ellipticity; the magnitudes (dependent on the peak height) and sign of the Kerr rotation are unaffected.

#### III. EXPERIMENTAL MOKE PARAMETER MEASUREMENTS

The Kerr angles of BiYIG, GdCo, and TbCo were measured using the expressions in Sec. II. The BiYIG  $(Bi_{0.8}Y_{2.2}Fe_5O_{12})$ 

sample was prepared by pulsed laser deposition on  $Gd_3Ga_5O_{12}$  as described elsewhere.<sup>24,25</sup> The remaining samples were grown on Si by D.C. magnetron sputter deposition with layer structure Ta(4)/Pt (4)/RECo/Ta(4)/Pt(2) with RE = Gd or Tb, and the values in parenthesis represent the thickness in nm. Samples of 50 nm BiYIG, 25 nm  $Gd_{0.33}Co_{0.67}$ , and 6 nm  $Tb_{0.12}Co_{0.88}$  with in-plane anisotropy were analyzed using a longitudinal MOKE magnetometer with a  $\frac{1}{2}$  the quarter waveplate was oriented with its slow axis along the s-pole, parallel to the polarization of the table of table of the table of tabl s-pole, parallel to the polarization of the incident light. MOKE hysteresis loops were collected at various combinations of  $\phi_A$ ,  $\phi_{W,s}$ (in 1° increments) and the normalized MOKE signal was recorded by in accordance with Fig. 1(b). The results of these measurements are  $\frac{6}{6}$ shown in Fig. 3. The similarity between Figs. 3(a) and 2(e) suggests that the BiYIG is dominated by Kerr ellipticity, whereas the 25 nm  $Gd_{0.33}Co_{0.67}$  and 6 nm  $Tb_{0.12}Co_{0.88}$  have  $\Delta I/\bar{I}$  plots indicative of substantial contributions from both Kerr rotation and ellipticity. These data were then fitted to Eq. (15) to determine  $\theta_k$  and  $\epsilon_k$ quantitatively. The contour lines in Fig. 3 show the agreement between the fitted model with the measured MOKE signal.

The values of the parameters extracted from the fit are shown in Table I. 6 nm Tb<sub>0.12</sub>Co<sub>0.88</sub> exhibits positive Kerr components while 25 nm Gd<sub>0.33</sub>Co<sub>0.67</sub> has negative  $\theta_k$  and  $\epsilon_k$ , indicating that the two samples are on opposite sides of magnetic compensation, i.e., Tb<sub>0.12</sub>Co<sub>0.88</sub> is Co-dominated, whereas Gd<sub>0.33</sub>Co<sub>0.67</sub> is Gd-dominated, consistent with previous reports of magnetic compensation points in

TABLE I. Measured longitudinal Kerr angles of various films measured via MOKE magnetometry.

	$oldsymbol{ heta}^{\circ}_{oldsymbol{k}}( imes 10^{-3})$	$\boldsymbol{\epsilon}^{\circ}_{\boldsymbol{k}}~( imes 10^{-3})$	$\left  \mathbf{\Phi}_{\boldsymbol{k}} \right ^{\circ} ( imes 10^{-3})$	$\gamma_D(\times 10^{-4})$
50 nm BIYIG	$11.5 \pm 0.9$	$72 \pm 1.3$	$73.0 \pm 1.3$	4.2
25 nm Gd <sub>0.33</sub> Co <sub>0.67</sub>	$-18.1 \pm 0.3$	$-6.5 \pm 0.2$	$19.2 \pm 0.3$	3.7
6 nm Tb <sub>0.12</sub> Co <sub>0.88</sub>	$7.1 \pm 0.3$	$4.0 \pm 0.2$	$8.1\pm0.3$	4.5



**FIG. 4.** Kerr data for 3 nm GdCo, measured by polar MOKE microscopy. (a) Normalized MOKE signal of 3 nm Gd<sub>0.4</sub>Co<sub>0.6</sub> with quarter waveplate fast axis parallel to incident polarization. Contour lines show fitted function. (b) Polar Kerr rotation,  $\theta_k$ ; ellipticity,  $\epsilon_k$ ; and complex Kerr angle magnitude,  $|\Phi_k|$ , as a function of Gd atomic fraction, *x*.

RECo amorphous alloys.<sup>5,26,27</sup> The depolarization factor of each sample was measured in situ by dividing the photocurrent at extinction by the photocurrent at maximum transmittance,  $\gamma_D = \frac{I_{ext}}{I_{max}}$ . A small variation in  $\gamma_D$  was observed, likely due to the combination of two effects. First, thickness and flatness variations across sample substrates lead to varying laser paths through the waveplate and analyzer. This combined with spatial inhomogeneity in the waveplate and analyzer results in a unique  $\gamma_D$  for each sample. The uncertainty of  $\theta_k$ and  $\boldsymbol{\epsilon}_k$  is the standard error from the fitting of the measured data to Eq. (15) and ranges from 2% to 5% for GdCo and TbCo and 2% to 8% for BiYIG. From Eqs. (11a) and (16a),  $|\Phi_k|$  is directly proportional to the magnitude of the extrema,  $|\Delta I/\bar{I}|_{max}$ , and from Eqs. (14) and (17), the relative magnitude of  $\theta_k$  and  $\epsilon_k$  is related to the position of the extrema in the  $\phi_A - \phi_W$  plane. As a result, the uncertainty of the Kerr components is dependent on the density of data collection near the extrema to ensure that the magnitude and position of  $|\Delta I/\bar{I}|_{max}$  are accurately captured. The BiYIG sample had much steeper extrema than the other samples as can be seen from the larger  $\Delta I/\overline{I}$  range displayed in Fig. 3(a). Since all three samples were measured in a 1° waveplate and analyzer angle increments, this results in a less certain fit for the BiYIG sample compared to the GdCo and TbCo samples. Taking higher density measurements of the BiYIG sample would have reduced the error to a similar value as the other samples.

A 3 nm  $Gd_xCo_{1-x}$  composition series of samples with perpendicular magnetic anisotropy (PMA) was analyzed using a polar widefield MOKE microscope with a 650 nm light. The Kerr angle of thinfilm GdCo is of particular importance due to its recent prevalence in domain wall motion,<sup>6,28,29</sup> voltage gating,<sup>3</sup> skyrmions,<sup>6,30,31</sup> and Brillouin light scattering experiments,<sup>32–35</sup> all of which depend on the GdCo Kerr angle. In these ferrimagnetic films, the Kerr signal primarily originates from the Co sublattice, making MOKE magnetometry a useful tool for determining the dominant sublattice.<sup>36</sup> A representative MOKE signal plot is presented in Fig. 4(a), and the resulting Kerr

angles as a function of Gd atomic fraction are plotted in Fig. 4(b) along with best fit lines for each Kerr component. We observe a linear decrease in  $|\Phi_k|$ ,  $|\theta_k|$ , and  $|\epsilon_k|$  with increasing Gd atomic fraction, consistent with previous reports in thicker films of rare-earth transition metal alloys but about 10x smaller in magnitude.<sup>27,37</sup> The  $\frac{1}{60}$  reduced value is likely due to the difference in thickness (3 nm vs  $\frac{1}{60}$  100–300 nm) and to attenuation by the capping layer's attenuating effect in our samples.<sup>13</sup> The measured GdCo composition range was kinited to its PMA range. In general, the polar Kerr angle is significantly larger than its longitudinal counterpart.<sup>13</sup> As a result, to invesultrathin 0.8 nm Co sample deposited on Pt exhibiting PMA and determined the polar Kerr angle:  $\theta_k = -(33.3 \pm 1.1) \times 10^{-3}$ ° and  $\epsilon_k = (14.9 + 0.6) \times 10^{-3}$ °. In samples under 30 nm, the Kerr rotation and ellipticity increase linearly with magnetic layer thickness.<sup>3</sup> Scaling up these values to 3 nm gives  $\theta_{k, 3nm} = -(125 \pm 4) \times 10^{-3}$ ° and  $\epsilon_{k, 3nm} = (56 \pm 2) \times 10^{-3}$ °. When compared to the extrapolated linear fit at x = 0 ( $\theta_{k,fit} = -(50 \pm 8) \times 10^{-3}$ °,  $\epsilon_{k,fit} = (42 \pm 10) \times 10^{-3}$ °), we find a reasonable agreement between the linear fit and measured Kerr ellipticity but a significant underestimation of the Kerr rotation compared to the measured value. This suggests that the initial addition of Gd to Co may nonlinearly reduce the Kerr rotation before settling into a linear dependence at higher Gd concentrations. A previous report has found the Kerr rotation to be directly proportional to the Co sublattice magnetization  $(M_{Co})$ .<sup>37</sup>  $M_{Co}$  is expected to be approximately linear over the composition range in Fig. 4(b) but drops steeply at low Gd concentrations due to the large atomic volume of Gd relative to Co, which may explain the high measured Kerr values of pure Co.

#### **IV. CONCLUSIONS**

The Kerr rotation and ellipticity can be measured using a standard MOKE magnetometer without augmentation. The ratio of

Kerr rotation to ellipticity is easily determined by recording the waveplate and analyzer angles at normalized MOKE signal maxima. Combined with the magnitude and sign of the normalized MOKE intensity, this allows for accurate calculation of the sign and value of the Kerr angle. We demonstrate the applicability of this technique to both longitudinal and polar configurations. Finally, we find that the complex Kerr angle of thin-film GdCo decreases linearly with increasing Gd content.

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#### AUTHOR DECLARATIONS

#### Conflict of Interest

The authors have no conflicts to disclose.

#### Author Contributions

Daniel H. Suzuki: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Methodology (lead); Writing - original draft (lead); Writing - review & editing (equal). Geoffrey S. D. Beach: Conceptualization (supporting); Funding acquisition (lead); Writing - review & editing (equal).

#### DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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