11. WAVE PROPERTIES OF LIGHT

You will investigate the wave properties of light: reflection, refraction, diffraction and interference. The light source is a helium-neon laser.

Theory

Why Study Light?

Physics is described as the study of matter and radiation. Since what is meant by light is in fact radiation, the study of light is at the heart of physics.

What is referred to loosely as "light" is commonly the electromagnetic radiation that is visible to the naked eye, extending in a color band from deep red to deep violet. Thus "light" occupies a narrow band in the spectrum (Figure 1). Light has the usual attributes of waves, namely *frequency*, *wavelength* and *speed*. The speed of light (c) in a vacuum has been measured at 3.00 x 10^8 ms^{-1} . In any material other than vacuum light travels at a speed less than c.

This experiment is mostly concerned with the wave aspects of light. For the particle or quantum aspects of light you should attempt the experiment "Particle Properties of Light".

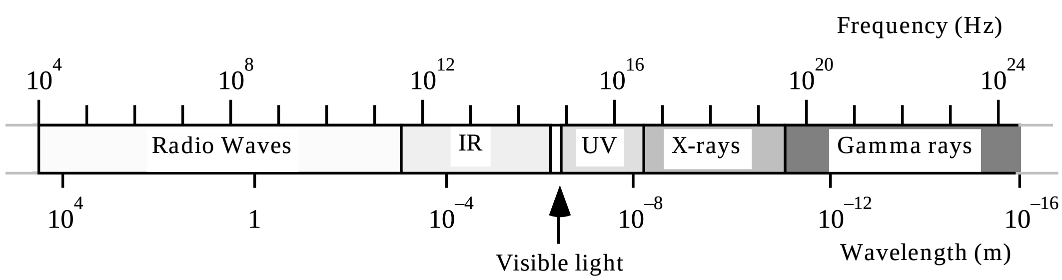


Figure 1. *A portion of the electromagnetic spectrum showing the narrow band occupied by visible light.*

Some Historical Background

The actual nature of light was the subject of much speculation from antiquity through to the 18^{th} century and beyond (see endnote 1). In the 18^{th} and 19^{th} centuries there evolved two schools of thought: the *particle* school and the *wave* school. (Isaac Newton, for one, was of the particle school.) It had been known for a long time that the properties of light called *reflection* and *refraction* could be explained if light was imagined to consist of a stream of particles like microscopic billiard balls. The properties of light called *diffraction* and *interference*, however, could only be explained satisfactorily if light was modelled as a wave. In this experiment you will concentrate on the wave properties of light. It is generally accepted today, however, that all electromagnetic radiation (whether light, radio, x rays, etc) has both wave and particle attributes.

Reflection

Reflection is possibly the most well known property of light, as it enables us to see our reflection in a mirror. Suppose a plane wave falls on a plane reflecting surface as is shown in Figure 2a. The angle θ between the ray[1] and the normal to the reflecting surface is called the *angle of incidence*. The wave has some velocity vector $\vec{v}$ in the medium as is shown in Figure 2b. The velocity vector can be resolved into components parallel and perpendicular to the surface. Theory predicts that the velocity component perpendicular to the surface is reversed upon reflection. The other component remains unchanged in a manner shown in Figure 2c. Thus *the angle of reflection equals the angle of incidence*. This is sometimes referred to as the *Law of Reflection*.

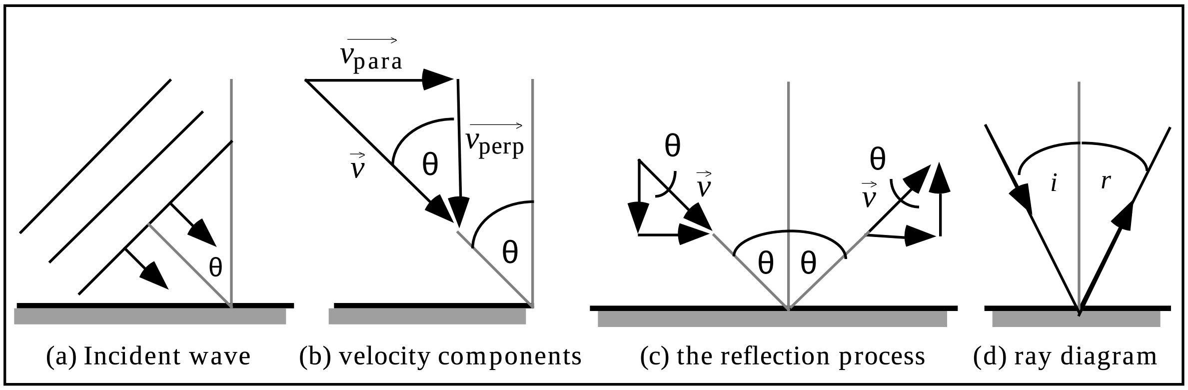


Figure 2. *Reflection of a plane wave at a plane surface. The direction of motion of the wave is described by a line or ray drawn perpendicular to the wave's leading surface. Angle i = angle r.*

Refraction

Refraction is also a property commonly observed almost every day. If we look through a window an object is often seen to be "displaced" from its normal position; this is *refraction*.

The case of reflection described in the previous section is essentially a special case, the case when the second, or reflecting, medium is opaque. A more general situation is when a portion of the incident beam passes into the second medium as is shown in Figures 3 and 4. If light travels at different speeds in the two media the beam will in general deviate from its original direction in the second medium; in other words, the beam will undergo *refraction*. Let us call this angle of refraction θ_2.

The special case of a single wavetrain falling on a boundary between two media at an angle of incidence of zero is shown in Figure 4a. Suppose the speeds of the wave in the two media are v_1 and v_2 respectively. Since the frequency of the wave must have the same value in the two media, the number of wave crests passing point A, say, per second equals the number of wave crests passing point B per second. Thus

$$f = \frac{v_1}{\lambda_1} = \frac{v_2}{\lambda_2}$$

or

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2}. \qquad \ldots[1]$$

The more general case occurs when the wave front falls on the boundary at an angle of incidence of, say, θ_1 degrees as shown in Figure 4b. From the two small triangles having the common side *d*, it can be seen that

$$\sin\theta_1 = \frac{\lambda_1}{d};\sin\theta_2 = \frac{\lambda_2}{d}.$$

Therefore
$$\frac{\sin\,\theta_1}{\sin\,\theta_2} = \frac{\lambda_1}{\lambda_2}$$

or
$$\frac{\sin\,\theta_1}{\sin\,\theta_2} = \frac{v_1}{v_2} \qquad \ldots [2]$$

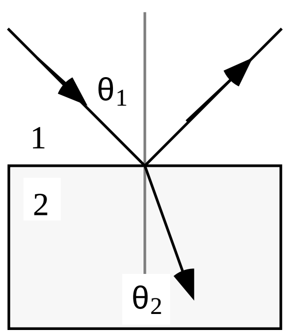
using eq[1]. Defining the index of refraction *n* of a medium as $n = c/v$, where *c* is the speed of light in a vacuum, eq[2] can be written

$$\frac{\sin\,\theta_1}{\sin\,\theta_2} = \frac{n_2}{n_1}$$

or
$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \ldots [3]$$

Eq[3]is called *Snell's Law*.

In this experiment you will study two examples of refraction which are common almost daily occurrences: refraction through a flat plate and refraction through a prism.



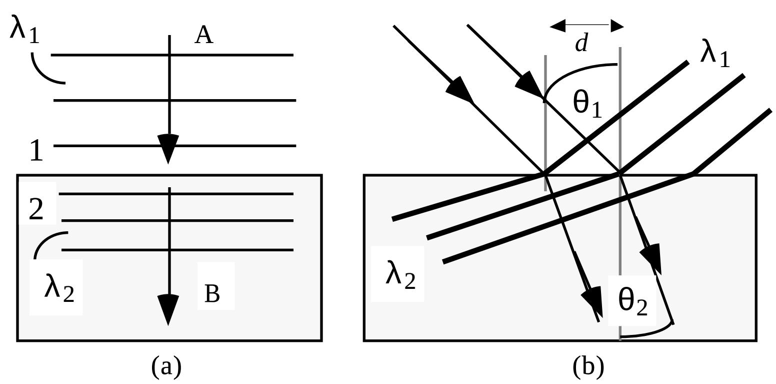


Figure 3. *A light ray encountering a boundary is partially reflected and partially refracted (shown $v_1 > v_2$) .*

Figure 4. *Single wavetrains encountering a boundary at angles of (a) zero degrees and (b) an arbitrary angle of θ_1 degrees. Refraction occurs when the angle of incidence is non-zero.*

Refraction Through a Transparent Plate

As has been stated above the refraction of light through a pane or plate of glass is observed by most of us every day. A light ray passing through a glass plate is deviated laterally from its original line by some amount *d* (Figure 5). You should be able to show that the following trigonometric relation applies to this laterally deviated ray:

$$(\cos i)(\tan r) = \sin i - \frac{d}{t} \qquad \ldots [4]$$

where *i* is the angle of incidence, *r* is the angle of refraction (inside the plate), and *t* is the thickness of the plate.

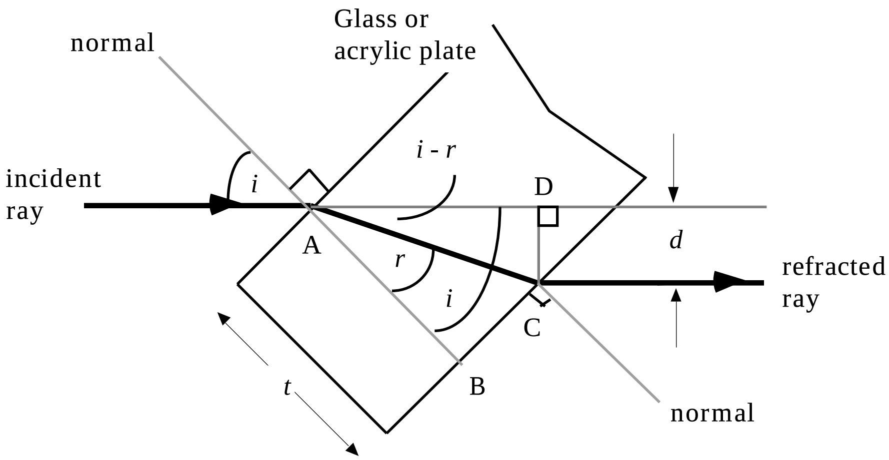


Figure 5. *A light ray passing through a transparent plate is displaced laterally from its original line. The refracted and incident rays are parallel.*

Refraction Through a Prism

Refraction through a prism is probably oberved less often than reflection or refraction through a plate. An application of this effect is in the so-called prism spectrograph (as in the experiment “The Particle Properties of Light”).

In general a light ray is deviated by a prism through some arbitrary angle that depends on the angle of incidence *i*. But at a special orientation the angle of deviation, say D, is a minimum as shown in Figure 6. It can be shown by experiment and theory that when D is a minimum, i.e., $D = D_{min}$, the part of the beam that is inside the prism is parallel to the bottom side. You should be able to demonstrate experimentally that when $D = D_{min}$

$$i = \frac{1}{2}(A + D), \quad r = \frac{1}{2}A \qquad \ldots [5]$$

where *A* is the so-called prism angle (typically 60˚).

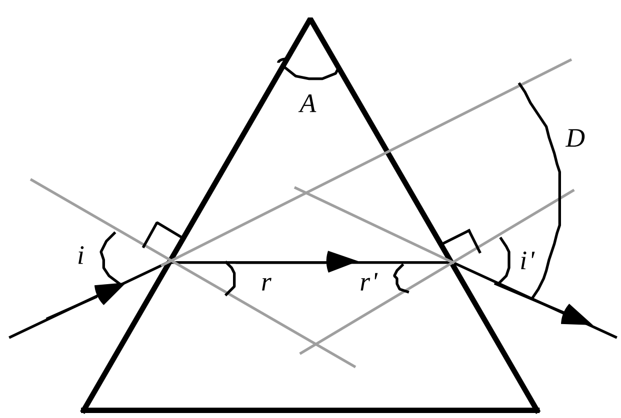


Figure 6. *When a ray of light passes through a prism such that the angle of deviation D is a minimum (D_{min}) the ray inside the prism is parallel to one side of the prism.*

Total Internal Reflection

Total internal reflection is not obvious in our everyday activities. When a beam of light travels from one medium into a second medium whose index of refraction is lower than the first, the beam can, under certain conditions, be totally reflected (Figure 7). At this angle of incidence, called the *critical angle* θ_C, the angle of refraction is 90˚. (In fact as the angle of refraction approaches 90˚, the intensity of the refracted beam approaches zero.) For angles of incidence greater than θ_C, the beam is entirely reflected.

This critical angle can be found from Snell's Law, eq[3]. Putting θ_2 = 90˚ ,

$$\sin\theta_C = \frac{n_2}{n_1}$$

$$= \frac{1}{n_1} \qquad \text{...[6]}$$

if the second medium is vacuum (or, to a good approximation, air).

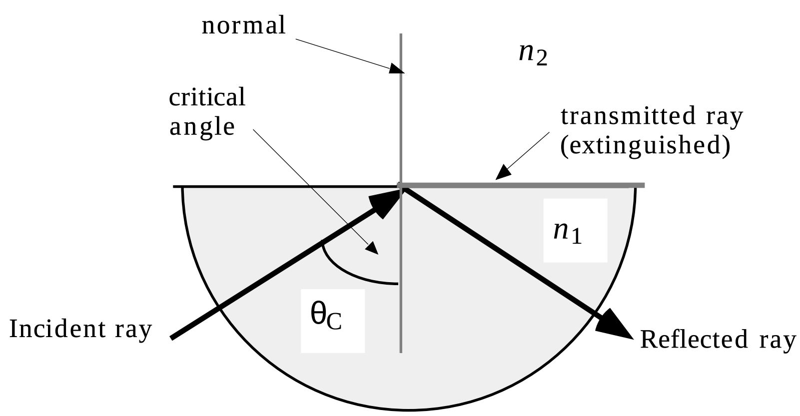


Figure 7. *Total internal reflection within a hemispherical section of plastic showing critical angle* θ_C.

Diffraction and Interference Through a Grating

For the study of light a diffraction grating is just as important a device as is a glass prism.

Diffraction can be explained as follows. All waves, whether water, sound, light and so on, do not always cast sharp shadows. In fact, the waves that are incident on one side of a small aperture as shown in Figure 8 are observed to radiate away on the other side in all directions. This effect is called *diffraction*. To describe this effect in terms of waves it is useful to think of the portion of the incident wave which passes through the aperture as the source itself of spherical wavelets. This idea of spherical wavelets is attributed to Christian Huygens (1629-1695) and is called *Huygens' principle*. It is useful also to imagine that the waves emanating from two or more such point sources can interfere with one other like any other kind of wave.

The diffraction grating is useful for showing the sum total of these effects, *diffraction* and *interference*. A diffraction grating is just a piece of glass or photographic emulsion which is etched with a large number of equally spaced parallel lines. The lines behave like opaque barriers to light while the untouched spaces between the lines serve as slits.

A parallel beam of light falling at an incident angle of zero on a grating will be diffracted as shown in Figures 9 and 10. It is assumed that the slits are narrow enough so that diffraction by each of them spreads light over a very wide angle on a distant screen behind the grating, and that interference can occur with light from all the other slits. Light rays that pass through each slit with essentially no deviation ($\theta = 0^\circ$) interfere constructively to produce a bright spot at the center of the screen. (This spot is given the order number n of 0.) At an angle θ such that rays from adjacent slits must travel an extra distance to reach the screen of $\Delta = n\lambda$, where n is an integer, constructive interference again occurs. Thus if d is the distance between slits,

$$\sin\theta = \frac{n\lambda}{d}, \quad n = 0, 1, 2 \text{ - -} \qquad \ldots [7]$$

in order to have a brightness maximum.

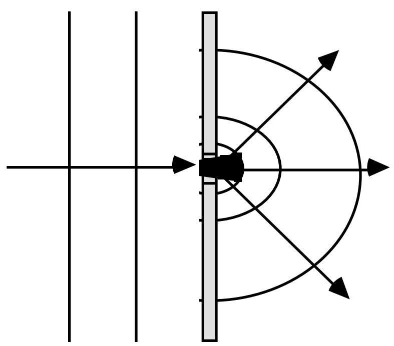


Figure 8. *When a wave encounters a hole in a barrier, the hole acts effectively as a new source of waves.*

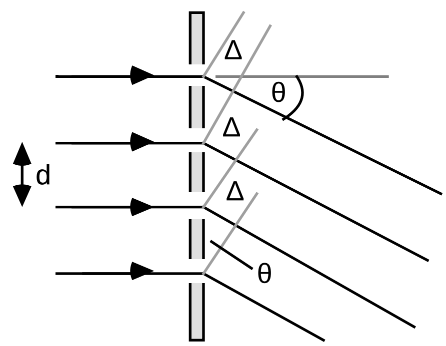


Figure 9. *The geometry of diffraction through a grating.*

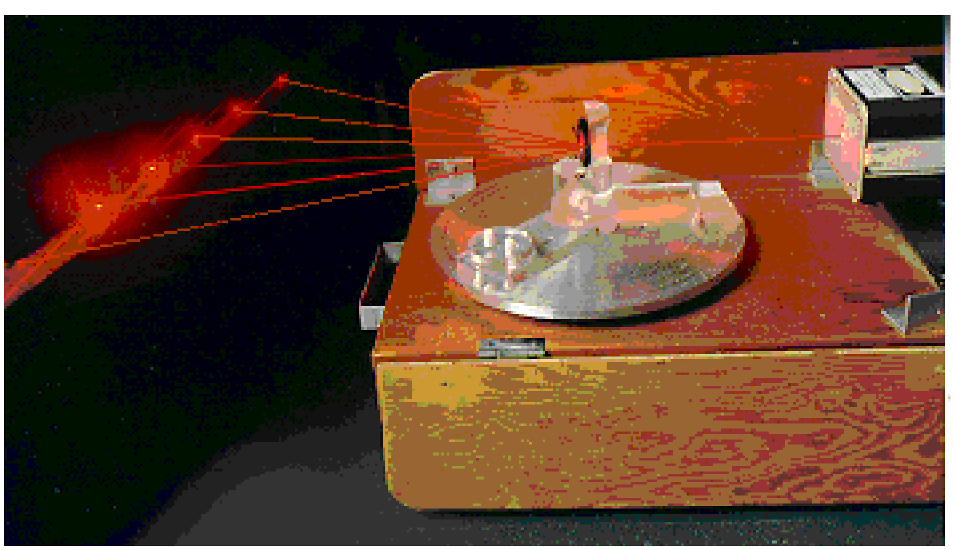


Figure 10a. *The setup showing the laser beam diffracting through the grating.*

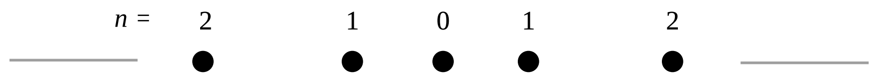


Figure 10b. *A few spots observed from the diffraction through a grating and their corresponding order number.*

The Experiment

Exercise 0. Preparation

Orientation

If you find your laser has been left on turn it OFF. The light source is a He-Ne (Helium-Neon) gas laser which emits red light of wavelength 633.0 nm (1 nm = 10^{-9} m) at a power of about 1.0 mW.

➠ IMPORTANT

<u>DO NOT LOOK DIRECTLY INTO THE LASER BEAM OR ITS REFLECTION</u> OR YOUR EYES MAY BE DAMAGED.

Components

Identify the apparatus (some items are stored in the drawer under the laser mount and fixed to a holder): a mirror, a horizontal scale, glass and plastic prisms (each of angle A = 60˚), glass and plastic plates, a plastic hemispherical section, two replica gratings labelled “300” and “600” (meaning number of lines / mm); and a diffraction ruler mounted on a black board.

Exercise 1. Reflection

The law of reflection can be tested easily. Mount the mirror and horizontal scale in such a way that you can easily read the angles of incidence and reflection from the graduated disk on the base of the apparatus. Measure a series of angles i and the corresponding angles r. Does the angle of incidence always equal the angle of reflection? Be honest; estimate realistically the errors in positioning the devices and estimating the center of the laser spot.

Exercise 2. Refraction Through Transparent Plates

Apply trigonometry to Figure 5 to prove eq[4]. (You may wish to postpone this until the end of the lab to save time.)

Eq[4] cannot be proven experimentally because r cannot be measured (inside the plate). The next best thing is to use eq[4] to calculate the plate’s refractive index. Therefore, vary i and find the corresponding deviations d for the glass and plastic plates. Calculate the corresponding angles r from eq[4]. Measure the thicknesses t with a vernier caliper. Finally, calculate n using Snell’s Law. Take enough data to obtain good average values. How well do your refractive indices agree with the data in Table 1?

Exercise 3. Refraction Through a Prism

Satisfy yourself that *D* is a minimum when the beam inside the prism is parallel to the prism's bottom side. (This may be easier to see in the case of the plastic prism.) To do this, let the refracted beam fall on the black board placed about 0.5 m away from the prism. Verify experimentally the first of eqs[5]. Calculate the refractive indices of the glass and plastic prisms and compare your results with those you obtained in Exercise 2. Time permitting, repeat the above using the hollow prism filled with tap water (or another fluid of your choice).

Table 1. *Refractive Indices of common materials*

Material	$c/v = n$
Air (STP)	1.0003
Water	1.33
Ethanol	1.36
Fused quartz	1.46
Benzene	1.50
Crown glass	1.52
Sodium chloride	1.53
Perspex plastic	1.489 (red light)
Flint glass	1.66
Diamond	2.42

Exercise 4. Total Internal Reflection

Find the critical angle for internal reflection within the hemispherical section. Calculate *n* from eq[6] and compare this value with values you obtained previously. Which are the more accurate?

Exercise 5. Diffraction and Interference

Note the number of lines per mm printed on the frames of the two replica gratings and calculate *d* (the distance between lines) for each. Set up the gratings and the "diffraction ruler" so as to obtain a number of diffraction orders or spots on the ruler. One way to test eq[7] is to use it to calculate λ, the wavelength of the laser light. Accordingly, for as many orders as you can record, calculate the corresponding $\sin\theta$s. Then calculate λ from eq[7]. How does your average value compare with the "accepted" value of 633.0 nm?

Videos and Physics Demonstrations on LaserDisc

The episode "Electromagnetic Radiation", from the series *Project Universe*, Tape #1

from Chapter 59 *Refraction and Internal Reflection*
Demos 22-06 to 22-15 *Refraction/Reflection from Plastic Block, Small Refraction Tank*, etc.

from Chapter 61 *Diffraction*
Demos 23-01 to 23-09 *Microwave Diffraction, Single Slit Diffraction*, etc.

from Chapter 62 *Interference*
Demos 23-10 to 23-21 *Microwave Double Slit Interference, Double Slit Interference*, etc.

Activities Using Maple

(Under Construction)

Stuart Quick 94

EndNotes for Wave Properties of Light

[1] A ray is a line drawn normal or perpendicular to a wavefront for the purpose of tracing a beam of light through a system. Its invention is attributed to Al Khazen, an Arab scholar of the middle ages.