Experiment 19
Polarization of light

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Introduction:

In this experiment we are analysing concepts that occur when light is polarized. Polarization of light is the ability to limit which axis the transverse electromagnetic waves can propogate along, this limiting of propagation has the effect of reducing the intensity of the light being polarized.

In the first part of the experiment 'Linearly Polarized Light' we will discuss the relationship between the change in intensity to the amount by which the source is polarized. We will do this using the following equation:

$$\%\text{ Polarization} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \cdot 100 \tag{1}$$

In the second experiment we will discuss the relationship between the angle of two polarizers and the intensity of the polarized light.

$$I = I_0 \, cos^2\theta \tag{2}$$

This relationship is known as 'Malus' Law'.

The third experiment we replicate the affects of polarization using a glass block. When our reflected beam is 100% polarised by the glass block we have found what is known as 'Brewster's Angle'. This angle has a relationship to the refractive index of the two mediums in which it propgates through,

$$tan\ \theta_p = \frac{n_t}{n_i} \tag{3}$$

We can use this relationship to help us find the refractive index of both acrylic and glass which should verify Brewster's angle.

Method:

Linearly Polarized Light: In order to produce linearly polarized light we set up an incandescent white bulb along a track, in order to create a sharp beam of light we used a convex lens which was placed directly in front of the light source until a sharp focused image appeared on a screen located at the opposite end of the track.

We used an optical fibre cable and a Vernier LabQuest as a photodetector, which recorded the background light intensity before the light source was switched on as well as the initial intensity of the incident light ray being produced, both measured in Lux.

Once those results had been noted a single polarizer was placed on the track between the sharp light beam and the optical fibre, this gave us our polarized intensity. The polarizer could be rotated at various angles, therefore we repeated this process for multiple polarizer orientations. Finally the results were analysed in accordance to Eq. 1 mentioned in the introduction.

Malus' Law: The set-up for Malus' Law requires us to again use an incandescent white bulb with its beam being focused by a convex lens, as well as the optical fibre however in order to observe the law of Malus we need to use two polarizers. One will be called a polarizer which remains rotated at 0°, another will be the Analyzer which we will rotate at various angles between 0° and 90°.

We first measured the background light intensity which in the results section of the report is referred to as the effective zero intensity. Then we tested what happens when our light is hitting a screen and we rotated the analyzer. This gave us a simulation of what type of results we would expect to see from our intensity readings as we increased the analyzer angle from 0° to 90°.

Once we had all of our values for the difference intensities and angles we had to plot a graph of I vs $cos^2\,\theta$. This graph, along with its analysis is located in the analysis section of the report.

When our analyzer angle reached 90° we could observe that no light was coming through to the optical fibre and the intensity readings were in accordance with what we had measured for the affective zero intensity. This is whats known as the Polaroids being "crossed", when this happened we inserted a third polarizer in between the two previous ones, this one at an angle of 45°.

Brewster's Angle: For this experiment in particular we had to swap out the incandescent white bulb and convex lens for a more traditional laser beam. We use a single polarizer and an acrylic block as well as a glass block.

Our first step was to set the polarizer placed on the track with the 0° - 180° axis horizontal. One of the two blocks was placed at the end of the track, on a rotating table which had marked lines to indicate where to place the block so that it is flush with the scored lines indicating the angle which the table was rotated at.

We had to rotate the block which had a laser beam hitting it, following the reflected laser light until it reaches its minimum intensity and becomes hardly visible. This is an indication that the light has been totally polarised in its reflected form and this angle which the glass block is rotated at is known as Brewster's Angle.

We repeated this process for the second block made of a different material with a different refractive index. The angle found this time varied slightly to the one found previously and we can use Eq. 3 discussed in the introduction to find the refractive index of each material and compare them with the accepted refractive index for each.

We also verified that the transmitted light and light being reflected were being polarised by using a second polarizer which was crossed with the first one. As discussed in the method for Malus' Law, if the light in question is polarized, once it passes through the second "crossed" polarizer, we should observe that no light is propagating out, this is exactly what we observed.

Results:

Linearly Polarized Light

Effective zero: 2.5 lux

Intensity without polarizer	
Time (s)	Intensity (lux)
0.00	229.7
0.05	218.9
0.10	225.1
0.15	225.6
0.20	231.6
0.25	227.2
0.30	236.8
0.35	233.3
0.40	232.2

Intensity with polarizer	
Time (s)	Intensity (lux)
0.00	65.9
0.05	66.7
0.10	65.1
0.15	66.5
0.20	65.3
0.25	66.7
0.30	65.5
0.35	66.7
0.40	65.9

Polarizer Angle (°) = 20	
Time (s)	Intensity (lux)
0.00	64.5
0.05	60.3
0.10	64.4
0.15	60.5
0.20	64.7
0.25	60.7
0.30	65.1
0.35	61.1
0.40	64.9

Polarizer Angle (°) = 40	
Time (s)	Intensity (lux)
0.00	74.9
0.05	68.8
0.10	75.1
0.15	68.8
0.20	74.9
0.25	70.1
0.30	75.3
0.35	67.4
0.40	75.5

Polarizer Angle (°) = 60	
Time (s)	Intensity (lux)
0.00	64.7
0.05	69.9
0.10	64.4
0.15	70.3
0.20	64.4
0.25	69.9
0.30	64.7
0.35	70.5
0.40	64.5

Law of Malus

Effective zero: 0.4 lux

Analyzer Angle (°) = 0	
Time (s)	Intensity (lux)
0.00	179.4
0.05	174.7
0.10	179.4
0.15	174.4
0.20	179
0.25	174
0.30	179.4
0.35	174.7
0.40	179.6

Analyzer Angle (°) = 20	
Time (s)	Intensity (lux)
0.00	162.8
0.05	154.8
0.10	166.1
0.15	167.1
0.20	153.6
0.25	164.8
0.30	165
0.35	159.8
0.40	153.2

Analyzer Angle (°) = 40	
Time (s)	Intensity (lux)
0.00	115.8
0.05	113.5
0.10	116.2
0.15	112.9
0.20	115.8
0.25	113.3
0.30	115.6
0.35	113.5
0.40	116

Analyzer Angle (°) = 60	
Time (s)	Intensity (lux)
0.00	62.6
0.05	64.5
0.10	62.2
0.15	64.5
0.20	62
0.25	64.5
0.30	61.8
0.35	64.5
0.40	61.3

Analyzer Angle (°) = 80	
Time (s)	Intensity (lux)
0.00	25.4
0.05	30
0.10	25.2
0.15	29.6
0.20	25
0.25	29.8
0.30	25
0.35	30
0.40	24.8

Brewster's Angle

Effective zero: 0.4 lux

Glass Block
Incident Angle (°) = 53

Acrylic Block
Incident Angle (°) = 56

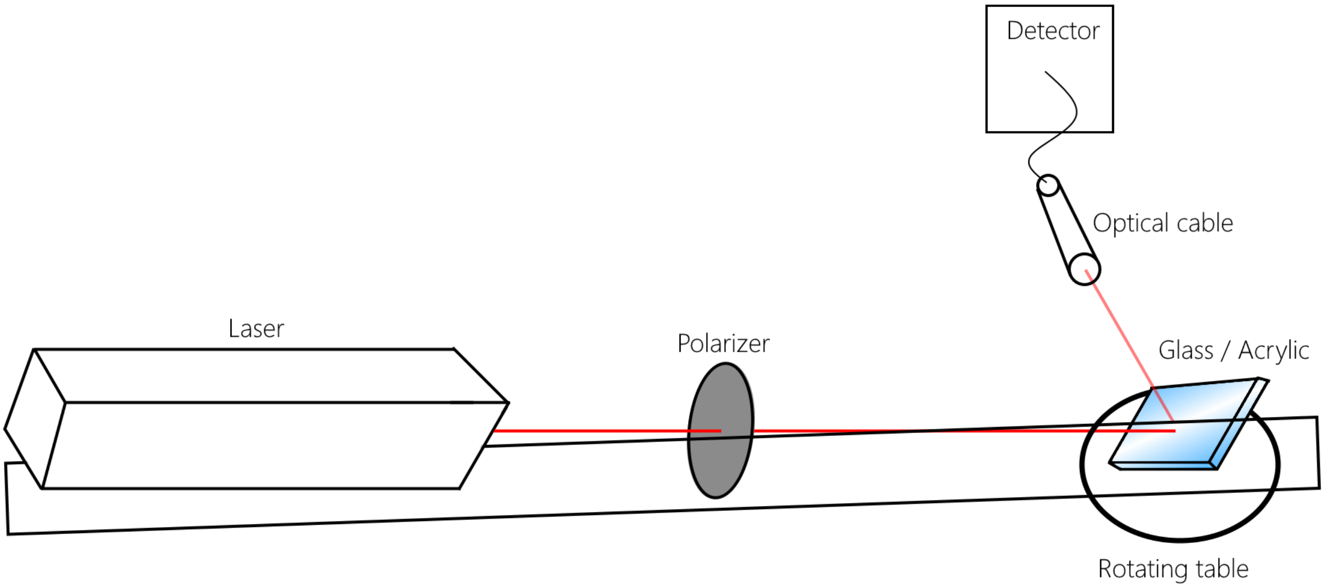

Figure 1: sketch of brewster's angle experimental arrangement

Analysis:

Linearly Polarized Light

We start out by finding the average value for the recorded intensities at the various angles listed in the results section. I have already subtracted 2.5 from each measurement in order to make sure I am using the true value for the intensity without the background intensity interfering

Average intensity without polarizer:

$$\frac{227.2 + 216.4 + 222.6 + 223.1 + 229.1 + 227.2 + 234.3 + 230.8 + 229.7}{9} = 226.7 \text{ lux}$$

This will become our I_{max} for the rest of the analysis.

Average intensity with polarizer:

$$\frac{63.4 + 64.2 + 62.6 + 64 + 62.8 + 64.2 + 63 + 64.2 + 63.4}{9} = 63.5 \text{ lux}$$

Average intensity with polarizer 20°:

$$\frac{62+57.8+61.9+58+62.2+58.2+62.2+58.6+62.4}{9} = 60.4 \text{ lux}$$

Average intensity with polarizer 40°:

$$\frac{72.4+66.3+72.6+66.3+72.4+67.6+72.8+64.9+73}{9} = 69.8 \text{ lux}$$

Average intensity with polarizer 60°:

$$\frac{60.1+62+59.7+60+59.5+62+59.3+62+58.8}{9} = 60.4 \text{ lux}$$

We will take these averages as our I_{min} values for the analysis. We now use Eq. 1 from the introduction to calculate the % of Polarization each beam of light is experiencing.

Something we need to keep in mind when carrying out this calculation is that each of our intensities actually has an uncertainty associated with it, in this case we were only able to record the intensity to 1 decimal places. This means that each of our intensities has an associated instrumental uncertainty of ± 0.05 lux.

Degree of polarisation (DOP):

Using Eq. 1:

(With polarizer 0°)

$$\% \text{ Polarization} = \frac{(226.7 \pm 0.05) - (63.5 \pm 0.05)}{(226.7 \pm 0.05) + (63.5 \pm 0.05)} \cdot 100 = 56.2\%$$

Error analysis:

$$\frac{\Delta x}{\Delta y} = \Delta z$$

$$\Delta x = \sqrt{(0.05)^2 + (0.05)^2} = 0.07$$

$$\Delta y = \sqrt{(0.05)^2 + (0.05)^2} = 0.07$$

$$\frac{\Delta z}{z} = \sqrt{(\frac{0.07}{163.2})^2 + (\frac{0.07}{290.2})^2} = 0.00049$$

$$\Delta z = 0.00049 \times 0.56 = 0.00028$$

$$0.00028 \times 100 = 0.028\%$$

Final value:

$$\boxed{56.2\% \pm 0.028\%}$$

(Polarizer angle 20°)

$$\% \text{ Polarization} = \frac{(226.7 \pm 0.05) - (60.4 \pm 0.05)}{(226.7 \pm 0.05) + (60.4 \pm 0.05)} \cdot 100 = 57.9\%$$

Error analysis:

$$\frac{\Delta z}{z} = \sqrt{(\frac{0.07}{166.3})^2 + (\frac{0.07}{287.1})^2} = 0.00049$$
$$\Delta z = 0.00049 \times 0.58 = 0.00028$$

$$0.00028 \times 100 = 0.028\%$$

Final value:

$$\boxed{57.9\% \pm 0.028\%}$$

(Polarizer angle 40°)

$$\% \text{ Polarization} = \frac{(226.7 \pm 0.05) - (69.8 \pm 0.05)}{(226.7 \pm 0.05) + (69.8 \pm 0.05)} \cdot 100 = 52.9\%$$

Error analysis:

$$\frac{\Delta z}{z} = \sqrt{(\frac{0.07}{156.9})^2 + (\frac{0.07}{296.5})^2} = 0.00050$$
$$\Delta z = 0.00050 \times 0.53 = 0.00027$$

$$0.00027 \times 100 = 0.027\%$$

Final value:

$$\boxed{52.9\% \pm 0.027\%}$$

(Polarizer angle 60°)

$$\% \text{ Polarization} = \frac{(226.7 \pm 0.05) - (60.4 \pm 0.05)}{(226.7 \pm 0.05) + (60.4 \pm 0.05)} \cdot 100 = 57.9\%$$

Error analysis:

$$\frac{\Delta z}{z} = \sqrt{(\frac{0.07}{166.3})^2 + (\frac{0.07}{287.1})^2} = 0.00049$$
$$\Delta z = 0.00049 \times 0.58 = 0.00028$$

$$0.00028 \times 100 = 0.028\%$$

Final value:

$$\boxed{57.9\% \pm 0.028\%}$$

Malus' Law

We start out by finding the average value for the recorded intensities at the various angles listed in the results section. Making sure to subtract 0.4 lux, the effective zero value to get our true intensities. We will also find the uncertainty associated with each average value so we can include these uncertainty bars on our graph.

Average intensity with polarizer 0°:

$$\frac{179 + 174.3 + 179 + 174 + 178.6 + 173.6 + 179 + 174.3 + 179.2}{9} = 176.\dot{7} \text{ lux}$$

Error Analysis:

$$\frac{\Delta x}{\Delta y} = \Delta z$$

$$\Delta x = \sqrt{(0.05)^2 + (0.05)^2 + (0.05)^2 + (0.05)^2 + (0.05)^2 + (0.05)^2 + (0.05)^2 + (0.05)^2 + (0.05)^2} = 0.19$$

$$\frac{\Delta z}{z} = \sqrt{(\frac{0.19}{1591})^2 + (\frac{0}{9})^2} = 0.0001$$

$$\Delta z = 0.0001 \times 176.\dot{7} = 0.02\dot{1}$$

Final Value:

$$\boxed{176.\dot{7} \pm 0.02\dot{1}}$$

Average intensity with polarizer 20°:

$$\frac{162.4 + 154.4 + 165.7 + 166.7 + 153.2 + 164.4 + 164.6 + 159.4 + 152.8}{9} = 160.4 \text{ lux}$$

Error Analysis:

$$\frac{\Delta z}{z} = \sqrt{(\frac{0.19}{1443.6})^2 + (\frac{0}{9})^2} = 0.0001$$

$$\Delta z = 0.0001 \times 160.4 = 0.02\dot{1}$$

Final Value:

$$\boxed{160.4 \pm 0.02\dot{1}}$$

Average intensity with polarizer 40°:

$$\frac{115.4 + 113.1 + 115.8 + 112.5 + 115.4 + 112.9 + 115.2 + 113.1 + 115.6}{9} = 114.\dot{3} \text{ lux}$$

Error Analysis:

$$\frac{\Delta z}{z} = \sqrt{(\frac{0.19}{1029})^2 + (\frac{0}{9})^2} = 0.0002$$
$$\Delta z = 0.0002 \times 114.\dot{3} = 0.02\dot{1}$$

Final Value:

$$\boxed{114.\dot{3} \pm 0.02\dot{1}}$$

Average intensity with polarizer 60°:

$$\frac{62.2 + 64.1 + 61.8 + 64.1 + 61.6 + 64.1 + 61.4 + 64.1 + 60.9}{9} = 62.7 \text{ lux}$$

Error Analysis:

$$\frac{\Delta z}{z} = \sqrt{(\frac{0.19}{564.3})^2 + (\frac{0}{9})^2} = 0.0003$$
$$\Delta z = 0.0003 \times 62.7 = 0.02\dot{1}$$

Final Value:

$$\boxed{62.7 \pm 0.02\dot{1}}$$

Average intensity with polarizer 80°:

$$\frac{25 + 29.6 + 24.8 + 29.2 + 24.6 + 29.4 + 24.6 + 29.6 + 24.4}{9} = 26.8 \text{ lux}$$

Error Analysis:

$$\frac{\Delta z}{z} = \sqrt{(\frac{0.19}{241.2})^2 + (\frac{0}{9})^2} = 0.0008$$
$$\Delta z = 0.0008 \times 26.8 = 0.02\dot{1}$$

Final Value:

$$\boxed{26.8 \pm 0.02\dot{1}}$$

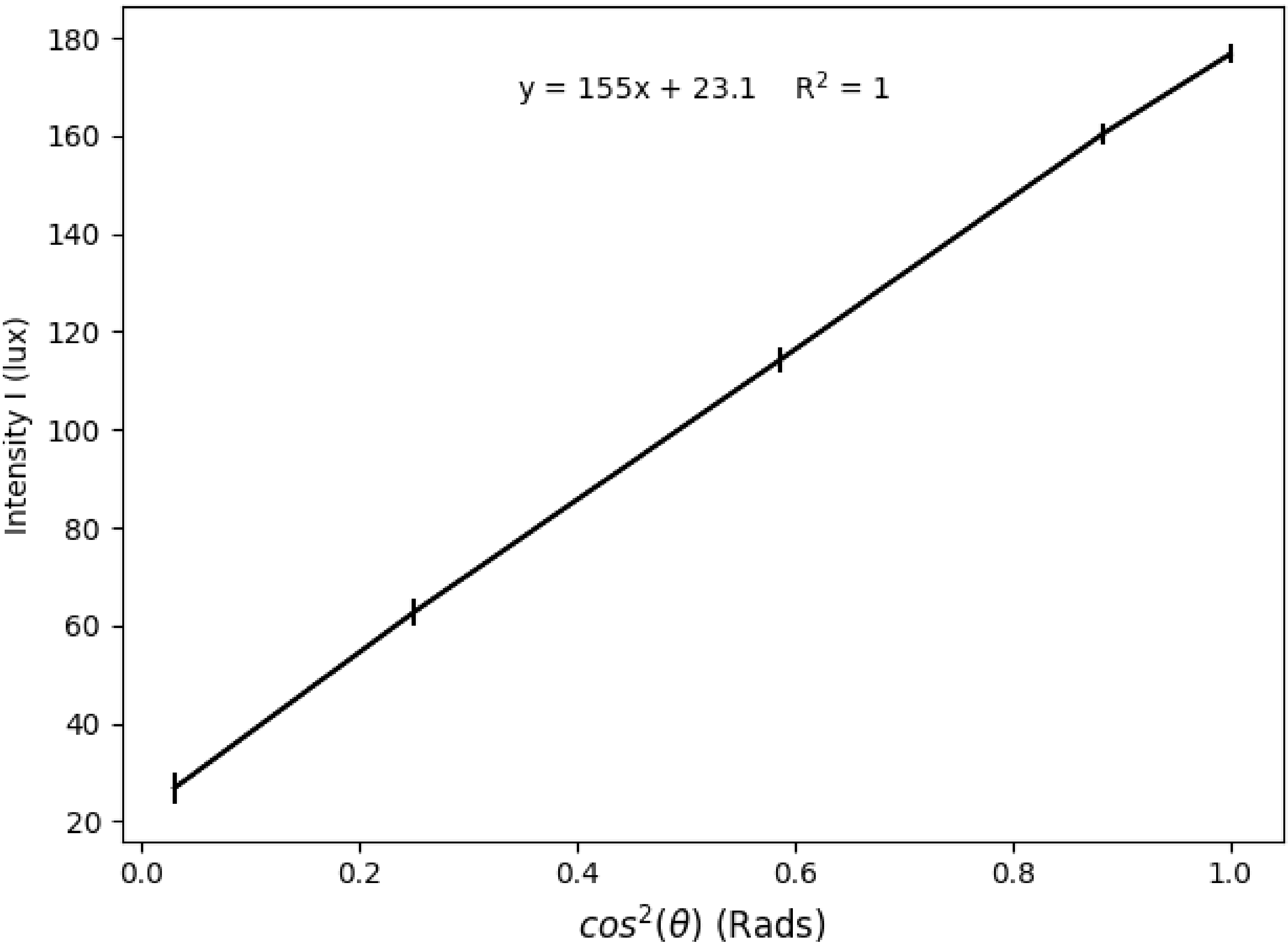

Figure 2: Graph of Malus' Law

Brewster's Angle

Using Eq. 3:

$$tan\theta = \frac{n_t}{n_i}$$

Where n_i is the refractive index of air and θ is the recorded angle in our results section.

$$n_t = tan(53°)(1) = 1.33$$

Error Analysis:

$53 \pm 0.5°$

$$\frac{\Delta tan\theta}{tan\theta} = \sqrt{(\frac{\Delta n_t}{n_t})^2 + (\frac{\Delta n_i}{n_i})^2}$$

$$\frac{\Delta tan\theta}{tan\theta} = \sqrt{(\frac{0.5}{1.33})^2 + (\frac{0}{1})^2} = 0.38$$

$$\Delta tan\theta = 0.38 \times 1.33 = 0.50$$

Final Value:

$$\boxed{1.3 \pm 0.5}$$

$$n_t = tan(56°)(1) = 1.48$$

Error Analysis:
$56 \pm 0.5°$

$$\frac{\Delta tan\theta}{tan\theta} = \sqrt{(\frac{\Delta n_t}{n_t})^2 + (\frac{\Delta n_i}{n_i})^2}$$
$$\frac{\Delta tan\theta}{tan\theta} = \sqrt{(\frac{0.5}{1.48})^2 + (\frac{0}{1})^2} = 0.34$$
$$\Delta tan\theta = 0.34 \times 1.48 = 0.50$$

Final Value:

$$\boxed{1.5 \pm 0.5}$$

Questions:

Q1: Is the incandescent white light polarized? From our first experiment we were able to analyse that the incandescent light is roughly 50% polarized. This seems to be fairly constant and doesn't vary much when changing the angle of the single polarizer.

Q2: Is the graph I vs cos^2 θ linear? Our graph of Intensity vs cos^2 θ shows a linear relationship between the two, this verifies Malus' Law.

Q3: Is any light transmitted when a third polarizer inserted between two crossed polarizers? Why? Give a diagram to support your answer. The three polarizer paradox is a well documented concept in physics, where when two polarizers are crossed at 90 degrees no light emerges, however if you add another polarizer in between at 45 degrees this affect doesnt happen. This is because the polarization of the photons are dependent on whatever the last filter they passed through was. In the case of the two crossed polarizers, once the photons haved passed through the vertical filter, the 50% of photons which passed through are considered to be vertically polarized, vertically polarized photons attempting to pass directly through a horizontally polarized filter will be entirely blocked causing no light to get through. In the second case the vertically polarized photons pass through a diagonal filter meaning that 50% of the photons make it through and become diagonally polarized, these photons are no longer at a complete opposite orientation to the horizontal filter and now 50% of these diagonally polarized photons will be able to pass through, resulting in the three polarizer paradox.

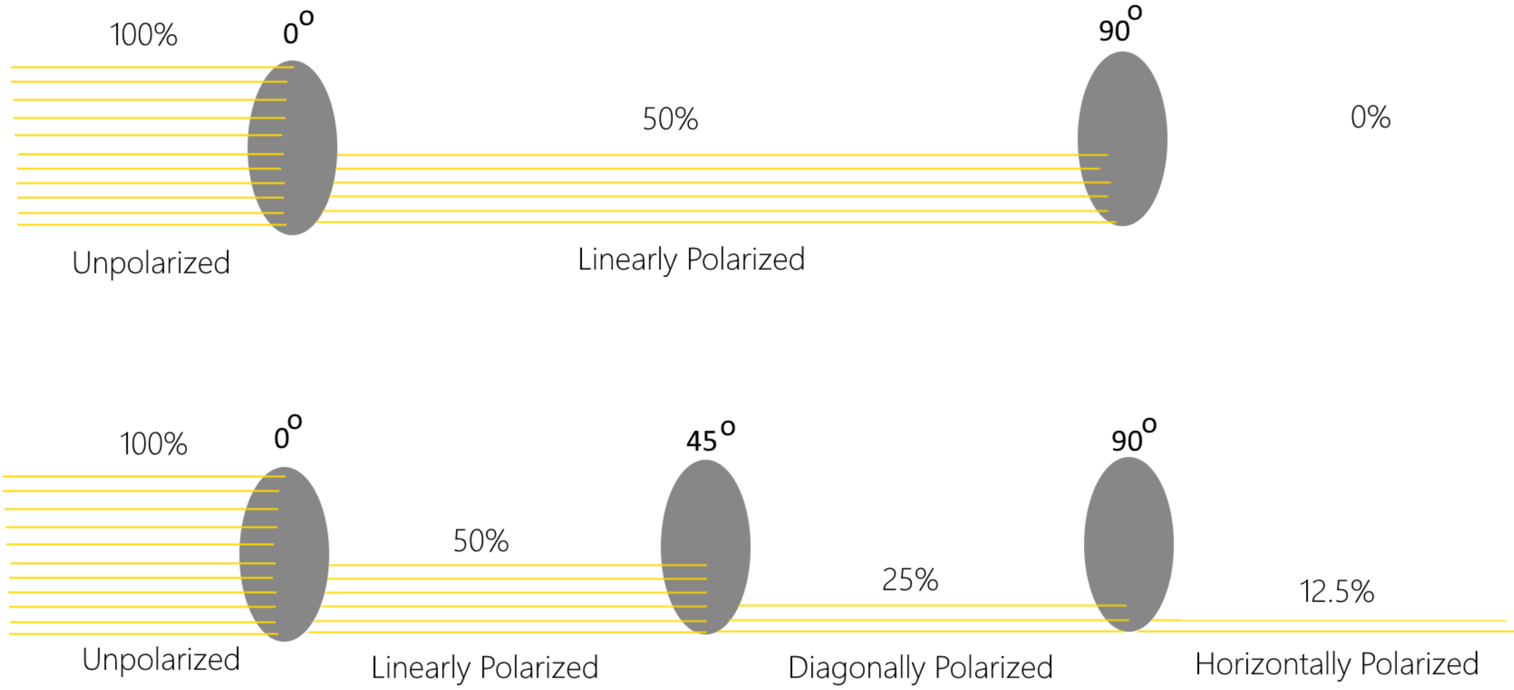

Figure 3: Digram of Triple Polarizer Paradox

Q4: In what plane is it polarized? The light reflected during the brewster's angle experiment is linearly polarized and polarized in the horizontal plane.

Discussion:

The most notable improvement in error could be made with the first experiment 'Linearly Polarized Light'. When beginning the measurement for these values, including the effective zero values the lights in the room were still on, which produced an effective zero value of 2.5 lux. Although we can still obtain accurate intensity results by subtracting this value from our recorded ones, once the lights in the room were turned off the background intensity went down to 0.4 lux which is a value much closer to the zero we are aiming for with our effective zero. In future it would be a good idea to wait until all light in the room is reduced as much as possible before beginning.

Another way to improve accuracy would be to take more measurements, unfortunately there was an issue with the LabQuest's calibration where the GUI was being unresponsive, this resulted in us only being able to record the first 9 values displayed on the screen despite the LabQuest itself being able to produce way more results in 10 seconds. If we had been able to use the LabQuest to its full advantage we would have had a way better average with a much lower uncertainty which could minimise outliers.

Both the photodetector and rotating table measured their respective values to 1 decimal place, if we used a more sensitive photodetector and a more accurate protractor we could greatly reduce the uncertainty associated with each measurement taken.

Conclusion:

We were able to observe that light becomes polarized by $\approx 50\% \pm 0.028\%$ regardless of the angle it is polarized by when using a single polarizing lens. We verified Malus' Law by graphing the relationship between I and $\cos^2\theta$ and observing a positive linear line of best fit with error bars of $\pm 0.02\dot{1}$ We were able to obtain a refractive index of 1.3 ± 0.5 for glass and 1.5 ± 0.5 for acrylic, both of which are well within the uncertainty of the known values with almost no discrepancies.