Spectral and dynamical measurements using the magneto-optical Kerr effect

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The Magneto-Optical Kerr Effect (MOKE) is a powerful tool for studying the magnetic properties of various materials such as thin film multilayers or magnetic nanostructures. This paper presents the construction of two systems for different MOKE measurements. The MOKE spectrometer is capable of measuring the magneto-optical Kerr rotation as function of photon energy between 1.55 eV to 3.1 eV (400 nm to 800 nm). Permalloy, Ni, Co and Ni antidot samples have been measured to calibrate the system. A large magneto-optical enhancement is observed for the antidot film in the expected energy range. The time-resolved MOKE (tr-MOKE) measurements are performed by exciting the samples with magnetic field pulses. The change in magnetization as a function of time is measured using continuous-wave light. When ready the system will be able to measure the magnetization in the time domain at a sub-nano second scale.
1 Author’s foreword

It is not far-fetched, at least not to me, to think that mankind’s fascination with magnetism goes way back into history. Imagine a blacksmith, sometime after 550 BC\(^*\), exhausted from a long day of hard labor on the way home with, let us say an axe, on his back. Suddenly his tired arms drops the axe on the ground and when picking it up a stone, and by the looks of it an ordinary one, clings next to the sharp blade. Mystified, the blacksmith gathers his last strength and hurries home to demonstrate his fascinating find.

What about the compass, an invention thought to be made even earlier\(^†\), of course it became a tool among others when it was common enough and many people probably used it without much consideration on how it really worked. But I like to think that some individuals, maybe on a ship off to an unknown destination, stopped their daily chores for a moment, looked upon a calm sea with wind in their face and a red brimming sun setting in the horizon and contemplated on such a wondrous thing as the compass.

Today it is hard to imagine a world without all the tools and gadgets that rely on magnetism. The laptop with its hard drive, the loudspeakers at a concert, all the entry cards and credit cards spread across the globe and all the electrical motors used in everything from washing machines to cars, the list goes on for almost forever. This report discusses some aspects of the physical phenomena that is magnetism and hopefully it will rise your interest for the subject.

2 Introduction

In a world with seemingly endless need for novel materials it is an everlasting quest for scientists and engineers to develop, or discover if you like, and manufacture these materials.

Magnetic thin films have for a long time been important technological materials and are used in e.g. sensors and hard drives. The magnetic properties of these thin films can be tailored in many ways, by patterns, multi-layers or by using different materials, to match the requirements at hand. Of course this is done not only to find suitable materials for industrial applications but also to investigate fundamental principles of physics. One very suitable way to study the magnetic properties of thin films is to use the magneto-optical Kerr effect (MOKE).

MOKE is, as the name suggest, a way of probing the magnetic properties of materials by means of light. It has an information depth of several tens of nanometers but it is still sensitive enough to probe very small amounts of material. Even mono-layers of materials can be investigated. MOKE and all other magneto-optical (MO) effects are either a direct or indirect outcome of the spin-orbit coupling.

\(^*\)It is believed that cast iron was first produced in China around this time[1]  
\(^†\)The origin of the compass is slightly shrouded in mystery, a thorough review of its history can be found here[2]. The compass was probably invented some hundred years B.C and also in China
Typical measurements performed with MOKE are hysteresis loop measurements, which give information about a material’s coercivity and saturation magnetization; spectral measurements, which give information about a material’s MO Kerr rotation as a function of photon energy (wavelength); and time-resolved (tr-MOKE) measurements which probe the MO properties of a material in the time regime.

This report presents the construction of a MOKE spectrometer capable of measuring the MO Kerr rotation between 1.55 and 3.1 eV (400-800 nm), and a measurement scheme for tr-MOKE measurements, which when ready will be able to investigate magnetic excitations down to the sub-nano second regime.

2.1 The magneto-optical Kerr effect

In the late 19th century Rev. John Kerr discovered something that later was going to be called the magneto-optical Kerr effect. There is a bit of discrepancy in the literature about when the discovery was made, with 1876[3], 1877[4, 5, 6] and 1888[7, 8] seemingly being the best bids, but this is of no concern for this report.

The basic principle of MOKE is that linearly polarized light becomes elliptically polarized and has its polarization angle rotated when reflected from a magnetized surface, as illustrated in Fig. 1. The discovery followed in the footsteps of another one made in the 1840’s[9] by Michael Faraday, namely the Faraday effect. The two are in fact identical in theory but the Faraday effect is used to describe the phenomenon in transmission rather than in reflection.

![Figure 1](image_url)

*Figure 1*: Linearly polarized light, blue, becomes elliptically polarized and has its polarization angle rotated, red, when reflected from a magnetized surface.

From a macroscopic point of view MOKE is commonly explained by a material’s $3 \times 3$ dielectric tensor $\epsilon_{ij}$ which governs a material’s MO properties. However, before going into this it is worthwhile to first pay attention to the polarization properties of light.

The polarization state of light is described by the two components, $x$ and $y$, of the electric field of light. Fig. 2 shows linearly polarized light, the two components of the
electric field are in phase and of equal magnitude. The polarization vector maps out a plane in space. The electrical field components $E_{0x}$ and $E_{0y}$ for circularly polarized light, another form of polarization illustrated in Fig. 3, are of equal magnitude as well but phase shifted exactly $\pm 90$ deg (or even multiples of $\pm 90$ deg). Here the polarization vector maps out a helix in space.

**Figure 2:** Linearly polarized light. The polarization vector, blue, consisting of the x and y components of the electrical field maps out a plane in space.

**Figure 3:** Circular polarized light. The polarization vector, blue, maps out a helix in space. The figure can be seen as illustrating both RCP and LCP light depending on the propagation of the beam. Towards the reader, RCP light, in through the paper, LCP light.

Naturally both right- and left-circularly polarized light (RCP and LCP respectively) exist, with RCP light defined as the rotation going clockwise with respect to the propagation direction of the beam. Circularly polarized light plays a special role since it can be used to describe every form of polarization. Fig. 4 shows both linearly and elliptically polarized light synthesized from RCP and LCP light.
Figure 4: (a) shows linearly polarized light synthesized by RCP and LCP light, (b) shows the same for elliptically polarized light.

MOKE can be studied under quite general conditions but the three configurations in Fig. 5 are of special interest.

Figure 5: The three basic geometries for MOKE, (a) polar, (b) longitudinal and (c) the transversal configuration. Notice the different directions of the magnetic field with respect to the plane of the incoming light.

In the polar configuration, (a), the direction of magnetization (M) in the material is perpendicular to the plane of the interface, in the longitudinal, (b), and transverse, (c), configurations, M is in the plane of the surface but parallel and perpendicular respectively with respect to the incoming light.

It is common to distinguish the incident linearly polarized light upon the sample between s- and p-polarized light since this affects the MO signal. S-polarized (p-polarized) light is defined as the electrical field vector normal (parallel) to the plane of incidence.

For both the polar configuration (p-MOKE) and longitudinal configuration (l-MOKE) the effect of magnetization is a rotation of the plane of polarization and an induced el-
lipticity of the reflected beam. The transversal configuration (t-MOKE) instead affects the intensity and phase of the reflected light.

Going back to the dielectric tensor and looking at a simple case for p-MOKE, i.e. we have an isotropic material where the magnetic field lies along the $z$-axis, the dielectric tensor takes the form:

$$
\epsilon_{ij} = \begin{pmatrix}
\epsilon_{xx} & \epsilon_{xy} & 0 \\
-\epsilon_{xy} & \epsilon_{yy} & 0 \\
0 & 0 & \epsilon_{zz}
\end{pmatrix}
$$

where $\epsilon_{xx} = \epsilon_{yy} = \epsilon_{zz} = \epsilon$. Generally both $\epsilon$ and $\epsilon_{xy}$ are complex numbers and wavelength dependent. For paramagnetic and diamagnetic materials $\epsilon$ is proportional to the external magnetic field $H$ whereas for ferromagnetic and ferrimagnetic materials it is proportional to the magnetization $M$ (since it is the spin-orbit coupling that is the dominant source of the MO signal for these materials)[10].

As linearly polarized light propagates through a magnetized medium along the direction of the magnetic field its two components, RCP and LCP, will experience different refractive indices: $n^\pm = (\epsilon \pm \epsilon_{xy})^{1/2}$. This will cause the RCP and LCP components to decompose, something referred to as birefringence, and to be reflected with different reflectivities. When these different reflectivities differ in magnitude the reflected light will exhibit some degree of ellipticity. If they instead have a phase difference the reflected light will have undergone a rotation of its polarization plane[11].

The p-MOKE effect is generally stronger than its l-MOKE counterpart and therefore suitable when large Kerr rotation values are desired[9].

2.2 Time-resolved and spectral MOKE measurements

The reason for performing MOKE spectroscopy already been nudged upon but a more comprehensive view is necessary. Typically, a MOKE spectra shows the MO Kerr rotation or ellipticity as a function of wavelength. The rise of computer technology has meant that MOKE spectra can be calculated to some extent and computer calculations are today widely used together with experimental data to verify physical theories, one of many examples of that can be found here[12]. Materials such as pure Ni, multi-layers or even structured films can be calculated. But for amorphous materials or complicated structures MOKE spectroscopy is, today, the only pertinent solution and the knowledge gained helps understanding how multi-layers, structures and different elements change the magnetic properties of a sample.

MOKE spectra also help increasing the sensitivity in other types of MOKE measurement by indicating for which energy the MO signal is at its maximum.

Tr-MOKE has gained a lot of interest in recent years. Most papers focus on extreme time resolution, down to femtosecond time scales, using expensive and complicated lasers and pump-probe systems[13, 14, 15]. In general these work by exciting, pump, the sample
by a short laser pulse and then probing the sample with another short laser pulse. The result of a measurement is a freeze frame picture of the MO signal, each measurement gives one data point.

Since the conventional theory behind MOKE assumes continuous-wave light\[16, 17\] the use of pump-probe systems has been somewhat controversial, and even though a recent paper\[18\] seems to have resolved this issue to some extent it is still something that pump-probe users have to take under consideration.

We present another system of measurement, simpler in its setup but not necessarily less sophisticated. Instead of pulsing the samples with optical pulses the samples are pulsed with a magnetic field and the precessional MO signal is measured with continuous-wave light. The field is created by letting a voltage pulse through a small conducting stripe on the samples. Even though this system will not reach the same time resolution as the pump-probe systems it immediately gives the whole dynamic signal instead of a freeze frame picture of each step.
3 Experimental

3.1 Spectral measurements

3.1.1 System buildup

In order to test the equipment; step motors, modulation options etc, a trial system was assembled on an optical table (Thorlabs), a schematic view of the setup is shown in fig. 6.

Figure 6: Schematic figure for the test setup. The dotted line represent the connections between the instruments and the red solid line represent the beam path. The polarizer and the analyzer are mounted into rotational stages controlled by a computer.

As the laser beam propagates through the system it is linearly polarized by the first polarizer, reflected by the sample and modulated by either the Faraday rotator or the chopper. Before hitting the photo-detector it passes through another polarizer (usually referred to as an analyzer). Both polarizers are mounted into rotational stages which enables full remote control from a computer. The modulation, performed by the chopper or the Faraday rotator, is used together with a lock-in amplifier (LIA) and is needed in order to increase the signal-to-noise (S/N) ratio of the measurements.

3.1.2 The lock-in amplifier

A LIA is in principle nothing more than an advanced AC voltmeter that relies on the orthogonality of sinusoidal functions to extract a signal, even from very noisy environments.
In short the LIA multiplies the input signal, with frequency $\nu$, with a reference signal, with frequency $\mu$. The resulting product is passed through a low pass filter which removes the AC signals. Generally the output is zero, but if $\nu = \mu$ the output will be a DC signal proportional to the input signal amplitude. It will also be proportional to the phase shift of the input signal and the reference signal which means that the LIA is a phase-sensitive device. In principle this means that any contribution to the input signal that does not have the same frequency as the reference signal will essentially be attenuated to zero.

Another aspect of the LIA that has to be taken under consideration during measurements is the time-constant which determines the bandwidth of the low pass filter. The low pass filter takes about five time constants to settle to its final value which means that the time-constant has to be matched with the speed of any real changes in the input signal that is to be measured.

The chopper modulation gives the light a certain frequency, which is adjustable. The modulation, however, is not sinusoidal but a square wave. This is no problem since the LIA takes the reference signal, passes it through a phase shifter and creates an internal reference with the same frequency as the external reference. It is not necessary for the input to be sinusoidal either, only periodic with a specific frequency, since the LIA takes the Fourier component of the input.

### 3.1.3 Test measurements

A LabVIEW program for the test setup was written in order to control the equipment from a computer. LabVIEW is, very briefly explained, a graphical programming language commonly used in scientific purposes since most scientific equipment have drivers for them in LabVIEW easily accessible.

It was written with the specific purpose of finding a zero position of intensity of light passing through the system with respect to the rotational position of the analyzer. The need for finding the position of extinction will be discussed in extent in the next section.

The front panel of the program is shown in the appendix Fig. 20. The program controls the rotational stages, the laser and receives data values from the LIA amplifier. To the upper left are two graphs. The leftmost shows the intensity of the light incident at the detector as a function of position of the analyzer and the one to the right shows the intensity/wavelength curve together with a fit of the curve. The two boxes to the upper right controls the rotational stages for the polarizers. The speed and the acceleration for the rotational stages are controlled by setting the values in the four small input boxes to the lower right.

Fig. 7 and Fig. 8 show two graphs, intensity versus rotational position of the analyzer, measured with the setup. The difference between them is due to the different types of modulation.
**Figure 7:** Intensity vs. analyzer position, measured with chopper as modulation. "RR" stands for right rotation, i.e. analyzer going from lower positional values to higher; vice versa for "LR".

**Figure 8:** Intensity vs. analyzer position, measured with Faraday rotator as modulation. "RR" stands for right rotation, i.e. analyzer going from lower positional values to higher.
The photodetector converts the incident light into a photocurrent, \( i \), that is proportional to the intensity of the light and the wavelength:

\[
i = I\rho(\lambda)
\]

where \( I \) is the intensity of the light and \( \rho(\lambda) \) is the spectral response of the detector. The detector is connected to the LIA with a BNC cable together with a 50 \( \Omega \) terminator connected to the BNC cable via a t-junction. In this way the photocurrent is transformed into a voltage, \( V \), which the LIA can measure. Since the value of \( R \) is known:

\[
V = I\rho(\lambda)R
\]

The well known Malus’ law states that the intensity of linearly polarized light passing through an ideal polarizer is given by:

\[
I = I_0\cos^2\theta
\]

where \( \theta \) is the angle between the polarization angle of the incoming light and the polarization axis of the polarizer, and \( I_0 \) is the initial intensity. Since the modulation of the chopper only pulses the light at a certain frequency in order to give the LIA a reference signal, the light itself is not modulated, the measurements performed with the chopper, Fig. 7 follows the expected \( \cos^2\theta \) behaviour. Since

\[
\cos^2 x \approx 1 - x^2
\]

around \( x = 0 \) the curves measured with the chopper as modulation could be fitted with a polynomial equation in order to find the position of extinction.

The modulation performed with the Faraday rotator is slightly more intricate. A Faraday rotator is in principle nothing more than a transparent medium, in this case a quartz tube (specified for 1.5-5.5 eV), within a coil, see Fig. 9. Linearly polarized light that propagates through the tube will suffer a rotation of its polarization plane when a magnetic field is applied along the direction of the tube.

\[\text{Figure 9: Schematic figure of a Faraday rotator, when a current is applied over the coil a magnetic field is produced along the direction of the rotator. The angle of rotation of the light depends on the material constant } \nu, \text{ the magnitude of the magnetic field, } B, \text{ and the length of the rotator, } d.\]
For a static field over the glass the rotation is given by:

$$\alpha = \nu dB$$  \hspace{1cm} (3.5)

where $d$ is the length of the rotator, $B$ is the magnitude of the magnetic field in the direction of the light, $\nu$ is the Verdet constant of the material, and $\alpha$ is the rotation angle. When used as modulation the Faraday rotator is driven by a sinusoidal voltage, 3 V peak-to-peak and a frequency of 1300 Hz, given by a current amplifier (iP900 Lab.gruppen) which in turn is controlled by the LIA. This gives an alternating field over the quartz tube and the rotation changes to:

$$\alpha = VdB_0 \sin \omega t$$  \hspace{1cm} (3.6)

This in turn will slightly modify Malus’ law, eq. 3.3, giving:

$$I = I_0 \cos^2(\theta - \alpha)$$  \hspace{1cm} (3.7)

The expansion of the expression in eq. 3.7 around $\alpha = 0$, i.e. a Maclaurin series, to a first order approximation is:

$$I \approx I_0 \left( \cos^2 \theta - 2 \cos(\theta) \sin(\theta) \alpha \right)$$  \hspace{1cm} (3.8)

Looking at eq. 3.2 it is clear that the voltage now constitutes of two components, one AC and one DC:

$$V_{ac} = -2R\rho(\lambda)I_0 VdB_0 \frac{\sin(2\theta)}{2} \sin(\omega t)$$  \hspace{1cm} (3.9)

$$V_{dc} = R\rho(\lambda)I_0 \cos^2\theta$$

As the LIA has $\sin(\omega t)$ as a reference signal it will single out and only measure the AC component and since:

$$V_{ac} \sim \sin(x) \approx x$$  \hspace{1cm} (3.10)

around $x = 0$ measurements performed with a Faraday rotator as modulation will approach $I = 0$ linearly as can be seen in Fig. 8. Curves measured with the Faraday rotator as modulation could therefore be fitted with a linear equation.

Fig. 7 also illustrates the limitations of the step motor. The figure has four curves, all measured under the same conditions, still they differ from each other. The curves labeled ‘RR’ are measured for a certain rotation direction of the analyzer, going from lower positional values to higher, vice versa for the curves labeled ‘LR’. The difference between the curves is due to the imperfect fitting of the cogwheels in the step motor and is usually referred to as backlash and is something that has to be taken into account in order to get correct measurement values. The minimum position is shifted approximately 0.3 degrees. between the two sets of curves, this is the same value stated in the specification sheet as the backlash for the rotational stages.

Both Fig. 7 and Fig. 8 show the good accuracy of the rotational stages, between each ”RR” and ”LR” curve the first polarizer is shifted back and forth to its original position, still the point of extinction differs less than 0.001 degrees.
3.1.4 Kerr spectrometer

A photo of the polar MOKE spectral system built up is shown in Fig. 10 and a schematic illustration in Fig. 11.

The principle of operation of the spectral system is to measure the point of extinction for the light going through the system with respect to the positional value of the analyzer, for each photon energy step. This position is recorded for both magnetization directions of the sample and used to calculate the Kerr rotation.

The spectral setup is similar to the test system apart from a few changes. The incident light beam is generated by a 300 W Xenon lamp and monochromatized by a monochromator with an adjustable spectral resolution which was set to approximately 0.5 nm. The light is linearly s- or p-polarized by the same polarizer as in the trial system and focused on the sample with a spot size of approximately $4 \times 1\, mm^2$.

The samples are placed, with double adhesive tape, in the middle of one of two cylindrical permanent magnets. One 1.5 cm in diameter and 3 cm thick reaching 0.45 T, and the other 8 cm in diameter and 4 cm thick reaching 0.6 T. The angle of incidence of the incoming light is approximately 4 degrees, it is close to normal incidence and can be approximated to polar geometry. The reflected beam is modulated with the Faraday rotator and goes through the analyzer.

The Faraday rotator is chosen ahead of the chopper due to more stable modulation. The intensity of the light is detected with a photomultiplier due to the lower intensity of the light (Xenon lamp compared to a laser).

For every photon energy step the analyzer is rotated and a zero intensity transmission
position is recorded. This is done for both magnetization directions $+\mathbf{H}$ and $-\mathbf{H}$. The angle setting difference of the analyzer is then $2\times \theta$ with any non-magnetic origin sample birefringence effects eliminated. By referencing the measurements to a non ferri- or ferromagnetic sample, e.g. a paramagnetic Al sample, spurious Faraday rotations in optical elements due to magnetic stray fields are eliminated as well.

The focusing lenses, seen in Fig. 10 and Fig. 11, used to direct the beam through the various elements in the beam path, are UV fused silica lenses (Thorlabs). Specified to work in the range of 185 nm to 2100 nm. To screen out any second or higher orders of diffraction from the monochromator cut-on filters (FEL0400 and FEL0650, Thorlabs) were placed directly after the output of the monochromator.

In order to get the photomultiplier operative, a control-box had to be constructed. This was used together with a power supply (HMP4040, Hameg) which fed the control box a DC voltage of 15 V. The control-box converted the input current to an adjustable control voltage for the photomultiplier which had a maximum gain of about $10^6$. The photomultiplier’s high sensitivity to light required shielding of stray light. This was achieved by mounting the photomultiplier at the end of a hollow tube and having a box covering the last part of the setup during measurements.

The LabVIEW program written for the spectral system was built up around an already existing program for the monochromator. Again, this was written specifically

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Figure 11: A schematic overview of the spectral setup. The dotted line represent the connections between the instruments and the red solid line represent the beam path. The part of the setup covered with a grey field is covered by the box seen in Fig. 10 during measurements.
for finding the position of extinction.

The front panel of the program is shown in the appendix Fig. 21. To the left are the control boxes for the monochromator, change of grating, change of calibration values, change of wavelength etc. To the right is the settings for the spectral measurements. The range of energy/wavelength and step-size, speed and acceleration (set to 0.1 degrees/s and 0.1 degrees/s² respectively during measurements) of the rotational stages, the range of rotation for the analyzer and the matching constant of the program to the LIA’s time constant. The range of rotation sets the interval, in degrees, in which the analyzer should rotate. Generally this was set to 0.9 degrees, giving a rotation around the position of extinction of about 0.45 degrees in both directions. The interval 0.9 degrees is long enough to get good linear fit to the data but still short enough to not slow down the measurement procedure too much. A full spectral scan of a sample takes about 30 minutes. The matching constant makes sure that only one intensity value is recorded for each step of the analyzer.

The program consists of two parts, a main program where the parameters are set and a subprogram handling the measurement. The front panel of the subprogram is shown in the appendix Fig. 22.

Fig. 12 shows a flow diagram for the two programs visualizing the measurement procedure. As the rotation of the analyzer begins the photomultiplier detects the intensity of the incoming light. For the start wavelength one needs to know, roughly, the position of extinction for the sample that is to be measured. This can rapidly be investigated by using the subprogram separately.

![Flow diagram for the two programs](image)

*Figure 12: Flow diagram for the two programs used for the spectral measurements. A main program runs a subprogram which in turn controls the rotational stages.*

The compensation for backlash is done by always measuring the point of extinction in the same direction of rotation for the analyzer. The analyzer is rotated to a position 3 degrees lower (start position of e.g. 75 degrees results in a rotation to 72 degrees) than the start position of the measurement and then rotated forward to the starting position.
This is done at a higher speed than the actual measurement thus improving the speed of the measurement procedure.

At the starting position for the analyzer the program is halted for 5 seconds where it sends an auto-gain signal to the LIA and changes the speed and acceleration of the rotational stages. The length of this stop can be changed with respect to the time constant of the LIA since it is the time constant that determines how long it takes for the LIA to perform an auto-gain operation.

However, there is another aspect that one has to take under consideration, if the stop time is too short the rotational stage for the analyzer does not have enough time to decelerate which means that it will move too fast with respect to the time constant giving a drift of the data points measured in the beginning of each wavelength step. This affects the linear fit of the curves, which in turn affects the position of extinction calculation and in the end the measurement as a whole.

The measurement data is collected by the program from the LIA and processed by a Matlab code sorting out the middle part of each curve and fits it to a linear equation. From this it calculates a position of extinction which also serves as the new nominal position to rotate around for the analyzer. Since the Kerr rotation could vary quite a bit with each energy step, but always smoothly, a feature of letting the program calculate the current speed of the change of the Kerr rotation was added. With this information the program could calculate a more suitable nominal position ensuring enough data points for a good linear fit.

Fig. 13 shows the curves for both magnetization directions for Al. The difference between the two curves is, as expected, almost zero. As the light passes through the system its angle of polarization will rotate differently depending on the photon energy. The curves thus show the inherent rotation of polarization in the system.

These kinds of curves are measured for all samples, by subtracting the two curves the Kerr rotation for each energy step is calculated. However, since the measurements have to be performed for both magnetization directions the sample has to be taken off the magnet, the magnet to be turned and the sample attached again. This of course affects the measurements since it is impossible to place the sample at the exact same position both times, the beam path will be slightly shifted and any stray fields on the optics will be altered when turning the magnet.
3.2 Time resolved measurements

Due to time limitations on the project no measurement data will be presented, the idea, though not yet realized, is to measure the precessional Kerr rotation of a sample, using continuous-wave light. A sample was received from another group with hopes of repeating parts of their measurement[19].

A schematic figure of the setup together with an illustration of a sample, not the one received but manufactured for testing the setup, is shown in Fig. 14.

The setup was created on the same optical table as for the spectroscopy measurements and the same setup with polarizers, lenses, photomultiplier and laser was used. SMA cables were soldered to the pin contacts in one end and connected to a pulse generator (AVMR-1A-B-P, Avtech) and an oscilloscope (MSO9254A Agilent Technologies) at the other. Having the stripe perpendicular with respect to the plane of the incoming laser beam results in a longitudinal MOKE setup.

By letting the pulse generator produce a square voltage pulse and applying this over the sample an Oersted field is produced. If the polarizers are crossed with respect to each other, the Kerr rotation of the light, due to the Oersted field, is measurable as an intensity change of the light going through the whole system. As the pulse propagates...
through the sample the intensity of the light will increase, or decrease depending on the positions of the polarizers and the direction of the Oersted field, and oscillate around a final value. Much like a dampened Sine curve.

If the pulse to the sample is very fast, i.e. has very low rise-time, it can be approximated as a Dirac pulse. Since a Dirac pulse contains, in practice, all frequencies up to a very high range it is very suitable to use when determining the frequency response of a medium. The signal due to the magnetic, and thus voltage, pulse can be analyzed using fast Fourier transforms (FFT) which reveals if there is a dominant precession frequency of the oscillations of the Kerr rotation.

Since a static field over the sample changes the frequency of the oscillations of the Kerr rotation[19], a quadrupole, Fig. 15, was made. The structure was printed in a 3-d printer as five individual parts, four coils and one casing. Each coil has 62 turns of 1.6 mm copper tread with a thin polymer insulation, together giving a maximum field of approximately 12 mT.

In order to be able to mount the sample holder, or samples, a vacuum holder was manufactured in acrylic glass. The vacuum holder was placed into an x-y translation stage which in turn was attached to the backside of the quadrupole casing (not shown in Fig. 15).
4 Results and discussion

4.1 Spectral measurements

Fig. 16 shows the Kerr rotation spectra for the permalloy sample. The green circle curve is measured with the setup described in this report whereas the blue triangular curve is a reference spectra measured elsewhere[20]. Both measurements are performed with the same sample albeit a few years apart. A straight line is drawn between each data point making it easier to follow the oscillations in the low energy regime.

The two spectra, blue and green, differ somewhat, but almost entirely in the magnitude of the Kerr rotation, qualitatively the two curves shows quite good resemblance. This can be explained by the type of magnetization.

Fig.17 shows a p-MOKE hysteresis measurement performed on the permalloy sample. The saturation magnetization is about 1 T. Clearly the small magnet, with a field of approximately 0.45 T, is not enough to saturate the sample in the out of plane direction. The size of the magnet is, furthermore, comparable to the size of the sample and thus too small to homogeneously magnetize the sample. Since the spot size of the light hitting the sample is not infinitely small, this will also affect the Kerr rotation. Both these effects decrease the magnitude of the Kerr rotation in the measurement and are the reason to why the green curve is shifted upwards with respect to the blue curve in Fig. 16.

A problem that already has been mentioned is the manual turning of the permanent magnets necessary to measure a spectrum. The sample position will shift slightly between $+\mathbf{H}$ and $-\mathbf{H}$ affecting the measurement. Another problem is the possibility of stray fields affecting all optic elements.

As earlier stated, a paramagnetic reference sample, in this case Al, is measured. The
Figure 16: Spectra for the permalloy sample, green circles, together with a reference measurement of the same sample, blue triangles, and a mirror sample, black squares. The difference in magnitude in the Kerr rotation for the blue and green curve is due to inhomogeneous magnetization of the sample.

Kerr rotation for this kind of sample should in principle be zero even with a magnetic field applied, as it is in Fig. 16, black curve. The maximum rotation for the Al sample is less than 0.001 degrees (measured with the small magnet). If, however, there is any stray field on the optical components in the system this can cause a Faraday rotation of the light passing through them. This will show up as a rotation for the mirror sample as well. So instead of having a flat, zero rotation, Kerr spectra for the mirror sample it will have a nonzero varying spectrum. Usually this is no problem since this rotation can be subtracted from a measurement performed on a magnetic sample by comparing them with a mirror sample. But since this system utilizes permanent magnets that manually have to be turned, the stray field on the optics will be slightly different from time to time since it is practically impossible to place the magnet at the exact same spot every time. It is therefore meaningless to subtract mirror values from a magnetic sample’s values since there is no way of knowing if it is the correct values that are subtracted.

For this setup the mirror spectrum instead tells us how accurate the system is in finding the correct Kerr rotation with respect to effects from stray fields. It can therefore be concluded that the effect of stray field is minimal on the spectrum showed in Fig. 16,
Figure 17: P-MOKE hysteresis curve for the permalloy sample showing a saturation magnetization of approximately 1 T.

i.e. on spectra measured with the small magnet.

Fig. 18 shows the atomic force microscopy (AFM) image of a Ni antidot sample with 248 nm (approximately) sized holes.

Figure 18: AFM image, 5×5 µm, of the patterned Ni sample. The hole size is approximately 248 nm. The Ni layer is approximately 25 nm with a 2 nm Au layer on top.

The Ni layer is about 25 nm thick and covered by a 2 nm thick Au layer for protection.

The Ni antidot Kerr rotation spectrum is showed together with its relative reflectivity
spectrum (measured elsewhere[20]) and the Kerr rotation spectrum of a continuous Ni film, 100 nm Ni covered by 2 nm Au, in Fig. 19. The intensity scale of the reflectivity spectrum is relative to that of the continuous Ni film.

**Figure 19:** Kerr rotation and relative reflectivity spectra (open green circles and gray crosses respectively) for the Ni antidot sample together with Kerr rotation for a continuous Ni film (open blue triangles). The MO response of the patterned sample is strongly enhanced around 2.65 eV due to surface-plasmon excitations.

Since a hole patterned sample has less mass than a continuous film, and therefore less collective magnetic moment, the expectation is that magnitude of the Kerr rotation is smaller for this sample. Fig. 19 shows that that is the case, but only for the lower energies. At higher energies it is not so. At just over 2.6 eV there is a local maximum of the Kerr rotation for the patterned film. The Kerr rotation is enhanced by a factor of roughly five compared to the continuous film. This is due to the surface-plasmon resonance, a phenomenon not to be covered by this report but a review of it can be found here[21, 22, 12]. To very briefly touch upon the subject; the light interacts with the hexagonal hole structure of the sample which leads to an enhancement of the plasma oscillations of the electrons at certain resonance frequencies, which in the end shows up as an increased Kerr rotation.

The energy match of the dip in reflectance and the increase of Kerr rotation at around 2.6 eV indicates a strongly enhanced MO signal due to surface-plasmon excitations.
A decrease in reflectance is expected at the surface-plasmon resonance frequencies[20]. The correspondence in energy also suggests that the system is working properly, two independent measurements performed at different locations by different people show the same phenomenon.

Again there were some problems with the magnetization. The large magnet naturally had a larger stray field affecting the optics in the setup. This led to a nonzero Kerr rotation for the Al mirror, sample. The maximum Kerr rotation measured (several measurements where performed with slightly different positions for the magnet) for the Al sample was almost 0.09 degrees. This should be interpreted in the way that there is a maximum error for the data values for the Kerr rotation in Fig. 19 of 0.09 degrees. This might seem as quite a lot since the maximum Kerr rotation for the continuous Ni film is slightly above 0.2 degrees. But keep in mind that the spectra for the Al sample always showed smooth features so that none of the peaks evident in Fig. 19 would disappear. They would only be shifted up or down by some value.

The Ni spectra measured do not match the ones found in literature perfectly, the shape of the curve is good but the magnitude of the Kerr rotation is slightly too large. This is most probably caused by the magnetization problems.

5 Conclusions and outlook

A p-MOKE spectral system has successfully been constructed. A LabVIEW program controlling the system has been written and the measurements performed show that the system accurately can measure the Kerr rotation as a function of photon energy.

The permalloy spectrum measured shows a good qualitative match with the reference measurement. The energy of the surface-plasmon enhanced Kerr rotation, for the patterned Ni sample measured, matches the reflectance measurement.

Improvements of the spectral setup includes incorporating an electromagnet into it. This would limit the stray fields and spurious Faraday rotation and give more stable and faster measurements.

The LabVIEW program could be improved by calculating the quality of fitting of the curves for each energy step. In this way the program could rerun the measurement for the energy steps where the fitting parameters are insufficient. It would also give error bars for the measurements.

Using a photoelastic modulator as modulation, instead of a Faraday rotator, would enable measurements of the ellipticity as well as the Kerr rotation as a function of photon energy. A new lamp, for the light source of the monochromator, together with a new photomultiplier would improve the spectral range.

In the future the spectral measurements will be faster and cover a wider photon energy range. This will benefit other types of measurements since it can be used to investigate for which photon energy a sample has its biggest MO response. More patterned samples will be analyzed and the quality of the measurements will improve.

The time limitations of the project unfortunately left the result section of the tr-MOKE measurement empty. But the work done has not been in vain. The setup
is working to a large extent. The quadrupole can achieve approximately 12 mT, the oscilloscope and the pulse generator are in place and working.

For the tr-MOKE a lot of things can and will be done. The system will be optimized with new cabling and better sample holder. When the system is up and running, patterned samples will be measured to investigate the time resolved magnetization of macro spins. Samples with multiple stripes will also be measured to investigate the dependence of spacing and width parameters of the stripes. Hopefully this will help understanding the physics behind tr-MOKE.
A Appendix

Figure 20: Front panel of the test setup program used for examine the functionality and precision of the rotational stages. The leftmost graph shows the light intensity vs. analyzer positional value. To the upper right are the control boxes for the rotational stages.
Figure 21: Front panel of the spectral measurement program. The program controls the rotational stages and the lock-in. To the left are the controls for the monochromator and to the right are the controls for the parameters for the spectral measurements. For each step in energy, a position of extinction is measured and calculated.
Figure 22: Front panel of the subprogram to the spectral measurement program. The left graph shows intensity versus position for the analyzer, the right one shows the same thing but with a linear fit to the curves added.
References


