A Magneto-Optical Kerr Effect Study

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science degree in Physics from the College of William and Mary

by

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Abstract

Magnetic properties of materials have long been a popular research topic within physics. In thin films, magnetization has great potential for industrial applications, such as development of new electrical components. This report will discuss one optical characterization methods used to study magnetic properties of thin films, the magneto-optical Kerr effect (MOKE). The report will also cover the apparatus used to observe the magneto-optical Kerr effect, as well as, the procedure used to optimize the system. Through the use of MOKE we will gain the necessary information in order to map the coercivity of thin films to describe the materials magnetocrystalline anisotropy.

Introduction

The magneto-optical Kerr effect is an observable electro-magnetic phenomena which occurs when linearly polarized light is reflected off a magnetized surface. Much like the Faraday effect, the Kerr effect occurs when light encounters a magnetic material. While the Faraday effect describes transmitted light, the Kerr effect describes the physical effect on the reflected light. The linearly polarized light, which is reflected from the magnetic surface, becomes ellipsoidally polarized and a rotation of the polarization's principal axis occurs. The rotation of this axis is referred to as the Kerr rotation, and is proportional to the magnetization of the reflecting surface. In nanomagnets the magnetic anisotropy is not only dependent on the material, but the size and shape of a sample also affect this property. There are a number of ways which nano-magnates can be used in advancing technologies, making the study of their magnetic anisotropy a very relevant topic in material science.

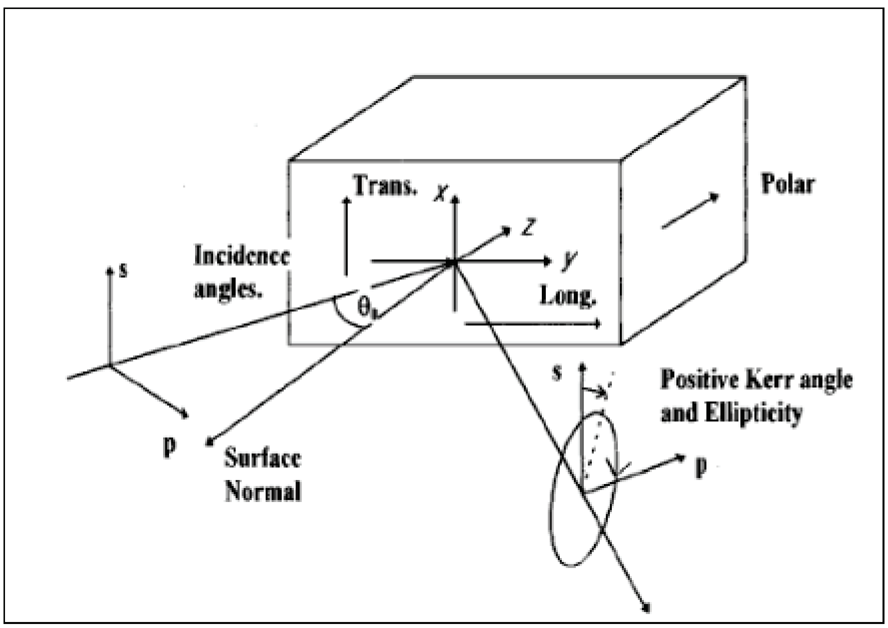

Fig. 1: Kerr Rotation (Nirajan Mandal 2010)

To understand the physical explanation of the Kerr rotation it is important to consider the surface conditions of the sample. The light which is reflecting has two linear polar configurations. The (s) polarization, coming from the german word senkrecht (perpendicular), defines the electric field perpendicular to the plan of incidence. The (p) polarization defines the electric field parallel to the plan of incidence. There are three geometries between the incident light and the magnetization of the sample which the magnetic-optical Kerr effect can occur. The MOKE apparatus will be configured in the longitudinal geometry, in which the incident beam is parallel to the magnetization of the sample.(Fig 1.) This configuration is used to measure in plane magnetization of thin films. Normally, when linearly polarized light is reflected off a metallic surface, it retains its polarization. In the case of a magnetized surface, the symmetry of the system does not hold and the polarization changes. The changes in polarization of the reflected light can be shown using the general dielectric tensor, given by:

$$\overleftrightarrow{\varepsilon} = \begin{bmatrix} \varepsilon_0 & i\varepsilon_z & -i\varepsilon_y \\ -i\varepsilon_z & \varepsilon_0 & i\varepsilon_x \\ i\varepsilon_y & -i\varepsilon_x & \varepsilon_0 \end{bmatrix}$$

$\varepsilon_i = \varepsilon_0 Q m_i$ where Q is the Voigt magneto optical constant and m_i is the ratio between the magnitude of magnetization in a given direction and the magnitude of saturation magnetization of the sample $m_i = \frac{M_i}{M_{sat}}$. As shown in the dielectric tensor, the off diagonal elements are proportional to the magnetization, causing the polarization state of the light at the surface to correlate with the magnetization of the sample. This forced correlation is expressed as the magneto-optical response, which will measured by the MOKE apparatus. The magneto-optical response is expressed as the rotation of the polarization of the in phase portion of incident light. The polarization of the out of phase portion of incident light also is effected by this response and experiences an ellipticity, this modification is know as Kerr ellipticity. Using the correlation between the reflected polarized light and the magnetization of the sample, it possible to observe the effect an external magnetic field has on the magnetization of the sample. The result of the MOKE measurement is a hysteresis loop with a slope equal to the permeability of the material $\mu = B/H$.

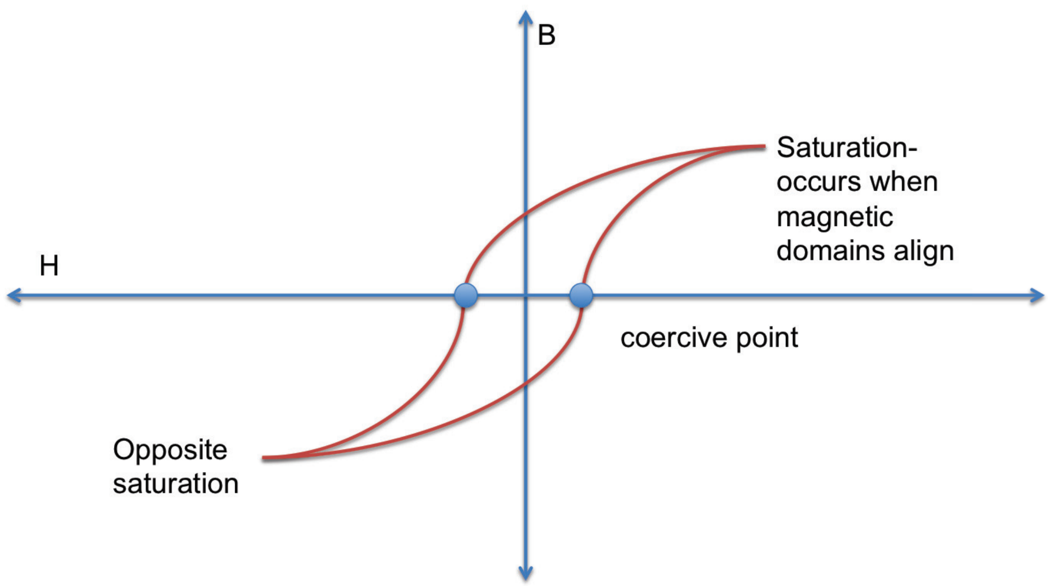

Fig. 2: Magnetization versus an applied magnetic field for a magnetic sample

The magnetization of a sample will reach a point in which the permeability becomes constant, this occurs when the magnetic domains within the martial are all aligned, as shown in Fig. 2 When this occurs the magnetization of the sample has reached its maximum or minimum possible value. The point at which the magnetization of a martial after reaching magnetic saturation returns zero is referred to as the coercive point. Coercivity describes how resistant a magnetized material is to demagnetization when exposed to an external field. Due to the crystalline structure of magnetic materials, the coercivity of a material is dependent on the angle between the in-plane magnetization and an applied external magnetic field. By mapping the changes in coercivity with respect to this angle , it is possible to describe the amount of energy needed to change the magnetization of a material with an external magnetic field in a particular direction. This measurement is called magneto crystalline anisotropy, and it is particularly useful in developing nano-magnets for industrial use.

MOKE Apparatus

The MOKE apparatus is constructed on a vibration isolation optical table. The setup consists of a 1mW red He-Ne laser (633nm), which is passed through an optical chopper of a given frequency. It is important that the frequency of the optical chopper is unique from any other electrical frequencies in the lab to preserve the integrity of the measurements. The beam then passes through a (s) linear polarizer onto the sample at an angle of 22.5°.

The sample is held on a rotational mount between two coils. The coils are connected to power supply that is controlled by the data acquisition computer. This allows the voltage fed to the coils and consequently the magnetic field generated by the coils to be controlled and recorded. The reflected light then passes through a (p) linear polarizer, before being focused onto a pre-amplifier photo-diode for detection. The signal is then amplified by a lock-in amplifier, which is locked to the same frequency as the optical chopper, reducing the effect of ambient light on the measurement. From the lock-in amplifier, the data is sent to the computer and recorded in automated MOKE LabVIEW program.

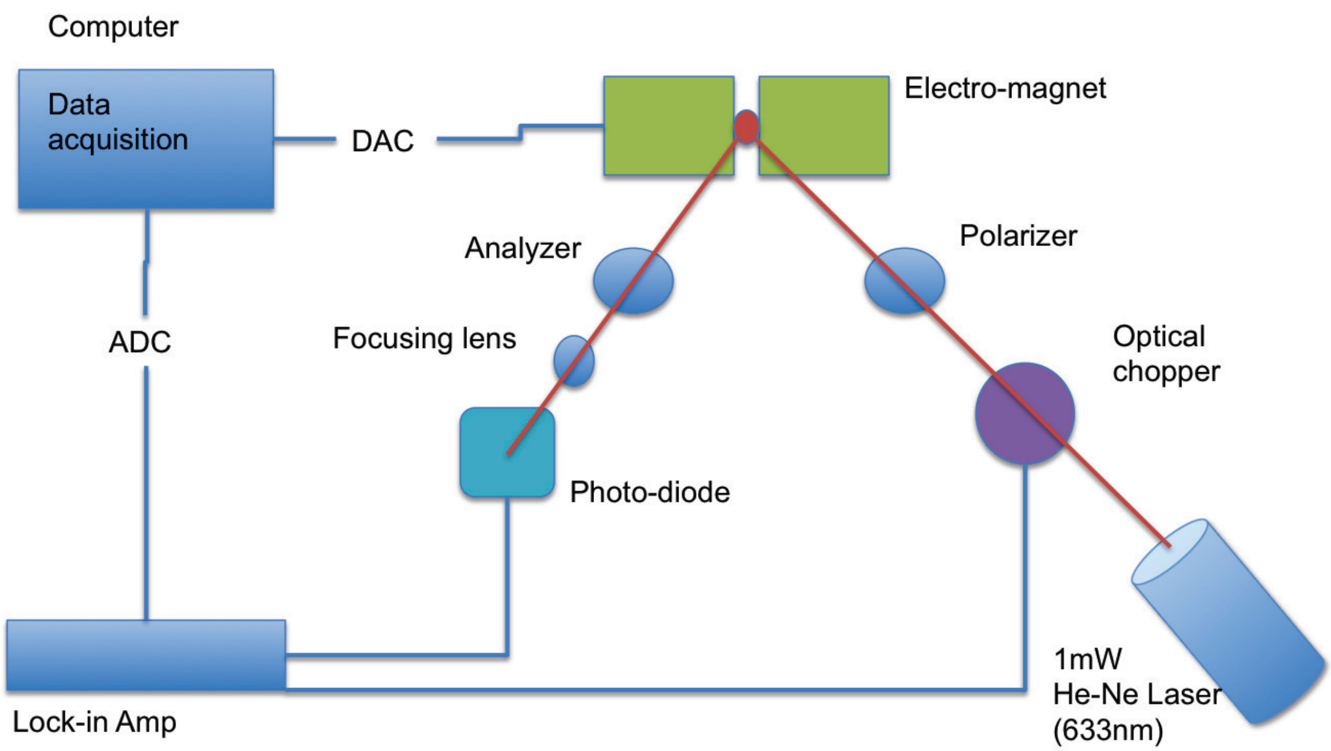

Fig. 3: Schematic of MOKE apparatus

The data collected from the MOKE apparatus ultimately produces a magnetization loop. This loop appears in the LabVIEW program as the plot of the voltage applied to the coils verses the measured voltage from the photo-diode. The voltage applied to the coils is directly proportional to the applied magnetic field, while the measured voltage is directly proportional to the magnetization of the sample. Finding the relation between the applied voltage and the external magnetic field, as well as, the relationship between the measured voltage and the magnetization of the sample, it will be possible to produce a magnetization plot. The magnetization plot takes the form of a hysteresis loop, and from this loop it will be possible to determine the magnetic domains of the sample for a given applied magnetic field.

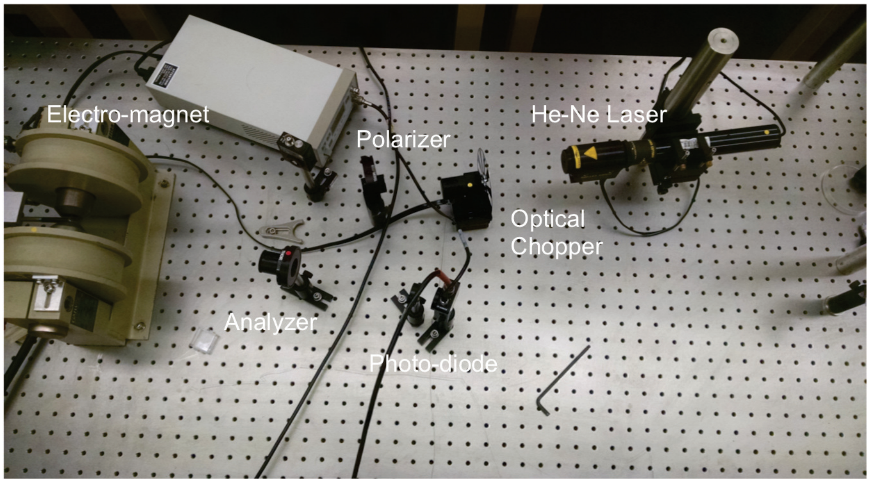

Fig. 4: Optical components of the MOKE apparatus

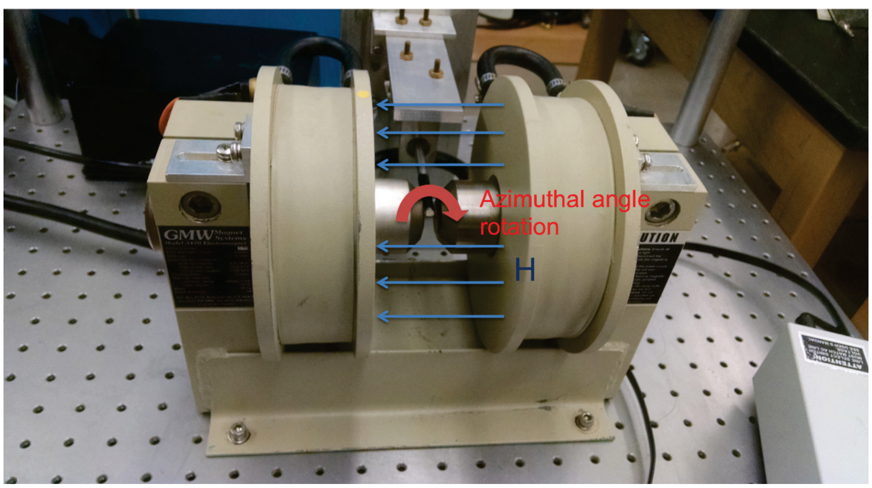

Fig. 5: Rotational mount in the magnetic field generator and azimuthal angle of sample

MOKE Optimization

Although the LabVIEW program automats the collection of data, there are many parameters, within both the program and apparatus, which can alter the effectiveness of the measurements. It is very important to adjust the (p) polarizer, so that it allows the most (p) polarized light through to the detector while blocking unpolarized light from effecting the measurement. Because the reflected light experiences the Kerr rotation and the polarization is ellipsoidal, the direction of (p) polarizer must match the rotation reflected light. When the (p) polarizer is aligned with the polarization of the reflected light, the MOKE apparatus will observe a clear hysteresis loop. If the polarizer is not aligned with the polarization of the reflected light the MOKE measurement will only produce noise, not the hysteresis loop needed to determine the magnetization of the sample. To test the optimization of the apparatus, a 10 nm sample of iron-palladium (FePd) was used to preform initial measurements.

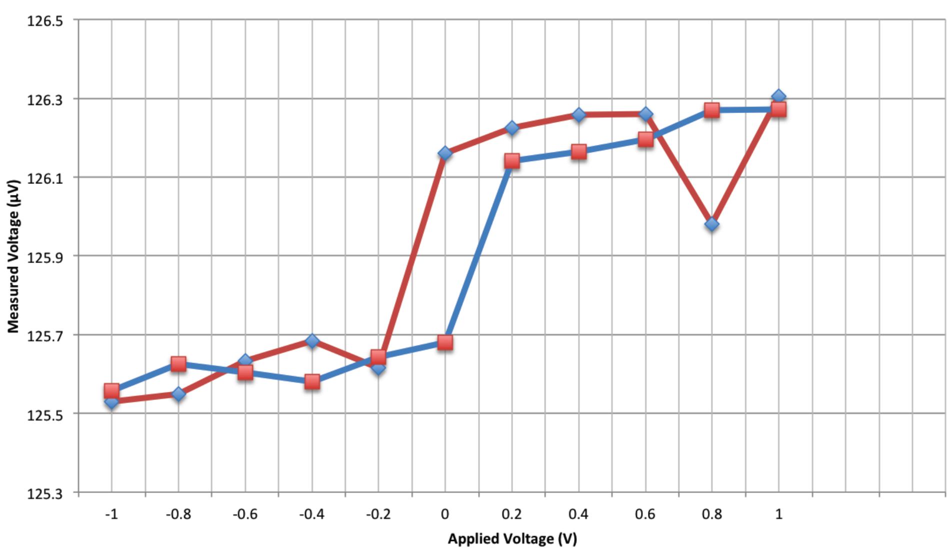

Fig. 6: Quick Measurement on FePd sample

In order to fine tune the direction of the polarizer, quick rough measurements are taken to observe the state of possible hysteresis loops. These measurements cover a larger range of applied voltages to ensure it contains the loop.(Fig. 6) As shown in the figure, the apparatus did roughly measure the magnetic hysteresis loop of the FePd sample. In order for do many of these rough measurements quickly, the readings for each applied voltage are not averaged and the steps between voltages are large.

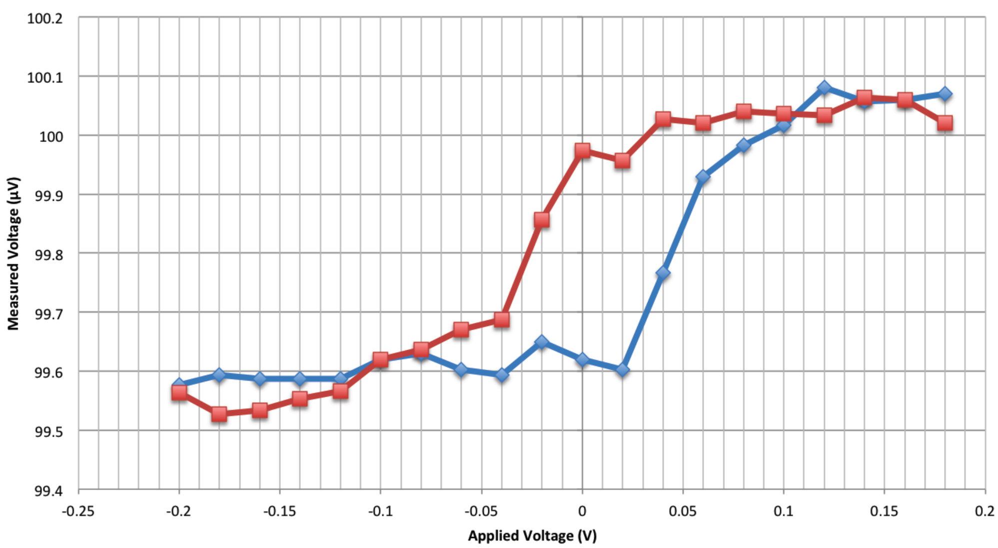

Fig. 7: Detailed Measurement FePd sample

Once a direction is found that provides an observable loop, a more precise measurement can be taken. These measurements, breaks the applied voltage into smaller steps and averages the measured voltage between 10-20 times for each step, to provide a less noisy measurement. (Fig. 7) While the measured loop is not perfectly clean, it is much cleaner than the quick initial measurements. The relationship between the voltages, and therefore the magnetization, is clear.

Results

Now that it was possible to observe the magnetization hysteresis loop for a sample at a fixed azimuthal angle within the sample surface plan, the rotational mount can be used to take multiple measurements to observe the changes in the sample's coercivity. In order to take measurements at different azimuthal angles it is crucial that the alignment of the sample and incident light are precise, so that the reflected beam stays in the same spot on the detector to preserve the integrity of the measurements. The initial measurement done to test the MOKE apparatus ability to preform measurements at multiple angles was done on the FePd sample. Ever 45^o a measurement was taken to ensure that the system stayed aligned and the magnetic hysteresis could be measured.

The measurements at all angles do have the shape of the magnetic hysteresis loop, see appendix A. There is only a small degree of asymmetry between the coercive points for some angles. To improve on these, future measurements will more precisely measure around the coercive points to ensure the magnetization behavior of the material is accurately captured.

Azimuthal angle	Voltage 1 (V)	Voltage 2 (V)	Avg. Voltage (V)	Coercivity (Oe)
0°	0.04435	0.04761	0.04598	95.8465
45°	0.05538	0.05217	0.05377	109.082
90°	0.04955	0.04862	0.04909	101.130

Fig. 8: Results of rotational measurement test

Taking the average of the two measured coercive fields for each loop, it is possible to find the coercivity for the sample at each azimuthal angle by using the relation:

$$y = 17.72727 + 1698.98221(x)$$

Where y is the coercivity and x is the applied voltage. (Fig 8) This relation was determined when calibrating the apparatus. Because there is an expected symmetry in coercivity of a sample, the coercivity was only calculated up to 90^o azimuthal rotation. Due to the uniform magnetic properties of FePd this anisotropy could reflect an anisotropy in the shape of the sample having an effect on its coercivity, as the shape of the sample is not exactly the same at every azimuthal angle.

The next stage in this experiment was to apply the MOKE measurements used on the FePd sample to a 10 nm sample of Ni, which is being studied for potential electronic applications. To more precisely map the coercivity of Ni sample, the magnetic hysteresis would be measured for smaller changes in angle. After attaching the Ni sample to the rotational mount a stationary measurement was conducted to get an initial measurement of the magnetic hysteresis loop.

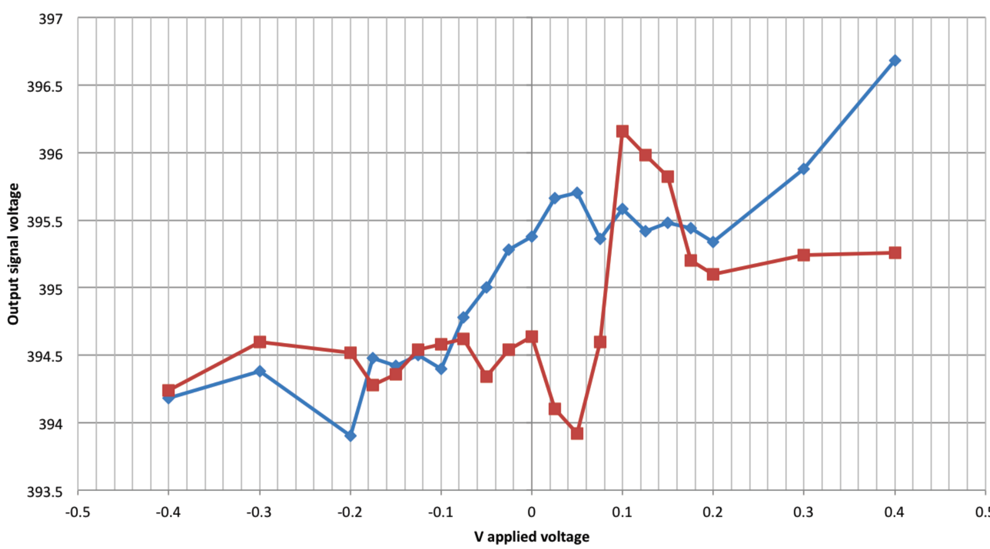

Fig. 9: Ni sample initial measurement

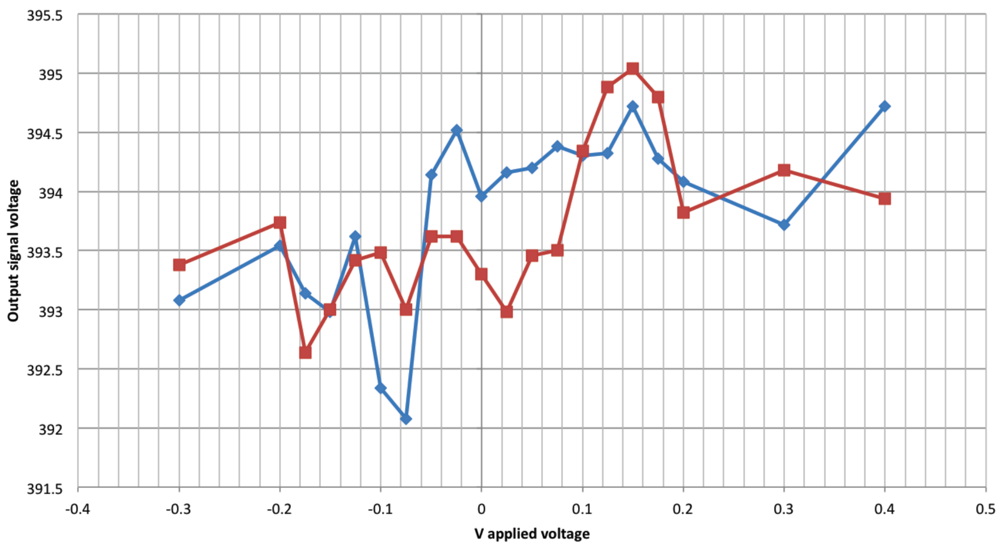

Fig. 10: Ni sample repeat measurement

Even after many adjustments to both the alignment of the MOKE apparatus, as well as, the LABView settings, there was still a lack of stability in the measurements on the Ni sample. As shown in Fig. 9 magnetic saturation seems to be occurring, but there is not a clear hysteresis loop as seen in the results of the FePd sample. When trying to retake the measurement for the Ni sample with the exact same parameters, even more unstably occurred.(Fig. 10) It was found that the cooling system for the magnetic field generator was malfunctioning. Without proper cooling the magnetic field generator became unstable when in prolonged use. With an varying magnetic field being generated, it was not possible to use the MOKE system to accurately measure the magnetic hysteresis loop of the Ni sample.

Conclusion

Through the use of the magneto-optical Kerr Effect, this study has shown that it is possible to measure the magnetization hysteresis loops of the FePd sample. The MOKE apparatus was capable of measure magnetic hysteresis at different angles between the sample and the applied magnetic field. Using these measurements, the coercivity of the sample can be calculated and any anisotropy can be observed. It was found that the coercivity of the FePd sample was dependent on the shape of the sample, this would explain the anisotropy found in the coercivity, despite the uniform magnetic properties of FePd. Applying this measurement technique it would be possible to further characterize the magneto crystalline anisotropy of FePb, and could be used in applying it to industrial applications. While it was not possible to complete the measurements on the Ni due to technical difficulties with the magnetic field generator, Ni should meet the conditions necessary for the magneto-optical Kerr Effect to occur.

Appendex A

The following data depicts the initial use of the rotational stage using a 10 nm sample of iron-palladium (FePd).

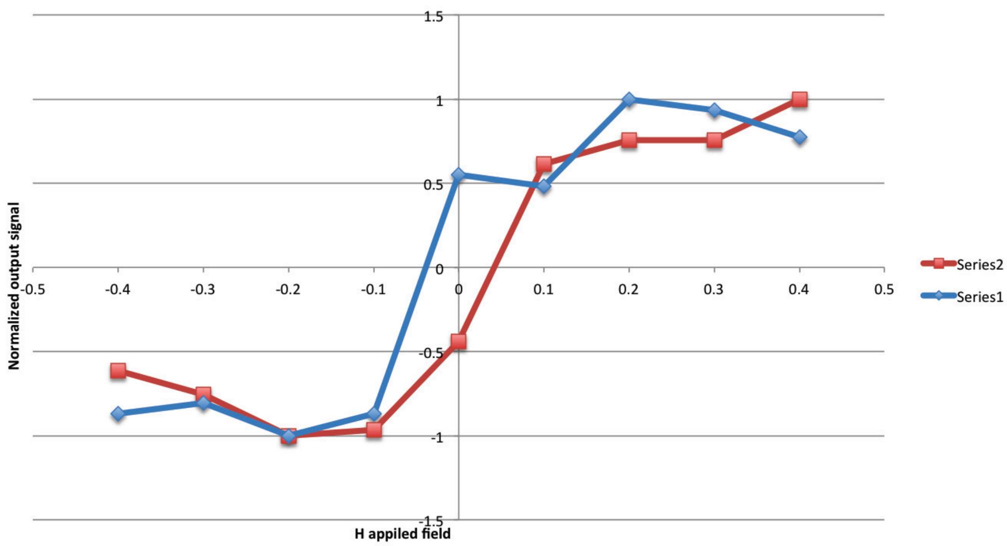

Fig. A.1: FePd 0^o

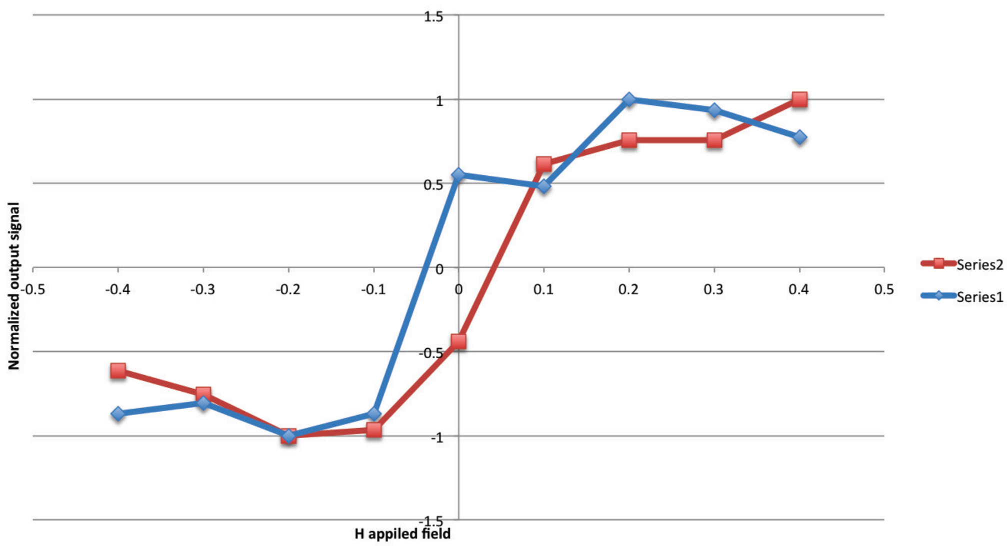

Fig. A.2: FePd 45^o

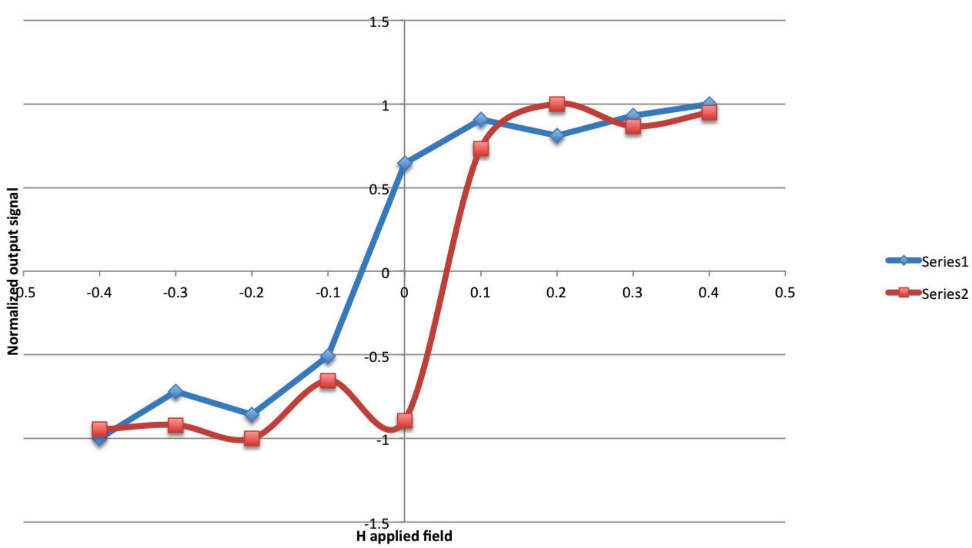

Fig. A.3: FePd 90^o

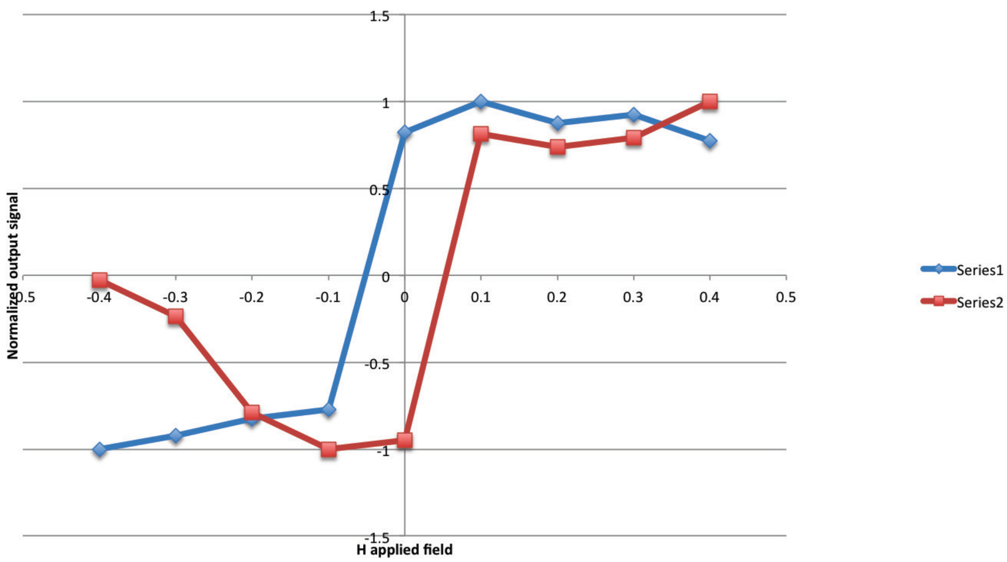

Fig. A.4: FePd 135^o

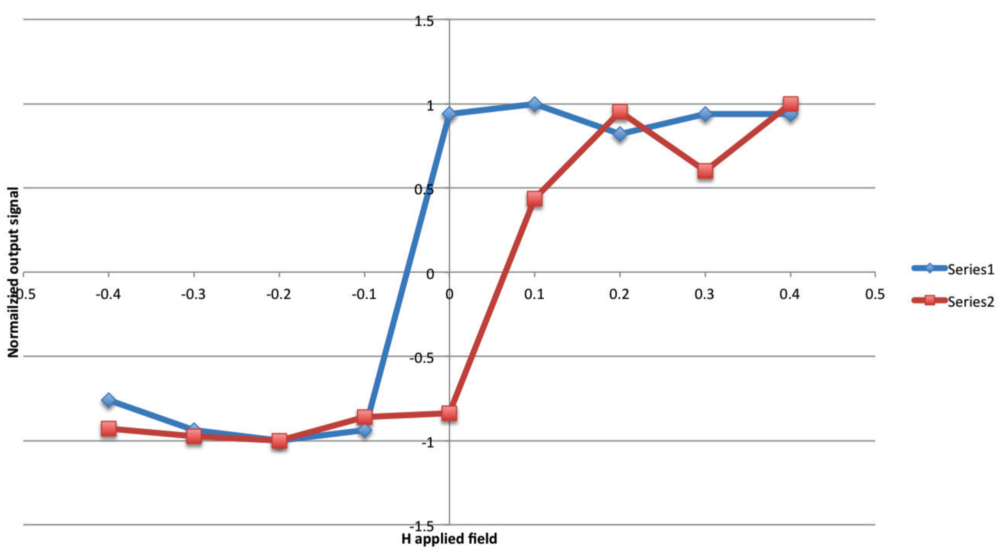

Fig. A.5: FePd 180^o

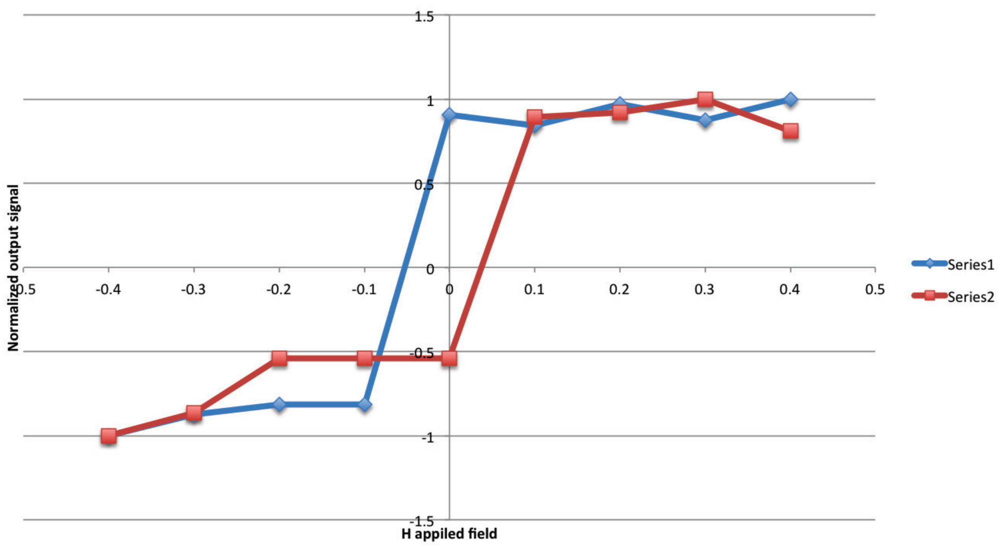

Fig. A.6: FePd 225^o

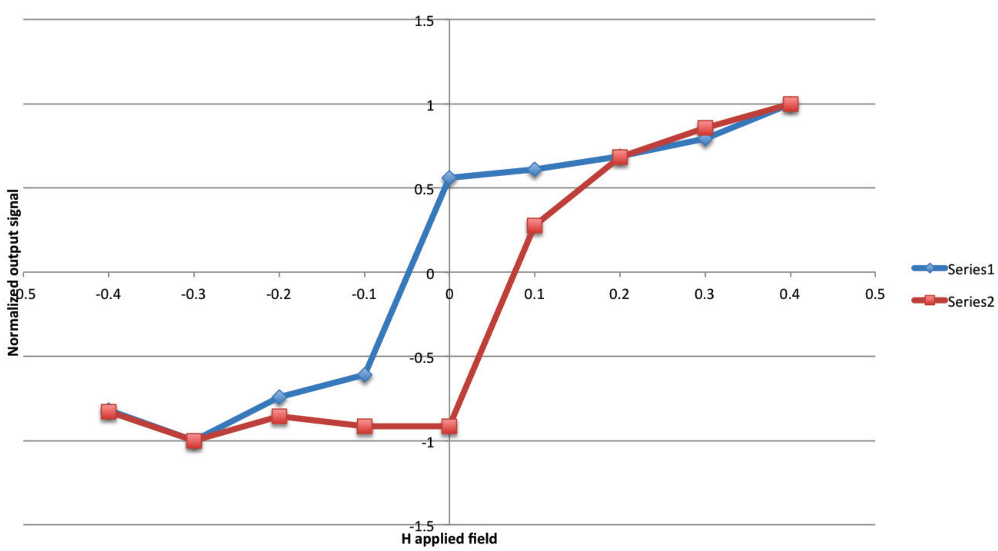

Fig. A.7: FePd 270^o

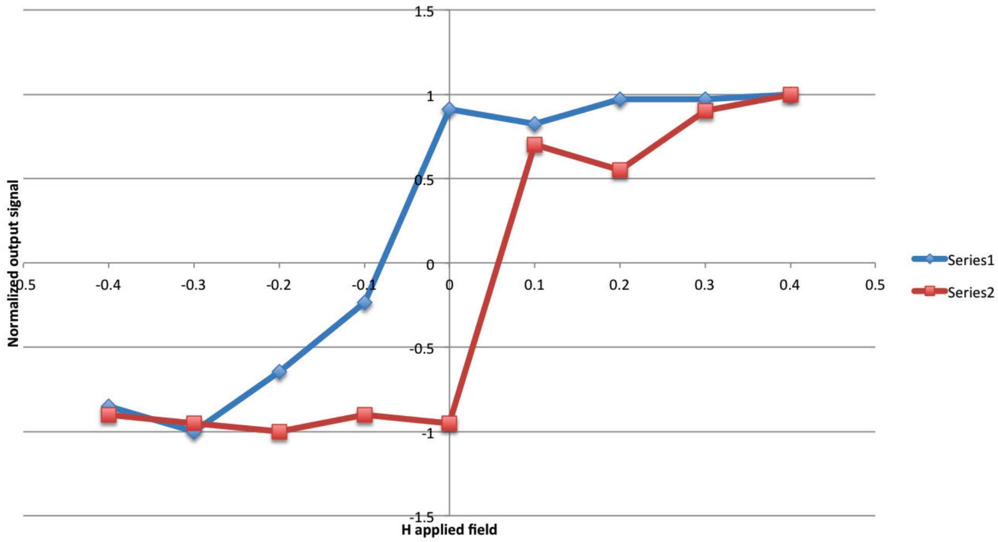

Fig. A.8: FePd 315^o

Acknowledgments

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References and Notes

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