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Twisting Lasers with the Faraday Effect

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Abstract

Our objective with this project was to create a system and procedure to quantify the magnetization of a material with polarized light by using the Faraday Effect, where the light is rotated according to the magnetization. This type of system has seen use in technologies such as magneto-optical drives and optical isolators, and is part of the study of optical materials, along with the similar MagnetoOptical Kerr Effect. Our system, specifically, is intended to be used as part of an advanced Physics Lab in the future. It uses an electromagnet to magnetize a sample, and a laser to observe the effects.

Keywords

faraday

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1 Introduction

Our objective with this project was to create a system and procedure to quantify the magnetization of a material with polarized light by using the Faraday Effect, where the light is rotated according to the magnetization. This type of system has seen use in technologies such as magneto-optical drives and optical isolators, and is part of the study of optical materials, along with the similar Magneto-Optical Kerr Effect. Our system, specifically, is intended to be used as part of an advanced Physics Lab in the future. It uses an electromagnet to magnetize a sample, and a laser to observe the effects.

2 Theory

The Faraday Effect states that circularly polarized light passing through an optically active material magnetized by a magnetic field with a direction parallel to that of the incident light will have its polarization rotated proportionately to the degree of magnetization. This is because the electrons in the material are affected by that magnetization, and in turn, they affect the left- and right-polarized components differently. For the linearly polarized light used in the experiment, the relationship still holds, but the rotation is also affected by the properties of the laser and substance, as seen below:

$$\Delta = \frac{d}{\lambda}\pi(n_L - n_R) \tag{1}$$

Where Δ represents the angle of rotation, d is the thickness of the material, λ is the wavelength of the light traveling through it, and n_L and n_R are the indices of refraction for left- and right-polarized light, respectively. With a magnetized film, that rotation can be characterized by an alternative equation:

$$\Delta = Bdv \tag{2}$$

where B is the incident magnetic field and v is the Verdet constant, an innate material property that measures the degree of rotation due to this effect, and has the units of radians per Tesla per meter. Our experiment had us use materials with known Verdet constants, which we used as reference for the veracity of our system.

3 Experimental Methods

The sample to be observed was placed between the two poles of the electromagnet, modified to allow a laser to travel through the sample in parallel with the magnetic field lines, as required by the Faraday Effect. The laser itself has a wavelength of 632.8 nm, and was passed through a linear polarizer before entering the magnet. Upon leaving, it encountered a beam splitter that split the beam into its horizontal and vertical components, which were then routed to the two ports on our detector. The polarizer was set so that those components were balanced in the absence of a sample, using the detector to check this. With a sample in place, the components become unbalanced yet again, so we set a half-wave plate to rebalance them in the absence of a magnetic field. Once again, we used the detector to balance them accurately. We also felt that the use of a lens was appropriate to focus the beam and maximize the incoming signal. Our detector was a homemade device that had three output channels: one for both of the input ports, and a third measuring the difference between them.

The system was controlled by a Labview program, which incremented the electromagnet according to a user-defined range and step size, and recorded the outputs from the detector at every step. Measurement started at 0 T, increased to the maximum range of 0.4 T first, then decreased to the minimum range at -0.4 T, before increasing back to 0 T. At each step, it recorded the output signals from the three channels, and recorded them to an array, which is then used to calculate and produce the graphs displaying the rotation as a function of the magnetic field.

The rotation was calculated as thus: with the half-wave plate set to balance the two incident components measured by the detector, that means the laser is polarized at $\pi/4$ radians, and that the components' intensities I_A and I_B observed at ports A and B on the detector are equivalent to one half of the intensity of the laser incident on the beam splitter, I_0. This indicates that the interaction can be described using a trigonometric identity:

$$\sin^2(\frac{\pi}{4}) + \cos^2(\frac{\pi}{4}) = \frac{1}{2} + \frac{1}{2} = 1 \tag{3}$$

$$I_0 = I_0 \sin^2(\theta) + I_0 \cos^2(\theta) = I_A + I_B \tag{4}$$

Let $I_A = I_0 \sin^2(\theta)$. The introduction of a rotation from the Faraday Effect is equivalent to adding a Δ to θ in both terms, meaning that it then becomes $I_A = I_0 \sin^2(\theta+\Delta)$. Using a Taylor Expansion and a small-angle approximation, we arrive at a simpler:

$$I_A(\Delta + \frac{\pi}{4}) = I_A(\frac{\pi}{4}) + \frac{d}{d\Delta} I_A(\Delta) \tag{5}$$

$$I_A(\frac{\pi}{4}) + \frac{d}{d\Delta}I_A(\Delta) = \frac{I_0}{2} + 2I_0\cos(\frac{\pi}{4})(-\sin(\frac{\pi}{4}))\Delta \quad (6)$$

$$\frac{I_0}{2} + 2I_0\cos(\frac{\pi}{4})(-\sin(\frac{\pi}{4}))\Delta = \frac{I_0}{2} - I_0\Delta = I_0(\frac{1}{2} - \Delta) \quad (7)$$

$$I_A = I_0(\frac{1}{2} - \Delta) \quad (8)$$

Since $I_A + I_B = I_0$, it follows that:

$$I_B = I_0(\frac{1}{2} + \Delta) \quad (9)$$

Subtracting the two gives us this:

$$I_A - I_B = I_0(\frac{1}{2} - \Delta) - I_0(\frac{1}{2} + \Delta) = -2I_0\Delta \quad (10)$$

Which gives us the rotation in terms of the intensities at both channels and the initial incident intensity, the latter of which can be removed by dividing both sides by I_0.

$$\frac{I_A - I_B}{I_0} = \frac{I_A - I_B}{I_A + I_B} = -2\Delta \quad (11)$$

Doing so means that the rotation can be quantified solely by the data recorded by the detector. We used that ratio as the rotation from the graphs, which have a slope of $-2\frac{\Delta}{B}$, and can be used in Equation (2) to yield the Verdet constant, provided the thickness of the sample is known.

The procedure then goes as follows: after making sure that the initial polarizer was balanced, a sample was then placed between the poles of the magnet, followed by using the half-wave plate to re-balance the system in its magnetically-neutral state. The laser was split into two polarized components, and those were routed to the detector, which measures their intensities. We tested magnetic field values from -0.4 T to 0.4 T, at a step size of 0.05 T. Data collection is handled by the computer, after which we produced a graph by manually calculating the rotation using Equation (11), and plotted it against the strength of the magnetic field. The slope of that line corresponds almost directly to the Verdet constant, as seen in Equation (2), and can be used along with the thickness of the sample to calculate it.

4 Results

We used two samples in our experiment, a block of glass, and a nickel film deposited on a glass slide with a thermal evaporator. With the use of a caliper, the glass had a measured thickness of 15.73 mm while the nickel had a thickness of 67 nm, which we had to measure with an atomic force microscope. The data from the glass gave us the graph depicted in Figure 1. The data fits to a linear curve, and the Verdet constant is taken from the slope to be 13.95

rad/(T*m). The glass block has an unknown composition, making it difficult to assess its Verdet constant, but it's consistent with similar materials.[2][1] It should not be taken as optically neutral, since the plot demonstrates a response to magnetization, meaning that it is contributing to the rotation. Accordingly, we repeated the procedure with an empty glass slide to compare to the graph produced by the nickel, as seen in Figure 2. This graph shows that the rotation contributed by the slide is consistent, and can be regularly removed from the signal to isolate the rotation due to the nickel, which is how Figure 3 was produced. Another property of magnetization is apparent with this sample; as the film magnetizes, it will eventually saturate, and stop responding to increases in the field strength. Our analysis accounted for this by taking the linear fit over the range where it wasn't saturated, and that gave us a Verdet constant of $9.03 * 10^5$ rad/(T*m), which, much like the glass, is an acceptable value for a 632.8 nm laser.[1]

Since the calculated constant for nickel is similar to other recorded values at this wavelength, this demonstrates that the system works as expected, and can use the Faraday Effect to measure the magnetization of a material. Something to note, though, is that Figure 1 has a reversed slope when compared to the other two graphs. This is due to the half-wave plate, since it has no obligation to consistently send the polarized components to the same channels. There are multiple orientations where the detector reads equal intensities at the two channels, and the difference between them is what it does with the components. Since the ratio we used to calculate the rotation is only concerned with the sum and difference of the recorded intensities, though, the only effect of this in our experiment is that it changes the calculated direction of the rotation, hence, the reversed slope. It has no effect on the outcome.

5 Conclusion

During this project, we designed a system and procedure that is capable of optically measuring the magnetization of a transparent material. We also tested them with a glass block and Nickel sample, and observed Verdet constants of 13.95 radians per Tesla per meter and $9.03 * 10^5$ radians per Tesla per meter, respectively. These values are similar to other experimental values for these materials, confirming the veracity of the results provided by the procedure. This system can now be adapted as-is into an advanced physics lab, or altered to measure the Magneto-Optical Kerr Effect, a similar phenomenon involving reflected light instead of transmitted light. It uses the same principles and equipment, but requires a significantly different configuration to observe than what we used here.

[1] The material we compared values for was BK-7 glass, which still has a somewhat different Verdet constant. This is likely due to the uncertainty around our sample, and that difference isn't too significant.

References

[1] R.L. Coren, M.H. Francombe. *Optical Faraday effect in ferromagnetic and ferrite films*. Journal de Physique, 1964, 25 (1-2), pp.233-237. 10.1051/jphys:01964002501-2023300. jpa-00205745

[2] Sarita Kumari, Sarbani Chakraborty. *Study of different magneto-optic materials for current sensing applications*. Journal of Sensors and Sensor Systems, 2018, 7, pp.421-431

Figures

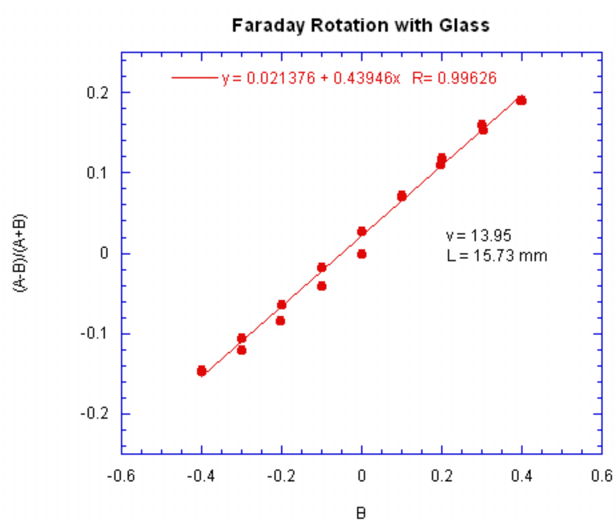

Figure 1: *Plot of the glass block's response to magnetization, depicting the magnetic field, B, versus the rotation.*

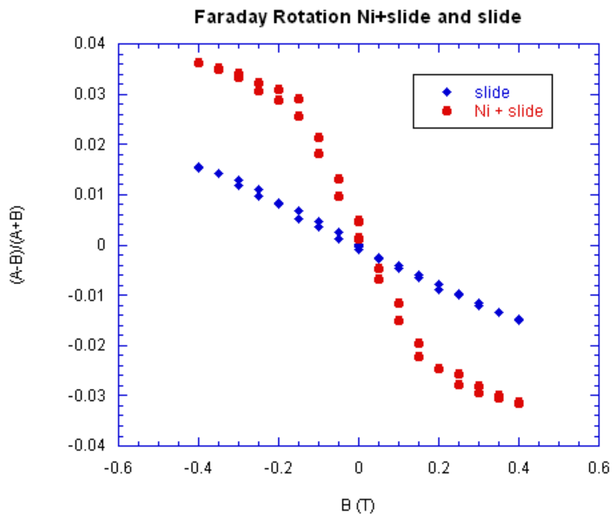

Figure 2: *Plot depicting rotation due to both the slide (in blue) and Nickel (red), in terms of magnetic field versus rotation.*

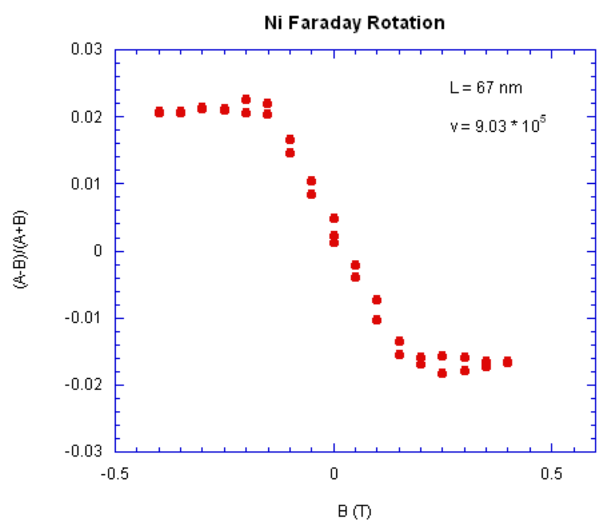

Figure 3: *Plot showing the Nickel film's magnetization individually, in terms of the magnetic field versus the rotation*