Developing a Setup to Study the Magneto-Optic Kerr Effect on Two Dimensional Magnetic Materials

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The goal of my time at the University of Michigan was to help setup a magneto-optic Kerr effect (MOKE) experiment to measure two-dimensional magnetic materials with a pump-probe scheme. I had three tasks for this experiment: to create samples of 2D materials, to align some optics in the MOKE setup, and to automate our data collection process.

1   Background

To understand the Kerr effect (any references to the Kerr effect in this paper refer to MOKE), one must first understand that linearly polarized light is just the superposition of two circularly polarized light waves, right circularly polarized light (RCP) and left circularly polarized light (LCP). If we reflect linearly polarized light off a ferromagnetic material, these circularly polarized waves will develop a phase difference, caused by the different propagation speeds of the circularly polarized light waves in the material. This phase difference causes the polarization plane of the linearly polarized light wave to rotate slightly. This is called the Kerr rotation, and it is caused by Kerr effect. The Kerr ellipticity is also caused by the Kerr effect, which is caused by the different absorption rates of light waves in the material. This affects the ellipticity of the light waves, making them more elliptical in shape [1, 2].

The rotation and ellipticity effects are closely related through the complex Kerr rotation:

$$\phi_K = \theta_K + i\epsilon_K$$

Where ϕ_K is the complex Kerr rotation, θ_K is the real Kerr rotation, and ϵ_K is the Kerr ellipticity. One can find the complex Kerr rotation through the dielectric tensor and optical conductivity tensor. For our situation, we can use the relation

$$\underline{\underline{\epsilon}}(\omega) = 1 + \frac{4\pi i}{\omega}\underline{\underline{\sigma}}(\omega)$$

Where $\underline{\underline{\epsilon}}(\omega)$ is the dielectric tensor, and $\underline{\underline{\sigma}}(\omega)$ is the optical conductivity tensor. When solved for the index of refraction, and the scalar dielectric functions are found, the following relation can be found:

$$\phi_K \approx \frac{\sigma_{xy}}{\sigma_{xx}\sqrt{1 + \left(\frac{4\pi i}{\omega}\right)\sigma_{xx}}}$$

This equation is accurate for angle rotations up to a few degrees [1]. The mathematics of the Kerr effect are not well covered in this paper, as my time researching was spent trying to observe the physical effect, not trying to calculate the specific values. These are just included to provide insight on what the Kerr effect is related to and depends on.
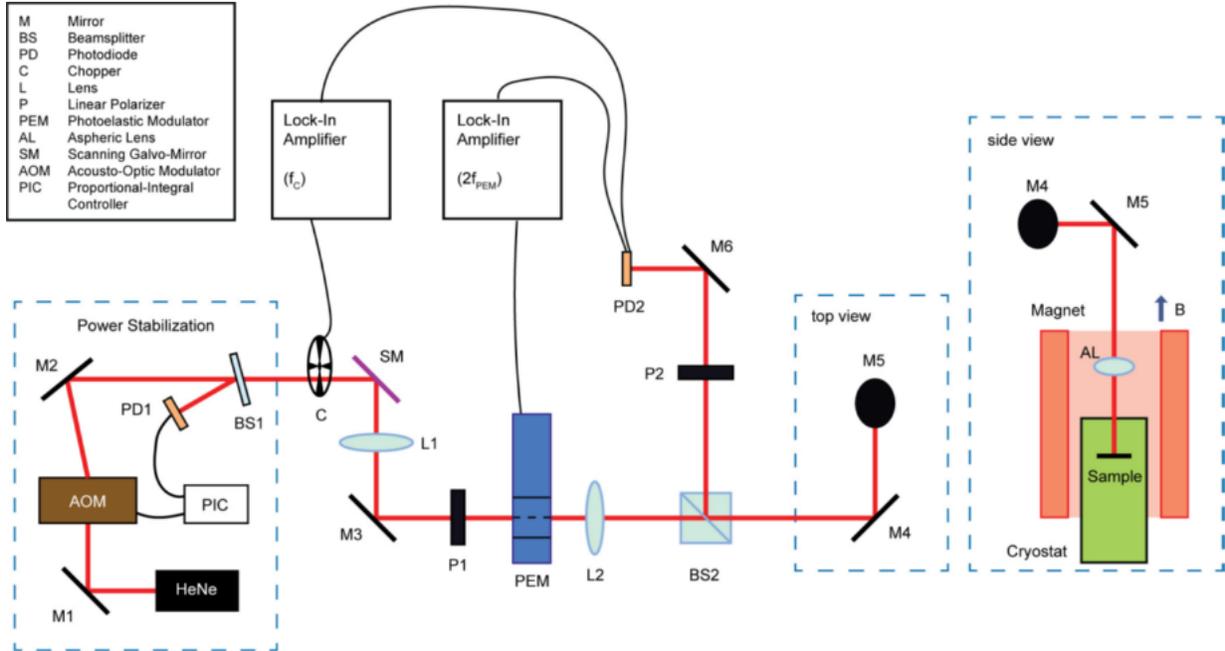

Figure 1. Picture of an experimental setup very similar to our own. [3]

2   Experimental Setup

Figure 1 is a MOKE setup extremely similar to the one the Zhao group is working on.

One major difference is the laser we used in our experiment. We used an ultrafast laser-based pump-probe scheme, while they used a continuous wave laser based static measurement. This pump-probe scheme contains two ultrashort pulses: pump and probe. The pump pulse is a high-energy pulse that will excite the sample we are hitting. Then, the probe pulse will allow us to observe how the sample changed because of the pump pulse.

Moving on to the rest of the setup, the power stabilization portion of the setup will not be covered in this paper, as that was done before the start of the REU program. After power stabilization, we have a chopper connected to a lock-in amplifier. These two devices reduce noise in our laser. Next, our laser passes through a lens and polarizer to get to our photoelastic modulator (PEM). The PEM

alternates our laser light between RCP and LCP light at a high frequency. After our PEM, we will get to our beam splitter (BS). Half of the beam will go through the BS and the other half is reflected downward to a beam block. The half that went through will be focused down right before it hits our sample. We want to hit one of the magnetic domains, as the Kerr effect will be seen only if we hit a uniform magnet. In the future, we want to be able to put our sample in a magnet's magnetic field to produce magnetic domains. However, we are currently relying on cooling the sample to below its Curie temperature, which will cause it to produce magnetic domains. When our laser hits the sample, LCP light and RCP light will be affected differently by the Kerr effect. Small fluctuations in the intensity (10^{-4} – 10^{-6} times the average intensity) of the beam will be seen. Since we are alternating between RCP and LCP with a certain frequency, this fluctuation will be sinusoidal in nature, with the same frequency as our alternating polarization. After we hit our target, our laser is reflected all the way back to the BS, where half of the light will go back through the entire laser setup, and half will be reflected upward. It will then hit a halfway plate (P2), which will put the polarization plane of linearly polarized light at a 45° angle. Circularly polarized light will not be affected by the halfway plate, but since we are alternating between two forms of circularly polarized light, our light will be partially linearly polarized when we do not have purely LCP and RCP light. So, most of the time, our light will be affected by the halfway plate.

This is where our setup and the setup pictured in figure 1 differ. After the halfway plate, our setup will have a Wollaston prism, which will separate the X and Y components of the incoming light into two beams at about a 20° angle. Since our polarization plane is at a 45° angle, our X and Y components will be equal. These beams will then hit our balance detector, which consists of two photodiodes. The detector takes the difference of the light hitting the photodiodes, and outputs it to our lock-in amplifiers. When light doesn't undergo the Kerr effect, the detector will output a zero.

When our light undergoes the Kerr effect, the polarization plane of linearly polarized light rotates slightly. So, our polarization plane will not be at a 45° angle after the half-way plate; it will be slightly off. This causes our X and Y components to become different, and we will see that in the output data of our balance detector. The oscillation of the polarization of our light caused this rotation to have a frequency, and it will be twice that of the oscillation of polarization.

My contribution to this setup was aligning the components after the BS with the help of a graduate student. Additionally, we had to align the Wollaston crystal correctly so the laser hit our balance detector correctly.

3   Cleaning Substrates and Creating 2-D Materials

In order to perform this experiment, we first need to create our targets. This is what I did during a large portion of the first half of the REU.

We first cut our SiO_2 substrates into 1cm by 1cm squares. We then put them into slots of a 3-D printed part pictured in figure 2. This part will go into a beaker, and the beaker will be filled with Acetone. We then place the entire beaker into an ultrasonic bath filled with water. The ultrasonic bath will use high intensity sound waves to dislodge particulates from the substrates. The bath will be run for 8 minutes. Then, we will replace the Acetone with Isopropanol first, then Methanol, and finally distilled water. The substrates are then taken out of the part, dried, and checked to see if they are clean.

Figure 2. Specialized 3-D printed part used for cleaning substrates

Once we have some clean substrates, we can start exfoliating material. The material is placed on a piece of tape, and another piece of tape is used to separate the material into thinner pieces. We try to make an approximate square shape of the material, so our substrates can have as much material on them as possible, and we waste as little material as possible. After the material is sufficiently thin, it is placed on our clean substrate. Air bubbles between the substrate and tape are rubbed out, and rubbing is continued for about 5 minutes, to ensure we have good contact between our material and the substrate. The tape is peeled off, and the sample is put under a microscope to find any potential monolayers.
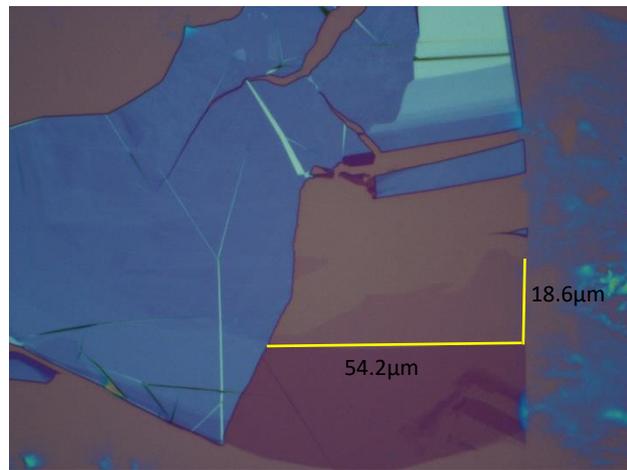

18.6μm

54.2μm

Figure 3. Example of finding 2-D materials

Figure 3 shows an example of some of the material I exfoliated. When looking for monolayers in these samples, one must look for the most transparent material they can find. Near the middle of this picture is a large piece of extremely transparent material. This would be a usable sample for our experiment. Generally, we wanted a monolayer that was at least 10μm by 10μm in size, so we could easily hit it with our laser. The piece pictured is one of the largest I exfoliated. The blue piece to the left of the monolayer is simply a thicker piece of material. To the right, leftover adhesive from the tape can be seen.

4   Data Acquisition

The last project I had this summer was to automate our data acquisition process. Specifically, I wanted to be able to record data automatically from our lock-in amplifier from previously written

code, and I wanted to be able to acquire that data directly on our computer, rather than through a web browser, which is what we had been doing in the past.

There is no prebuilt software that allows you to record data from the lock-in amplifier directly to a computer, but Zurich Instruments, the maker of our lock-in, provide an API that one can use to develop the software we needed. This was my job.

The program that we wanted to call this new code from is in MATLAB, so it was a natural choice to pick the MATLAB API. This software consists of many different function calls, but they are in the same general format:

ziDAQ(command, instance, node [if necessary], value [if necessary])

The command parameter is a string that tells the program what it should do. Some common commands include subscribe, set, get, execute, read, and unsubscribe. The instance is simply an instance of the data module one would want to use.

h = ziDAQ('dataAcquisitionModule');

This statement would mean h is an instance of the data acquisition module. There are other modules, but this is the one I used to collect data. The node is a path to a certain variable that one can access, for instance 'dataAcquisitionModule/device' would let someone access the device variable of the data acquisition module. The path only needs to be specified if the variable needs to be accessed or written to, like with the set and get commands. Lastly, the value parameter is only used with the set command, and it simply changes the value of a specified variable.

The program I created is similar to one of the examples that Zurich Instruments provides. However, I had to edit portions of this code to make it usable for our situation. Collecting the data and outputting this data to csv files was not a trivial task. Eventually, I was able to create a program that can be called from previously written code to start data collection of our lock-in amplifier. This program takes the name of a lock-in amplifier and a time limit as parameters and will record data on the specified lock-in for the specified amount of time. It will then output the data of the subscribed data paths in separate csv files, named according to their data path.

5 Acknowledgements

References

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[3] Huang, Bevin; Clark, Genevieve; *et al*. (2017). *Layer-Dependent Ferromagnetism in a van der Waals Crystal Down to the Monolayer Limit*. Nature: International Journal of Science. 546