

Experiment 18:The Faraday Effect

From PhysicsLab

Introduction

“Impelled by a belief in the unity of the forces in nature, Michael Faraday sought, and in 1845 provided, the first phenomenological evidence for the connection between light and magnetism when he discovered the effect that still bears his name. He found that plane-polarized light, propagating through matter parallel to a static magnetic field, underwent a systematic rotation of its plane of polarization.”

Thus begins an interesting paper by David A. Van Baak on the topic of Faraday rotation in atomic gas. Although carefully studied from the time it was discovered, this remarkable effect was not theoretically understood until the development of quantum mechanics. Many textbooks also discuss this topic.²

Although the effect is typically small, Faraday rotation has found important practical applications. In modern fiber optic telecommunications networks, it is used as the canonical optical isolator.³

This is an extremely important component of such networks since it prevents the multiple propagation of reflected signals. Faraday rotation has important applications in optical modulators as well as uses in analytic apparatus for mixtures of hydrocarbons.

Apparatus

The TeachSpin FR1-A consists of four basic components: the Light Source, the Solenoid (magnetic field source), the Analyzer Polaroid and the Optical Detector. Each one will be described separately.

A. The Light Source

A red laser pointer is used as the light source. It operates at a nominal wavelength of approximately 650 nm with a power output of about 3 mw. A polarizing filter bonded to the laser module increases its polarization to about 95%. The laser requires a voltage regulated supply of 4 volts and 40 mA. Power connections for this are on the BACK of the TeachSpin AALSI-A audio amplifier box. The red banana plug should be connected to the positive terminal post of the supply. Reversing the power supply voltage will destroy the laser. Note: it is important to protect both leads to the laser from an electrostatic shock. Keep the connectors shorted to each other until they are connected to their supply.

The laser beam must be adjusted by the operator to traverse the solenoid along its central axis. This can be accomplished by manipulation of the four nylon thumb screws on the laser mount, while sighting the beam on a white index card, adjusting until it is approximately centered both at the entrance and exit of the solenoid. Do not overtighten the screws. Coarse adjustments, if necessary, can be made by turning the laser mounting post. This usually requires a blade screwdriver to loosen and retighten the post; otherwise the laser mounting box is prone to become loose on top of the post. The beam alignment should be double-checked after a glass rod sample or liquid cell is inserted into the solenoid.

B. Solenoid

The solenoid has the following physical specifications: Length: 150 mm Wire

Size: #18 double insulated DC

Turns/layer: 140

Resistance: 2.6 Ω

Number of Layers: 10

The approximate calibration constant for the unit, measured at the center of the solenoid is:

$$B = (11.1 \text{ mT} / \text{A}) I$$

where I is in amperes and B is in millitesla.

The magnetic field does vary along the axis of the solenoid. Such variation may be significant for certain samples, particularly those that extend outside the coils. The axial magnetic field profile (variation along the length) can be measured using a Hall effect probe, as in the Electromagnetism lab. (In principle, you don't have to.)

The maximum safe continuous current through the solenoid is 3 amperes. The BK Precision power supply can deliver currents from 0 – 3 A. The supply has controls for voltage and current, and will supply a current consistent with the smaller of those two settings, and the solenoid electrical resistance of approximately 2.6 Ohms. In “constant current” (C.C.) mode, the voltage will adjust to maintain a constant current if the coil resistance increases slightly from heating. Care should be taken to assure that the unit does not overheat when operating near the 3 ampere specification.

C. Polarization Analyzer

The unit is equipped with a rotatable Polaroid film (a linear polarizer) in a calibrated mount. The decal is marked in 5 deg increments.

D. Detector

The detector is a silicon photodiode connected in series to one of three resistors; 10K, 3K, 1K. The photodiode is a *current source* and is a linear detector, as long as the voltage across it is less than about 0.3 volt. Saturation is occurring if the voltage exceeds this value, and the detector output will be sublinear. Connecting the photodetector output to a digital voltmeter allows you to measure a voltage which is linearly proportional to the intensity of light landing on the diode active area. (Note: if the intensity is too high, the linear proportionality will fail. Higher intensities require a lower setting of the switchable resistor. **Be sure to keep the detector voltage below 0.3 volt.** This can be accomplished by using the proper load resistor and monitoring the bias voltage. Since the laser diode light source is high intensity, it will be necessary to use the lower values of load resistors for some Faraday rotation experiments.

E. Sample

FRI-A comes with one glass rod sample. Its specifications are:

Diameter: 5 mm

Length: 10 cm

Material: SF - 59

The sample can be removed from the solenoid by first removing the detector and analyzer, and using a long cotton swab as a push-rod. The soft foam rings cushion the rod from hard contact with the solenoid. **The glass rods are extremely fragile, and additional care must be taken not to touch the highly-polished ends of the glass.**

Experiments

A: Malus's Law

With the sample removed from the solenoid, measure the intensity of the light transmitted through two polarizers (one on the laser, the other the analyzer) as a function of the relative angle between them, using a position of maximum intensity as the reference angle. Take several data points between the maximum and minimum intensities. The expectation is that the intensity should vary as $I = I_0 \cos^2(\varphi - \varphi_0)$ (Malus' Law), where φ_0 is the reference angle. Generate a linearized plot of the results, representing intensity I with the measured voltage.

Next, insert the glass rod until it is approximately centered in the solenoid, where the magnetic field will be fairly uniform.

Are there any differences as a result of the light now passing through the rod (before you apply magnetic field)?

B: "DC" measurement of the Verdet Constant.

When current is passed through the solenoid, a magnetic field is created parallel to the propagation direction of the light. The field slightly magnetizes the glass inside the solenoid, and this causes the plane of polarization of the light to turn very slightly as the light propagates through the glass.

The angle of rotation of the polarization axis (in radians) can be described by $\theta = VBl$,

where B is the strength of the magnetic field, l is the length of the rod, and V is called the Verdet constant, it is a parameter specific to the material (and the wavelength of light) which reflects how strongly the light interacts with the magnetization. The units of V given in the literature vary and include radians/millitesla centimeter and degrees/gauss centimeter.

There are several ways the Faraday rotation can be measured. Both of the methods given below should be tried.

Method 1 - Extinction

1. Set the analyzer polarizer at 90deg with respect to the entrance polarizer. This gives maximum extinction of the light to the detector. You can see this by sighting the beam on the white index card.
2. Connect a current regulated supply to the solenoid.
3. Measure the angle of rotation of the analyzer necessary to return to maximum extinction when the solenoid's magnetic field is turned on.
4. Find the rotation angle for a variety of magnetic fields.

Describe what happens when you reverse the direction of the magnetic field?

Does the magnetic field affect the photodiode detector itself?

Method 2- Returning to Fixed Intensity Value

1. Set the analyzer at 45 deg with respect to the entrance polarizer.
2. Repeat the procedure described in Method 1. This time, however, adjust the analyzer angle so that the detector output returns to the value found before the magnetic field is turned on.
3. How does the value of the initial angle affect the results?

By graphing your data and analyzing the results, attempt to determine the Verdet constant from both of these Procedures. Which method is best? Why?

C: "AC" measurement of the Verdet Constant

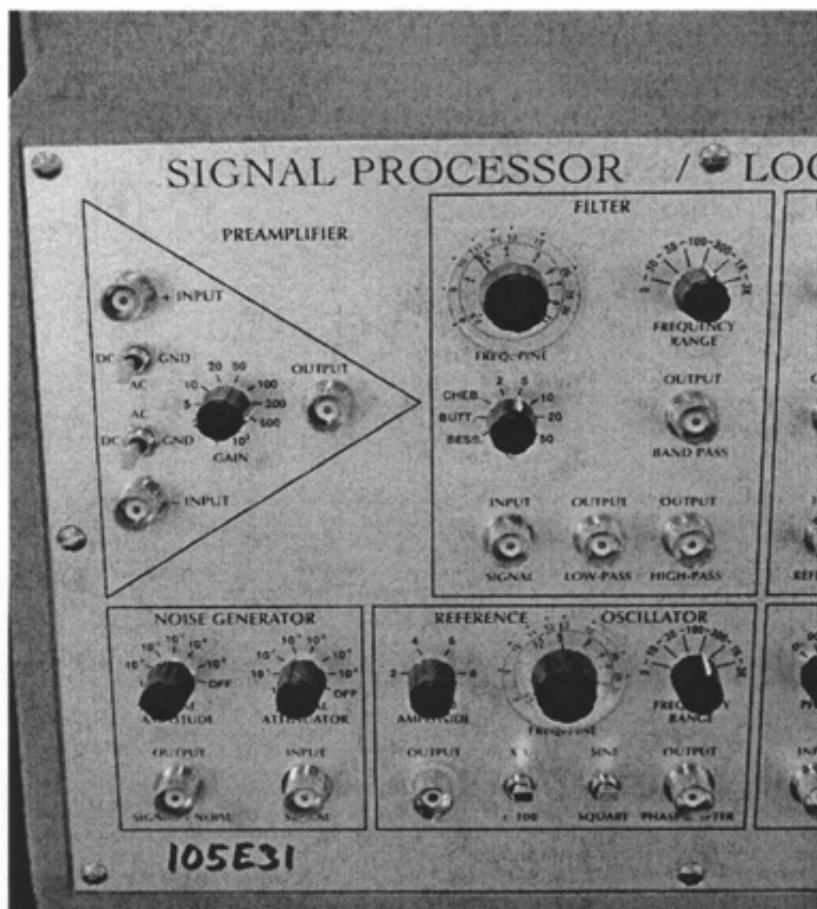
Passing a sinusoidal current through the solenoid should give rise to small oscillation of the intensity detected after the polarizer, at the same frequency as the current. You can try to detect this with the digital voltmeter set to measure "AC" volts, or by looking at the signal on the oscilloscope.

A sine wave for AC magnetic field generation is obtained from the variable amplitude reference oscillator output of the TeachSpin Signal Processor unit (shown in the Figure below). Adjust the amplitude of this wave to approximately 1 Volt peak-to-peak, and use a frequency in the 300 Hz – 1 kHz range. On its own, this oscillator cannot supply much current, so the voltage sine wave must be routed through the TeachSpin Audio Amplifier (use the AC input), which then drives the solenoid. Start with the attenuator setting of the Audio Amplifier at "1", corresponding to maximum gain. You can use one of the "BNC to banana" adapter cables to monitor the voltage across the solenoid using one of the channels of the oscilloscope. Ensure that the amplitude is not so high that the shape of the waveform coming out of the amplifier becomes distorted.

The Faraday effect will give rise to a small AC variation in the plane of polarization of the light transmitted from the glass rod, which will be manifested as an AC variation in the intensity transmitted by the analyzer polarizer. This AC amplitude will also change with the orientation of the analyzer polarizer. Investigate this dependence by measuring the AC Faraday signal for different angular positions of the analyzer polarizer.

The preamplifier and filter modules of the Signal Processor can be used to improve detection of the small AC Faraday signal. Set the gain of the preamplifier to 10 and connect the photodiode output to the "+" input, with the three-position switch at its middle position (AC coupling). Compare the output of the preamp to the previous reading with the AC voltmeter, and also look at it on the oscilloscope.

The amplifier makes the signal easier to detect, by increasing its amplitude relative to



the minimum voltage resolutions of the meter and the scope. In addition to the signal of interest, however, there is also noise on the output of the photodiode, from stray light and other sources. The preamp amplifies this noise just as much as it increases the signal. Since the signal frequency is known, however, you can selectively remove some of the noise from the measurement by passing the preamplifier output through a bandpass filter, in the filter module of the Signal Processor.

Figure 1. The TeachSpin Signal Processor front panel. The Reference Oscillator, Preamplifier, and Filter modules are used in Part C of this experiment.

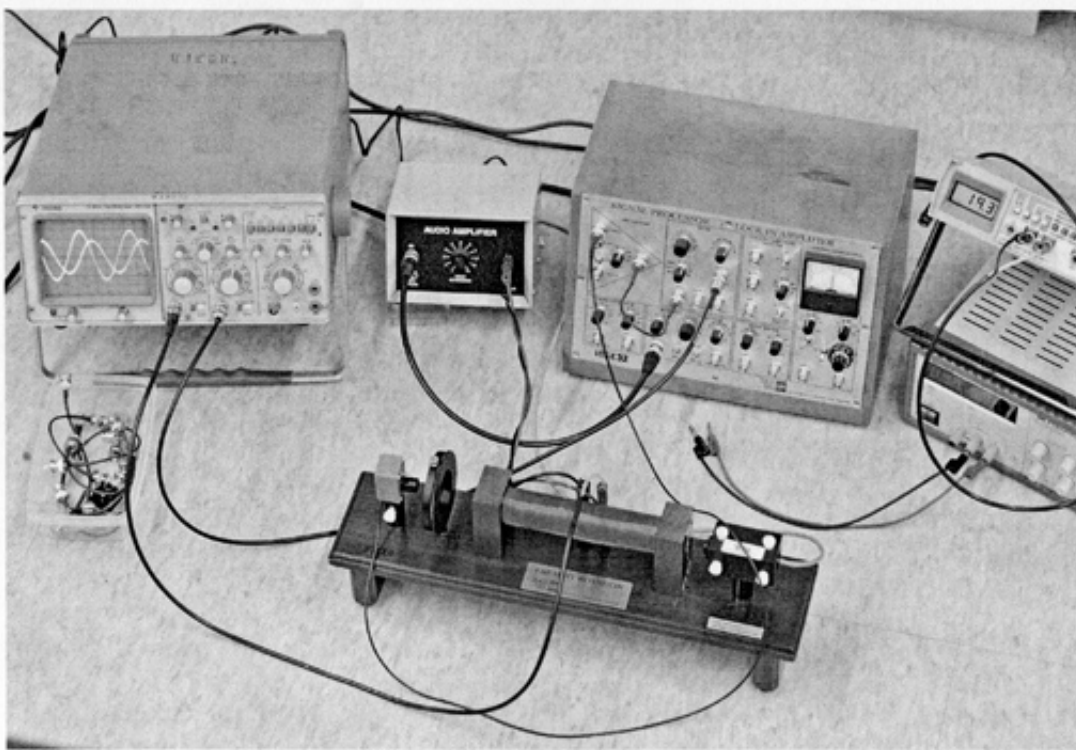


Figure 2. Configuration of the AC measurement of the Faraday Effect. Here, the photodiode signal passes through the preamplifier and the bandpass filter, and is monitored on the oscilloscope (smaller trace). Channel 1 of the scope is looking at the voltage across the solenoid. The Faraday signal amplitude can also be measured by the Fluke meter set to read AC volts.

It is important to check for any “background” contributions to the signal that are unrelated to the Faraday effect, such as electrical crosstalk, by blocking the laser beam (you can use the index card) and seeing if the signal vanishes or not. Also perform a test by running the AC current amplitude in the solenoid to zero by dialing the Audio Amplifier attenuator knob to “0”. Does the measured AC amplitude go to zero?

Estimate the Verdet constant from the AC Faraday data.

Question: Show that the amplitude of the AC Faraday signal should be proportional to the slope of an intensity – versus – polarizer angle curve (Malus’s law curve, as in Part A, but with the max. intensity adjusted to account for the presence of the rod.)

- Acknowledgement

This write-up was developed starting from the Faraday Effect experiment manual of Teachspin, Inc., written by J.F.

References

1. D.A. Van Baak, "Resonant Faraday rotation as a probe of atomic dispersion." Am. J. Phys. 64 (6), June, 1996. This paper has an excellent set of references for both the historical story of this discovery and modern practical applications of the effect. The paper also contains references to student experiments and theoretical papers analyzing this phenomenon.

2. Eugene Hecht, "Optics," Addison-Wesley (Fourth Edition).

3. See, for example, www.integratedphotonics.com

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