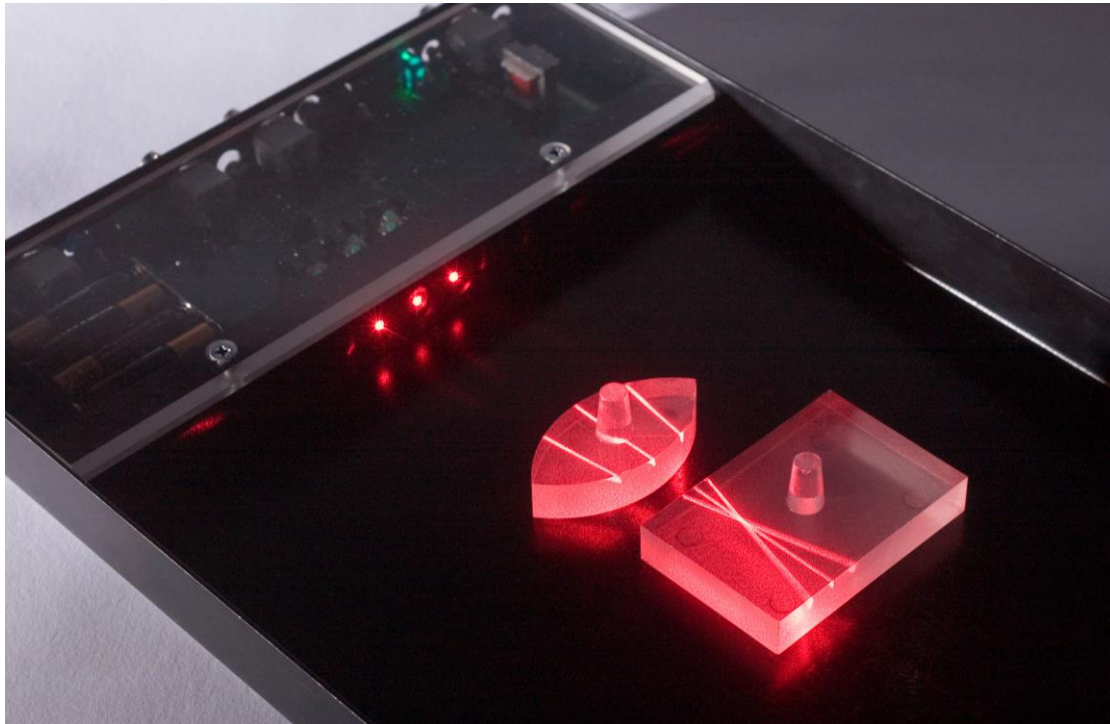


minilabs™



# Experiments in Photonics



Laser Pathways.

# A note from the development team

Photonics, the study of light, has become the most important area of physics in recent years, with many Australian Universities at the forefront of this research. The Australian National University in Canberra developed the first successful device to teleport a laser beam. This has massive implications for the future of cryptography and quantum computers.

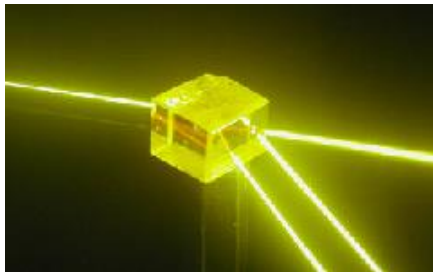
There are many exciting areas of research; from producing a Bose-Einstein-Condensate (an entirely new form of matter) to searching for gravity waves using a very large laser detector based on the interference of light.

If the 20th century was the era of electronics, the 21st is the era of photonics.

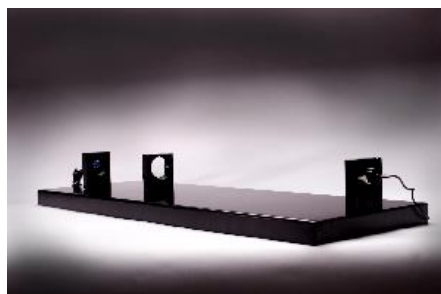
In order for Australian students to make the most of the exciting opportunities forthcoming in the age of photonics, they need to be equipped with the knowledge and skills that are in demand now and into the future.

Here at Minilabs we have developed the first and only complete photonics laboratory in a box. The Photonics Minilab comes with comprehensive notes guiding you through some famous historical experiments as well as those at the cutting edge of physics.

For teaching photonics at your school, the Photonics Minilab is *everything* you need.

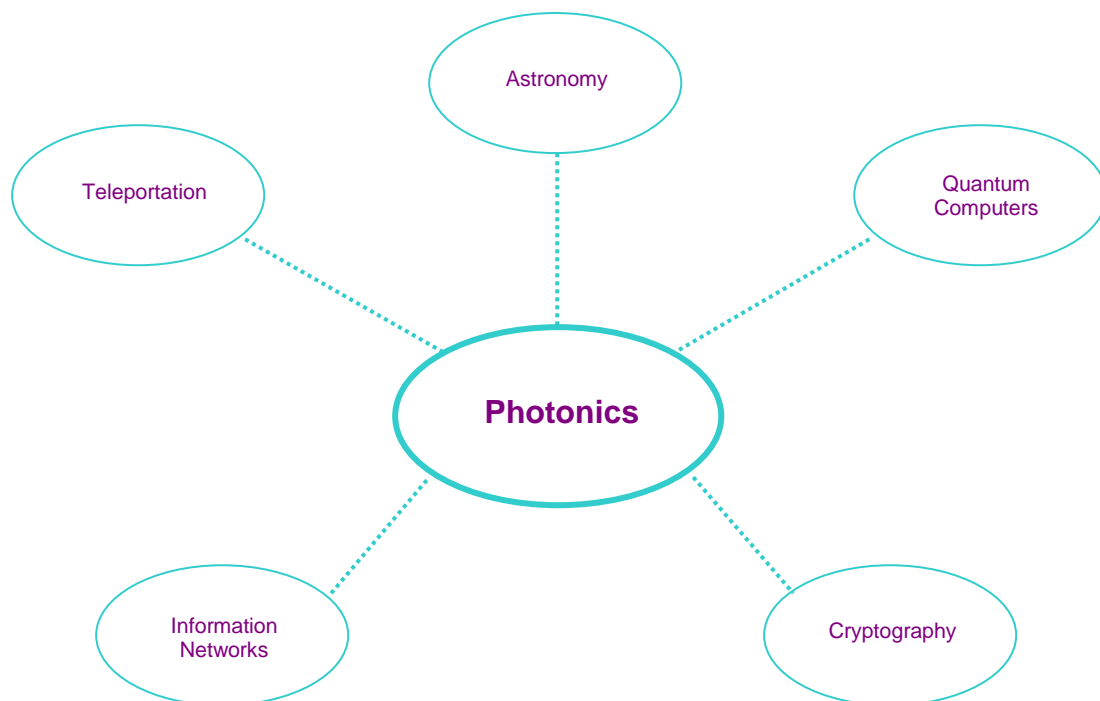


Quantum computer memory crystal, Photograph courtesy of Research School of Physical Sciences, Australian National University



Minilab II, Photograph by Minilabs

The photonics industry has grown rapidly in recent years, and the curriculum is changing to reflect its importance. Many devices we use everyday rely on the physical properties of light. Barcode scanners in supermarkets have lasers reflected by rotating mirrors, nearly all of our communication, voice or data, is transmitted by lasers coupled into fiber optic cables. Photonic devices are rapidly replacing electronic for reasons of safety, power consumption, speed, reliability and sometimes because of their bizarre quantum properties. Many of the most innovative research areas are centred around photonics.



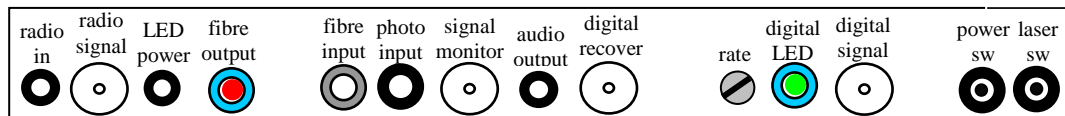
Photonics is a cutting edge field in physics, and its importance will grow ever stronger. As scientific knowledge increases, industry will follow, creating more demand for expertise in this exciting technology.

# Notes

Minilab II is normally supplied complete with the lasers and the electronic components.

An oscilloscope is a valuable accompaniment to Minilab II to visualise some of the waveforms. The relevant section provides a guide to the settings on the instrument.

Minilab II is self-contained and runs off 4 AAA batteries. Connections are made through the panel built into the end of the bench.



Minilab II comes with an earphone; but we have achieved excellent outcomes using a set of computer speakers.



Minilab II Connections

# LASER SAFETY



Lasers are part of everyday life and most households currently have them built in to many devices such as DVDs, CDs and computers.

The most common use of lasers is in the scanners used in shops to read barcodes and price items.

The laser is an essential device or tool in education and industry and many professions routinely use this technology.

We believe it is essential for students to be able to use lasers in a safe manner with the risks reduced to a minimum.

We use a Class 2 laser similar to that found in laser pointers. The strength of this laser is similar to that of the sun. Just as staring at the sun will cause damage, continuous shining of the laser into the eye will produce eye damage and blindness.

If a class 2 laser beam accidentally shines into the eye the person will blink and move the head to reduce exposure. Just like catching a ball coming out of the sun, our reflexes are fast enough to save our vision.

The lasers have been contained in a safety bench to prevent the beam from escaping.

Also white cards should be used to find the laser beam and the beam should always be viewed from above.

Please see Appendix A for a detailed description of laser classifications.

## SAFETY RULES

- **Do not stare at the laser beam**
- **Beware of reflections**
- **View the laser beam from above**
- **Use a white card or screen to trace the path of the laser beam**

## Contents

- 1.1 Reflection
- 1.2 Refraction through Blocks, Prisms & Lenses
- 1.3 Total Internal Reflection and Critical Angle
- 1.4 Dispersion in an Optical Fibre
- 1.5 Diffraction and Interference using a Laser

- 2.1 Lenses and Chromatic Dispersion
- 2.2 Diffraction: An Introduction
- 2.3 Emission and Absorption Spectroscopy
- 2.4 The Prism Spectrometer
- 2.5 Band Gap Energy
- 2.6 Young's Double Slit
- 2.7 Polarisation
- 2.8 Analog Modulation: Free Space
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- 2.10 Optical Fibre Basics and Digital Modulation
- 2.11 Inverse Square Law
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# 1.1 Reflection

## Aims

Explore how light rays reflect from mirrors

Understand and confirm the Law of Reflection

## Introduction:

Light travels through space in straight lines, along the path that takes the shortest time. This can be seen with phenomena such as shadows or eclipses. When light meets the boundary of two different media (eg. the surface of water, a mirror, or between different gases), its direction changes. For example, when light hits a mirror, its direction of propagation changes, and the light is reflected. When we see the moon, we are really looking at light from the sun that has been reflected off the moons' surface, not the moon shining. The direction of travel of the reflected light is not a random direction, but the direction determined by the Law of Reflection. This law states:

“The angle of reflection ( $\theta_r$ ) of a light beam must equal its angle of incidence ( $\theta_i$ ).”

Mathematically,

$$\theta_r = \theta_i$$

Both angles are measured with respect to the normal of the reflecting surface, as shown in figure 1.

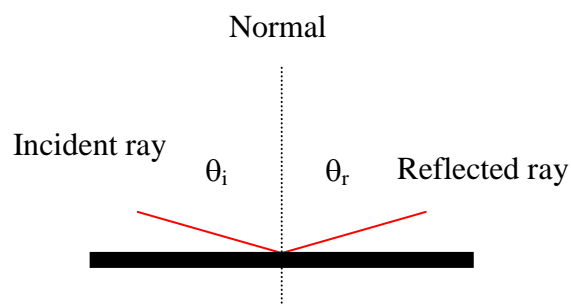
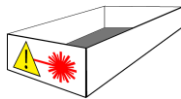
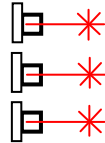
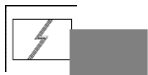
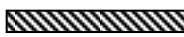



Figure 1.1 – Reflection off a flat mirror

In this experiment you will test the Law of Reflection using different shaped mirrors, and changing the angle of incidence.

## Equipment

	Laser bench		Lasers		Slide Holder
	Flat Mirror		Curved Mirror	Screen/Card Protractor, Ruler	



**Do not stare at the laser beam**  
**Beware of reflections**  
**View the laser from above,**  
**Use card or a screen to trace the path of the laser beam**

## Activity

In this experiment you will test the Law of Reflection.

Activate the lasers using the toggle switch. Block two of the lasers with the slide holder.

Lay a piece of white paper on the bottom of the optical table, using the screen or card to make sure the laser path goes across the middle of the sheet. Position the mirror on the sheet so that it makes an angle with the laser beam, as shown in figure 1.1.2

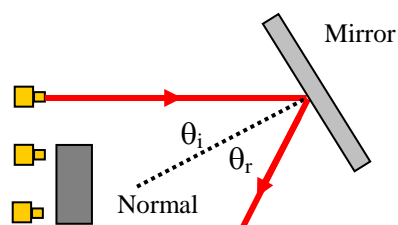


Figure 1.1.2 – Experimental set up

Trace around the mirror with a pencil, and use the screen or card to help trace the path of the laser beam both onto and away from the mirror.

Repeat several times (at least five times), each time moving the mirror so it makes a different angle with the laser beam.

Record your results in a table. Remember to include appropriate units.



Do your results confirm the Law of Reflection?

Every experiment has some degree of error associated with it. A well designed experiment is one that minimises the amount of error introduced with each measurement.

Questions:

1. In this experiment, where do you think there is error introduced?
2. Estimate how accurate your measurements are. How could you make them more accurate?
3. Do your results confirm the Law of Reflection to within the range of your error?

### Additional Activity

Repeat the experiment, this time using both the inside and the outside of the curved mirror. Is the Law of Reflection still obeyed? (Hint: You may want to work out some method of drawing a tangent and a normal to the surface of the mirror.)

Questions:

4. Do your results for the curved mirror obey the Law of Reflection?
5. Do you think the error for the curved mirror would be larger or smaller than the error for the flat mirror? Why?
6. Compare your results from the flat mirror and the curved mirror. Which set of results obeys the Law of Reflection most closely? On this basis, which mirror has the smallest error associated with it?

# 1.2 Refraction

## Aims

Explore how light rays refract through the plastic block

Understand Snell's Law, and use it to determine the refractive index of the block

Investigate how light travels through convex and concave lenses

## Introduction

We saw in the reflection experiment that light travels in straight lines until it meets the boundary of two media.

Refraction occurs when light meets the boundary of two media, and the light continues through the second. For example, when light hits the boundary between air and water, its path bends, but it still continues through the water. If you stick a pen in a glass of water, it appears to bend when it touches the water. This is because light travels at a different speed through water than it does through air.

In fact, light travels at a different speed in every medium. It travels fastest in a vacuum – the speed at which it travels is referred to as the speed of light, and is denoted  $c$ . The speed of light is known very accurately, but for most purposes:

$$c = 3 \times 10^8 \text{ m/s}$$

is good enough. The speed of light in any other medium is defined as the speed of light (in a vacuum,  $c$ ) divided by the refractive index ( $n$ ) of the medium. Mathematically,

$$v = c/n$$

The refractive index of any material is greater than or equal to one ( $n_{\text{vacuum}} = 1$  but otherwise  $n > 1$ ). The refractive index of air is very close to one,  $n_{\text{air}} \approx 1.008$

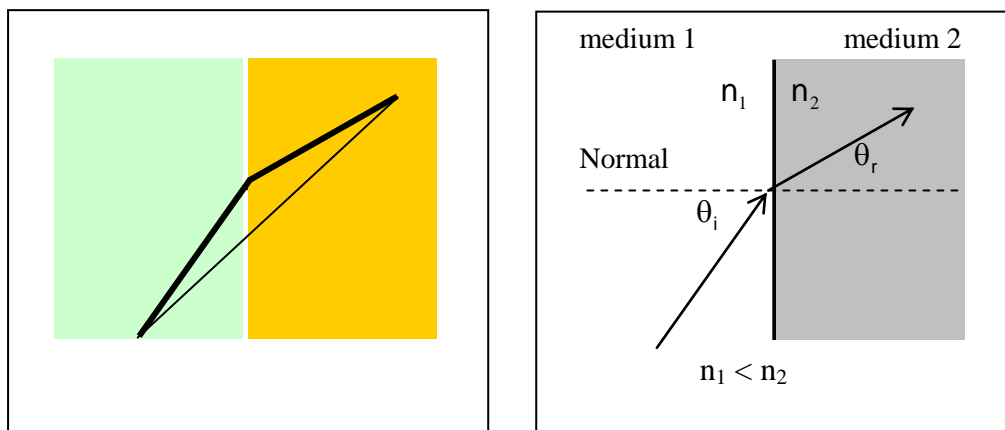


Figure 1.2.1 Paths from grass to sand and refraction

Figure 1.2.1 shows the refraction of light as it passes from one medium to a denser medium. An analogy is to consider running from grass to sand. The direct route is not always the quickest as the best way is to stay on the grass longer.

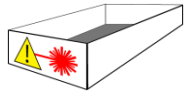

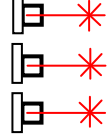
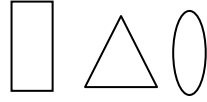
The direction of propagation of light in the second medium depends on the angle of incidence ( $\theta_i$ ), the refractive index of the first medium ( $n_1$ ), and the refractive index of the second medium ( $n_2$ ). The Law of Refraction is known as Snell's Law, and is given by:

$$n_1 \sin(\theta_i) = n_2 \sin(\theta_r)$$

## Activity

In this experiment you will use Snell's Law to determine the refractive index of the plastic block.

## Equipment

	Laser Bench		Slide Holder	Protractor, ruler, screen or card
	Lasers		Plastic block, prism and lens	



**Do not stare at the laser beam**  
**Beware of reflections**  
**View the laser from above,**  
**Use card or a screen to trace the path of the laser beam**

Place a sheet of paper on the base of the laser bench. Turn on the laser and position the plastic block at an angle to the laser beam, Figure 1.2.2 Block two of the beams with the slide holder.

Draw around the block and use a screen or card to trace the path of the laser beam. Mark where the beam enters and leaves the plastic block.

Measure the angle of incidence  $\theta_i$  and the angle of refraction  $\theta_r$ . Take several measurements at different angles for the block.

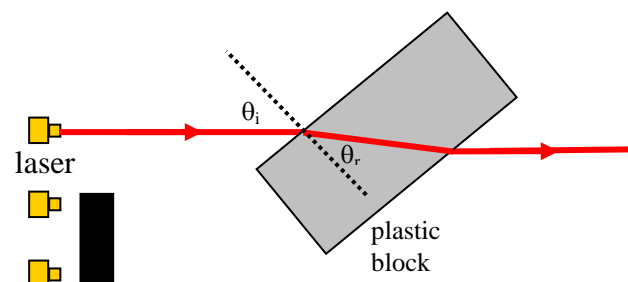


Figure 1.2.2 Refraction through a plastic block

Draw up a table and fill in the results for  $\theta_i$  and  $\theta_r$ .

$\theta_i$	$\theta_r$	Refractive Index $n_2$	Speed of light in the block

Are the angles of incidence the same as the angles of refraction?

If the angles are different it means the refractive index of the block is different to air.

The refractive index of air is 1.00. Use Snell's law to calculate the refractive index  $n_2$  of the block and fill in the table.

The velocity of light in a vacuum  $c$  is 300,000 km/s.

In the block the speed of light  $v$  is given by  $v = \frac{c}{n_2}$

How fast is the light in the plastic block? Put the results into the table

### Additional Activity

Repeat the procedure using the  $60^\circ$  prism, Figure 1.2.3 tracing out a few ray paths and then calculating the refractive index of the prism using Snell's Law.

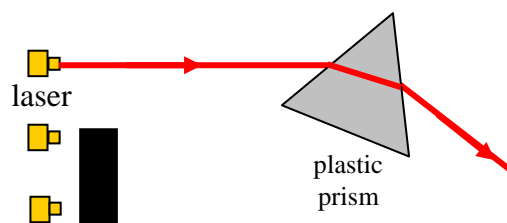


Figure 1.2.3 Tracing light rays through the prism



**Do not stare at the laser beam**  
**Beware of reflections**  
**View the laser from above,**  
**Use card or a screen to trace the path of the laser**

## Lenses

The exercise can be continued using the flat plastic lenses and all three lasers.

Plastic or glass has a refractive index different to air so light bends by refraction as it passes through the boundaries.

Convex lenses will refract light rays towards the centre of the lens and cause parallel beams to converge to a point. This point is known as the focal point and its distance from the lens is known as the focal length.

Concave lenses will refract light rays away from the centre of the lens and cause parallel beams to diverge. If the diverging rays were traced *backwards*, towards the light source, then they would converge to a point. This is the focal point of a concave lens, and as it lies on the same side as the light source it is assigned a *negative* value.

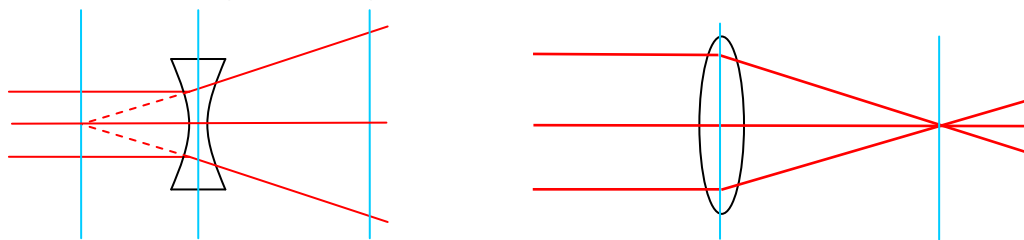


Figure 1.2.4 Concave and Convex lenses

## Activity

Place a sheet of paper on the base of the laser bench. Turn on all three lasers and trace the laser beams through the different lenses shown below. The point where they cross is the focal point.

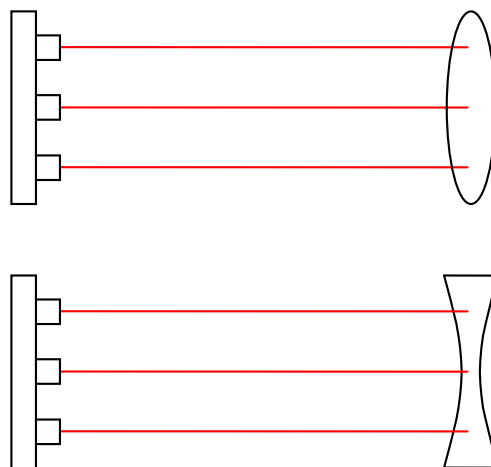
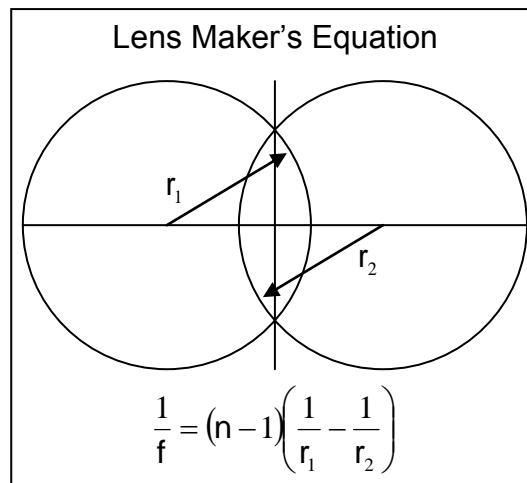


Figure 1.2.5 Determination of focal lengths of convex and concave lenses

Determine the focal length of each lens. Refer to the earlier notes to deal with the concave lens.

What is the relationship between the curvature and thickness of a lens and its focal length?



### Additional Activity

Use the lens maker's equation to find the radius of curvature of the different lenses.

$$\frac{1}{f} = (n - 1) \left( \frac{1}{r_1} - \frac{1}{-r_2} \right) \quad \text{Lens maker's equation}$$

Assume the two radii of curvature are equal and  $n = 1.5$  for the plastic lenses

Does the lens maker's equation apply to concave lenses?

# 1.3 Total Internal Reflection

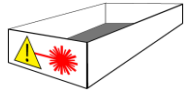
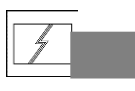
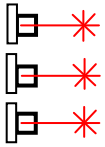
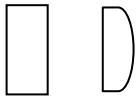
## Aims

To observe total internal reflection  
 To measure the critical angle

## Introduction

Total internal reflection occurs when the refractive index of the medium through which the light is passing is greater than the surrounding refractive index. The light is confined to the central medium.

## Equipment

	Laser Bench		Slide Holder	
	Lasers		Block and semi-circular block	Protractor, ruler, screen/card



**Do not stare at the laser beam**  
**Beware of reflections**  
**View the laser from above,**  
**Use card or a screen to trace the path of the laser beam**

## Activity

Place a sheet of paper on the base of the laser bench, turn on the laser and place the block so light enters through the end, Figure 1.3.1

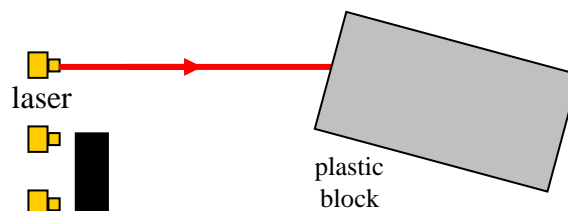


Figure 1.3.1 Total Internal Reflection

Locate the laser beam and record at least three light paths through the block. The light should not escape from the sides of the block. This is total internal reflection and occurs when the transmitting medium has a higher refractive index than the outside medium.

Refer to the table with the results for Refractive Index and consider if these results are consistent with Total Internal Reflection.

This is how optical fibres transmit light and their design is dependent on getting the refractive indices correct.

## Additional Activity

Light is refracted when it meets a boundary of different refractive index. As the angle of incidence  $\theta_i$  is increased, the refracted angle  $\theta_r$  of the beam exiting the block increases. When  $\theta_r = 90^\circ$  total internal reflection occurs. The angle of incidence is recorded and is called  $\theta_c$ . This is the critical angle.

Set up the semicircular block so the laser passes through the centre of the block.

Rotate the semicircular block until no light passes through and the beam is reflected out of the front surface. Mark the position of the block and laser path.

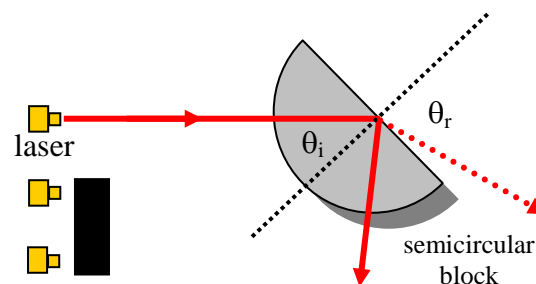


Figure 1.3.2 Measuring the critical angle  $c$

Measure the critical angle  $\theta_c$ . This requires a degree of judgement as to when total internal reflection of the laser beam has occurred.

Why can the effect of refraction be ignored on the front surface?

Is the Law of Reflection upheld?



# 1.4 Dispersion in an Optical Fibre

## Introduction

Light travels through an optical fibre by total internal reflection. Digital pulses of light based on a binary code are normally used to send information through optical fibres. As the pulses of light travel through the fibre they tend to spread out and may eventually overlap. If this occurs the signal becomes corrupted and the information is lost.

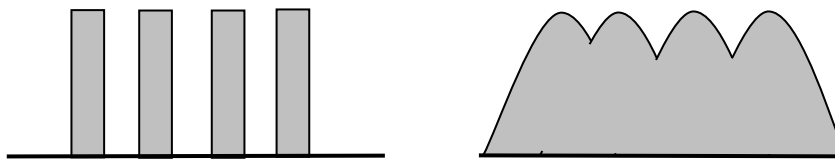


Figure 1.4.1 Digital signal showing pulse spreading.

There are two main types of dispersion. Modal dispersion occurs because the light travels through the fibre by total internal reflection and can take different paths.

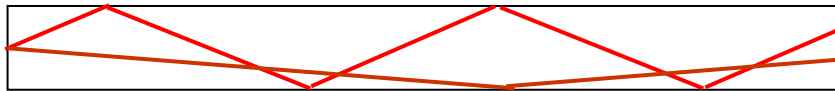


Figure 1.4.2. Modal dispersion in an optical fibre

Figure 1.4.2 shows the paths of two light rays through a length of fibre.

If each light ray travels at the same speed which one will arrive at the exit of the fibre first?

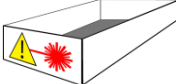
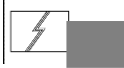
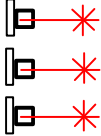

## Aims

To understand modal and chromatic dispersion in optical fibres

Measure mode lengths to find the critical angle

Explain how digital information can be corrupted in an optical fibre

## Equipment

	Laser Bench		Slide Holder	
	Lasers		Lucite rod	Protractor, ruler, screen/card



**Do not stare at the laser beam**  
**Beware of reflections**  
**View the laser from above,**  
**Use card or a screen to trace the path of the laser beam**

## Activity

Locate the length of smoked Lucite rod and position it so the laser beam passes through the rod as shown in figure 1.4.3. The smoked Lucite should allow the laser beam to be visualised and marked out on a sheet of paper underneath the rod.

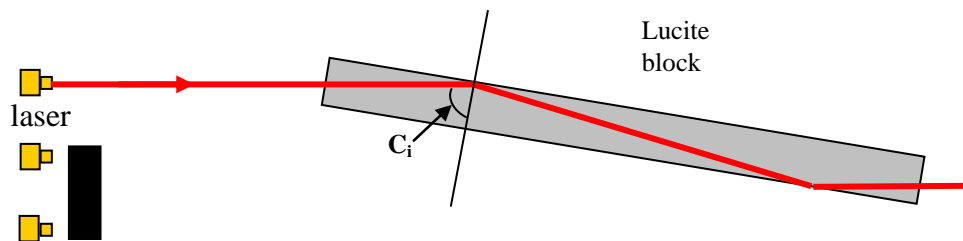


Figure 1.4.3 Measuring modes

Make sure the laser enters the centre of the rod. Mark and measure the path length of the laser for the direct beam that undergoes no internal reflection. Then mark and measure path length for one, two, three etc internal reflections up to the maximum that can be seen.

Measure the angle of internal reflection  $C_i$  for each pattern drawn. Plot the results on a graph to show path length against angle of internal reflection. Extrapolate the graph to the critical angle previously measured. This is the maximum path length.

The piece of smoked Lucite is acting as a multimode fibre. Each path represents a mode.

Why would a much longer length of fibre have many more modes or path lengths?

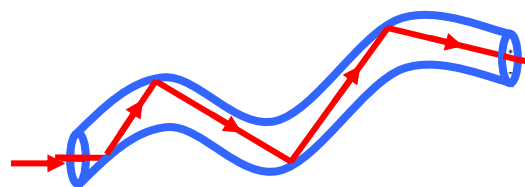



Figure 1.4.4 Light path through a Fibre

Multimode fibres are only used for relatively short fibre links whereas especially designed single mode fibre with a very small core diameter (5 microns or less) is used for long distance communications.



Material or chromatic dispersion occurs because light of different wavelengths or colours travels at different velocities through the fibre. A white light source has a very broad range of wavelengths so would be most unsuitable for signal transmission in optical fibre.

Lasers have extremely narrow spectral widths and appear to have a single colour output and are ideally suited to data transmission. However chromatic dispersion still occurs with these devices.

How does dispersion affect the potential rate of signal transmission?

# 1.5 Laser Diffraction and Interference

## Introduction

When light passes an edge it spreads out causing diffraction. There are two different types of diffraction – Fresnel and Fraunhofer. Fraunhofer diffraction is the special case where the image is collected at a large distance compared to the size of the aperture.

Fresnel diffraction is the general case and is mathematically much more complex. When we talk about diffraction in this experiment we will be referring to Fraunhofer diffraction. Diffraction is important in the design of optical instruments.

The shape of the aperture determines the shape of the diffraction pattern. For example a circular aperture will produce a diffuse circular pattern known as Airy's disc.

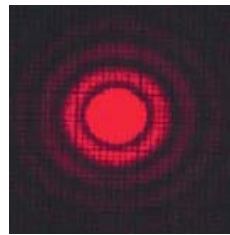


Figure 1.5.1 Laser diffraction pattern of a small hole

When you look at a distant street lamp there may be a corona surrounding it. This is actually a diffraction pattern determined by the aperture of your eye. Occasionally the moon exhibits a corona due to diffraction from the small water droplets or ice crystals in the air above us.

The dimensions of the interference pattern observed can be calculated if we know the wavelength ( $\lambda$ ) of the light, the size of the aperture ( $d$ ) and the distance from the aperture to the screen ( $L$ ).  $W$  is the width of the central maximum.

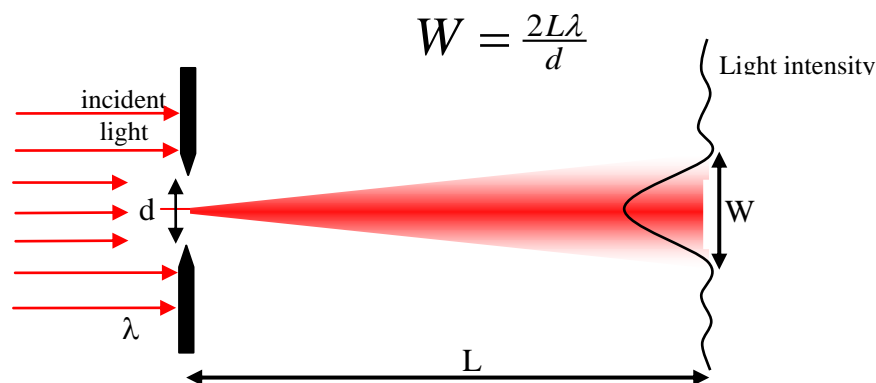


Figure 1.5.2 Diffraction and light intensity through a slit

In general terms the smaller the aperture the greater the effect of diffraction and interference. This knowledge is useful because many optical instruments have small circular apertures.

Usually for an optical instrument it is desirable to limit the diffraction. This means  $W$  must be as small as possible. By inspection of the equation above we can see that we need to make  $d$  as large as possible. Microscope objective lenses provide an example, with the better lenses having the larger apertures.

A diffraction grating is a slide that contains thousands of tiny parallel lines etched into a piece of film. Typically a grating has 600 lines per millimetre or the spacing between lines is about 1.6 microns or 0.0016mm.

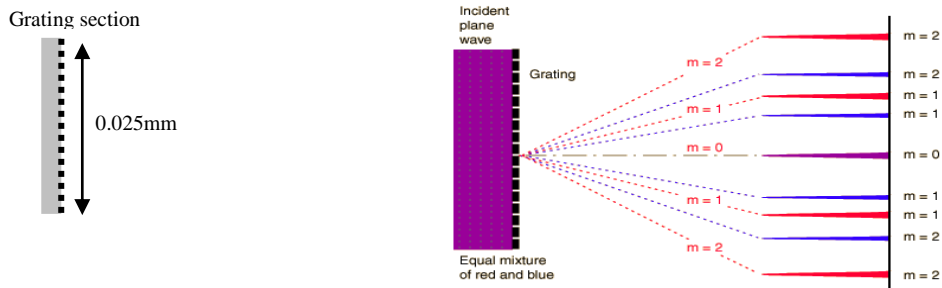


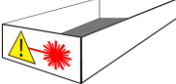
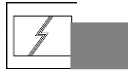
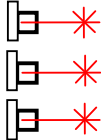

Figure 1.5.3 Diffraction grating. Line spacing is about 1.6 microns.

Monochromatic or light of a single colour allows for the detailed investigation of diffraction phenomena. This experiment complements Diffraction: An Introduction in Section 2.

## Aims

- To observe diffraction through a grating
- Calculate the wavelength of a laser using a diffraction grating

## Equipment

	Laser Bench		Slide Holder	
	Lasers		Cut grating and single slit slide	Protractor, ruler, screen/card



**Do not stare at the laser beam**  
**Beware of reflections**  
**View the laser from above,**  
**Use card or a screen to trace the path of the laser beam**

## Activity

Switch on the lasers and use the slide holder to block the two outer beams.

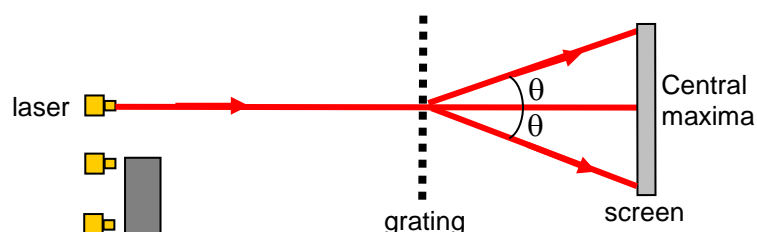


Figure 1.5.4 Measuring the wavelength of a laser diode

Insert one of the diffraction gratings into the slide holder and observe how the light is split into separate dots. Part of the beam goes straight through and can act as a reference point. Place a piece of paper under the slide holder. Use a screen or piece of card to locate the dots. Mark the position of the dots, central maxima and laser source. Measure the angle  $\theta$  and use this angle in:

$$n\lambda = d \sin\theta$$

to calculate the wavelength of the laser.  $n = 1$  as the laser dots are first order (look through the grating at a white light (**not the laser**) to observe first and second order spectra.  $D$  is the distance between the lines on the grating and can be calculated from the lines/mm quoted on the grating.

The wavelength of the laser is normally quoted in nanometres ( $1\text{nm} = 10^{-9}$  metres) so your answer needs to be converted into these units.

## Measuring the Width of Diffracting Objects

The numerical relationship between the width of a slit or hair and wavelength can be measured using the laser. The relationship between the width of the central diffraction maximum and wavelength can also be investigated.

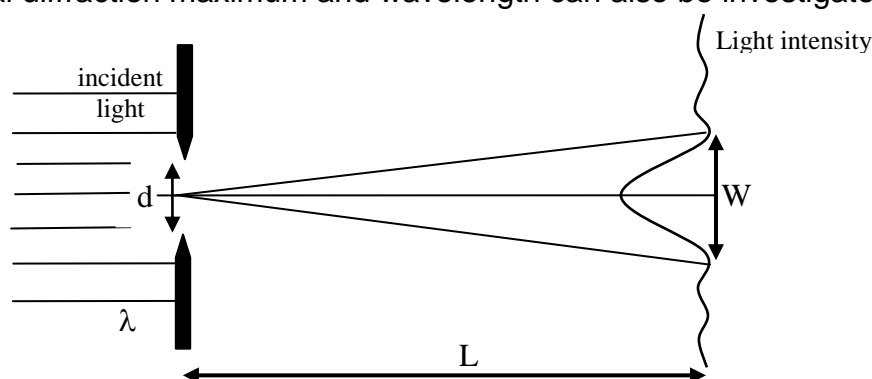


Figure 1.5.5 Single slit diffraction to show  $\lambda/W$  relationship

The width of a slit,  $d$ , can be calculated using the equation:

$$W = \frac{2L\lambda}{d}$$

$W$  is the width of the central maximum,  $\lambda$  is laser wavelength and  $L$  the distance from the screen to slit.

A relationship also exists between the wavelength, angle to the first maximum of constructive interference and width of diffracting object, figure 1.5.6.

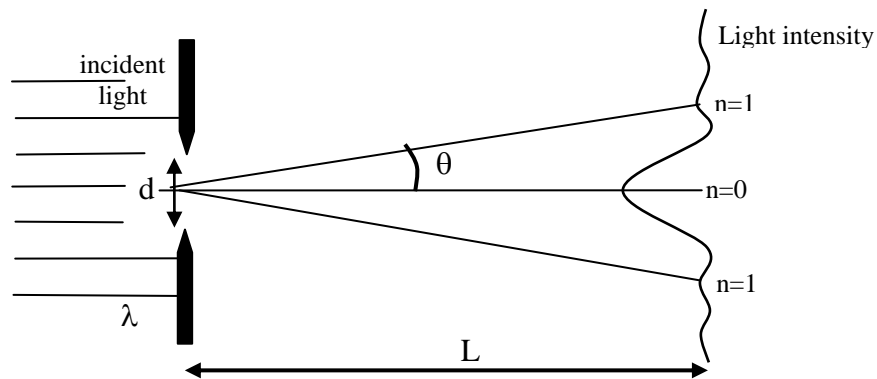


Figure 1.5.6 Measuring  $d$  using the first maxima.

The equation  $n\lambda = d \sin\theta$  can be used to calculate the diffracting aperture.

## Extra Activity

Use the cut down single slit slide and then a hair to produce a diffraction pattern. Use the equations to calculate the size of the diffracting object (Either use your value for the wavelength of the laser or 650nm)

Do you think a hair and a slit are equivalent in diffraction calculations?