



ASTRONOMY
CENTRE FOR
EDUCATORS

FARADAY ROTATION

Jameer Manur

Astronomy Centre for Educators,
Inter-University Centre for Astronomy and
Astrophysics

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Keywords: Faraday rotation, Verdet constant, State of Polarization, Malus's law

Level and stream: UG/PG (Science, Engineering)

Prerequisites: Basics of polarisation and polarised light, Magneto-optical effect

Learning objective:

Understanding of Opto-magnetic effect, Verdet constant, understanding Malus Law

Materials:

Laser, Polarizers, Solenoid, Power supply, Photometer, CRO, Digital multimeter

1 | Introduction

1.1 | Historical background

In 1845, Michel Faraday discovered that when the polarised light passed through a medium in the presence of an external magnetic field parallel to the direction of propagation of light and material, the plane of linear polarisation rotates. This effect causing change in the plane of linear polarization is called the Faraday Rotation effect, also known as the Opto-magnetic effect. This was the first evidence showing light's interaction with the magnetic field.

Polarization state of light can be expressed as a coherent superposition of left-hand circular polarisation (LCP; clock-wise) and right-hand circular polarisation (RCP; counter-clock-wise) components of the electromagnetic field. When polarised light passes through a (Faraday) material in presence of (an external) magnetic field, the RCP and LCP components experience different refractive indices, resulting in an additional relative phase difference (say, $\Delta\eta$) between the electromagnetic fields associated with the two circular polarization components. This in turn manifests in rotation of the plane of linear polarization by an angle (θ), where $\theta = \Delta\eta/2$. The amount of rotation of the plane of polarization depends on the magnetic field (B), length of the (Faraday) material (L), and the Verdet constant (V), which is a material property and gives a qualitative measure of Faraday rotation ability of the material. The equation below combines how the amount of Faraday rotation depends on the above mentioned parameters.

$$\theta = VBL$$

Where, θ is in radian, V (Verdet constant) is in radians/T/m L is in meter)

1.2 | Aims and Objectives

This experiment aims to study the Faraday rotation effect and examine its dependence on the magnetic field, the Verdet constant of the material and the path length of the Faraday material.

In astronomy Faraday rotation is used to study the magnetic fields present in the various celestial objects. By measuring the Faraday rotation at different frequencies one get to know the strength and structure of the magnetic fields and study the role in various astrophysical processes.

Observationally, Faraday rotation can be studied using a technique called polarimetry. By measuring the polarization properties of electromagnetic waves at different wavelengths, astronomers can determine the amount of rotation and infer the properties of the magnetic fields. Radio observations, in particular, are well-suited for studying Faraday rotation due to their long wavelengths, which results in a larger rotation effect compared to optical wavelengths.

2 | Experiment setup

We use a red laser (532 nm) as a polarized light source. Even a 5 mW power laser, which is readily available in market, is intense enough for this experiment. To ensure that the light is completely linearly polarized, we insert a polarizer just after the laser. The solenoid is to be placed next to the polarized light source and a Faraday Material is to be placed inside, so as to be in the path of the light. The axis of the material, typically of cylindrical shape, is thus aligned with the direction of propagation of the light. Another polarizer is to be kept in the light path after the solenoid, where it can be rotated, and which acts as an analyzer. The analyzer is rotated systematically about the light path, to realize different orientations of the optical axis, and intensity of the light emerging from the analyzer is measured as a function of the analyzer rotation angle.

2.1 | Measuring magnetic field

One must measure the magnetic field accurately inside the solenoid. One can measure the magnetic field using the Gaussmeter in the lab. In case of non-availability of it, we can theoretically estimate the magnetic field inside the solenoid as a current function. And also, one can design the solenoid using the parameters given below.

$$B = \mu_0 NI/L$$

Where B is magnetic field in Gauss, μ_0 is vacuum permeability has value $4\pi \times 10^{-7}$ Henry/meter, N is the number of turn on the solenoid, I is current in Ampere and L is length of solenoid in cm.

The magnetic field inside a solenoid is obtained simply by applying Ampere's law using the above equation.

Here, B is the magnetic field, μ_0 is the material's permeability, N is the number of turns, I is the current applied, and L is the length of the solenoid. A simple solenoid can be designed and fabricated in lab using an enamel insulated copper wire (18 gauge) and using non-metal material on which it can be wound, as shown in the picture below. Here, a plastic pipe (15 mm) and wooden materials are used as a non-conducting support to construct the solenoid, which can sustain up to 4 amp current and generate magnetic field strengths of 200-300 gauss.

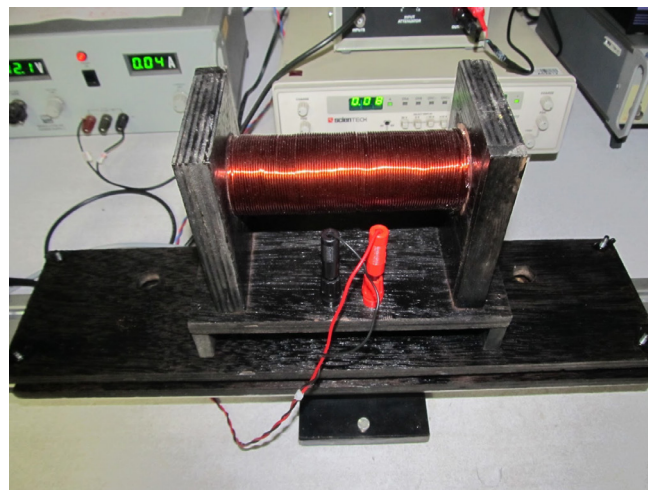


Figure 2.1: Solenoid used in Faraday Rotaton experiment

2.2 | Faraday Material

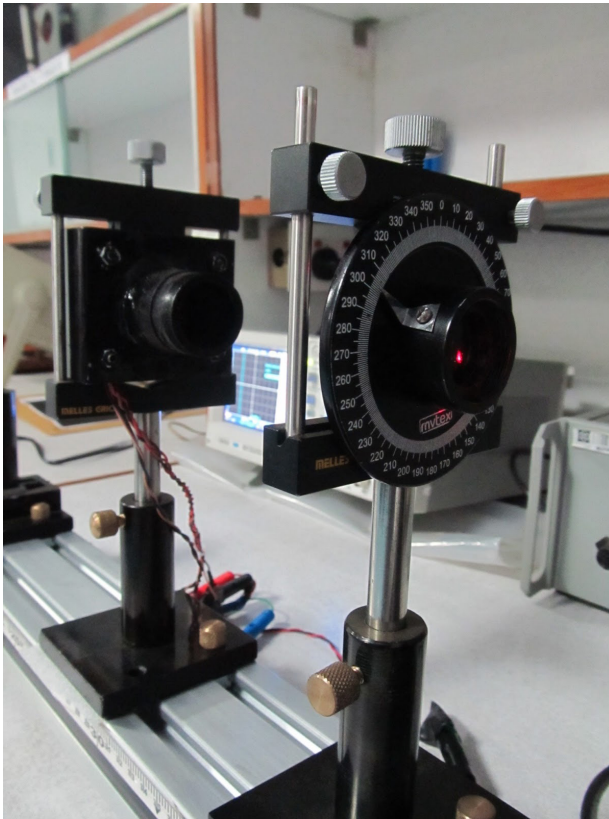


Figure 2.2.1: Polarizer with rotating scale holder

The Faraday material is one of the important component in this experiment. While selecting the Faraday material, one needs information on its Verdet constant. The Faraday material needs to be placed at the centre of the solenoid, particularly in the region where the generated magnetic field in the direction of light propagation is adequately large and uniform. Among suitable materials, such as Distilled Water, SF-59 (Lead Silicate glass), Benzene, TGG (Terbium Gallium Garnet), etc., the TGG crystal has highest Verdet constant.

- Polarizers

We need two polarizers in this experiment. One is on the source side which converts light to very close to 100% linearly polarized light. The second polarizer, which acts as the analyzer, is to be used on the detector side, where we can rotate it for measuring light intensity at a different angles of its rotation. Polarizers and rotatory holders for them, as shown in the image below, are readily available in market.

- Photodetector

One needs a good photodetector to accurately measure small changes in the intensity of the light. There are a lot of good photodetectors along with amplifiers available nowadays in the market one can buy that or else one can design the complete photometer using good photodetector. The output can be connected to the voltmeter or any other measuring device.

- Hardware/equipment required

1. Laser light (532/650 nm, 5mw)
2. Solenoid
3. Faraday material (such as TGG, SF59), in form and shape suitable for placement inside the solenoid
4. Polarizers
5. Photodetector
6. Multimeter
7. CRO
8. DC-Power supply

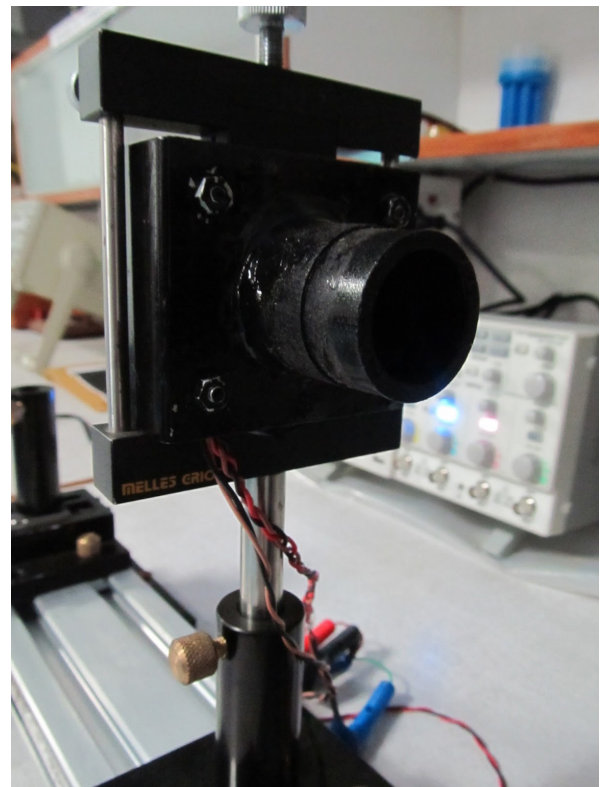


Figure 2.2.2: Photometer

- Software requirement

Any software which can plot the graphs eg, Matlab/origin/Excel/python

- Verdet constant

The Verdet constant is an optical constant that describes the strength of the Faraday Effect for a particular material. It is a proportionality constant between the angle of rotation and the product of the magnetic field and path length through the sample. The Verdet constant for most materials is extremely small and is wavelength-dependent. It is strongest in substances containing paramagnetic ions, such as terbium. The highest Verdet constants are found in terbium-doped dense flint glasses or in terbium gallium garnet crystals (TGG).

2.3 | Malus's law verification: Measurements using Malus's law

When the optical axes of polarizer and analyzer match, and if the light from the former passes directly to the latter, the intensity of the emerging light would be highest, say I_0 . When the relative angle between the optical axes of polarizer and analyzer is ' ϕ ', noting that intensity is proportional to the square of the field amplitude, the transmitted intensity (I) will vary as,

$$I = I_0 \cos^2 \phi$$

$$I = I_0 (1 + \cos(2\phi)) / 2$$

When we measure the transmitted intensities as a function of the analyzer rotation (across the range of 360 degrees), we thus expect to see two cycles of sinusoidal variation. Such measurements are to be made in two cases separately, that is with and without a magnetic field. In the presence of a magnetic field, the incident plane of polarization of light undergoes Faraday rotation (by an angle θ), so the whole Malus curve will be seen to be shifted by the same angle. Hence, the amount of Faraday rotation can be estimated from the relative shift of the Malus curve across the angle coordinate.

2.4 | Procedure

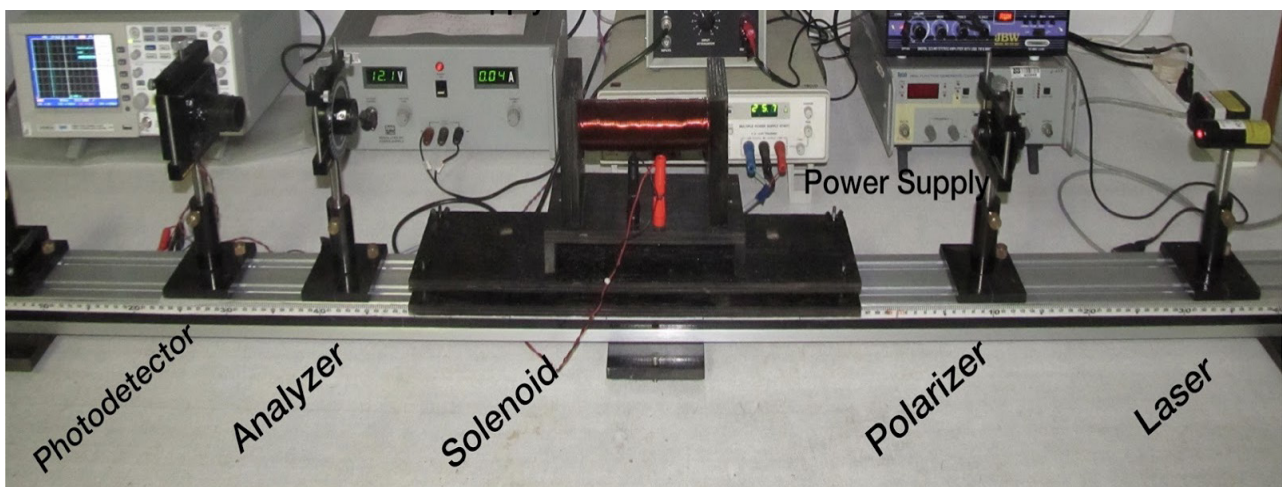


Figure 2.4.1: Faraday Rotation set-up with all equipments

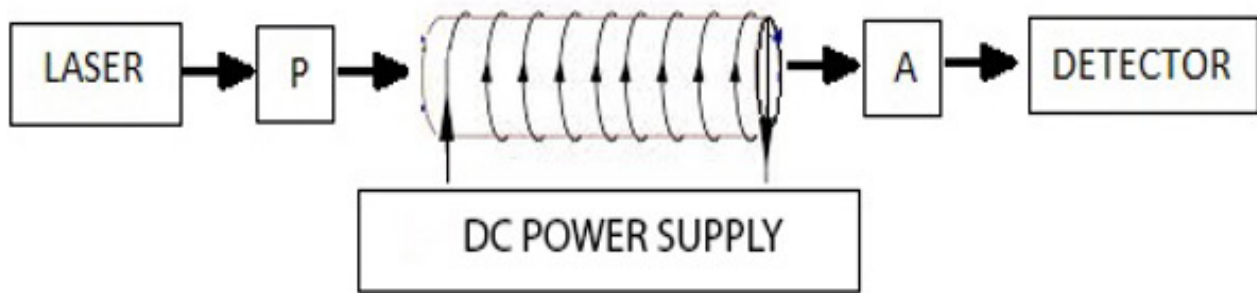


Figure 2.4.2: Block diagram of the Faraday Rotation experiment

- The procedure and steps of the experiment are as follows.
1. Turn on the laser light and pass it through the polarizer to convert it into ~100% linearly polarized light.
 2. Keep the Faraday material inside and at the centre of the solenoid where the magnetic field is uniform.
 3. Apply the DC current to the solenoid to generate the magnetic field.
 4. Apply the appropriate current to the solenoid such that it should not heat up or exceed the current level of the coil.
 5. Calculate the amount of magnetic field after applying the current by using the parameter and specification of the solenoid.
 6. Keep the analyzer optical axis at an angle such that you get the maximum light at the output and mark it as a polarization axis without applying a magnetic field.
 7. Measure the maximum and minimum voltage that would be observed when the analyzer is rotated, and set the gain of the photodetector suitably for a desired output range.
 8. Measure the output voltage for one complete rotation of the analyzer at every interval of 5 or 10-degree angle.
 9. Observe the minima and maxima output on the measuring devices.
 10. Now apply the magnetic field and measure the output voltage for one complete rotation and observe the change in the angle in the state of polarization.
 11. Plot both graphs with and without a magnetic field, measure the angle θ and verify the Verdet constant of the material.

3 | Observations

Take observation first without a magnetic field at every small angle possible, say 5-10 degrees for 360 degrees. Then take observation with a magnetic field for 360 degrees, plot the graph voltage vs angle and see the shift in the angle graphically.

Sr. No.	Angle (θ)	Voltage (Without magnetic field)	Voltage (With magnetic field)
1	0		
2	10		
3	20		
4	30		
5	40		
6	50		
7	60		
8	70		
9	.		
.	.		
.	.		

4 | Results

After taking observations, plot the graph, and measure the shift in the angle on the graph. Substitute an average value with the formula, calculate the Verdet constant of the material, and verify Malus law.

$$\theta = VBL$$

$$V = \theta/BL$$

Where, B is the magnetic flux measured in Gauss L is the length of the Faraday material or crystal. The magnetic field can be calculated using the given formula and substitute the value on the above equation

$$B = \mu_0 NI/L$$

Where, I is the applied current to the solenoid, N is the number of turns in the solenoid, and L is the length of the solenoid.

Verify the Verdet constant of the material with the predicted value and error while experimenting. The graph plotted below is an example of the observations. Where the blue colour graph line is without applying a magnetic field and the red colour graph line is with the magnetic field. It is very clear that the state of polarization is shifted by some angle after applying the magnetic field. For SF59 crystal it

shifted was by around 2 degree and for TGG crystal it was around 4 degree at around 150 Gauss of magnetic field.

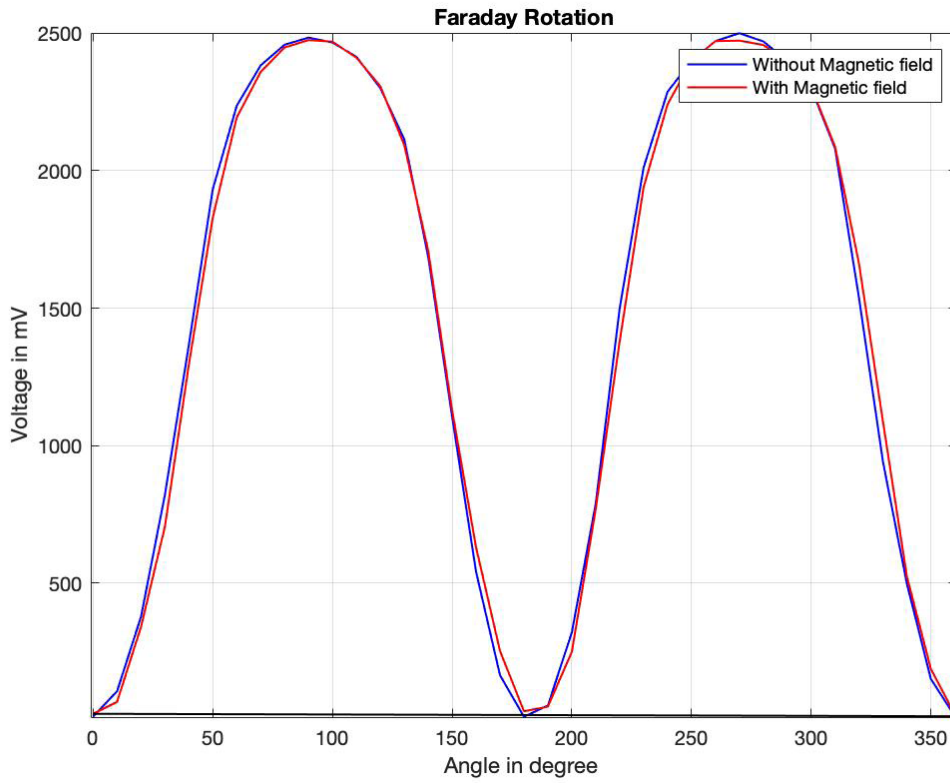


Figure 4.1: A sample result shows plot with and without magnetic field

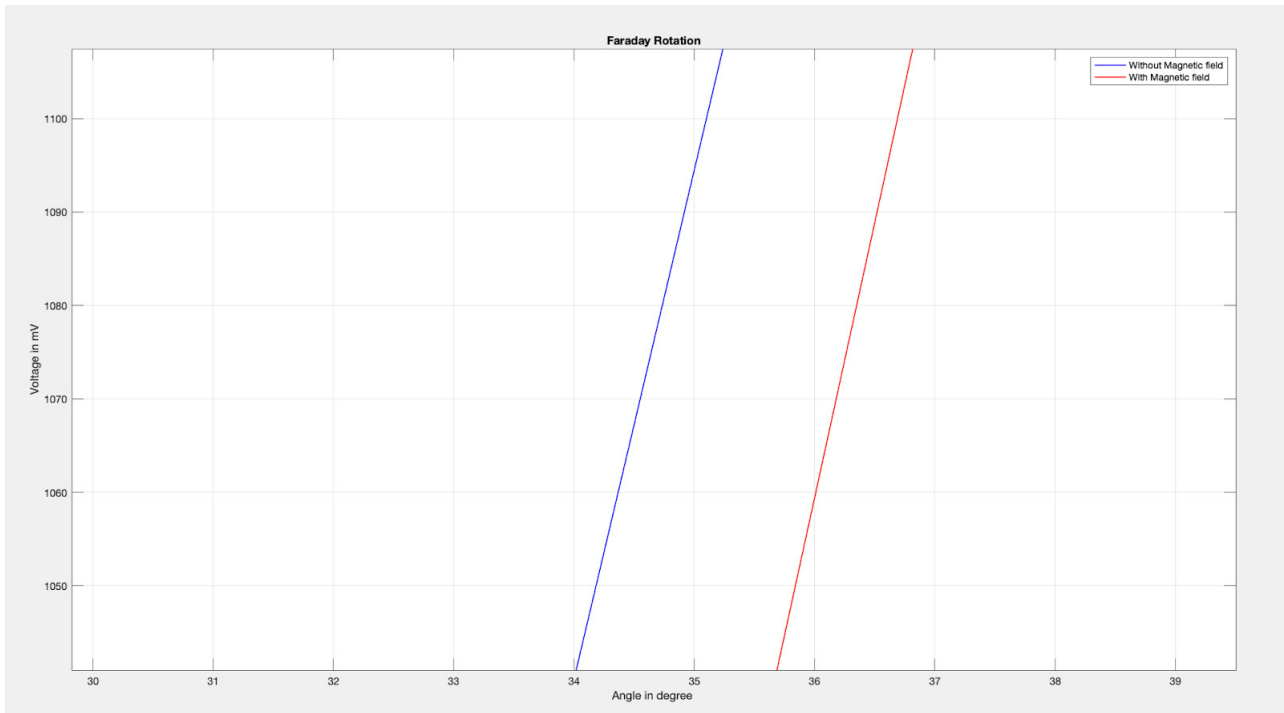


Figure 4.2: Zoom in view of shift in the polarization angle after applying magnetic field

5 | Cost of the Experiment

One can design the experiment in the lab after buying the required components from the sources. Many scientific instrument manufacturers have designed this experiment, and one can buy from them.

Laser: 3000 INR

Polarizers: 3000 INR

Solenoid: 3000 INR

Photodetector: 3000 INR

SF59 crystal: 1000 INR

Total ~ 15000 INR

One can buy the experiment setup from the following vendors directly or can design at the lab.

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6 | References

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7 | Acknowledgements

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