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| RESEARCH ARTICLE

The Investigating of the Effect of Magnetic Field on a Flint Glass for Optical Isolators Applications

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| ABSTRACT

In this study, the effect of a magnetic field on a Flint Glass for optical isolator applications has been reported. A flint glass and a laser light source with a wavelength of 650nm were used as a medium and a light source, respectively. The magnetic field was produced by applying a current through a coil. The linearly polarized light was passed through the medium in the presence of a magnetic field, and the angle of rotation was measured. The angle of rotation was plotted versus magnetic field strength and fitted linearly. The experimental results showed that the flint glass becomes optically active in the presence of a magnetic field because it rotates the plane of linearly polarized light, and this rotation increases with respect to the magnetic field linearly. The Verdet constant was calculated $10.46\, rad\, T^{-1}m^{-1}$ for 650nm, which is a large coefficient for the rotation of the plane of polarized light.

| KEYWORDS

Faraday rotator, flint glass, optical isolator, polarized light

| ARTICLE INFORMATION

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1. Introduction

Optical isolators are devices which allow the light to travel in one direction. They protect a source from back reflection (Wang, 2012). Optical isolators and circulators are based on Faraday rotation (Cheng, 2013). Faraday rotation was discovered in 1845. Faraday showed that the plane of a linearly polarized light is rotated as it is passed through a diamagnetic material in the presence of a magnetic field (Cheng, 2003). This rotation depends on the length of the diamagnetic material in which the light travels (l), the strength of the magnetic field (B) and a constant coefficient called the vedit constant.

$$\theta = VlB$$

The coefficient V is a property of the material and is different for different materials [Borrelli, 1994, Thamaphat, 2006]. To know the stability of a material for building an optical isolator and circulator, knowing this constant is essential. The material which has a large Verdet constant is more suitable for building an optical isolator as compared to material with a small Verdet constant. The most important element in an optical isolator is the Faraday rotator (Weber, 1986). The two most commonly used materials for making a Faraday rotator for the 700–1100 nm range are terbium doped borosilicate glass (TDB) and terbium gallium garnet crystal (TGG). For TGG at 632 nm, the Verdet constant has been reported as −131 rad/(T·m), whereas it falls to −38 rad/(T·m) at 1064 nm. For lead-bismuth-gallate and tellurite glasses at a wavelength of 475 nm, it is 69.33 rad $T^{-1}m^{-1}$ and 54.91 rad $T^{-1}m^{-1}$, respectively (Barczak, 2022). To measure the Verdet constant for a material, one way is the experimental technique in which polarized light is passed through a diamagnetic material in the presence of an external magnetic field, and the amount of rotation is recorded. Figure (1) shows the Faraday rotation setup.

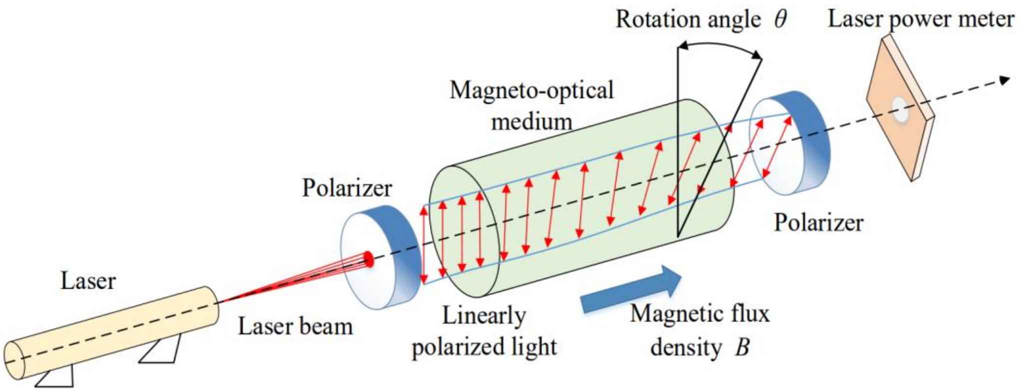

Figure (1): Schematic diagram of Faraday rotation (Wang, 2019).

The linearly polarized light is produced from the polarizer where a laser beam is passed. Figure (2) visualize the polarization of unpolarized light.

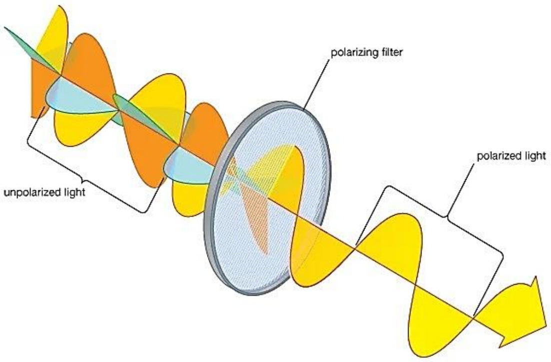

Figure (2): Polarization of an unpolarized light.

It should be noted that the angle of linearly polarized light that propagates in the material; rotates as a function of frequency (Borrelli, 1994).

Light is an electromagnetic wave, and the electric field of the light, propagating in the z-direction, is presented as:

$$\vec{E} = \vec{E}_0 \exp\big(i(kz - \omega t)\big) \quad (1)$$

Where; $\vec{E}_0$ is the amplitude of the electric field [8]. The electric field component is a vector oscillating in the plane perpendicular to the z-axis, $\vec{E} = (E_x, E_y)$.

Polarized light is generated when the direction of the electric field $\vec{E}$ in the plane perpendicular to the z axis, is constrained in some manner. The electric field can be decomposed into two perpendicular components. The general case is elliptically polarized light in which the components have a constant phase φ and the tip of the electric vector traces an ellipse. Where;

$$E_x = E_{0_X} \exp\big(i(kz - \omega t)\big)\ ,\ \ E_y = E_{0_y} \exp\big(i(kz - \omega t + \varphi)\big)$$

Linearly polarized light is a special case of elliptically polarized light in which the two components of the electric field are in phase ($\varphi = 0$).

$$E_x = E_{0_X} \exp\big(i(kz - \omega t)\big)\ ,\ \ E_y = E_{0_y} \exp\big(i(kz - \omega t)\big) \quad (2)$$

In this case, the electric field vector traces a straight line.

Faraday rotation combines elements of optics and electromagnetism (Valev, 2008). Not just Faraday Effect but other magneto-optical effects like Magneto-Optic Kerr Effect, Zeeman Effect, and Cotton-Mouton Effect also reveal the relation between optics and magnetism. These effects all originate from the change of the magnetic field on the mechanism inside the substance and reveal the relation between light and the magnetism of matter (Wang, 2019). Based on optical principles, when a light wave enters a transparent medium, in some certain materials, it splits into two components, ordinary and extraordinary rays. This is called birefringence. The ordinary ray follows Snell's law, but the extraordinary ray does not follow it (Douplik, 2013). The decomposed rays are polarized circularly with right and left rotations. They will either be working with or against the magnetic field. The component working with the magnetic field will get an increase in velocity, but the component working against the magnetic field will get a decrease in velocity. It causes the different speeds for two rays, and at the end of the medium, they combine together, indicating a rotation in the plan of polarization. On the other hand, the precession of the angular momentum of an electron in the atoms of a material leads to different indices of refractions for the right and left polarization of light. It causes the rotation of the plane of polarized light. Nowadays, Faraday rotation is observed from a single confined spin (Atature, 2007). The microscopic origin of magneto optical rotation is the inequality that is created by the splitting of the ground or excited state energy levels due to applied magnetic field. When the applied magnetic field is parallel to the direction of light propagation, then the angle of Faraday rotation θ_F is;

$$\theta_F = \frac{\pi}{\lambda}(n_+ - n_-)l$$

Where; λ is the wavelength of propagated light, l is the length of the medium and n_+ and $n_-$are the refractive indices for right and left circularly polarized light. The Verdet constant of a material is dependent on wavelength and temperature; this is notable from the quantum mechanical expression for Faraday rotation;

$$\theta_F = \frac{4\pi v^2 N}{ch}\left[\frac{(\bar{n}^2+2)^2}{\bar{n}}\right]\sum_a \frac{\exp\left(-\frac{hv_a}{KT}\right)}{\exp\left(-\frac{hv_a}{KT}\right)}) \sum_{a,b} \frac{[< a|X|b >< b|Y|a >]}{v^2 - v_{ab}^2}\ l,$$

Where; $\bar{n}$ is the average refractive index, v_a is the ground state splitting, v is the light frequency, v_{ab} is the frequency difference between the ground state and excited state, and X and Y are the components of the electric dipole moment (Weber, 1986).

In this research, the rotation of the plane of a linearly polarized light in a flint glass in the presence of an external magnetic field at room temperature has been investigated. And through that, the Verdet constant of the flint glass has been determined. Flint glass is a material with a high refractive index and low Abbe number (high dispersion). Currently, known flint glasses have refractive indices of 1.45 up to 2 and an Abbe number of 50 to 55 or less (Kurosawa, 1985).

2. Materials and Method

To investigate the rotation of the plane of a linearly polarized light, a laser beam with a wavelength of 650 nm was used as a source. This light was then linearly polarized by a polarizer. A power supply with a coil (2508 turns) was used to produce the external magnetic field. A flint glass with a 10 cm length was placed inside the coil, the place where the magnetic field was produced. Analyzer and detector were another apparatus of this research. Figure 3 shows the experimental setup of this experiment.

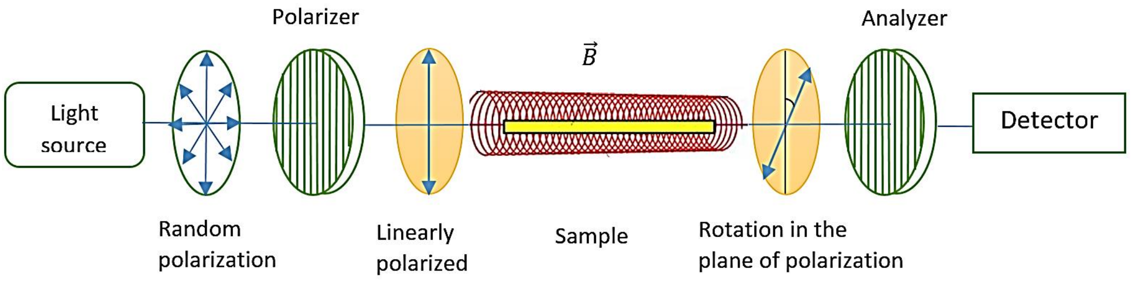

Fig 3. Experimental setup for a Faraday Effect.

The current through the coil was set at zero, and the analyzer was adjusted to zero. Then the reading on the detector was noted. The current was increased to some value, and correspondingly the reading was changed. To obtain the initial detector reading at zero current, the fine screw on the analyzer was rotated. Then, the analyzer reading corresponding to this θ was noted. The procedure was repeated for different values.

3. Results and Discussions

The magnetic field was produced by passing a current through a coil. The variation of magnetic field versus current was studied. With increasing the applied current, the magnetic field strength was also increased. The length of the coil was 15 cm, and the number of wire turns was 2508. The magnetic field strength was calculated using the following formula:

$$B = \mu_0 n I \tag{3}$$

Where μ_0 is the permeability of free space ($\mu_0 = 4\pi \times 10^{-7} T.m\, Amp^{-1}$), n is the number of turns in the coil per unit length, and I is the applied current [14]. The applied current was varied from 0.4 Amp up to 3.2 Amp with an increment; of 0.2 Amp, and the corresponding magnetic fields were calculated using the above formula (table 1).

Table 1. Measured values of rotation angle and calculated values of magnetic fields corresponding to applied current.

NO	Current (Amp)	Magnetic field (Tesla)	Rotation (deg)	Rotation (rad)
1	0.4	0.0084	0.9	0.016
2	0.8	0.0168	1.2	0.021
3	1.2	0.0252	1.8	0.031
4	1.6	0.0336	2.2	0.038
5	2	0.0420	2.8	0.049
6	2.4	0.0504	3.2	0.056
7	2.8	0.0588	3.8	0.066
8	3.2	0.0672	4.4	0.077

From equation (3), the fact that the magnetic field is directly proportional to the applied electric current is illustrated in Figure 4.

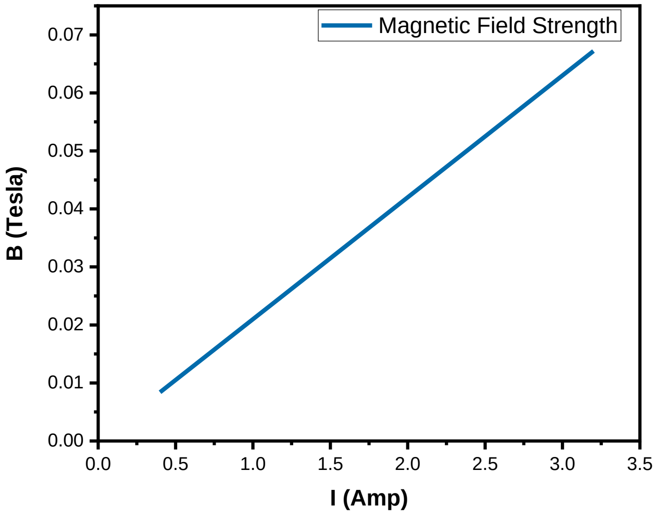

Fig.4. The plot of magnetic field versus applied current.

This plot was drawn and designed using *origin-project software*. According to Maxwell's equations, this relationship is established (Vasyliunas, 2005).

The rotations of the planes of polarized light were recorded using an analyzer. As the current was increased, the rotation of the planes of polarized light was increased as well. That's mean; as the intensity of the magnetic field increases, the rotation changes in the plane of polarized light also increase (Thamaphat, 2006). Figure 5 shows the variation of rotation angles with respect to magnetic field strengths. It was plotted using *origin-project software.*

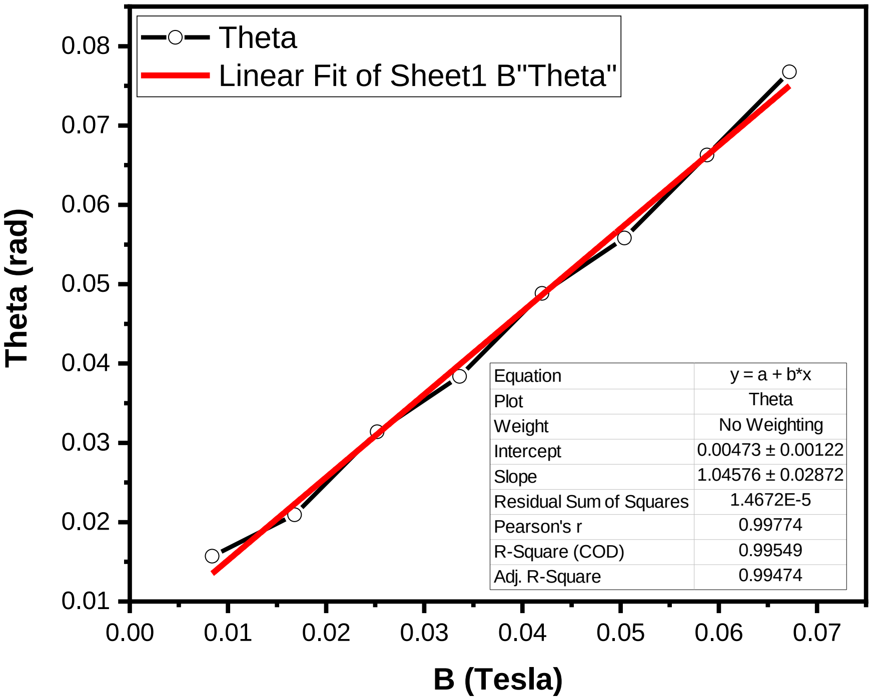

Figure 5. Plot of rotation angle versus magnetic field strength.

The plot indicates that the relation between theta (angle of rotation) and the magnetic field strength is linear.

The slope of the line is around 1.046 rad/T. On the other hand, the angle of rotation is a function of the length of the medium through which the light travels. Hence; by considering the length of the flint glass (10 cm), we get the following;

$$V = \frac{slope}{l} = \frac{1.046\frac{rad}{T}}{0.1\,m} = 10.46\,rad\,T^{-1}\,m^{-1}$$

This value is a constant for the flint glass, which is called Verdet Constant. The magnitude of the angle by which light is rotated at specific wavelengths, temperatures, and the applied magnetic field is directly proportional to the Constant, which is an intrinsic bulk property of an optically transparent material (Carothers, 2022). The suitable diamagnetic material for Faraday rotation is glasses with high lead content, which are available in large sizes and of excellent optical quality. The flint glass is a SiO_2 with lead or potassium (Weber, 1986).

4. Conclusion

The applied magnetic field variation was linear with respect to the applied current. The rotation of the plane of polarized light was variable with respect to the magnetic field. As the strength of the magnetic field was enhanced, the rotation was increased proportionally. For example; for 0.0084T, the rotation was 0.9deg, and for 0.0168T, the rotation was varied to 1.2deg. It indicates that the magnetic field effects on medium, and the medium, in turn, effects on the polarized light. From the variation of the rotation with respect to the magnetic field, the main characteristic property (Verdet constant) was determined. It was obtained $10.46\,rad\,T^{-1}\,m^{-1}$, at 650 nm wavelength, indicating a large Faraday Effect for Flint glass. The findings concluded that the materials which are optically inactive in the presence of a magnetic field change their nature and become optically active. They rotate the plane of polarized light under the influence of a magnetic field and hence can be used as the main component in the Faraday rotator.

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Conflicts of Interest: The authors declare no conflict of interest.

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