Study of polarization of light

Objectives:

1. To analyze linearly polarized light

2. To verify Malu's law

3. To rotate the state of polarization of a linearly polarized light using a half wave plate

4. Conversion of linearly polarized light into elliptically/circularly polarized light using quarter wave plate

Theoretical background:

Polarization is a property applying to transverse waves that specifies the geometrical orientation of the oscillations. In a transverse wave, the direction of the oscillation is perpendicular to the direction of motion of the wave. An electromagnetic wave, such as light, consists of a coupled oscillating electric and magnetic field which are always perpendicular to each other. By convention, the "polarization" of electromagnetic waves refers to the direction of the electric field.

When the polarization state of a light wave changes more rapidly than we can detect it, it is known as **unpolarised light**, because all the effects of polarization average out. The unpolarised light can be considered to be composed of two linear orthogonal polarization states with complete incoherence (Fig. 1). Light from most natural sources such as, the sun, flames and incandescent lamps are examples of unpolarized light.

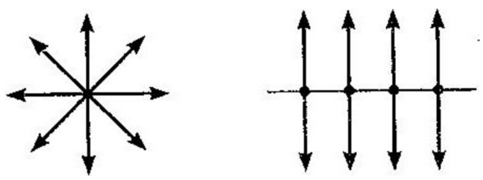

Fig. 1: Unpolarized light- the dots marked on the right side figure represent direction of polarization into/out of the plane of the paper

It is possible to convert unpolarized light to linearly (or plane) polarized light by restricting the oscillations of electric field vectors to one particular orientation only. This can be done by using a polarizer, which usually make use of birefringent properties of certain crystals (quartz, calcite etc). However, many other methods are available to produce linearly polarized light.

When a beam of natural (unpolarized) light is incident on a polarizer, the transmitted beam is linearly polarized with the direction of vibration parallel to the transmission axis of the polarizer as shown in Fig. 2. If the intensity of the incident beam is I_0, the intensity of the transmitted beam is $I_0/2$. Any rotation of the polarizer changes the orientation of the linearly polarized light but not its intensity.

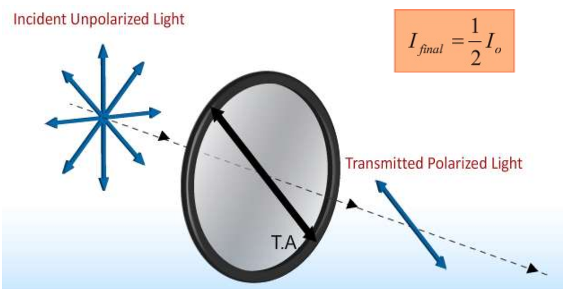

Fig. 2: Converting an Unpolarized light to a plane polarized light using a polarizer

Analysing linearly polarized light: An ideal linear polarizer has 100% transmission for linearly polarized light for an orientation parallel to its transmission axis and zero transmission at an orientation orthogonal to it. To verify this, one can use another identical polarizer which is known as the analyzer because of its use. If a linearly polarized beam coming out of the first polarizer is incident on the second polarizer (analyser), the irradiance of the transmitted beam will vary with the rotation of the analyser. If the transmission axes of both the polarizer and analyzer are parallel to each other, a plane polarized light with maximum intensity will be obtained. If the transmission axes are orthogonal to each other, no light will be obtained at the output as shown in Fig. 3.

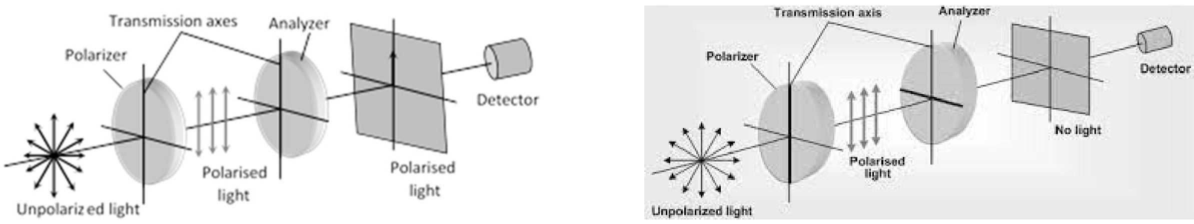

Fig. 3: Analyzing a linearly polarized light using a polarizer and analyzer

Malus's law:

For a linearly polarized light with intensity I_0, the intensity transmitted through an ideal analyzer, I, can be described by Malus's law as follows:

$$I = I_0 \cos^2 \theta \qquad (1)$$

where θ is the angle between the incident linear polarization and the polarization axis. This means intensity of the transmitted light becomes twice maximum and twice zero on one complete rotation of 360^0. Malus's Law plays an important role in the modulation of light intensity.

Wave Plates (Retarders):

While polarizers select certain polarizations of light, discarding the other polarizations, ideal wave plates modify existing polarizations without attenuating, deviating, or displacing the beam. They do this by retarding (or delaying) one component of polarization with respect to its orthogonal component. Wave plates are made of birefringent materials (quartz, mica, polymers, etc.) that have different indices of refraction for light linearly polarized along one or the other of two certain perpendicular crystal axes. When a laser beam falls on such a material, it gets divided into two rays: one is called the ordinary ray and the other one is called extra-ordinary ray. The refractive indices seen by the ordinary and extra-ordinary ray are denoted as n_o and n_e. This causes a relative phase difference between the two emergent beams which is expressed as:

$$\boldsymbol{\varphi = \frac{2\pi}{\lambda}(n_0 - n_e)d} \qquad \textbf{(2)}$$

where *d* is the thickness of the crystal and $\boldsymbol{\lambda}$ is the wavelength of the laser beam in vacuum.

Depending on the values of the relative phase difference $\boldsymbol{\varphi}$**,** the state of polarization of the emerging light can be further classified. For $\boldsymbol{\varphi} = n\pi$ (n = any integer), the state of polarization of the emerging light remains if the incident light is linear. When $\boldsymbol{\varphi} = (2n+1)\pi/2$, the state of polarization becomes circular provided the amplitudes of the ordinary and extra ordinary rays are equal. All other intermediate values of $\boldsymbol{\varphi}$ will give rise to elliptical polarized light.

Half wave plate:

If the thickness of the birefringent crystal is such that the phase difference between the two emergent beams is π, the retarder is termed as a half wave plate. Suppose a linearly polarized light is normally incident on a half wave plate, and its plane of polarization is at an angle θ with respect to the fast axis, the emergent light will have its polarization axis rotated by an angle 2θ (Fig. 4a). The same result will be found if the incident wave makes an angle θ with respect to the slow axis.

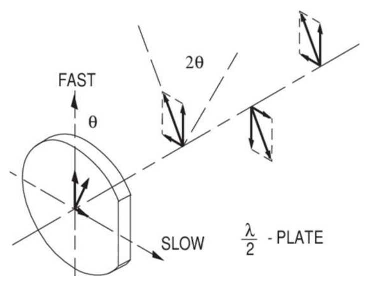

Fig. 4: (a) Half wave plate rotates direction of linear polarization

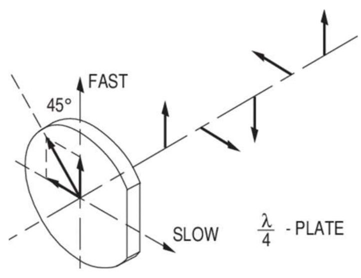

Fig. 4: (b) Quarter wave plate converts linear polarization to circular polarization

Quarter wave plate:

Similarly, if the thickness of the birefringent crystal is such that the phase difference between the two emergent beams is $\pi/2$, the retarder is termed as a quarter wave plate. Suppose linearly polarized light is normally incident on a quarter wave plate, and its plane of polarization is at an angle 45^0 with respect to the fast axis, the emergent light will have circular polarization. If the angle is anything between 0 to 90^0 but not 45^0, then the emergent light will have elliptical polarization.

Apparatus:

1. He-Ne laser with power supply with mount
2. Polarizer and analyzer (identical to polarizer)
3. Half waveplate
4. Quarter wave plate
5. Photo-detector
6. Digital multimeter, resistor, breadboard and connecting cables
7. Optical bench/breadboard with suitable optical posts and post holders

Procedure:

1. Switch on the laser system first and make sure that it remains on for sufficiently long time to get a stable output. The output of the photodetector is connected to a resistor on a breadboard. The voltage across the resistor is measured by a digital multimeter. This photo voltage is directly proportional to the intensity of the laser beam falling on the detector.
2. Place the polarizer on the optical rail.
3. Place the detector on the optical rail and align the laser, polarizer and the detector such that their axes are in the same line.
4. Note down the voltage corresponding to the dark current value (if any) on the multimeter by blocking the laser beam. If you get a non-zero value, then subtract it every time from the voltage value you measure when the laser beam is allowed to fall on the detector.
5. Rotate the polarizer and try to ascertain the state of polarization of the input laser beam by looking at the readings on the multimeter (Is it strictly unpolarized?).

(I) To analyze linearly Polarized light:

1. Adjust the polarizer axis by rotating it slowly till you get maximum voltage on the multimeter.
2. Now insert the analyzer between the polarizer and the photodetector as shown in Fig. 5. Adjust its axis by rotating it with respect to the polarizer till you see a maximum voltage on multimeter display. At this position the axes of the polarizer and analyzer are parallel to each other.

Fig. 5: Set up for analyzing linearly polarized light

   Note down the angular positions of the polarizer and analyzer. In ideal case, both the readings should be the same for a set of identical polarizer and analyzer.
3. From here onwards the position of the polarizer will remain fixed at this value. The angular position of the analyzer will be the offset. You need to correct your acquired data using this offset to get the correct angular position of the analyzer with respect to the polarizer.
4. Now carefully rotate the analyzer, initially in steps of, say 20^0. You may need to reduce the steps while you approach the positions of maximum or minimum. Use your judgement and accordingly choose the increment steps. Rotate the analyzer till you observe two maxima and two minima in a full rotation. Note down the angular positions and the corresponding voltage values on the multimeter display in Table 1 and plot the data (use polar graph).
5. Comment on the values of minima obtained (is it close to zero or not so low?)

(II) To verify Malus's law:

1. Use the data acquired above in step 5 to fill in Table 2.
2. The voltage value measured is relatable to the intensity of light.
3. Using Eq. 1, plot the data to get a straight line and verify Malus's law. Use least square fit for the graph.

(III) Rotation of Polarization:

Bring back the entire set up so that the axes of polarizer and analyzer are parallel again and note the reading on the multimeter.

1. Insert a half wave plate, with its axis set at zero, in between the polarizer and analyzer as shown in Fig. 6 so that the optical axis is maintained.

Fig. 6: Set up for studying polarization state of light using half/quarter wave plate

2. If you notice any change in the multimeter reading, then rotate the half wave plate slowly so that you get back the same reading on the multimeter. Note down the angular position of the half wave plate. Now this position should be recalibrated as the zero position, if there is an offset.
3. Rotate the half wave plate to any angular position, **θ**, with respect to the recalibrated zero position (say 45^0).
4. Keeping the position of the polarizer unchanged, carefully rotate the analyzer. Use your judgement again and accordingly choose the increment steps. Rotate the analyzer till you observe two maxima and two minima in a full rotation. Note down the angular positions and the corresponding voltage values on the multimeter display in Table 3 and plot a suitable graph. Do you see a rotation of the polarization state of the laser beam by 2**θ** (in this case 90^0)?

(IV) To produce elliptical/circularly polarized light:

1. Remove the half wave plate. Bring back once again the entire set up so that the axes of polarizer and analyzer are parallel and note the reading on the multimeter.
2. Insert a quarter wave plate, with its axis set at zero, in between the polarizer and analyzer as shown in Fig. 6 aligning in the same optical axis. Follow the step 2 of the Procedure (III) mentioned above to readjust the zero position of the quarter waveplate. Note down the offset, if any.
3. Rotate the quarter wave plate to any angular position, **θ** (between 0 to 90^0), with respect to the recalibrated zero position. To produce circularly polarized light, fix the position at 45^0.
4. Keeping the position of the polarizer unchanged, carefully rotate the analyzer. Use your judgement again and accordingly choose the increment steps. Rotate the analyzer till you observe two maxima and two minima in a full rotation. Note down the angular positions and the corresponding voltage values on the multimeter display in Table 4 and plot a polar graph.
5. Comment on the values of minima obtained. Comment on the state of polarization of the laser beam falling on the detector.

Observations:

Sl No.	Angular position of the analyzer (**θ** in deg)	Corrected angular position of the analyzer (**θ** in deg)	Voltage (V)

Table: 1 Angular position of the polarizer = …

Table: 2

Sl No.	Corrected angular position of the analyzer (**θ** in deg)	$\text{Cos}^2 \boldsymbol{\theta}$	Voltage (V)

Table: 3

Angular position of the polarizer = … Angular position of the half wave plate = …

Sl No.	Angular position of the analyzer (**θ** in deg)	Corrected angular position of the analyzer (**θ** in deg)	Voltage (V)

Table: 4

Sl No.	Angular position of the analyzer (**θ** in deg)	Corrected angular position of the analyzer (**θ** in deg)	Voltage (V)

Angular position of the polarizer = …   Angular position of the quarter wave plate = …

Results and discussions:

References:

1. E. Hecht, Optics.
2. The Feynman Lectures on Physics, Vol. 1.
3. Figures in theoretical background section are collected from various internet sources.