Tandem magneto-optical Kerr effect magnetometer for the study of quadratic effects

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Abstract. It has recently been observed that strong quadratic magneto-optical Kerr effects (QMOKE) are present in cobalt-based Heusler compounds thin films. In this contribution we present a magnetometer dedicated to the study of QMOKE in magnetic thin films. The system consists of two MOKE magnetometers working in tandem, and is equipped with a quadrupole magnet which affords any in-plane field. The first magnetometer operates at an angle of incidence of 45°, and is sensitive to the combined longitudinal MOKE and QMOKE signals. In the second magnetometer, the light impinges on the sample at perpendicular incidence, and this magnetometer is thus only sensitive to the QMOKE component. Representative measurements illustrating the capabilities of this instrument are presented.

1. Introduction
Magneto-optical Kerr effect (MOKE) magnetometry is a powerful method for the study of magnetic materials and their properties, including their anisotropy, domain structure, and magnetization reversal [1]. In our ongoing study of Co-based Heusler compounds, which are strong material contenders for the next generation of spintronic devices [2], we have found that the quadratic MOKE (QMOKE) is quite strong in these compounds [3, 4]. In fact, the amplitude of this effect seen in Co$_2$FeSi(001) films is the largest ever reported [3]. To further study this complex system, we have built a tandem MOKE magnetometer which is sensitive to both the QMOKE and the longitudinal MOKE (LMOKE) signals, and allows the use of the “8 field method” [5]. This new instrument will facilitate a systematic study of QMOKE in Co-based Heusler compound thin films.

2. Description of the instrument
The instrument consists of two MOKE magnetometers working in tandem. A scheme of the instrument is presented in Fig. 1. For both systems, the light of an ultra-low noise diode laser ($\lambda=638$ nm) is s-polarized using a polarizer with a polarization degree of 99.99% and an extinction ratio of 10,000:1. The light then passes through a beam expander and is focused onto the surface of the sample. The polarization of the reflected light is then analyzed by a Wollaston prism, and the intensity of the two orthogonally polarized beams is monitored by a pair of photodiodes.
The detector works as an opto-electrical bridge circuit to achieve a better signal-to-noise ratio. Motorized rotators align the Wollaston prism/detector via an automated routine, in order to minimize the differential signal $I_1 - I_2$, where $I_1$ and $I_2$ are the intensities measured by the two photodiodes. For $I_1 - I_2 \approx 0$ there is a direct proportionality between the normalized differential signal $(I_1 - I_2)/(I_1 + I_2)$ and the Kerr rotation [6].

In the first system, the light impinges on the sample at an angle $\theta$ of 45°. In this configuration, the measured Kerr rotation contains (1) the LMOKE component, which is proportional to the in-plane magnetization in the direction along the incidence of light ($M_L$); (2) the polar MOKE (PMOKE) component which is proportional to the out-of-plane component of the magnetization ($M_P$); and (3) QMOKE components, which are proportional to second-order terms of the magnetization components, $M_L M_T$ and $M_L^2 - M_T^2$, where $M_T$ is the in-plane component of magnetization which is perpendicular to the incident light. In the second system the light is directed by a beamsplitter onto the sample at normal incidence. The reflected light passes again through the beamsplitter and is collected by the second detector. The MOKE sensitivity to $M_L$ is proportional to $\sin \theta$, where $\theta$ is the angle of incidence. At normal incidence ($\theta = 0^\circ$), the LMOKE contribution to the Kerr rotation thus vanishes. In magnetic thin films, the demagnetizing fields usually coerce the magnetization into the sample plane. Under these conditions, the polar component of magnetization can be neglected, and the measured Kerr rotation arises only from QMOKE contribution.

With the two detector working in tandem it is possible to measure the combined LMOKE and QMOKE as well as the QMOKE components at the same time, without any further data processing.

The sample is placed in the center of two pairs of magnet-poles, which allow to set a magnetic field in any in-plane direction. It is possible to measure longitudinal and transverse magnetic reversal loops, as well as use the “8 field method” to determine the different QMOKE contribution in saturation, as described below and in full detail in Refs. 3 and 5.

The sample holder is fixed to a $x$, $y$, $z$-positioning stage and an in-plane rotator, so that the sample orientation can be change with respect to the plane of incidence. The in-plane positioning and rotation of the sample are motorized.

The software was programmed using LabView™ by National Instruments. The software consists of three packages which (1) perform the data acquisition from the two detectors and the minimization of the differential signal; (2) interface with the power supplies of the magnets and
read the field values measured by Hall probes; (3) interfaces with the stepper-motor controller for sample positioning and rotation. The software enables a fully automated measurement routine for the desired combination of sample position, orientation, and applied magnetic field(s). In the cases presented here, these are typically the in-plane rotation and longitudinal field for rotational scans, or the “8 field method” (when a transverse field is also applied, see Fig. 2). However, measurements such as transverse magnetization and position-dependent probing are just easily achieved.

3. Representative measurements
In this section, we briefly highlight measurements possible with this instrument. Except for the “8 field method” measurements, only the longitudinal magnet was used for the measurements presented below.

Rotational scans. Kerr rotation loops as a function of magnetic field strength were measured using the LMOKE arm of the instrument as a function of in-plane rotation for a 30 nm thick Co$_2$MnAl(001) sample (Fig. 3a). As can be seen in Fig. 3b, where the coercive field $H_c$ is plotted as a function of in-plane orientation $\alpha$, the sample exhibits four-fold symmetry, which is presentative of the cubic magnetocrystalline anisotropy of the sample.

![Figure 3.](image-url) (a) Representative hysteresis loop and (b) polar plot of the coercive fields for a Co$_2$MnAl(001) thin film.

Tandem measurements. Loops were measured for a 90 nm thick Co$_2$FeSi(110) sample known to exhibit QMOKE. The results are shown in Fig. 4. The measured Kerr rotation loop measured for $\theta = 45^\circ$ exhibits an asymmetry with respect to an inversion of the magnetic field. The symmetric and asymmetric components of the Kerr signal $\phi$ may be arithmetically extracted using [3, 7]

$\text{LMOKE}_{\uparrow\downarrow} \rightarrow \phi_{\text{sym}} = \frac{\phi(H_{\uparrow\downarrow}) - \phi(-H_{\downarrow\uparrow})}{2}; \quad \text{QMOKE}_{\downarrow\downarrow} \rightarrow \phi_{\text{asym}} = \frac{\phi(H_{\downarrow\downarrow}) + \phi(-H_{\downarrow\uparrow})}{2}$

where the arrows indicate the branches of the loop with increasing (\uparrow) and decreasing (\downarrow) field strengths. As is indicated, the component that is symmetric upon field inversion is attributed to the longitudinal component of the Kerr signal (LMOKE) and shown as a solid line in the upper panel of Fig. 4, and the asymmetric component is attributed to a quadratic component (solid line, Fig. 4 lower panel). The extracted QMOKE signal corresponds to the measured signal for the perpendicular beam, albeit with a different amplitude due to the different angles of incidence of the two geometries [1].
QMOKE “8 field method”. For the quantitative study of QMOKE, one considers the Kerr signal, which in its simplest form is expressed as [3, 5]

\[ \phi_s = a' \cdot M_L + [b + a \cdot \cos(4\alpha)] M_L M_T - \frac{a}{2} \sin(4\alpha) \times [M_L^2 - M_T^2] \] (1)

considering second-order magneto-optical terms, where \( M_i \) is a component of the magnetization, and \( a, a', \) and \( b \) are optical weighting factors containing information about the anisotropy and amplitude of the QMOKE.

The various components of the signal can be separately evaluated for a given in-plane orientation \( \alpha \) by using the “8 field method”, where the Kerr rotation \( \phi \) is measured in saturation for 8 in-plane field orientations, and applying:

\[ \phi_{\text{sat}}^{M_L} = \frac{\phi_8 - \phi_4}{2}; \quad \phi_{\text{sat}}^{M_L M_T} = \frac{\phi_1 + \phi_5 - \phi_3 - \phi_7}{4}; \quad \phi_{\text{sat}}^{M_L^2 - M_T^2} = \frac{\phi_8 + \phi_4 - \phi_2 - \phi_6}{4} \]

where the subscripts correspond to the fields \( H_n \) defined in Fig. 2. The results obtained for a L21-ordered Co2MnSi(001) thin film are presented in Fig. 5. The measured Kerr effects are seen to follow the behaviour of Eqn. 1. These measurements allow the quantitative determination of the \( a \) and \( a' \) parameters, which relate to the magnitude and anisotropy of the QMOKE [3, 5].

4. Conclusions
We have presented a tandem MOKE magnetometry system which is capable of measuring the LMOKE and QMOKE for magnetic thin films. Such a system is required to undertake a systematic and quantitative study of the amplitude and anisotropy of the QMOKE in thin films, in particular Co-based Heusler compounds.

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