

Scattering of Polarized Light in Optically Active Turbid Medium

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Abstract

We studied optical properties of polarized light scattered off a turbid medium. Based on the experimental setup, and using Muller calculus, we developed a model that provided us with optical information of the scattered light like amount of surviving linear polarization and optical rotation of the light after scattering. The scattered light was detected laterally, perpendicular to the direction of the propagation of light. Optical rotation and the degree of linear polarization was measured for various concentrations of Mie scatterers and also for various concentrations of optically active and achiral substance.

Contents

1	Introduction	3
1.1	Light as Transverse Wave	3
1.2	Polarization	4
1.3	Photo Elastic Modulator	6
2	Theory	8
2.1	Background	8
2.2	Experimental Setup	9
2.3	Model	10
3	Experimental Methods	15
4	Results	15
5	Conclusions	20
6	Acknowledgment	21

1 Introduction

Light and its manipulation has been the subject of interest since antiquity. While a number of optical technologies were developed well before modern optics took its pace, the fundamental properties of light was vaguely understood. There were great deals of confusion on properties like, speed of light and if the light is wave and how it gets transmitted. The wave nature of the light made a strong hold when Thomas Young (1773-1829) came up with the double slit experiment to show the interference pattern of light. But, it was not well understood if the light wave is longitudinal or transverse. At this moment, light waves were considered to be longitudinal, just like sound wave. [1] Michael Faraday (1791-1867), with experimental observations, was able to relate light with electromagnetism by altering the polarization direction of a beam by a strong magnetic field. James Clerk Maxwell (1831-1879) summarized and extended all the empirical knowledge on the subject in a single set of mathematical equations and was able to show, theoretically, that the light, as electromagnetic field, could propagate as a transverse wave.

1.1 Light as Transverse Wave

Consider a plane wave, $\vec{E}(x,t)$, propagating in vacuum in positive x -direction where, \vec{E} is constant over each of infinite set of planes perpendicular to the x -axis. From Gauss's Law, which is one of the four Maxwell's equations, we have:

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0} \quad (1)$$

where, ρ is volume charge density and ϵ_0 is electric permittivity of free space. Since, there is no charge enclosed in the space where the field is traveling, $\rho = 0$. Hence,

$$\vec{\nabla} \cdot \vec{E} = 0 \quad (2)$$

or,

$$\frac{\partial E_x}{\partial x} = 0 \quad (3)$$

since, \vec{E} is not a function of either y or z . Also, we know that $\vec{E} \neq 0$. Then, equation (3) tells us that \vec{E} is constant for all values of x which does not correspond to a traveling wave advancing in the positive x -direction. Hence, it follows that the electromagnetic wave has no electric field component in the direction of propagation and the \vec{E} field associated with the plane wave is exclusively

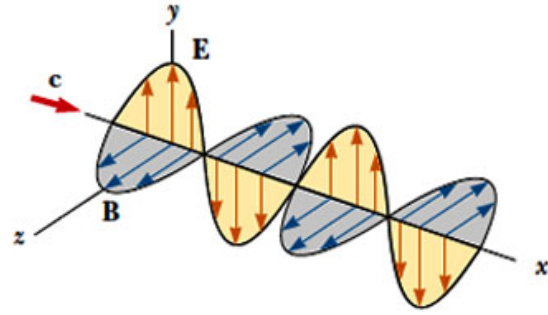


Figure 1: Representation of an Electromagnetic Wave [2]

transverse. At the same time, we know that a time varying \vec{E} field generates \vec{B} field and vice versa, which are everywhere perpendicular to the direction in which \vec{E} and \vec{B} changes, respectively. This transverse nature of electromagnetic wave can be represented in a diagram as in Figure 1. It turns out that the transverse wave model of electromagnetic wave becomes very useful in explaining the polarization property of the light.

1.2 Polarization

Light waves from most of the light sources in the nature generate unpolarized light. Unpolarized light is a superposition of light of two orthogonal states of polarization, with a relative phase that fluctuates randomly.[3] We can represent the two orthogonal components of a plane electromagnetic wave traveling in the z direction as:

$$\vec{E}_x(z, t) = \hat{i}E_{0x}\cos(kz - \omega t) \quad (4)$$

and,

$$\vec{E}_y(z, t) = \hat{j}E_{0y}\cos(kz - \omega t + \phi) \quad (5)$$

where ϕ is the relative phase between the two components. The total field is the vector sum of the two components, $\vec{E} = \vec{E}_x + \vec{E}_y$. The state of polarization depends on ϕ and the relative magnitudes of E_{0x} and E_{0y} .

If $\phi = 0$ or integral multiple of $\pm 2\pi$, the waves are in phase and the resultant field vector becomes:

$$\vec{E} = (\hat{i}E_{0x} + \hat{j}E_{0y})\cos(kz - \omega t) \quad (6)$$

The resultant wave has a fixed amplitude $(\hat{i}E_{0x} + \hat{j}E_{0y})$ and is linearly polarized. Same follows for the condition when the two waves are 180° out of phase, i.e. ϕ is an odd integer multiple of $\pm\pi$. In such case we get,

$$\vec{E} = (\hat{i}E_{0x} - \hat{j}E_{0y})\cos(kz - \omega t) \quad (7)$$

Another kind of polarization occurs, named as circular polarization, when the amplitude of the orthogonal waves are equal ($E_{0x} = E_{0y} = E_0$) and the relative phase difference $\phi = -\pi/2 + 2m\pi$, where $m = 0, \pm 1, \pm 2, \dots$. The resultant wave is:

$$\vec{E} = E_0[\hat{i}\cos(kz - \omega t) + \hat{j}\sin(kz - \omega t)] \quad (8)$$

As we can see, the direction of \vec{E} is time varying and not restricted at any plane. In fact, the resultant electric field vector (\vec{E}) is rotating clockwise at an angular frequency of ω as seen by observer toward whom the wave is moving (i.e. looking back at the source). Such wave is called right circularly polarized wave. On the other hand, if the phase difference is $\phi = \pi/2 + 2m\pi$ where, $m = 0, \pm 1, \pm 2, \pm 3, \dots$ the resultant wave is:

$$\vec{E} = E_0[\hat{i}\cos(kz - \omega t) - \hat{j}\sin(kz - \omega t)] \quad (9)$$

This resultant wave rotates counter clockwise and the wave is called left-circularly polarized.

For the most values of ϕ and the two amplitudes E_{0x} , E_{0y} , the light beam is said to be elliptically polarized. The end of the electric field vector traces out an ellipse as the wave moves through a fixed plane normal to the propagation direction. In fact, both linear and circularly polarized light can be considered as special case of elliptically polarized light.

These polarized lights have various applications in industry. Among others, there have been a number of researches with the use of the polarized light to characterize highly scattering turbid materials. Many natural and synthetic systems have disordered properties making them turbid.

Examples are biological tissues, interstellar gases, colloidal suspensions and micro crystalline solids. Optical examinations of these random media are challenging due to extensive multiple scattering of light which scrambles information that might have been encoded in the light beam.[4] Interestingly, it has been found that the light scattered from random heterogeneous media which used to be believed to be a scramble actually has some correlation and order like effects that can be studied.

While studying the diffusely scattered light off turbid media with incident polarized light, it has been observed that some polarization effects are preserved to an extent that can be experimentally detected. It has been observed that linear preservation of linear polarization holds in isotropically Rayleigh-like scattering medium. On the other hand, circularly polarized light preserves its polarization state better than linearly polarized light in a medium composed of anisotropic (forward directed) Mie Scatterers.[5] We will be dealing the scattering of the latter kind.

In our project, we will be using linear polarizers to achieve polarized light. One can get linearly polarized light by using an instrument that separates the superposition of two equal-amplitude incoherent, orthogonal plane polarized light, discards one and transmits other. Such an instrument is called linear polarizer. The plane polarized light will have an orientation parallel to a specific direction called the transmission axis of polarizer.

1.3 Photo Elastic Modulator

We mentioned above that the circularly polarized light preserves its polarization state better when it is scattered off medium with Mie Scatterers. In our experiment, we will be using micro-spheres as our scatterers which will act as Mie Scatterers. Therefore, the plane polarized light that we obtain using a linear polarizer will have to be converted to circularly polarized light. This can be done by using photoelastic modulator (PEM) which enables sensitive measurements of a small polarized fraction in a predominantly depolarized background, as would be the case for diffusely scattered light.[4]

We use PEM -90 from Hinds Instrument which can be used for the production of alternating left and right circular light. The basis of the operation of the instrument is photoelasticity. Photoelasticity is based on the principle of birefringence. Birefringence is the property of an

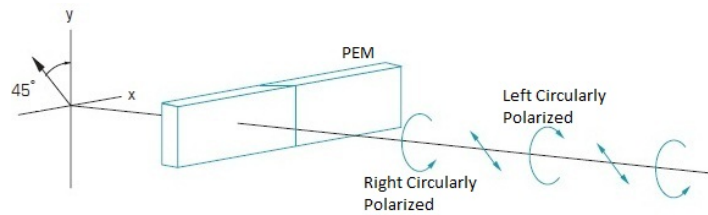


Figure 2: PEM converts a linearly polarized light into pulse of left and right circularly polarized light. [6]

optically anisotropic crystal due to which a ray of light passing through it experiences two different refractive index. Photoelastic materials show birefringence due to stress and the magnitude of the refractive indices at each point in the material is directly due to the state of stress at that point. When a ray of plane polarized light passes through a photoelastic material, it gets resolved along two principal stress directions and each of these components experiences different refractive indices. This leads to retardance leading to the phase difference between two plane polarized rays which alters the polarization state of the incident light.

The incoming light on the PEM should be linearly polarized in a plane which is at 45° with the long axis of the modulator. The light coming out of the PEM surface oscillates between left and right circularly polarized light with elliptically polarized light between these extremes. [6] Therefore, this device provides controlled, circularly polarized light which vary over time in the direction of polarization at the PEM's resonant frequency of 50kHz.

Here, by means of birefringence modulation and synchronous detection we investigate the effects of medium's turbidity on the polarization state of multiply scattered light. Synchronous detection is made possible by lock-in amplifier. Lock-in amplifier uses a technique known as phase-sensitive detection to single out the component of the signal at a specific reference frequency and phase.[7] The signal is first amplified and then multiplied by the lock-in reference using a phase-sensitive detector or multiplier. It is suggested to refer to the manual published by Stanford Research Systems [7] for understanding detailed functional mechanism of lock-in amplifier.

2 Theory

2.1 Background

To derive useful expressions for degree of polarization of multiply scattered light, let us consider the general experimental arrangement presented in Figure 3. To fully account for both polarized and depolarized light, we can work with 4×4 Muller matrices and 4×1 Stokes vectors. Light of any arbitrary polarization state can be represented as Stokes vector (S) of the form:

$$\mathbf{S} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \quad (10)$$

where, I represents the incident irradiance, Q reflects the tendency for the polarization to resemble either a horizontal ($Q > 0$) plane polarization state or vertical ($Q < 0$) one. Similarly, U represents the tendency for the light to resemble a plane polarized state oriented in the direction of $+45^\circ$ ($U > 0$) or in the direction of -45° ($U < 0$) or neither ($U = 0$). And, V represents the tendency of the beam towards right handedness ($V > 0$), left handedness ($V < 0$), or neither ($V = 0$). [1]

The intensity I is directly measurable with a photodetector. For any light beam, the terms are related as:

$$I^2 \geq Q^2 + U^2 + V^2 \quad (11)$$

The equality holds for completely polarized light and the inequality for partially polarized light. Moreover, for partially polarized light, it can be shown that the degree of polarization is given by

$$DOP = \frac{\sqrt{Q^2 + U^2 + V^2}}{I} \quad (12)$$

The degree of linear polarization, i.e the linearly polarized fraction is :

$$DOP_L = \frac{\sqrt{Q^2 + U^2}}{I} \quad (13)$$

Similarly, the degree of circular polarization is:

$$DOP_T = \frac{V}{I} \quad (14)$$

Here, we are interested on the linear and circular depolarizations that occurred due to multiple scattering within the turbid sample. Therefore, we illuminated the sample with a pulsed polarized light beam which underwent the diffusive interaction with the scattering medium of the sample. The leftover polarization properties of the diffused light was then detected at 90^0 , synchronously with the incident polarization modulation. The leftover linear and circular polarization fractions, β_L and β_C , respectively, are defined in terms of the incident (subscript i) and scattered (subscript s) polarization states as:

$$\beta_L = \frac{DOP_{L,s}}{DOP_{L,i}} \quad (15)$$

and

$$\beta_C = \frac{DOP_{C,s}}{DOP_{C,i}} \quad (16)$$

Calculations hereafter depends on the arrangements of optical elements in the experiment. The scheme of the arrangement of the apparatus in the experiment is shown in Figure 3.

2.2 Experimental Setup

In this arrangement, a Helium-Neon acts as the laser source which emits light of $633nm$ wavelength. The emitted light passes through a chopper which generates a pulsed light. The beam is then passed through linear polarizer oriented at an angle of 45^0 to the vertical. The beam, then, propagates through PEM where it gets modulated into pulse of circularly polarized light. The light then passes through the turbid sample with microspheres and gets scattered. The scattered photons directed 90^0 to the direction of incident beam pass through analyzer which are then

detected by photomultiplier tube (PMT).

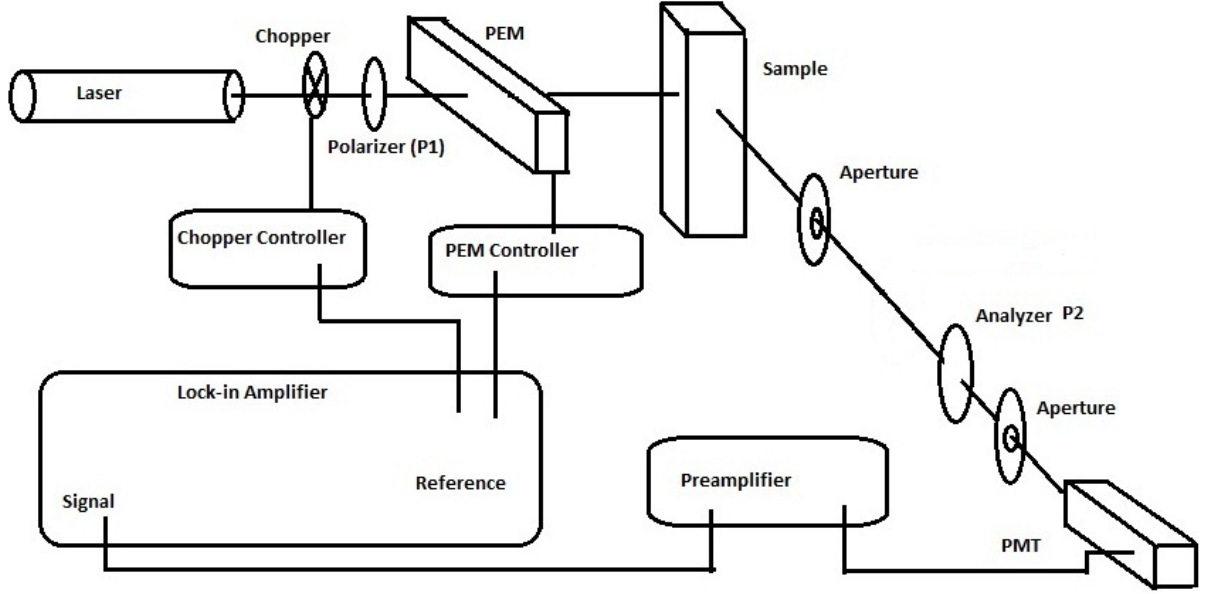


Figure 3: Experimental setup for measuring degrees of polarization and optical rotation of scattered light.

Based on the arrangements of optical components in the setup, we can model the polarization effects by representing the components with Mueller matrices. In Mueller calculus, an optical element that acts on a light beam is represented by multiplication of the incident light Stokes vector by the Muller matrix for that optical component. The resultant is the Stokes vector for the transmitted beam. Muller matrices for various optical components are available at various sources, but the challenging part is to construct a matrix for the turbid sample.

2.3 Model

The Stokes vector for the arrangement in Figure 1 can be written as:

$$(S)_A = [P2(\theta)][sample](PEM)(P1)(S_i) \quad (17)$$

Muller matrix for a linear polarizer oriented at θ is given as:[8]

$$\mathbf{M} = \begin{bmatrix} 1 & \cos 2\theta & \sin 2\theta & 0 \\ \cos 2\theta & \cos^2 2\theta & \cos 2\theta \sin 2\theta & 0 \\ \sin 2\theta & \cos 2\theta \sin 2\theta & \sin^2 2\theta & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (18)$$

In our case, the incident light is passed through linear polarizer (P1) oriented at an angle of 45° . The Muller matrix that represents the polarizer will then be:

$$\mathbf{P1} = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (19)$$

We discussed above that the PEM acts as retarder. Therefore, we can use the Muller matrix that represents linear retarder with fast axis angle (θ) and retardance (δ):[9]

$$\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\theta + \cos \delta \sin^2 2\theta & \cos 2\theta \sin 2\theta - \cos 2\theta \cos \delta \sin 2\theta & \sin 2\theta \sin \delta \\ 0 & \cos 2\theta \sin 2\theta - \cos 2\theta \cos \delta \sin 2\theta & \cos \delta \cos^2 2\theta + \sin^2 2\theta & -\cos 2\theta \sin \delta \\ 0 & -\sin 2\theta \sin \delta & \cos 2\theta \sin \delta & \cos \delta \end{bmatrix} \quad (20)$$

We will be using PEM in such a way that its modulation axis is horizontal ($\theta = 0$). Therefore, the Muller matrix that represents the PEM will be:

$$\mathbf{PEM} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos \delta(t) & -\sin \delta(t) \\ 0 & 0 & \sin \delta(t) & \cos \delta(t) \end{bmatrix} \quad (21)$$

So, the entire process of passing of a unit-irradiance unpolarized light through a linear polarizer oriented at 45° and then through PEM can be expressed as following in terms matrices:

$$\begin{aligned}
S_I &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos \delta(t) & -\sin \delta(t) \\ 0 & 0 & \sin \delta(t) & \cos \delta(t) \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \\
&= \begin{bmatrix} 1 \\ 0 \\ \cos \delta(t) \\ \sin \delta(t) \end{bmatrix} \tag{22}
\end{aligned}$$

where $\delta = \delta_0 \sin(2\pi ft)$. f is the resonant frequency of PEM oscillation while δ_0 is the maximum retardation imposed. If we compare equation (23) with equation (10), the matrix representation becomes obvious. The element that is equivalent to V in equation (10) is 0 because, the plane polarized light incident on the sample does not have any vertical or horizontal component. Instead, the plane polarized light is oriented on $\pm 45^\circ$ from the vertical which gets retarded by the PEM and hence we get the component $\cos \delta(t)$. Similarly, that light incident on the sample has circular component which generates the element $\sin \delta(t)$.

We model turbid sample as an optical rotator which rotated the light with an angle of α^0 . The transformation matrix for rotation is given as:[10]

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \vec{i} \cdot \vec{i}' & \vec{j} \cdot \vec{i}' & \vec{k} \cdot \vec{i}' \\ 0 & \vec{i} \cdot \vec{j}' & \vec{j} \cdot \vec{j}' & \vec{k} \cdot \vec{j}' \\ 0 & \vec{i} \cdot \vec{k}' & \vec{j} \cdot \vec{k}' & \vec{k} \cdot \vec{k}' \end{bmatrix} \tag{23}$$

where the primed vectors represent the direction after the rotation. Here, we assume our coordinate system in such a way that the the the rotation occurring will be through an angle α about the z axis. Therefore, the rotation matrix that represents the sample will be:

$$T_s = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\alpha) & \sin(2\alpha) & 0 \\ 0 & -\sin(2\alpha) & \cos(2\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (24)$$

Also, the turbid sample acts as a depolarizing medium imposing linear and circular depolarizations β_L and β_C . Muller matrix for such a depolarizer is: [11]

$$D_S = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \beta_L & 0 & 0 \\ 0 & 0 & \beta_L & 0 \\ 0 & 0 & 0 & \beta_C \end{bmatrix} \quad (25)$$

The beam incident (equation (24)) on the turbid sample will experience the effects of optical rotations and depolarizations induced by the medium. Therefore, the Stokes vector for the transmitted beam will be:

$$S_T = D_S \cdot T_S \cdot S_I = \begin{bmatrix} 1 \\ \beta_L \sin(2\alpha) \cos \delta(t) \\ \beta_L \cos(2\alpha) \cos \delta(t) \\ \beta_C \sin \delta(t) \end{bmatrix} \quad (26)$$

For arrangement with the linear analyzer oriented at an angle of θ^0 to the horizontal, information about the circular polarization is lost, but the optical rotation α and the degree of linear polarization β_L can be determined. We multiply the Stokes vector from equation (26) and multiply with the Muller Matrix for a linear polarizer given as equation (18) for a linear analyzer oriented at θ^0 and select the resulting Stokes parameter. We achieve:

$$\begin{aligned} I_A &= 1 + \beta_L \cos(2\theta) \sin(2\alpha) \cos \delta(t) + \beta_L \sin(2\theta) \cos(2\alpha) \cos \delta(t) \\ &= 1 + \beta_L \cos \delta(t) \sin 2(\alpha + \theta) \end{aligned} \quad (27)$$

It has been observed from the experiment that the measured light intensity is actually:

$$I_A = k_A \{1 + \beta_L \sin[2(\alpha + \theta)] \cos \delta(t)\} \quad (28)$$

where k_A is an experimental constant which is not important. The signal observed at the detector is the function of user defined variable like the analyzer angle (θ), PEM retardation ($\delta(t)$), optical rotation (α_L) and linear depolarization (β_L).

To facilitate the data analysis with the help of equation (28), we can expand the time dependent retardation terms $\cos \delta(t)$ and $\sin \delta(t)$ in a series of spherical harmonics using the following expressions.

$$\cos(z \sin \psi) = J_0(z) + 2 \sum_{k=1}^{\infty} J_{2k} \cos(2k\psi) \quad (29)$$

$$\sin(z \sin \psi) = \sum_{k=0}^{\infty} J_{2k+1}(z) \sin[(2k+1)\psi] \quad (30)$$

where J_n are the Bessel functions of the first kind of order n . Since lock-in amplification isolates signals at specific signals at frequencies ($1f$ and $2f$), we can expand the series up to the $2f$ terms, with $z = \delta_0$ and $\psi = 2\pi f$. Now,

$$I_A = k_A \{1 + J_0(\delta_0)\beta_L \sin[2(\alpha + \theta)] + 2J_2(\delta_0) \times \beta_L \sin[2(\alpha + \theta)] \cos(2\pi \cdot 2f)\} \quad (31)$$

The ratio of the signal of the photocurrent at $2f$ to the constant (dc) signal removes the constant k_A and yields,

$$(2f/dc)_A = \frac{2J_2(\delta_0)\beta_L \sin[2(\alpha + \theta)]}{1 + J_0(\delta_0)\beta_L \sin[2(\alpha + \theta)]} \quad (32)$$

Hence, by dividing the signals at $2f$ obtained by varying the analyzer angle θ by the signals at dc we can extract the parameters α and β_L by fitting the data ratios to the curve described by equation (34). However, no information about the circular polarization can be obtained from this setup. Insertion of quarter wave plate have been found to be useful for the determination

of β_C . [12]

3 Experimental Methods

The experimental setup is shown in Figure 3. HeNe laser is the source of the unpolarised light which is first passed through a chopper to create pulsed light with certain pulse frequency. The dc signal was measured by chopping the beam at low frequency of 150Hz and synchronously detecting it with the same lock-in amplifier (Stanford Research Systems, SR350). The light then, passed through a linear polarizer oriented at 45° to the vertical and then through photoelastic modulator (PEM) which modulates the incident light into circularly polarized beam. The PEM (Hinds, PEM-90) had its modulation axis horizontal and the modulation frequency (f) was set at 50 KHz. The resultant time-varying elliptically polarized light was incident on a 1cm-sq quartz spectrophotometer cuvette that contained the liquid turbid suspension.

The detector arm was placed perpendicular to the incident beam facing the cuvette. Laterally scattered light was passed through a pin hole aperture to block stray light and then through linear polarizer before reaching the photomultiplier tube (PMT). PMT signal was fed to preamplifier (Stanford Research Systems, SR570) before entering the lock-in amplifier which enabled the detection of the photocurrents at the PEM modulation frequency and its first harmonics ($1f$ and $2f$).

By measuring signals at $2f$ and dc at various angular settings of the analyzer, a plot of $2f/dc$ vs θ was drawn for each sample. The θ range was between 30° and 150° to encompass a large part of the cyclic function of equation (34). PEM retardation (δ_0) was set to 3.469 radians to generate the larger values of $J_0(\delta_0)$ and $J_2(\delta_0)$. Maximizing these coefficients ensures a large amplitude of the $2f/dc$ signal variation as a function of θ . This, though, makes the curve fit more sensitive to changes in β_L .

4 Results

In Figure 4, we present the results observed from a sample of 0.5% i.e. 5g/L suspension of $8\mu m$ diameter microspheres in pure de-ionized water. The vertical axis of the graph is the ratio of lock-in amplifier photocurrent at $2f$ to the dc signal measured from the mechanical chopper frequency of $150Hz$. The lock-in amplifier photocurrent can be observed as amplitude of signal in a oscilloscope and so can be the signal from the mechanical chopper. The average of the ratio obtained was calculated

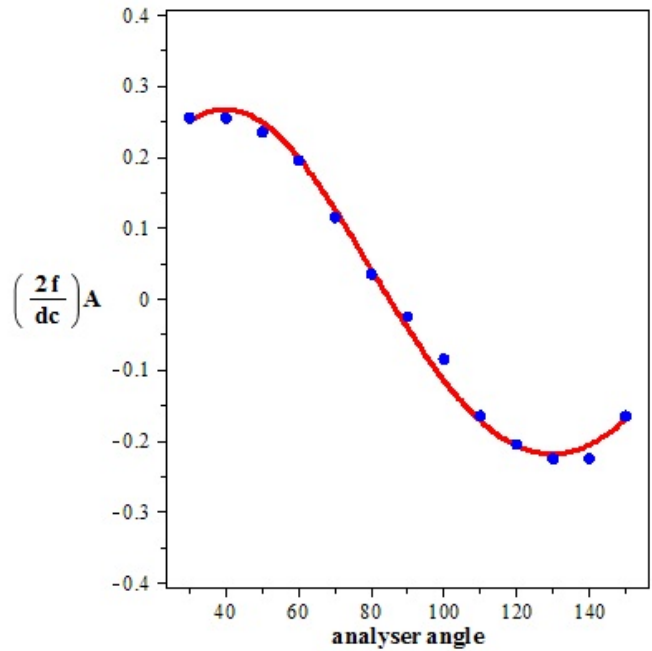


Figure 4: Variation of $2f/dc$ values with the angular orientation of analyser for a turbid sample of 0.5% microspheres in de-ionized water.

and then subtracted from the initial ratios so as to achieve the ordinate values that correspond to the negative phase reading of the $2f$ signal in the lock-in amplifier. The detection of the signal was done laterally at 90^0 because it might be the detection direction that may be suitable for biomedical diagnostic applications or potential materials analysis.[12]

The PEM retardation δ_0 was set to 3.469 rad to maximize the magnitude of the $2f/dc$ ratio.[12]. The points are the values of the ratios while the line is the theoretical best fit obtained from the Equation (34). The parameters that were adjusted for fitting the data were $\alpha = 5.0^0$ and $\beta_L = 26\%$. Due to the lack of a software that would assist for the automatic determination of the parameters α and β , the values were manually fitted. Among other errors that might have been carried on while calculating the numbers, manual choice of the parameters also prevents one from acquiring the optimal fitting parameters. We can observe a close correspondence of the experimental data and theoretical curve, and the values of $\alpha \sim 0^0$, $\beta < 100\%$ appear to be reasonable and are expected for a turbid achiral sample. [12]

A similar process can be done for the other concentrations of the 8 micrometers microsphere solution. The concentrations we chose were 0.2%, 0.5%(discussed above), 0.15%, and 1% microsphere solution. As we can see from Figure (5) , we initially observe that the ampli-

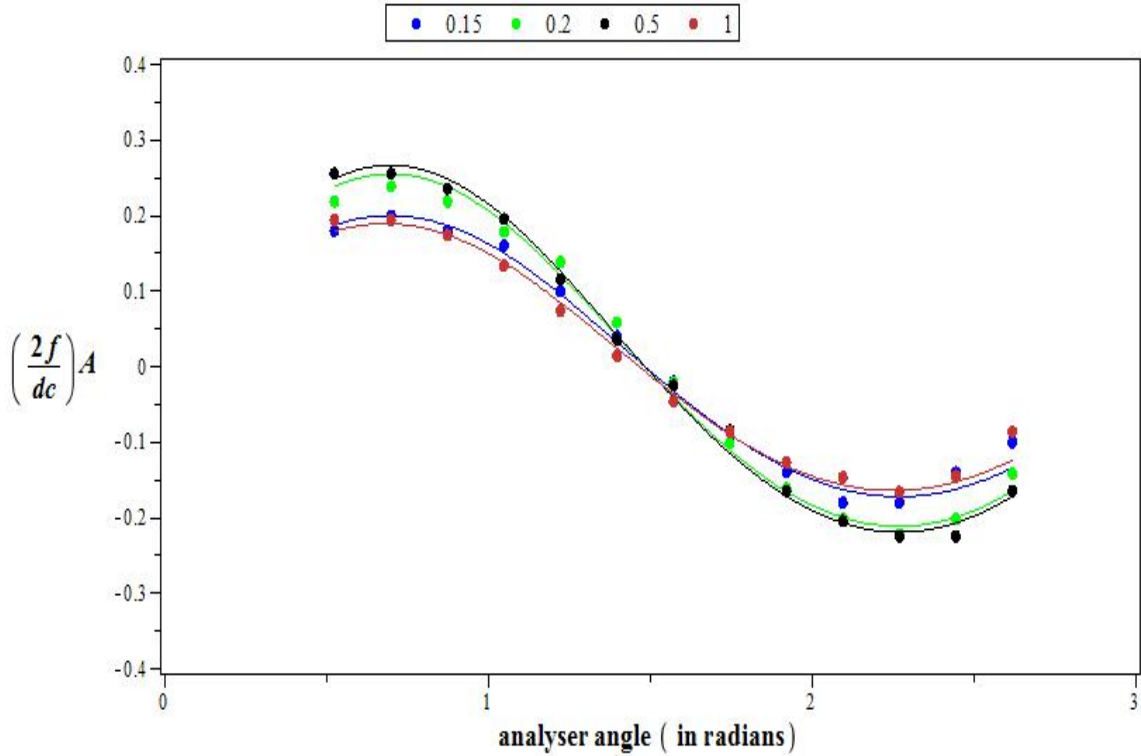
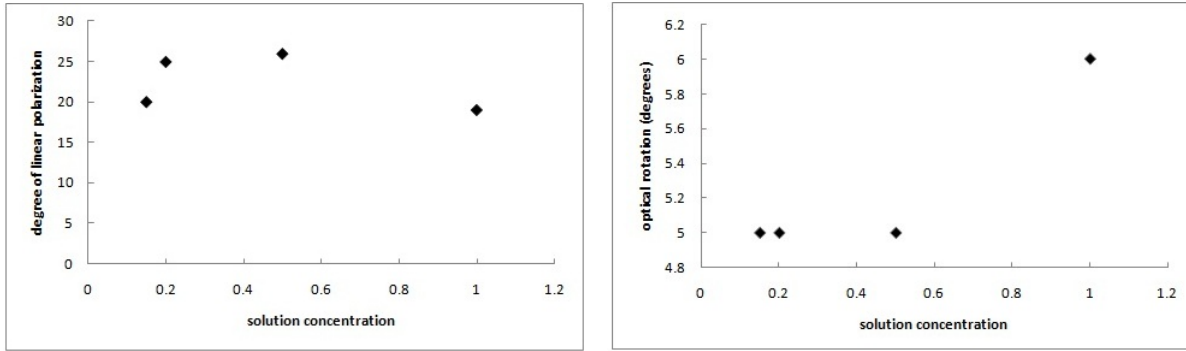


Figure 5: Variation of $2f/dc$ values with the angular orientation of analyser for a turbid sample of various concentrations of $8\mu m$ microspheres. The blue data points and fit is for 0.15% solution, while the green, black and brown data points and fits are for 0.2%, 0.5% and 1% respectively.

tude of the curve increases while increasing the concentration except when the concentration of the microsphere was 1%. Since the amplitude of the curve depends on the surviving linear polarization fraction (β_L), we can see that the linear polarization survives more as the concentration increases except when the concentration was 1%. It might be because with the 1% solution the diffused light overwhelms the background. For further discussion about the optical behavior, we can see the change in the value of the surviving linear polarization and also the optical rotation.

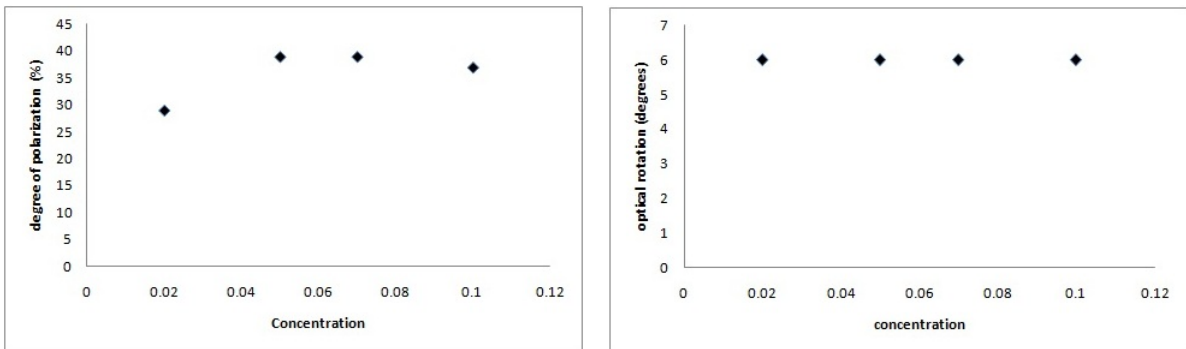
As we can see from Figure 6, the degree of linear polarization appears to increase for lower concentrations of the turbid sample. With a high concentration of the microphones, it appears that most of the light gets scattered and a the amount of the surviving linear polarization fraction decreases. On the other hand, it appears that the optical rotation for lower concentration of the microspheres are quite similar up to certain concentration while the rotation increase with the higher concentration.



(a) Amount of surviving linear polarization for various concentrations of $8\mu m$ microsphere solutions. (b) Amount of optical rotation due to the various concentration of the $8\mu m$ microsphere solutions.

Figure 6: Degree of polarization and optical rotation of various concentrations of $8\mu m$ microspheres.

In order to further investigate the case, we did other experiments by using various concentrations of $1.5\mu m$ microspheres in pure de-ionized water. Figure 7 represents the percentage the surviving linear polarization and the optical rotation for various concentrations of $1.5\mu m$ microsphere solution. Similar to the observations we had for $8\mu m$ solutions, we can see that the degree of polarization initially increases, but decreases for the solution of 1% concentration. Optical rotation appears to remain constant for varying concentrations of microspheres. Also, it is notable that the degree of polarization is retained more for $1.5\mu m$ microsphere solution and its optical rotation is also larger.

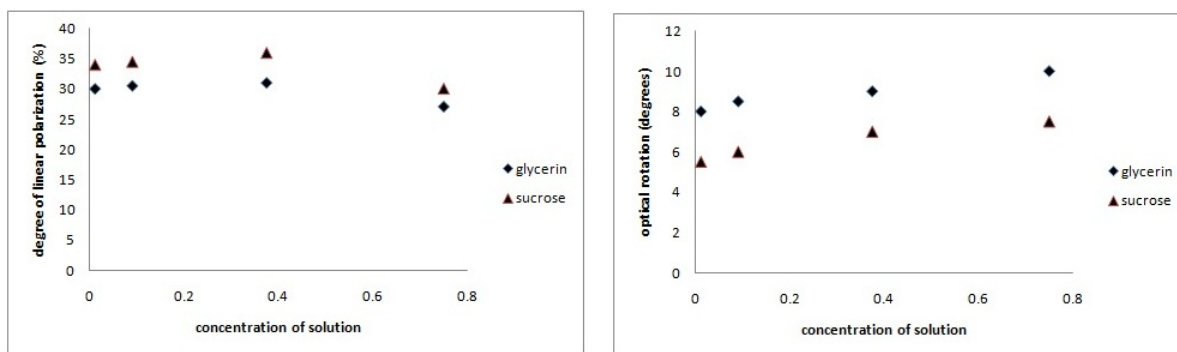


(a) polarization for various concentrations of $1.5\mu m$ microsphere solutions. (b) Amount of optical rotation due to the various concentration of the $1.5\mu m$ microsphere solutions.

Figure 7: Degree of polarization and optical rotation of various concentrations of $1.5\mu m$ microspheres.

Another question to investigate during the process is to check if the amount of surviving polarization and optical rotation are dependent on the chirality state of the solution. There-

fore, we decide to investigate the phenomenon with sucrose solution and glycerin. Sucrose is optically active material while the glycerin is achiral. [13]



(a) Amount of surviving linear polarization for various molar solutions of glycerin and sucrose. (b) Optical rotation for various molar solutions of glycerin and sucrose.

Figure 8: Degree of polarization (β_L) and optical rotation of various molar concentrations of glycerin and sucrose. All the solutions have same concentration (0.05%) of $1.5\mu m$ microsphere solution.

All the solutions in Figure 6 have a fixed concentration of microspheres of 0.05% and lateral detection direction. The portion of surviving linear polarization appears to exhibit similar behavior that was observed for varying concentrations microspheres. It should be noted that increasing sucrose or glycerin concentration does not scatter light as much as increasing concentration of microspheres which can also be seen in graph (a) of Figure 7 and 8. The polarization preservation can be expected simply because of lower scattering. On the other hand, optical rotation appears to increase with increase in the concentration of sucrose or glycerin. Hence even in the condition that the samples have same amount of microspheres, these samples do not have the same scattering properties. In some literatures [12], it has been mentioned that the chiral nature of the dissolved molecules is unimportant in enhancing the degree of linear polarization, and the effect is entirely due to refractive index matching. We can see from Figure 8(b) that the behavior of optical rotation in glycerin (achiral) and sucrose (chiral) medium is similar, with the only difference being on the magnitude of the rotation.

5 Conclusions

While it might be thought that a polarized light scattering from a turbid medium will be completely depolarized, such scattered light actually retains some polarization properties that can be useful for investigation of the properties of the medium. Here, we developed a methodology of calculating degree of linear polarization and optical rotation for a polarized light passing through various optical components.

Microspheres of diameters $1.5\mu m$ and $8\mu m$ served as the Mie scatterers for our experiments. Considering the fact that Mie scattering depends on the radius of the scatterer [14], we were expecting there might be some differences in the optical parameters. We were able to observe that linear polarization was preserved more for solutions containing smaller microspheres and also have larger optical rotation. We also studied the effect of the concentrations of optically active material with same concentration of microspheres. The behavior of the surviving linear polarization stayed similar as in case of varying microsphere concentration for varying the concentration of optically active material in the medium.

An encouraging result was seen regarding the optical rotation due to the change in the concentration of optically active medium in the sample. We observed that the optical rotation increased with increase in concentration of both sucrose and glycerin which is an indication that the optical rotation might not necessarily depend on the chirality of the substance, but with the refractive index matching between the scattering medium and the solution as claimed in literature. [12]

The issue of optical activity of scattering polarized light can further be studied with various improvements that have been done during a semester of working on this project. One of the important studies can be done by comparing the optical activity of scattered light by using left and right chiral molecules in turbid medium. While this was suggested by my mentor, Dr. Amer Lahamer, I could not complete the task due to lack of time and also unavailability of both left and right water soluble chiral molecules in the lab. Another modifications that can be done in the experiment is by studying the changes in optical behavior at various angles of detection. We only performed the detection at an angle of 90^0 with respect to the direction of propagation of light.

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