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# Polarization of Light using Wave Plates and Study of Birefringence

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## 1 Aim

- Measuring the light intensity as function of the analyzer position.
- Using the quarter wave plate to produce circularly polarized light.
- To study the effect of polarization of a plane polarized light by half wave plate and quarter wave plate.
- To measure the intensity at different angles and verify the phenomenon of linear and circular polarization.

## 2 Apparatus

- Light source,
- Polarizer,
- Analyzer,
- Half-wave plate,
- Full-wave plate,
- Photo detector.

## 3 Introduction

A wave plate or retarder is an optical device that alters the polarization state of a light beam travelling through it. A typical wave plate is simply a birefringent crystal or a double refracting plastic foil with a carefully chosen thickness.

If a beam of parallel light strikes perpendicularly a wave plate the light beam is splitted into two components due to its double refracting properties. The two components have planes of oscillation perpendicular to each other and slightly different phase velocities. For a quarter-wave plate the thickness of the foil is chosen in such a manner that the light component whose electric field vector oscillates in parallel to the rotation lever lags by a  $\lambda/4$  behind other perpendicular oscillating light component. For a half-wave plate the thickness is chosen so that the created phase difference has the amount of  $\lambda/2$ .

In this experiment monochromatic light falls on a quarter-wave and half-wave plate. The polarization of the emergent light is investigated at different angles between the optic axis of the wave plates and the direction of the incident light.

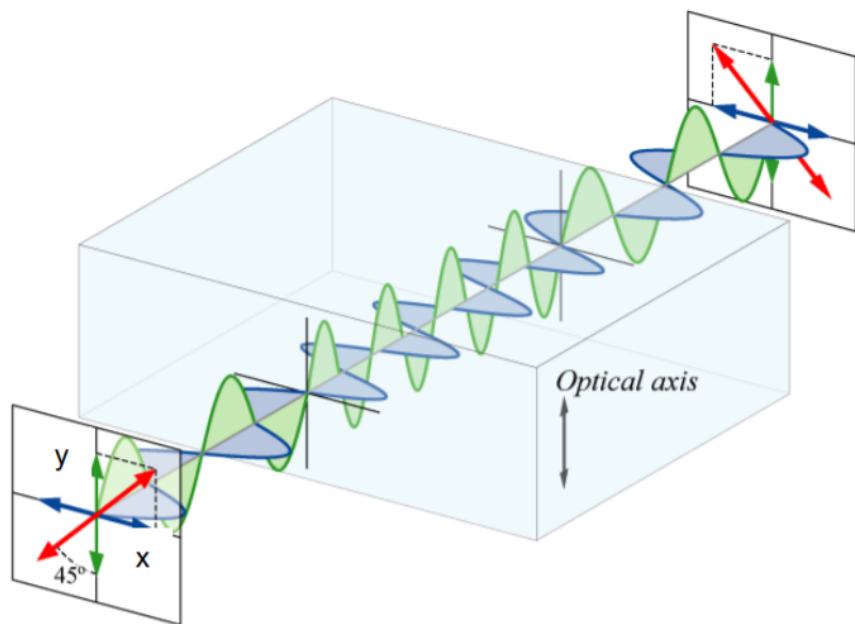


Figure 1: A half-wave plate schematically. Linearly polarized light entering a wave plate can be resolved into two waves, parallel (shown as green) and perpendicular (blue) to the optical axis of the wave plate. In the plate the parallel wave propagates slightly slower than the perpendicular one. At the far side of the plate the parallel wave is exactly half of a wavelength delayed relative to the perpendicular wave.

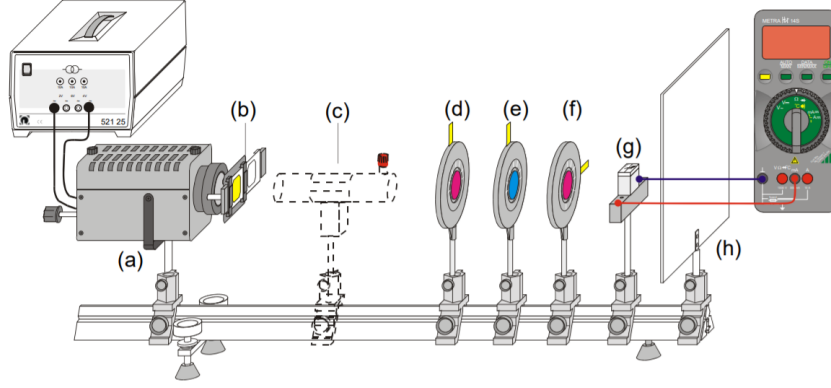


Figure 2: Experimental setup for investigating the type of polarization of the emergent light (schematically). (a) halogen lamp (d) polarizer (g) Si photo cell (b) picture slider with filters (e)  $\lambda/4$  or  $\lambda/2$  wave plate (h) translucent screen (c) heat protection filter (f) analyzer

## 4 Schematic

## 5 Theory

A retarder (or waveplate) resolves a light wave into two orthogonal linear polarization components by producing a phase shift between them. The type of polarization depends on this phase difference.

A retarder is an anisotropic slab that has different magnitudes of refractive indices along its different axes. Light waves can be thought of as the superposition of two perpendicular components once it enters the retarder. Thus, the components experience different refractive indices. The speed of light in a medium is inversely proportional to its refractive index. Hence, one component lags the other in phase.

The two types of retarders we consider are: **Half-Wave and Quarter-Wave Plates**. A half wave plate retards one component by  $180^\circ$ . In terms of the path difference, there is a shift by  $\frac{\lambda}{2}$  i.e. half a wave. A quarter wave plate retards one component by  $90^\circ$  i.e. by  $\frac{\lambda}{4}$  or quarter of a wave.  $E_0$  is the amplitude of the electric field vector emerging from the polarizer and  $\varphi$  the angle between the polarizer and the quarter wave plate. At a time  $t$  the state of vibration of the two component rays is described by:

$$\begin{aligned} E_1(t) &= E_0(t) \cdot \sin \varphi t \cdot \sin \omega \cdot t \\ E_2(t) &= E_0(t) \cdot \cos \varphi t \cdot \sin \omega \cdot t \end{aligned} \quad (1)$$

In the case of the double refracting quarter wave plates the thickness causes a path difference of  $\lambda/4$  (i.e. a phase difference of  $\pi/2$ ) between the two rays. When emerging the quarter wave plate they combine to a resultant ray which

can be described by the parametric equations:

$$\begin{aligned} E_1(t) &= E_0 \cdot \sin \varphi t \cdot \sin \omega \cdot t \\ E_2(t) &= E_0 \cdot \cos \varphi t \cdot \sin \omega \cdot t \end{aligned} \quad (2)$$

These equation describe an rotating E vector in the direction of propagation, i.e. perpendicular to the x- and y-axis about a fixed axis (1). For the angles  $\varphi = 0^\circ$  and  $\varphi = 90^\circ$  we obtain plane polarized light intensity after the quarter wave plate:

$$I = I_0 \sim E_0^2 \quad (3)$$

For an angle  $\varphi = 45^\circ$ ,  $\sin \varphi = \cos \varphi = \frac{1}{\sqrt{2}}$  and the amount of the rotating E vector is given by:

$$E = \sqrt{E_1^2 + E_2^2} = \frac{E_0}{\sqrt{2}} \quad (4)$$

The light is circularly polarized and the intensity is given by:

$$I = \frac{I_0}{2} \sim \frac{E_0^2}{2} \quad (5)$$

At all other angles  $\varphi$  other than  $0^\circ, 45^\circ, 90^\circ$  the transmitted light is elliptically polarized. The tip of the E vector rotating about the axis parallel to the direction of propagation describes an ellipse with the semi axes  $a$  and  $b$ :

$$\begin{aligned} E_a(t) &= E_0 \cdot \sin \varphi t \cdot \sin \omega \cdot t \\ E_b(t) &= E_0 \cdot \cos \varphi t \cdot \sin \omega \cdot t \end{aligned} \quad (6)$$

The intensity for any angle  $\varphi$  between analyzer and quarter wave plate (here e.g.  $\varphi = 30^\circ = 60^\circ$ ) is given by:

$$I \sim E_0^2 \cos^2 \varphi \cos^2 \alpha + E_0^2 \sin^2 \varphi \sin^2 \alpha \quad (7)$$

The half wave plate produces plane polarized light. For different positions  $\varphi$  of the half wave plate only the polarization plane changes. For example, if the position of the half wave plate is changed about  $45^\circ$  the polarization plane changes about  $90^\circ$ . **Linear polarization** is when the different components of the light wave are retarded such that there is a phase difference of  $0^\circ, 180^\circ$  or  $360^\circ$  between them. **Elliptical polarization** is when the phase difference is  $90^\circ$ .

The light from the analyser is incident on a photo receptor which measures its intensity. The readings are taken in terms of the current measured. For the rest of the experiment, we treat this current as the intensity ratio in order to verify with the formulae.

## 6 Observations and Results

1. Angle of polarizer,  $\theta = 120^\circ$
2. Rotation of half-wave/quarter-wave plate,  $\varphi = 45^\circ$

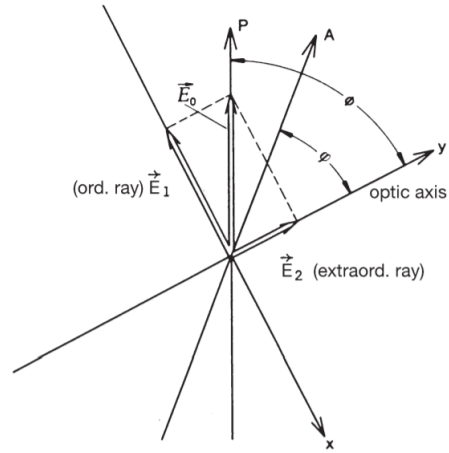


Figure 3: Splitting of polarised light in a double-refracting crystal (P = polarizer, A = analyzer).

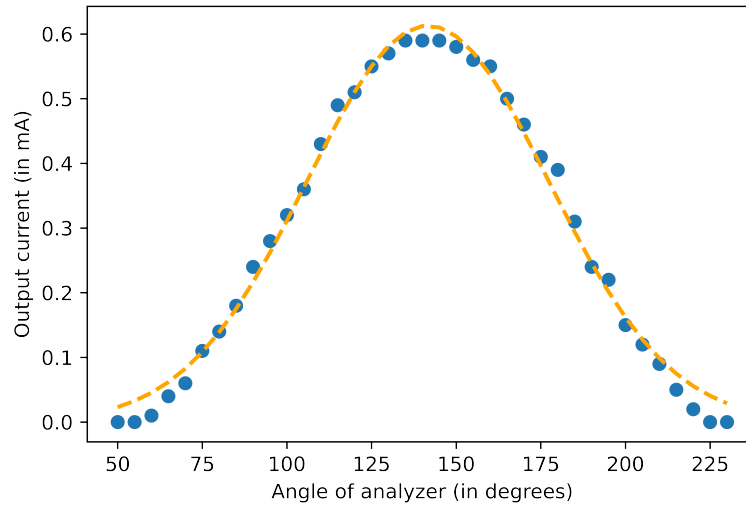


Figure 4: The  $I \sim \alpha$  plot for half-wave plate

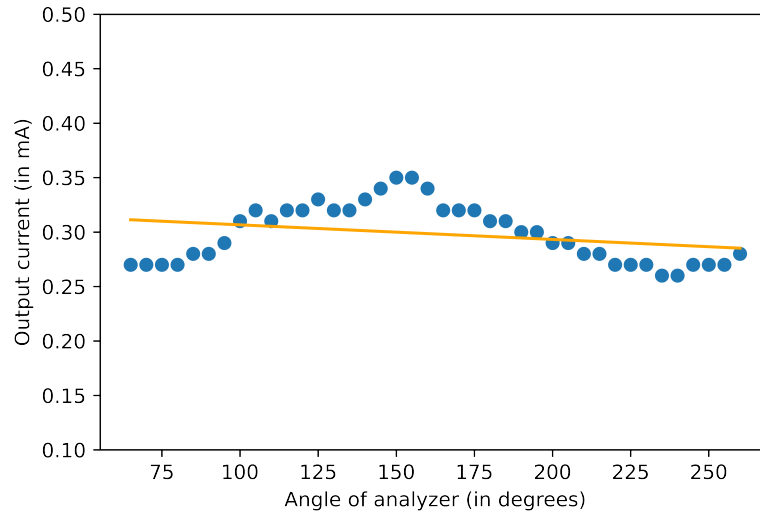


Figure 5: The  $I \sim \alpha$  plot for quarter-wave plate

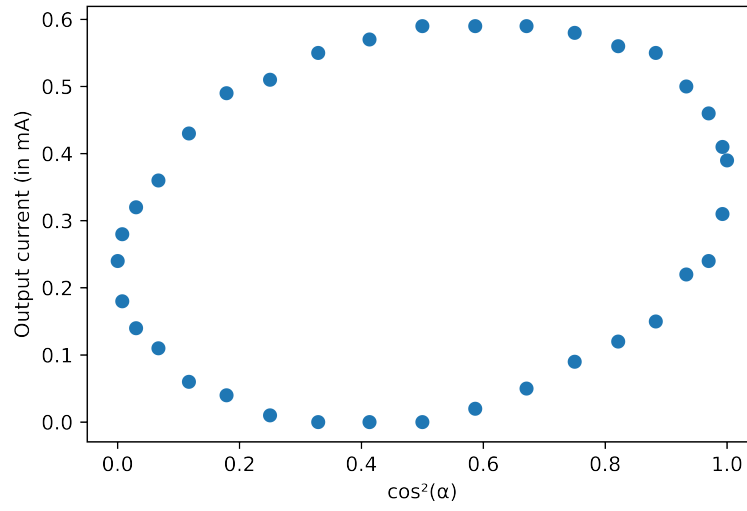


Figure 6: The  $I \sim \cos^2 \alpha$  plot for half-wave plate

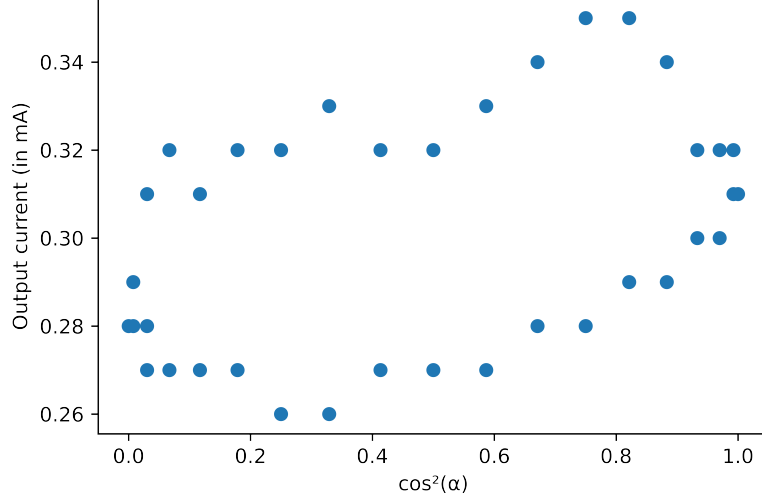


Figure 7: The  $I \sim \cos^2 \alpha$  plot for quarter-wave plate

## 7 Result and Discussion

1. The photo current is proportional to the light intensity. The light intensity is proportional to the electric field vector to the square:  $I \sim E^2$ .
2. The current plot of the half-wave plate appears to a squared sinusoidal wave. This is as expected for linear polarization.
3. The current against squared cosines of the angle is expected to be a straight line. However, the plot we have is elliptical. One reason could be that the retardation was not completely by  $\pi$  which could be the fault of the wave-plate.
4. The current of the quarter-wave plate appears to be a straight line parallel to the x-axis for the most part i.e. almost constant. We expect this for circular polarization.
5. In circular co-ordinates we expect the plot to be a circle i.e. the radial distance acts as current (which we expect to be constant). Our plot is slightly distorted but the extremities are almost similar values. Hence, we can, for argument sake, take this to be approximated as circular behaviour. This level of distortion could be attributed to manual errors or discrepancies in the photo detector.



Table 1: The readings for half-wave plate

Table 2

Analyzer angle (in degrees)	Current (mA)
50	0
55	0
60	0.01
65	0.04
70	0.06
75	0.11
80	0.14
85	0.18
90	0.24
95	0.28
100	0.32
105	0.36
110	0.43
115	0.49
120	0.51
125	0.55
130	0.57
135	0.59
140	0.59
145	0.59
150	0.58
155	0.56
160	0.55
165	0.5
170	0.46
175	0.41
180	0.39
185	0.31
190	0.24
195	0.22
200	0.15
205	0.12
210	0.09
215	0.05
220	0.02
225	0
230	0

Table 3

Squared cosine of analyzer angle	Current (mA)
0.41	0
0.33	0
0.25	0.01
0.18	0.04
0.12	0.06
0.07	0.11
0.03	0.14
0.01	0.18
0.00	0.24
0.01	0.28
0.03	0.32
0.07	0.36
0.12	0.43
0.18	0.49
0.25	0.51
0.33	0.55
0.41	0.57
0.50	0.59
0.59	0.59
0.67	0.59
0.75	0.58
0.82	0.56
0.88	0.55
0.93	0.5
0.97	0.46
0.99	0.41
1.00	0.39
0.99	0.31
0.97	0.24
0.93	0.22
0.88	0.15
0.82	0.12
0.75	0.09
0.67	0.05
0.59	0.02
0.50	0
0.41	0

## 8 Conclusion

Thus, through the experimental process we have tried to understand and visualize the two types of polarization.

## 9 Precautions

1. Do not look directly into the light source.
2. Make sure the polarizer, wave-plate, analyser are along the same line.
3. Do not touch the transmitting surfaces with bare hands
4. Turn off the source when not in use.

Table 4: The readings for quarter-wave plate

Table 5

Analyzer angle (in degrees)	Current (mA)
65	0.27
70	0.27
75	0.27
80	0.27
85	0.28
90	0.28
95	0.29
100	0.31
105	0.32
110	0.31
115	0.32
120	0.32
125	0.33
130	0.32
135	0.32
140	0.33
145	0.34
150	0.35
155	0.35
160	0.34
165	0.32
170	0.32
175	0.32
180	0.31
185	0.31
190	0.3
195	0.3
200	0.29
205	0.29
210	0.28
215	0.28
220	0.27
225	0.27
230	0.27
235	0.26
240	0.26
245	0.27
250	0.27
255	0.27
260	0.28

Table 6

Squared cosine of analyzer angle	Current (mA)
0.18	0.27
0.12	0.27
0.07	0.27
0.03	0.27
0.01	0.28
0.00	0.28
0.01	0.29
0.03	0.31
0.07	0.32
0.12	0.31
0.18	0.32
0.25	0.32
0.33	0.33
0.41	0.32
0.50	0.32
0.59	0.33
0.67	0.34
0.75	0.35
0.82	0.35
0.88	0.34
0.93	0.32
0.97	0.32
0.99	0.32
1.00	0.31
0.99	0.31
0.97	0.3
0.93	0.3
0.88	0.29
0.82	0.29
0.75	0.28
0.67	0.28
0.59	0.27
0.50	0.27
0.41	0.27
0.33	0.26
0.25	0.26
0.18	0.27
0.12	0.27
0.07	0.27
0.03	0.28