FARADAY ROTATION

Instructor's Guide to TeachSpin's FR1-A Apparatus

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I. 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.[1] Although carefully studied from the time it was discovered, this remarkable effect was not theoretically understood until the development of quantum mechanics. References in Van Baak's paper provide some insight into current efforts both experimentally and theoretically, even for nonlinear optics. Many textbooks also discuss this topic.[2]

Although the effect is typically small, Faraday rotation has found important practical applications. In modern fiber optic communications 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.

We strongly urge the instructor to make use of these references. Copies of two American Journal of Physics articles have been included in this manual to facilitate student exploration of the literature on the Faraday effect. Although it is an important effect, it is frequently omitted in the standard courses in E&M and Optics in both the undergraduate and graduate physics and engineering curriculum.

TeachSpin originally thought of this apparatus in connection with our teaching Signal Processor/Lock-In Amplifier. It seemed to us that the Faraday effect was an ideal experiment to show both interesting physics and the power of lock-in detection for extracting weak signals from background noise. It was with this in mind that we designed FR1-A. However, in the direct DC mode, the unit can certainly be used without lock-in detection. It must be noted that this unit comes with only one monochromatic light source, a laser pointer with a wavelength of about 650 nm. Instructors who want the student to explore the interesting frequency dependence of the effect will have to supply their own polarized light sources at other wave lengths. The Polaroid film analyzer has a useful polarizing capability from 400 to 800 nm. Since the Faraday effect is a slowly varying function of wavelength, the intensity stability of the light source is more important than its frequency stability. The diode laser is an ideal source for these measurements.

II. APPARATUS

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. Although the output is approximately 60% polarized, the laser light is directed through a polarizing filter which increases its polarization to about 95%. Since this filter is not permanently bonded to the laser, it is important to adjust its rotation position to achieve maximum power output of the light source. This will occur when the polarization axis of the laser corresponds to that of the filter. This can easily be adjusted visually by inserting a white card at the entrance to the solenoid.

The laser requires a voltage regulated supply of 4 volts and 40 mA. *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. TeachSpin's audio amplifier unit AALS1-A has a voltage regulated (4V) supply output specifically designed for this laser diode light source.

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 using a white card both at the entrance and exit of the solenoid. The sample glass rod, or other samples, should be removed from the solenoid during the alignment procedure. After alignment, the sample can be reinserted into the solenoid.

B. Solenoid

The solenoid has the following physical specifications:

Length: 150 mm	Wire Size: #18 double insulated
Turns/layer: 140	DC Resistance: 2.6 Ω
Number of Layers: 10	

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

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

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 which extend outside the coils. We recommend that the students measure the axial magnetic field profile using TeachSpin's Hall Effect Probe HE1-A, or other equivalent field measuring apparatus.

The maximum continuous current through the unit is 3 amperes. For times of the order of 30 seconds, however, 10 amperes can be used without damaging the solenoid or its supports. **Extreme care** should be taken to assure that the unit does not overheat when exceeding the 3 A specification.

Since Faraday rotation measurements can easily be performed in 10-15 seconds by a student familiar with the equipment, it is possible to use these larger solenoid currents and thus obtain larger rotations.

C. Analyzer Polaroid

The unit is equipped with a rotatable Polaroid film in a calibrated mount. The decal is · marked in 5° increments. This limits the accuracy of an angular measurement to about 2°. This is a conservative estimate. Some students may claim 1° set-ability. You be the judge.

D. Detector

The detector is simply a photodiode connected in series to one of three resistors; 10K, 3K, 1K. The photodiode is a *current source* and is a linear photonic detector, as long as the voltage across it is less than about 0.3 volt. Saturation begins to occur when this bias voltage appears across the diode. This makes the detector nonlinear.

It is wise to work at bias voltages well below the 0.3 volt value. 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

FR1-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, analyzer and light source. This gives the experimenter unrestricted access to the solenoid's bore. Care should be taken not to damage the end of the glass sample. They are highly polished. Any push-rod should have a soft end covered by optical tissue or its equivalent.

III: EXPERIMENTS

A. Malus's Law

With the sample removed from the solenoid, students can measure the intensity of the transmitted light through two polarizers (one on the laser, the other the analyzer) as a function of the relative angle between them. They should also derive a simple theoretical calculation of this "law."

Be Careful!! This is a simple experiment, but one must not saturate the diode detector. Use the correct load resistor.

B. Measure the Verdet Constant, v, DC.[4]

The Verdet constant is defined by the relationship:
$$\theta = vB\ell$$
where B is the strength of the magnetic field in millitesla, ℓ is the length in centimeters and θ, in radians, is the angle of rotation of the axis of the polarization after passing through the medium in the magnetic field. The units of v are then: radians/millitesla centimeter. These are by no means universal units. The units given in the literature vary and include degrees/gauss centimeter.

First, you may wish to independently measure the magnetic field inside the solenoid rather than using the B = 11.1I calibration we have supplied. The field inside is not constant along the entire length. It drops off to about half the maximum value at the ends. TeachSpin's HE1-A Hall Effect Probe is an ideal instrument to measure this axial field, but other Hall sensor probes will also do the job. Such a calibration will allow the student to make corrections to their determination of the Verdet constant.

Place the 10 cm glass rod inside the solenoid, supporting it on the foam rubber sleeves. Make sure it is located in the center. Using any white surface (a business card will do) align the laser beam so that the light enters and exits along the center axis of the solenoid. It is important that this be done carefully so that the entire laser beam passes through the glass rod.

Now there are several ways the Faraday rotation can be measured. Both of the methods given below should be tried by the students so that they can explain which one is more accurate and why.

1. Method 1 – Extinction
   a. Set the analyzer polarizer at 90° with respect to the entrance polarizer. This gives maximum extinction of the light to the detector.
   b. Connect a current regulated supply to the solenoid.
   c. Measure the angle of rotation of the analyzer necessary to return to maximum extinction when the solenoid's magnetic field is turned on.
   d. 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?

2. Method 2 – Returning to Fixed Intensity Value
   a. Set the analyzer at 45° with respect to the entrance polarizer.
   b. 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.
   c. How does the value of the initial angle affect the results?

It should be straightforward to determine the Verdet constant from either of these measurements. Which method is best? Why?

C. Measure the Verdet Constant AC[5]

A more accurate and more sensitive method of determining Verdet constants uses lock-in detection and ac magnetic fields. TeachSpin originally developed FR1-A to accompany its teaching Signal Processor/Lock-In Amplifiers (SPLIA1-A) since Faraday rotation was a good example of a "small" physical effect that can easily be measured with lock-in detection techniques. This was also independently realized by Jain etc. all who have written an excellent article on how this measurement is carried out. We have enclosed a copy of their American Journal of Physics article for your convenience.

Lock-In detection affords some additional possibilities for the student.
   1. The relative angle at which to set the polarizer to obtain the maximum signal is easily determined.
   2. The relative phase angle of the ac signal as a function of Polaroid angle can be examined.
   3. The student develops an understanding of the process of obtaining an absolute measurement of v from these ac measurements.

D. Measurements of Verdet Constants in Liquids

The ac lock-in detection method allows one to detect extremely small Faraday rotations and thus small Verdet constants without using extremely large magnetic fields. Various liquids exhibit the Faraday effect and their constants can be measured with this apparatus. A glass cell with flat optical ends and a filling tube at one end will hold an appropriate liquid sample. With such a sample holder, however, the liquid will not all be in the same magnetic field. Part of the sample will even be outside the solenoid.

This presents an interesting challenge for the student's determination of the Verdet constant. It requires that the axial field profile be measured first, and a simple computer program or hand held calculator algorithm be developed to extract v from the measurements. This can easily be done since the Faraday effect is a linear function of the magnetic field.

IV. 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. Alan Portis, "Electromagnetic Fields," Wiley, pp 467 – 474.
    Eugene Hecht, "Optics," Addison-Wesley (Third Edition), p 862.

3. Electro-Optics Technologies, Inc. www.eotech.com

4. Frank J. Loeffler, "A Faraday rotation experiment for undergraduate physics laboratory." Am. J. Phys. 51 (7) July, 1983.

5. Aloke Jain et. al., "A simple experiment for determining Verdet constants using alternating current magnetic fields." Am. J. Phys. 67 (8) August, 1999.