Experiment 237: Investigation of Polarised Light

Aim

The aim of this experiment is to acquire a basic understanding of the concepts and mechanisms of polarisation. You will be able to investigate and verify various optical principles and also create and manipulate different kinds of polarised light via the use of polarisers, wave plates and simple reflection.

References

1. Sears & Zemansky, "University Physics" (4^{th} ed.)
2. Pedrotti & Pedrotti, "Introduction to Optics" (any edition)
3. E. Hecht, "Optics" (any edition)
4. R.M.A. Azzam and N.M. Bashara, "Ellipsometry and polarized light", North-Holland, 1977. (General Library: 535.52 A99 1987)
5. D. Clarke, "Polarized light and optical measurement", Pergamon Press [1971]. (General Library: 535.5 C59).
6. D. Goldstein, "Polarized light", (electronic resource).

Lab Safety

WARNING: BEFORE HANDLING THE EQUIPMENT READ THIS.

Do not look into the laser beam!
This may cause permanent damage to your eye. Be aware of the path and reflections of the laser at all times. Make sure that it will not do harm to others!
Do not touch any of the reflective surfaces of the optical equipment.

Theory

Light and Polarisation

Light is an electromagnetic wave that has oscillating electric and magnetic fields. These fields are mutually orthogonal to each other and are also perpendicular to the direction of propagation. The frequency of the oscillation gives light its characteristic colour in the visible spectrum (for example, the light used in the experiment has a frequency of 474 THz and appears red). We use the direction of the electric field vector to define the polarisation of the light. If the tip of the electric field vector traces out the same path over time (at a fixed point in space), we say that the light is *polarised.* This path can take many forms, for example, a straight line (linear polarisation), a circle (circular polarisation), or more generally, an ellipse (elliptical polarisation).

Not all light is polarised. Light from an incandescent bulb is not polarised as it is made up of many different frequencies, each with different polarisations which vary rapidly with time. This type of light is referred to as *randomly polarised*[1] light.

[1] Sometimes this is inaccurately referred to as *unpolarised* light. The light is polarised; it's just that the polarisation is changing too rapidly for us to measure. See Hecht or Pedrotti.

Light from a laser is not necessarily polarised, although it often is. It is quite possible to obtain lasers with randomly polarised outputs. Note that *any* light source (thermal or laser) can be polarised if it is passed through a suitable optical element, *ie* a polariser.

Brewster's Angle

At a boundary between media of different refractive index (for example, air and glass), incident light is, in general, both refracted and reflected. The plane that contains the input and output beams and the surface normal is known as the plane of incidence and is always used as the reference plane. Light with electric field in the plane of incidence is known as p-polarised light while light with electric field perpendicular to the plane is known as s-polarised. When the reflected and refracted beams are at 90° to each other, the incident beam is at a special angle called Brewster's angle (θ_B). At this angle, the reflected light is entirely s-polarised. This is shown in Fig.1.

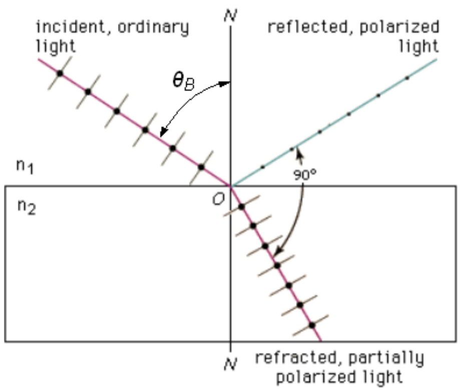

Figure 1: Light incident at Brewster's angle. The dots represent a polarisation plane into the page.

Brewster's angle is given by:

$$\tan\theta_B \equiv \frac{n_2}{n_1}\,. \tag{1}$$

Brewster Window

When a laser is constructed, manufacturers sometimes insert what is known as a *Brewster window* in the resonant cavity, to exploit the Brewster's angle phenomenon. This increases the losses for s-polarised light in the resonator dramatically, so that this mode never reaches the laser threshold, and thus ensures that all light from the laser is (p) polarised. (This window can be seen through the clear part of the HeNe laser tube used in this experiment. See Fig.2.)

Malus' Law

When linearly polarised light of intensity I is normally incident on a polariser, the intensity after the polariser is given by Malus' law:

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

where θ is the angle between the transmission axis of the polariser and the electric vector of the linearly polarised light.

Question 1: If unpolarised light passes through a polariser whose transmission axis is at an angle ϕ to the horizontal, what is the ratio of final intensity to initial intensity? Why?

Birefringence and wave plates

Certain crystalline materials, such as quartz or calcite, have refractive indices that depend on the orientation of the electric field vector of the light relative to the crystal. These types of material are called birefringent materials and they are extremely useful in optics since they allow us to make excellent polarisers and wave plates.

A polariser produces linearly polarised light from a randomly polarised source. See either Hecht or Pedrotti for a description of polarisers based on birefringent crystals.

Wave plates have two well defined, orthogonal directions (or axes) for which the refractive indices are slightly different. Since the speed of propagation is (inversely) proportional to the refractive index, these directions can be thought of as the "slow" and "fast" axes of the wave plate. The difference between these refractive indices is called the birefringence Δn and the product of this with the wave plate's thickness d gives the relative delay. For example, a quarter-wave plate will delay light travelling parallel to the slow axis by one quarter of a wave, *ie* $\pi/2$, with respect to light travelling parallel to the fact axis. So a quarter-wave plate can convert linearly polarised light into circularly polarised light and *vice versa*. The other common type of wave plate is the half-wave plate which, as the name suggests, delays light on the slow axis by one half of a wavelength *ie* π. A half-wave plate can be used to rotate the polarization direction of linearly polarised light.

Apparatus

There are several things that should be noted about the apparatus used in this experiment.

1. The Photocurrent amplifier is not calibrated so may only be used to compare relative intensities of light. The adjustment knob can be used to alter the gain of the detection.
2. The laser in use has a wavelength of 632.8 nm and is a HeNe gas laser (1.5 mW max power).
3. The black glass used for demonstration of Brewster's angle must NOT be handled on the surface but instead on the edge. This goes for all other optical components as well.
4. Between lab sessions and when you finish, make sure to store the optics appropriately. **Always store optical components upright to stop dust settling on them.**
5. When not in use, the black glass and wave plates should be kept in the box accompanying the experiment.

Procedure

Setup and Alignment

Before any experiments can be performed the HeNe laser beam must be aligned to point straight along the optical rail. This can be done using the alignment aperture (black rod with the pinhole in it). Place it in a fixed carrier (LEOI-40-1) and adjust the laser mount to ensure the beam passes through it at various distances along the rail.

Insert the goniometer into a fixed carrier and secure the carrier on the end of the optical rail. Unpack the black glass and secure it on the center of the dial in the slot in the clamping arm. Make sure to align the front face of the long side of the glass along the 90° axis of the dial as shown in Fig. 2.
NOTE: Remember, handle the glass plate carefully, and ensure you do not touch its reflective surfaces. Another important setup procedure is the alignment of the *Brewster Window*, used to ensure a single polarisation of the laser output. The HeNe laser may already be correctly adjusted, but still check that the angled window on the end of the laser is aligned perpendicular to the rail as in Fig. 2, *ie*, it appears side on when viewed from above. Doing so should result in a horizontally polarised beam. (You may need to realign the beam with the aperture after making these adjustments.)

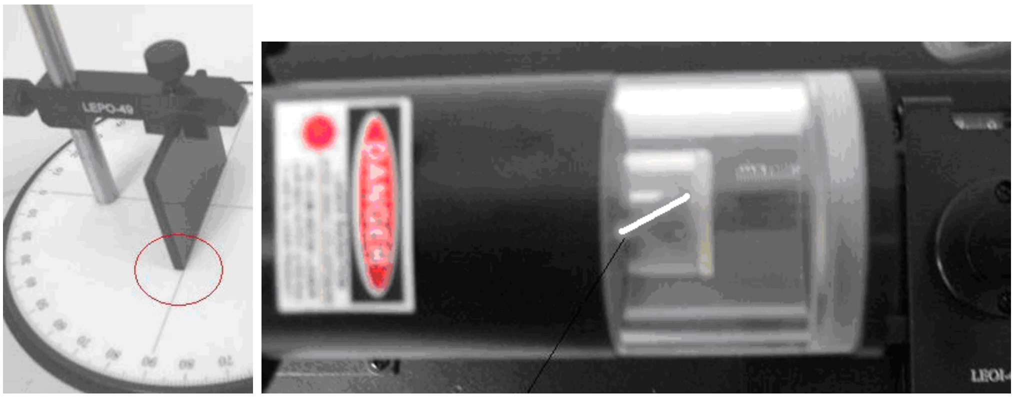

Figure 2: The correct alignment of the black glass on the goniometer, and the Brewster Window (highlighted in white) as seen from above.

One final note. Due to the nature of the photocurrent amplifier, it is best to adjust the gain knob appropriately before making any measurements and thereafter leave it alone. If you make adjustments between experimental procedures it will only mean the intensity values obtained will not be comparable throughout the experiment. However, if you make adjustments in between individual measurements of a given procedure, your data will be useless.

Finding Brewster's Angle

(1) Insert a polariser into a fixed carrier and place the carrier next to the laser. Adjust the polariser to allow output of horizontally polarised light.

(2) Insert the detector into a hole on the rotating arm of the goniometer and connect the detector to the amplifier. Make sure the face of the detector points towards the center of the dial.

(3) Turn on the laser and photocurrent amplifier. By adjusting both the goniometer dial and photodetector (keeping the reflected spot on the detector while varying the angle of incidence/reflection), determine the angle at which the power drops to a minimum. This is *Brewster's Angle*, as defined by Eq.1.

Question 2: What is the refractive index of the black glass? What would Brewster's angle be if the same experiment were performed under water? ($n_{\text{water}} \approx 1.33$).

Verifying Malus' Law

(4) Remove the detector from the goniometer mount and insert it into the X-Y adjustable carrier (LEOI-40-3). Place this at the end of the rail, just ahead of the goniometer and with no obstructions to the beam, adjust its position so as to maximise the detected intensity.

(5) In addition to the polariser already in position and calibrated for horizontal polarisation, construct a second polariser assembly (as before), and place this behind the first on the optical rail. Similarly adjust it (ie, maximise the detected signal through both). Record the intensity detected with the polarisers in this optimum position (this is I_0).

(6) Next turn the second polariser by $10°$ and record the output.

(7) Continue adjusting and recording the intensity for orientations up to $360°$ in steps of $10°$.

(8) Plot a graph of the relative polariser angle vs. intensity from the resulting data.

Question 3: How does your result compare to what you expected? Discuss!

Investigating the action of half- and quarter- wave plates

Before performing the following procedures you may want to make some diagrams illustrating the action of both a quarter- and a half- wave plate to make sure you understand their actions.

Polarisation rotation

(9) Construct a half-wave plate assembly. Place the wave plate into a polarisation / wave plate holder and tighten the screw (ask your demonstrator for a screwdriver if necessary). Place this into a fixed carrier (you may need to use the one holding the goniometer). Although not a necessity, aligning the mark on the wave plate (approximately denoting its optic axis) with the arrow on the holder may aid in the measurements.

(10) Reset the two polarisers, still in place, to allow for horizontal light transmission and then place the wave plate assembly in between them.

(11) Place a piece of paper on the far side of the setup to observe the laser spot. Rotate the half-wave plate until the spot disappears.

(12) Rotate the wave plate by 15° and then compensate by similarly rotating the second polariser until the spot again disappears. Record the change in angle of the polariser required to achieve this. (Don't forget about errors! There may be a range of angles for which the spot disappears.)

(13) Repeat the process, incrementing the wave plate by 15°, until coming full circle.

(14) Plot a graph of your results, wave plate angle vs. polariser angle.

Question 4: What do you notice about the gradient of your plot? What can you conclude about the rotational action of the half-wave plate? Explain.

Question 5: Both a polarizer and a half-wave plate can be used to obtain linearly polarized light of a given orientation. What are the advantages and disadvantages of each device for this purpose?

Circular and elliptical polarisations

(15) Replace the half-wave plate with the quarter-wave plate, and the paper with the photodetector.

(16) Reset both polarisers to allow for the transmission of horizontally polarised light.

(17) Starting with the optic axis aligned with the polarisers, rotate the quarter-wave plate. Record the angles at which intensity maxima and minima occur.

(18) Attempt to find a wave plate angle for which, when you rotate the second polariser, the intensity stays approximately constant. CHECK THE VALIDITY OF THIS!!

(19) Remove the second polariser and replace the photodetector with the goniometer. Align the black glass and goniometer so that the beam reflects through both the quarter-wave plate and original polariser, finally forming a spot on the front of the laser. You need to be able to distinguish this reflection from the incident beam.

(20) With the polariser still aligned for horizontal light, rotate the quarter-wave plate and note the angles at which the reflected beam disappears.

Question 6: What is occurring in step 17 of the above procedure? What do these maxima and minima correspond to?

Question 7: What does the angle you found in step 18 correspond to?

Question 8: Knowing that a mirror changes the "handedness" of circularly polarised light, what is occurring in step 20? Describe the polarisation of the beam at various points along the experiment setup.

Question 9: What factors must be considered when deciding on the thickness of a half- or quarter- wave plate?

Question 10: Considering the equation for the electric field of an electromagnetic plane wave travelling in the z direction

$$\mathbf{E} = \mathbf{E}_0 \exp(i(kz - \omega t)) \tag{3}$$

whose x and y components can be decomposed as

$$E_x = E_{0x} \exp(i(kz - \omega t)),\ E_y = E_{0y} \exp(i(kz - \omega t + \phi)) \tag{4}$$

What do the different variables of these components need to be to correspond to:

- Linearly polarised light?
- Circularly polarised light?
- Elliptically polarised light?
- Randomly polarised light?

Write up

Your report must include:

1. Presentation of all your data and plots, and relevant discussion of your results.
2. Answers to all questions.

List of Equipment

1. Optical rail
2. HeNe Laser Holder
3. HeNe Laser Tube
4. Alignment Aperture
5. 3x Fixed Carrier (LEOI-40-1)
6. X-Y-Adjustable Carrier (LEOI-40-3)
7. Optical Goniometer (LEPO-49)
8. Lens Holder (LEPO-9)
9. Polariser / wave plate holder (LEPO-52)
10. Photocell Detector Head (LEPO-60)
11. Photocurrent Amplifier (LEPO-60)
12. Black Glass
13. 3x Polariser / wave plate mounts
14. 2x Polarisers
15. Half-wave plate
16. Quarter-wave plate

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