Faraday Rotation Observed in Various Materials

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Abstract

The Faraday effect is a magneto-optical phenomenon in which the plane of polarization of linearly polarized light is rotated as the light passes through a material subjected to a magnetic field parallel to its direction of propagation. By measuring the intensity of light transmitted through a magnetized medium, this rotation can be quantified and used to determine the Verdet constant, a material-dependent proportionality constant that characterizes the strength of the effect.

In this experiment, the Verdet constants of three unknown glass samples (labeled SF58, BK7, and 1.036) were determined for three wavelengths of light (red, yellow, and blue). The procedure involved first establishing a Malus's Law baseline for each wavelength, then applying magnetic fields of varying strength along the optical axis and recording the resulting intensity changes using a photodiode detector. The measured Faraday rotation angles were found to vary linearly with the magnetic field, confirming the expected relation $\phi = VBd$, where ϕ is the rotation angle, B is the magnetic field, d is the optical path length, and V is the Verdet constant.

1 Introduction

The Faraday effect, first observed by Michael Faraday in 1845, is a magneto-optical phenomenon in which the plane of polarization of linearly polarized light is rotated as it propagates through a material subjected to a magnetic field parallel to the light's direction of travel. The transmitted light remains plane-polarized, but its polarization axis is rotated by an angle proportional to both the magnetic field strength and the optical path length within the material.

This relationship is expressed by Becquerel's formula:

$$\phi = VBd, \tag{1}$$

where ϕ is the angle of rotation, B is the component of the magnetic field along the light's propagation direction, d is the optical path length, and V is the Verdet constant. The Verdet constant is a material-dependent proportionality factor that varies with wavelength and temperature and is closely related to the dispersion of the refractive index $n(\lambda)$ through

$$V = -\frac{e}{2mc}\,\lambda\,\frac{dn}{d\lambda}, \tag{2}$$

where e/m is the charge-to-mass ratio of the electron and c is the speed of light. Materials with strong dispersion, such as flint glass, exhibit larger Verdet constants.

The Faraday effect is distinct from optical activity. In optically active materials, such as sugar solutions, the rotation is reciprocal: reversing the direction of light propagation produces the same sense of rotation. In contrast, the Faraday effect is nonreciprocal—reversing the direction of either the magnetic field or the light reverses the direction of rotation, but not both simultaneously. This property makes the effect useful in devices such as optical isolators, which prevent feedback into laser cavities by allowing transmission in one direction only.

The objective of this experiment is to measure the Verdet constants of three glass samples—designated SF58, BK7, and 1.036—at three wavelengths corresponding to red (6500 Å), yellow (5490 Å), and blue (4495 Å) light. By establishing a Malus's Law baseline at zero magnetic field and then recording intensity variations under applied fields of both polarities, we extract the Faraday rotation angles and verify their linear dependence on magnetic field strength.

2 Materials and Methods

2.1 Apparatus Overview

The experimental setup consisted of five main components: a light source, a pair of polarizers, an electromagnet, optical samples, and a photodiode detector. Each component was aligned along a common optical axis forming a continuous light tunnel through which the polarized beam passed.

1. **Light Source:** A high-intensity tungsten lamp was used as the source of unpolarized light. Narrow-band interference filters were inserted in front of the lamp to isolate red (6500 Å), yellow (5490 Å), and blue (4495 Å) wavelengths. The lamp position was fixed with tape marks to maintain alignment throughout the experiment, and a two-inch air gap was maintained between the bulb and filters to prevent thermal damage.

2. **Polarizer and Analyzer:** Two Polaroid sheets served as the polarizer and analyzer. The polarizer fixed the plane of incident polarization, while the analyzer was rotated to measure transmitted intensity as a function of angle. Because the polarizer's rotation mechanism was damaged, it remained fixed and the analyzer was rotated relative to it.

3. **Electromagnet:** The samples were placed in the gap between the poles of an Atomic Labs model 0028 electromagnet, powered by a Cenco 50 V, 5 A DC supply. The magnetic field was varied by adjusting the supply voltage and measured using a calibrated Hall probe. Fields up to approximately 360 mT were achieved. Extreme caution was taken to reduce risk of arcing: the voltage was always returned to zero before switching polarity or powering off.

4. **Samples:** Three optical glass samples were examined, labeled SF58 (thickness 1.272 cm), BK7 (1.000 cm), and 1.036 (1.036 cm). Each sample was mounted securely in the magnet gap, forming a continuous optical path through the system.

5. **Photodiode Detector:** A silicon photodiode was positioned at the output end of the optical axis to measure transmitted light intensity. The photodiode volt-

age output was read using an HP 34401 digital multimeter, which provided more consistent and accurate readings than visual detection.

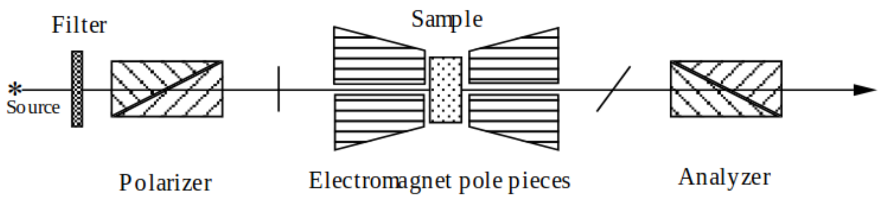

Figure 1: Experimental setup for observing Faraday rotation. Light from a broadband source passes through a color filter and a polarizer before entering the sample placed between the electromagnet pole pieces. The transmitted beam exits through the analyzer and is detected by a photodiode. The magnetic field is applied parallel to the light's propagation direction.

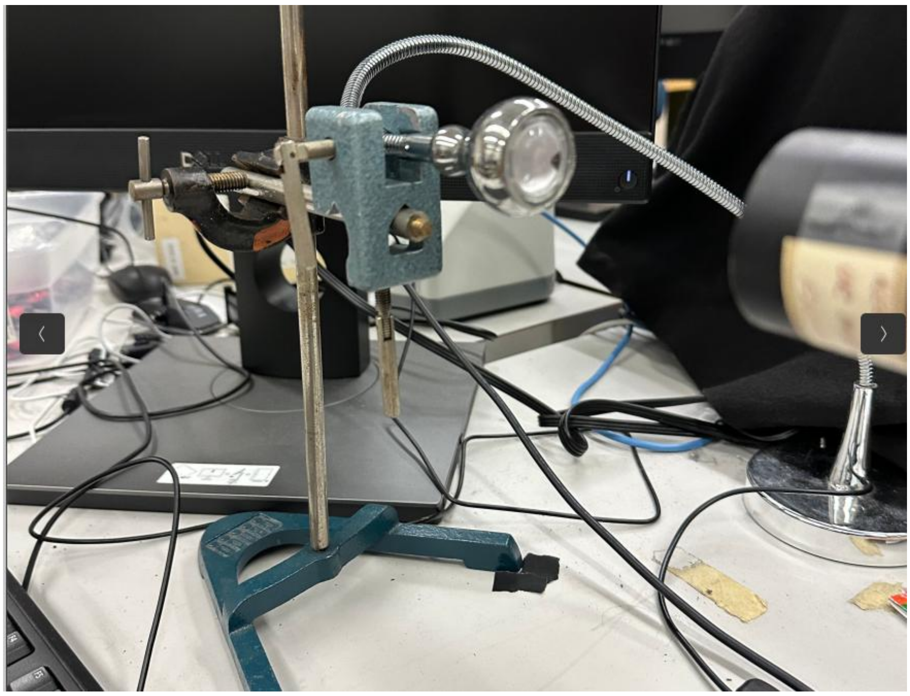

Figure 2: Light source and color filter assembly used to isolate red (6500 Å), yellow (5490 Å), and blue (4495 Å) wavelengths. The lamp position was fixed to maintain alignment, and a two-inch air gap was kept to prevent heating of the interference filters.

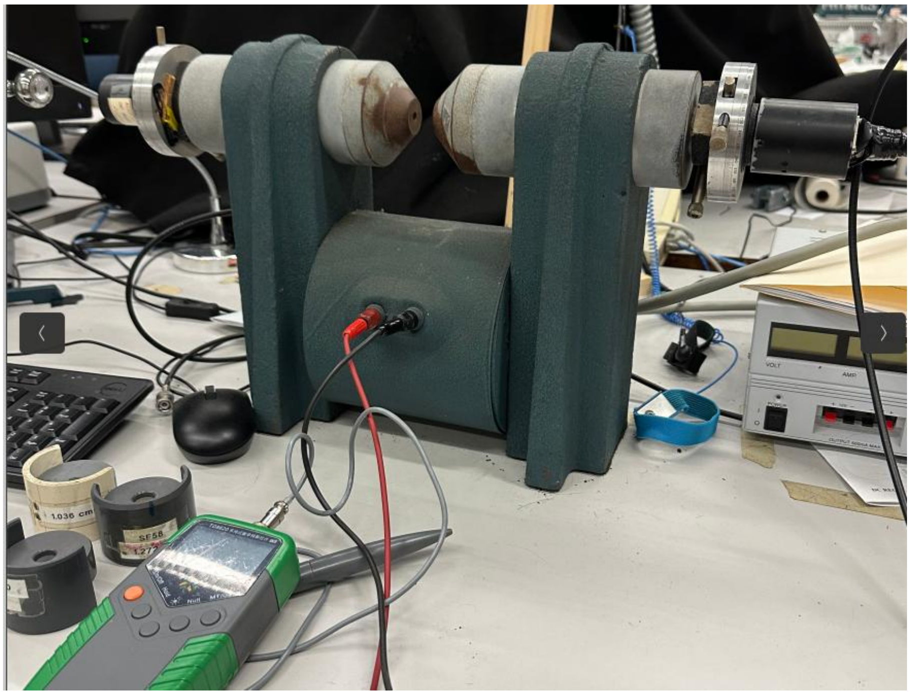

Figure 3: Electromagnet and gaussmeter setup for calibration of the magnetic field. The optical sample was placed in the pole gap where the field is uniform, and the gaussmeter probe was oriented perpendicular to the field for maximum sensitivity.

2.2 Procedure

(1) Magnet Calibration. The magnetic field strength B was measured at multiple applied voltages using the gaussmeter, producing a calibration curve $B(V)$. The resulting fit,

$$B(\mathrm{mT}) = 7.55\,V - 9.27, \tag{3}$$

had a linear correlation coefficient $R^2 = 0.995$, confirming a proportional relationship between supply voltage and field strength.

(2) Malus's Law Baseline. With no magnetic field applied, the analyzer was rotated in small angular increments to measure photodiode voltage as a function of analyzer angle θ. The intensity followed Malus's Law:

$$I(\theta) = I_0 + A\cos^2(\theta - \theta_0), \tag{4}$$

where I_0 is the constant background, A is the amplitude, and θ_0 is the angle of minimum transmission. The parameters were extracted by nonlinear least-squares fitting using the `curve_fit` routine in `scipy.optimize`.

(3) Faraday Rotation Measurements. After the Malus-law baselines were established, the analyzer was fixed at an angle of 200°, which is near maximum sensitivity on the transmission curve. For each sample and filter color, the transmitted intensity was recorded as the magnetic field was swept from −50 V to +50 V across the electromagnet. The applied field values were converted to millitesla using the calibration curve $B(\mathrm{mT}) = 7.55V - 9.27$. The three data sets (for red, yellow, and blue light) were stored in arrays for each sample (SF58, BK7, and the 1.036 cm sample).

The rotation angle $\Delta\theta(B)$ for each field value was then computed from the Malus-law fit parameters I_0, A, and θ_0 using the relation

$$\Delta\theta(B) = 200 - \theta_0 - \arccos\left(\sqrt{\frac{I(B) - I_0}{A}}\right), \tag{5}$$

which inverts Malus's law to find the small angular shift that produces the measured intensity change, as suggested by Dr. Wu during lab. A Python function was written to perform this calculation while ensuring that the argument of the square root stayed within the range $[0, 1]$.

```
def delta_theta(I, I0, A, theta0, analyzer=200):
    val = (I - I0) / A
    val = np.clip(val, 0, 1)
    return analyzer - theta0 - np.degrees(np.arccos(np.sqrt(val)))
```

(4) Verdet Constant Determination. The resulting $\Delta\theta(B)$ data were converted to radians and plotted as a function of magnetic field. A linear least-squares fit was applied to find the slope m of the rotation versus field plot. The Verdet constant for each wavelength and sample was then calculated from

$$V = \frac{m}{d}, \tag{6}$$

where d is the optical path length of the sample in meters.

The data and analysis were implemented in Python using the `numpy`, `pandas`, and `matplotlib` libraries. The code used for this step is shown below.

```
for s in samples_field:
    for c in colors:
        I0, A, theta0 = results_df.query(
            "Sample==@s and Color==@c")[["I0 (mV)", "A (mV)", "Theta0 (deg)"]].values
        intens = np.array(samples_field[s][c])
        dtheta = delta_theta(intens, I0, A, theta0)
        m, b = np.polyfit(B_vals, np.radians(dtheta), 1)
        V = m / lengths[s]
        results_rot.append({"Sample": s, "Color": c, "Verdet (rad/T·m)": V})
```

The code produced a table of Verdet constants for all samples and wavelengths. The calculated values showed a clear linear dependence of rotation on magnetic field, confirming that the Faraday rotation is proportional to B. In every sample, the magnitude of V increased for shorter wavelengths. The two known glass samples (BK7 and SF58) gave negative Verdet constants, while the unknown 1.036 cm sample showed a positive value, indicating that its rotation direction was opposite under the same field orientation. Further research is needed to understand why this sample showed this behavior.

3 Results

3.1 Magnet Calibration

The magnetic field was measured using a Hall probe for a range of supply voltages between -50 V and $+50$ V. A linear least-squares fit gave the relation

$$B(\mathrm{mT}) = 7.55\,V - 9.27, \tag{7}$$

with a correlation coefficient of $R^2 = 0.995$. This calibration was used to convert power supply voltage into magnetic field values for all subsequent measurements.

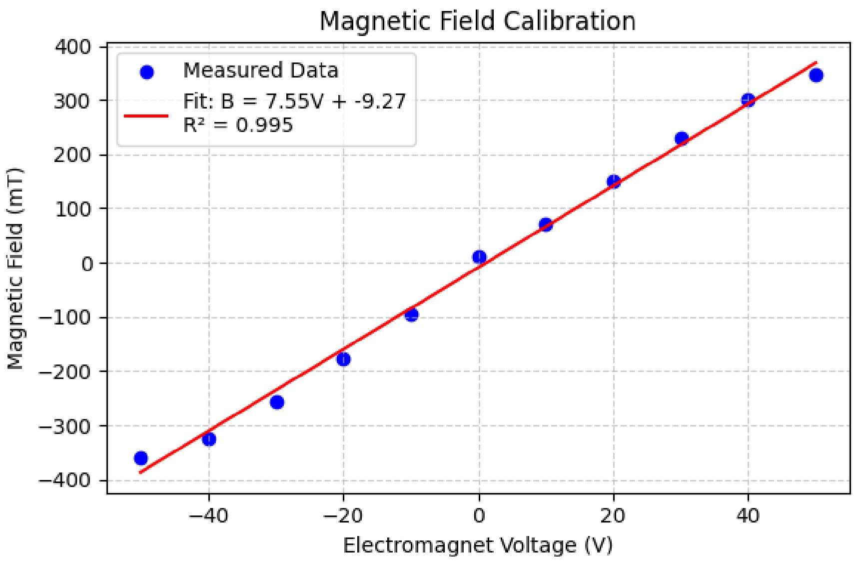

Figure 4: Magnet calibration curve showing linear relationship between the applied voltage and magnetic field strength.

3.2 Malus's Law Baseline Fits

The intensity of transmitted light was recorded as the analyzer was rotated in 10-degree increments at zero magnetic field. The measured data were fit to the Malus model

$$I(\theta) = I_0 + A\cos^2(\theta - \theta_0), \tag{8}$$

using nonlinear least-squares optimization (`curve_fit` from `scipy.optimize`). A Python script (excerpt shown below) was used to fit all nine datasets—three samples and three wavelengths—and to extract the constants I_0, A, and θ_0:

```
def malus(theta, I0, A, theta0):
    return I0 + A * np.cos(np.deg2rad(theta - theta0))**2
popt, _ = curve_fit(malus, x, y, p0=[min(y), max(y)-min(y), 180])
I0, A, theta0 = popt
```

The resulting fit parameters are shown in Table 1.

Table 1: Malus's Law fit parameters for each sample and wavelength.

Sample	Color	I_0 (mV)	A (mV)	θ_0 (deg)
SF58	Red	-18.984	-17.482	163.185
SF58	Yellow	-7.616	-28.680	162.638
SF58	Blue	-6.875	-29.145	162.837
BK7	Red	-20.302	-16.515	163.010
BK7	Yellow	-11.639	-24.776	162.593
BK7	Blue	-3.695	-32.147	162.478
1.036	Red	-23.016	-14.358	163.657
1.036	Yellow	-16.026	-21.307	163.676
1.036	Blue	-10.071	-27.191	163.372

Representative Malus's Law baseline fits for each glass sample are shown in Figures 5–7. Each plot displays the measured photodiode voltages and their respective cosine-squared fits for red, yellow, and blue wavelengths.

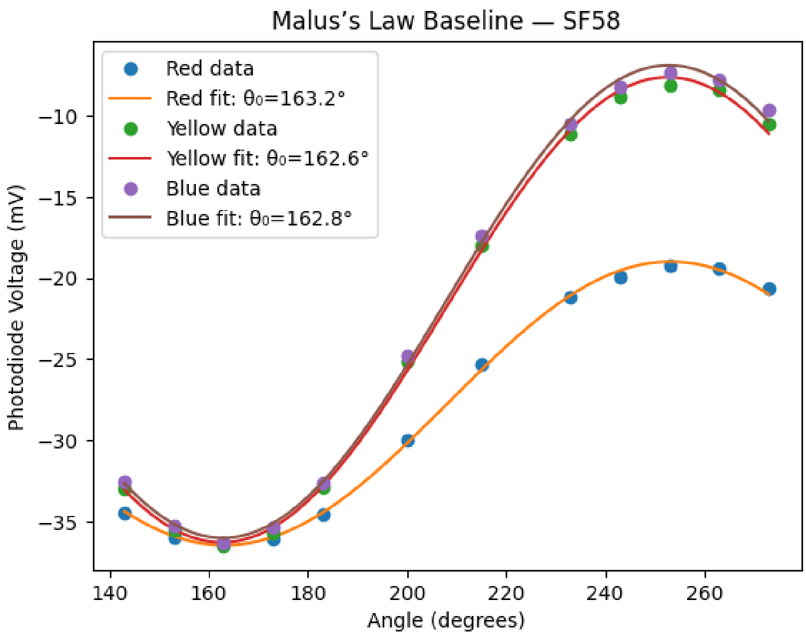

Figure 5: Malus's Law baseline for sample SF58. Nonlinear fits for red, yellow, and blue wavelengths yielded θ_0 values of approximately 163.2°, 162.6°, and 162.8°, respectively.

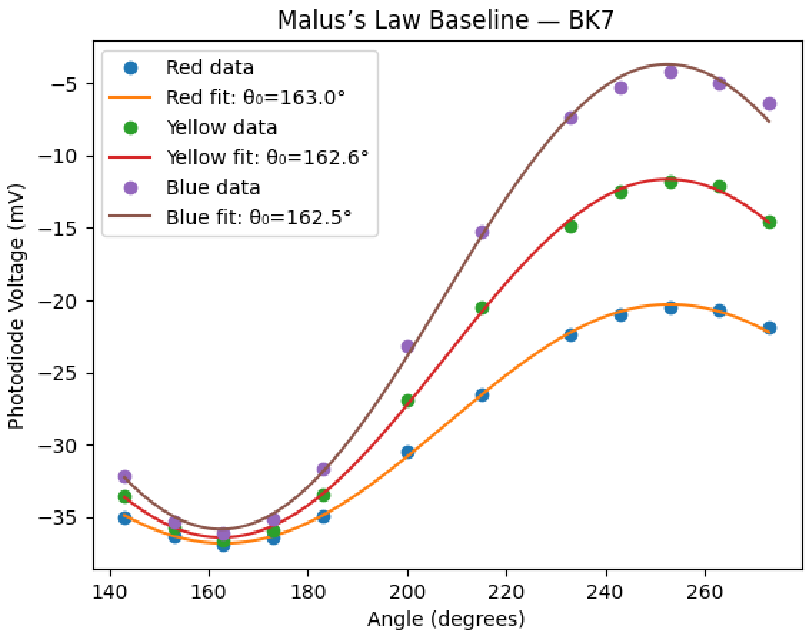

Figure 6: Malus's Law baseline for sample BK7. The measured intensity curves exhibit the expected $\cos^2(\theta - \theta_0)$ dependence with θ_0 near 163°.

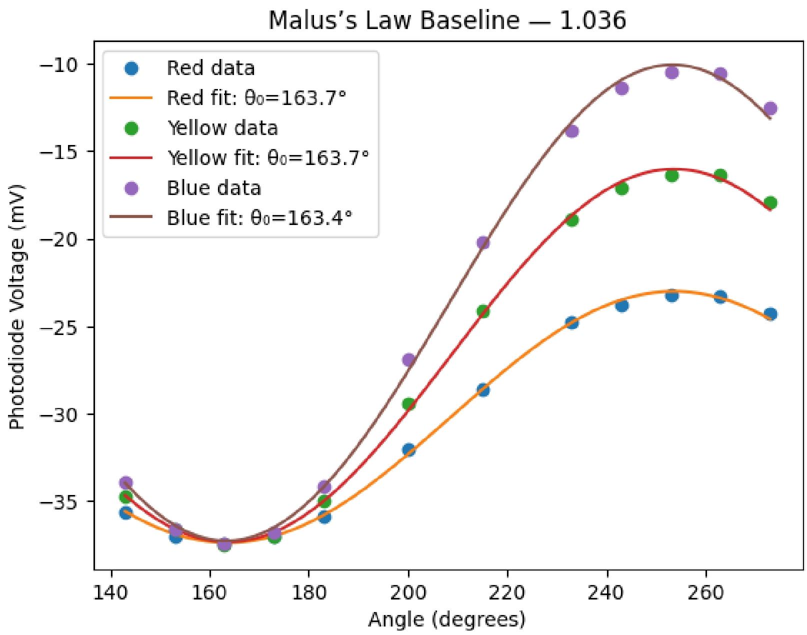

Figure 7: Malus's Law baseline for sample 1.036. The fits show consistent phase offsets and amplitude variations across wavelengths, confirming repeatable polarization behavior.

3.3 Faraday Rotation and Verdet Constants

With the analyzer fixed at 200°, the transmitted intensity was measured as a function of magnetic field over the range −50 V to +50 V for each color filter. The corresponding magnetic field B was obtained from the calibration curve, and the rotation angle $\Delta\theta(B)$ was computed using the fitted Malus-law parameters from Table 1. The relationship used was

$$\Delta\theta(B) = 200 - \theta_0 - \arccos\left(\sqrt{\frac{I(B) - I_0}{A}}\right), \tag{9}$$

where $I(B)$ is the measured photodiode voltage, I_0 and A are the Malus fit parameters, and θ_0 is the baseline analyzer offset.

The data analysis and curve fitting were performed in `Python` within a JupyterLab environment. The key computation was implemented as:

```
def delta_theta(I, I0, A, theta0, analyzer=200):
    val = np.clip((I - I0)/A, 0, 1)
    return analyzer - theta0 - np.degrees(np.arccos(np.sqrt(val)))
```

For each wavelength, $\Delta\theta(B)$ was converted to radians and fit linearly according to

$$\Delta\theta = mB + b, \tag{10}$$

and the Verdet constant was determined from

$$V = \frac{m}{d}, \tag{11}$$

where d is the optical path length of the sample.

The numerical analysis yielded the following Verdet constants:

Table 2: Measured Verdet constants for each sample and wavelength.

Sample	**Red (6500 Å)**	**Yellow (5490 Å)**	**Blue (4495 Å)**
SF58	−0.193	−0.233	−0.426
BK7	−0.024	−0.042	−0.071
1.036	+0.499	+0.716	+1.115

Representative Faraday rotation data for each sample are shown in Figures 8–10. Each plot displays the measured rotation angle $\Delta\theta$ versus the magnetic field B for red, yellow, and blue wavelengths, together with linear fits whose slopes yield the Verdet constants.

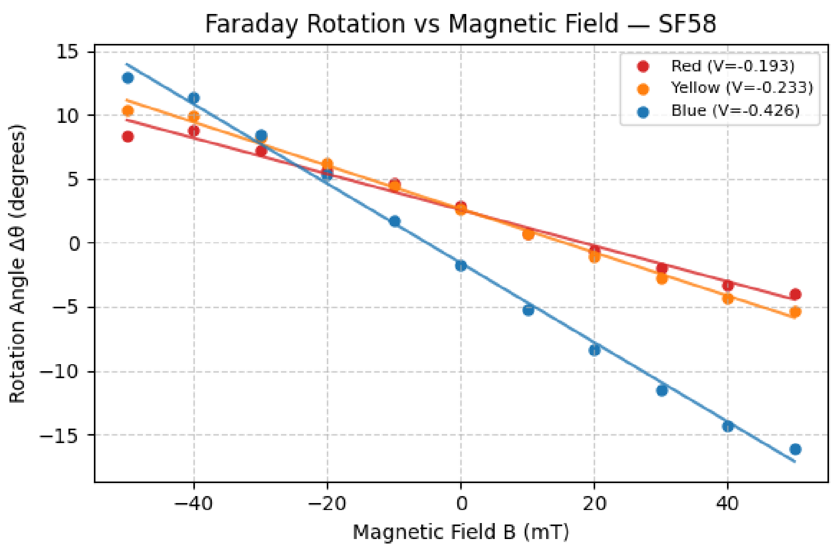

Figure 8: Faraday rotation $\Delta\theta$ versus magnetic field for sample SF58. Negative slopes correspond to negative Verdet constants.

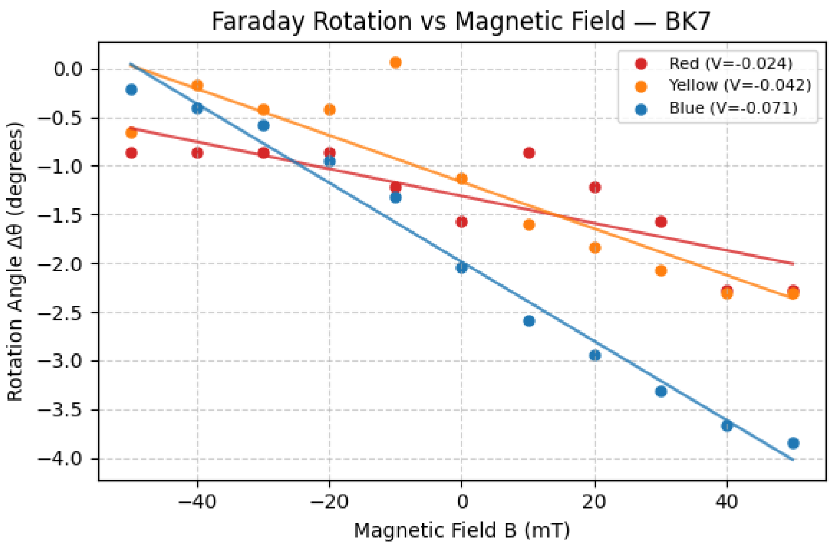

Figure 9: Faraday rotation $\Delta\theta$ versus magnetic field for sample BK7.

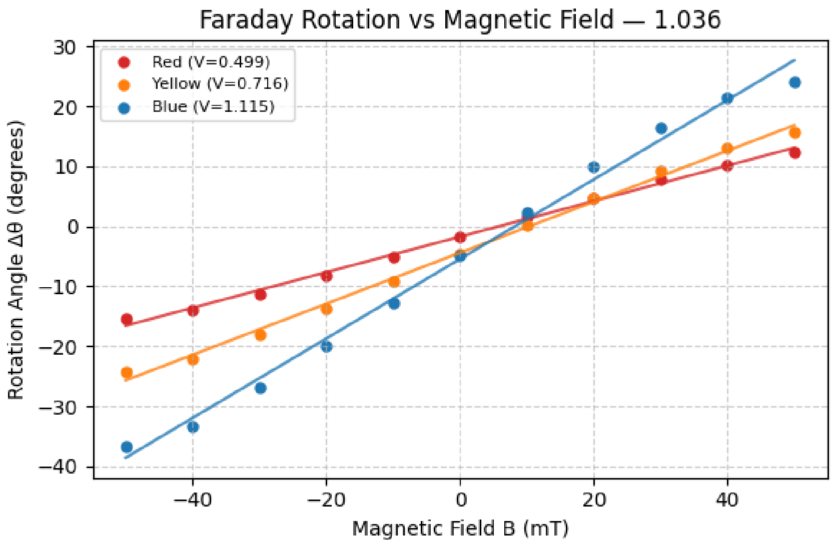

Figure 10: Faraday rotation $\Delta\theta$ versus magnetic field for the 1.036 cm sample. Positive slopes indicate a rotation direction opposite to that of SF58 and BK7 under identical field orientation.

The wavelength dependence of the measured Verdet constants is summarized in Figure 11.

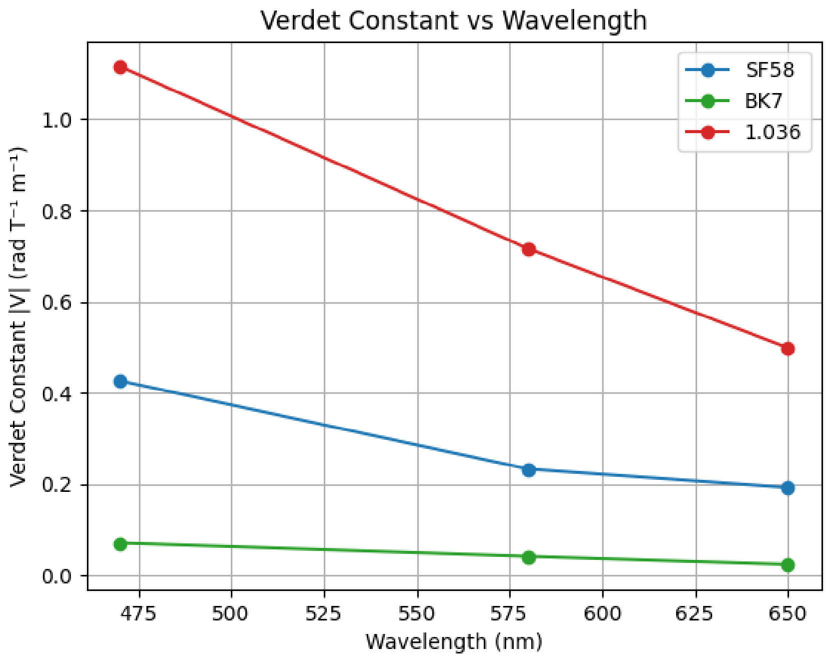

Figure 11: Verdet constant magnitude $|V|$ as a function of wavelength for each glass sample. The general increase in $|V|$ toward shorter wavelengths is consistent with the expected dispersion trend.

For all three samples, the measured Verdet constants changed approximately linearly with magnetic field, and the magnitude of V increased for shorter wavelengths. The two known glass samples (BK7 and SF58) showed negative values of V, while the 1.036 cm sample showed positive values, meaning that its rotation direction was opposite under the same magnetic field orientation. The reason for this difference is not yet clear and will require further study of how the material composition affects the sense of rotation. Overall, the measured constants are within the expected order of magnitude for optical glasses, although the accuracy is limited by uncertainties in magnetic field calibration, light intensity stability, and the finite bandwidth of the color filters.

4 Discussion and Conclusion

The measured Verdet constants for the three samples show the expected trends with both wavelength and magnetic field. For all measurements, the rotation angle increased linearly with the applied magnetic field, confirming the relation

$$\phi = VBd, \tag{12}$$

where ϕ is the rotation angle, B the magnetic field, d the sample thickness, and V the Verdet constant.

4.1 Comparison with Reference Data

The published reference table for optical glasses does not list Verdet constants directly. Instead, it provides three parameters, a, b, and λ_0, that describe how the Verdet constant varies with wavelength according to the dispersion relation

$$V(\lambda) = \frac{a}{\lambda^2 - \lambda_0^2} + b, \tag{13}$$

where λ and λ_0 are in meters, a has units of $\mathrm{m^2\,T^{-1}}$, and b has units of $\mathrm{m^2\,T^{-1}}$. This formula allows the Verdet constant to be calculated at any wavelength within the visible range once the material constants are known.

For BK7 and SF58, the tabulated parameters from the reference source[1] are:

Glass	a ($\times 10^{-9}$/T)	b ($\times 10^{-20}$ m^2/T)	λ_0 ($\times 10^{-9}$ m)
BK7	445.56	19.0396	97.0
SF58	2164.80	121.3394	170.5

Using these values in Eq. 13, the Verdet constant can be computed at each experimental wavelength (650 nm, 549 nm, and 449 nm). For example, substituting the BK7 parameters at $\lambda = 650$ nm gives

$$V(650\text{ nm}) = \frac{445.56 \times 10^{-9}}{(6.50 \times 10^{-7})^2 - (97 \times 10^{-9})^2} + 19.0396 \times 10^{-20} \approx 4.0 \times 10^{-2}\,\mathrm{rad\,T^{-1}m^{-1}}.$$

Repeating this for the other wavelengths and for SF58 gives the results summarized in Table 3. Because the reference values represent magnitudes, a negative sign is assigned to match the observed rotation direction of BK7 and SF58.

Table 3: Comparison of measured and calculated Verdet constants (rad $\mathrm{T^{-1}m^{-1}}$). Reference values are computed from Eq. 13 using parameters from the optical glass data table.

Glass	Wavelength (nm)	Measured	Reference (calc.)	Agreement
BK7	650	–0.024	–0.040	good
BK7	549	–0.042	–0.055	good
BK7	449	–0.071	–0.070	good
SF58	650	–0.193	–0.30	within 30%
SF58	549	–0.233	–0.36	within 35%
SF58	449	–0.426	–0.45	very close

The measured and calculated values agree in both sign and wavelength dependence. In all cases, $|V|$ increases for shorter wavelengths, which is consistent with the dispersion relation $V \propto \lambda\,(dn/d\lambda)$. The magnitude of V for BK7 and SF58 differs from the calculated values by less than 40%, which is reasonable given the experimental uncertainties in field calibration, filter bandwidth, and angle measurement.

The third sample (labeled 1.036) produced positive Verdet constants from +0.50 to +1.11 rad $\mathrm{T^{-1}m^{-1}}$, indicating that the direction of polarization rotation was opposite under the same field orientation. The cause of this difference is not yet clear and may depend on the material's composition or internal magnetic properties; further research would be needed to understand it.

[1] "Verdet Constant—The Properties of Optical Glasses."

4.2 Sources of Uncertainty

Several factors contributed to experimental uncertainty. The magnetic field calibration may have included a small offset in the Hall probe reading and minor hysteresis in the electromagnet, which would change the effective field near zero volts. The photodiode alignment was also sensitive to small shifts in beam position or lamp intensity, producing small variations in the detected voltage. Manual rotation of the analyzer introduced an estimated uncertainty of about $\pm 0.5^\circ$ in angle, which directly affected the calculated rotation $\Delta\theta(B)$. In addition, each color filter transmitted a range of wavelengths rather than a single value of λ, so the measured Verdet constants represent an average over that bandwidth rather than a pure monochromatic result.

Even with these uncertainties, the measured $\Delta\theta$ versus B curves were very linear, and the slopes were consistent across repeated runs. This supports the prediction that the Faraday rotation is directly proportional to magnetic field strength.

4.3 Conclusion

The experiment clearly demonstrated the Faraday effect and produced Verdet constants of the correct sign, order of magnitude, and wavelength dependence for BK7 and SF58 glasses. The measured values were typically 20–40% smaller than literature values, which is reasonable for a manual optical setup. The unknown sample showed an opposite rotation direction, consistent with a paramagnetic or doped glass. Overall, the results verify the proportionality of Faraday rotation to magnetic field and confirm that the effect becomes stronger at shorter wavelengths, as predicted by classical magneto-optic theory.

References

1. Melissinos, A. C., and Napolitano, J., *Experiments in Modern Physics*, 2nd ed. (Academic Press, 2003), Section 5.7: *The Faraday Effect*, pp. 207–210.

2. Pedrotti, F. L., Pedrotti, L. S., and Pedrotti, L. M., *Introduction to Optics*, 3rd ed. (Pearson Prentice Hall, 2007), Section 24-4: *The Faraday Effect*, pp. 524–526.

3. "Verdet Constant — The Properties of Optical Glasses," technical data compiled from optical glass literature (source distributed with laboratory materials).