POLARIZATION OF LIGHT

REFERENCES

Halliday, D. and Resnick, A. , Physics, 4th edition, New York: John Wiley & Sons, Inc, 1992, Volume II, Chapter 48-1, 48-2, 48-3.

(2weights)
(1weight-exercises 1 and 3 **or** 1 and 2)

OPTICAL REQUIREMENTS

Be careful not to leave your fingerprints on the optical surfaces of lenses or Polaroid sheets.

1. The optical bench and the goniometer (rotating support) should be leveled using the spirit level provided.

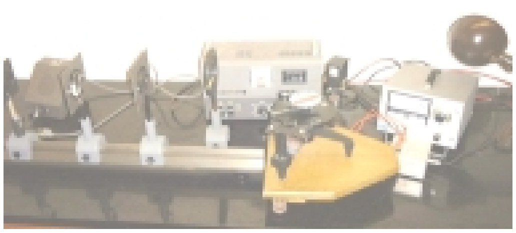
2. All optical components should be centred at approximately the same height.

3. Light should be focused on the photodiode diffusing screen, and the diaphragm should be adjusted so that the light spot is slightly smaller than the screen.

4. Note that while light intensity is being measured, the background light (room light, etc.) must be reduced to a minimum. To facilitate the reading of meters and angles, etc., a flashlight with a red filter is provided. The photodiode responds very little to red light.

Do not overload the ammeter. Start from the least sensitive scale and switch step by step to the scale that gives maximum sensitivity.

INTRODUCTION



Light, viewed classically, is a transverse wave. Namely, the underlying oscillation (in this case oscillating electric and magnetic fields) is along directions perpendicular to the direction of propagation. This is in contrast to longitudinal waves, such as sound waves, in which the oscillation is confined to the direction of propagation. Light is said to be linearly polarized if its oscillation is confined to one direction (the direction of the oscillation of the electric field is defined as the direction of polarization). Most light sources in nature emit unpolarized light i.e., the light consists of many wave trains whose directions of oscillation are completely random.

Light may be polarized by passing it through a sheet of commercial material called Polaroid, invented by E.H. Land in 1938. A sheet of Polaroid transmits only the component of light polarized along a particular direction and absorbs the component perpendicular to that direction.
Consider a light beam in the *z* direction incident on a Polaroid which has its transmission axis in the *y* direction. On the average, half of the incident light has its polarization axis in the y direction and half in the *x* direction. Thus half the intensity is transmitted, and the transmitted light is linearly polarized in the *y* direction.

I. MALUS' LAW

Suppose we have a second piece of Polaroid whose transmission axis makes an angle θ with that of the first. The ***E*** vector of the light between the Polaroids can be resolved into two components, one parallel and one perpendicular to the transmission axis of the second Polaroid.

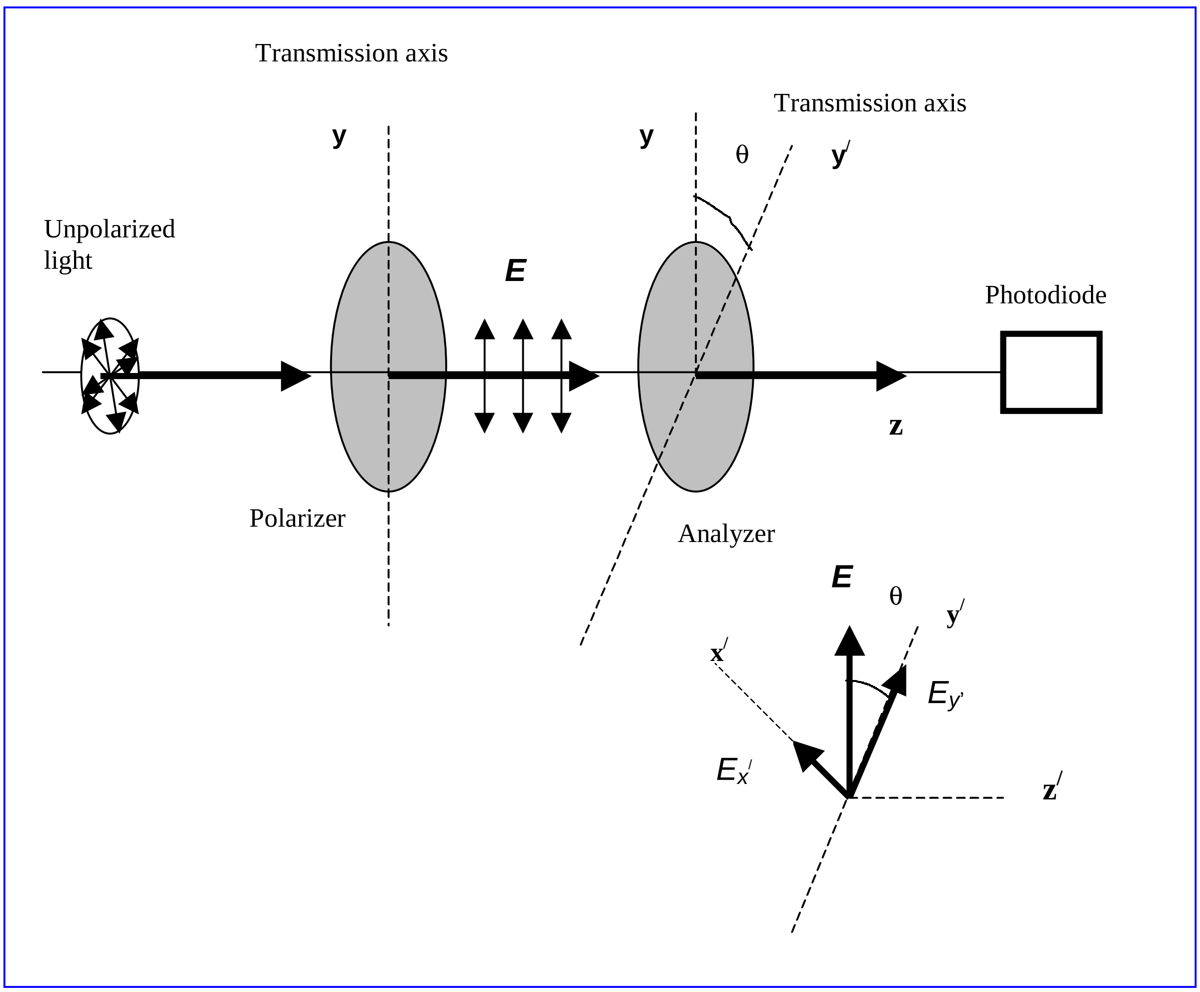


Figure 1. Two Polaroids with their transmission directions making an angle θ with each other.

If we call the direction of transmission of the second Polaroid y', $E_{y'} = E\cos\theta$ and $E_{x'} = E\sin\theta$. Only the component $E_{y'}$ is transmitted by the second Polaroid. The intensity is proportional to the square of the amplitude. Thus the intensity transmitted by both Polaroids can be expressed as $I(\theta) = E_{y'}^2 = E^2\cos^2\theta$. If $I_{max} = E^2$ is the intensity **between** the two Polaroids, the intensity transmitted by both Polaroids is:

$$I(\theta)=I_{max}\cos^2\theta \qquad (1)$$

This equation is known as Malus' law after its discoverer, E.L. Malus (1775-1812). It applies to any two polarizing elements whose transmission directions make an angle θ with each other. When two polarizing elements are placed in succession in a beam of light as described here, the first is called the **polarizer** and the second is called the **analyzer**. As you will see, **no light reaches the photocell when the polarizer and analyzer are crossed (θ=90^o).**

EXERCISE 1

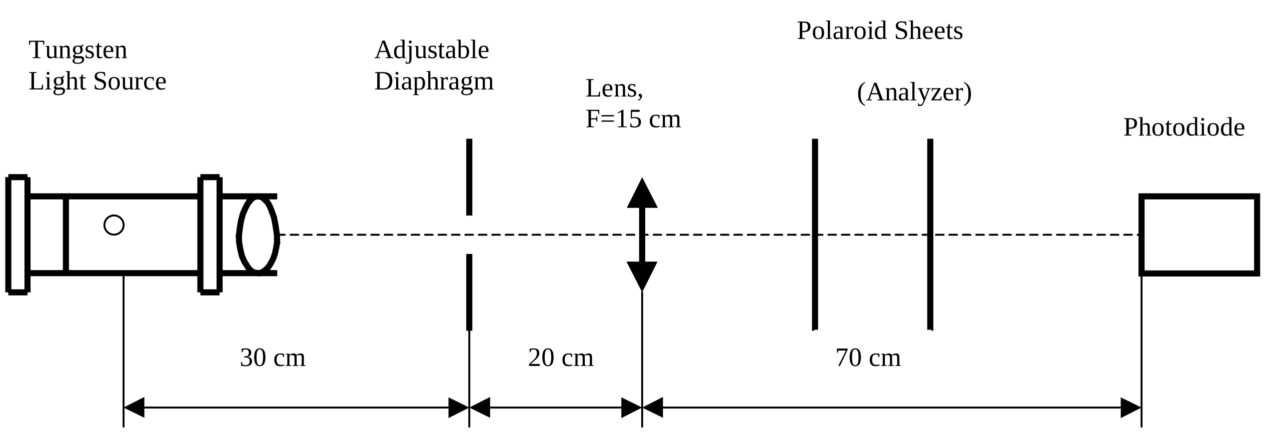


Figure 2. The setup for the test of Malus' law.

1. Make sure that the polarizer and analyzer are properly aligned at the beginning of the experiment.

2. Measure the intensity of polarized light transmitted through an analyzer as a function of angle between the axis of transmission of the polarizer and analyzer. In Exercises 1 and 2 take your measurements each 5^o. Compare the intensity with that predicted by Malus' law.

EXERCISE 2

1. Insert another piece of polarizing material (another Polaroid) **between the aligned polarizer and the analyzer so that** the angle between the axis of the polarizer and the insert is 45^o.

2. Record the intensity of the light transmitted through the **analyzer** as you change the orientation of the **analyzer with respect to the polarizer** from 0^o (parallel) to 90^o (crossed polarizer and analyzer) while **keeping an angle of 45^o between the polarizer and the insert.** Try both directions of rotation ($+90^o$ and -90^o). Plot the $I(\theta)$ graph and try to explain it. Take measurements each 15^o.

2. Have the **polarizer and analyzer crossed**. Now instead of rotating the analyzer, **rotate the insert**. In this part of the experiment you will measure the intensity of the light transmitted through an **analyzer** as a function of angle b**etween the polarizer and the insert**. Again, try both directions of rotation ($+90^o$ and -90^o). Try to predict the outcome before you measure the experimental dependence.Verify your prediction. Why does no light reach the photocell at $\theta=0^o$ and $\theta=90^o$?

II. REFLECTANCE

When unpolarized light is reflected from a plane surface, eg., that separating air and glass or air and water, the reflected light is partially polarized. This is due to the fact that the **reflectance (the ratio of reflected intensity to the incident intensity)** of light depends on the polarization itself. The degree of polarization depends on the angle of incidence and the indexes of refraction of the two media.

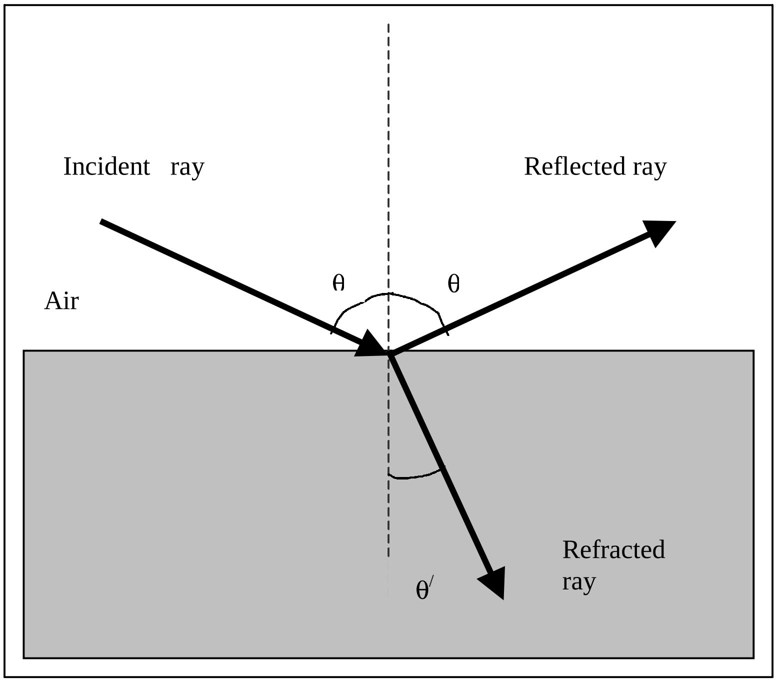


Figure 3. Incident, reflected and refracted rays

For reflection from a glass surface (air-glass interface) one can show from wave theory that :

$$R_{//}=\frac{\tan^2(\theta-\theta')}{\tan^2(\theta+\theta')} \qquad \text{(2a)}$$

and

$$R_{\perp}=\frac{\sin^2(\theta-\theta')}{\sin^2(\theta+\theta')} \qquad \text{(2b)}$$

where θ is the angle of incidence, and θ' is the angle of refraction. $R_{//}$ and $R_{\perp}$ refer to the reflectances for polarized light whose direction of polarization lie in the plane of incidence and perpendicular to the plane of incidence, respectively. The plane of incidence is the plane containing the incident ray, the normal to the surface and the reflected ray.

Note that θ' is **not** measured in this experiment and must be inferred from Snell's law of refraction:

$$\frac{\sin\theta'}{\sin\theta} = \frac{1}{n}$$

where n is the index of refraction of the refracting material.

Figure 4 shows initially unpolarized light incident at the polarizing angle θ_p, for which the reflected light is completely polarized **with its electric field vector perpendicular to the plane of incidence.** The electric field vector ***E*** of the incident wave can be resolved into the components of ***E*** parallel to the plane of incidence (indicated by arrows) and components perpendicular to the plane of incidence (indicated by the dots).

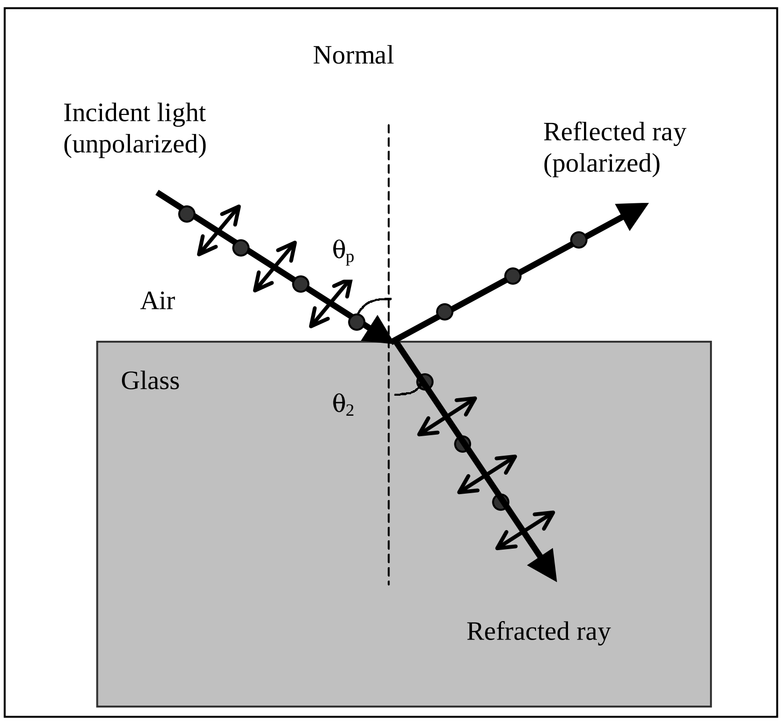


Figure 4. Unpolarized light incident at the polarizing angle.
Note: If the incident light has no component of E perpendicular to the plane of incidence (the light is polarized in the plane of incidence), there is no reflected light.

Note that in equation (2a), $R_{//} = 0$ when $\theta + \theta' = \pi/2$ (i.e. the reflected and refracted rays are perpendicular to each other). Thus when the angle of incidence of **the initially unpolarized light** is such that the reflected and refracted rays are perpendicular to each other, **the reflected light is completely polarized** in the direction perpendicular to the plane of incidence (i.e. parallel to the interface between the two media). This result was discovered experimentally by Sir David Brewster in 1812.

It can be shown that this condition is satisfied if $\tan\theta_p = n$ for the angle of incidence $\theta = \theta_p$ (θ_p is called Brewster's angle or the polarizing angle).

EXERCISE 3

The optical setup for this part of the experiment is shown in Figure 5.

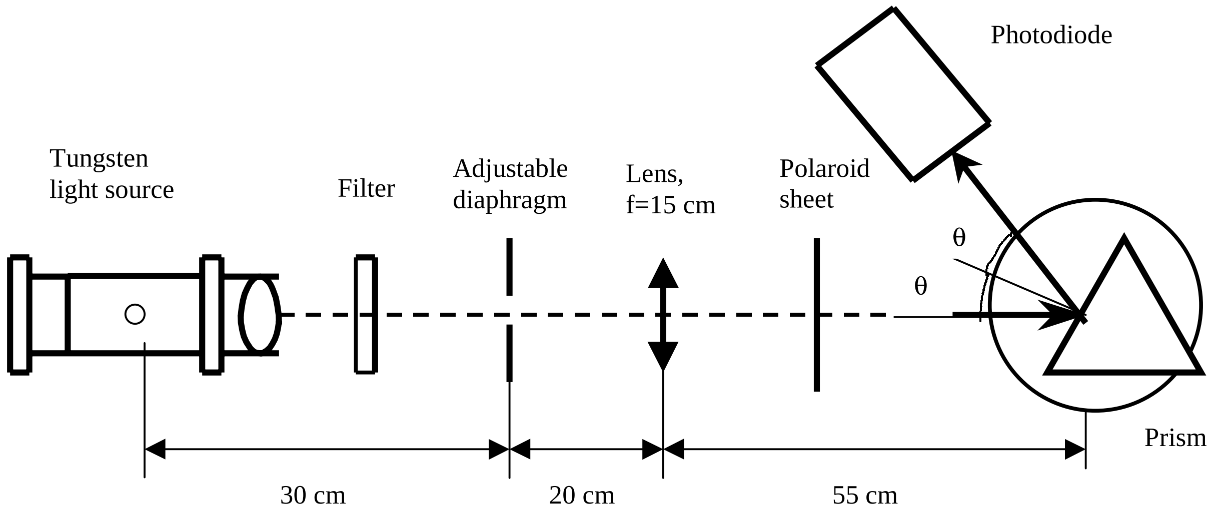


Figure 5. The optical setup for the study of polarization by reflection.

Calculate the expected Brewster's angle.

1. Swing the goniometer and the phototube arm and make sure that the reflected spot sweeps the same height at all possible angles.

2. Make sure that the reflected light beam at zero degree incidence refocuses at the diaphragm. Read this angle setting on the goniometer. This will be the reference angle from which the angles of incidence and reflection are to be measured.

3. A blue filter should be placed in the light path. The reason for using this filter is two-fold:

(a) Since the index of refraction depends on the wave length of the incident light, using a relatively monochromatic light source should render the interpretation of results relatively simple.

(b) The response of a vacuum phototube is linear to a certain light intensity specific to that tube and having such filters ensures that the light intensity does not exceed this limit.

The blue filter has its maximum transmission for λ= 420 nm. The index of refraction of the prism for this wave length will be marked on the inside of each box.

4. Measure the incident light intensity with the prism removed. Measure the intensity of reflected light for a set of incident angles (each 5^o) and for each of the two modes of polarization:

(a) vector ***E*** parallel to the plane of incidence

and

(b) vector ***E*** perpendicular to the plane of incidence.

Plot the reflectances $R_{//}$ and $R_{\perp}$ as a **function of the incident angles.** Results can be compared with formulae (2a), (2b). Explain your observations. Determine Brewster's angle (i.e. the polarizing angle) from your experiment and compare with the calculated value.

EXERCISE 4

1. As an additional exercise, think of ways to verify that the direction of polarization does not change in the process of reflection and test them out. You need to use a second Polaroid (as an analyzer) again.

2. Finally, verify that for the initially unpolarized light incident at Brewster's angle the reflected light is completely polarized.

3. We observe a type of polarized light every day. In fact, the light reflected from all dielectric shiny surfaces is at least partially polarized. Sun glasses made of polarizing material can be very effective in cutting out glare such as reflection from snow or large water surfaces. How do polaroid sun-glasses work?

(dh-1974, 1983, jbv 1990,ta-2000)

APPENDIX

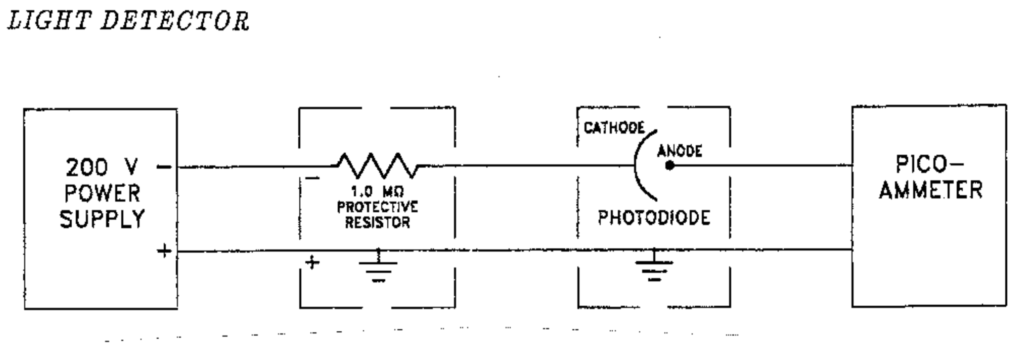


Figure 6. Photodiode Circuit

The measuring circuit for the light intensity is shown in Fig.2. It consists of a phototube (RCA 929) connected in series to a high voltage supply, a resistor and a pico-ammeter. When a metallic surface is exposed to light, electrons are ejected from the surface (the photoelectric effect). The number of electrons ejected is proportional to the intensity of light falling on the surface. The ejected electrons are accelerated by a fixed 200 V potential difference and collected as a steady current at the anode.