REVIEW OF SCIENTIFIC INSTRUMENTS **78**, 120901 (2007)

Perspective: Tools of modern magnetic materials research: Vector and Bragg magneto-optical Kerr effect for the analysis of nanostructured magnetic arrays [Rev. Sci. Instrum. 78, 121301 (2007)]

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(Received 9 November 2007; accepted 12 November 2007; published online 12 December 2007)

The magneto-optical Kerr effect[1] (MOKE) is an indispensable and extremely versatile tool in modern magnetic materials research.[2] It is based on the proportionality of MOKE to the magnetization $\boldsymbol{M}$ as probed by a linearly polarized light beam after reflection at a magnetized surface (or film). MOKE is quantified by the complex Kerr rotation angle, $\boldsymbol{\Theta}_K=\theta_K+i\varepsilon_K$, of the polarization vector, where θ_K is the rotation angle and ε_K is the ellipticity of the polarized light after reflection. It probes the bulk of the sample within the penetration depth of the light of about 10–50 nm, and is, hence, not a pure surface probe. As compared to conventional magnetometry being performed, e.g., with a superconducting quantum interference device (SQUID), MOKE has a number of crucial advantages: (1) Its setup is comparatively simple and of low cost. (2) Data collection is straightforward and quickly done, usually within less than 1 s. (3) Its accuracy and sensitivity reach that of SQUID magnetometry and can reliably measure, e.g., the magnetic properties of submonolayer ferromagnetic samples. (4) Its application is touchless, where the sensing light beam may easily reach the sample from ambient to, e.g., cryogenic and high field environment through a glass window. (5) Intense laser light sources allow for sensing higher order magneto-optical effects. (6) Ultrashort laser light pulses allow for sensing magnetization dynamics on time scales down to 10 fs. (7) MOKE microscopy allows for imaging ferro- or ferrimagnetic domains on a micrometric scale in its conventional fundamental wave mode[3] and is capable of viewing antiferromagnetic 180° domains in the optical second-harmonic mode in suitable systems.[4] (8) MOKE spectroscopy is to a certain degree element-specific and may thus resolve details of complex magnetization reversal processes, e.g., in multilayer structures.[5] This feature is perfected in the x-ray absorption regime, where magnetic circular and linear dichroisms have become extremely powerful and versatile tools for studying element-specific magnetization reversal processes and domain patterns in transmission.[6]

Two other MOKE techniques have recently come into the focus of attention, which definitely surpass the possibilities of conventional "single channel," as, e.g., SQUID magnetometry: *vector and diffracted* MOKE, often referred to as V- and D-MOKE.

V-MOKE satisfies the need to measure not only the component of $\boldsymbol{M}$ along the applied field but also the orthogonal magnetization component(s) in order to reconstruct the complete magnetization vector. To this end, various strategies have been developed.[7–12]

In a setup chosen by Vavassori,[11] complete vector magnetometry is possible without any moving element in a conventional MOKE setup. It involves a HeNe laser, whose beam passes a rotatable polarizer, hits the sample under an angle of incidence of 25°, after reflection passes a photoelastic modulator[13] operated at a frequency $\omega/2\pi\approx 50$ kHz, passes a second polarizer, and is detected by a photodiode. A magnetic field can be applied both parallel and perpendicular to the plane of incidence by means of a double-axis electromagnet. By choosing both polarizations, s and p, detecting the modulated signal at both ω and 2ω, and rotating all optical elements (except the sample) in a second set of measurements by ±45°, one can find all the data, which suffice to calculate all three vector components of the normalized magnetization, m_x, m_y. and m_z.

The setup of Schmitte *et al.*[12] exclusively probes longitudinal MOKE with s-polarized light (y direction). If the magnetization $\boldsymbol{M}$ lies in the xy plane, the MOKE signal is proportional only to its x component, M_x, while the y-component M_y remains undetected in s polarization. It is registered by its s-polarized longitudinal MOKE signal upon rotating the plane of incidence by 90° into the yz orientation while keeping the sample and the field fixed. In practice, the same target is reached by keeping the plane of incidence fixed but rotating the sample and the field together by 90°.

Rotation of the optical and magnetic components is completely avoided by using a combination of longitudinal and transverse MOKEs (Ref. 7) but at the expense of enhanced calibration efforts, since both measured signals are not commensurate.

V-MOKE has become very successful in analyzing the magnetization reversal of nanostructured ferromagnetic thin films and multilayers involving complex nucleation and magnetization rotation processes. Care has to be taken to avoid or to correct for quadratic Kerr effect contributions. They may cause asymmetries in hysteresis curves, which are not present in direct magnetometry.[14]

The D-MOKE technique was pioneered by Geoffroy *et al.*[15] and is sometimes also called "Bragg-MOKE."[12] It is advantageous if identically magnetized microstructures are periodically arranged, e.g., as mechanical or magnetic (i.e., domain) one- or two-dimensional patterns. As in crystallography, the benefits of $\boldsymbol{k}$-space diffractometry of periodic structures with complex unit cells are met in this method. The material acts like a diffraction pattern, where the diffraction orders may contain magnetic information via the rotation and/or ellipticity of the emerging light. The magnetic

0034-6748/2007/78(12)/120901/2/$23.00

form factor $f_n^{(m)} = \int m(\boldsymbol{r}) \exp(in\boldsymbol{G}\cdot\boldsymbol{r}) d^2 r$ integrated over one unit cell and extracted at the nth diffraction spot ($\boldsymbol{G}$=reciprocal lattice vector) allows one to evaluate the internal magnetization distribution $m(\boldsymbol{r})$ by Fourier transformation.[15–20] The electric field in the nth-order diffracted beam from a magnetic patterned surface may be written as $E_n = E_0(r_{pp(ss)} f_n + r_{pp(ss)}^{(m)} f_n^{(m)})$, where E_0 is the incident electric field, f_n the structural form factor of the grating, and $r_{pp(ss)}$ and $r_{pp(ss)}^{(m)}$ the nonmagnetic and magnetic $p(s)$-polarized reflectivities of the material, respectively. It has to be noticed that both $r_{pp(ss)}$ and $r_{pp(ss)}^{(m)}$ are in general differently angular dependent according to their individual Fresnel coefficients. It turns out that good agreement between observed and calculated D-MOKEs usually requires micromagnetic calculations,[21] e.g., on the basis of object-oriented micromagnetic framework (OOMMF) software.[22]

D-MOKE is considered a novel technique, which can yield information on the magnetic spin structure within micro- or even nanosized magnetic structures. As with any diffraction method, D-MOKE requires a periodic arrangement of exactly equal elements. Micromagnetic calculations are indispensable for a detailed understanding of the magnetic form factors. Hence, any transformation of the D-MOKE signal from Fourier into the real space should be accompanied by simulations. If successful, the method might compete with or even surpass other magnetic imaging methods such as photo-electron emission microscopy (PEEM). Recently the D-MOKE method has been combined with V-MOKE which allows to determine the complete magnetization vector data at the nth diffraction spot.[23]

This perspective has been written within the framework of Sonderforschungsbereich 491 being funded by the Deutsche Forschungsgemeinschaft.

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