Magneto-optical microscopy
(incl. time-resolved)

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1. Introduction

Important for the understanding of the origin of magnetic properties and technological application of magnetic materials is the ability to observe the *magnetic domain structure*. One method, practiced since decades, is magneto-optical microscopy using conventional imaging optics. Magneto-optical microscopy is one of the most versatile techniques to image magnetic domains and magnetization processes. The method is based on the magneto-optical *Faraday or Kerr effect*, i.e. the rotation of linearly polarized light in dependence of the magnetization direction on transmission or reflection from a non-transparent sample, respectively. In this presentation the principles of magneto-optical microscopy, mostly Kerr microscopy and magnetic imaging based on magneto-optical indicator films, will be reviewed. A special emphasis will be on *time-resolved* imaging techniques.

2. Fundamentals of magneto-optical microscopy

The interaction of a plane-polarized electromagnetic light wave with a magnetic material can be illustrated in an image based on the effect of the Lorentz force on the electrons set in motion by the electrical vector ***E*** of the wave. This influence is represented in Fig. 1 for the longitudinal Kerr effect. The Lorentz movement generates a magnetic contribution to the reflected light amplitude, the so-called Kerr amplitude ***K***, which is polarized perpendicularly to the normally reflected amplitude ***N*** and causes rotation of the light through interference with ***N***. In the simplest case, for domains with opposite magnetization, a maximum domain contrast is produced if e.g. an analyzer blocks most of the reflected light of one domain type. The domain contrast in the image is directly *sensitive to the magnitude and direction of magnetization*. Additional magneto-optic effects will be discussed.

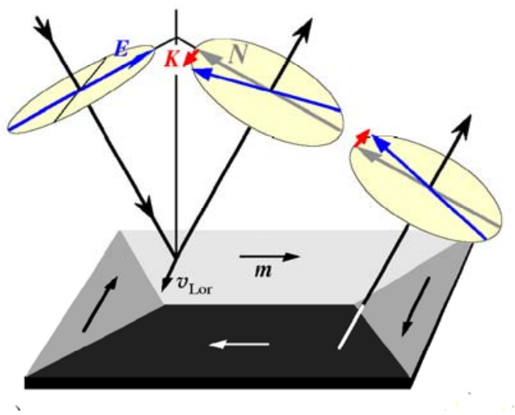

Fig. 1 (a) Illustration of the longitudinal Kerr effect (taken from [1])

Arbitrary magnetic fields can be applied during observation so that domain nucleation and magnetization processes can be observed easily. Possibly the utmost advantage over other domain observation methods is the *speed and time-resolution* in which images can be acquired.

A magneto-optical microscope is essentially a *polarization microscope*, with which maximum lateral resolution of around 300 nm can be achieved using oil immersion objectives with a high numerical aperture. The main components of a wide-field microscope are represented schematically in Fig. 2. As the magneto-optical contrast is rather weak, a *highly intensive light source* is used, usually a high-pressure xenon or mercury lamp. Lasers can be used for wide-field illumination in principle, but some effort is required to obtain the necessary incoherent light source from the coherent laser light. For scanning microscopy, the use of low noise lasers is used on regular basis. As the magneto-optical contrast might be very weak, significant enhancement is possible by video microscopy and digital image processing in the case of wide-field microscopy. A possible *background image subtraction* process is best carried out in real time at video frequency, making it possible to view magnetization processes in real-time. For laser based scanning microscopes, usually *lock-in techniques* are used for contrast enhancement and reduction of signal-to-noise ratio.

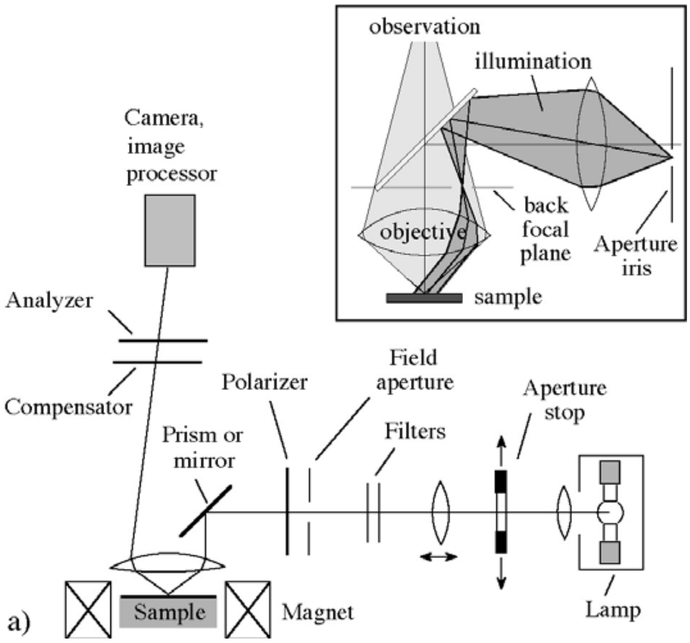

Fig. 3 (a) Schematic representation of the main components of a Kerr microscope. The inset shows the beam path of an optical reflected light microscope. The aperture iris is displaced from the optical axis to generate oblique incidence of light (adapted from [1]).

3. Practical Aspects

The optical technique has many advantages. The magnetization can be observed directly without ambiguity. The samples are not destroyed or damaged during observation and the process of observation does not influence the magnetization. The shape and size of the sample are largely arbitrary. *Imaging* through transparent or semi-transparent *covering layers* can be achieved. Free sample manipulation is easily possible during observation. High or low temperature, mechanical stress or, most importantly, *arbitrary magnetic fields* may be applied, allowing to study magnetization processes easily. The same effects that are used for imaging may also be used for the magnetic characterization of the material, i.e. local hysteresis curves may be obtained by just plotting the average intensity of the Kerr images as a function of applied field. Examples for all of the above will be presented. Due to its linearity and direct sensitivity to the magnetization vector ***m***, the Kerr effect can be used for a *quantitative determination* of the magnetization direction [2].

However, besides these advantages there are also a number of obstacles. Often samples have to be prepared so that they are reasonably flat and smooth on a scale exceeding the chosen lateral resolution. The resolution is limited to magnetic domains larger than about 0.2 µm, corresponding to an *optical resolution of about 0.3 µm*. On metals, only the *surface magnetization* in a layer of the penetration depth of some 10 nm can be seen. In bulk samples it restricts the possibilities of domain studies to surface domains (which in most cases are different from underlying volume domains). For thin film studies this is not necessarily a disadvantage. Using a rotatable compensator, the phase of the Kerr amplitude, generated in a certain depth, can be adjusted relative to the regularly reflected light amplitude. In this way light from selected depth zones can be made invisible if their Kerr amplitude is adjusted out of phase with respect to the regular light, *layer-selective magneto-optical microscopy* is possible then.

4. Time-resolved imaging

Time-resolved observation of periodic magnetization processes is e.g. possible by *stroboscopic imaging*, using either by a *triggered video* camera or a *pulsed light source* [2]. This can be done by laser scanning techniques or by wide-field techniques. Triggering the light or camera pulses with precise timing relative to a field pulse and sweeping the delay time of probing yields a series of corresponding pictures of *periodic or quasi-periodic* processes. An experimental setup of such a stroboscope, as we recently installed it at IFW-Dresden, is shown in Fig. 4.

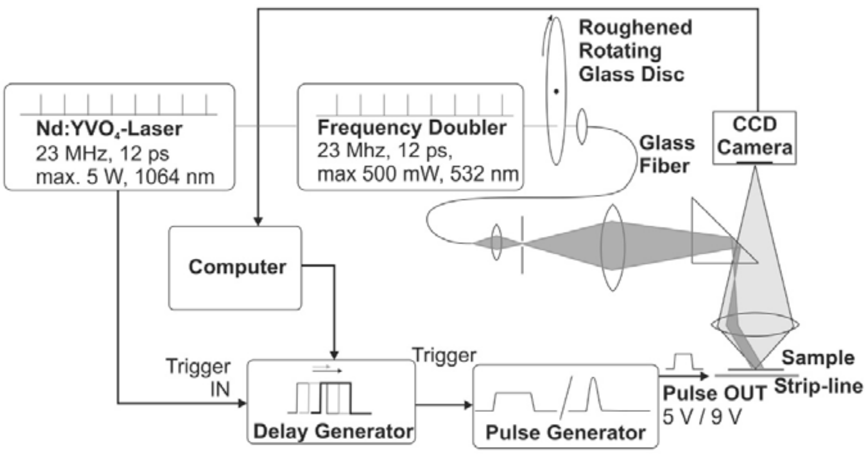

Fig. 4 Schematics of an experiment for stroboscopic domain imaging, implemented in a regular wide-field Kerr microscope. The time resolution is obtained by illumination with a pulsed laser. The laser-based stroboscope allows a time resolution of below 20 ps.

As the Kerr signals on small time scales are *usually* too weak to obtain single-shot images (depends also on chosen time-resolution), an averaging over a number of images at each time delay is necessary to obtain reasonable contrast. Prerequisite is that the fast magnetization processes are reproducible. The use of wide-field Kerr microscopy for dynamic imaging has the advantage, that also the domain ground states and quasi-static processes (i.e. in slowly changing fields) can be studied for comparison.

One simple example is discussed here. The magnetization processes initiated by high-frequency fields or by field pulses are very different from those in slowly varying fields. As the switching, e.g. of a soft magnetic film element, in pulsed fields occurs in the nanosecond regime, one has to consider that the magnetization (or the domains) will not be able to instantaneously follow the magnetic field. To reach the new magnetization direction, it will have to spin about the field axis, a process called *precessional motion* that is gradually opposed by damping. Therefore remagnetization processes in pulsed fields may not be seen as a simple switch of magnetization direction. An example of such an experiment on a Permalloy film element is shown in Fig. 5.

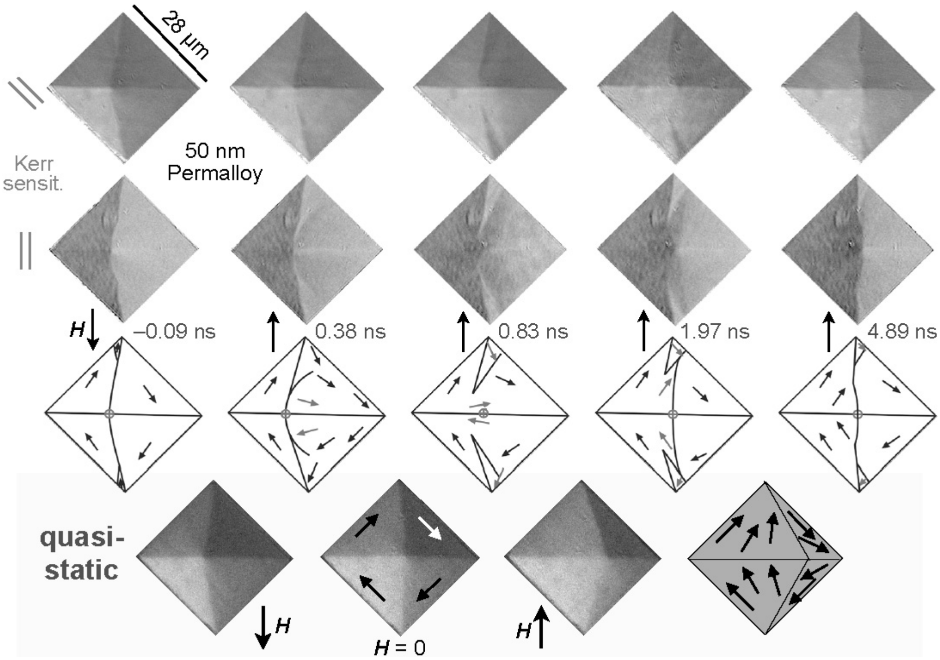

Fig. 5 Magnetization process of a Permalloy square element of 50 nm thickness, initiated by a diagonal, low-amplitude field pulse around the Landau ground state. In a slowly varying field (bottom row) the center vortex is shifted reversibly around its equilibrium position. In a pulsed field (upper three rows of images) the domain walls and the vortex cannot follow the field pulse. Rather rotational processes occur, until the walls are restored after about 5 ns.

5. Conclusions

Magneto-optical microscopy is a *versatile method* for the experimental analysis of magnetic microstructures, only *limited by resolution* down to a few tenths of a micrometer. The *dynamic capability* and the compatibility with *arbitrary applied fields* make Kerr microscopy ideally suited for the investigation of fast and slow magnetization processes. Due to the direct sensitivity and *linear dependence on the magnetic polarization*, the method allows the quantitative determination of magnetization vector fields at the surface of soft magnets.

Bibliography (Reviews)

[1] A. Hubert and R. Schäfer: Magnetic Domains. The Analysis of Magnetic Microstructures. Springer Verlag, Berlin (1998)

[2] M. Freeman and W. K. Hiebert, in "Spin Dynamics in Confined Magnetic Structures I", ed. by B. Hillebrands and K. Ounadjela, Springer Berlin (2002)