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Installing and optimizing the MOKE setup

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Abstract

This report is about rebuilding and optimizing the signal to noise ratio (S:N) of the magneto-optical Kerr effect (MOKE) setup. The S:N is improved by successive steps of adjustments to the setup. The measurements are done with SiO$_x$ and a reference sample is used to compare the signal to noise ratio with the setup rebuilding. There are three main reasons for the improved S:N. First, the replacement of the PEM, with magnetic components, by one without magnetic components. Then, absorbing the unwanted reflections of the laser with black paper. And finally covering the PEM with an especially designed aluminium box with layers of plastic holding air. The signal to noise ratio for the SiO$_x$ improved form 1.87 to 5.15 at the highest S:N. Compared to the setup before the S:N for the reference sample improved with a factor 3.
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Chapter 1

Introduction

In 1877 the scotish scientist John Kerr discovered the Kerr effect. The magneto-optical Kerr effect (MOKE) is a world-wide used mechanism for research on magnetic samples. The principle exists of a reflecting light beam, whereby the reflecting beam has a change in polarization state after it reflects on a magnetic sample. This effect is proportional to the magnetization of a sample, therefore the Kerr effect is used as tool to study the magnetic properties. Through to the limited penetration depth of the light beam the Kerr effect is extremely useful for surface analysis of samples. With the recent developments of thin-film samples is the Kerr effect a very powerful research tool. The aim of this project is to install the MOKE setup in a new lab and improving the signal-to-noise ratio (S:N).

The outline of this report is as follows the definition of the Kerr rotation and ellipticity and the measuring procedure is shown in chapter 2. In chapter 3 the setup of the MOKE will be shown and explained and the working of the photo-elastic modulator will be outlined. In chapter 4 the definition of the noise for this project is explained and discussed. Furthermore the samples are described that were used to improve the S:N. In chapter 5 the results are given and an insight in the causes of the noise. The last chapter gives the conclusions and a discussion is made upon these.
Chapter 2

The Magneto-optical Kerr effect

The Scottish scientist John Kerr discovered in 1877 that the polarization state of light could be changed by reflection at the surface of a magnetic material [2]. This is called the Magneto-optical Kerr effect (MOKE). The effect is characterized by changes in phase and amplitude of the light undergoing reflection. This is respectively known as Kerr rotation and Kerr ellipticity. The origin of the effect can be explained by regarding linear polarized light as the superposition of two circularly polarized components, of equal amplitude and opposite direction. Left circularly polarized light (LCPL) and right circularly polarized light (RCPL).

A relative change in phase of the two components will leave there superposition linear, but there resultant will have undergone rotation with respect to its original direction. Furthermore a relative change in the amplitude of the components will result in an elliptical superposition. Figure 2.1 gives an illustration of these effects. In this chapter the Magneto-optical Kerr effect is explained by a macroscopic description of the Kerr effect and followed by an introduction to it's microscopic origin. Finally some research applications of the MOKE will be pointed out.

2.1 Definition

Considering the complex Fresnel reflection coefficients for right circularly polarized light $r_+$ and left circularly polarized light $r_-$ [1]:

$$r_+ = r_+ e^{i\phi_+}$$  \hspace{1cm} (2.1)

$$r_- = r_- e^{i\phi_-}$$  \hspace{1cm} (2.2)

with $r_\pm$ the amplitude, and $\phi_\pm$ the phase of the circularly polarized light. Now if linearly polarized light is represented as the superposition of two circularly polarized components, of equal magnitude and opposite sense, then the Kerr rotation $\theta_K$ is formulated by:

$$\theta_K = \frac{1}{2} (\phi_+ - \phi_-)$$  \hspace{1cm} (2.3)

And the Kerr ellipticity $\epsilon_K$ is formulated by:

$$\epsilon_K = \frac{r_+ - r_-}{r_+ + r_-}$$  \hspace{1cm} (2.4)

There are three different observation geometries commonly used in discussing the MOKE. These three are the: Polar, Longitudinal and Transverse Kerr geometry which are shown in
Figure 2.1: (a) Linearly polarized light is the superposition of two circularly polarized components of equal amplitude and opposite sense. (b) A relative phase-shift, $\psi$, between these components causes the resultant to be rotated. During this the superposition remains linear and this effect is called the Kerr rotation $\theta_K$. (c) Changing the relative amplitude of the one of the components causes the superposition to become elliptical, this is known as Kerr ellipticity $\epsilon_K$.

Figure 2.2: The three different configurations of the MOKE set-up. With $\Theta_i$ the angle of incidence and $H$ the applied magnetic field.
The choice of which geometry is used depends on the magnetic anisotropy of the sample. In-plane magnetization is monitored by the Longitudinal or Transverse Kerr effect. In this case the angle of incidence \( \Theta \) is preferably equal to the Brewster angle of the sample. In studies on samples with perpendicular magnetization, where the Polar Kerr effect is used, the angle of incidence is minimal.

2.2 Macroscopic description

In general optical response is given by the dielectric constant \( \varepsilon \) according to \( \vec{D} = \varepsilon \vec{E} \). Where the dielectric constant links the displacement \( \vec{D} \) to the electric field \( \vec{E} \). This is only valid if the materials are isotropic or have high symmetry \([4]\). However, if the symmetry is lowered this description fails and a dielectric tensor should be used. Therefore Magneto-optical effects are mostly described by the dielectric tensor \( \varepsilon \). From general symmetry arguments it follows that for solids with cubic symmetry in which the magnetization \( \vec{M} \) lies along the symmetry-axis (z-axis), the dielectric tensor \( \varepsilon \) has the following form in Cartesian coordinates \([5]\):

\[
\begin{pmatrix}
\varepsilon_{xx} & \varepsilon_{xy} & 0 \\
-\varepsilon_{xy} & \varepsilon_{xx} & 0 \\
0 & 0 & \varepsilon_{zz}
\end{pmatrix},
\]

where each of the components \( \varepsilon_{ij} \) is complex. Optical anisotropy of a sample is described by the off-diagonal terms \( \pm \varepsilon_{xy} \). The diagonal elements are even functions of \( \vec{M} \) and the off-diagonal components are odd functions of \( \vec{M} \).

To connect normal incidence of light that is reflecting and the complex dielectric tensor components, it is convenient to describe the Magneto-optical effect using circularly instead of linearly polarized light. Transformation of equation (2.5) to cylindrical coordinates yields:

\[
\bar{\varepsilon} = \begin{pmatrix}
\varepsilon_{xx} + i\varepsilon_{xy} & 0 & 0 \\
0 & \varepsilon_{xx} - i\varepsilon_{xy} & 0 \\
0 & 0 & \varepsilon_{zz}
\end{pmatrix}
\]

The complex index of refraction is defined by:

\[
\tilde{n} = n - i\kappa.
\]

Here, \( n \) is the refractive index and \( \kappa \) is the so-called extinction coefficient \([6]\). For RCPL (+), respectively, LCPL (-) the complex index of refraction can be defined by \([7]\):

\[
\begin{align*}
n^2_{+} &= \tilde{n}_{xx} + i\tilde{n}_{xy}, \\
n^2_{-} &= \tilde{n}_{xx} - i\tilde{n}_{xy}.
\end{align*}
\]

Assuming that \( |\varepsilon_{xy}| \ll |\varepsilon_{xx}| \). From this equation it is clear to see that the Magneto-optical effect arises from a non-zero off-diagonal element of the dielectric tensor \( \varepsilon \). From the complex Fresnel reflection coefficients equations (2.1) and (2.2) it follows that a sample can only show a Kerr effect if it possesses optical anisotropy \( (\tilde{n}_{+} \neq \tilde{n}_{-}) \). For linearly polarized light that is travelling in the opposite z-direction to a sample, the reflection coefficient for normal incidence is given by \([8]\):

\[
\tilde{r} = \frac{\tilde{n} - 1}{\tilde{n} + 1}
\]
Using the Fresnel expressions for Kerr rotation $\theta_K$ (2.3) and Kerr ellipticity $\epsilon_K$ (2.4) the Magneto-optical Kerr effect is given by:

$$\theta_K = \theta_K - i\epsilon_K = \frac{\varepsilon_{xy}}{\sqrt{\varepsilon_{zz} \cdot (\varepsilon_{zz} - 1)}}$$

Again it is shown that the off-diagonal tensor components (i.e. $\varepsilon_{xy}$) are responsible for the Magneto-optical effect.

MOKE is used to study surface effects, therefore the absorption of light is also of importance, since it further limits the extent to which the magnetization is examined. The intensity of light after absorption by the sample at distance $z$ along the propagation path is defined by:

$$I(z) = I(0)e^{-Kz}, \quad (2.12)$$

with $K$ the absorption coefficient of a substance at wavelength $\lambda$ given by:

$$K = \frac{4\pi\kappa}{\lambda}, \quad (2.13)$$

where $\kappa$ the extinction coefficient according to equation (2.7). The Kerr effect signal stems only about twice the penetration depth of the light of which the intensity of the light is reduced to $\frac{1}{e}$. The penetration depth $d_p$ is defined by the following equation:

$$d_p = K^{-1} = \frac{\lambda}{4\pi\kappa}, \quad (2.14)$$

For metals in the visible wavelength range, $d_p$ is typically in the range of 25-50 nm. This means that techniques such as MOKE that make use of optical analysis cannot be used to fully investigate bulk magnetic properties. However, this fact makes MOKE an ideal tool for examining the magnetic behavior of ultrathin films deposited on bulk magnetic substrates. On such measurements the attention will be concentrated on the interaction between the deposited film and substrate in stead of the net magnetization of the sample as a whole. The applications of this will be better shown in the next chapter.

2.3 Measurement technique

A description of the signal that is detected is given during this section. The signal is read out by the detector connected to a lock-in amplifier on which the intensities of the $f$ and $2f$-components of the light can be qualified respectively $I(f)$ and $I(2f)$. The amplitude of the detector signal can be determined by means of a Jones matrix calculation. Linearly polarized light at an angle of $45^\circ$ has a Jones representation of \cite{9}:

$$E_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (2.15)$$

in cartesian coordinates. This is the light in front of the photo-elastic modulator (PEM), while it passes through the PEM the light will be modulated into circularly polarized light alternating between states of right and left circularly polarized light. The working of the
PEM will be further explained in chapter 3. The Jones matrix for de modulation M of the PEM is [8]:

\[
M = \begin{pmatrix}
e^{i\frac{\delta_y}{2}} & 0 \\
0 & e^{-i\frac{\delta_y}{2}}
\end{pmatrix}
\]  

(2.16)

with \(\delta_y\) the retardation of the y-phase, caused by the modulation of the y-component by the PEM with frequency \(f\), expressed by:

\[
\delta_y = \delta_{y0} \cdot \sin 2\pi ft
\]  

(2.17)

The representation of the light after it passed the PEM follows from multiplying the linearly polarized light with the modulation it undergoes:

\[
E_2 = M \cdot E_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{i\frac{\delta_y}{2}} \\ e^{-i\frac{\delta_y}{2}} \end{pmatrix}
\]  

(2.18)

After the light has travelled through the PEM is becomes circularly polarized therefore the Jones representation has to be in circular coordinates. To obtain the expression in circular coordinates, the transformation matrix from cartesian to circular coordinates is given by:

\[
T_{c-c} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ 1 & -i \end{pmatrix}
\]  

(2.19)

Applying this transformation on the representation \(E_2\) gives the following equation:

\[
E_3 = T_{c-c} \cdot E_2 = \frac{1}{2} \begin{pmatrix} e^{i\frac{\delta_y}{2}} + ie^{-i\frac{\delta_y}{2}} \\ e^{i\frac{\delta_y}{2}} - ie^{-i\frac{\delta_y}{2}} \end{pmatrix}
\]  

(2.20)

The key of the MOKE measurements is the reflection of the light beam on the magnetic sample. The reflection of light at the sample is given by the Jones matrix:

\[
R = \begin{pmatrix} \tilde{r}_+ & 0 \\ 0 & \tilde{r}_- \end{pmatrix}
\]  

(2.21)

with \(\tilde{r}_\pm\) according to equations (2.1) and (2.2). After multiplying the representation of the light after the PEM equation (2.20) with the reflection matrix \(R\) the representation becomes:

\[
E_4 = R \cdot E_3 = \frac{1}{2} \begin{pmatrix} \tilde{r}_+(e^{i\frac{\delta_y}{2}} + ie^{-i\frac{\delta_y}{2}}) \\ \tilde{r}_-(e^{i\frac{\delta_y}{2}} - ie^{-i\frac{\delta_y}{2}}) \end{pmatrix}
\]  

(2.22)

Finally the light travels through an analyzer before reaching the detector. The Jones matrix for the linear analyzer is represented, in circular coordinates, by:

\[
A = \begin{pmatrix} 1 & e^{-i2\phi} \\ e^{i2\phi} & 1 \end{pmatrix}
\]  

(2.23)

with \(\phi\) the angle between the major axis of the elliptically polarized light and the x-axis. The light polarization \(E_5\) of a MOKE measurement in front of the detector can be written as a combination of the expressions explained before:

\[
E_5 = \left(\frac{\vec{p}}{\vec{q}}\right) = A \cdot E_4
\]  

(2.24)
where $E_4$ is shown in equation 2.22 and $\bar{p}$ and $\bar{q}$ are vector components. The intensity $I_5$ of the light beam reaching the detector is given by:

$$I_5 = |E_5|^2 = E_5^* \cdot E_5 = p^* \cdot p + q^* \cdot q$$

(2.25)

where the $p^*$ is the complex conjugate of $p$. From this equation we obtain that it is not necessary to transform back to cartesian coordinates since the intensity of the light is insensitive to it. The intensity $I$ can be obtained by straightforward multiplying of equation (2.24):

$$I = \frac{1}{4} [r_+^2 + r_-^2 + (r_+^2 - r_-^2) \sin \delta + 2r_+r_- \cos \delta \cdot \sin (2\phi + \Delta \Theta)]$$

(2.26)

with $\Delta \Theta = \phi_+ - \phi_- = 2\theta_K$ see equation (2.3). If $(r_+ - r_-) \ll (r_+ + r_-)$ than the expression for $I$ is given by:

$$I = \frac{R}{2} [1 + 2\epsilon_K \cdot \sin \delta + \cos \delta \cdot \sin 2(\phi + \theta_K)]$$

(2.27)

with $R = \frac{1}{2}(r_+^2 + r_-^2)$ and $\epsilon_K$ and $\theta_K$ respectively given by equations (2.3) and (2.4). Recalling equation (2.17) $\sin \delta$ and $\cos \delta$ can be expanded into Bessel functions of order $n$, $J_n(x)$ [10]:

$$\sin \delta = \sin (\delta_0 \cdot \sin (2\pi ft)) = 2J_1(\delta_0) \sin 2\pi ft + \cdots$$

(2.28)

$$\cos \delta = \cos (\delta_0 \cdot \sin (2\pi ft)) = J_0(\delta_0) + 2J_2(\delta_0) \cdot \sin (4\pi ft) + \cdots$$

(2.29)

Neglecting higher order terms, the Bessel functions are shown in figure (2.3). $I$ consists of frequency components $I(0)$, $I(f)$ and $I(2f)$:

$$I(0) = \frac{1}{2} R [1 + J_0(\delta_0) \cdot \sin (2\phi + 2\theta_K)]$$

(2.30)

$$I(f) = \frac{1}{2} R [4\epsilon_K \cdot J_1(\delta_0)]$$

(2.31)

$$I(2f) = \frac{1}{2} R [2J_2(\delta_0) \cdot \sin (2\phi + 2\theta_K)]$$

(2.32)

Thus $I(f)$ and $I(2f)$ depend on $\epsilon_K$ and $\theta_K$. If $\phi \ll \theta_K$, then $\phi + \theta_K \approx \theta_K$ and $2\theta_K$ can be determined by rotating the analyzer through $2\phi$ until $(2f)$ vanishes. In practice this method is not accurate and it is easier to measure $I(0)$, $I(f)$ and $I(2f)$ directly. For $\phi = 0$ and $\theta_K$ is small, then we have:

$$\sin (2\theta_K) \approx 2\theta_K \ll 1$$

Then follows from (2.31) and (2.32):

$$\epsilon_K = \frac{I(f)}{4J_1(\delta_0) \cdot I(0)}$$

(2.33)

$$\theta_K = \frac{I(2f)}{4J_2(\delta_0) \cdot I(0)}$$

(2.34)

Mentioned before $\epsilon_K$ is determined by measuring the $f$-component of the signal and that $\theta_K$ is proportional to the $2f$-component. To have the maximal signal both $I(f)$ and $I(2f)$ must be maximized. This is done by maximizing the Bessel functions terms seen in figure 2.3, respectively, $J_1(\delta_0)$ and $J_2(\delta_0)$.
maximum $J_1(\delta_0)$ is by $\delta_0 \approx 1.89$ Rad

maximum $J_2(\delta_0)$ is by $\delta_0 \approx 3.05$ Rad

The optimal retardation-amplitudes are therefore different for $\varepsilon_K$ and $\theta_K$. $I(f)$ and $I(2f)$ are measured by lock-in amplifiers where the reference is set at $f$ for the Kerr ellipticity and at $2f$ for Kerr rotation. In a measurement the analyzer is set in a certain angle so that the $I(2f)$ measured on the detector is equal to zero. This corresponds to the zero setting of $\phi$ if no magneto-optical active sample is present. The setting of the analyzer is not very critical, because a small $\phi$ will give an offset on $I(2f)$ but will cancel out if the Kerr signal is measured for both polarities of the magnetization direction of the sample. An advantage of using a PEM with the underlined method is that the $f$ and $2f$ signals are proportional to the ellipticity and rotation.
Chapter 3

The setup

The key to application of MOKE is the change of polarization state of circularly polarized light into rotated elliptically polarized light after reflection on a magnetic material. This change can be divided in two separate contributions, rotation $\theta_K$ and ellipticity $\epsilon_K$, which are proportionally with the $\vec{M}$ of the sample. In the MOKE setup a laser in combination with the PEM is used to create circularly polarized light. This light is focused on the sample with a couple of lenses, resulting in a small spot-size on the sample. Therefore highly localized analysis of the samples is possible.

The MOKE is mainly used for examining ultrathin films. Some examples of the use of the MOKE are the following measurements: Hysteresis loop measurements, antiferromagnetic exchange-coupling studies, kerr anisotropy studies and measuring to determine the Curie temperature $T_c$. In this chapter the setup of the MOKE is shown and explained. Furthermore additional attention is given for the PEM.

3.1 Setup description and measurement procedure

In this section the MOKE setup used during this project is explained step by step. The setup to measure the MOKE is depicted in figure 3.1. As a light source a He-Ne laser with a wavelength of $\lambda = 632.8$ nm is used. The laser light first passes through the lens pairs $L_1$ ($f = -50$ mm) and $L_2$ ($f = 200$ mm). The combination of these lenses causes to increase the cross-section of the laser beam. The following lens $L_3$ ($f = 500$ mm) is used to focus the laser on the sample. The laser spot on the sample has a diameter of approximately 70 $\mu$m. After lens $L_3$ polarizer $P_1$ causes the light to be linearly polarized at 45° with respect to the optical axis of the PEM. Then, when the linearly polarized light passes through the PEM it will change into circularly polarized light alternating between right and left circularly polarized light. The operating wavelength of the PEM is set at 632.8 nm and the retardation of the PEM is set on, repetitively, 1,89 Rad for $\epsilon_K$ or 3,05 Rad for $\theta_K$ measurements. A more in dept explanation of the PEM will given in the following section.

The light reflects on the sample which is mounted on a sample holder connected to a step motor. The sample holder is placed in between two magnetic poles with a magnetic-field sweep from -3,2 kGauss till 3,2 kGauss. The reflecting light beam is nullified by analyzer $P_2$ at zero field to eliminate the offset and then projected on the detector with lens $L_4$ ($f = 80$ mm). The detector is connected to a lock-in, with the PEM frequency signal as a reference, and measures the intensity of the reflected beam. For the lock-in the sensitivity is set dependant
on the measurement and the time constant is set at 3 μm. The lock-in is set on f or 2f reference for respectively $\epsilon_K$ or $\theta_K$ measurements. To start a measurement the phase of the lock-in is adjusted so that the detected signal on the lock-in amplifier reads zero. After nullifying the lock-in phase is changed 90° then a measurement can start.

From the lock-in the measurement data will be read out by a PC. The PC furthermore determines the strength of the magnetic field and the position and the scan route of the sample. Finally, the $I(f)$ or $I(2f)$ are measured and from them $\epsilon_K$ or $\theta_K$ are calculated. The model numbers and specifications of the individual components are listed in appendix D.

### 3.2 Photo-elastic Modulator

In this setup a PEM is used to modulate the laser light into circularly polarized light. A PEM consists of a birefringent crystal mounted on a piezo-electric crystal, which vibrates with a frequency $f \approx 50$ kHz. In figure 3.2 the structure of the PEM is shown. The oscillating pressure from the piezo-electric crystal changes the optical axis of the birefringent element so that it causes the phase change of the parallel component of the light to be alternately retarded or advanced. As a result, electromagnetic radiation traversing the crystal in the z-direction experiences a periodic advancement or retardation of its y-phase relative to its x-phase. The amplitude of the vibration determines the retardation. If the amplitude corresponds to $\frac{\lambda}{4}$ retardation, and if the incoming light is linearly polarized at 45° with respect to the vibrating direction of the PEM (i.e. y-axis) than the light will alternate between LCPL and RCPL states with a frequency $f \approx 50$ kHz. This is illustrated in figure 3.3, furthermore it illustrates

---

**Figure 3.1: The measurement setup of MOKE with the polarization modulation technique.**

---
the principle how the PEM may be exploited to measure both $\theta_K$ and $\epsilon_K$. Figure 3.3(a) gives the time dependence of the retardation and corresponding state of polarization with a circle of $\frac{1}{4}$. In 3.3(b) it is shown that if the reflective sample shows no Kerr effect, the x-projection $E_x$ of the light reaching the detector will remain constant, in other words the intensity behind an analyzer whose axes lies along the x-axis will not change. Kerr rotation in the sample will introduce a 2$f$-oscillation in the intensity behind the analyzer 3.3(c). A Kerr ellipticity causes different vector lengths for LCP and RCP, resulting in a $f$-component in the detector signal 3.3(d). Thus with the PEM, $\theta_K$ and $\epsilon_K$ can be determined by measuring the $f$ and 2$f$ signal of the detector signal. In the next section the detector signal is calculated and shown how both Kerr effects follow from the measured 2$f$ and $f$ intensities.
Figure 3.3: (a) retardation as function of time, (b) polarization state of the light vector, (c) polarization state with Kerr rotation, (d) polarization state with Kerr ellipticity (after Sato [11]).
Chapter 4

Definition of the noise

The aim of this project is to rebuild the MOKE setup and improve the S:N. In this chapter the noise is defined and characterization is given for the used sample SiO$_x$ and the reference sample. The reference sample is used to give an identification of the improvement compared to the setup before rebuilding.

4.1 SiO$_x$

To get a good indication of the noise it first has to be properly defined. So that it is possible to compare the different measurements to improve the signal to noise ratio. In this project the standard measurement parameter is the standard deviation (SD). The SD is used as an indication of the amount of noise on a line. It is only accurate as a measure parameter if the line with the noise has no slope. The magnetization of a diamagnet reacts inversely proportional to an applied magnetic field. In this project a piece of commercial available SiO$_x$ wafer is used, when this diamagnetic sample is put into a magnetic field the response of the sample is given in figure 4.1(a). This figure shows that the SiO$_x$ sample has a diamagnetic response to an applied external field from $\sim-0,7$ kGauss till $\sim0,7$ kGauss. The signal is small because of the small magnetic susceptibility [13].

To remove the slope of the graph a linear fit is made and than subtracted from the same graph, leaving a straight line with an average of zero, see figure 4.1(b). With the graph in 4.1(b) the SD is an accurate method to measure the noise. To level the occasional excesses of the noise every measurement is repeated ten times and as a measurement parameter the average of the ten different SD’s is taken.

Before continuing it has to be sure that the SiO$_x$ SD measurements procedure distinguishes noise and no signal. In general the SD decades with $\sqrt{n}$ according to Poisson, because it is a statistical effect. This decade is tested with SiO$_x$. Therefore, the SiO$_x$ sample is measured a couple of times: First time with one time averaging, second time with two times averaging, third time with four times averaging and so on. The SD plotted as a function of $n$ on a double-logarithmic scale should give an gradient of $g = -\frac{1}{2}$. Figure 4.2 shows the plotted graph for the diamagnetic sample SiO$_x$ and the slope of the graph is $(g = -0,55 \pm 0,06)$ thus the SD distinguishes noise. To determine the signal to noise ratio also a signal has to be defined. For the SiO$_x$ measurements is this the Kerr rotation at an applied field of 0,5 kGauss.
Figure 4.1: (a) the Kerr rotation of SiO$_x$ measurement (b) The noise after subtraction of the linear fit

Figure 4.2: The SD as a function of the amount of measurements $n$, where the noise is measured with: one, two and four times averaging. The gradient of the graph is $(-0.55±0.06)$ so the SD distinguishes noise.
4.2 Reference sample

During the project also some measurements are done with a reference, to define a S:N of the setup before it was rebuild. As a reference sample a Co/FeMn/Co/AlOₓ/Co sample is used, the hysteresis loop of this sample, measured with the setup before it was rebuild for this project, is shown in figure 4.3(a). It beyond the scope of this report to explain the entire hysteresis loop. For our purpose it is used to compare the S:N with the old setup.

The data used for calculation of the SD is the part of the measurement where the sample is saturated from this the slope is removed and the SD determined as a signal the Kerr rotation at 0.5 kGauss is taken. In figure 4.3(b) the area which is indicated by a circle is brought to a close up. The noise is measured from this part of the hysteresis curve of the Co/FeMn/Co/AlOₓ/Co sample shown in figure 4.3(b) the reference SD is 0.00333 arb.u.. The signal height of the hysteresis loop is 0.413 arb.u. combined with the SD gives this a S:N ratio of: 124. This value is used in chapter 5 to compare the change in signal to noise ratio with the rebuild setup.
Chapter 5

Improving the signal to noise ratio

The main goal of this project is to improve the signal to noise ratio of the MOKE setup. All the measurements to compare the different setups are done with SiO$_x$ and some are repeated with the Co/FeMn/Co/AlO$_x$/Co sample to show the improvement compared to the old setup. In this chapter every change in the setup will be shown and explained one by one. For all the different setups SiO$_x$ measurements are shown and explained, the reference sample is measured only for some adjustments to the setup. Only 2f (Kerr rotation) measurements are done to examine the noise. Every measurement is ten times repeated, as mentioned in chapter 4, and the average is calculated for the SD and signal.

5.1 PEM with and without magnetic components

A PEM can be affected by the stray field of the magnetic poles, magnetic components in the controller. If the controller is affected by the stray field of the magnet it could cause a slightly different operating frequency or retardation of the PEM. This influence is tested by comparing the measurements of the PEM with a controller with magnetic components and the PEM controller without any magnetic components. The results are given in table 5.1 for SiO$_x$ and the reference sample. Next to the SD also the signal and the S:N is given. The SD and signal are determined according to the procedure that is discussed in chapter 4.

The results in the table 5.1 show that the signal remains the same while the noise is reduced so the S:N increases. For the SiO$_x$ sample the S:N ratio increases from 1.78 to 2.67 an improvement of a factor 1.5. The increase of the S:N ratio for the reference sample is even a factor 2.14.

<table>
<thead>
<tr>
<th>Sample</th>
<th>PEM with magnetic components</th>
<th>$\overline{SD}$ [arb.u.]</th>
<th>$signal$ [arb.u.]</th>
<th>S:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_x$</td>
<td>PEM with magnetic components</td>
<td>(1.4 ± 0.1) $\cdot 10^{-3}$</td>
<td>0.0025 ± 0.0004</td>
<td>1.78</td>
</tr>
<tr>
<td>SiO$_x$</td>
<td>PEM without magnetic components</td>
<td>(9.4 ± 0.7) $\cdot 10^{-4}$</td>
<td>0.0025 ± 0.0004</td>
<td>2.67</td>
</tr>
<tr>
<td>Ref</td>
<td>PEM with magnetic components</td>
<td>(3.2 ± 0.2) $\cdot 10^{-3}$</td>
<td>0.281 ± 0.005</td>
<td>88</td>
</tr>
<tr>
<td>Ref</td>
<td>PEM without magnetic components</td>
<td>(1.5 ± 0.1) $\cdot 10^{-3}$</td>
<td>0.283 ± 0.005</td>
<td>189</td>
</tr>
</tbody>
</table>
Table 5.2: The determined values for the measurements with and without any reflection.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Without stopping reflections</th>
<th>With stopping reflections</th>
<th>lab lights off</th>
<th>Without stopping reflections</th>
<th>With stopping reflections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si$_x$</td>
<td>$(9.4 \pm 0.6) \cdot 10^{-4}$</td>
<td>$(7.3 \pm 0.5) \cdot 10^{-4}$</td>
<td>$(7.1 \pm 0.5) \cdot 10^{-4}$</td>
<td>$(1.5 \pm 0.1) \cdot 10^{-3}$</td>
<td>$(9.2 \pm 0.7) \cdot 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$0.0024 \pm 0.0005$</td>
<td>$0.0025 \pm 0.0004$</td>
<td>$0.0025 \pm 0.0004$</td>
<td>$0.28 \pm 0.01$</td>
<td>$0.277 \pm 0.007$</td>
</tr>
<tr>
<td>S:N</td>
<td>2.55</td>
<td>3.42</td>
<td>3.52</td>
<td>187</td>
<td>301</td>
</tr>
</tbody>
</table>

5.2 Blocking the laser reflections

Figure 3.1, the MOKE setup, shows that the laser light has to pass through several optical elements before reaching the detector. Every optical element causes unwanted reflection of the laser beam. Interference of the reflections with the incoming laser beam causes loss of stability of the laser beam. In an attempt to improve the S:N, all laser reflections are absorbed by a piece of black paper. In table 5.2 the results of this new setup are compared to the old setup without any stopping of reflections. Besides this table 5.2 also shows a measurement of SiO$_x$ sample where the lab light are turned off are shown.

From the results for the SD and S:N in the table 5.2. It shows that by blocking the reflections the S:N increases and when turning the lab lights off another increase is shown. For the SiO$_x$ sample this gives an improvement of a factor 1.38 and for the reference sample blocking the reflections results in an improvement of a factor 1.60.

5.3 Analyzer chances

Vibrations of the optical components in general, but in view of the construction in particular, of the analyzer and detector could cause extra noise. To test this an other placement of the detector and analyzer is tried. First the detector and analyzer are placed as shown in figure 5.1(a), because it has only one connection to the table it is expected to be more sensitive for vibrations. In figure 5.1(b) shows the adjusted setup of the detector, lens (L4) and the analyzer is given. This new setup has two connections to the optical table and is expected to be more stable. Furthermore, to facilitate the nullification of the signal at zero field an analyzer with a more precise micro screw on it is used. The influence of these changes are checked and the result is shown in table 5.3.

From the table it follows that the changes of the detector and analyzer have no or little effect on the SD of the noise and S:N.

5.4 Analyze the “speaker effect”

After determine the influence of the magnetic components of the PEM the “speaker effect” of the PEM is determined. The PEM consists of a vibrating crystal mounted in a box and therefore this whole box acts like a speaker. The vibrating air could be picked up by the optical components, whereby also unwanted signal or noise with the reference frequency can be measured.
Figure 5.1: Two different ways to place the detector, analyzer and lens. (a) Shows the old setup and (b) the new setup.

Table 5.3: The noise and signal calculated for: different analyzers, different ways of mounting the detector shown in figure 5.1 and when the detector is put behind the focusing point of lens (L4).

<table>
<thead>
<tr>
<th>Sample</th>
<th>$SD$ [arb.u.]</th>
<th>Signal [arb.u.]</th>
<th>S:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>old setup for the detector (fig 5.1a)</td>
<td>$(7.0 \pm 0.3) \cdot 10^{-4}$</td>
<td>$0.00242 \pm 0.00009$</td>
<td>3.47</td>
</tr>
<tr>
<td>new setup for the detector (fig 5.1b)</td>
<td>$(7.0 \pm 0.3) \cdot 10^{-4}$</td>
<td>$0.00243 \pm 0.00009$</td>
<td>3.47</td>
</tr>
<tr>
<td>analyzer without micro screw</td>
<td>$(7.1 \pm 0.4) \cdot 10^{-4}$</td>
<td>$0.00249 \pm 0.00007$</td>
<td>3.51</td>
</tr>
<tr>
<td>analyzer with micro screw</td>
<td>$(6.7 \pm 0.4) \cdot 10^{-4}$</td>
<td>$0.00250 \pm 0.00007$</td>
<td>3.73</td>
</tr>
</tbody>
</table>

The influence of the acoustic noise is determined by covering the optical head of the PEM with an aluminium box, the design of this box and a photograph of it is shown in Appendix B. The inside of the box was filled with two layers of plastic holding air. Therefore the PEM lies completely pressed within these layers and the acoustic noise fades away in these layers. Next to that an another measurement is done where the holes the laser has to pass through are covered. The coverage is applied to stop all the sound waves leaving the PEM. A disadvantage of the coverage is that it induces a lot of extra reflections. In table 5.4 are the results of these efforts to minimize the “speaker effect” of the PEM shown. In table 5.4 it is shown that the coverage of the PEM improves the S:N. The SD of the PEM protection with the laser holes covered is larger than without coverage of the holes. The S:N ratio improves for the SiO$_x$.

Table 5.4: Comparing the different coverings of the PEM on noise (SD), signal and the S:N

<table>
<thead>
<tr>
<th>Sample</th>
<th>$SD$ [arb.u.]</th>
<th>Signal [arb.u.]</th>
<th>S:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_x$ no box</td>
<td>$(6.7 \pm 0.4) \cdot 10^{-4}$</td>
<td>$0.00245 \pm 0.00007$</td>
<td>3.66</td>
</tr>
<tr>
<td>SiO$_x$ box without holes coverage</td>
<td>$(5.3 \pm 0.3) \cdot 10^{-4}$</td>
<td>$0.00251 \pm 0.00007$</td>
<td>4.74</td>
</tr>
<tr>
<td>SiO$_x$ box with holes coverage</td>
<td>$(5.9 \pm 0.3) \cdot 10^{-4}$</td>
<td>$0.00226 \pm 0.00006$</td>
<td>3.83</td>
</tr>
<tr>
<td>SiO$_x$ no box</td>
<td>$(9.3 \pm 0.8) \cdot 10^{-4}$</td>
<td>$0.282 \pm 0.007$</td>
<td>303</td>
</tr>
<tr>
<td>SiO$_x$ box without holes coverage</td>
<td>$(7.5 \pm 0.7) \cdot 10^{-4}$</td>
<td>$0.280 \pm 0.006$</td>
<td>373</td>
</tr>
</tbody>
</table>
sample measurements by a factor 1.3 and for the reference sample by a factor 1.23.

5.5 Angle of the PEM

The crystal of the PEM has depth of $d \approx 5$ mm shown in figure 3.2 this means that when the laser passes through two reflections of the beam appear. If the PEM is set perpendicular on the laser beam the reflection of the laser starts to interfere with the upcoming beam. This effect is unwanted because the laser intensity is not uniform anymore and therefore causing noise. Even if the PEM stands under an angle with the beam the interference of the two reflecting laser beams cause the intensity of the laser to vary. To determine the ideal angle of the PEM with respect to the incoming laser, SiO$_2$ sample measurements are done for different angles. In figure 5.2(a) the result are shown for these measurements. On the x-axis the angle between the incoming light and the PEM is displayed and on the y-axis the average SD of ten similar measurements.

As expected, at zero degrees there is significant influence of the reflecting beam. For the other angles this influence is smaller. The graph in figure 5.2(b) shows the measurement without zero to clarify which angle results in the lowest noise. The line is drawn to guide the eye. From this graph it is determined that the SD is almost equal for the angles between $-3^\circ$ and $12^\circ$. The angle with the lowest SD is $3^\circ$ and the corresponding $SD = (4.85 \pm 0.2) \cdot 10^{-4}$ arb.u.. The signal for the different angles is plotted in figure 5.3. As expected remains the signal the same for angles above zero which is shown in the graph. For angles below zero the signal is smaller. The signal at $3^\circ$ is $0.0025 \pm 0.0001) \cdot 10^{-4}$ giving a S:N ratio for the ideal angle of 5.15.
Figure 5.3: The signal at an applied field of -0.5 kGauss from the measurements with SiO$_x$ plotted against the angle of the PEM.

5.6 Magnetic stray-field influence on the laser

Not only the PEM is affected by the stray field of the magnet also the laser might be affected by the stray fields of the magnetic poles. This means that the noise would be getting larger when working with high fields. In this section the influence of that stray field on the laser is explored. To measure the influence of the stray field on the laser an intensity scan is made for $\approx 40$ sec on one place of the sample. During this measurement all the things where exactly the same as by a normal MOKE measurement except for measuring the intensity instead of the MO signal. The field is varied from 0 till $\approx 3.2$ kGauss. There are no changes in the circumstances so the intensity is a line without any gradient. From the different intensity measurements the SD is calculated and plotted against the applied magnetic field as shown in figure 5.4.

From this graph it is clear to see that there is no increase in the SD of the intensity if the field is getting larger. Furthermore the intensity remains the same for all the different applied magnetic fields. In the graph in figure 5.4 is shown that the SD varies independently of the magnetic field.
Figure 5.4: Graph of the SD of the intensity as function of the applied field. To check the influence of the stray field on the intensity of the laser. On the x-axis the applied field and on the y-axis the SD of the intensity with a line of the average intensity.
Chapter 6

Conclusion and discussion

In figure 6 an overview is given of all these measurements. The different numbers on the x-axis correspond to the different adjustments in the setup as described in chapter 5. In appendix C from the SiO$_x$ measurements of figure 6 the graphs are shown. In figure 6 the SiO$_x$ and the reference sample measurements are shown. All the data is determined from ten adjustments on the MOKE setup. The graph shows an improvement of the S:N meaning that the performance of the setup is improved. First there was the replacement of the old PEM, with the magnetic components, with a PEM without magnetic components (step 1-2 in figure 6). This causes an improvement by a factor 1.5. So we may conclude that the stray field of the magnet does affect the PEM with magnetic components. It could be that the stray field has an influence on the operating frequency and retardation.

The second improvement is the absorbing of the reflections of the laser with black paper (step 2-3). Without any reflections the laser beam is not affected by any interference so the noise contribution of the laser is reduced. Turning of the lab light results in no significant improvement of the S:N as seen in step 3-4 in figure 6. So the influence of the lab lights is small. This mainly because the detector is already protected from outside light with a black cloth. Adjusting the placement of the analyzer, lens and detector (shown in figure 5.1) gives no improvement in the S:N (step 4-5). This means that the old placement of the detector is just as stable as the new one. By using an analyzer with a more precise micro screw (step 5-6) gives an improvement of the S:N. This because the analyzer with the micro screw is more stable and therefore less sensitive for vibrations of any kind.

The large improvement seen in step 6-7 is causes by covering the PEM with an aluminium box filled with plastic holding air. The vibrating crystal of the PEM acts like speaker, but with the coverage of the box and air the noise is extinguished. In step 7-8 the same coverage is applied, but with using micro glasses to block the laser holes. This kind of blockage causes the S:N to decrease. Therefore, the reflections caused by the glasses have a larger influence on the noise than the sound waves, caused by the vibrating PEM, leaving through the hole. Covering the PEM improves the S:N for the SiO$_x$ sample measurements by a factor 1.3 and for the reference sample by a factor 1.23. From this we conclude that the PEM acts like speaker and using this kind of coverage improves the S:N ratio. As a remark has to be stated that only a beginning is made with analyzing the „speaker effect“ of the PEM. This implies that further research can be conducted on this matter especially on the coverage of the laser holes. The last step in the graph in figure 6.1 is the adjustment of the angle of the PEM with respect to the incoming laser beam. The ideal angle is 3°, at this angle the S:N is 5.15. The
laser intensity is not affected by the stray field of the magnet as seen in figure 5.4. So the stray field doesn't affect the intensity of the laser.

The graph gives a clear impression of the reduced noise, and the signal remains the same throughout the project. The S:N ratio has improved from 1.78 till 5.15 for the SiO₂ sample at the end of optimizing. For the reference sample the increase of the S:N ratio from 88 till 373.

Unfortunately is this not the final S:N ratio, as seen in the overview graph in figure 6 there is an decrease of the S:N indicated with the not filled data points. In the time of not measuring changes could have happen at the lab or setup. The laser is turned on and off a couple of times and therefore losing its stability. Therefore, the intensity of the laser could fluctuates more than before and as a result inducing more noise to a measurement. In the graph in figure 5.4 is also shown that the SD varies independently of the magnetic field. An another reason is that because the Room temperature (RT) MOKE setup is in the same lab as the low temperature (LT) MOKE setup, where a turbo pump could create noise at its operating frequency that could affects the measurements. During that period there was also work done on the LT-MOKE setup and there were some cables placed above the RT-MOKE. During this activity it could be possible that someone of something accidently hit the optical

Figure 6.1: An overview of all the measurements to optimize the MOKE setup. On the y-axis the SD of the MO signal as an indication of the noise and on the x-axis the changes in the setup.
table, and because the outline of the setup is very critical and sensitive it could be affected. The exact reason for the increase of the noise is could not be determined.

At the end of the project the S:N ratio for the SiO$_x$ sample is 3.29, approximately an improvement of a factor 2 to compared to the beginning where the ratio was 1.87. For the reference sample the S:N ratio is 252, an improvement compared to the beginning with a ratio of 88. Compared to the setup before rebuilding the S:N ratio increased for the reference sample from 124 till 252 at the end and for the optimal setup 373. The S:N ratio increased thus by, respectively, a factor 2 and 3. The signal between the old and rebuild setup is different, this is remarkable because the same setup with the same components is used. One cause could be that the laser lost stability in the time of inactivity. In this project the unexpected increase of noise not determine, this is a interesting subject for further research.
Appendix A

The actual setup

In chapter 3 the setup is shown and explained. The photograph of the setup is shown in this appendix. In figure A.1 the part of the setup on the optical table is shown.

Figure A.1: View of the longitudinal MOKE setup. The entire setup is located on an optical table measuring 1.5 x 1 m. The used apparatus is numbered: the laser (1), lens pair (2), focusing lens (3), the polarizer (4), PEM (5), the magnet (6), the sample holder (7), the step motor (8), the analyzer (9), the lens (10) and the detector (11).
Appendix B

PEM coverage

In the results it is shown that the S:N improves if the “speaker effect” of the PEM is stopped. This improvement accomplished with a coverage of the PEM. In this appendix the technical drawing and a photograph of this coverage is shown. In figure B.1 the photos of the coverage of the PEM is shown. It is shown that the box is covered with plastic holding air and the complete coverage exists of two identical parts. This causes the absorption of the sound waves the vibrating crystal causes.

Figure B.1: The PEM coverage shown consisting of two identical parts. The box as a whole in the first photograph and one part independently where it is shown that the box is covered with plastic containing air.
The holes where the laser passes through are also covered in an effort to improve the S:N. The attempt to cover the laser holes was done with a rubber ring and a microscope glass shown in figure B.2.

Figure B.2: The coverage of the laser holes applied on both sides of the box. A rubber band with a microscope glass glued on top of it. The shining pieces on the rubber band are the glue.
The technical drawing of the aluminium box is shown in figure B.3.

Figure B.3: The technical drawing of the aluminium box. The total coverage is this piece shown in the drawing made twice and then filled with the plastic holding air.
Appendix C

An indication of the noise

In figure C.1 the improvement of the S:N is shown. To get an indication of the noise and signal height for every point in that graph a SiO$_2$ measurement is shown. The measurement has the same S:N as the corresponding point.

Figure C.1: An overview of the improvement of the S:N in the graph in figure 6. The number under a graph corresponds to the an SiO$_2$ with the same number in figure 6.
Appendix D

Apparatus listings

<table>
<thead>
<tr>
<th>Component</th>
<th>Apparatus</th>
<th>Serial number</th>
</tr>
</thead>
<tbody>
<tr>
<td>LASER</td>
<td>Spectra Physics HeNe model 133 (1.5 mW)</td>
<td>QC U38</td>
</tr>
<tr>
<td>PEM</td>
<td>Hinds International Inc. PEM 90-D</td>
<td>1624-E</td>
</tr>
<tr>
<td>Lock-in amplifier</td>
<td>EG &amp; G model 5209 (0.5 Hz - 120 kHz)</td>
<td>IR32299</td>
</tr>
<tr>
<td>Detector</td>
<td>non-proprietary Si Photodiode</td>
<td></td>
</tr>
<tr>
<td>Magnet</td>
<td>non-proprietary</td>
<td></td>
</tr>
<tr>
<td>Gauss meter</td>
<td>Simes magnetic instruments model 912</td>
<td>6-169</td>
</tr>
<tr>
<td>Polarizer</td>
<td>Polaroid sheet</td>
<td></td>
</tr>
<tr>
<td>Analyzer</td>
<td>Polaroid sheet</td>
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<tr>
<td>Polarizer holder</td>
<td>Linos</td>
<td></td>
</tr>
<tr>
<td>Analyzer holder</td>
<td>Linos</td>
<td></td>
</tr>
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<td>Mirrors</td>
<td>Linos</td>
<td></td>
</tr>
<tr>
<td>Lenses</td>
<td>Linos</td>
<td></td>
</tr>
<tr>
<td>Step motor</td>
<td>Driel USA encoder MIKE</td>
<td>18236</td>
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Bibliography


