

Measuring magnetic hysteresis through the magneto-optical Kerr effect

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ABSTRACT

A device for measuring the magneto optical Kerr effect was constructed and implemented for use in conjunction with experiments taking place at the Stanford Synchrotron Radiation Lightsource. The setup was intended for sample screening and characterization prior to study using X-ray techniques at the synchrotron facility. The project utilized a HeNe laser and a simple optical table setup. Results from the setup provided measurable hysteresis of thin film magnetic samples. Hysteresis loops were compared with the Stöner-Wohlfarth model in order to validate the results and accuracy of the device.

INTRODUCTION

Magnetic data is ubiquitous in today's digitized society. From messages stored on home computers to credit cards used every day by billions, magnetic bits have infiltrated almost every aspect of the modern world. The number of people who speak English, the so called international language, seems inconsequential in comparison to the innumerable computer hard drives and other devices that speak the language represented by these tiny magnetic symbols. Magnetic memory capitalizes on a ferromagnetic material's ability to retain a certain magnetic alignment after being exposed to an external magnetic field. Through the study of ferromagnetism it is possible to advance the design of ever more powerful magnets. Such advances would facilitate reductions in the size and weight of electronic devices incorporating them, such as electric motors and audio speakers, and improve the capacity of magnetic data storage [1]. The magneto-optical Kerr effect (MOKE) has proved to be a useful research tool for understanding ferromagnetism and magnetic hysteresis. The MOKE occurs when light reflected from the surface of a magnetized material experiences a change in its polarization. Studying this rotation of polarized light provides insights into the magnetic behavior of materials that could be useful in forthcoming technologies which cram more information into ever smaller bits and manipulate these bits faster and faster [1]. The MOKE is a simple and popular research tool; however, the diffraction limit of visible light inhibits the study of atomic scale magnetism using this method. To overcome this limitation, X-rays from synchrotron sources around the world are employed to study magnetic properties on a smaller scale. While the use of synchrotron X-rays is much more effective and essential for the ongoing study of magnetism, providing ultrafast imaging of nanoscale dynamics, the MOKE method still serves as an efficient research tool for magnetic materials due to its low cost and simplicity. For this reason a device to measure the MOKE was

needed to facilitate the characterization of magnetic samples prior to studies conducted using X-ray methods at the Stanford Synchrotron Radiation Lightsource.

Observing and quantifying the MOKE is simple and remarkably straightforward. The process involves measuring the rotation of plane polarized light using two polarizing filters and a photodiode sensor. The first polarizer is placed between a laser light source and the target sample. The second polarizer is placed between the sample and the photodiode with its axis of polarization orthogonal to the first, thereby achieving extinction and essentially impeding all light from reaching the photodiode. When testing non-magnetic samples, no light is transmitted through the second filter because the polarizers are set at extinction. When a sample is magnetized, light reflected from the sample experiences a rotation in its plane of polarization. This rotation allows light to pass through the second polarizing filter, striking the photodiode and producing an output signal. A more intense signal from the photodiode denotes an increase in the rotation of the polarization and therefore an increase in the magnetism exhibited by the sample. By observing the magnetic behavior of a sample in this way, it is possible to gain insight into several important magnetic properties including the remanence, coercive field, and saturation field of a ferromagnetic material. Fig. 1 denotes the setup implemented for measurement of the MOKE at the SSRL.

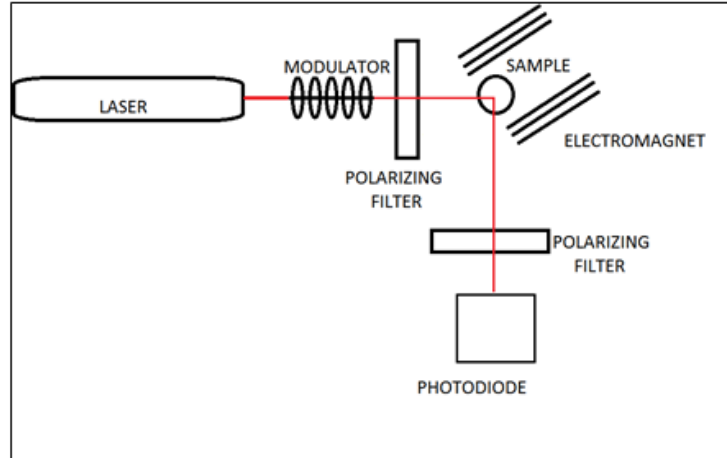


FIG 1. Diagram of MOKE device setup

INSTRUMENTS AND METHODS

The MOKE setup was mounted and operated on a Thor Labs Performance Series optical breadboard. Linos Photonics polarizers were used in conjunction with a red 5 mW JDS Uniphase HeNe laser. An adjustable air-gap electromagnet provided a magnetic field of up to 400 mT in order to magnetize target samples. Sample sizes were small, roughly 1 cm². Beam blocks were used as a means of containing any stray laser beams and preventing the operator from accidental direct eye exposure. In order to obtain sizeable readings; signals from the photodiode were amplified using a Keithley 427 current amplifier. A Stanford Research Systems SR 830 lock-in amplifier was used to obtain the data from the current amplifier. Data sent to the magnet was controlled synchronously via the lock-in amplifier and a National Instruments GPIB USB connector. Before striking the sample, the laser beam was passed through an induction coil with a glass center in order to modulate the input signal using the Faraday Effect. The lock-in amplifier was used to provide an AC signal to the modulator and lock on to the characteristic frequency of the photodiode signal with the intention of eliminating noise from the measurement system. Power to the setup was provided by two Kepco 8 amp power sources, one to power the

electromagnet and the other the modulation coil. Signals from the photodiode were recorded and analyzed using MathWorks MATLAB.

In order to begin measurements, the field strength of the electromagnet was calibrated using Microsoft Excel. A linear regression was used to correlate the output from the lock-in amplifier and the field strength of the electromagnet (Fig. 2). A corresponding conversion factor was then incorporated into the computer programming in order to have accurate control over the field strength. Thin film magnetic samples were mounted on an adjustable Thor Labs stage within the field of the electromagnet and aligned to reflect the incident beam directly onto the photodiode. An incident angle of 45 degrees was used in order to maximize the Kerr rotation. A graphical user interface designed in MATLAB was used to control the experiment. Experiment parameters were defined through the MATLAB user interface before beginning the measurement process. Upon program initiation, the magnetic field strength was incrementally increased; starting from a zero field, until reaching a user-defined peak. After reaching its maximum value, the magnetic field was stepped back to a zero field and then to an equal negative peak field. Photodiode readings were taken in synchronization with the sweeping field so that each field strength had a corresponding diode reading. Field strength was then plotted against the diode readings in order to visualize the results of each measurement. By plotting each individual point it was possible to observe and quantify the magnetic hysteresis of the thin film magnetic samples. The instrumentation proved successful in providing reliable data consistent with prior results.

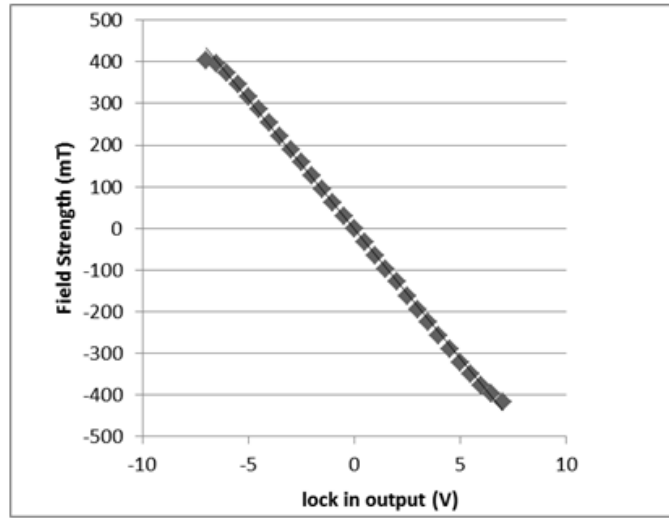


FIG 2. Calibration plot for the electromagnet. Line fit was linear with a scaling factor 62.139

RESULTS AND DISCUSSION

Hysteresis loops collected from a sample of CoFeB agree with the well-known hysteretic behavior of other thin films. Magnetic materials will exhibit different hysteresis loops based on the direction in which the external field is applied. There exists a so called “easy axis” of magnetization along which a material prefers to align itself. By analyzing samples in directions both parallel and perpendicular to the easy axis of magnetization we were able to confirm the effectiveness of our device using the Stöner-Wohlfarth model. The Stöner-Wohlfarth (SW) model, developed in 1948, describes the rotation of magnetization in single domain magnetic structures. The SW model states that the energy associated with a single domain particle with magnetization M and volume V , in a magnetic field H , is given by:

$$E = KV\sin^2\Theta - MVH\cos(\varphi - \Theta) \quad (1)$$

where φ is the angle between the applied field and the easy axis and Θ is the angle between the magnetization of the sample and the easy axis (See Fig. 3). The shape of the hysteresis loop

depends on the orientation ϕ of the external field relative to the easy axis. The hysteresis loop is the magnetization component of the sample M plotted against the external field H [1]. The SW model predicts that when the applied field is parallel to the easy axis of magnetization that the hysteresis loops will be square in nature, exhibiting an abrupt switch in alignment as the external field reaches the value of the coercive (or switching) field. As ϕ is increased to 90° hysteresis will diminish and M will move gradually from one direction of magnetization to the other. Fig. 4 denotes the hysteresis loops predicted by the SW model for values of ϕ between 0 and 90° . Fig. 5 represents data collected from the CoFeB sample. As can be clearly seen, experimental results agree with the Stöner-Wohlfarth model. As the sample was rotated from position (a) to position (c) the square nature of the hysteresis loop diminished. Lingering hysteretic behavior observed at $\phi = 90^\circ$ is not consistent with the SW model and could be attributed to the fact that the SW model assumes a single domain particle whereas the CoFeB sample is not a true single domain particle. However, the dependence of the hysteresis loop on ϕ provides confirmation that the device is suitable for accurately measuring the MOKE with precision acceptable for the purposes intended.

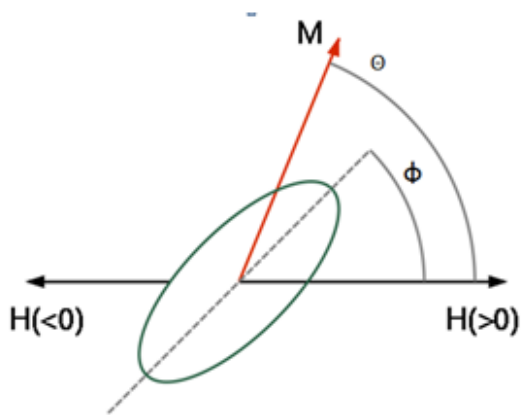


FIG. 3. Relationship between direction of applied field H , magnetization direction M and easy axis (dashed line).

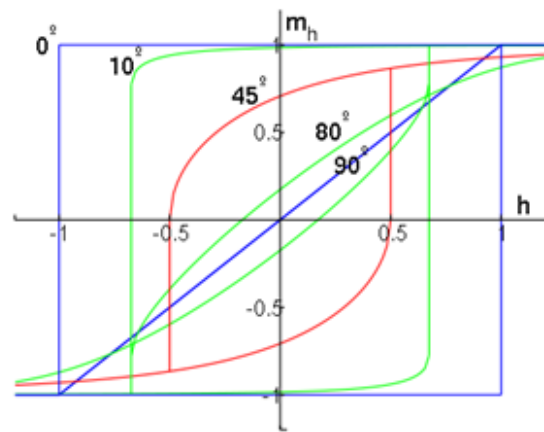


FIG 4. Hysteresis loops predicted by the Stoner-Wohlfarth model for several values of ϕ

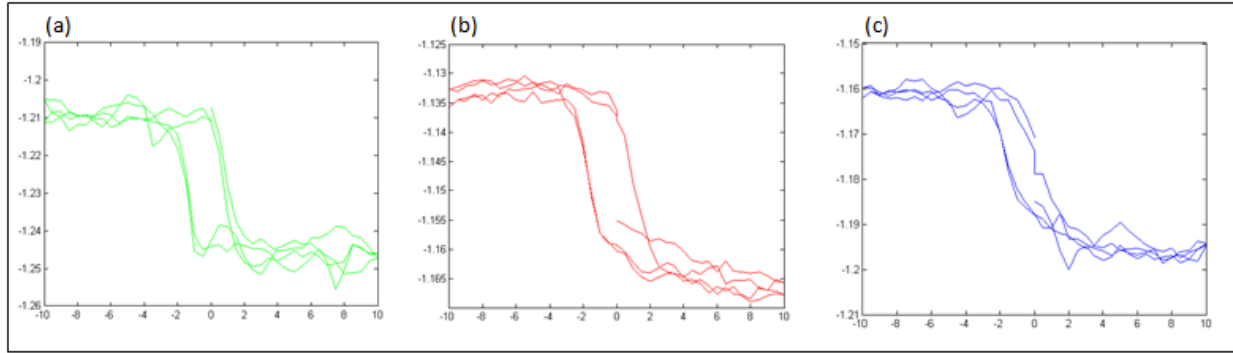


FIG 5. Hysteresis loops obtained from MOKE device showing behavior as predicted by Stöner-Wohlfarth model. (a) $\phi=0^\circ$, (b) $\phi=45^\circ$, and (c) $\phi=90^\circ$.

Reducing background noise in order to increase measurement accuracy was a concern from the inception of the project. The modulator shown in Fig. 1 and described in the instruments section was intended to reduce background noise through a lock-in method. The modulator was intended to produce a frequency which could be locked-in by the amplifier, effectively drowning out background noise. Although the modulation technique was successful, use of the modulator was of little benefit in improving data quality and was not used in collecting the data presented in this report. This result was not singular to this particular setup. It has been previously observed that hysteresis loops collected by means of lock-in detection of the photodiode output and use of an incident beam whose polarization is modulated was no better than obtained by the DC method [2]. Inclusion of the modulator was not detrimental in any way to the project but could have been foregone.

While measuring hysteresis loops it was found that a more accurate and distinct observation of the Kerr effect came when the polarizing filters were not placed precisely perpendicular to each

other. By setting the second polarizer at small angle δ away from extinction it was possible to observe a greater Kerr rotation. Past studies have shown that the Kerr rotation ϕ' is related to the measured light intensity by:

$$\phi' = \frac{\delta}{2} \frac{I - I_0}{I_0} \quad (2)$$

Where I_0 is the intensity for zero Kerr rotation and I is the measured light intensity at the time of interest. For a given Kerr rotation the measured intensity change with respect to the average I_0 is

$$I - I_0 = 2|E|^2 \delta \phi' \quad (3)$$

$|E|^2$ symbolizes the intensity of the reflected light in the original polarization state. I_0 represents the fraction of this light transmitted through the analyzer filter rotated from extinction by an angle δ [3]. An angle δ of one to three degrees was found to be the most effective in this case.

CONCLUSION

Magnetic memory and other magnetic devices are at the forefront of today's advancing technological society. New developments in the field are largely dependent on synchrotron X-ray methods to enhance understanding of atomic scale interactions and structures. However, MOKE studies remain a useful tool for sample analysis due its simplicity and relatively low cost [1]. A device for measuring the MOKE was successfully constructed for use in conjunction with studies taking place at beam line 13-1 at the SSRL. Previously proven methods were used to construct the device and the validity of data was confirmed using the Stöner-Wohlfarth model. Setup and initial testing of this device have been successful, encouraging further implementation of the MOKE for increased sample screening and characterization.

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