Magneto-Polarimetry Advanced Lab

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0. SYNOPSIS

Introduction: The magnetic properties of materials serve as a critical test of our fundamental understanding and play a crucial role in almost every current and future technology. Magneto-optical measurements can be used to probe the magnetic properties of a material. Although this is only one of many experimental techniques that can probe magnetic properties, its sensitivity, flexibility, and simplicity make it one of the most powerful tools to study materials.

Objective: This experiment will learn about polarized light and how to use polarization measurements to study magnetic materials. The student will learn basic experimental techniques of magneto-polarimetry and gain a better understanding of the magnetic properties of materials.

Goals:

1. Understand the fundamental principles of magneto-polarimetry.
2. Test and calibrate the magneto-polarimetry system.
3. Use the magneto-polarimetry system to probe magnetic materials.

Grading: Though the quality and quantity of your data are important, you will be mainly evaluated on your efforts in making and analyzing your measurements. Time spent repairing or improving the measurement apparatus will be taken into account in your evaluation. Extra credit will be given if you are able to improve the measurement and/or analysis techniques.

Timetable: Please check Section 8A for a detailed timetable of material that will be covered in this lab.

Please read the *Guide to writing the lab report* before starting to write your report! Please read the *Guide to the oral report* and talk to Dr. Cerne about your abstract and presentation before the oral report abstracts are due!

I. INTRODUCTION

Spectroscopy is a powerful tool to study and characterize materials. By applying magnetic fields to these materials, spectroscopy reveals new information about the nature of the material. Whereas conventional spectroscopy typically measures only the intensity of light, ignoring the shape of the electromagnetic wave that is transmitted through or reflected off the materials, polarimetry is sensitive to how the electric field of this light varies in space and time. Any changes that the sample produces in the spatio-temporal shape of the incident electromagnetic wave, its polarization, can provide critical information about the sample that is hidden from conventional spectroscopy.

II. MAGNETO-OPTICAL KERR EFFECT

The polarization of light will change if it interacts with a material that has any deviations from perfect symmetry. In the magneto-optical Kerr effect (MOKE), an applied magnetic field or magnetization breaks the spatial and time-reversal symmetries of the sample, causing the polarization of light reflected from the material to change. Specifically, if one shines linearly polarized light on the sample, the polarization of the reflected beam can be modified in two ways. The new polarization can have a different orientation, with its primary polarization axis rotated with respect to that of the incident light polarization axis (Kerr rotation), and/or the new polarization can become elliptical, with the tip of the electric field tracing out an ellipse in time (Kerr ellipticity). Figure 1 depicts the longitudinal geometry (the applied magnetic field $\mathbf{B}_{long}$ is in both the plane of the sample surface and the plane of incidence).

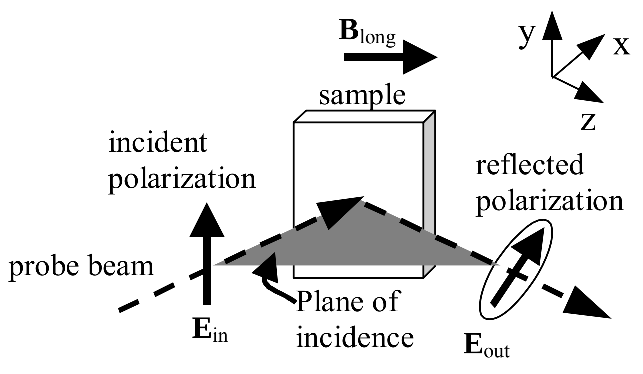


Fig. 1. Magneto-optical Kerr effect. In this case the applied magnetic field $\mathbf{B}_{long}$ is in both the plane of the sample surface and the plane of incidence, which is the longitudinal MOKE geometry.

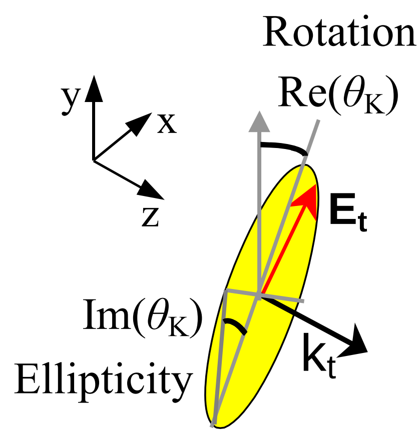


Fig. 2. Geometrical representation of the complex Kerr angle θ_K. Re(θ_K) is related to the orientation of the ellipse's major axis whereas Im(θ_K) is related to the minor to major axis ratio.

The polarization change can be represented by the complex Kerr angle, $\tan\theta_K = r_{xy}/r_{yy}$ where r_{yy} and r_{xy} are the diagonal and off-diagonal reflection amplitudes. The reflection amplitudes are complex numbers relating the phase and amplitude of the reflected electric fields E_x' and E_y' to the incident electric field E_y (linearly polarized in the y-direction), with $E_y' = r_{yy}E_y$ and $E_x' = r_{xy}E_y$. For small changes in the incident polarization, $\mathrm{Re}(\theta_K)$ is related to the component of E_x' that is in-phase with E_y', leading to the rotation (orientation of the polarization ellipse's major axis) of the reflected beam's polarization. On the other hand, $\mathrm{Im}(\theta_K)$ is related to the component of E_x' that is 90° out of phase with E_y', leading to the to ellipticity (minor to major axis ratio of the polarization ellipse) of the reflected beam. The rotation and ellipticity in the beam are shown in Fig. 2. Note that if the reflected light remains polarized completely in the y-direction, i.e., the polarization does not change, $E_x' = 0 \rightarrow r_{xy} = 0 \rightarrow \theta_K = 0$.

As mentioned earlier, any optical anisotropy in the sample will produce a Kerr effect. In MOKE, however, since the Kerr angle is proportional to the magnetization, the Kerr effect is primarily used to probe the magnetization of the sample. The magnetization in different directions as a function of different parameters such as temperature, magnetic field, and sample composition, provides critical information for understanding the magnetic and electronic properties of the sample. There are other ways to measure magnetization, but MOKE is one of the simplest and most sensitive techniques currently used.

III. POLARIMETRY

The key challenge to MOKE and other polarization-sensitive techniques is to determine the polarization of light with high accuracy and sensitivity. In this section we will discuss using a photoelestic modulator to completely determine θ_K

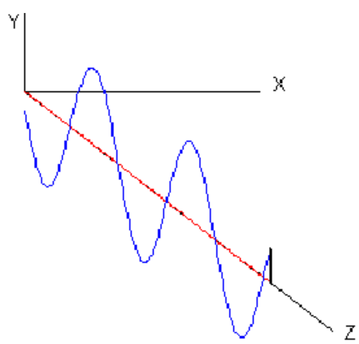
A. Polarized Light.

Before discussing polarimetry techniques, it is important to first introduce basic concepts concerning polarized light. Electromagnetic radiation (light) is composed of coupled electric and magnetic traveling waves that are orthogonal to each other. To simplify the representation of electromagnetic radiation, one focuses on the electric wave and does not even draw the magnetic wave (which can be easily determined once the electric wave is known). Therefore, when one refers to the polarization of light, one is talking about the behavior of the *electric* wave.

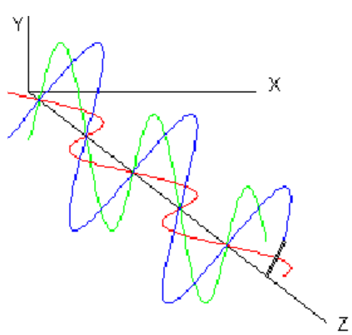
The simplest polarization is linearly polarized light. Figure 3a) shows an electric wave that is linearly polarized in the y-direction. This wave is traveling in the z-direction, with the electric field oscillating up and down as the wave moves. Any polarization state can be produced by vectorially adding (remember, electric fields are vectors) two orthogonal linear polarizations. These two orthogonal polarizations form a "basis" from which any polarization can be produced. For example, if one adds a wave that is polarized perpendicular to the wave in Fig. 3a), one can create linearly polarized light that is tilted away from the y-direction, as shown in Fig. 3b).

Furthermore, if the horizontally and vertically polarized waves are phase-shifted by moving one along the z-axis with respect to the other, one can produce an elliptically polarized wave, as shown in Fig. 3b).

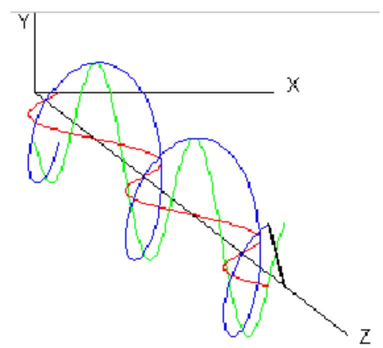
These waves are simulated graphically at Dr. Cerne's web site: http://www.physics.buffalo.edu/cerne/education/polarization.html. Try changing the amplitudes and phase difference of the vertical and horizontal waves to produce new polarizations. Use this interactive simulation to produce circularly polarized light where the electric field at any given point along the z-axis rotates in a circle. Left and right circularly polarized light also form a "basis" from which any polarization, including linearly polarized light, can be produced. The easiest way to distinguish left from right is to compare the spiral that the electric field makes with threads on a conventional (right-handed) screw or bolt. If the helicity is the same, the wave is right-handed, otherwise it is left-handed. You can switch to the circularly polarized basis (using left/right or clockwise/counterclockwise polarized waves) to produce any polarization by pressing the "Linear Basis/Circular Basis" button.



a) vertical linearly polarized



b) linearly polarized tilted at 27°



c) elliptically polarized with tilted major axis

Fig. 3. Three examples of different polarizations that are obtained by adding electric field waves polarized in the x- and y-directions. a) a vertically linearly polarized; b) a horizontally polarized wave (red on Cerne website) is added to the vertically polarized wave (green) to produce a linearly polarized wave that is tilted (blue); c) the horizontally and vertically polarized waves are phase-shifted by moving one along the z-axis with respect to the other. This produces an elliptically polarized wave.

Use the interactive graphical polarization demonstration on Dr. Cerne's website at http://www.physics.buffalo.edu/cerne/education/polarization.html to answer the following questions:

 Question 1: Using the linear basis, produce linearly polarized light that is tilted 45° from the y-axis.

 Question 2: Using the linear basis, produce: a) left circularly polarized light; b) right circularly polarized light; c) elliptically polarized light with the major axis along the y-axis; d) elliptically polarized light with the major axis tilted from the y-axis.

🍎 Question 3: Using the circular basis, produce: a) vertically linearly polarized light; b) horizontally linearly polarized light; c) linear polarized light that is tilted from the y-axis; d) elliptically polarized light with the major axis along the y-axis; d) elliptically polarized light with the major axis tilted from the y-axis

🍎 Question 4: Can you think of any other "basis" sets that are used in mathematics?

A sample can change the polarization of reflected and transmitted light in several ways. The Faraday/Kerr angle includes both real and imaginary terms. The real term corresponds to a simple geometric rotation of the polarization vector about the direction of propagation. The imaginary term relates directly to the ellipticity of the polarization. If the sample is axially symmetric along H, the transmittance tensor is diagonal when represented in the circular polarization basis. Therefore, changes in the incident polarization only depend on: 1. The relative difference in the phase of left versus right circularly polarized transmitted (reflected) light due to $\mathrm{Re}\,\theta_F$ ($\mathrm{Re}\,\theta_K$), which leads to a rotation (circular birefringence or Faraday rotation) in the linearly polarized incident light; and 2. The relative difference in the transmission (reflection) of left versus right circularly polarized light due to $\mathrm{Im}\,\theta_F$ ($\mathrm{Im}\,\theta_K$),which introduces ellipticity (circular dichroism) to the linearly polarized incident light. For samples with differences in the index of refraction and absorption of *linearly* polarized light, differences in absorption (linear dichroism) lead to Faraday/Kerr rotation and differences in linear index (linear birefringence) leads to Faraday rotation. The effects of the sample on the transmitted polarization are simulated at: http://www.physics.buffalo.edu/cerne/education/Faraday3.html.

B. Kerr Angle

Assuming the sample is isotropic in-plane and that the magnetic field/magnetization is normal to the surface (not the case of the longitudinal Kerr measurement in this advanced lab), one can conveniently describe the transmission and reflection of light using the circular basis, with $n_\pm$ and $k_\pm$ describing the index of refraction and absorption coefficient, respectively for right/left (+/-) circularly polarized light. In transmission, differences in indices n_+ and n_- lead to a rotation in the axis of the linear polarized incident light a while difference in absorption constants k_+ and k_- lead to an ellipticity of the linear polarized incident light. Please see http://www.physics.buffalo.edu/cerne/education/Faraday3.html using the circular basis.

In reflection, the dependence of the rotation and ellipticity signals on n and k is reversed.

The reflection amplitude $r_\pm$ for + and – circularly polarized light on a bulk material is given by:

$$r_\pm = \frac{\tilde{n}_\pm - 1}{\tilde{n}_\pm + 1}, \tag{1}$$

where the complex index of refraction is given by $\tilde{n}_\pm = n_\pm + k_\pm$. Note here that if the $\tilde{n}_\pm$ is real ($k_\pm = 0 \leftrightarrow$ no absorption), no phase shifts (except for possibly 180^{o}) occur in the reflected light. Equation (1) is basically the same equation as for linear polarized light (e.g., Eq. 9.147 on p. 397, Electrodynamics, 3rd Ed., Griffiths). Interestingly, it appears that in going from a linear to circular basis, one uses the same equations but replaces the linear conductivity σ_{xx} with $\sigma_\pm$, and $\tilde{n}$ with $\tilde{n}_\pm$.

The complex Kerr angle θ_K is worked out in http://www.physik.fu-berlin.de/~bauer/habil_online/node5.html and is given by:

$$\begin{aligned}\theta_K \approx \tan\theta_K &= \frac{i2\left(\tilde{n}_- - \tilde{n}_+\right)}{1-\varepsilon} \\ &= \frac{2}{1-\varepsilon}\left[-\left(k_- - k_+\right) + i\left(n_- - n_+\right)\right]\end{aligned} \tag{2}$$

As in Eq. (1) it is clear that if there is no absorption ($k_+= k_-=0$) and ε is real, θ_K is purely imaginary, and therefore only ellipticity but no rotation is induced in the reflected polarization. Neglecting the complex ε in the denominator, it is also clear form Eq. (2) that the rotation of the polarization, which is related to $\mathrm{Re}\,\theta_K$, is proportional to the circular dichroism $\left(k_- - k_+\right)$, while the ellipticity, which is related to $\mathrm{Im}\,\theta_K$, is proportional to the circular birefringence $\left(n_- - n_+\right)$. The complex ε in the denominator will tend to mix the real and imaginary parts of the expression in the bracket, but if the imaginary part of ε is small compared to 1, the association of Kerr rotation with circular dichroism and Kerr ellipticity with circular birefringence is a reasonable approximation.

For the longitudinal Kerr effect geometry used in this lab, the linear polarization basis ($\perp$ and $\|$ linear polarizations) is more appropriate. The reflection amplitude for linear polarized light on a bulk metal surface is given by:

$$r_{\perp\|} = \frac{1-\tilde{\beta}_{\perp\|}}{1+\tilde{\beta}_{\perp\|}} \tag{3}$$

where $\tilde{\beta}_{\perp\|} = n_{\perp\|} + ik_{\perp\|}$ (e.g., Eq. 9.147 on p. 397, Electrodynamics, 3rd Ed., Griffiths). In this case, if there is no absorption ($k_{\perp\|} = 0$), there are no phase shifts in the reflected linear polarizations, and hence the $\perp$ and $\|$ reflected linear polarizations are in-phase and no ellipticity will result. If the $n_\perp \neq n_\|$, the amplitudes of the reflected $\perp$ and $\|$ linear polarizations will be different and Kerr rotation will result. Unlike the Kerr effect in the circular basis, now ellipticity in the reflected beam only occurs if there is real absorption.

C. Photoelestic Modulator

In order to sensitively measure both the real and imaginary parts of θ_K, the radiation that is reflected off the sample is analyzed using a photoelastic modulator (PEM). By modulating the polarization of the reflected light, the PEM allows one to determine the polarization of that light. The PEM consists of a block of optically isotropic crytal and two piezoelectric transducers that create stress alternations at the resonant frequency of $\omega_{PEM} \approx 50\ \mathrm{kHz}$ as shown in Fig. 4. By driving the optical head at the resonant frequency, large swings in the strain in the horizontal direction can be achieved, which in turn create significant swings in the index of refraction in that direction. Therefore, the index of refraction in the x-direction $n_x(t)$ varies as:

$$n_x(t) = n_0 + \Delta n \sin(\omega_{\mathrm{PEM}} t), \tag{4}$$

whereas the index of refraction in the y direction $n_y(t)$ remains constant:

$$n_y(t) = n_0 = \mathrm{Constant}. \tag{5}$$

Here n_0 and Δn are the value for the unstrained index of refraction and the difference in index of refraction produced at the peak of the strain oscillations, respectively.

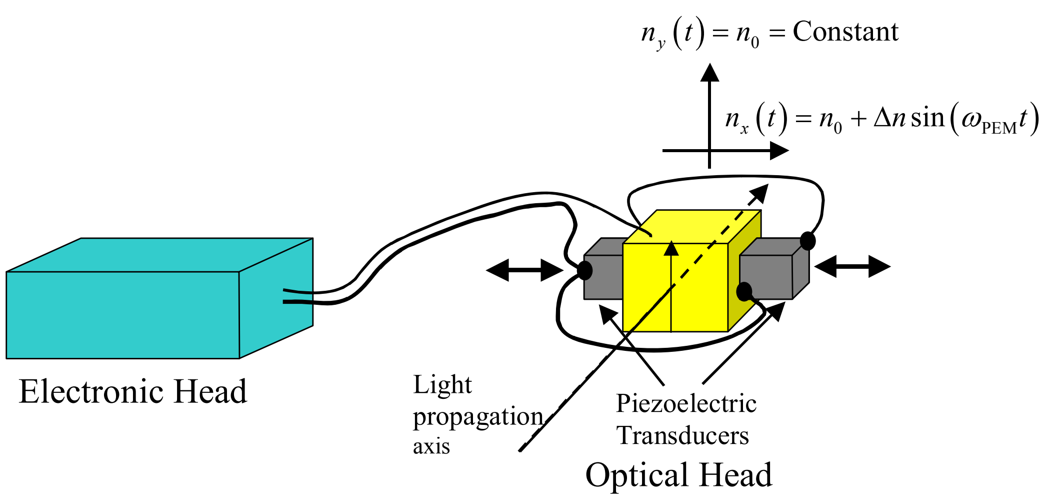


Fig. 4. The photoeleastic modulator (PEM).

Since the speed of light in a material depends on the material's index of refraction, the time dependent difference between n_x and n_y allows the PEM to periodically retard the phase of one linear polarization component $E_x'\hat{x}$ with respect to the orthogonal component $E_y'\hat{y}$ as follows:

$$E_x'\hat{x}+E_y'\hat{y}\xrightarrow{\text{PEM}}\left(E_x'e^{i\delta(t)}\right)\hat{x}+E_y'\hat{y} \tag{6}$$

where $\delta(t)$ is the sinusoidal phase modulation of $E_x'\hat{x}$ with respect to $E_y'\hat{y}$, and is given by:

$$\begin{gathered}\delta(t)=\beta\cos\left(\omega_{\text{PEM}}t\right)\\ \beta=2\pi\frac{\Delta L}{\lambda}=2\pi\frac{\Delta nD}{\lambda}\end{gathered} \tag{7}$$

where β is the phase modulation amplitude, ΔL is the effective optical path difference for $\hat{x}$ and $\hat{y}$ polarized radiation due to Δn (the maximum difference between n_x and n_y), D is the thickness the PEM crystal, λ is the wavelength of the radiation, and ω_{PEM} is the PEM modulation frequency. The phase modulation amplitude β is also referred to as the retardance, and describes how far (in waves or radians) one linear polarization is shifted from the other. For example $\beta = 0.50\text{ wave} = 3.14\text{ rad}$ means that the wave polarized in the y-direction is periodically shifted half a wavelength ahead of the wave polarized in the x-direction. A more detailed description of the PEM is given in the technical references at the end of this manual. The optical axis of the PEM is oriented parallel to that of the laser radiation along $\hat{y}$, so that no modulation occurs unless the sample produces an $\hat{x}$ component in the polarization by either rotating the polarization (Kerr rotation) or introducing ellipticity to the polarization (Kerr ellipticity). A detailed description of how the modulations produced by the PEM are used to determine θ_K is given in Section C*ii*.

D. Calibration

The accuracy and sometimes even the validity of polarimetry measurements of new signals from a sample depends crucially on the calibration of all the known elements in the system. In this section we explore independent measurements to calibrate and characterize critical components of the system.

i. Calibration of PEM

The main parameter that needs to be calibrated for the PEM is the retardance amplitude given in Eq. (4). Since the strain field, and hence the index of refraction difference experienced by a beam as it passes through the PEM depends on where the beam went through, the actual retardance amplitude can vary as well for a given PEM retardance setting. For accurate measurements, it is critical to calibrate the PEM retardance with using exactly the same light path as will be used to measure the sample.

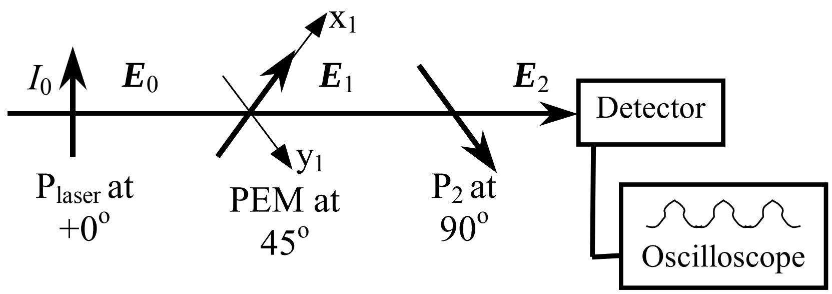


Fig. 5. Calibration of PEM retardance

There are several ways to calibrate the PEM retardance, as can be seen in the technical notes at the end of this manual. Here we discuss one technique that is shown in Fig. 5. The PEM is placed at 45^o between two crossed polarizers. For perfect polarizers, no light would illuminate the detector if the PEM were turned off, or at times when the PEM retardance is zero. The predicted intensity signals $I(t)$ and the PEM retardance $\delta(t)$ are plotted as functions of time for various PEM retardance amplitudes β in Fig. 6. As the PEM retardance approaches 0.50 wave, the transmission signal increases toward the maximum value of I_0, as seen by the peaks in Fig. 6a). The maximum signal at the detector is when the PEM retardance reaches ½ wave (see arrows on the bottom half of Fig. 6), at which point the PEM rotates the polarization by 90^o, allowing 100% transmission through the second polarizer. This can be seen by the peaks in Fig. 6b). If the PEM retardance increases past ½ wave, the transmission signal begins to drop again, as can be seen by the small dip near the maximima in Fig. 6c). Since the curvature of the transmission signal near the peak below ½ wave is negative (Fig. 6a) while the curvature of the transmission signal near the peak above ½ wave is poistive (Fig. 6c), the curvature at the peak at 0.50 wave is zero, which means the peak is flattened as can be seen by the flattened region circled in Fig. 6b). This flattening of the transmission signal peaks is characteristic of the PEM retardance amplitude being at ½ wave and is not very sensitive to the alignment of the PEM and polarizers, as can be seen by the dashed curve in Fig. 6, where the PEM and polarizers are misaligned. This makes this calibration of the PEM relatively insensitive to other factors, and therefore more accurate.

The signals that are shown in Fig. 6 are calculated by projecting components of the electric fields onto the various elements, and propagating the electric field as it progresses through each element. After passing through the PEM, part of the initial electric field E_0 is along the PEM's x-axis (x_1) and part is along the y-axis (y_1). The component of E_0 along the PEM's y-axis experiences a time dependent phase shift $e^{i\delta(t)}$ and therefore the transmitted E_0 electric field becomes:

$$\vec{E}_1 = \left(E_0 \cos 45°\right)\hat{x}_1 - \left(E_0 e^{i\delta(t)} \sin 45°\right)\hat{y}_1 = E_0 \frac{\sqrt{2}}{2}\left(\hat{x}_1 - e^{i\delta(t)}\hat{y}_1\right) \tag{8}$$

$\vec{E}_1$ is then projected onto the second polarizer, which only allows components parallel to its axis to pass. As a result, the magnitude of the electric field $\vec{E}_2$ that is then transmitted through the second polarizer is:

$$E_2 = E_0 \frac{\sqrt{2}}{2} - E_0 \frac{\sqrt{2}}{2} e^{i\delta(t)} = E_0 \frac{\sqrt{2}}{2}\left(1 - e^{i\delta(t)}\right) \tag{9}$$

The resulting intensity I_2 that illuminates the detector is just the magnitude of $\vec{E}_2$ squared:

$$\begin{aligned} I_2 &= \frac{1}{2} c\varepsilon_0 \left|E_2^2\right| = \frac{1}{2} c\varepsilon_0 E_2 E_2^* = \frac{1}{2} c\varepsilon_0 E_0^2 \frac{1}{2}\left(1-e^{i\delta(t)}\right)\left(1-e^{-i\delta(t)}\right) \\ &= \frac{I_0}{2}\left(2-2\cos\delta(t)\right) = I_0\left(1-1\cos\delta(t)\right) = I_0\left(1-1\cos\left[\beta\cos\left(\omega_{\text{PEM}}t\right)\right]\right) \end{aligned} \tag{10}$$

where E_2^* is the complex conjugate of E_2 and we have used Eq. (4) to substitute for $\delta(t)$. The result is more complicated if the polarizers and PEM are not oriented exactly in 45° increments, but the basic approach is identical. Note that the signal depends on $\cos\left[\beta\cos\left(\omega_{\text{PEM}}t\right)\right]$, a cosine of a cosine, which can be expanded in terms of even harmonics of ω_{PEM} in a Fourier series:

$$\begin{aligned} \cos\left[\beta\cos\left(\omega_{\text{PEM}}t\right)\right] = J_0(\beta) + 2J_2(\beta)\cos\left(2\omega_{\text{PEM}}t\right) + 2J_4(\beta)\cos\left(4\omega_{\text{PEM}}t\right) \\ + 2J_6(\beta)\cos\left(6\omega_{\text{PEM}}t\right) + \ldots \end{aligned} \tag{11}$$

where J_n are the nth order Bessel functions. Note that the coefficient for the second harmonic signal is $2J_2(\beta)$ while the coefficient for the fourth harmonic signal is $2J_4(\beta)$. Therefore if one could tune the detector so that it is only sensitive to the $2\omega_{\text{PEM}} \approx 100$ kHz signal, one would get a result that is proportional to $J_2(\beta)$. In the next Section we will use lock-in amplifiers to extract these signals at various harmonics of ω_{PEM} to gain information about the polarization of light that enters the PEM.

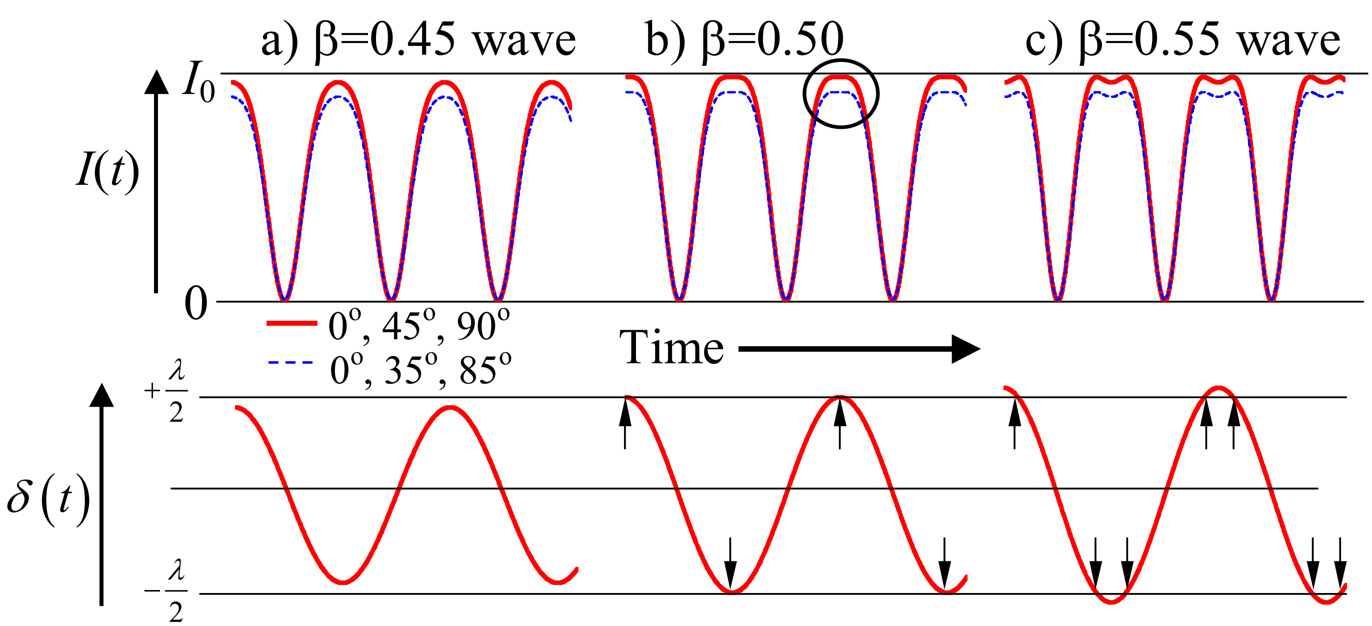


Fig. 6. Detector signal on oscilloscope for PEM retardance amplitudes of: a) 0.45 wave, b) 0.50 wave, and c) 0.55 wave. The thick solid curve is for the ideal case where the first polarizer is at 0°, the PEM is tilted to 45°, and the last polarizer is tilted at 90° with respect to vertical. The dashed line is for the misaligned case, where the angles are 0°, 35°, and 85°. Note that the flattening of the maximum, circled region in b), is unaffected by this misalignment. Vertical arrows in bottom half indicate times when the retardance reaches 0.50 wave.

 Question 5: Using the linear basis, produce linearly polarized light that is tilted 45° from the y-axis.

 Question 6: Verify using Mathcad or Maple, that the Fourier expansion for $\cos\left[\beta\cos\left(\omega_{\text{PEM}}t\right)\right]$ is correct.

 Question 7: A lock-in amplifier (see Sec. V.C.) is used to measure the magnitude of each harmonic component in the detector signal for the configuration shown in Fig. 8b (polarizer P_1 is slightly shifted from vertical). If the signal at 100 kHz ($2\omega_{\text{PEM}}$) is 4.00 times bigger than the signal at 200 kHz ($4\omega_{\text{PEM}}$), what is the PEM retardance β?

 Question 8: Using the same approach as shown in Eqs. (5)-(7), calculate the detector signal as a function of time if the last polarizer were at an arbitrary angle θ (not necessarily 45°) with respect to the PEM.

ii. Calibration of polarimetry system

The experimental setup for measuring the polarization of light after it has been reflected off the sample is shown in Fig. 7. Linearly polarized light from the laser illuminates the sample. The magnetic field at the sample causes changes in the polarization of the reflected light, which then passes though the PEM and a linear polarizer P_2, oriented at 0° and 45° with respect to vertical, respectively. For MOKE measurements, $\mathbf{H}\neq 0$ and P_1 is removed from beam path. For calibration, $\mathbf{H}=0$ and P_1 is rotated by a small angle, as will be discussed in the second part of this section.

By projecting the electric field components of the polarization onto each optical element as in Eqs. (5)-(8), one can calculate the relationship between the signal at the detector and the complex Kerr angle θ_K:

$$\begin{aligned}\text{Re}\left[\theta_K\right] &= \frac{1}{4J_2(\beta)}\frac{I_{2\omega_{\text{PEM}}}}{I_0}\\ \text{Im}\left[\theta_K\right] &= \frac{1}{4J_3(\beta)}\frac{I_{3\omega_{\text{PEM}}}}{I_0}\end{aligned} \tag{12}$$

where J_n is the nth order Bessel function, and $I_{n\omega_{\text{PEM}}}/I_0$ is the ratio of the intensity of the signal at the nth harmonic of ω_{PEM} and the intensity of the signal at the chopping frequency ω_{PEM}. In Eq. (9), it is assumed that θ_K is small. The Bessel functions arise from the expansion of $\cos\left[\beta\cos\left(\omega_{\text{PEM}}t\right)\right]$ and $\sin\left[\beta\cos\left(\omega_{\text{PEM}}t\right)\right]$ as in Eq. (7) and (8). Note that unlike Eq. (7), in this case we also have a term proportional to $\sin\left[\beta\cos\left(\omega_{\text{PEM}}t\right)\right]$, which produces even and odd harmonics, which in turn requires both even and odd Bessel functions. The even harmonics are related to the rotation $\text{Re}\left[\theta_K\right]$, whereas the odd harmonics are related to the ellipticity $\text{Im}\left[\theta_K\right]$. Lock-in amplifiers are used to measure the relevant frequency components coming from the detector. Ideally, three lock-in amplifiers are used: one running at ω_0 for the average intensity I_0, one running at $2\omega_{\text{PEM}}$ for the rotation signal $I_{2\omega_{\text{PEM}}}$, and one running at $3\omega_{\text{PEM}}$ for the rotation signal $I_{3\omega_{\text{PEM}}}$. To see a polarimetry setup using three lock-in amplifiers, please visit Dr. Cerne's lab in Fronczak 103. However, lock-in amplifiers, especially ones that operate above 100 kHz, are relatively expensive, typically \$4000, so only one lock-in is used in this lab. Since I_0 is proportional to the laser power, which is relatively constant, one can use a single lock-in amplifier to measure either $I_{2\omega_{\text{PEM}}}$ or $I_{3\omega_{\text{PEM}}}$ with the resulting signals being proportional to $\text{Re}\left[\theta_K\right]$ or $\text{Im}\left[\theta_K\right]$, respectively.

$$\begin{aligned}\text{Re}\left[\theta_K\right] &= \frac{1}{4J_2\left(\beta\right)}\frac{I_{2\omega_{\text{PEM}}}}{I_0} \propto I_{2\omega_{\text{PEM}}} \\ \text{Im}\left[\theta_K\right] &= \frac{1}{4J_3\left(\beta\right)}\frac{I_{3\omega_{\text{PEM}}}}{I_0} \propto I_{3\omega_{\text{PEM}}}\end{aligned} \tag{13}$$

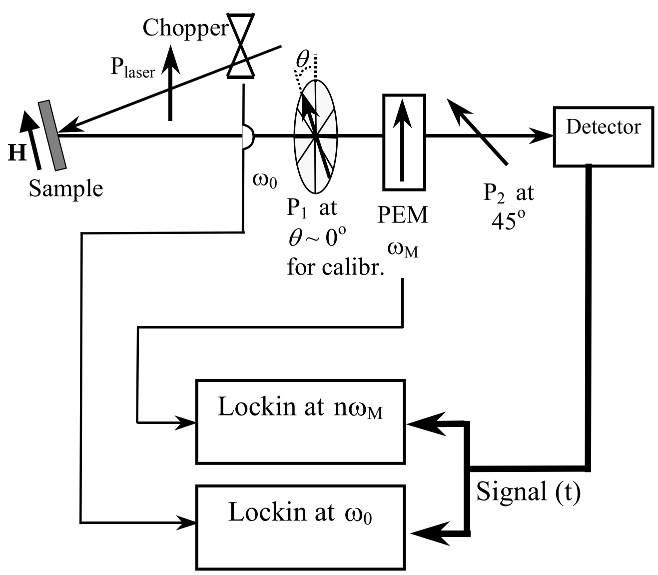


Fig. 7. Calibration of MOKE system using a linear polarizer. For calibration, **H**=0 and P_1 is rotated by a small angle. For MOKE measurements, **H**≠0 and P_1 is removed from beam path.

To measure $\text{Re}\left[\theta_K\right]$ or $\text{Im}\left[\theta_K\right]$ absolutely one also needs to measure I_0, but in typical MOKE experiments one is only interested in qualitative changes in θ_K as a function of applied magnetic field, so as long as the laser intensity is stable, one does not need to measure I_0. To minimize the background signal due to a misaligned PEM, adjust the orientation of the PEM to minimize the $I_{2\omega_{\text{PEM}}}$ signal. This will ensure that the PEM axis is parallel to the laser polarization.

In principle, if β is known and all the optical elements are ideal and optimally oriented, one can immediately use Eq. (9) and the measured signals to obtain

θ_K. However, the components may not be ideal and they may be slightly misaligned. For example, it is difficult to place P_2 at exactly 45^0, and one often finds that it is off by a few degrees. This slightly changes the signals. Furthermore, it is useful to change the polarization in a known and controlled way so that the sensitivity and stability of the polarimetry system can be characterized. Therefore, we can use a linear polarizer after the sample to change the polarization by a known amount, and then compare the resulting signal with predictions, as shown in Fig. 8. The magnetic field at the sample is turned off, so all the changes in the polarization are due to changes in the orientation of the linear polarizer. The relationship between the signal at the detector and the orientation angle θ with respect to vertical of the linear polarizer is given by:

$$\theta = \frac{1}{4J_2(\beta)} \frac{I_{2\omega_{\mathrm{PEM}}}}{I_0} \tag{14}$$

Since θ can be measured independently, one can check the accuracy of the polarimetry system by comparing the measured value of θ with the value obtained from the polarimetry system. The Thor Labs precision rotation stage rotates 2.4 Arc Min. (0.04^o) per micrometer division when locked. You should be able to see steps in the $I_{2\omega_{\mathrm{PEM}}}/I_0$ or $I_{2\omega_{\mathrm{PEM}}}$ signal as the micrometer is rotated by 1 division increments. Be careful of the backlash in the system (after changing direction, it takes about a division of motion in the new direction before the rotation begins).

 Question 9: In principle, one could use the first harmonic of ω_{PEM} to obtain $\mathrm{Im}[\theta_K]$, but in Eq. (9) the third harmonic is used. Can you think of some arguments for and against this choice? Hint: Are there any other sources for noise signals that are at $1\times\omega_{\mathrm{PEM}}$?

 Question 10: The small transverse electric field $\vec{E}_x$ that is produced by a sample or by rotating a polarizer (see Figs 1-3) could also be measured using a linear polarizer alone instead of the PEM/polarizer system. Describe how this would work and what are the advantages/disadvantages of using only a linear polarizer to measure Kerr rotation/ellipticity?

 Question 11: One could measure θ_K using a single lock-in amplifier by measuring I_0, $I_{2\omega_{\mathrm{PEM}}}$, and $I_{3\omega_{\mathrm{PEM}}}$ sequentially, and then taking the ratios in Eq. (9). Describe the advantages/disadvantages of this technique compared to measuring all three signals and their ratios simultaneously.

IV. MEASUREMENTS

A. Testing and Calibration

Before using any measurement system to probe new, i.e., unknown, samples, it is critical to test and calibrate the system against known quantities. The ultimate goal of this section is to measure the complex Kerr angle θ_K as function of applied magnetic field in magnetostrictive films from Dr. W.A. Anderson's lab (UB Electrical Engineering Dept.). In order to quantititatively characterize these samples, the magnetic field, the PEM retardance, and the polarimetry system must be calibrated.

i. Calibrating the magnetic field

Ultimately, the magnetic field will be set from the computer, which sends a control voltage to the input of the Kepco power supply, which in turn sends a current through the electromagnet, which then produces a magnetic field at the sample. The magnet has already been calibrated using a gaussmeter. The lock-in amplifier's digital-to-analog (DA) output was set to various voltages and the corresponding magnetic fields at the sample were measured. This allowed one to determine the calibration factor that converts the desired magnetic field value that is set at the computer into the appropriate voltage that the computer sets on the lock-in amplifier's DA output.

Question 12: By looking in the Labview programs, find the value of the magnetic field to lock-in voltage calibration factor. Start in the block diagram of Magscan_7265.vi program in D:\Labview_Programs\Mag_Sweep. Note the calibration may be in a subprogram (sub-vi) inside magnetscan_7265.vi.

Question 13: Write a simple Labview program that adds, subtracts, multiplies, or divides two numbers. You will need two numerical inputs (indicators), one numerical output (control), and a numerical slider/knob control to choose which arithmetic operation will be performed.

ii. Calibrating the PEM

Using the technique shown in Fig. 5 to determine the setting on the PEM that produces a retardance of ½ wave. Set up the laser, PEM, and polarizers as shown in Fig. 5. Initially set the wavelength on the PEM controller (you can set this from the computer using set-W.vi in D:\Labview_Programs\PEM) to 632.8 nm (the wavelength of the HeNe laser). Gradually increase the PEM retardance until the trace flattens near the top. Note the retardance reading on the PEM controller should be close, but may not be exactly 0.500 wave.

Section **IV**.**B**.*ii.* presents another technique for setting the PEM retardance to a known value.

Measurement Assignment 1: Using an oscilloscope determine the retardance setting on the PEM (with the wavelength set to 632.8 nm) that produces a retardance of ½ wave. Check if the results depend on how the laser beam goes through the PEM. Are the measurements better with the beam entering the PEM at normal incidence, or with the PEM tilted? Why?

Question 14: If the wavelength on the PEM controller is set to 2000 nm, what retardance setting would you expect to produce a retardance of ½ wave at 632.8 nm? Note that a retardance setting of ½ wave for 2000 nm means that the vertical and horizontal waves are shifted by $(1/2)\times(2000\text{ nm}) = 1000\text{ nm}$, which would be a full wave of retardance for 1000 nm wavelength light and two full waves for 500 nm wavelength light.

 Measurement Assignment 2: With the wavelength on the PEM controller set to 2000 nm, record the retardance values at which the trace peaks flatten. These occur at odd multiples of ½ wave retardance.

iii. Characterizing linear polarizers and calibrating the polarimetry system

A perfect linear polarizer completely extinguishes linearly polarized light that is perpendicular to the polarizer's polarization axis and perfectly transmits linearly polarized light that is parallel to the polarization axis. No polarizer is perfect and the quality of a polarizer is measured by the extinction ratio, the ratio of the perpendicularly polarized intensity that should be nominally blocked and the parallel-polarized intensity that should be perfectly transmitted. For a perfect polarizer, the extinction ratio is exactly zero.

Set up the optical system shown in Fig. 8a. Connect the detector output to Input A and the chopper reference signal to Ref. By blocking the beam at a fixed frequency, the chopper modulates the laser intensity shining on the detector, and the lock-in amplifier selects this frequency to measure the intensity of the laser with greater sensitivity. Use a chopping frequency between 100-200 Hz. As a linear polarizer, P_1 or P_2, is rotated the signal from the detector will change. We can measure the extinction ratio by determining the minimum (polarizer axis perpendicular to laser polarization) and maximum (polarizer axis parallel to laser polarization) signals on the detector and taking their ratio. The degree to which light is linearly polarized can be quantified by the polarization ratio, which is the ratio of the intensity of the linear polarized light to the intensity of circularly polarized light. For example, a perfect polarizer at exactly 90^o to the main axis of light with a linear polarization of 500:1 will allow approximately 1 part in 500 through. On the other hand, if the light was perfectly linearly polarized and the polarizer was perfect, no light would get through.

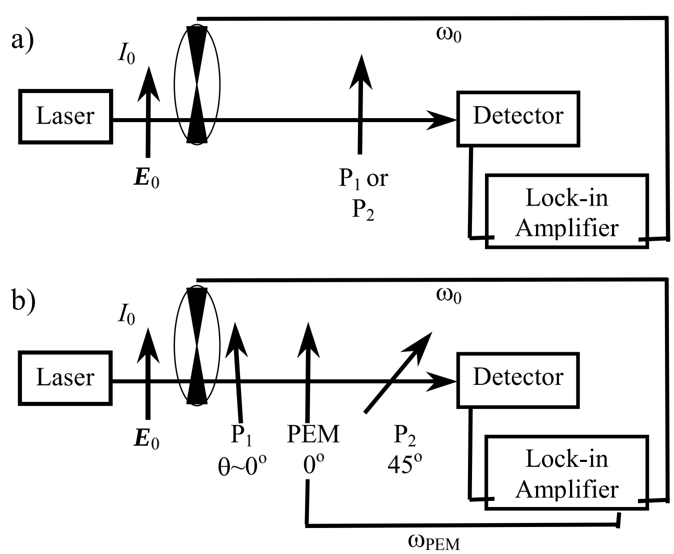


Fig. 8. Characterization of linear polarizers a) and calibration of polarimetry system (and Bessel function measurement) b). In b) the lock-in amplifier is either measuring the signal at ω_0 (at front reference input) or at harmonics of ω_{PEM} (at rear reference input).

 Question 15: Why is it a bad idea to run the chopper at 60 Hz, or multiples of 60 Hz?

Question 16: The detector also measures light from the room lights, which may be of greater intensity than the laser at the detector. Do the room lights disturb the laser intensity measurement if you use a lock-in amplifier? Is it better, or does it make no difference, to place the chopper directly in front of the laser or the detector when measuring laser intensity? Explain

Measurement Assignment 3: Use the lock-in amplifier to measure the signal on the detector at the chopper frequency. Change the phase on the lock-in amplifier and observe the behavior of the x and y channel signals. Does the behavior make sense?

Measurement Assignment 4: Measure the signal at higher harmonics, e.g., 2nd, 3rd, 4th, etc., of the chopped frequency. Does the signal contain higher harmonics? Why? If so, do the amplitudes of the harmonics make sense? Hint: what are the Fourier components of a square wave?

Measurement Assignment 5: Determine the extinction ratio of the linear polarizers. Assume the laser polarization intensity ratio is 500:1 (it may actually be better). Add a polarizer in front of the laser and measure the extinction ratio when the second polarizer is rotated. Does the first linear polarizer increase or decrease the degree to which the laser light is polarized? Since the polarizers are nominally the same, these two measurements can be used to approximately determine both the degree to which the laser is polarized and the extinction ratio of the polarizers.

By rotating a linear polarizer by a known amount, one can change the polarization a known amount and compare the resulting signal from the polarimetry system with the signal predicted in Eq. (9). Set up the laser, PEM, and polarizers as shown in Fig. 8b. The PEM reference signal is connected to the TTL Ref. Input in the back of the lock-in amplifier. For measuring signals $I_{n\omega_{\mathrm{PEM}}}$ that are at harmonics of the PEM frequency ω_{PEM}, set the lock-in amplifier reference to be external rear panel (RP). For measuring the average intensity signal I_0 at the chopper frequency ω_0, set the lock-in amplifier reference to be external front panel (FP). Using the PEM retardance calibration technique that is described in the previous section, set the PEM retardance to be ½ wave for 632.8 nm radiation. Using the Labview program timescan_7265.vi or timescan_7265ratio.vi (which toggles between the $I_{n\omega_{\mathrm{PEM}}}$ and I_0 signals and calculates the ratio $I_{n\omega_{\mathrm{PEM}}}/I_0$) in D:\Labview_Programs\Time_Sweep to keep track of the signal at $2\omega_{\mathrm{PEM}}$ as a function of time, rotate the first linear polarizer by known increments (for example, 1$^{\mathrm{o}}$) and compare the steps in the signal recorded by timescan_7265.vi with the predicted changes. If you are using one lock-in amplifier, you must measure I_0 (signal at the chopper frequency ω_0), $I_{2\omega_{\mathrm{PEM}}}$ (signal at the second harmonic of the PEM modulation frequency ω_{PEM}), and $I_{3\omega_{\mathrm{PEM}}}$ (signal at the third harmonic of the PEM modulation frequency ω_{PEM}), separately. The ratios $I_{2\omega_{\mathrm{PEM}}}/I_0$ and $I_{3\omega_{\mathrm{PEM}}}/I_0$ can then be calculated to obtain calibrated results. Since the chopped signal is a square wave whereas the lock-in uses a sinusoidal reference, the lock-in will measure only the first harmonic of the square wave, which is $4/\pi$ larger than the amplitude of the square wave. As a result, the measured values for $I_{n\omega_{\mathrm{PEM}}}/I_0$ ratios will be read by a factor of $\pi/4$ lower and your raw normalized ratios must be multiplied by $4/\pi$ to correct this error.

 Measurement Assignment 6: Check the accuracy of the polarimetry system by rotating the first linear polarizer in Fig. 8 by 1 degree and comparing the resulting change in the signal with the predicted change. What are possible sources for the difference between the measured and predicted signals? Do you understand why your $I_{n\omega_{\mathrm{PEM}}}/I_0$ ratios must be corrected by multiplying by $4/\pi$?

 Measurement Assignment 7: Check to see how small a rotation of the linear polarizer can be detected by the polarimetry system. This determines the sensitivity of the system to small polarization rotations, i.e., $\mathrm{Re}[\theta_K]$.

 Measurement Assignment 8: What happens to $I_{2\omega_{\mathrm{PEM}}}$ (signal at the second harmonic of the PEM modulation frequency ω_{PEM}) when a chopper is placed in the beam, as in Fig. 8. Can you explain the change?

 Measurement Assignment 9: Do you see any changes in the $3\omega_{\mathrm{PEM}}$ and $4\omega_{\mathrm{PEM}}$ signals when the linear polarizer is rotated? Why?

B. Measuring physical properties

Since the polarization of reflected/transmitted light will be affected by any changes in the symmetry of a material, Kerr/Faraday measurements are a very powerful probe with many different applications. The polarization of the reflected/transmitted light is very sensitive to even small changes in the symmetry of a material, which in many cases do not measurably affect the intensity of reflected/transmitted light. In this section we will use polarization measurements to characterize strain and magnetic anisotropies. Since the amplitude of the Kerr/Faraday signals is proportional to Bessel functions, these measurements also provide an experimental way to determine Bessel functions.

i.Measuring strain in plexiglass

As was discussed in the PEM section, strain will cause the index of refraction of a material to change. In this section you will probe different parts of a strained plexiglass plate.

 Measurement Assignment 10: Use the experimental setup shown in Fig. 8b. Place the plexiglass plate in front of the PEM. Measure changes in the intensity of the transmitted light (chopped), the second and third harmonic signals of the PEM, and the ratios of the PEM harmonics to the chopped signals as you move the beam on the plate from high strain areas (near the inside end of the slot) to low strain areas. Use the time scanning programs to record these signals as you move the plate with respect to the beam, keeping track of the times when the sample is moved to different places.

ii.Measuring Bessel functions

Because the PEM signals typically are sinusoidal functions of the PEM retardance β and the PEM retardance is itself a sinusoidal function of time, the signals depend on sinusoidal functions of sinusoidal functions. As shown in Eq. (8), these complicated functions can be expanded into a sum of simpler harmonic components, with the amplitude of nth harmonic component proportional to the nth order Bessel function $J_n(\beta)$. As result, the polarization measurements can be inverted to actually determine the $J_n(\beta)$ as a function of β. The Bessel functions can be measured using the setup shown in Fig. 8b. Use the Retardance_Sweep.vi or Retardance_Sweep_ratio.vi (which toggles between the $I_{n\omega_{\mathrm{PEM}}}$ and I_0 signals and calculates the ratio $I_{n\omega_{\mathrm{PEM}}}/I_0$) program to measure the $I_{n\omega_{\mathrm{PEM}}}$ or $I_{n\omega_{\mathrm{PEM}}}/I_0$ signals, which are proportional to J_n, as function of β.

Measurement Assignment 11: Determine $J_2(\beta)$ and $J_4(\beta)$ as functions of β. Hint, the signal due to a non-zero horizontal field $\vec{E}_x$ is proportional to $J_2(\beta)$. Hint: You should try measuring the signal at $2\omega_{\mathrm{PEM}}$ as a function of β for one orientation of the first polarizer (see Fig. 8). For small polarizer orientations this does not work and one must repeat the measurement for another polarizer orientation and subtract the two curves. What does this say about the orientation of the polarizer's optical axis as β is increased. Check if the results depend on how the laser beam goes through the PEM. Are the measurements better with the beam entering the PEM at normal incidence, or with the PEM tilted? Why?

Measurement Assignment 12: Can you think of a way to increase the signals when measuring $J_1(\beta)$ and $J_3(\beta)$ as functions of β? Try directing the HeNe beam through a high strain area in the plexiglass plate when measuring the first and third PEM harmonics. What happens? Why?

Measurement Assignment 13: Use the results of Measurement Assignments 11 and 12 to set the PEM to a known retardance. This is an alternative way of calibrating the PEM retardance. How do the results from this technique compare with the calibration obtained in Measurement Assignment 1 in Section **IV**.**A**.*ii*?

iii. MOKE measurements on magnetic materials

The three geometries for the magneto-optical Kerr effect (MOKE) shown in Fig. 9 are characterized by the direction of the magnetic field with respect to the sample and the plane of incidence (the plane formed by incident and reflected beams). Note the direction of the probe polarization does not determine the geometry. For example, the longitudinal Kerr effect could be measured using light that is either polarized parallel to the plane of incidence (p-polarized) or perpendicular to the plane of incidence (s-polarized). The polar Kerr geometry (Fig. 9 a) typically uses light at near normal incidence with the sample magnetized perpendicular to its surface. In this geometry, both the Kerr rotation and ellipticity are proportional to the sample's magnetization **M**. In the longitunal Kerr geometry (Fig. 9 b) the sample magnetization lies **both** in the plane of the sample surface and the plane of incidence. As with the polar Kerr effect, both the Kerr rotation and ellipicity are proportional to the sample's magnetization **M**. However, unlike the polar Kerr effect, **no Kerr effect is observed at normal incidence**. The transverse Kerr geometry is qualitatively different from the polar and longitudinal cases. In the transverse Kerr, the only signal that is generated is a change in the amplitude of reflected light when the incident light is p-polarized (electric field lies in the plane of incidence). The reflected polarization does not change, remaining linearly polarized. The change in reflection amplitude is proportional to **M**. For s-polarized incident light, no effects are observed.

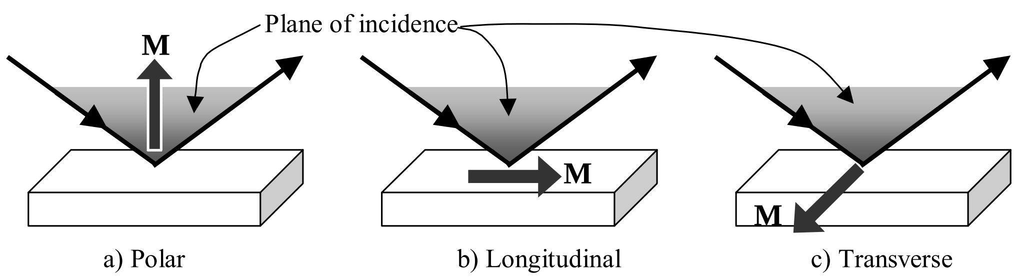


Fig. 9. Longitudinal Magneto-Optical Kerr Effect (MOKE) Geometries

The experimental setup for longitudinal/transverse MOKE is shown in Fig. 10. Note that for longitudinal MOKE, the angle of incidence should be as large as possible.

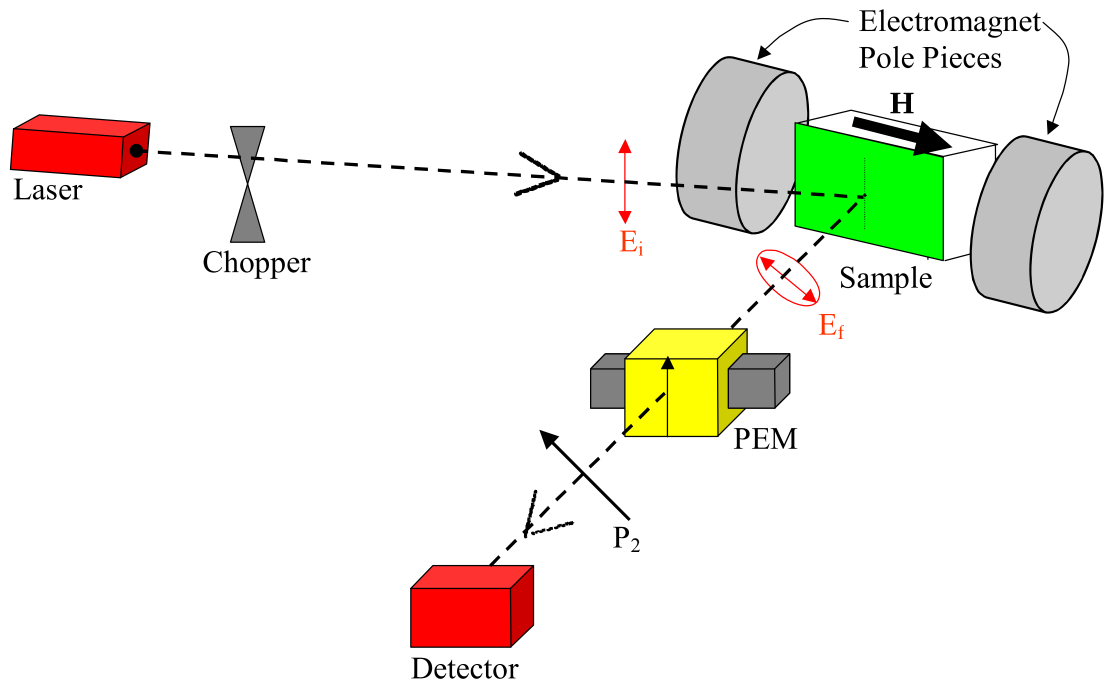


Fig. 10. Longitudinal MOKE Setup

 Question 17: Consider how one would set up the equipment provided in this lab to perform polar and transverse MOKE. Sketch the setup for these geometries.

iv. Magnetostrictive films

A key aspect in materials science and technology is combining distinct properties in a single material. For example, the field of spintronics aims at coupling and controlling electronic and magnetic properties of materials while magneto-optics uses magnetic fields to change optical properties and/or uses optical properties to probe magnetic properties. When a material is compressed or stretched, its magnetic properties can be dramatically altered. This phenomenon is known as magnetostriction and can be used to either change the magnetic properties by applying strain or to probe the strain by measuring the magnetic properties. Dr. Anderson's group in UB's Electrical Engineering Department is developing new magnetostrictive materials to study this effect and to produce materials that have new technological applications. The samples consist of **single films ($Tb_{0.4}Fe_{0.4}$ or $Fe_{0.5}Co_{0.5}$) or multilayer films ($Tb_{0.4}Fe_{0.4}/Fe_{0.5}Co_{0.5}$) deposited on Si substrates**. When the films are grown in multilayer structures, significant improvements can be achieved in terms of magnetostriction compared to single layer materials. Investigation of stress induced anisotropy on these multilayer magnetostrictive thin films will lead to the potential commercial applications in magnetostrictive devices. The sample that is used in this Advanced Lab was grown and characterized by J.H. Tan, from Dr. Anderson's group. These samples are strained in one direction, so that direction has different magnetic properties than the other. By measuring the MOKE signal as a function of applied field, one can observe differences depending on whether the applied magnetic field is along the strained direction or not. The magnetic properties along a particular axis can be probed by measuring the magnetization (or the MOKE signal) as a function of applied magnetic field along that axis. Since the magnetization in ferromagnets depends on the history of how the magnetic field was applied, the magnetization versus applied magnetic field forms a hysteresis loop as shown in Fig. 11. The magnitude of the applied magnetic field required to cause the magnetization M to change sign is called the coercive field H_C. The maximum value of the magnetization as the applied field goes to infinity is called the saturation magnetization M_S. The value of the magnetization that remains once the applied magnetic field is turned off (H=0) is the remanent magnetization M_R. The area inside the hysteresis loop is proporional to the energy dissipated as heat as the ferromagnet is driven around the loop. **Soft** ferromagnets are easy to magnetize and therefore exhibit hysteresis loops enclosing a small area while **hard** ferromagnets are more difficult to magnetize and therefore exhibit hysteresis loops enclosing a larger area. In Fig. 11, one can see that the hysteresis loop for the magnetic field applied in the direction of the strrain is significantly different from the case where the applied magnetic field is perpendicular to the strain.

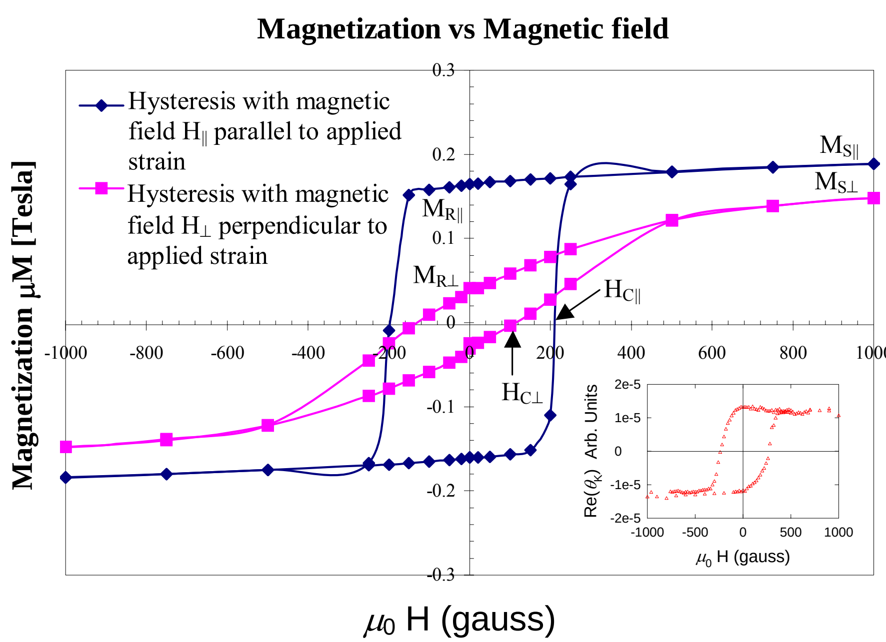


Fig. 11. Magnetization of a $[Tb_{0.4}Fe_{0.4}/Fe_{0.5}Co_{0.5}]_3$ multilayer film sample provided by J.H. Tan from Dr. Anderson's group (see paper in Section VIIIC at the end of this manual). The inset shows the hysteresis loop for Re(θ_K) in the same range of H for a different sample.

If you are using one lock-in amplifier, you must measure I_0 (signal at the chopper frequency ω_0), $I_{2\omega_{\text{PEM}}}$ (signal at the second harmonic of the PEM modulation frequency ω_{PEM}), and $I_{3\omega_{\text{PEM}}}$ (signal at the third harmonic of the PEM modulation frequency ω_{PEM}), separately. The ratios $I_{2\omega_{\text{PEM}}}/I_0$ and $I_{3\omega_{\text{PEM}}}/I_0$ can then be calculated to obtain calibrated results.

 Question 18: In Fig 11, which axis is the hard axis and which is the easy/soft axis for the applied magnetic field?

 Question 19: What are some situations where a hard ferromagnet is desirable? What are some situations where a soft ferromagnet is desirable?

 Question 20: What is the difference between H and B?

 Measurement Assignment 14: Measure the complex θ_K as a function of applied magnetic field along the **easy** axis of the film. How do $\text{Re}\left[\theta_K\left(H\right)\right]$ and $\text{Im}\left[\theta_K\left(H\right)\right]$ compare.

 Measurement Assignment 15: Measure the complex θ_K as a function of applied magnetic field along the **hard** axis of the film. How do $\text{Re}\left[\theta_K\left(H\right)\right]$ and $\text{Im}\left[\theta_K\left(H\right)\right]$ compare. How do these results compare with the easy axis measurements?

 Measurement Assignment 16: By measuring a plain Si or GaAs (behaves qualitatively similar to Si) substrate, determine the contribution to θ_K from the Si substrate on which the $Tb_{0.4}Fe_{0.6}$,/$Fe_{0.5}Co_{0.5}$ films are grown. Does the substrate affect the θ_K hysteresis loops?

 Question 21: How would you measure Kerr rotation caused by a sample if you only had a linear polarizer and a detector, i.e., no PEM? At what angle would you place the linear polarizer with respect to the laser polarization axis before applying a magnetic field to rotate the polarization? Why.

 Measurement Assignment 17: Test the system that you proposed in Question 21. When you use a second polarizer mounted on the precision rotation stage to mimic the sample (the same way you did the calibration/sensitivity measurements), how small a polarization rotation change can you detect? Attempt to measure Kerr rotation caused by applying a magnetic field to the sample using this setup. Does it work?

V. EQUIPMENT AND TECHNIQUES

A. Linear Polarizer

An ideal linear polarizer allows 100% transmission of the electric field that is polarized along the polarizer axis and completely blocks the electric field that is polarized perpendicular to the axis. No polarizer is ideal. For example, the transmittance for the selected polarization is not 100%, some of the wrong polarization can "leak" through, and the polarization after the polarizer may no longer be perfectly linearly polarized.

 Question 22: Rotating a linear polarizer before the PEM will affect the $\mathrm{Re}[\theta_K]$, the $\mathrm{Im}[\theta_K]$, or both that are measured by the polarimetry system shown in Fig. 8?

B. PEM

In order to set a retardance, one needs to specify the wavelength. For example, shifting the vertical and horizontal linear polarization components by 250 nm produces a ½ wave retardance for 250 nm wavelength light, but only a ¼ wave retardance for 1000 nm wavelength light. Therefore, the PEM has two parameters, retardance and wavelength, that must be set by the user. The quickest way to set these parameters on the PEM is to use the set-R.vi and set-W.vi Labview programs in D:\Labview_Programs\PEM. The retardance and wavelength are displayed on the PEM's front panel and can also be set by using the up/down arrows on front panel. The front panel of the PEM is shown in Fig. 12.

Note, the wavelength setting on the PEM does not have to be the same as the wavelength of light used. There are many combinations of retardance and wavelength values that are equivalent. For example, setting the PEM to ½ wave at 500 nm (a shift of 250 nm) is equivalent to setting the PEM to ¼ wave at 1000 nm, or even 1/8 wave at 2000 nm. Since the maximum retardance value that can be set at the PEM is 1.000 wave, the advantage of setting the wavelength to a value greater than the wavelength of light used is that real retardances that are greater than 1 can be achieved (see Question 23). For example, if one is using 500 nm wavelength light, but sets the PEM to 2000 nm, one can retard the light by up to 4 full wavelengths. This is very useful for measuring the Bessel functions, which show oscillations that are one the order of several wavelengths of retardance. The disadvantage of setting the PEM to wavelengths that are significantly longer that the actual light, for example 10000 nm for 500 nm light, is that the resolution of the retardance suffers (see Question 24 below).

The PEM **optical head is fragile**, so handle it with care. **Only turn on the PEM power supply if the cables from the power supply, electronic head, and optical head are fully connected**.

Question 23: The light source emits a wavelength of 633 nm and the PEM is set to 5000 nm (5.000 μm). What is the maximum retardance in waves that can be imposed on the 633 nm light. Remember, the PEM only allows the retardance setting to go up to 1.000.

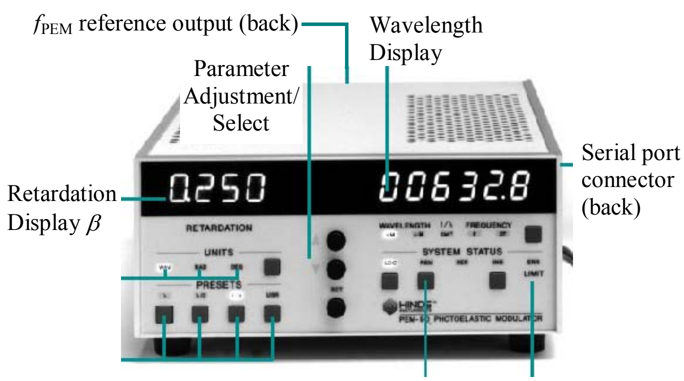


Fig. 12. Hinds PEM-90 controller front panel.

Question 24: Since one can only set the retardance to the nearest 0.001 wave, what is the resolution in the actual retardance (the smallest retardance increment of the 500 nm light that can be set) for the arrangement in Question 23?

C. Lock-In Amplifier

Lock-in detection is a remarkable technique that allows one to detect very small signals that are buried in large amounts of background noise. Imagine trying to hear some whisper from a few meters away while you are standing in front of an enormous speaker at a rock and roll concert. The trick that the lock-in detection technique uses is to modulate the small signal at a known frequency and then amplify only that reference frequency while filtering out all the others. For example, if the whisperer were making sounds at a known frequency, for example 0.5 Hz, the observer would have a better chance of hearing them by listening for a periodic sound at that frequency. Lock-detection does even more than that. By only amplifying the signal at the reference frequency, one can ignore all the sounds that are modulated at other frequencies. Since any reasonable sound pattern in time can be represented as a sum of sines and cosines (Fourier's theorem), if one can take the Fourier transform of the sound pattern one can separate the amplitude of the sine/cosine component at the reference from all the unwanted frequencies. Fig. 13a) shows a complicated pattern that consists of many background components, and one signal component at the reference frequency ω_0. For simplicity, we have chosen discrete frequencies, but in principle there could be a continuum of frequencies making up the pattern.

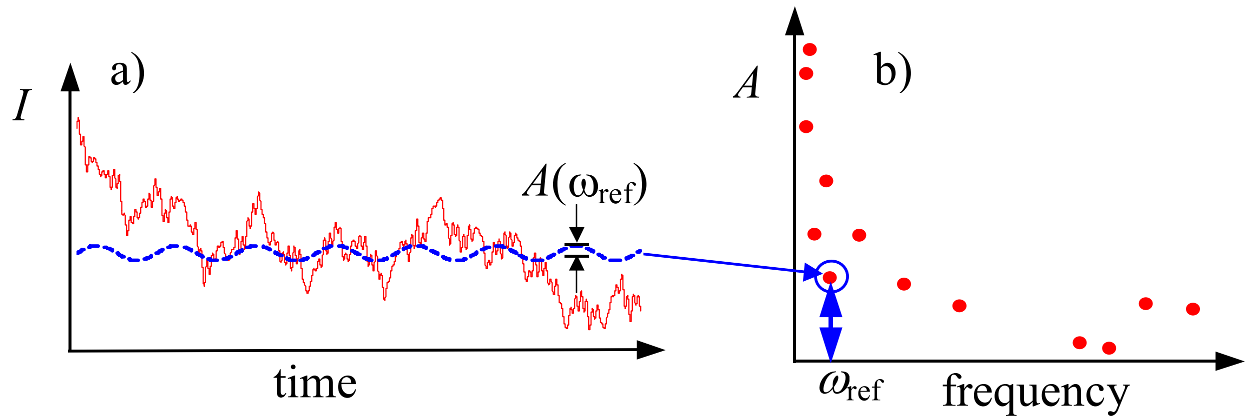


Fig. 13. a) Signal intensity I as a function of time and b) the Fourier transform of $I(t)$, which represents the amplitudes $A(\omega)$ of the frequency components that add to make up $I(t)$. Note that the weak component (dashed blue line in a)) at ω_{ref} is easily separated from the other non-desired frequency components in the Fourier transform in b) (see circled point).

A lock-in amplifier uses analog (or now more commonly digital) electrical processing to take the Fourier transform of the measured intensity signal to separate and amplify the signal at ω_{ref}. Mathematically, the Fourier coefficients are obtained by the following expression:

$$I(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} A(\omega)\, e^{-i\omega t} d\omega \rightarrow A(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} I(t)\, e^{i\omega t} dt \tag{15}$$

So how do we obtain the amplitude $A(\omega_{\text{ref}})$ of our desired signal at ω_{ref}? According to Eq. (9), we simply multiply the time-dependent signal $I(t)$ by $e^{i\omega_{\text{ref}} t}$ and integrate (average) over time, as shown below.

$$A(\omega_{\text{ref}}) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} I(t)\, e^{i\omega_{\text{ref}} t} dt \tag{16}$$

The complex notation $e^{i\omega_{\text{ref}} t} = \cos(\omega_{\text{ref}} t) + i \sin(\omega_{\text{ref}} t)$ is used instead of simply sines or cosines in order to keep track of the phases as well as amplitudes of the Fourier coefficients. In principle $A(\omega)$ is complex, which means that it can represent both the amplitude and phase of the Fourier component at ω. The lock-in amplifier does exactly the same thing. First it multiplies the total input signal by a strong reference signal that is at ω_{ref}. Then it averages the signal over time. These two steps allow the small signal at ω_{ref} to be isolated from the background signals. Figure 14 provides a graphical explanation of how this process works. In Fig. 14a-d, the various components of the input are multiplied by the reference signal. Note that only when the component of the input signal that is at ω_{ref} produces a strictly positive result when it is multiplied by $I_{\text{ref}}(t)$ as shown in Fig. 14c. If the frequencies are different, or if the frequencies are the same but $I_{\text{ref}}(t)$ is 90° out of phase with the signal component, the product oscillates symmetrically about zero. Since the phase of a signal can be critical in many of measurement scenarios, for example the phase between the applied voltage and resulting current provides critical information in probing reactive (LCR) circuits, the lock-in amplifiers ability to measure both phase and amplitude is extremely useful. When the product $I*I_{ref}$ (right column in Fig. 14) is averaged over time, only the input signal component at ω_{ref} produces a non-zero result, all the other frequency component in the input signal average to zero! In this way, the lock-in amplifier can select, and then amplify, only the frequency component in the input that is at ω_{ref}. All other background signals at other frequencies are eliminated.

The front panel of the 7265 lock-in amplifier is shown in Fig. 15. You will be using two inputs (signal from the detector and reference input from the PEM 1*f* connector) on the front panel, and the analog-to-digital output (ADCH1) for the voltage used to control the Kepco power supply for the magnet. Also located on the rear panel is the GPIB (general purpose interface bus) cable which allows communication between the computer and the lock-in. The LCD display shows the lock-in settings (on right side) and the signals (on left side). The parameters can be varied using the ↑↓ parameter adjustment keys. The menu button allows one to set all the parameters, such as

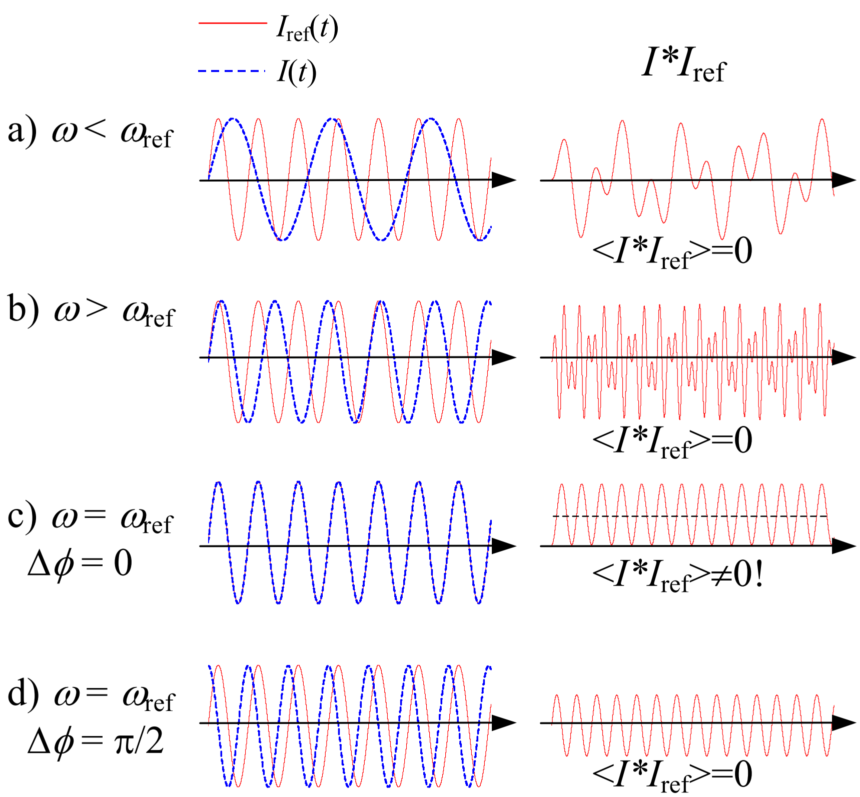


Fig. 14. The product of input signals $I(t)$ and reference signals $I_{ref}(t)$ (left colum) for a) $\omega < \omega_{ref}$; b) $\omega > \omega_{ref}$; c) $\omega = \omega_{ref}$, $\Delta\phi = 0$; and d) $\omega = \omega_{ref}$, $\Delta\phi = \pi/2$. Note that except for the case in c), the product $I*I_{ref}$ (right column) oscillates symmetrically about zero, and therefore averages over time to zero ($< I*I_{ref}>=0$).

time constant, harmonic to measure, etc. Note that one can choose which harmonic of the signal (e.g., $1\omega_{\mathrm{PEM}}$, $2\omega_{\mathrm{PEM}}$, $3\omega_{\mathrm{PEM}}$, $4\omega_{\mathrm{PEM}}$, etc) the lock-in measures.

Do not leave lock-in turned on for more than a few minutes if it is not connected to the detector.

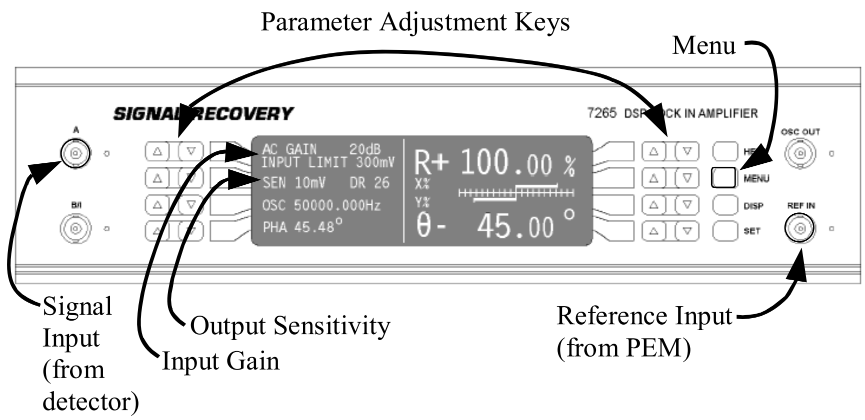


Fig. 15. Front panel of the 7265 DSP lock-in amplifier

 Question 25: What would signal would a lock-in amplifier produce if $\omega = \omega_{\mathrm{ref}}$ but the phase difference between $I(t)$ and $I_{\mathrm{ref}}(t)$ were π (180°)? What if the phase shift were $3\pi/2$ (270°)?

 Question 26: What is the difference between an analog and a digital signal processing (DSP) lock-in amplifier?

 Question 27: On the DSP 7265, the signal can be amplified before it is digitized, mixed, and averaged, or after. Describe the optimal settings for the input gain and the output sensitivity.

 Question 28: In this lab and external reference is used to trigger the lock-in. However, the lock-in amplifier can generate its own reference, which is sent to the “Oscillator Output” connector. Think of some situations where this could be used for an experimental measurement. Hint: how could you measure the complex reactance of an LCR circuit?

D. Electromagnet

This electromagnet (Varian) is used to produce static or slowly ramping magnetic fields between –3.5 T and +3.5 T. The magnetic field is achieved by passing a current through two side-by-side Helmholtz coils that are on either side of the sample (see Fig. 10). The bipolar power supply (Kepco BOP 20-20) shown in Fig. 16 can sweep continuously through zero. The static magnetic field is set either manually using the current control knob on the front panel or externally from the computer using kepco_set_H.vi in D:\Labview_Programs\Mag_Power. A switch on the upper right of the Kepco front panel allows the manual/external control mode to be set. When external control is selected, the voltage on the current programming input, which comes from the DA output of the lock-in amplifier, is used to control the current. Note that the rating for the power supply is 20 A at 20 V, and the supply will saturate when either the voltage or current maximum is reached, whichever comes first.

When running the magnet, be sure that tap water is running with valve open 1/8 of a turn. Be sure to turn off tap water when finished.

For measurements of the MOKE signal as a function of magnetic field, use the Magscan_7265.vi or Magscan_7265.vi (which toggles between the $I_{n\omega_{\mathrm{PEM}}}$ and I_0 signals and calculates the ratio $I_{n\omega_{\mathrm{PEM}}}/I_0$) program in D:\Labview_Programs\Mag_Sweep. Please refer to the Kepco manual for further details on operating the power supply

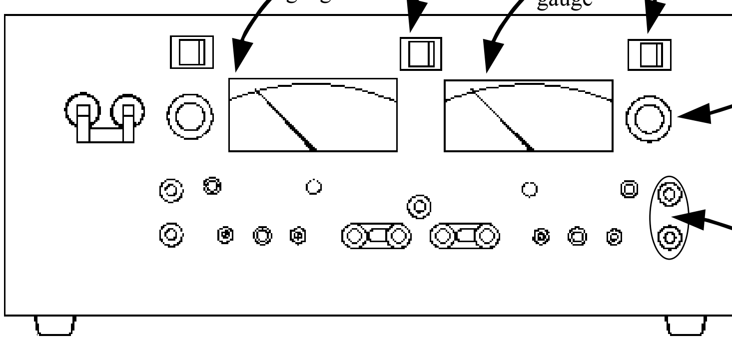


Fig. 16. Front panel of the Kepco BOP 20-20 bipolar power supply.

 Measurement Assignment 18: By looking at how the current going through the magnet is related to the voltage across the magnet, determine the resistance of the magnet.

E. Data recording, analysis and reporting

Recording data is important, but it is often tempting to be careless about it. Make up your mind to take the time to do it carefully, fully and neatly. Use a bound notebook. Write the date at the start of a new day. Note the time of the start and the end of a series of measurements such as a warming run. Write all of the relevant information such as specimen description, current, temperature, etc. If you are making many runs, it is useful to record the runs in a tabular format in your lab book. Write comments in the comments box on the Labview program's front panel while you are taking data. Be sure to also record the run and the relevant information in your lab book. COMPUTERS ARE EXTREMELY USEFUL FOR RECORDING DATA, BUT DO NOT RELY SOLEY ON THE COMPUTER TO KEEP TRACK OF YOUR MEASUREMENTS. <u>The date and time should always be recorded by the acquisition software</u>. You may discover later that you neglected to write something important. The time of the plot is often of great help in reconstructing exactly what you did. Do not try to decide whether the run that you are about to begin will be important enough to require writing down all the information. You may realize later that something interesting happened or that it turned out to be the only really good run in some respect. If it is worth doing it is worth taking notes about.

Labview programs control the equipment and acquire the data from them. **If the STOP button is pressed or if the Labview program is allowed to run to completion, the data in the run are automatically saved to a Labview datalog format file and the user is prompted to enter a filename. If the abort button (stop sign) is pressed to terminate the program, the data are not saved. Do not save the Labview programs themselves. This will not save your data.**

The data are saved in a Labview logfile format and can only be accessed with Logfile_Read2.vi in D:\Labview_Programs\Data_Log. It is recommended that all the data for a given day be saved in the same file, e.g., jcAug2305.dat, jcAug3405.dat and jcAug2505.dat in D:\Labview_Programs. Since Labview cannot read from and write to the same file simultaneously, make sure that Logfile_Read2.vi is not accessing the data file when another program, such as Magscan_7265.vi tries to append new data to that file at the end of a run. This program allows one to quickly go through the data, and exports selected data to standard ASCII format files that can be used by Sigmaplot or Excel.

Recommended software:

- Labview- interface software that allows the computer to control and monitor external devices, e.g., multimeter, lock-in amplifier, electromagnet, temperature sensor, etc. The program act as virtual instruments (VI's) that create front panels on the computer screen that mimic (indicate and control) real hardware. Labview programs use the extension *.vi. The Labview programs are named and organized into folders according to the type of function they serve, e.g., measuring signal as time is swept, magnetic field is swept, PEM retardance is swept. There are two versions of the seep programs: the first simply measures one signal at a time, the second set (*ratio.vi) toggles between the PEM signal and the chopped signal, providing a ratio of these two signals.
- SigmaPlot- data analysis software allows one to analyze and plot data. SigmaPlot programs use the extension *.jnb.
- Mathcad- mathematical analysis software that can be used to perform analytical as well as numerical calculations. Mathcad programs use the extension *.mcd.
- Mathematica- similar to Mathcad but has a more powerful for performing analytical/symbolic calculations.
- Microsoft PowerPoint-Useful for creating slides for oral presentations.
- Microsoft Word-Useful for writing up lab reports.
- Mathtype- Convenient tool for writing mathematical expressions within Microsoft Word and PowerPoint.

VI. Advisories

Here are some suggestions for running an maintaining the equipment.

- Turn off all equipment when finished for the day. Remember to turn off the photodetector switch.
- Do not turn on and off the HeNe laser more than necessary. If running all day, keep the laser on. **Do not allow laser radiation to enter your eye directly!**
- The linear polarizers are aligned to within 5^o of the scale on the rotation mounts. Do not assume that if the mount reads 0^o that the polarizer is exactly at 0^o.
- When running the magnet, be sure that tap water is running with valve open 1/8 of a turn. Be sure to turn off tap water when finished.
- The PEM optical head is fragile, so handle it with care. Only turn on the PEM power supply if the cables from the power supply, electronic head, and optical head are fully connected.
- Do not leave lock-in turned on for more than a few minutes if it is not connected to the detector.
- The maximum retardance of the PEM is ½ wave at 1000 nm, or 0.79 wave at 633 nm. Do not exceed this value.
- Do not use steel tools near the pole pieces when the magnet is energized.

VII. Questions and Measurement Assignments

Below is a list of questions and measurement assignments that are given throughout this manual. You should complete the following questions and measuring assignments before writing your lab report.

Questions

 Question 1: Using the linear basis, produce linearly polarized light that is tilted 45^o from the y-axis.

 Question 2: Using the linear basis, produce: a) left circularly polarized light; b) right circularly polarized light; c) elliptically polarized light with the major axis along the y-axis; d) elliptically polarized light with the major axis tilted from the y-axis.

 Question 3: Using the circular basis, produce: a) vertically linearly polarized light; b) horizontally linearly polarized light; c) linear polarized light that is tilted from the y-axis; d) elliptically polarized light with the major axis along the y-axis; d) elliptically polarized light with the major axis tilted from the y-axis

 Question 4: Can you think of any other “basis” sets that are used in mathematics?

 Question 5: Using the linear basis, produce linearly polarized light that is tilted 45^o from the y-axis.

Question 6: Verify using Mathcad or Maple, that the Fourier expansion for $\cos\left[\beta\cos\left(\omega_{\text{PEM}}t\right)\right]$ is correct.

Question 7: A lock-in amplifier (see Sec. V.C.) is used to measure the magnitude of each harmonic component in the detector signal for the configuration shown in Fig. 8b (polarizer P_1 is slightly shifted from vertical). If the signal at 100 kHz ($2\omega_{\text{PEM}}$) is 4.00 times bigger than the signal at 200 kHz ($4\omega_{\text{PEM}}$), what is the PEM retardance β?

Question 8: Using the same approach as shown in Eqs. (5)-(7), calculate the detector signal as a function of time if the last polarizer were at an arbitrary angle θ (not necessarily 45°) with respect to the PEM.

Question 9: In principle, one could use the first harmonic of ω_{PEM} to obtain $\text{Im}\left[\theta_K\right]$, but in Eq. (9) the third harmonic is used. Can you think of some arguments for and against this choice? Hint: Are there any other sources for noise signals that are at $1\times\omega_{\text{PEM}}$?

Question 10: The small transverse electric field $\vec{E}_x$ that is produced by a sample or by rotating a polarizer (see Figs 1-3) could also be measured using a linear polarizer alone instead of the PEM/polarizer system. Describe how this would work and what are the advantages/disadvantages of using only a linear polarizer to measure Kerr rotation/ellipticity?

Question 11: One could measure θ_K using a single lock-in amplifier by measuring I_0, $I_{2\omega_{\text{PEM}}}$, and $I_{3\omega_{\text{PEM}}}$ sequentially, and then taking the ratios in Eq. (9). Describe the advantages/disadvantages of this technique compared to measuring all three signals and their ratios simultaneously.

Question 12: By looking in the Labview programs, find the value of the magnetic field to lock-in voltage calibration factor. Start in the block diagram of Magscan_7265.vi program in D:\Labview_Programs\Mag_Sweep. Note the calibration may be in a subprogram (sub-vi) inside magnetscan_7265.vi.

Question 13: Write a simple Labview program that adds, subtracts, multiplies, or divides two numbers. You will need two numerical inputs (indicators), one numerical output (control), and a numerical slider/knob control to choose which arithmetic operation will be performed.

Question 14: If the wavelength on the PEM controller is set to 2000 nm, what retardance setting would you expect to produce a retardance of ½ wave at 632.8 nm? Note that a retardance setting of ½ wave for 2000 nm means that the vertical and horizontal waves are shifted by $(1/2)\times(2000\text{ nm}) = 1000\text{ nm}$, which would be a full wave of retardance for 1000 nm wavelength light and two full waves for 500 nm wavelength light.

Question 15: Why is it a bad idea to run the chopper at 60 Hz, or multiples of 60 Hz?

Question 16: The detector also measures light from the room lights, which may be of greater intensity than the laser at the detector. Do the room lights disturb the laser intensity measurement if you use a lock-in amplifier? Is it better, or does it make no difference, to place the chopper directly in front of the laser or the detector when measuring laser intensity? Explain

Question 17: Consider how one would set up the equipment provided in this lab to perform polar and transverse MOKE. Sketch the setup for each geometry.

Question 18: In Fig 11, which axis is the hard axis and which is the easy/soft axis for the applied magnetic field?

 Question 19: What are some situations where a hard ferromagnet is desirable? What are some situations where a soft ferromagnet is desirable?
 Question 20: What is the difference between H and B?
 Question 21: How would you measure Kerr rotation caused by a sample if you only had a linear polarizer and a detector, i.e., no PEM? At what angle would you place the linear polarizer with respect to the laser polarization axis before applying a magnetic field to rotate the polarization? Why.
 Question 22: Rotating a linear polarizer before the PEM will affect the $\mathrm{Re}[\theta_K]$, the $\mathrm{Im}[\theta_K]$, or both that are measured by the polarimetry system shown in Fig. 8?
 Question 23: The light source emits a wavelength of 633 nm and the PEM is set to 5000 nm (5.000 μm). What is the maximum retardance in waves that can be imposed on the 633 nm light. Remember, the PEM only allows the retardance setting to go up to 1.000.
 Question 24: Since one can only set the retardance to the nearest 0.001 wave, what is the resolution in the actual retardance (the smallest retardance increment of the 500 nm light that can be set) for the arrangement in Question 22?
 Question 25: What would signal would a lock-in amplifier produce if $\omega = \omega_{\mathrm{ref}}$ but the phase difference between $I(t)$ and $I_{\mathrm{ref}}(t)$ were π (180$^{\mathrm{o}}$)? What if the phase shift were $3\pi/2$ (270$^{\mathrm{o}}$)?
 Question 26: What is the difference between an analog and a digital signal processing (DSP) lock-in amplifier?
 Question 27: On the DSP 7265, the signal can be amplified before it is digitized, mixed, and averaged, or after. Describe the optimal settings for the input gain and the output sensitivity.
 Question 28: In this lab and external reference is used to trigger the lock-in. However, the lock-in amplifier can generate its own reference, which is sent to the “Oscillator Output” connector. Think of some situations where this could be used for an experimental measurement. Hint: how could you measure the complex reactance of an LCR circuit?

Measurement Assignments

 Measurement Assignment 1: Using an oscilloscope determine the retardance setting on the PEM (with the wavelength set to 632.8 nm) that produces a retardance of ½ wave. Check if the results depend on how the laser beam goes through the PEM. Are the measurements better with the beam entering the PEM at normal incidence, or with the PEM tilted? Why?
 Measurement Assignment 2: With the wavelength on the PEM controller is set to 2000 nm, record the retardance values at which the trace peaks flatten. These occur at odd multiples of ½ wave retardance.
 Measurement Assignment 3: Use the lock-in amplifier to measure the signal on the detector at the chopper frequency. Change the phase on the lock-in amplifier and observe the behavior of the x and y channel signals. Does the behavior make sense?
 Measurement Assignment 4: Measure the signal at higher harmonics, e.g., 2$^{\mathrm{nd}}$, 3$^{\mathrm{rd}}$, 4$^{\mathrm{th}}$, etc., of the chopped frequency. Does the signal contain higher harmonics? Why? If so, do the amplitudes of the harmonics make sense? Hint: what are the Fourier components of a square wave?
 Measurement Assignment 5: Determine the extinction ratio of the linear polarizers. Assume the laser polarization intensity ratio is 500:1 (it may actually be better). Add a polarizer in front

of the laser and measure the extinction ratio when the second polarizer is rotated. Does the first linear polarizer increase or decrease the degree to which the laser light is polarized? Since the polarizers are nominally the same, these two measurements can be used to approximately determine both the degree to which the laser is polarized and the extinction ratio of the polarizers.

 Measurement Assignment 6: Check the accuracy of the polarimetry system by rotating the first linear polarizer in Fig. 8 by 1 degree and comparing the resulting change in the signal with the predicted change. What are possible sources for the difference between the measured and predicted signals?

 Measurement Assignment 7: Check to see how small a rotation of the linear polarizer can be detected by the polarimetry system. This determines the sensitivity of the system to small polarization rotations, i.e., $\mathrm{Re}\left[\theta_K\right]$.

 Measurement Assignment 8: What happens to $I_{2\omega_{\mathrm{PEM}}}$ (signal at the second harmonic of the PEM modulation frequency ω_{PEM}) when a chopper is placed in the beam, as in Fig. 8. Can you explain the change?

 Measurement Assignment 9: Do you see any changes in the $3\omega_{\mathrm{PEM}}$ and $4\omega_{\mathrm{PEM}}$ signals when the linear polarizer is rotated? Why?

 Measurement Assignment 10: Use the experimental setup shown in Fig. 8b. Place the plexiglass plate in front of the PEM. Measure changes in the intensity of the transmitted light (chopped), the second and third harmonic signals of the PEM, and the ratios of the PEM harmonics to the chopped signals as you move the beam on the plate from high strain areas (near the inside end of the slot) to low strain areas. Use the time scanning programs to record these signals as you move the plate with respect to the beam, keeping track of the times when the sample is moved to different places.

 Measurement Assignment 11: Determine $J_2(\beta)$ and $J_4(\beta)$ as functions of β. Hint, the signal due to a non-zero horizontal field $\vec{E}_x$ is proportional to $J_2(\beta)$. Hint: You should try measuring the signal at $2\omega_{\mathrm{PEM}}$ as a function of β for one orientation of the first polarizer (see Fig. 8). For small polarizer orientations this does not work and one must repeat the measurement for another polarizer orientation and subtract the two curves. What does this say about the orientation of the polarizer's optical axis as β is increased. Check if the results depend on how the laser beam goes through the PEM. Are the measurements better with the beam entering the PEM at normal incidence, or with the PEM tilted? Why?

 Measurement Assignment 12: Can you think of a way to increase the signals when measuring $J_1(\beta)$ and $J_3(\beta)$ as functions of β? Try directing the HeNe beam through a high strain area in the plexiglass plate when measuring the first and third PEM harmonics. What happens? Why?

 Measurement Assignment 13: Use the results of Measurement Assignments 8 and 9 to set the PEM to a known retardance. This is an alternative way of calibrating the PEM retardance. How do the results from this technique compare with the calibration obtained in Measurement Assignment 1 in Section **IV**.**A**.*ii*?

 Measurement Assignment 14: Measure the complex θ_K as a function of applied magnetic field along the **easy** axis of the film. How do $\mathrm{Re}\left[\theta_K(H)\right]$ and $\mathrm{Im}\left[\theta_K(H)\right]$ compare.

 Measurement Assignment 15: Measure the complex θ_K as a function of applied magnetic field along the **hard** axis of the film. How do $\mathrm{Re}\left[\theta_K(H)\right]$ and $\mathrm{Im}\left[\theta_K(H)\right]$ compare. How do these results compare with the easy axis measurements?
 Measurement Assignment 16: By measuring a plain Si or GaAs (behaves qualitatively similar to Si) substrate, determine the contribution to θ_K from the Si substrate on which the $Tb_{0.4}Fe_{0.4}/Fe_{0.5}Co_{0.5}$ films are grown. Does the substrate affect the θ_K hysteresis loops?
 Measurement Assignment 17: Test the system that you proposed in Question 21. When you use a second polarizer mounted on the precision rotation stage to mimic the sample (the same way you did the calibration/sensitivity measurements), how small a polarization rotation change can you detect? Attempt to measure Kerr rotation caused by applying a magnetic field to the sample using this setup. Does it work?
 Measurement Assignment 18: By looking at how the current going through the magnet is related to the voltage across the magnet, determine the resistance of the magnet.

VII. References

Manuals

- Hinds PEM
- Kepco power supply
- Signal Recovery 7265 lock-in amplifier
- Labview

Books

- Polarized light in optics and spectroscopy, D.S. Kliger, J.W. Lewis, and C.E. Randall, Academic Press Inc., 1990.
- Magnetism in condensed matter, S. Blundell, Oxford University Press, 2001.

Papers (at the back of this binder)

- Magneto-optical Kerr effect spectroscopy: Magnetism in a new light, R. Atkinson, Hinds Technical Paper (2001).
- Polarized light and its interaction with modulating devices- A methodological review, J.C. Kemp, Hinds Technical Paper (1987).
- Measurement of the infrared magneto-optic properties of thin-film metals and high temperature superconductors," J. Cerne, D.C. Schmadel, L. Rigal, and H.D. Drew, Rev. Sci. Instr. 74, 4755-4767 (2003).

Web sites

- http://www.physics.buffalo.edu/cerne/education/polarization.html
- http://www.physics.buffalo.edu/claw/

VIII. Appendix

A. Lab Timetable

Here is a rough outline of the topics that will be covered during the session:

Day 1: Measuring the intensity of light using a lock-in amplifier and characterizing polarizers. Complete Questions 15, 16, and 25-28 and Measurement Assignments 3-5.

Days 2 and 3: Introduction to polarized light and the PEM, calibrating the PEM, testing the sensitivity and calibration of the polarimetry system. Complete Questions 1-8, 14, 23, and 24, and Measurement Assignments 1, 2, 6-9.

Day 4: Measuring strain in plexiglass and determining the first four Bessel functions. Complete Measurement Assignments 10-12.

Day 5: Setting up MOKE measurements. Complete Questions 9-13 and Measurement Assignments 6 and 7 (this time with light reflecting off sample) and 14.

Day 5- end of session: Completing measurements, making absolute MOKE measurements on magnetic films, comparing measurements on the strained and unstrained axes of magnetic films, measuring MOKE background from GaAs, comparing rotation and ellipticity signals. Complete Questions 17-22 and Measurement Assignments 15-18.

B. Guide to writing the lab report

The lab report should clearly and concisely summarize the experimental techniques and the measured results. Here are some guidelines in writing the report:

1. Do not copy from this manual and paste directly into your report any of the text, equations, or figures (unless they are from a published paper, which must be properly referenced). **The report must be in your own words using your own figures.**
2. Reference in the main body of your report every figure that is included. Each figure should have a brief description in the text, and the figures should be used to support the statements that you are making in the text. **DO NOT STAPLE A SERIES OF UNREFERENCED FIGURES TO THE BACK OF YOUR REPORT.**
3. Axes on all graphs should be clearly labeled, including units.
4. Explain how/why the measurement technique works. You should have at least one figure showing the experimental setup.
5. Report error bars on all measured values, and discuss sources for the errors and how to minimize them. Make sure you understand the difference between statistical and systematic errors.
6. Discuss what the data are telling you. Do the results make sense?

C. Guide to the oral report

The oral report should clearly and concisely summarize the experimental techniques and the measured results. Here are some guidelines for the oral report:

1. The talk is 10 minutes followed by a 2 minute question period.
2. You should plan on presenting no more than 15 slides. 10 minutes is not a long time! You may have some slides prepared as backup if more detailed explanations are requested during the 2-minute question period.
3. You should motivate and provide background for the lab, but do not spend more than a few minutes on introductory material.
4. Practice the talk with a timer.
5. Do not copy from this manual and paste directly into your oral report any of the text, equations, or figures (unless they are from a published paper, which must be properly referenced). **The report must be in your own words using your own figures.**
6. Try to have a title at the top of each slide that summarizes the slide.
7. Explain how/why the measurement technique works. You should have at least one slide showing the experimental setup.
8. Axes on all graphs should be clearly labeled, including units. Point out the axes and what it is being plotted when you introduce the graph.
9. Use the pointer during your talk and try to face the audience when speaking.
10. Make sure text and figure details are clearly visible to audience that is at the back of the room.
11. Report error bars on all measured values, and be prepared to discuss sources for the errors and how to minimize them.
12. Discuss what the data are telling you. Do the results make sense?

D. Format for Advanced Lab Written Reports

Based on B. D. McCombe's NMR report outline

I. Introduction and Background

What is the experiment all about? What are you trying to measure and why? Perhaps some historical background to put the experiment in perspective. This should be relatively brief. Please reference all material that you use, including the lab manual, papers, and books.

II. Theory

You do not need to <u>derive</u> all the necessary formulae. **But**, you should provide enough physical reasoning so that you can convince the reader that you understand how the necessary formulae are obtained.

III. Experimental Details

What is the approach and how are the measurements made? Provide sketches of the important apparatus. Refer to the appropriate equations in Part II in this discussion. Provide a simple description of how the apparatus works; a block diagram is useful. What are the sources of error? Be clear and concise.

IV. Results

This and the following section form the main body of your report.

Present your data and the error analysis carefully. You should include <u>examples</u> of data for each of the measurements used. **Do not include all of the data in the body of the report, just a typical example of each; you may place relevant additional data in an appendix. Label all plots (including axes) neatly and carefully with all the necessary information on the plot or in a figure caption. All figures and Tables should have an explanatory caption!!**

Be sure that you plot your data carefully and neatly! You must ***refer in the text*** to any plots or tables appearing in the main body of the report. Don't include Figs. 1 -10 and then only mention Fig. 3 in the text!

V. **Discussion**

This is where the physics comes in. I want you to demonstrate to me that you have actually achieved a basic understanding of all the techniques, their advantages and disadvantages, and whether or not these expectations are realized. Compare with theoretical predictions where possible. Some idea of why there are discrepancies if there are any -- effects of errors; general trends.

VI. **Conclusions and Suggestions**

What have you learned about the experiment? What were the problems? What could you do to improve the data? What could be done to improve the equipment?

E. Physical Interpretation of the Complex Kerr Angle

Assuming we the sample is isotropic in-plane and that the magnetic field/magnetization is normal to the surface, one can conveniently describe the transmission and reflection of light using the circular basis, with $n_\pm$ and $k_\pm$ describing the index of refraction and absorption coefficient, respectively for right/left (+/-) circularly polarized light. In transmission (Faraday effect), a difference in indices n_+ and n_- lead to a rotation in the axis of the linear polarized incident light a while difference in absorption constants k_+ and k_- lead to an ellipticity of the linear polarized incident light. Please see http://www.physics.buffalo.edu/cerne/education/Faraday3.html using the circular basis.

In reflection measurements probing the polar Kerr effect (H and/or M perpendicular to sample surface), the dependence of the rotation and ellipticity signals on *n* and *k* is reversed.

The reflection amplitude $r_\pm$ for + and – circularly polarized light reflecting off a bulk material is given by:

$$r_\pm = \frac{\tilde{n}_\pm - 1}{\tilde{n}_\pm + 1}, \tag{17}$$

where the complex index of refraction is given by $\tilde{n}_\pm = n_\pm + k_\pm$. Note here that if the $\tilde{n}_\pm$ is real ($k_\pm = 0 \leftrightarrow$ no absorption), no phase shifts (except for possibly 180°) occur in the reflected light. Equation (1) is basically the same equation as for linear polarized light (e.g., see Eq. (3)). Interestingly, in going from a linear to circular basis, one uses the same equations but replaces the linear conductivity σ_{xx} with $\sigma_\pm$, and $\tilde{n}$ with $\tilde{n}_\pm$.

The complex Kerr angle θ_K is worked out in http://www.physik.fu-berlin.de/~bauer/habil_online/node5.html and is given by:

$$\begin{aligned} \theta_K \approx \tan\theta_K &= \frac{i2\left(\tilde{n}_- - \tilde{n}_+\right)}{1-\varepsilon} \\ &= \frac{2}{1-\varepsilon}\left[-\left(k_- - k_+\right) + i\left(n_- - n_+\right)\right] \end{aligned} \tag{18}$$

As in equation (1) it is clear that if there is no absorption ($k_+ = k_- = 0$) and $\varepsilon = \tilde{n}^2$ is therefore also real, θ_K is purely imaginary, and therefore only ellipticity but no rotation is induced in the reflected polarization. Neglecting the complex ε in the denominator, it is also clear form Eq. (2) that the rotation of the polarization, which is related to $\mathrm{Re}\,\theta_K$, is proportional to the circular dichroism $\left(k_- - k_+\right)$, while the ellipticity, which is related to $\mathrm{Im}\,\theta_K$, is proportional to the circular birefringence $\left(n_- - n_+\right)$. The complex ε in the denominator will tend to mix the real and imaginary parts of the expression in the bracket, but if the imaginary part of ε is small compared to 1, the association of Kerr rotation with circular dichroism and Kerr ellipticity with circular birefringence is a reasonable approximation.

For the longitudinal Kerr effect geometry (H and/or M in the sample surface and in the plane of incidence), the linear polarization basis ($\perp$ and $||$ linear polarizations) is more appropriate. The reflection amplitude for linear polarized light on a bulk metal surface is given by:

$$r_{\perp||} = \frac{1-\tilde{\beta}_{\perp||}}{1+\tilde{\beta}_{\perp||}} \tag{19}$$

where $\tilde{\beta}_{\perp||} = n_{\perp||} + ik_{\perp||}$ (e.g., Eq. 9.147 on p. 397, Electrodynamics, 3rd Ed., Griffiths). In this case, if there is no absorption ($k_{\perp||} = 0$), there are no phase shifts in the reflected linear polarizations, and hence the $\perp$ and $||$ reflected linear polarizations are in-phase and no ellipticity will result. If the $n_{\perp} \neq n_{||}$, the amplitudes of the reflected $\perp$ and $||$ linear polarizations will be different and Kerr rotation will result. Unlike the polar Kerr effect in the circular basis, now ellipticity in the reflected beam only occurs if there is real absorption.

F. Magnetostriction paper

Effect of Stress-induced Magnetic Anisotropy on the Properties of Giant Magnetostrictive Single Layer and Multilayer Thin Films

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ABSTRACT

Giant magnetostrictive thin films deposited on nonmagnetic substrates can constitute effective sensors and actuators for microdevices. In this work, we investigated the effects of a stress-induced anisotropy on the magnetic properties of $Tb_{0.4}Fe_{0.6}$, $Fe_{0.5}Co_{0.5}$ single layer films and $[Tb_{0.4}Fe_{0.6}/Fe_{0.5}Co_{0.5}]_n$ multilayers deposited on Si substrates. The magnetostrictive thin films were fabricated by means of RF sputtering and were subjected to a post-deposition annealing treatment. The uniaxial magnetic anisotropy was induced by bending the substrate before deposition and then allowing it to resume its original flat shape after depositing the film. The heat treatment was performed in a vacuum system with a vacuum of 10^{-6} Torr. The magnetic properties of the fabricated specimens were measured using a SQUID. SEM and XRD analyses were performed to ensure that the thermal treatment would relax the internal stresses induced during the deposition process without crystallizing the film. The thickness of the single layer thin films studied was between 300 and 800 nm while multilayer samples consisted of 6 layers with each layer thickness ranged from about 20 to 40 nm. Compared to single layer samples, multilayer samples with stress anneal growth exhibited an improvement in magnetic saturation by a factor of two while maintaining a low coercive field. Manipulations of the magnitude and direction of magnetic anisotropy was observed by introducing various values of tensile and compressive stress into the film.

INTRODUCTION

For the development of micro-actuators and sensors in MEMS, giant magnetostrictive materials have become increasingly important. By combining exchange-couple giant magnetostrictive materials (amorphous $Tb_{0.4}Fe_{0.6}$) and materials with large magnetic polarizations (FeCo), multilayer magnetic thin films exhibit significant improvement in terms of high magnetostriction at low field and high magnetostrictive susceptibility compared to single layer thin films [1]. The amorphous rare earth transition metal TbFe has rather low magnetization due to its rare earth nature. FeCo is magnetically soft, has a very high magnetization and a sizable magnetostriction. In order to achieve the polarization enhancement and the anisotropy reduction, careful study of the magnetic, magnetostrictive and mechanical characteristic of these multilayers must be done [1]. To further improve the magnetostrictive properties by controlling the uniaxial anisotropy, stress annealing growth was introduced to these multilayer magnetostrictive thin films structured as $[TbFe/FeCo]_n$. These could lead to the potential commercial applications in magnetostrictive devices.

EXPERIMENTAL

RF magnetron sputtering was used to form the multilayer magnetostrictive thin films structured $[TbFe/FeCo]_n$ on Si substrates from Tb:Fe, 40:60 and Fe:Co, 50:50 targets. The base pressure of the sputtering chamber was 6×10^{-6} Torr. A titanium pump was used prior to sputtering to reduce oxygen level in the chamber. A residual gas analyzer (RGA) monitored the gas composition in the chamber before and after sputtering. The sputtering process was done under a RF power of 150 W with 3 mTorr Ar pressure in the chamber. The sputtering rate was approximately 2 nm/min for FeCo and 10 nm/min for TbFe. The thickness of each layer was maintained as 20 nm, measured using scanning electron microscopy (SEM). Three main factors which influence the properties of the deposited films were identified: sputtering process parameters, amount of external stresses applied and post-deposition annealing. The sputtering and heat treatment parameters were optimized for improving the low field magnetostriction and the magnetostrictive susceptibility of the films.

Tensile and compressive stress biasing was introduced into 4×20 mm^2 rectangular films by using a special fixture to bend the samples mechanically during sputtering growth. The schematic setups are shown in Figures 1 and 2. For the compressive stress, the wire was placed beneath the substrate to control the curvature of the substrate which is related to the amount of stress applied onto the film. In the tensile case, two metal pieces were placed at both ends of the sample while a metal rod was used to press down the substrate in the middle. The films were annealed in a vacuum of the order of 10^{-2} Torr at an optimized temperature of 350 C. This temperature is sufficient to allow the stress in the magnetic film to be relieved but low enough to prevent crystallization. The samples were then released and cut into 4×4 mm^2 pieces after the thermal treatment. This stress annealing growth gave a much larger anisotropy compared to those induced by intrinsic stress such as thermal expansion or lattice mismatch.

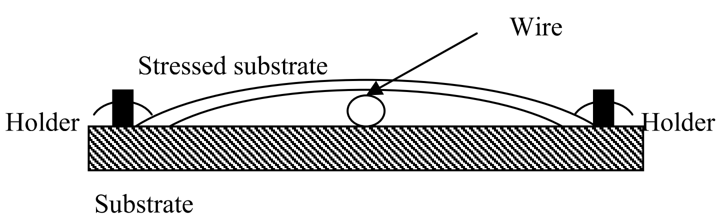


Figure 1. Schematic of the setup for the compressive stress study

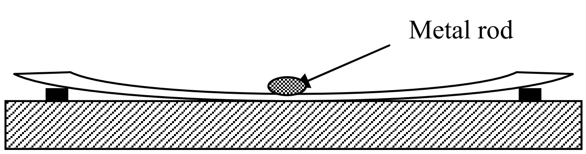


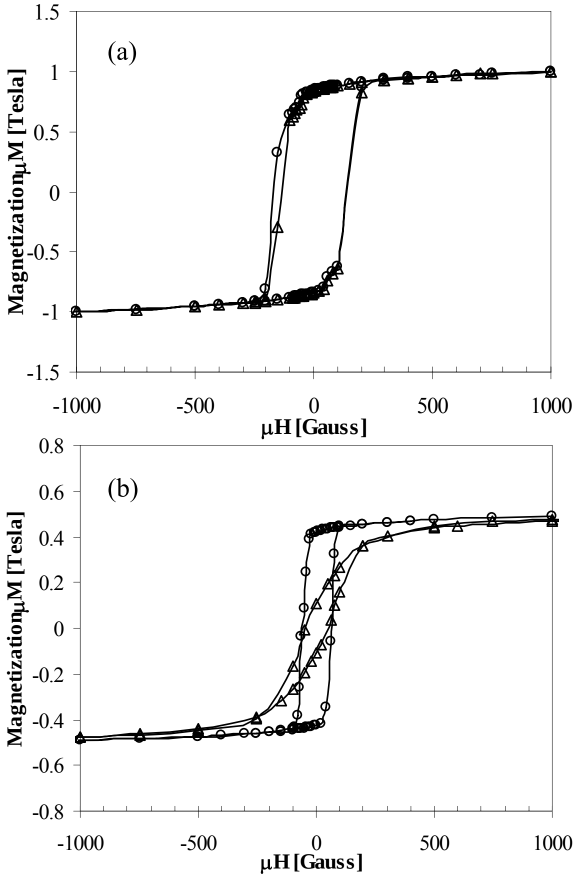
Figure 2. Schematic of the setup for the tensile stress study

A Superconducting QUantum Interference Device (SQUID) was used to measure the magnetic hysteresis loops in both the parallel and perpendicular directions of the films. Auger Electron Spectroscopy (AES) identified the material throughout the film and verified the uniformity of each layer. The amorphous nature of the film was confirmed by X-ray diffraction (XRD).

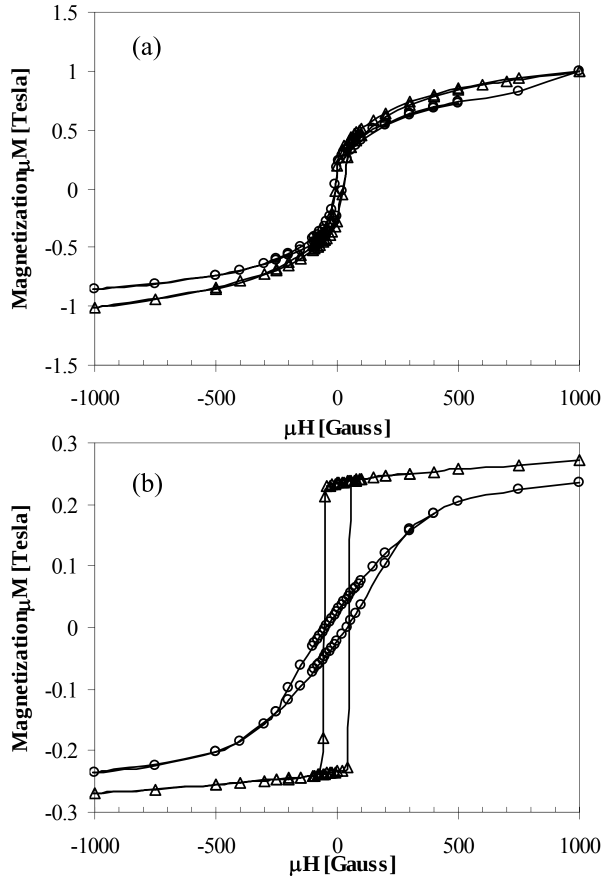
RESULTS AND ANALYSIS

Single layer TbFe magnetostrictive thin film

In order to study the behavior of multilayer magnetostrictive thin film structured as $[TbFe/FeCo]_n$, the properties of single layer samples should first be investigated. Single layer $Tb_{0.4}Fe_{0.6}$ thin films were sputtered on the silicon substrates under applied tensile and compressive stress. Since the film was annealed while the stress was induced in the film, the intrinsic stress induced anisotropy could be neglected. Figures 3(b) and 4(b) indicate that magnetic anisotropy was observed in both samples which were under tensile and compressive stress. These results agree with the theoretical expectation in which the easy axis should be in the 90° direction of the applied field if the film experienced a tensile stress. Similarly, the easy axis should be parallel to the applied field if the film was under a compressive stress. As shown in Figures 3(a) and 4(a), the as-grown, non-stressed samples demonstrated similar hysteresis loops in both directions of applied field. These results were also consistent with the theoretical prediction since the intrinsic stress should be relieved after thermal treatment (annealing at 350 C, 1 hr). The amount of strain applied in both tensile and compressive stressed samples was 6×10^{-6}**.** Magnetization saturations in both cases were in the range of 0.25 Tesla to 0.5 Tesla, with tensile stressed sample saturation slightly higher than for the compressive stressed sample.



Δ Field applied at 0° of tensile stress direction (hard axis)
○ Field applied at 90° of tensile stress direction (easy axis)



Δ Field applied at 0° of compressive stress direction (easy axis)
○ Field applied at 90° of compressive stress direction (hard axis)

Figure 3.(a) Hysteresis observed with field applied at 0 and 90° of a sample as grown, without stress. (b) Hysteresis observed with a field applied at 0 and 90° to the tensile stress applied showed significant in-plane anisotropy in the sample

Figure 4.(a) Hysteresis observed with field applied at 0 and 90° of a sample as grown, without stress (b) Significant in-plane anisotropy observed in the sample with compressive stress.

It was critical to maintain the film in the amorphous state. Therefore, XRD and SEM were used to confirm the state of the film after thermal treatment in Figure 5 (a) and (b). XRD did not show a peak for TbFe and the SEM profile indicated that the crystallization did not occur at 350 C. The crystallization of the sample would influence the magnetostriction properties of TbFe and also increase the coercive field. High magnetostriction at low field would be difficult to achieve in a multilayer sample that is crystalline.

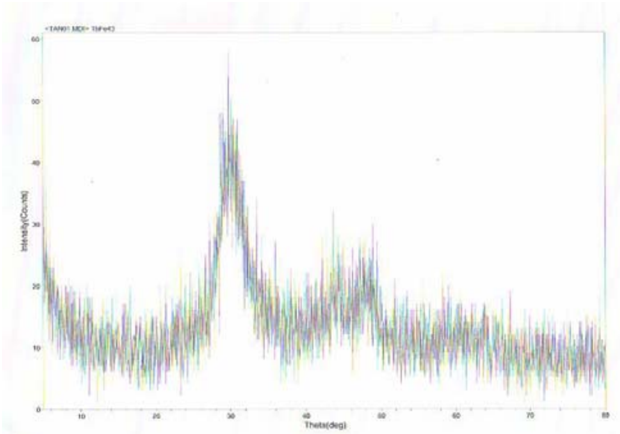


Figure 5(a). X-ray Diffraction (XRD) of a TbFe sample annealed at 350 C. This profile verified that the sample remained in the amorphous state after thermal treatment.

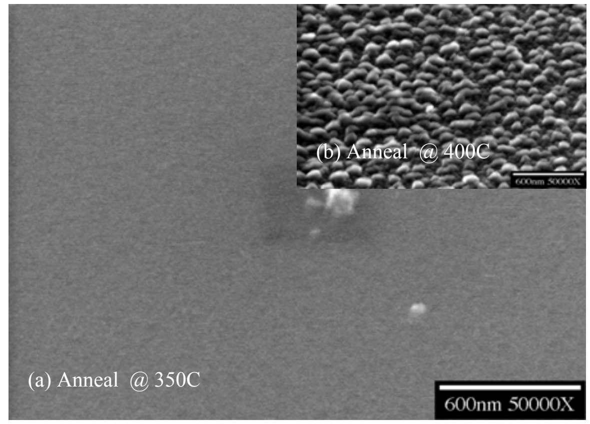


Figure 5(b). SEM profile of the surface morphology of the TbFe sample annealed at 350 C and 400 C..

Multilayer $[TbFe/FeCo]_n$ magnetostrictive thin film

In multilayer samples, amorphous TbFe exhibits high magnetostriction while crystalline FeCo combines both very high magnetization and good magnetoelastic properties. With stress annealing growth, magnetic and magnetostrictive properties were improved by controlling the uniaxial anisotropy. The amount of strain applied in the multilayer sample was 7×10^{-7}. Although the mechanical bending applied to the sample substrate was limited, it was sufficient to produce a high anisotropy field. Eq 1 shows the relations of the anisotropy field (H_k), the sample stress (σ) and magnetostriction constant (λ_S).

$$\lambda_S = \frac{\mu_0 M_S}{3}\frac{H_k}{\sigma} \qquad (1)$$

Figure 6(a) represents the easy and hard axis hysteresis loops of a multilayer sample with structure $[TbFe/FeCo]_n$ where n=3. The hysteresis loop at both 0 and 90° to applied field of Figure 6(a)(i) was taken from the film annealed at 350 C, while Figure 6(a)(ii) was taken from a tensile stressed film which was annealed at 350 C. In contrast to the single layer TbFe film, the multilayer film demonstrated higher magnitude of magnetization saturation by a factor of 2 due to the polarization enhancement of FeCo. It also maintained a reasonable strength of magnetic anisotropy. Based on the results from several research groups, the magnitude of this stress anneal induced anisotropy is much larger than the anisotropy induced by field annealing and intrinsic stress [2]. An image of the domain structure of the film with tensile stressed anneal is shown in Figure 6(b) [3]. It suggests that the in-plane transverse or longitudinal uniaxial anisotropy can be controlled by applying varies value of tensile and compressive stress.

To further improve the magnetic and magnetostrictive characteristics of this multilayer thin film, several important issues had to be investigated. Due to the ratio of TbFe and FeCo in the film, optimization for number of layers and the total film thickness would increase magnetization while maintaining a reasonable coercive field which is directly related to the magnetostriction. The amount of stress applied to the film and the annealing temperature need to be further studied because they determined the magnitude of anisotropy induced in the film.

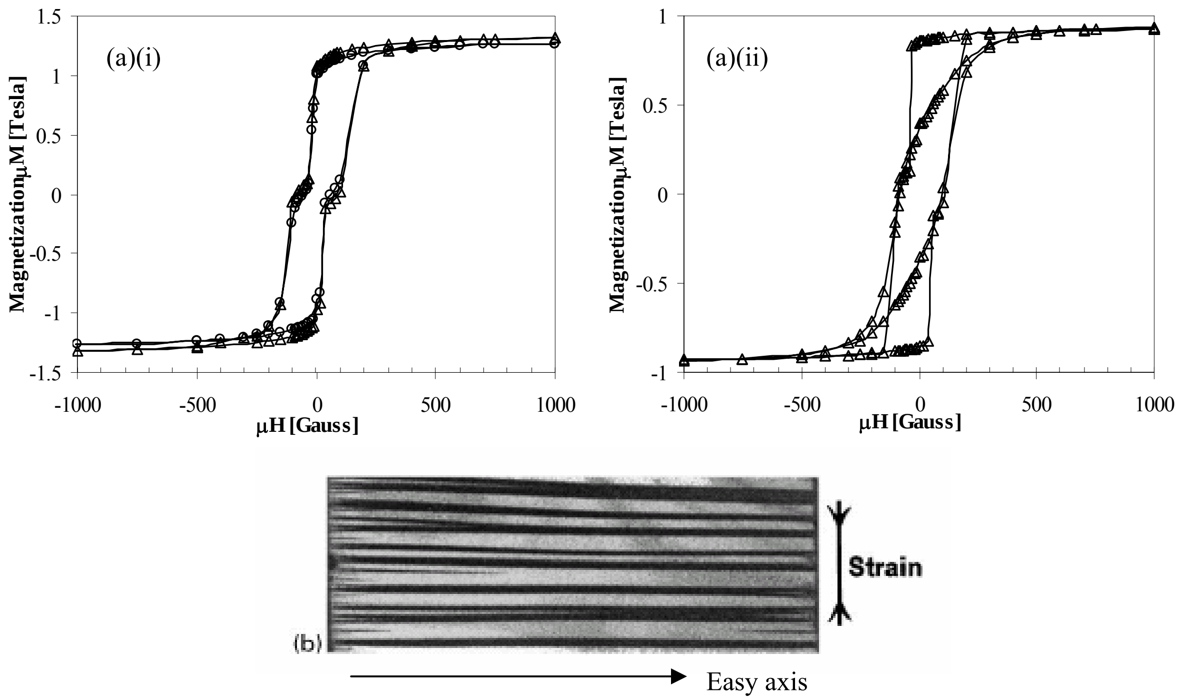


Figure 6(a). Stress annealing on a multilayer thin film. Hysteresis loop of (i) annealed unstressed film with field applies at 0 and 90°. (ii) film annealed under tensile stress with field applied at both 0 and 90° to stress. (b) MOKE (Magneto –Optic Kerr Effect) domain image at remanence. [3]

CONCLUSIONS

Properties of single and multilayer magnetostrictive thin films were characterized. In short, high magnetostriction at low field and high magnetostrictive susceptibility magnetic thin film could be achieved by combining multilayer thin films with high magnetostrictive and high polarization materials. With stress anneal growth, controllable anisotropy in both magnitude and direction could also be achieved.

ACKNOWLEDGEMENT

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REFERENCES

[1] E. Quandt, A. Ludwig, *Journal of applied physics*, **85, 8**, p6232 (1999)
[2] M. Ali, R. Watts, W.J Karl, M.R.J. Gibbs, *Journal of magnetism and magnetic materials*, 190, p199 (1998)
[3] M. Ali, R. Watts, *Journal of magnetism and magnetic materials*, 202, p85 (1999)