Ma12: Magneto-optical Kerr effekt and magnetic anisotropies

1. Introduction

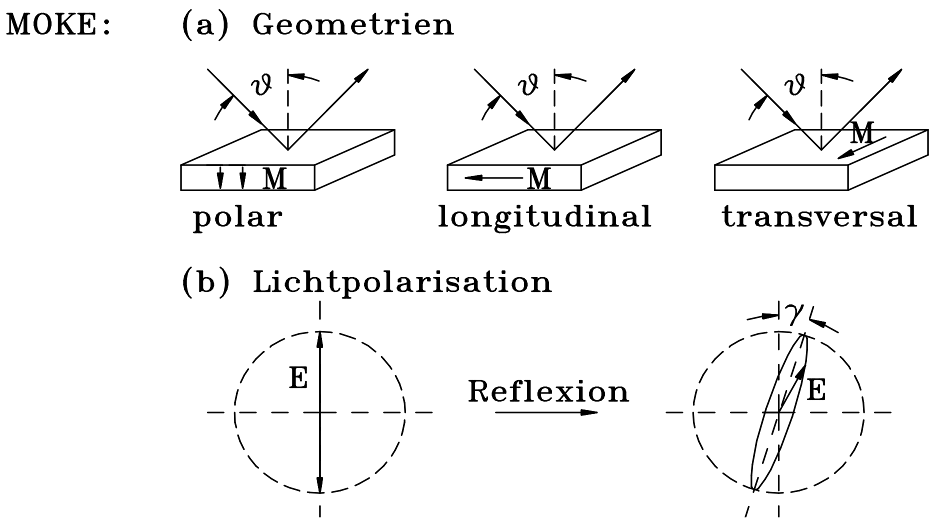
The **magneto-optical Kerr-effect (MOKE)*** is suitable to examine the magnetic properties of **ferromagnets** through optical polarization measurements. There are three different MOKE measurement configurations: the **polar, longitudinal and transversal geometry** (Figure 1a). This experiment will focus on the longitudinal MOKE. To a good approximation, the MOKE signal is proportional to the sample magnetization and allows the recording of MOKE **hysteresis loops** from which physical quantities such as **coercitivity**, **remanence** and **magnetic anisotropy** constants can be calculated.
This experiment aims to introduce the MOKE measurement principal. Using longitudal MOKE, the magnetic properties of a thin bcc-Fe (001) single crystal will be examined.
Measurements of the **hard** and **easy magnetization axis** in the film plane allow predictions about the **shape- and crystal anisotropy**.
Finally, a polar **Kerr microscope** is used to visualize the domain pattern of a rare-earth iron garnet film and to examine the behaviour of the domains in external magnetic fields.

***Students should familiarize themselves with highlighted terms and topics.**

2. Theory

2.1 Magneto-optical Kerr effect

Magneto-optical effects occur when light is transmitted through magnetized matter (Faraday-effect, Voigt-effect) and when light is reflected from a magnetized surface (Kerr-effect). A change of the **polarization direction** (Kerr-rotation) and an **ellipticity** of the transmitted or reflected light is observable (Figure 1b), depending on the polarization of the incoming light and the magnetization of the sample. These magneto-optical effects have a quantum mechanical nature and are caused by spin orbit interaction [1]. From a phenomenological point of view, the Kerr-effect can be described by the off-diagonal elements of the dielectric tensor ε or the off-diagonal elements of the conductivity tensor σ.



2.2 Magnetic anisotropy

The spontaneous magnetization of a ferromagnet appears due to the isotropic exchange interaction. Owing to the magnetic dipole-dipole interaction and the spin-orbit coupling, there are preferred directions for the spontaneous magnetization inside a crystal.
The crystal anisotropy $\mathbf{E_{cryst}}$ [2,3] describes the differences of energies per volume for the spontaneous magnetization along different crystal axes. The directions with lowest energies are called easy axes. In *bcc* Fe, the [100] direction is the easy axis, whereas the [110] and the [111] directions are hard axes.

Besides the crystal anisotropy, there also exists the so-called shape anisotropy E_{shape}, that describes the magnetic stray field energy per volume as function of the magnetization direction. $\mathbf{E_{shape}}$ [7,8] depends on the shape of the magnetic sample. For an ellipsoidal sample (approximated shape of the sample in the experiment) one yields:

$$E_{shape} = \frac{\mu_0}{2} H_D M_S = \frac{\mu_0}{2} N M_S^2$$

where M_S is the saturation magnetization (Fe: $\mu_0 M_S$ = 2,1 Tesla), and N the demagnetization factor, which depends on the magnetization direction. $H_D = N M_S$ is the demagnetization field, which superposes the external magnetic field in an antiparallel orientation.

References: [2,3,4]

2.3 Hysteresis loops

Magnetization hysteresis curves may be quite complex regarding their shape. There are different domain states for low external magnetic fields, depending on the shape induced demagnetization field and easy and hard axes. As a result, the sample is not magnetized homogeneously, which is only the case in thin films or small samples. Although it is difficult to describe the hysteresis loops for easy and hard directions quantitatively, it is possible to make a rough estimate for the anisotropy constant K_1 from the difference between hard and easy axis hysteresis loops.

References [2,3]

2.4 Magnetic domains

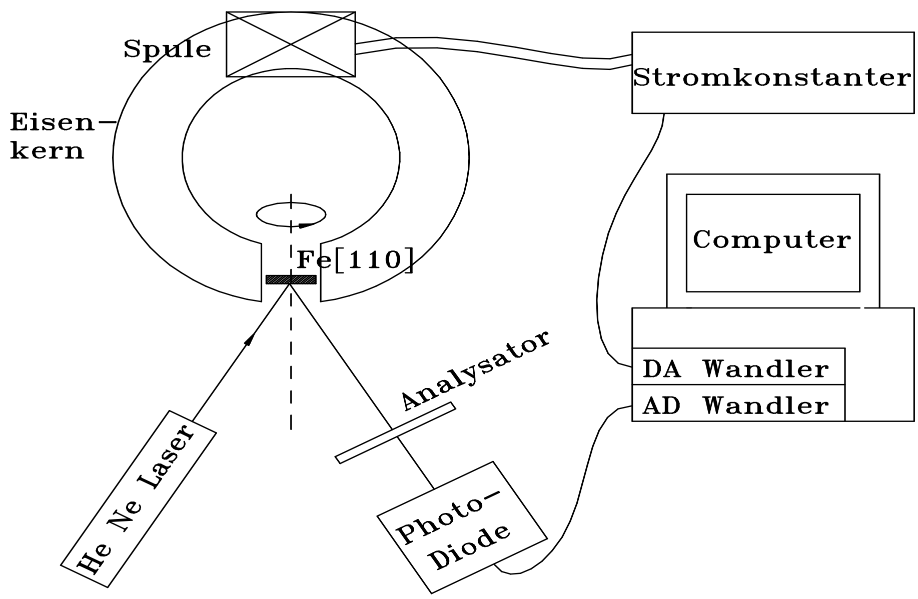
A ferromagnetic sample in remanence builds up a magnetic domain pattern. The exchange interaction favours a parallel alignment of all magnetic moments, but this would cause energetically unfavourable stray fields. Furthermore, the building of domain walls (**Néel and Bloch walls**) consumes energy. Thus, the domain pattern is governed by the minimum of the total energy, which is a combination of exchange interaction, stray field energy, crystal anisotropy and Zeeman energy [4]. The rare-earth iron garnet film examined in this experiment has an easy axis perpendicular to the surface and a large Kerr rotation (> 1°) [5]. The film has a maze domain structure with a constant domain width in the remanent state.

References [4,5]

3. Experimental setup

The experimental set up is shown in Fig. 2. For the MOKE measurements, a linearly polarized He-Ne laser (output: 0.5 mW) is used as light source. The laserbeam is reflected from the Fe film and then passes a polarization filter (analyzer). The intensity of the light is recorded with a photodiode. Since the Kerr rotation of the Fe film is small (<< 1°), a direct measurement of the Kerr rotation is impossible through a single positioning of the analyzer. Instead, one can rotate the analyzer. This way the Kerr rotation is measured by using the intensity contrast in dependency of the angle of the analyzer. The signal of the photodiode is amplified and recorded on a computer with an A/D converter. The sample is placed in a ring shaped iron core, which is wrapped by a coil. The magnetic field is proportional to the computer-controlled current of the coil and can be calibrated using a Hall-probe. The sample is rotatable and can be magnetized along the [100] or the [110] direction of the bcc Fe film.

For visualization of the domains, a Kerr microscope is used. The Kerr microscope is equipped for polar MOKE geometry using a CCD camera. An electromagnet is used for the generation of the external magntic field.



4. Experimental goals

4.1 Magnetic Field Calibration

Measure the magnetic induction B a) inside the center of the slit, and b) on the sample position, as a function of the coil-current, using a Hall-probe (ranging ±4 A). An approximately linear behaviour is expected. For the calibration, use the proportionality factor measured in the sample position.

Before the experiment: Calculate a theoretical approximation for the calibration factor in the center. For the theoretical derivation, use Ampere's law. Number of coil windings 300; slit width 12 mm).
Compare this theoretical derivation to the measured value in the center.

4.2 Magnetic anisotropy

Familiarize yourself with the installed experimental setup. Prepare the setup for a measurement in s-polarization. Vary the parameters of the setup in order to achieve a good signal-to-noise ratio. Record hysteresis loops for different sample orientations and try to identify the easy and hard axes by the shape of the hysteresis loops.
Discuss the different shapes for the hysteresis loops along the easy axis and hard axis.

Before the experiment: Derive an expression for the crystalline magnetic anisotropy energy (per volume) as a function of angle between magnetization and crystal axes and anisotropy constants K_l (l = 0,1,2, etc.; to first order in K). Express the anisotropy constant K_1 in terms of the energy difference between the two in plane crystal directions.

Determine the crystal anisotropy constant K_1 from the measured hysteresis loops.
The shape of the sample resembles a cylinder (thickness a few hundred micrometers) with a circular/elliptical shape. Does shape anisotropy play a role inside the film plane? Estimate the strengths of the magnetic field in order to saturate the magnetization perpendicular to the sample surface.

4.3 Contrast and Kerr rotation

The Kerr Θ_K cannot be measured directly. Instead, the contrast c, a measure for the signal to noise ratio, can be used. The contrast is defined as

$$c = (I_+ - I_-)/I_0$$

where I_+ and I_- are the saturation signals at both magnetic field directions and I_0 is the average intensity.
Use **Malus's law** for the intensity transmitted through a polarizer within the small angle approximation to obtain an expression of the contrast in terms of the analyzer position α and the Kerr rotation Θ_K.

Before the experiment: Derive the appropriate formula before the experiment!

Record the contrast for analyzer angles of approximately ±5° relative to the extinction angle for **s- and p-polarized light** (angle of incidence relative to the sample surface 45°). Calculate the longitudinal Kerr rotation of Fe from this data.
Also record the contrast as a function of angle of incidence respective to the surface for s-polarized light. Measure at 2° off the extinction angle and vary the angle of incidence from approx. 25°-45°. Compare your results to theoretical calculations [7,8].

4.4 Kerr microscopy

Record domain patterns of the rare earth iron garnet film with the Kerr microscope. Invert the magneto-optical contrast by rotating the polarizer and try to separate magnetic domains from the non magnetic background. Estimate the width of the domains in remanence.
Increase the external magnetic field and record the changes until only a single domain state remains.
Change the magnetic field direction and redo the experiment.
Suppose you would record a polar hysteresis loop of this sample. What would the loop look like?

5. Literature

All literature given can be found in the university library (books) and online through university access (publications).

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