# Chapter 5

# Polarisation

## Objectives

1. To verify Malus' Law
2. To find Brewster's Angle (Brewster's Law) by studying the polarisation properties of light

## Introduction/Theory/Background

In an electromagnetic plane wave that is linearly polarized the electric field vector E is oriented along the plane perpendicular to the direction of propagation of the wave. This, if the direction of propagation is z, the E vector is in the x-y plane. Since this E vector can be along an direction in the x-y plane, we can think of it as a superposition of two perpendicular vectors, one along x and the other along y. These two components must be in phase for the light to be linearly polarized. (If there is well-defined and constant phase difference between these components, the light is elliptically polarized.) If, however, the two components have no well-defined phase relationship, i.e. if they are incoherent, then the light is unpolarized.

Polarisers are made of a material comprising of long chain molecules, all having the same orientation. When unpolarised light is incident upon the polarisers, the electric field component along the molecules chains is absorbed, leaving only the perpendicular component to pass through. Thus the light that passes through the polariser is perpendicular to the alignment of the molecules, and is in a single plane - this light is then polarised.

### Malus' Law

Malus's Law states that for unpolarised light passing through a polariser and an analyser, the intensity of the resulting beam which is picked up by a photodiode follows:

$$\boxed{I(\theta) = I_\circ \cos^2 \theta} \tag{5.1}$$

where $I_\circ$ is the maximum intensity detected by the photodiode, and $\theta$ is the angle between the transmission axis of the analyser and the transmission axis of the polariser.

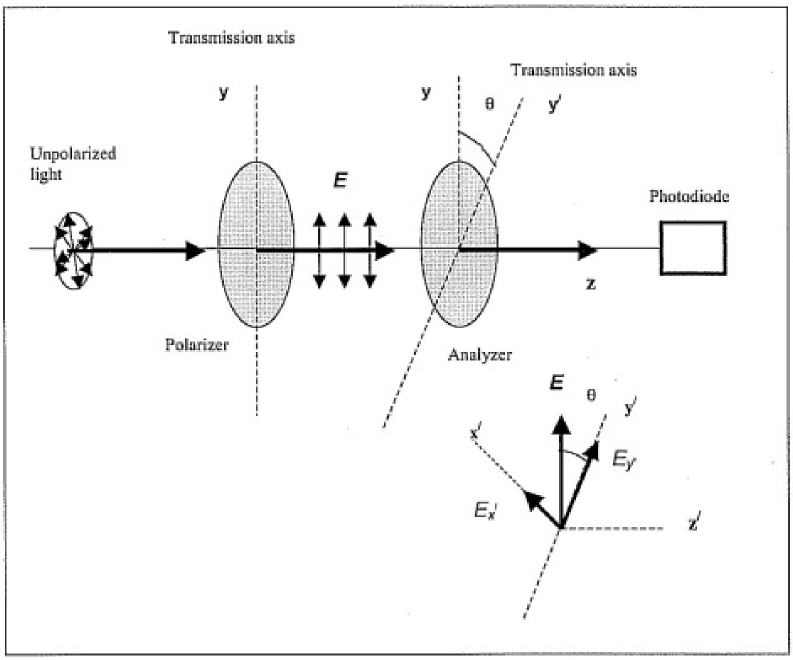


Figure 5.1: Set-up to test Malus's Law.

First, unpolarized light is incident on an polarizer, which is essentially a polaroid, This allows only one polarization to go through, and so, post polarizer, you have, effectively, linearly polarized light. Now this linearly polarized light is incident on the analyzer, and this is what gives you Malus' law. So it's not that you need unpolarized light to verify Malus' law: what you need is linearly polarized light. If it were possible to generate linearly polarized light directly, then there would be no need for the polarizer.

To test Malus's Law, the light is passed through a polariser an an analyser. The polariser and the analyser are both identical, and are given different names only because of the position they take within the set-up, thus the polariser and the analyser can be interchanged and will cause difference to the set-up. The angle $\theta$ in the expression $I(\theta) = I_\circ \cos^2\theta$ is the angle between the transmission axis of the first polariser and the transmission axis of the analyser. When collecting data for Malus's Law, $\theta$ is the variable that we control. The orientation of the transmission axis can be controlled by rotating the analyser - this is how $\theta$ is varied.

> Transmission axis - The transmission axis of a polarizer is the axis such that light with its electric field oriented parallel to this axis will be transmitted.

I is the intensity of the incoming electromagnetic wave. The final polarised beam transmitted by the analyser is incident upon a photodetector. This is a photodiode, made of semiconducting material, and is a reverse biased diode (this is to increase the efficiency of the photodetector - a reverse biased diode produces a higher current than a forward biased diode for the same amount of incident light). When light hits the photodiode, electrons are excited within the semiconductor, and form a current. The current generated by the incident light is proportional to the intensity of the incident beam. Thus the intensity $I$ is just the current in our case. The photodetector used was a pinhole detector - this was so that when detecting the incident beam, which was diffused, we could get the centre of it, and not have an arbitrary amount of light detected.

## Brewster's Angle

When light is reflected at a surface, the reflection coefficients are different for the polarization with E parallel to the plane of incidence and the polarization with E perpendicular to the plane of incidence. (The plane containing the incident, reflected, and transmitted rays.) Thus when unpolarized light, which can be regarded as an incoherent superposition of these two polarizations,is incident on the surface, the reflected light in general contains more of one polarization than the other. There exists a certain angle of incidence at which the polarization with E perpendicular to the plane of incidence is perfectly transmitted. A a consequence, the reflected light contains only the other polarization, and is thus perfectly linearly polarized.

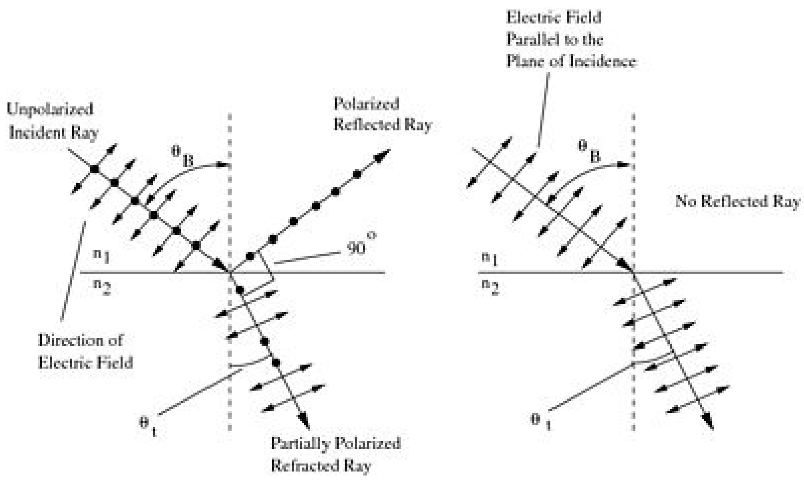


Figure 5.2: If unpolarized light is incident on a medium, then at the Brewster angle, the light comes out perfectly s-polarized as shown in the left hand side image. If the incident beam was perfectly p-polarized to begin with, there is no reflection at the Brewster angle at all as shown in the right hand side image.

Since, we know that at Brewster's angle, the angle between the reflected and refracted beam is 90°. For an angle of incidence $\theta_B$, and an angle of refracted wave $r$,

$$r + \theta_B + 90^\circ = 180^\circ \quad \text{or in other words,} \quad r = 90^\circ - \theta_B$$

From Snell's Law,

$$\frac{\sin \theta_B}{\sin r} = \mu$$

$$\frac{\sin\theta_B}{\sin(90^\circ - \theta_B)} = \frac{\sin\theta_B}{\cos\theta_B} = \mu$$

From this, we arrive at an expression for Brewster's Angle:

$$\boxed{\tan\theta_B = \mu}$$

A graph of reflectance for the air-glass interface as a function of the angle of incidence is shown in the figure 5.3. This can be obtained from Fresnel's equations. at normal incidence, the parallel and perpendicular polarisation waves to the plane of incidence are physically identical and have the same reflectance. As the angle of incidence increases, the parallel component drops and the perpendicular component rises until the Brewster's angle is reached. As the angle of incidence approaches 90°, all of the incident light is reflected so that the medium acts as a mirror.

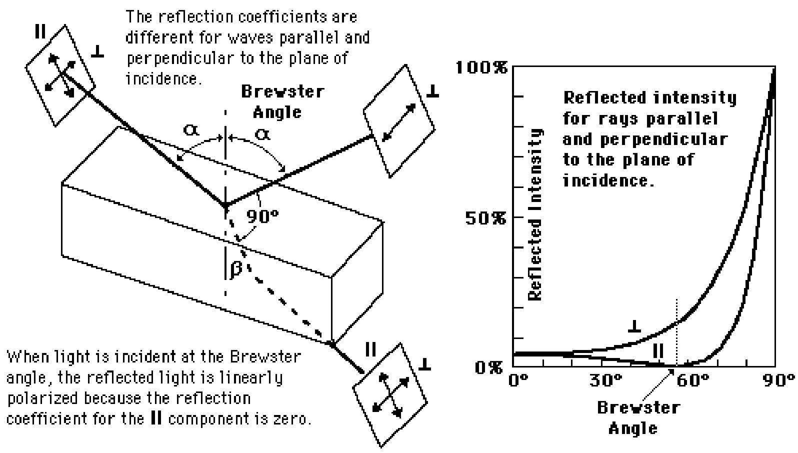


Figure 5.3: Reflectance for rays perpendicular and parallel to the plane of incidence, derived from Fresnel's equations.

# Experimental Setup

## Apparatus

1. Kinematic Laser mount
2. Diode laser with power supply
3. Polariser Rotator
4. Analyzer Rotator
5. Pinhole detector with output measurement unit
6. Cell Mount
7. Optical Breadboard

8. Rotation Stage
9. Glass Slides

### Warnings and Precautions

1. Handle the equipment with gloves to avoid dirt and grease.
2. Ensure that the equipment is covered before leaving.
3. The laser's intensity can change slightly if left on for an extended period of time.
4. Don't go for just a visual analysis of Brewster's angle because this method prone to very large errors, instead use the light sensor itself.

## Procedure

### Malus' Law

- Place the laser, the polariser, the analyser and the photodetector (connected to the output measurement unit) all in a single line on the optical bread board.
- Figure out whether using or not using a beam widener makes a difference in this experiment. As the laser beam passes through the first polariser, set the $0°$ for the angle on the polariser $P1$ corrresponding to the angle for which maximum intensity is detected by the photodetector.
- Now, introduce the analyser $P2$ between $P1$ and the photodetector.
- Again, rotate the transmission axis until the maximum intensity is detected, and align the $0°$ angle reading to this point.
- Then, rotate the transmission axis of $P2$ to study the variation of intensity of the beam.

### Brewster's Angle

- Place the laser and a glass slide on a rotation stage in line on the optical breadboard.
- Do this experiment with and without a polariser and compare the results. One can move the photodetector around the glass slide at a fixed distance - to do this, one can tape the photodetector to a metal ruler, and attach the ruler to the bottom of the rotation stage under the glass slide, such that the ruler rotates around the glass slide.
- To determine when the laser is normally incident on the glass slide, rotate the glass slide until the reflected beam coincides with the incident beam, and set this to correspond the $0°$ marking on the circular angular ruler.
- Then rotate the glass slide in $2°$ intervals and the photodetector along with it such that the reflected beam is directed at the pinhole.

Is it beneficial to use a diffuser lens in this part of the experiment?

## Expected Outcome- Malus' Law

Plot the intensity of the transmitted beam against the angle of the transmission axis of the analyser with respect to the polariser and fit the graph to a $cos^2$ curve and verify Malus's law. Representative data is shown in figure 5.4.

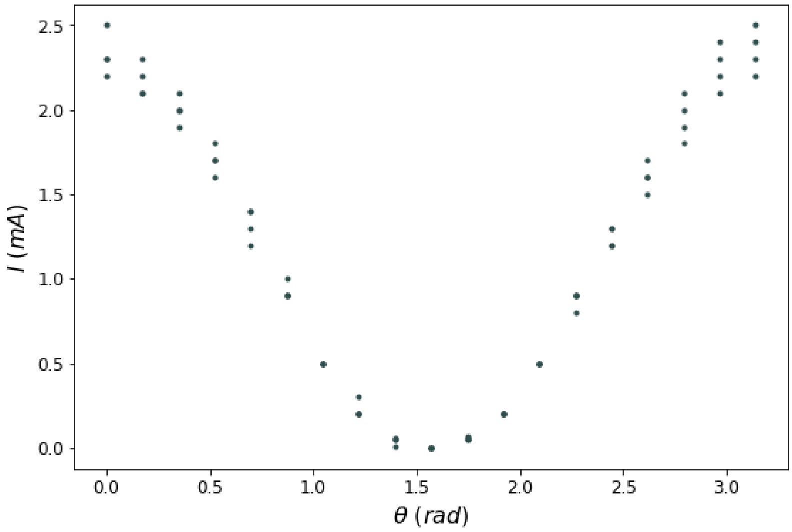


Figure 5.4: Intensity with varying angle of the transmission axis of the analyser.

## Expected Outcome - Brewster's

Plot the reflected beam intensity vs the angle of incidence on the glass slide. A clear minimum in the intensity can be obtained at the Brewster's angle as shown in the figure 5.5. Calculate the Brewster's angle and hence the refractive index of the medium. Paying attention to the data obtained in figure 5.5, which component (parallel or perpendicular to the plane of incidence) are you looking at? Is it consistent with the figure 5.3 obtained from the Fresnel's equations? Can you verify the Fresnel's equations using this setup?

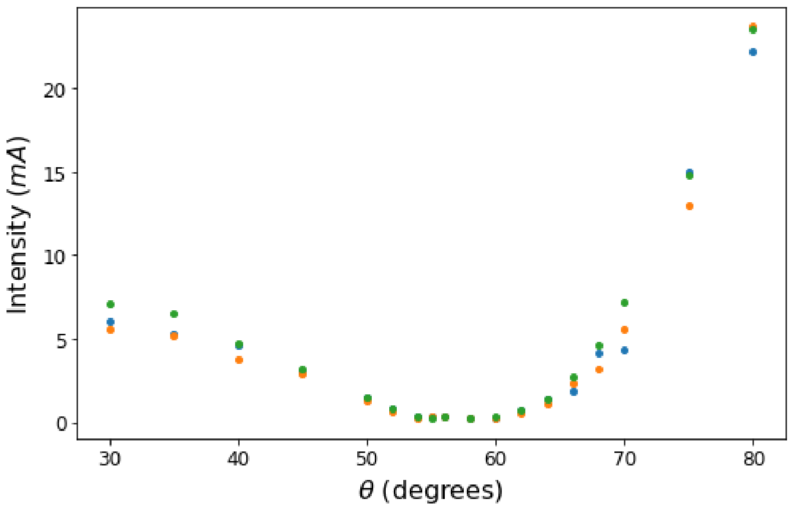


Figure 5.5: Data for intensity of reflected beam vs angle of incidence on the glass slide