Polarization of Light

Components required: white light source, adjustable slit, optical goniometer, black glass plate, polarizer (2), ¼ waveplate (632.8 nm), polarizer (waveplate) holder (3), lens holder, He-Ne laser, laser holder, iceland crystal with holder, beam expander, lens f'=150 mm.

Principle: For light emitted from a natural light source, the direction of the electric vector E is random due to the random thermal motion of molecules. Natural light becomes partially polarized through reflection, refraction or absorption of some media, whose electric vector is dominated in one specified direction. If the electric vector is completely constrained in one direction (or in one plane along the propagation direction), it is called as plane polarized light or linearly polarized light. If the trajectory of the end of the electric vector forms an oval or a circle in the plane perpendicular to the direction of light propagation, the light is called elliptically polarized light or circularly polarized light.

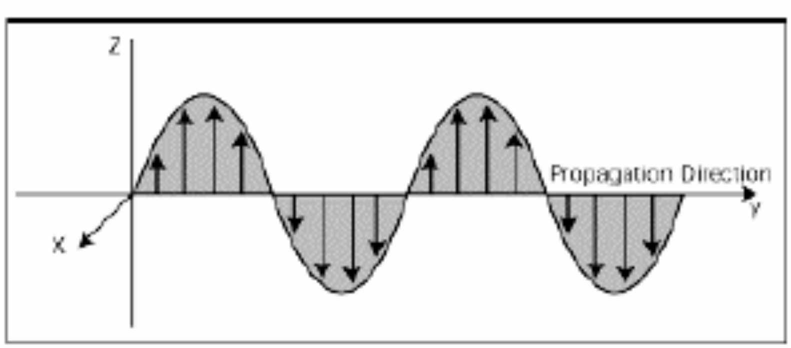
Theory:

Light Polarization: In classical physics, light of a single color is described by an electromagnetic field in which electric and magnetic fields oscillate at a frequency, (ν), that is related to the wavelength, (λ), as shown in the equation

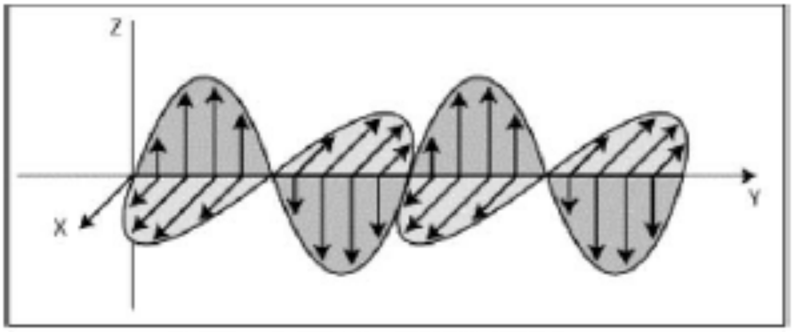
$$c = \lambda\nu$$

where c is the velocity of light. Visible light, for example, has wavelengths from 400-750 nm.

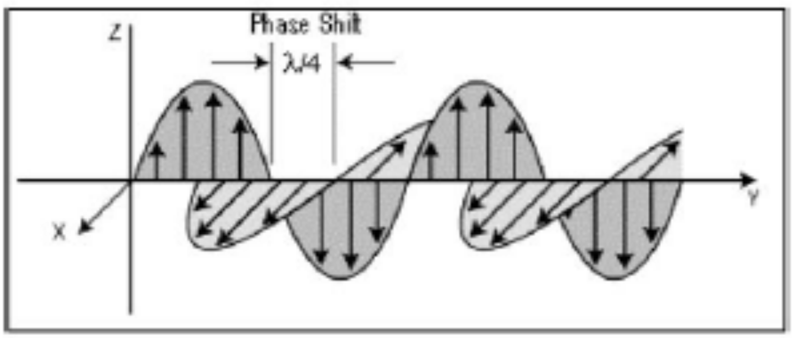
An important property of optical waves is their polarization state. A vertically polarized wave is one for which the electric field lies only along the z-axis if the wave propagates along the y-axis (Figure 1A). Similarly, a horizontally polarized wave is one in which the electric field lies only along the x-axis. Any polarization state propagating along the y-axis can be superposed into vertically and horizontally polarized waves with a specific relative phase. The amplitude of the two components is determined by projections of the polarization direction along the vertical or horizontal axes. For instance, light polarized at 45° to the x-z plane is equal in amplitude and phase for both vertically and horizontally polarized light (Figure 1B).



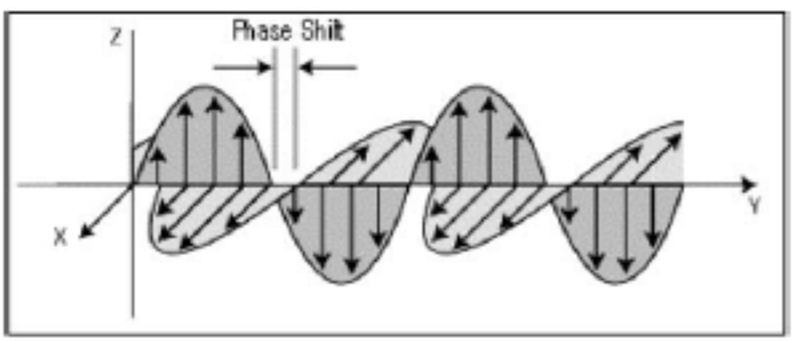
A. Linearly Polarized Light in the Vertical Direction



B. Linearly Polarized Light at 45 Degrees



C. Circularly Polarized Light



D. Elliptically Polarized Light

Fig 1: Various polarization of light.

Circularly polarized light is created when one linear electric field component is phase shifted in relation to the orthogonal component by $\lambda/4$, as shown in Figure 1C.

Elliptically polarized light represents an arbitrary phase shift between the two electric field components, as seen in Figure 1D.

We produce linearly polarized light when we send unpolarized light through a polarizing medium whose axis is in line with the desired linear polarization. Passing this polarized light through a second polarizer allows only the components that are parallel to the polarizing axis to emerge while the orthogonal component is absorbed. If vertically polarized light is sent through a polarizer oriented at 45° the emerging light is reduced in amplitude by a factor of $1/\sqrt{2}$ and in intensity by 50% of the original intensity. If vertically polarized light is sent through a horizontally oriented polarizer no component of the original light is parallel to the polarization direction and no light emerges.

Retardation

Another useful tool for manipulating polarized light is the phase retarder. Phase retardation is accomplished by making the optical path length for one of the orthogonal polarizations different than the other.

Quarter Wave Retarder
If the orthogonal electric field components are equivalent, a phase shift in one component will result in circularly polarized light, as shown in part C of Figure 1. Retarders that cause this shift are known as quarter wave retarders. They have the unique property of turning elliptically polarized light into linearly polarized light or of transforming linearly polarized light into circularly polarized light when the fast axis of the quarter wave plate at 45° to the incoming polarization plane. This is done using birefringent, uniaxial materials having two different refraction indices. Light polarized along the direction with the smaller index travels faster and thus this axis is termed the fast axis. The other axis is the slow axis.

Alignment of quarter wave retarders is accomplished with the use of a linear polarizer and a mirror as demonstrated in Figure 2. Using a Polarizing Beam Splitter, vertically polarized light is passed through a quarter wave plate and onto a mirror. When the angle between the fast axis of the quarter wave plate and the polarization plane is at 45°, the reflected light has a polarization that is 90° to the polarization of the original source. This maximizes the light at B and minimizes the light at reference point A, as shown in Figure 2.

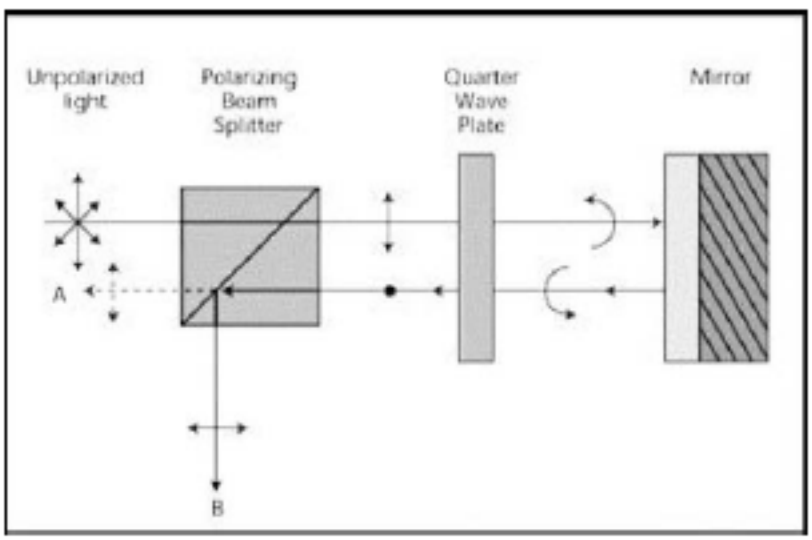


Fig. 2. A quarter wave alignment technique

Half Wave Retarder: A retarder that produces a $\lambda/2$ phase shift is known as a half wave retarder. Half wave retarders can rotate the polarization of linearly polarized light to twice the angle between the retarder fast axis and the plane of polarization. Placing the fast axis of a half wave retarder at 45° to the polarization plane results in a polarization rotation of 90°. Passing circularly polarized light through a half wave plate changes the "handedness" of the polarization. This is the same as shifting the horizontal polarization in Figure C by one λ.

Optical Isolators: Retarders used in conjunction with polarizers provide many useful devices. For example, optical isolation can be achieved by combining a linear polarizer with a quarter wave retarder. Properly aligning the quarter wave retarder with the linear polarizer turns linearly polarized light into circularly polarized light. Because circularly polarized light exhibits a shift in handedness upon specular reflection, the reflected light is now linearly polarized and rotated 90° from the light leaving the isolator. Horizontally polarized light falling on a vertically aligned polarizer is rejected.

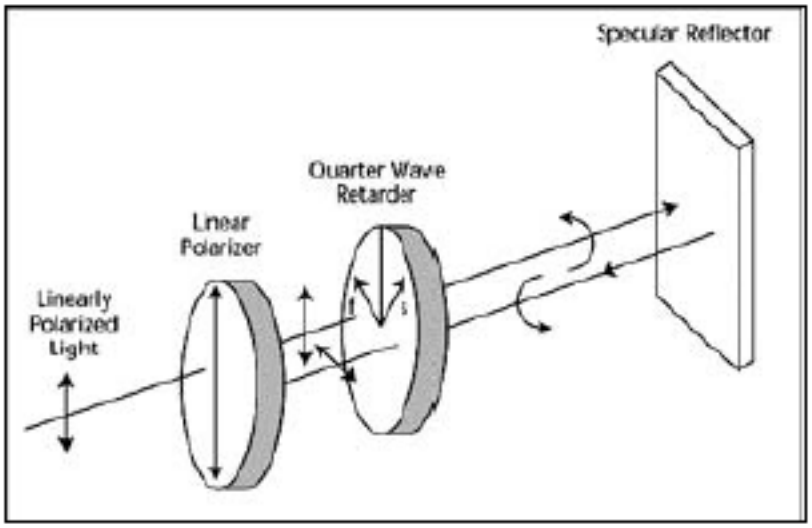


Fig. 3. Demonstration of optical isolation

Optical Attenuators

An optical attenuator is built by combining two linear polarizers and a half wave plate. The input and output polarizers are crossed so that no light passes through them, however, inserting the half wave plate allows light to pass through the device. The amount of light is determined by the angle between the optical axis of the incoming polarizer and half wave plate. Placing the half wave plate's optical axis at 45° to the incoming polarizer achieves a maximum transmission; aligning the optical axis of the half wave plate with either of the input or output polarizers optical axes gives the minimum transmission. How close the minimum is to zero transmission depends on the quality of the polarizers and half wave plate used in the device.

Replacing the half wave plate with a device that varies the polarization, such as a variable retarder, creates a variable attenuator. This configuration is shown in Figure 4. When we align the fast axis of the variable retarder at 45° to the input polarizer and modulate the retardance between half wave and full wave, transmission varies between maximum and minimum creating an optical shutter chopper.

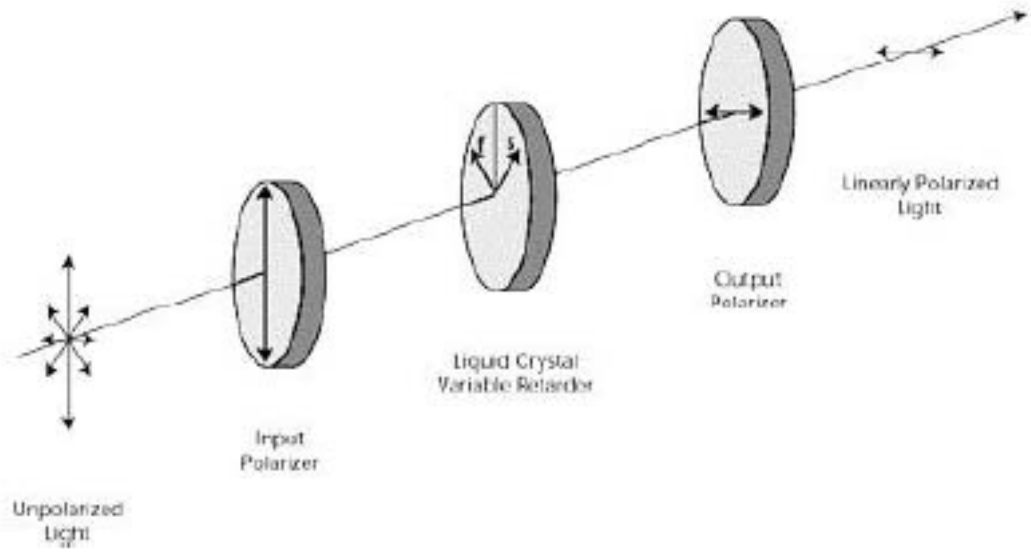
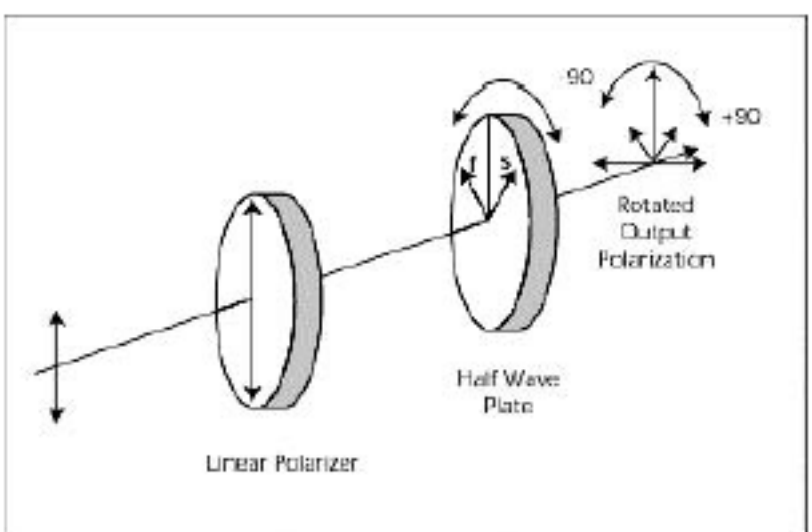


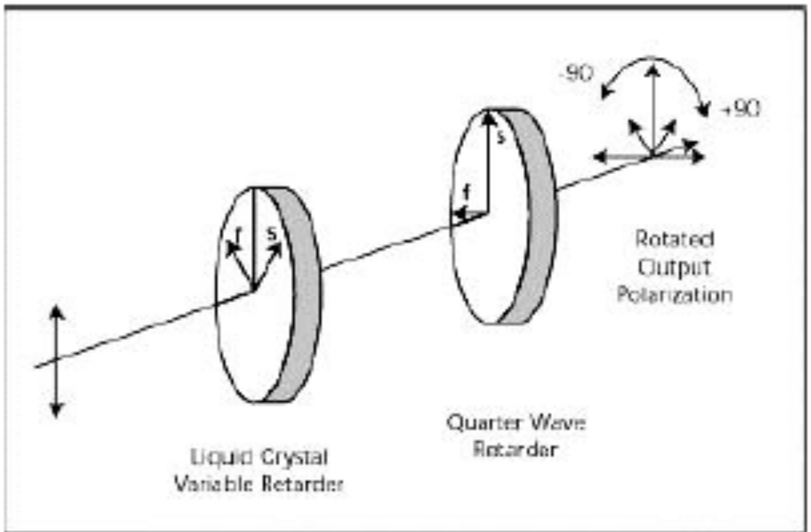
Fig. 4. The Variable Attenuator Configuration

Polarization rotator

A simple polarization rotator consists of a half wave plate in linear polarized light. Rotating the half wave plate causes the polarization to rotate to twice the angle of the half wave plate's fast axis with the polarization plane, as shown in Figure 5A. We achieve variable polarization rotation by aligning the fast axis of a variable retarder at 45° to the incoming polarization and following this component with a quarter wave retarder with it's slow axis aligned with the incoming polarization as seen in Figure 5B. The amount of rotation achieved depends on the amount of retardance exhibited by the first retarder. The polarization axis is rotated to an angle that is one-half the phase shift provided by the variable retarder.



A. Polarization rotation with a half wave plate



B. Variable polarization rotation with a variable retarder

Fig. 5. A demonstration of polarization rotation

Variable Beam Splitter

We can create a variable beam splitter by putting linearly polarized light through a half wave plate in combination with a polarizing beam splitter. The polarization of the light through the beam splitter governs the amount of light the beam splitter transmits and reflects. Aligning the retarder axis with the input vertical polarization achieves total reflection by the beam cube.

Conversely, rotating the half wave plate's fast axis to a 45° angle with the input polarization plane provides total transmission through the beam splitter. Replacing the half wave plate with a variable retarder whose fast axis is at 45° to the incoming polarization gives us the same beam splitting results as before with no mechanical motion. Varying the retardance between the 0 and half wave values creates an optical switch.

Conclusion

In this application note we have given a basic description of light polarization and some of the tools used to control the polarization state of light. Retarders and polarizers were used in simple devices that provide some of the common manipulations required wherever light is being measured.

a. Polarization by reflection and the Brewster angle

When natural light incidents on the interface of two media (e.g. air and glass), both the reflected and the transmitted (refracted) light rays become partially polarized.

Experimental Procedure:

Sequentially place white light source, lens (f'=150 mm), adjustable slit, and optical goniometer on the optical rail, align them at the same height, and let the filament of the light source locating on the front focal point of the lens (the interval between the two carriers is about 162 mm). After passing through the slit, the approximately parallel beam will hit to the disc of the optical goniometer, and leave a light track on the surface of the disc. Vertically mount the black glass along the 90°-90° line on the disc firmly. Then, place the polarizer holder mounted with polarizer *A* to the hole on the arm of the goniometer assembly, as seen in Figure 4.10-1. Let the light beam incident on the glass surface at an arbitrary angle, rotate polarizer *A* to check the polarization status of the reflected beam.

When rotating *A*, the transmitted light will vary alternatively between bright and dark, indicating that the reflected beam is partially polarized. When the incident angle is close to 56°30', the reflected light can be almost extinguished. This incident angle is called the Brewster Angle. Since the vibration plane of this linearly polarized light is perpendicular to the incident plane, the polarization direction of polarizer *A* can be determined.

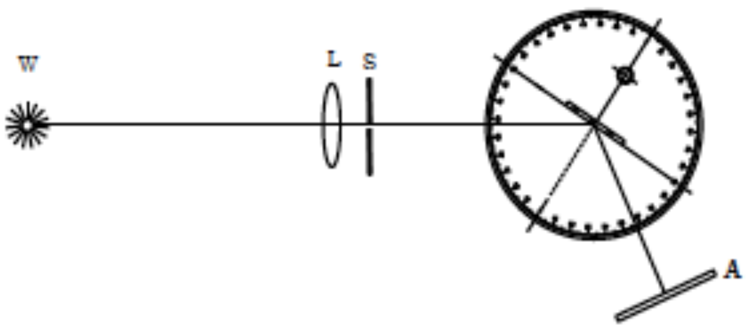


Figure 4.10-1 Schematic of the setup for generating polarized light by reflection

b. Polarization by dichroic material

Some materials have selective absorption to the polarization components of polarized light. Absorption may be stronger at one vibration direction, but weaker in the orthogonal direction. This is the dichroic characteristic of the materials. An H-type polarizer is created by attaching iodine to the hydrocarbon chain of one stretched long chain polymer film. A larger number of parallel aligned iodine-containing long-chain molecules form a grid structure that has a small spacing of less than light wavelength. Since the iodine atom has highly conductivity, the electric field component parallel to the grid is easier to be absorbed, while the vertical component is easier to transmit. Therefore, the dichroic film can be used to check the polarization status of a light beam.

Place two polarizers onto the optical rail with the one closer to the light source for the generation of polarized light, and the one behind as an analyzer. Rotate the analyzer, the intensity variation of the output light can be observed.

c. Birefractive characteristic of crystal

Put an iceland spar on a piece of printed paper, and we will see two distinct images of words. One image will remain fixed as the crystal is rotated, and the light ray through the crystal is 20

called "ordinary ray" since it behaves just as a ray through a glass. However, the other image will rotate with the crystal, tracing out a small circle around the ordinary image. This light ray is called "extraordinary ray". This is the phenomenon of birefringence. See Figure 4.10-2.

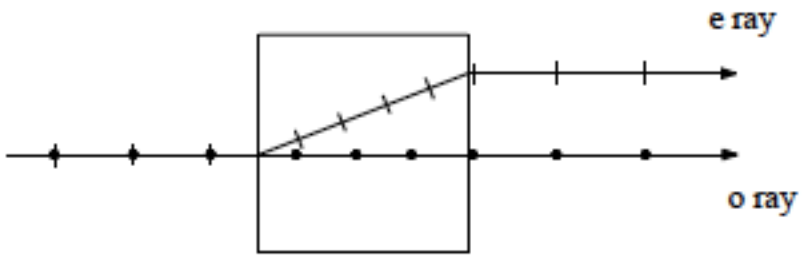


Figure 4.10-2 Schematic of birefringence

Place the iceland crystal with holder on the optical rail, illuminate the small hole in front of the crystal with a white light source, observe the transmitted light behind the iceland crystal with naked eyes, rotate the mount of the crystal, determine the "ordinary ray" and the "extraordinary ray" according to their intensity variations. Finally, use an analyzer with known polarization direction to determine the polarization directions of the o-ray and the e-ray.

d. Elliptically polarized light

Create a linearly polarized beam using the reflection method discussed above, i.e. an expanded laser beam passes a slit to be incident on the glass at the Brewster angle. See Figure 4.10-3, place quarter-wave plate *Q* on the goniometer arm to create elliptically polarized light. Mount analyzer *A* and white screen *C* on the two ends of an adapter piece and place them behind analyzer *A*. Rotate the analyzer while observing the dark and bright intensity variation of the transmitted light. At the dark location, the analyzer direction is the minor axis direction of the ellipse.

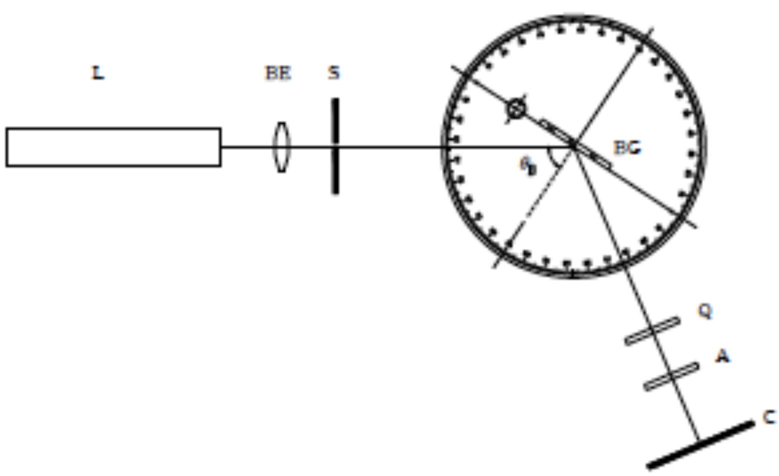


Figure 4.10-3 Schematic of experiment setup

e. Circularly polarized light

Place a He-Ne laser at one end of the optical rail, expand the laser beam using a beam expander, place two polarizers in the optical path of the expanded laser beam on the other end of the optical rail. Rotate one of the two polarizers to get output light extinguished, this means the axes of the two polarizers are perpendicular. Insert a quarter-wave plate between the two polarizers, and rotate it until the output light extinguished again. Further rotate the quarter-wave plate by 45°, the light behind the quarter-wave plate is now is now circularly polarized. Next, rotate the analyser (the polarizer following the waveplate), the intensity of the output light will be constant

4.11 Effect of optical activity

Components required: Sodium lamp (with ground glass on window), polarizer with rotary holder (2), liquid cell with holder, lens holder with lens f'=150 mm, glucose powder (user supply), distilled water (user supply), and measuring cup (user supply).

Principle: When linearly polarized light passes through certain solid substances or solutions, the plane of polarization of the light rotates by a certain angle. This phenomenon is called the effect of optical activity and the optical rotatory angle is called the specific rotation of the substance. The specific rotation of a solution depends on a number of parameters such as the substance in the solution, the concentration of the solution, the sample path length, the temperature of the solution, and the wavelength of the light. If other parameters are fixed, then the specific rotation, φ, is linearly proportional to the concentration of the solution, ρ in unit of g/cm3, and the sample path length, l, unit decimetre (dm), as

$$\varphi = \alpha \cdot \rho \cdot l \qquad (4.11\text{-}1)$$

where α is a coefficient representing the polarization rotation power of the substance in the solution, in unit of degree.cm3/dm.g.

Experiment:

Place the Sodium lamp at one end of the optical rail, place the lens (f'=150 mm) on the rail at a distance of about 150 mm away from the lamp window to form an approximately parallel beam. Put two polarizers in the optical path behind the lens, and rotate them to achieve light extinction as observed behind the second polarizer (analyzer). Next, mount the liquid tube (filled with prepared glucose solution) between the two polarizers, observe the output light, and rotate the analyzer to achieve light extinction again.

Using Eq. (4.11-1), from the measured rotation angle φ and the cell length l, if the solution concentration ρ is known, the polarization rotation power α of glucose solution can be derived, or, if α is known, the concentration ρ can be acquired. Note: α is temperature dependent, so it needs to be modified from a standard value at 20 °C by approximately -0.02°/°C.

After experiment, clean the liquid tube.

4. Photoelastic Modulator Calibration:

Objective: To configure the photoelastic modulator (PEM) as a quarter waveplate (birefringent phase difference of 2π radians) and measure its peak-to-peak retardation.

Equipment:

HeNe laser (red 632.8nm) PEM-80 by Hinds International, Inc.

3X Graduated Rotatable Plates
Mounting posts
Focusing lens
Two Polaroids (first Polarizer, second Analyzer)
Sensor Newport 818-SL
Hitachi Oscilloscope
Optical rail >1 meter in length

Equipment Specification: PEM-80 System: Series I, FS-5, Aperture 1.65cm, wavelength transmittance range (micron): 0.8-2.6, resonant frequency: 50kHz, Optical element: Fused Silica, Rectangular shape, half-wave retardation: 1 micron, quarter-wave retardation: 2 micron, visible to infrared. Please consult the various manuals located in the laboratory for further specifications.

Procedures:

I. Optical Arrangement: All optical devices were secured down on optical posts and rail as illustrated in Figure 1. The arrangement and the experiment were conducted on a covered optic table under darkness with minimum amount of ambient light.

<u>PEM-80 Controller (set in local mode):</u>

* Peak-to-Peak Retardation: this dial controlled the modulation amplitude,
* Phase Reference “F”: a BNC connected to the external trigger input on the oscilloscope,
* Sensor output: connected to the input/CH1 dc mode on the oscilloscope.

<u>Oscilloscope:</u>

- dc level for the ground was adjusted to eliminate the background ambient light inside the covered optic table, Volts/div at 50mV, Time/Div at 5μ sec.

<u>Polarizer and Analyzer:</u>

Both were Polaroids mounted vertically on graduated rotation plates to allow precise and incremental rotation. The first Polaroid was labeled as the Polarizer and the second commonly labeled as the Analyzer. The horizontal axis, parallel to the surface of the optical table, was arbitrarily chosen as 0^o.

PEM optical element/transducer: It was also mounted vertically on a graduated rotation plate to allow precise and incremental rotation. The graduation was in 1/10 of a degree, permitting finer adjustment of rotation. The horizontal axis, parallel to the surface of the optical table, was arbitrarily chosen as 0^o.

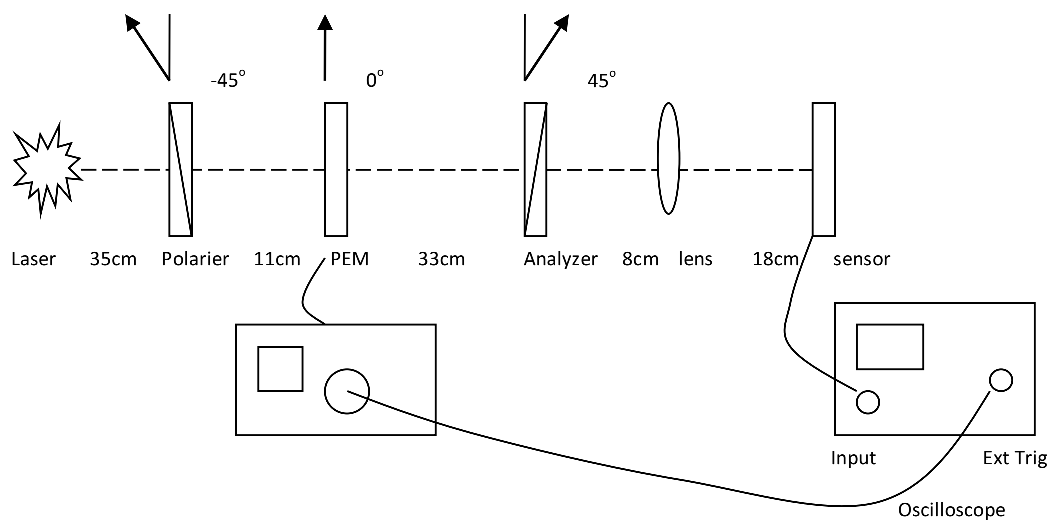
Sensor/Detector: This detected a dc signal after transmission from the Analyzer, which was either a un-modulated or modulated amplitude. The dc signal displayed as a flat line on the oscilloscope.

Figure 1 – Setup

II. Configuration Steps:

Step I. Alignment of the Polarizer and the Analyzer to be 90^{o} apart: When the transmission axes of the Polarizer and the Analyzer were perpendicular to each other, the extinction of the red monochromatic light would occur. The PEM-80 Controller would not be activated throughout this step and the Peak-to-Peak Retardation dial kept at "000," thereby not modulating the monochromatic red light. The PEM optical element should be kept at 0^{o}. The Polaroid should be kept at 0^{o} and the Analyzer rotated clockwise incrementally from 0^{o} to 360^{o} until the minimal amplitude of the sensor output would occur. The un-modulated amplitude of the sensor output should be measured on the oscilloscope and recorded. After finishing this step then proceed to Step II.

Step II. Orientation of the PEM Optical Element to be 45^{o} between the two Polaroids: This orientation would be equivalent to the Polarizer and the Analyzer at -45^{o} and 45^{o} relative to the modulator axis of the PEM optical element. The PEM Peak-to-Peak Retardation dial would be



activated without over-straining the optical element during this step. When over-straining occurred, the "Retardation Limit" indicator on the front panel of the PEM-80 Controller would flash, which should be avoided. The PEM optical element should be rotated in small increments, either CW or CCW from 0^{o} to 90.0^{o} until a steady maximum amplitude would be detectable.

Step III. Maximizing Modulated Amplitude with Peak-to-Peak Retardation:

This would be performed simply by changing incrementally the Peak-to-Peak Retardation dial on the front panel of the PEM-80 Controller without over-straining the optical element. The modulated amplitude should be compared to the un-modulated amplitude for maximization.

Data Analysis

I. Alignment of the Polaroid and the Analyzer to be 90^{o} apart:

When the Polaroid was kept at 0^{o} and the Analyzer rotated clockwise, the minimal amplitude of the sensor output occurred when the Analyzer was rotated at 272^{o}, equivalent of the two crossed at 90^{o} apart, or extinction of the red monochromatic light. The PEM-80 Controller was not activated throughout this procedure and its Peak-to-Peak Retardation dial was kept at 000, thereby the monochromatic red light was not modulated. The maximum un-modulated amplitude of the sensor output was maintained at 175mV when the Analyzer was between 150 to 210^{o} of rotation (Figure 2).

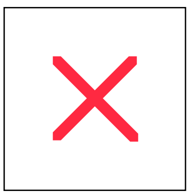


Figure 2

II. Orientation of the PEM Optical Element to be 45^{o} between the two Polaroids:

During this step, the PEM Peak-to-Peak Retardation dial was arbitrarily set at “200” to avoid over-straining the optical element. The “Retardation Limit” indicator on the front panel of the PEM-80 Controller flashed several times when the dial setting exceeded “300” during rotation manipulation of the optical element. To avoid erroneous modulation, it was best to wait a period of time to allow the optical element to relax from the over-stretching and over-compression before one could re-start this step.

The maximum modulated amplitude of the sensor was maintained at 150mV when the PEM optical element was rotated between CCW 36.0^{o} to 48.0^{o} (Figure 3). This was lower than the un-modulated amplitude of 175mV obtained earlier in the first step, indicating further maximization was possible. Thereafter, the optical element was arbitrarily kept at 46.0^{o} to permit further maximization of the modulated amplitude in the next step. This was accomplished by changing the Peak-to-Peak Retardation dial on the PEM-80 Controller. For reasons unclear at present, rotating the optical element in a CW fashion soon set off the “Retardation Limit” indicator flashing.

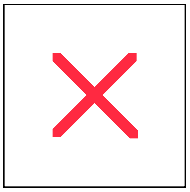


Figure 3

III. Maximizing Modulated Amplitude with Peak-to-Peak Retardation:

The last step was performed simply by increasing incrementally the Peak-to-Peak Retardation dial on the front panel of the PEM-80 Controller. The maximized modulated amplitude returned to 175mV when the dial setting was greater than 750 (Figure 4), which was arbitrarily chosen as the safe setting to avoid over-straining the optical element. When a quarter-wave plate was inserted between the PEM optical element and the Analyzer, the sensor detected 170mV and the quarter-wave plate had absorbed 5mV of modulated amplitude. This indirectly showed that the experimental steps had successfully configured the PEM-80 to be a quarter-wave plate.

In summary, the PEM-80 Controller setting was selected to be 750, the Polaroid at 0^{o} and the Analyzer at 272^{o}, and finally the PEM optical element at -46.0^{o} to be configured as a quarter-wave plate.

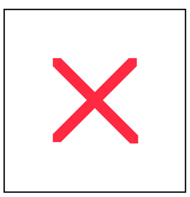


Figure 4

Technical References

(1) “PEM-80 Photoelastic Modulator Operation & Service Manual” & “Application Notes” by Hinds International, Inc. (1982, 1987).

(2) “Polarized Light & Its Interaction with Modulating Devices” by J.C. Kemp, Jan. 1987, published by Hinds International, Inc.

Problems:

1. A beam of unpolarized light with intensity of 43 W/m^3 is sent into a system of two polarizing sheets with polarizing directions at $\theta_1 = 70°$ and $\theta_2 = 90°$ to the y-axis. What is the intensity of light transmitted by the system?

2. At a beach the light is generally partially polarized due to reflections off sand and water. At a particular beach on a particular day near sundown, the horizontal component of the electric field is 2.3 times the vertical component. A standing sunbather puts on polarizing glasses; the glasses eliminate the horizontal field component. (a) What fraction of the light intensity received before the glasses were put on now reaches the sunbather's eyes? (b) The sunbather, still bearing the glasses, lies on his side. What fraction of the light intensity received before the glasses were put on now reaches his eyes?

3. The unpolarized light is sent into a system of three polarizing sheets. The angles θ_1, θ_2 and θ_3 of the polarizing directions are measured counter clock wise from the positive direction of y axis. Angles θ_1 and θ_3 are fixed, but angle θ_2 can be varied. The following figure gives the intensity of light emerging from sheet three as a function of θ_2. What percentage of the light's initial intensity is transmitted by the three sheet system when $\theta_2 = 90°$.

4. We want to rotate the direction of polarization of a beam of polarized light through 90° by sending a beam through one or more polarizing sheets. (a) What is the minimum number of sheets required? (b) What is the minimum number of sheets required if the transmitted intensity is to be more than 60% of the original intensity?

5. An optical fiber has a plastic core (n_1=1.58) which is surrounded by a plastic sheet (n_2=1.53). A light ray is incident on one end of the fiber at an angle θ. The ray is to undergo total internal reflection at point A, where it encounters the core-sheath boundary (thus there is no loss of light through that boundary). What is the minimum value of θ that allows total internal reflection at A?

6. An unpolarized beam of light is sent into a stack of four polarizing sheets, oriented so that the angle between the polarizing directions of adjacent sheets is 30°. What fraction of the incident intensity of light is transmitted by the system?

7. A beam of initially unpolarized light is sent through two polarizing sheets placed one on the top of the other. What must be the angle between the polarizing direction of the sheets if the intensity of the transmitted light is to be one-third the incedent intensity?

8. Three polarizing sheets are stacked. The first and third are crossed; the one between has its polarizing direction at 45.0° to the polarizing directions of the other two. What fraction of the intensity of an originally unpolarized beam is transmitted by the stack?

9. A polaroid sheet and an analyzer are placed such that their transmission axes are co-linear. The analyzer is then rotated by 22.5 ^{o}. What is the irradiance of the transmitted light as a fraction of its previous value?

10. You have three ideal linear polarizers. Light of irradiance 1000 W/m ^{2} is shone through two of the polarizers, with their transmission axes placed at a relative angle of 40 ^{o}. What is the intensity of the transmitted light? Now place the third polarizer at an angle of 20 ^{o} between the other two. What is the irradiance?

11. What is Brewster's angle for reflection from air off a glass ($n = 1.52$) surface?

12. Write the equation for the linearly polarized light wave of angular frequency σ and amplitude E_0 propagating along the x-axis with its plane of vibration at 30 ^{o} to the xy -plane (assume that $\mathbf{E} = 0$ when $x = 0$ and $t = 0$).