# CHAPTER 15

# Light — A Wave?

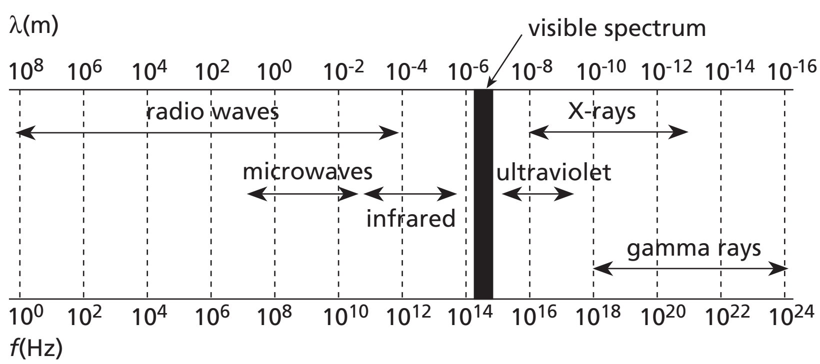
## 15.1 INTRODUCTION

Have you ever wondered about the following things concerning light?

- If a camera lens is made of clear glass, why does it look purple?
- Why do soap bubbles look so colourful?
- If you had a powerful enough microscope, could you see a single atom?
- How can light be both a wave and a particle? Surely it is one or the other?

In Chapter 14 we investigated the properties of two-dimensional waves; in particular, water waves. The reason for this was that they are easier to observe and investigate in the laboratory. It is now time to investigate the properties of light; in particular, visible light. However, visible light, the light that enables us to see objects, is just a small part of all the electromagnetic waves that are around us. Radio waves, microwaves, infrared waves, for example, all travel through space at the speed of $3 \times 10^8$ m s$^{-1}$ and make up a part of that group of waves called electromagnetic waves.

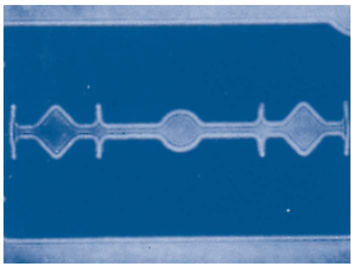
**Figure 15.1**
The electromagnetic spectrum.




But we seem to be jumping the gun. We are assuming that light travels through space by means of wave motion and not as particles. The particle nature of light is another issue and will be taken up in a later chapter. However, we can show that light does exhibit wave characteristics similar to those of water waves. Again, it is impossible to investigate the properties of all electromagnetic waves in a school laboratory, but we can investigate visible light waves as several of their effects can be seen with the unaided eye.

## THE PROPERTIES OF LIGHT WAVES 15.2

**Photo 15.1**
Diffraction of light through a razor blade — the diffraction of light occurs around the edges of objects and through small apertures.



Light is a form of energy that propagates (travels) through empty space. The propagation of this energy does not require a medium, as proven by light energy from the Sun being able to reach us here on Earth where it can be converted to other forms such as heat used in solar hot water systems, or to electrical energy used by solar powered cars to race across the Northern Territory.

Several of those properties of water waves investigated in Chapter 14 can be applied to light and observed in the laboratory but this requires detailed observation as the wavelength of visible light waves ranges from $4 \times 10^{-7}$ m to $7 \times 10^{-7}$ m. These waves are much too small to be seen with the unaided eye.

Light waves or light rays can, like water waves, be reflected and refracted. This can very easily be seen in the laboratory using a laser or light boxes. However, these properties are not exclusive to wave characteristics and will be discussed in Chapters 17 and 18, where physical optics, such as the uses of mirrors, prisms, and lenses, are investigated.

In this chapter we will investigate the properties of light with respect to two distinct wave characteristics — **diffraction** and **interference**. If light has wave characteristics then the diffraction and interference of light waves should be observable.

## DIFFRACTION OF LIGHT 15.3

**Photo 15.2**
The interference pattern produced by the diffraction of white light through a narrow slit.

Recall that diffraction is the bending of waves as they pass through an aperture or around the edge of an object in their path. This bending of waves is more noticeable if the wavelength of the waves is comparable to the size of the aperture. Also, if an object is placed in the path of the waves a 'shadow' is produced if the object is of the same size as the wavelength. (Revise Section 14.4.) Can this effect be observed with light? Remember, to observe this effect the slit or the object in front of the waves has to be of the same size as the wavelength of the waves, and light waves have very short wavelengths. However, this effect can be observed! Light does bend around the edges of objects to produce diffraction fringes. Objects seem to be blurred at the edges when light shone on them is focused on a screen. Photo 15.1 shows the diffraction fringes produced by white light passing the edges of a razor blade. The edges of the blade appear blurred and dark bands appear in the small apertures in the blade.

Diffraction of light can also be produced when light passes through a very narrow slit. Photo 15.2 shows the diffraction pattern produced on a screen when white light passes through a very narrow slit.

**Photo 15.3**
The diffraction pattern produced by a single slit using monochromatic (red) light from a laser.

### Activity 15.1 FINGER FRINGES

1. Place your index and middle fingers very close together.
2. Put these fingers up close to one eye, close the other and look at a distant light.
3. Slowly start to separate these fingers and you will notice that black lines appear between your thinly separated two fingers. These are diffraction fringes.

You may have noticed at night in rainy weather how scratches on a car's windscreen produce long shafts of light, sometimes with black bands across them. This too is diffraction.

This pattern can be seen much more clearly if a laser and a commercially prepared narrow slit are used.

If different colours of light are used the pattern changes. If red light is used the pattern spreads out more than when blue light is used. Recall the diffraction of water waves. The larger the wavelength compared with the slit, the more the pattern spreads out and is noticeable. This would suggest that the wavelength of red light is larger than that of blue light. The reason these diffraction bands occur will be analysed in Section 15.5.

## 15.4 INTERFERENCE

One of the earliest reasons for suggesting that light did not behave like a wave and did not have wave characteristics was that it did not produce interference patterns normally associated with the interaction of waves from two sources.

Can you suggest why? Remember, for a stabilised pattern to be produced the two sources have to continuously generate waves in phase (coherent). Therefore they would have to have the same frequency. Also, for a reasonable pattern with a number of widely separated nodal lines to be produced requires the separation of the two sources to be small compared with the wavelength of the waves. (Refer to Figures 14.18 and 14.19.) Can you describe how an experiment could be designed for the interference of light to be observed?

**Thomas Young** (1773–1829), a brilliant English academic, made a place for himself in history with his investigations into the nature of light. Young studied medicine at university and later practised in London. He was always interested in sight and made large contributions to the understanding of the eye and eye defects, but his name is remembered in physics for his investigations into how light propagates.

Up to the nineteenth century, Sir Isaac Newton's reputation was enough to uphold the belief within the scientific community in the corpuscular theory of light developed 100 years earlier. Newton had suggested, with explanation, that light travelled as particles (corpuscles). This will be discussed more fully in Chapter 29, Quantum Physics.

Young raised the old debate on whether light travelled as waves or as particles in a paper, *Respecting Sound and Light*, published in 1800. His experimental work with light produced supporting evidence to suggest that light had wave properties. In 1801 Young proved the interference of light. In 1803 he gave a demonstration of the interference of light at a lecture called 'Experiments and Calculations Relative to Physical Optics'. The constructional design of his experiment allowed interference fringes to be produced, something that had not been done previously.

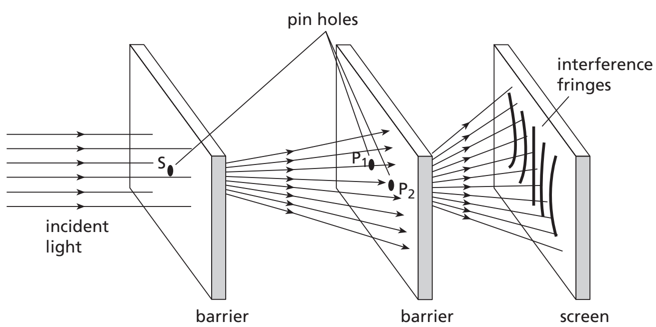



**Figure 15.2**
The set-up used by Young to produce interference of light waves.

To understand how this was done refer to Figure 15.2. Light from a source was directed onto an opaque sheet with a single pinhole. Light passed through this hole and was incident on two more pinholes, which were very close together, in another barrier. Light from these two pinholes was incident on a screen placed at a long distance from the barrier. Fringes as shown in Figure 15.3 appeared on the screen. These fringes disappeared when one of the pin-holes was covered up — this is an indication that the phenomenon was the result of light from the two pinholes interfering.

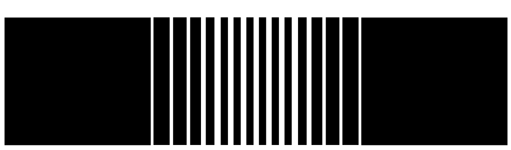


**Figure 15.3**
The interference pattern produced by light incident on a pair of closely spaced slits.

Young suggested, and demonstrated using Huygens's principle, that each pinhole acted like a point source of light, producing circular waves that radiated outward. The intersecting crests and crests, troughs and troughs, produced coloured fringes, and intersecting crests and troughs produced dark fringes. The interference pattern he drew resembled that of water waves. Again, it was Young's unique constructional design of the experiment that allowed these fringes to appear and remain stable — in the one place. Remember, to obtain a stable pattern the sources of the waves have to be continually in phase, that is, producing crests at the same time. This was the problem that previous exponents of the wave theory of light did not appreciate. Light is produced from the atoms of the light source, and since there are many atoms in the source and they do not produce light waves at the same time, we never have two light waves that are **coherent** (in phase and of the same frequency). Also, interference is most noticeable when the two sources are close together compared with the wavelength of the waves.

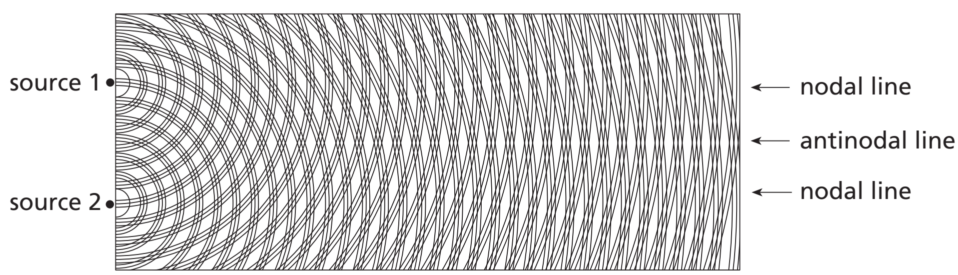
## Activity 15.2 YOUNG'S EXPERIMENTAL DESIGN

Discuss how Young overcame the above difficulties.

By using a barrier with a single pinhole as the source of light, light that arrived at the second barrier with the two pinholes was essentially from the one source. Therefore crests arrived at the two pinholes at the same time. This made the light through these pinhole sources in phase and of the same frequency. The pinholes were also very close together.

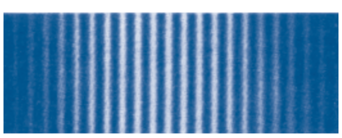
The similarity between the pattern drawn by Young and the pattern produced by water waves from two sources added experimental evidence to the suggestion of the wave nature of light.

**Figure 15.4**
The interference of light waves. The intersection of crests and crests, troughs and troughs etc. produces a pattern similar to that of two-source interference of water waves.




Today Young's pattern is a great deal easier to produce in the laboratory. We use a laser, as the light produced by it is **monochromatic** (of one wavelength) and coherent. Using a monochromatic light source produces fringes of the one colour (see Photo 15.4) and the pattern is not complicated by different colours overlapping.

**Photo 15.4**
The interference pattern produced by monochromatic light (red) through a pair of thinly separated slits.



## Activity 15.3 INTERFERENCE FRINGES

1. Shine a laser on a screen placed at the front of the room.
2. Place a prepared two-slit slide over the front of the laser making sure that the two slits are in front of the light.
3. Observe and draw the pattern produced on the screen.
4. What happens to the pattern on the screen if slides with different slit separations are used?

Mathematically, the relationship that exists between the positions of the fringes on the screen and the slit separations is similar to that found for water waves (Figure 15.5).

Waves from S are arriving at $S_1$ and $S_2$ in phase. These then act as two coherent sources of light.

*Note:* the distance between the two sources $S_1$ and $S_2$ is very small compared with the distance to the screen.

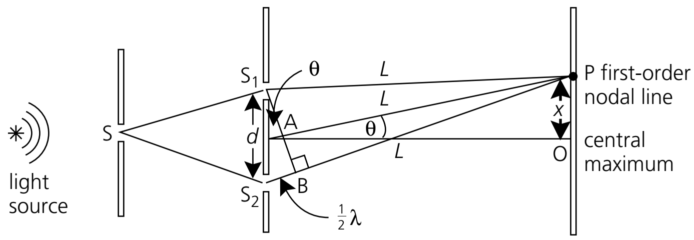



**Figure 15.5**
A schematic diagram of Young's set-up used to explain the positioning of the first-order node at P (not drawn to scale).

Let's look at a point P, a point on the first nodal line.

As already explained in Chapter 14, the path difference for all points on the first nodal line is $(n - \frac{1}{2})\lambda$. Therefore $S_2P - S_1P = (n - \frac{1}{2})\lambda$, or, since $n = 1$, $S_2P - S_1P = \frac{1}{2}\lambda$.

If we draw a line from $S_1$ to the line $S_2P$ to meet $S_2P$ at B so that $S_1P = BP$, then $S_2B = \frac{1}{2}\lambda$.

Since $d$, the distance between the slits, is very much smaller than $L$, the distance to the screen, the lines from $S_1$ to point P and $S_2$ to point P are approximately parallel and therefore $S_1B$ is approximately perpendicular to $S_2P$.

## EI Activity 15.4 THE INTERFERENCE ASSUMPTION

Just to make it clear in your mind that the above is a reasonable assumption:

1. Place two dots 1 mm apart on one side of your page and draw lines from these dots to another point on the opposite side of your page. You get the idea! These lines are close to being parallel.
2. Now if you could do this again making the dots 0.10 mm apart and draw lines from these dots to a point 3.0 m away what would you find?
3. Can you consider that the rays of light from the Sun are parallel? Explain.

In Figure 15.5 △ $S_1S_2B$ is similar to △ APO, therefore angle $S_2S_1B$ = angle OAP, which we will call θ.

From triangle $S_1S_2B$:

$$\sin\theta = \frac{S_2B}{S_1S_2} = \frac{\frac{1}{2}\lambda}{d}$$

From triangle APO:

$$\sin\theta = \frac{x}{L}$$

(*Note:* L is approximately equal to *AP* since *AO* is very large and *x* is very small, as seen in Activity 4.)

**NOVEL CHALLENGE**

Explain why a pair of car headlights does not produce an interference pattern. Justify your answer mathematically, stating what assumptions you have made about the data.

Therefore:

$$\sin\theta = \frac{\frac{1}{2}\lambda}{d} = \frac{x}{L}$$

If P is a point on the second nodal line, $S_2B$ will be $1\frac{1}{2}\lambda$, then:

$$\sin\theta = \frac{1\frac{1}{2}\lambda}{d} = \frac{x}{L}$$

In general, for a point on the '*n*th' nodal line,

$$\sin\theta = \frac{(n - \frac{1}{2})\lambda}{d} = \frac{x}{L}$$

If P was a point on the first antinodal line then the path difference $S_1B = 1\lambda$. (Recall that the path difference for points on the *n*th antinodal line = $n\lambda$.)
Then, in $\triangle\ S_1S_2B$:

$$\sin\theta = \frac{1\lambda}{d}$$

For a point on the second antinodal line:

$$\sin\theta = \frac{2\lambda}{d}$$

In general, for all points on the '*n*th' antinodal line:

$$\sin\theta = \frac{n\lambda}{d} = \frac{x}{L}$$

where $n$ is the order of the fringe, $n = 1, 2, 3, \ldots$; $\lambda$ is the wavelength of the light used in metres; $x$ is the distance from the central maximum in metres; $L$ is the distance from the slits to the screen in metres; $d$ is the distance between the slits in metres.

Using these equations Young was able to determine the wavelength for each colour of visible light. Young also used the principle of interference of light waves to explain the coloured pattern produced by reflected light from soap bubbles and thin films. (This will be explained in Section 15.6.)

## Example

Monochromatic light from a laser was shone on to a pair of parallel slits 0.20 mm apart. The interference pattern produced was observed on a screen placed at the other end of the laboratory 3.0 m from the laser. It was observed that the first-order bright fringe was 9.0 mm from the central maximum.

**(a)** Draw a labelled diagram showing the set-up necessary to obtain these results.
**(b)** Determine the wavelength of the light used.
**(c)** Determine the distance to the third-order dark fringe.
**(d)** Determine the thickness of the central maximum.

## Solution

**(a)** See Figure 15.6.

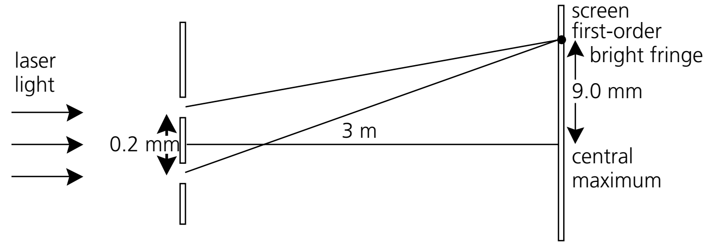



**Figure 15.6** The answer to the example problem (previous page).

**(b)**

$$\sin\theta = \frac{n\lambda}{d} = \frac{x}{L}$$

$$\frac{1\lambda}{d} = \frac{x}{L}$$

$$\frac{1\lambda}{2 \times 10^{-4}} = \frac{9.0 \times 10^{-3}}{3.0}$$

$$\lambda = 6.0 \times 10^{-7}\ \text{m}$$

$$\lambda = 600\ \text{nm}$$

**(c)** Destructive interference

$$\sin\theta = \frac{(n - \frac{1}{2})\lambda}{d} = \frac{x}{L}$$

$$\frac{(3 - \frac{1}{2})\lambda}{2 \times 10^{-4}} = \frac{x}{3.0}$$

$$x = 2.4 \times 10^{-2}\ \text{m}$$

**(d)** The thickness of the central maximum is the distance from the first nodal line on one side to the first nodal line on the other. That is, it is two times the distance from the middle of the central maximum to the first nodal line.

$$\sin\theta = \frac{(n - \frac{1}{2})\lambda}{d} = \frac{x}{L}$$

$$\frac{(1 - \ )\lambda \times 640 \times 10^{-9}}{2 \times 10^{-4}} = \frac{x}{3.0}$$

$$x = 510 \times 10^{-5}\ \text{m}$$

$$= 5.1\ \text{mm}$$

Therefore the thickness of the central maximum = 2 × 5.1 = 10.2 mm.

## Questions

1 Monochromatic light of wavelength 580 nm is incident on a pair of slits 0.10 mm apart. An interference pattern is observed on a screen 2.8 m from the slits.

**(a)** What is the distance of the second-order dark fringe from the central maximum?

**(b)** Determine the distance from the central maximum to the fourth-order bright fringe.

**(c)** Determine the thickness of the central maximum.

2 Monochromatic light was shone on a pair of slits separated by a distance of 0.15 mm. The third-order dark fringe appeared 2.1 cm from the centre of the central maximum on a screen placed 1.8 m from the source. Determine the wavelength of the light used.

**3** Blue light of wavelength $4.4 \times 10^{-7}$ m was shone on a pair of slits that were separated by a distance of 0.20 mm. The resulting interference pattern was observed on a screen 2.4 m from the source.

**(a)** Determine the distance from the central maximum of the first-order and second-order bright fringes.

**(b)** If red light of wavelength $6.6 \times 10^{-7}$ m was used instead of the blue light where would the first-order and second-order bright fringes now appear?

**(c)** Draw the fringes from part **(a)** and **(b)** showing their relative positions. (Use red and blue biros.)

**(d)** What would happen to the pattern obtained if the distance between the slits was doubled?

**(e)** Express the wavelength of the red and blue light in nanometres.

## SINGLE-SLIT DIFFRACTION 15.5

Before Young's interference experiment rekindled the debate on the nature of light, an Italian Jesuit priest, **Francesco Grimaldi** (1618–63), demonstrated diffraction of light. He demonstrated, through a series of experiments in his monastery laboratory, that light can bend around objects. When objects were illuminated with narrow beams of light, bright lines appeared inside the shadow of objects where sharp shadows were expected. This is difficult to observe with normal sunlight as white light is made of a mixture of colours (**polychromatic**). However, it is more easily observed if monochromatic light is used. Grimaldi called this phenomenon 'diffraction' (from the Latin *fragere* = 'to break').

### EI Activity 15.5 SINGLE-SLIT DIFFRACTION

Place a single slit in front of a laser and observe the pattern produced on a screen. A pattern similar to the earlier photo in Section 15.3 (p. 321) should be observed.

The pattern produced, even though similar to a double-slit interference pattern, has a number of differences:

- The bright bands are not regularly spaced.
- The central bright band is much wider than the others.
- The central bright band is much brighter than the next one.
- The brightness of each band decreases from the central maximum.

It was not until 1819 when a French engineer **Augustine Fresnel** (1788–1827), using his mathematical abilities, together with Huygens's wavefront principle, Young's interference explanation, and a relatively new mathematics (calculus), explained these observations.

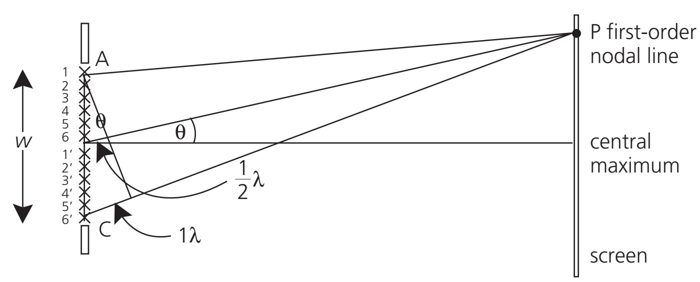



**Figure 15.7**
For single-slit diffraction the slit is divided into Fresnel zones to help to explain the interference pattern.

Fresnel used these tools to explain, for example, how the first dark fringe was produced (Figure 15.7). He divided the slit into two regions, known as **Fresnel zones**. He then paired up six points in the two zones, 1 and 1′, 2 and 2′ etc. Since the slit was very small, all of these 12 points were on the same wavefront arriving at the slit and therefore in phase. These 12 points then acted as point sources of secondary wavelets (Huygens's principle).

Now let us consider pairs of points within the slit. Point 1 and 1′ can be considered as small point sources of wavelets that are in phase, therefore as the path difference $1'P - 1P$ is $\frac{1}{2}\lambda$ waves arriving at P from these two points destructively interfere, producing a dark spot. Similarly $2'P - 2P = \frac{1}{2}\lambda$, and $3'P - 3P = \frac{1}{2}\lambda$. Light from these pairs of points destructively interferes, producing the first-order dark fringe at P.

Yes, you may say, but there is an infinite number of points between C and A and we could have paired up different points. This is true, which is why Fresnel needed the use of calculus to do a thorough mathematical interpretation of what was going on. However, the above analysis is enough for a reasonable understanding of how a dark fringe appears at point P, when the distance from C to P is $1\lambda$ further than from A to P.

Take another example (Figure 15.8) where we have a first-order bright fringe and $DP - AP = 1\frac{1}{2}\lambda$.

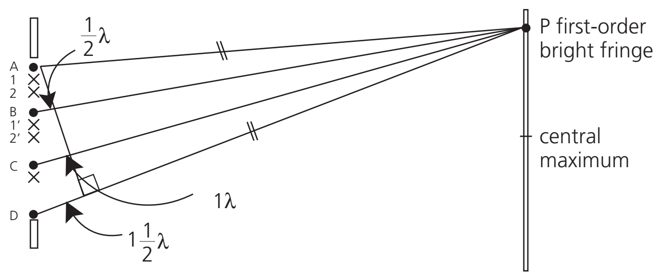



**Figure 15.8**
For the first-order bright fringe the slit is divided into three Fresnel zones with $\frac{1}{2}\lambda$ path difference between the top and bottom of each zone.

We now divide the slit into three 'Fresnel zones' (A to B, B to C, C to D), the bottom of each zone to point P being $\frac{1}{2}\lambda$ further than the top of the zone to point P. We again pair up six points within the zones.

Notice again that $1'P - 1P = \frac{1}{2}\lambda$ and $2'P - 2P = \frac{1}{2}\lambda$ etc., which makes wavelets produced in these two Fresnel zones, AB and BC, destructively interfere. However, light from the bottom third of the slit does not interfere with other parts of the slit, thus producing light at point P but only one-third as bright as the central region where light from the entire slit strikes.

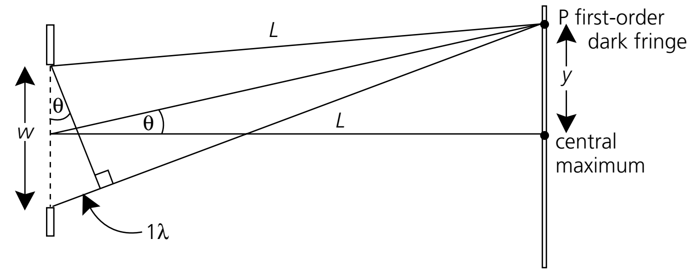
Again you may say this only occurs because of the selective choice of points, but this is only to aid in the explanation. With a much more thorough mathematical interpretation the results would be the same — a bright fringe occurs at P, which is one-third as intense as the central maximum.

## EI Activity 15.6 FURTHER SINGLE-SLIT INTERFERENCE INVESTIGATIONS

1. It would be a very worthwhile activity to carry out the above procedure to analyse:
   **(a)** the second-order dark fringe (divide the slit into four zones);
   **(b)** the second-order bright fringe.
2. What do you notice about the intensity of the second-order bright fringe?

Using the same assumptions as for double-slit interference we can obtain a mathematical relationship, similar to that of two-slit interference, between the positions of the fringes, the slit width, $w$, and the wavelength of the light used (Figure 15.9).

**Figure 15.9**
The first-order dark fringe is produced when the slit is divided into two Fresnel zones and the path difference between the top and the bottom of the slit is 1λ.




*For destructive interference — dark fringes:*

$$\sin\theta = \frac{1\lambda}{w} = \frac{y}{L}$$

$$\sin\theta = \frac{2\lambda}{w} = \frac{y}{L}$$

$$\therefore \sin\theta = \frac{n\lambda}{w} = \frac{y}{L} \text{ for the } n\text{th-order dark fringe.}$$

*For constructive interference — bright fringes:*

$$\sin\theta = \frac{1\frac{1}{2}\lambda}{w} = \frac{y}{L}$$

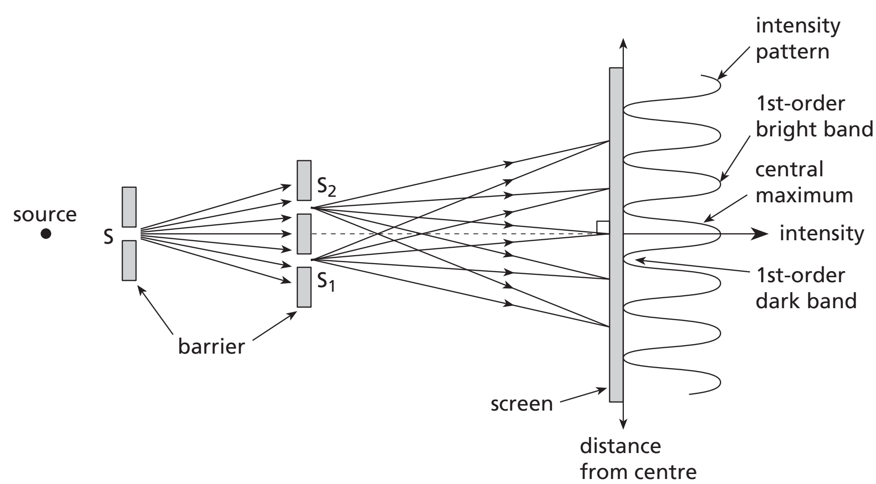
$$\sin\theta = \frac{2\frac{1}{2}\lambda}{w} = \frac{y}{L}$$

$$\therefore \sin\theta = \frac{(n+\frac{1}{2})\lambda}{w} = \frac{y}{L} \text{ for the } n\text{th-order bright fringe.}$$

Notice the difference between these equations and those obtained for two-slit interference. Two-slit destructive interference occurred when the path difference was an odd number of half wavelengths ($\frac{1}{2}\lambda$, $1\frac{1}{2}\lambda$, . . .) and constructive interference occurred when there was an even number of half wavelengths (1λ, 2λ . . .). *For single slits it is the opposite*.

The intensity pattern is also worthy of note: for two-slit interference the intensity of each bright band was fairly constant, producing an intensity pattern shown in Figure 15.10. The bands were also equally spaced, while for the single slit the central maximum is twice as wide and the intensity falls off as the band number increases. (Refer to Figure 15.11.) As an aid to your understanding, you should make a table setting out conditions for constructive and destructive interference from single and double slits.

**Figure 15.10**
The intensity pattern produced by a pair of slits is equally spaced and the maximums are of about equal intensity.



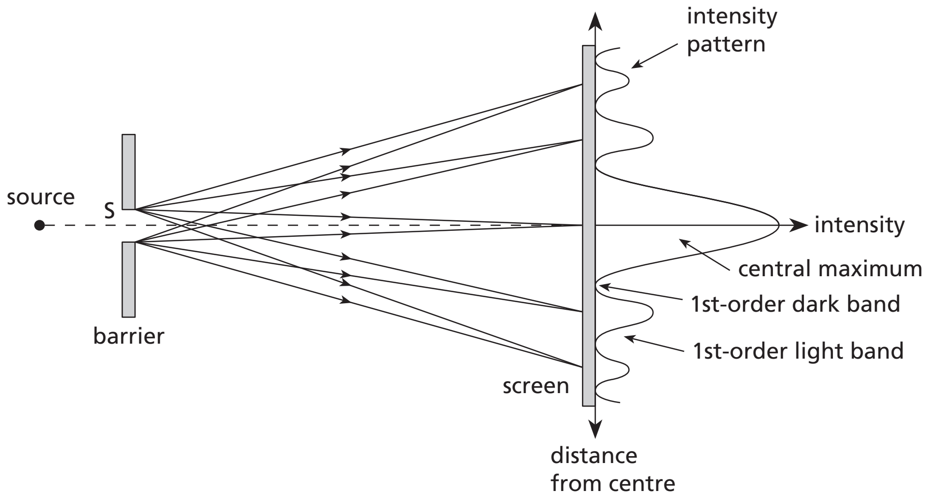



**Figure 15.11**
The intensity pattern produced by a single slit.

Fresnel's explanation supported the experimental evidence of Grimaldi.

## Example

Monochromatic light of wavelength $5.2 \times 10^{-7}$ m is shone onto a single slit of width 0.10 mm. This produces an interference pattern on a screen 3.0 m from the slit. Find the distance from the centre of the central maximum to the first-order bright fringe.

## Solution

$$\sin\theta = \frac{(n+\frac{1}{2})\lambda}{w} = \frac{y}{L}$$

$n = 1$, then

$$\frac{1\frac{1}{2}\lambda}{w} = \frac{y}{L}$$

$$\frac{1\frac{1}{2} \times 5.2 \times 10^{-7}\text{ m}}{0.10 \times 10^{-3}} = \frac{y}{3.0}$$

$$y = 2.3 \times 10^{-2}\text{ m}$$

$$y = 2.3\text{ cm}$$

# Questions

4 Find the width of the central maximum when light of wavelength 520 nm is shone on a single slit of width 0.050 mm and the interference pattern is observed on a screen 2.8 m from the slit.

5 Monochromatic light of 585 nm is shone on a slit of width $8.0 \times 10^{-2}$ mm and the interference pattern is produced on a screen 1.8 m from the source.
- **(a)** Find the distance from the centre of the pattern to the first-order dark fringe.
- **(b)** Find the distance to the second-order dark fringe.
- **(c)** What is the width of the central maximum?
- **(d)** What is the width of the first-order bright fringe?
- **(e)** What do you notice about the width of the central maximum and the other bright fringes?

6 A helium–neon (He–Ne) laser produces light of wavelength 632.8 nm. A single slit of unknown width was placed in front of the laser and the resulting pattern observed on a screen 2.8 m from the slit. The distance from the middle of the central maximum to the first dark band was 8.8 mm. How wide was the slit?

**Figure 15.12**
The diffraction produced by a single circular aperture consists of concentric light and dark bands.

## Resolving power of optical instruments

The interference and diffraction effects have consequences for the development of optical instruments. The diffraction pattern produced by light shone through a circular aperture consists of a circular bright centre with circular bright and dark bands, as shown in Figure 15.12.

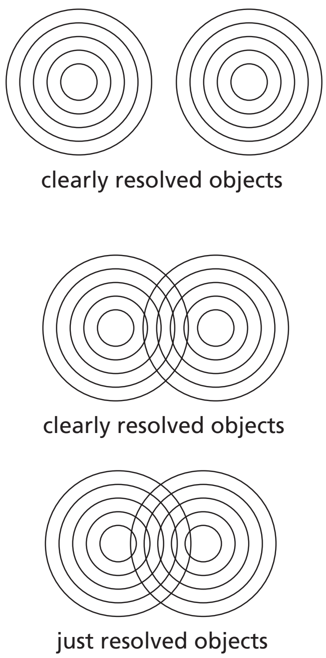
This diffraction changes with the size of the aperture. If the aperture increases in size the width of the central maximum and the size of the diffraction pattern decrease. The reverse is also true. For light bands:

$$\sin\theta = \frac{(n - \frac{1}{2})\lambda}{w} = \frac{y}{L}$$

If $w$ increases then $y$ decreases.

This has consequences for optical instruments. If a telescope is used to observe light from stars in the sky, the pattern observed through the lens, a circular aperture, will consist of a central light spot with an alternating dark and bright band diffraction pattern. If two stars slightly separated in the sky are observed, overlapping diffraction patterns will be seen. If the sources of light move closer together the diffraction fringes confuse viewing of the sources. Eventually you may not be able to identify the two separate sources as the bright central maxima merge.

**Figure 15.13**
The diffraction patterns merge as the objects are moved closer, making resolution poor.




The **resolving power** of an instrument is the angular separation of the sources, which enables you to tell you are viewing two sources.
This is given by the following formula, known as the 'Rayleigh Criterion'.

$$\theta = 2.5 \times 10^5 \frac{\lambda}{d}$$

where $\theta$ is the angle subtended between the sources measured in seconds of arc; $\lambda$ is the wavelength of the light used in metres; $d$ is the diameter of the aperture in metres.

### Example

What is the resolving power of the Hubble space telescope, which has an aperture of 1.8 m, when viewing two sources of red light of wavelength 650 nm?

### Solution

$$\theta = 2.5 \times 10^5 \frac{\lambda}{d}$$
$$= 2.5 \times 10^5 \frac{650 \times 10^{-9}}{1.8}$$
$$= 0.090 \text{ seconds of arc}$$

Similar effects are produced when viewing two specimens using microscopes. If blue light is used to illuminate the specimens better resolving power is obtained.

## Questions

7 Find the resolving power of a microscope whose objective lens is 0.50 cm in diameter **(a)** when blue light of 450 nm is used to illuminate the two sources; **(b)** when red light of 650 nm is used to illuminate the two sources. **(c)** Which colour of light would be best used to distinguish between two closely spaced specimens?

## Diffraction gratings

A diffraction grating consists of a block of glass with many grooves cut into it by a diamond lathe. These grooves are very close together and, once cut, become opaque. Therefore the block of glass acts like many double slits. Typically these gratings have thousands of grooves per centimetre, which makes the distance between the slits very small. For example, if there are 10 000 grooves per centimetre then the distance between each pair of slits will be $\frac{1}{10\,000}$ or $10^{-4}$ cm.

This results in interference patterns being very spread out when incident on a screen.

### Example

If light of 600 nm was shone on the above diffraction grating and the interference pattern was produced on a screen 2.0 m from the grating, what would be the distance from the central maximum to the first maximum?

### Solution

$$\sin\theta = \frac{n\lambda}{d} = \frac{x}{L}$$

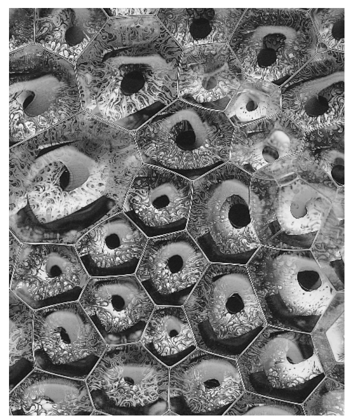
$$\frac{1 \times 600 \times 10^{-9}}{1 \times 10^{-6}} = \frac{x}{2}$$

$$x = 1200 \times 10^{-3}\ \text{m}$$

$$x = 1.2\ \text{m}$$

This is a large distance compared with those distances obtained in previous double-slit problems.

**Photo 15.5**
The colourful interferences effects produced by white light reflecting from soap bubbles (see also inside back cover).



## Questions

**8** Yellow light of 590 nm is shone on a diffraction grating that contains 10 000 lines per cm and the pattern is produced on a screen 2.2 m from the grating.
- **(a)** What is the distance from the central maximum to the second-order bright fringe?
- **(b)** What is the distance from the central maximum to the third-order bright fringe?

**9** Violet light of 400 nm is shone on a diffraction grating that has 5000 lines per cm.
- **(a)** What is the angular deviation of the second-order bright fringe?
- **(b)** What is the angular deviation of the third-order bright fringe?
- **(c)** What will be the order of the last bright spot that will be seen for this set-up? Explain why this will occur.

# 15.6 THIN FILMS

Very spectacular colourful interference effects may be observed when a light wave is reflected from a thin film, such as oil floating on water, or a soap bubble, as shown in Photo 15.5 (see also colour section).

## EI Activity 15.7 SOAP BUBBLES

Dip a loop of wire into some washing-up detergent. Pull it out and gently blow into the loop to make soap bubbles. Observe the colours of light produced by light reflecting from the bubble.

To explain mathematically how this occurs we will use an example of a thin film of water on a piece of glass. When a light wave strikes the upper surface of the water (see

**Figure 15.14**
Interference effects occur when light reflects from two surfaces of a film. Rays A and B can constructively or destructively interfere.

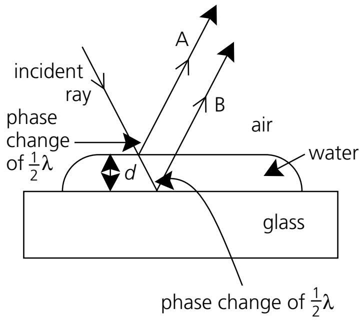



Figure 15.14) it will set up a multitude of reflected waves due to the reflection from the upper surface, the reflection from the lower surface, and multiple zigzags between the surfaces. In Figure 15.14, only the first two reflections are shown. These are the most important and are the strongest as other light will be absorbed.

To find the conditions for constructive and destructive interference between these two waves, let us make a simplifying assumption that the incident wave is nearly perpendicular to the surface. The two most intense waves are those that suffer only one reflection: the wave that reflects from the upper surface (wave A) and the wave that reflects on the lower surface (wave B). Now for a rhetorical question: under what condition will these two waves constructively interfere in the air above the film?

Obviously, the wave that reflects from the bottom surface has to travel further than the wave reflected from the top surface. If the thickness of the film is $d$, then the **path difference** is equal to $2d$. Provided that this distance is equal to one, two, three, etc. wavelengths, the wave reflected from the upper surface will meet crest to crest with the wave from the lower surface. They will be 'in phase' and will constructively interfere — be bright; or have a maximum amplitude. Note, however, that both waves are striking a 'fixed' boundary, that is, a boundary where the wave strikes a more dense medium than the one it is travelling in. In this case *both* waves will be reflected upside-down and will undergo a half wavelength ($\frac{1}{2}\lambda$) **phase change**. Wave A then is $\frac{1}{2}\lambda$ out of phase with the incident wave and, if the film is $\frac{1}{2}\lambda$ thick, wave B will be one-and-a-half wavelengths ($\frac{3}{2}\lambda$) out of phase with the incident wave — one wavelength due to the path difference and $\frac{1}{2}\lambda$ due to phase change on reflection. Hence, waves A and B will be in phase with each other and constructively interfere. If the film was $\frac{1}{4}\lambda$ thick, the path difference would be $\frac{1}{2}\lambda$ and waves A and B would be $\frac{1}{2}\lambda$ out of phase — B would be $1\lambda$ out of phase (or in phase) with the incident wave while A would be $\frac{1}{2}\lambda$ out of phase with the incident wave. Therefore A and B would destructively interfere, producing a dark region.

There are many situations that can be explained using interference of waves. The explanation depends on the optical density (refractive index) of the film and the bounding media. The following are a few examples.

**1** *A film bounded on one side by a medium of* lower *optical density and on the other side by a medium of* higher *optical density* Examples are:
- a water film on glass (air–water–glass)
- an oil film on water (air–oil–water)
- a magnesium fluoride ($MgF_2$) coating on a glass lens (air–$MgF_2$–glass). (Refer to Figure 15.14.)

Table 15.1 is a summary of the interference effects of various thicknesses of the film.

## Table 15.1

| | THICKNESS OF FILM ($d$) | | | |
|---|---|---|---|---|
| | $\frac{0}{4}\lambda$ | $\frac{1}{4}\lambda$ | $\frac{2}{4}\lambda$ | $\frac{3}{4}\lambda$ |
| Path difference due to distance travelled ($2d$) | $\frac{0}{2}\lambda$ | $\frac{1}{2}\lambda$ | $\frac{2}{2}\lambda$ | $\frac{3}{2}\lambda$ |
| Phase difference due to reflection | $0\lambda$ | $0\lambda$ | $0\lambda$ | $0\lambda$ |
| Sum = total phase difference between A and B | $0\lambda$ | $\frac{1}{2}\lambda$ | $\frac{2}{2}\lambda$ | $\frac{3}{2}\lambda$ |
| Constructive (C) or destructive (D) interference | C | D | C | D |

*Summary:* Destructive interference occurs at odd $\frac{1}{4}\lambda$ thicknesses.
*Formulae:* For *destructive* interference: $2d = (m + \frac{1}{2})\lambda$, where $m = 0, 1, 2, \ldots$
For *constructive* interference: $2d = m\lambda$, where $m = 0, 1, 2, \ldots$

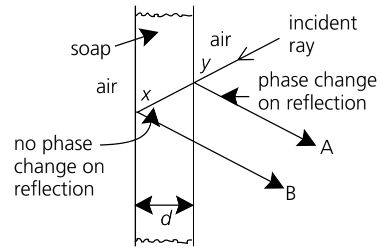
**2** *A film bounded on both sides by media of lower density or by media of higher density*
Examples are:

- *Type A* A low–high–low density distribution; for example, a water film or soap film in air (air–soap–air) (Figure 15.15).

Since the waves are reflected from a lower density material at X there will be no phase change, but wave A will still undergo a $\frac{1}{2}\lambda$ phase change at Y.

Table 15.2 is a summary of the resulting interference that occurs for various film thicknesses.

**Figure 15.15**
The different effects depend on the medium bounding the film. This is a low–high–low optical density situation.



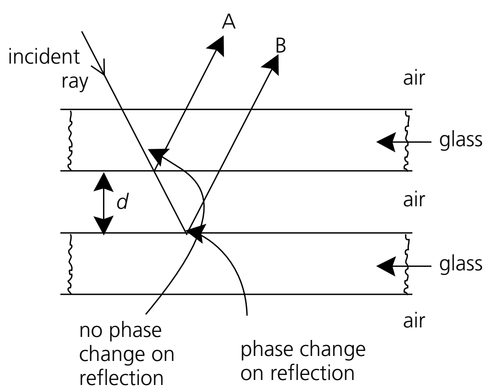

## Table 15.2

| | THICKNESS OF FILM ($d$) | | | |
|---|---|---|---|---|
| | $\frac{0}{4}\lambda$ | $\frac{1}{4}\lambda$ | $\frac{2}{4}\lambda$ | $\frac{3}{4}\lambda$ |
| Path difference due to distance travelled ($2d$) | $\frac{0}{2}\lambda$ | $\frac{1}{2}\lambda$ | $\frac{2}{2}\lambda$ | $\frac{3}{2}\lambda$ |
| Phase difference due to reflection | $\frac{1}{2}\lambda$ | $\frac{1}{2}\lambda$ | $\frac{1}{2}\lambda$ | $\frac{1}{2}\lambda$ |
| Sum = total phase difference between A and B | $\frac{1}{2}\lambda$ | $\frac{2}{2}\lambda$ | $\frac{3}{2}\lambda$ | $\frac{4}{2}\lambda$ |
| Constructive (C) or destructive (D) interference | D | C | D | C |

*Summary:* Destructive interference occurs at even $\frac{1}{4}\lambda$ thicknesses.
*Formulae:* For *destructive* interference: $2d = m\lambda$, where $m = 0, 1, 2, \ldots$
For *constructive* interference: $2d = (m + \frac{1}{2})\lambda$, where $m = 0, 1, 2, \ldots$

- *Type B* A high–low–high distribution; for example, an air film between glass slabs (glass–air–glass) (Figure 15.16).

**Figure 15.16**
This is a high–low–high optical density situation.




*Note:* as one of the waves undergoes a phase change and the other does not, this situation is similar to that of 2: Type A, and the same table can be used.

A summary of the above situations is given in Table 15.3.

## Table 15.3

| SITUATION | DESTRUCTIVE INTERFERENCE | CONSTRUCTIVE INTERFERENCE |
|---|---|---|
| L–M–H | $2d = (m + \frac{1}{2})\lambda$ | $2d = m\lambda$ |
| L–M–L | $2d = m\lambda$ | $2d = (m + \frac{1}{2})\lambda$ |
| H–M–H | $2d = m\lambda$ | $2d = (m + \frac{1}{2})\lambda$ |

## Colours

The colours seen from oil slicks, Christmas beetles' wings and soap bubbles arise from such interference effects. Since the colours of light have different wavelengths the thickness of a film may be $\frac{1}{2}\lambda$ for one colour but it will not be $\frac{1}{2}\lambda$ for all colours. Therefore constructive interference will occur at different film thicknesses for each colour of light.

You can see that by analysing both the path difference between the two waves and the phase changes on reflection, it can be determined whether the two waves will constructively interfere (producing light) or destructively interfere (producing an absence of light). Different portions of an oil or soap film usually have different thicknesses, and they therefore give constructive interference for different wavelengths at different positions. This results in a pattern of bright coloured bands or fringes.

*Note:* the symbol $\lambda$ in the above explanations stands for the wavelength of the light *in the film* and will be different from that in air as light travels more slowly in materials. Remember the frequency does not change. The value of $\lambda$ in the material can be calculated from the wavelength in air by the formula:

$$\lambda_{\text{film}} = \frac{\lambda_a}{n_{\text{a-film}}}$$

where $\lambda_{\text{film}}$ = the wavelength of the light in the film; $\lambda_a$ = the wavelength of the light in air; $n_{\text{a-film}}$ or just $n_{\text{film}}$ = the absolute refractive index of light going from air to the film. This will be discussed more in Chapter 18.

### Example 1

What is the smallest thickness of water film that would produce constructive interference when viewed in reflected light of wavelength of 650 nm in air? ($n_{\text{a-water}} = 1.33$.)

### Solution

The wavelength of the light in water:

$$\lambda_w = \frac{\lambda_a}{n_{\text{a-w}}} = \frac{650}{1.33} = 489 \text{ nm}$$

For air–water–air constructive interference to occur $2d = (m + \frac{1}{2})\lambda$ (see the previous section) then:

$$2d = (0 + \tfrac{1}{2})489 \text{ nm}$$
$$d = 0.5 \times \frac{489}{2}$$
$$d = 122 \text{ nm}$$

### Example 2

To reduce the reflection of light from a glass lens ($n = 1.50$), a coating of magnesium fluoride is added ($n_{MgF_2} = 1.36$). What minimum thickness should this film be to produce destructive interference and remove as much reflection as possible? Consider the average wavelength of light in air to be 520 nm.

**Solution**

$$\lambda_{MgF_2} = \frac{\lambda_a}{n_{a-MgF_2}} = \frac{520}{1.36} = 382 \text{ nm}$$

For this case (low–medium–high) we will have destructive interference at:

$$2d = (m + \tfrac{1}{2})\lambda$$
$$d = \frac{(m + \frac{1}{2})\lambda}{2} = \frac{1}{2} \times \frac{382}{2} = 95.6 \text{ nm}$$

## Questions

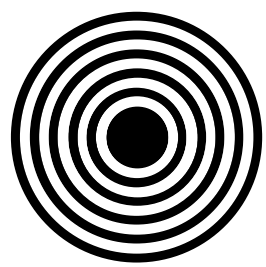
**10** A soap film is 100 nm thick. What wavelength of light will be most strongly reflected by this film; that is, what colour will it appear? ($n_{soap}$ = 1.33.)

**11** A film of kerosene 4500 angstroms thick floats on water. White light, a mixture of all visible colours, is vertically incident on the film.
**(a)** Which of the wavelengths contained in the white light will give maximum intensity upon reflection?
**(b)** Which will give minimum intensity?
(*Note:* 1 angstrom (Å) = $10^{-10}$ m, $n_{kero}$ = 1.2.)

**12** The wall of a soap bubble floating in air has a thickness of 400 nm. If sunlight strikes the wall perpendicularly, what colours in the reflected light will be strongly enhanced as seen in air? The refractive index of the soap film is 1.35.

**13** A thin oil slick of refractive index 1.3 floats on water. When a beam of white light strikes this thin film vertically, the only colours enhanced in the reflected beam seen in air are orange–red (650 nm) and violet (430 nm). What is the thickness of the oil slick?

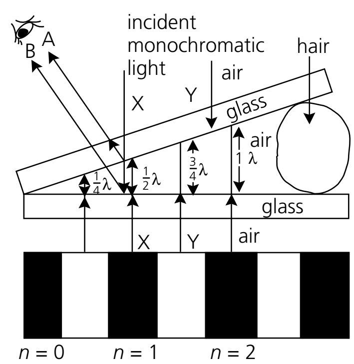
**Figure 15.17**
Newton's rings are produced by a plano-convex lens resting on a piece of glass.



## Newton's rings

Interference effects can also arise in a narrow gap between a flat glass plate and a slightly curved glass plate. The convex surface of the curved glass will touch the plate at the centre but leave a gradually widening gap as the distance from the centre increases. At the bright rings, the width of the gap will produce constructive interference of the reflected light. The dark (destructive) rings are called **Newton's rings**.

**Figure 15.18**
The varying thickness of the film in the case of a wedge produces light and dark bands corresponding to the different thicknesses.




## Wedges

The same result as Newton's rings occurs if two thin glass slides are placed together with a hair between one end. However, this time the bands will be regularly spaced.

Interference can be used to measure the thickness of the hair. At position X where the air gap is $\frac{1}{2}\lambda$ thick we will observe destructive interference between rays A and B (refer to example 2 type B) producing a dark fringe if a particular colour of light is used.

When the thickness is $\frac{3}{4}\lambda$ thick at Y we will observe a light fringe. We would thus observe dark and light fringes regularly spaced between the apex of the slides and the hair.

### Example

Two glass slides are separated by a human hair. When viewed from above, dark interference bands are produced as a result of wedge interference. If the 50th dark band occurs above the hair when red light of wavelength 650 nm is reflected from the glass slides, what is the thickness of the hair?

### Solution

As this is an example 2 type B problem (refer to thin films, section 15.6), destructive interference occurs when:

$$2d = m\lambda$$
$$2d = 50\lambda$$
$$d = 25 \times 650 \text{ nm}$$
$$d = 1.60 \times 10^4 \text{ nm}$$

**NOVEL CHALLENGE**

CD players will soon use a blue-green laser of wavelength 400 nm. *How high (or deep) will the pits be?*

## Questions

**14** The edge of a piece of paper is placed between the ends of two glass slides. The other ends of the slides are in contact. These slides are then illuminated from above with red light of wavelength 700 nm and the interference pattern produced by reflected light is observed. The 200th dark fringe is observed over the edge of the page. What is the thickness of the paper?

**15** Students viewing the interference properties of soap bubbles dipped a wire loop into a soap solution and held it vertically for a few seconds. When this loop was illuminated with blue light of wavelength 450 nm and reflected light viewed, dark bands appeared. It was observed that the bottom of the loop contained the 50th blue band. How thick is the soap at the bottom of the loop of wire? Would you expect a regular, evenly spaced pattern of blue and dark bands to appear?

## Compact discs

The digital on/off process used in compact discs relies on the destructive interference of reflected laser light. A CD player uses a gallium–arsenide (Ga–As) laser of wavelength 840 nm. The tiny pits in a CD are one-quarter of a wavelength deep so they produce a path difference of $2 \times \frac{1}{4}\lambda$ ($\frac{1}{2}\lambda$) compared with light that is reflected from the upper surface. (See Figure 15.19.) Destructive interference occurs and no light returns to the pick-up photodiode. This is read as 'off'. When light strikes the surface where there is no pit, there is no phase difference between reflected waves, hence the digital pulse is read as 'on'. The subsequent stream of digital on/off pulses is converted to the studio signal and then amplified to become the output sound.

Further discussion of the principles of CDs and DVDs as part of modern sound technology occurs in Chapter 16.10.

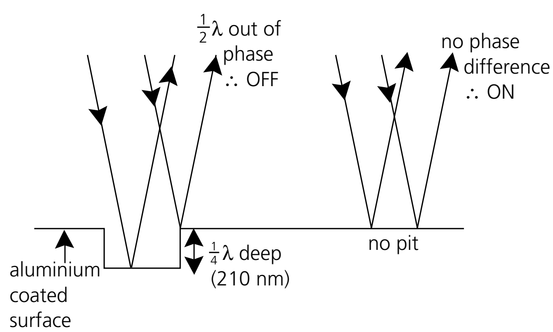



**Figure 15.19**
CD players and CD discs use interference effects in the replication of sound.

## 15.7 ELECTROMAGNETIC RADIATION

By the 1880s experimental evidence provided more support for the wave theory of light. In 1849 Armand Fizeau measured the speed of light in media other than air and showed that light travelled more slowly in dense materials. This supported the wave theory of refraction and opposed Newton's corpuscle or particle theory, which suggested that light particles travelled faster in more dense materials. However, the nature of light waves was still not understood.

A Scottish physicist, **James Clerk Maxwell** (1831–79), explained the nature of light waves based on electric and magnetic interactions, which is still the accepted theory today. This explanation was built on Oersted's theories that electric current produced magnetic fields, and Faraday's experiments that showed that changing magnetic fields induced electromotive forces and electric fields. Maxwell suggested that a changing electric field would result in a changing magnetic field, which in turn would produce a changing electric field — one inducing the other in a self-propagating process. He suggested the possibility of transverse **electromagnetic waves** propagating through space as changing electric and magnetic fields that are at right angles to each other, as shown in Figure 15.20. He developed general mathematical equations for these electromagnetic waves. The experimental value for the speed of light was found to be close to that predicted by his equations, suggesting that light was in fact electromagnetic in origin.

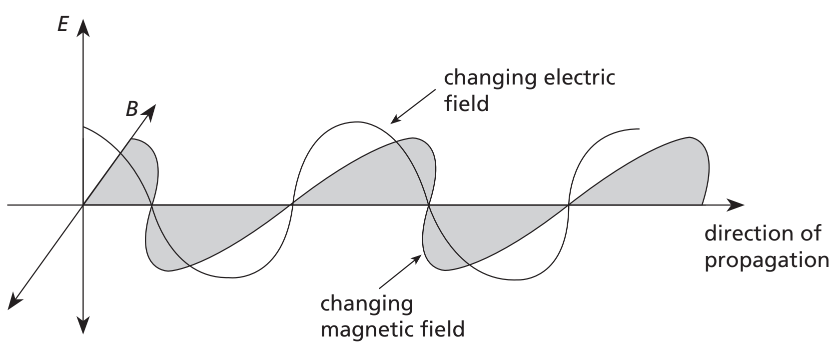



**Figure 15.20**
A diagrammatic representation of an electromagnetic wave with the changing magnetic and electric fields at right angles to each other and to the direction of propagation.

In general terms Maxwell suggested that electromagnetic waves had the following characteristics:

- They consisted of changing electric and magnetic fields.
- The electric and magnetic fields are at right angles to each other as well as to the direction of propagation — the waves are transverse in nature.
- The speed of the waves is dependent on the electric and magnetic properties of the material in which they are travelling. In air or a vacuum, the speed of light is $3 \times 10^8$ m s$^{-1}$.

In 1887 Heinrich Hertz (1853–94) produced experimental evidence to support Maxwell's explanation of the propagating electromagnetic fields. Using varying voltages, Hertz created a spark across the terminal of a primary loop of wire. The spark or discharge was the result of varying electric fields produced between the ends of the loop. Hertz was able to cause a spark to be produced across the ends of a second detector loop of wire placed some distance from the primary loop (Figure 15.21). This release of energy in the detector loop of wire suggested that energy had been carried by waves from the primary to the secondary loop. Hertz spent a great deal of time investigating the waves produced by the primary loop and discovered that they had all the normal characteristics of waves. After being produced by accelerating and decelerating charged particles the propagating waves travelled at a speed of $3 \times 10^8$ m s$^{-1}$ in air and slowed down when they travelled through different media.

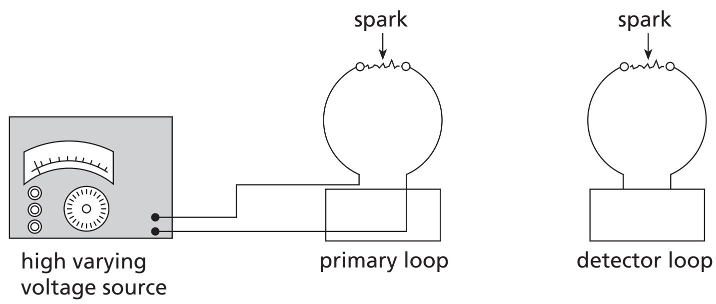



**Figure 15.21**
A schematic representation of Hertz's apparatus showing that changing voltages in the primary coil produce electromagnetic waves that can be detected in a detector loop of wire.

The frequency of the waves was controlled by the frequency of the changing speeds of the particles at the source. The frequency of generation of the waves in the source produced different wave frequencies, wavelengths, and visible light colours. The wavelengths associated with each colour of light are given in Table 15.4. (See Figure 15.22.) The relationship between the frequency, wavelength and speed of these waves is the same for all waves and is given by the general wave equation $c = f\lambda$.

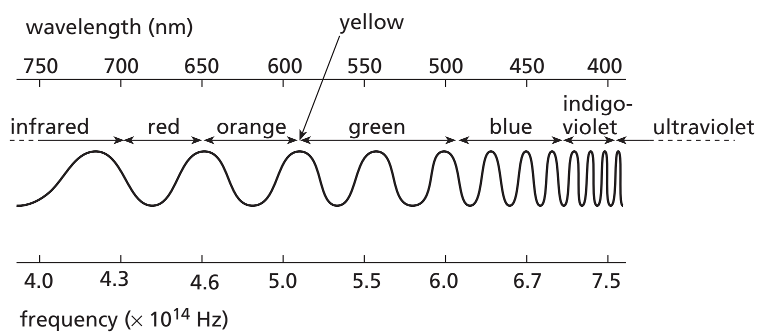



**Figure 15.22**
The visible light spectrum.

**✔ TEST YOUR UNDERSTANDING**

Stealth Bombers are invisible to radar because they reflect the waves up and down rather than back to the radar station. *How could you detect them with radar, then? A good answer could be worth millions.*

**Table 15.4 THE RANGE OF WAVELENGTHS OF VARIOUS ELECTROMAGNETIC WAVES**

| COLOUR | WAVELENGTH (nm) |
|---|---|
| Ultraviolet | 200–400 |
| Indigo–violet | 400–420 |
| Blue | 420–490 |
| Green | 490–580 |
| Yellow | 580–590 |
| Orange | 590–650 |
| Red | 650–700 |
| Infrared | ≥ 700 |

However, visible light is only a part of the entire electromagnetic spectrum, which ranges from radio waves of frequencies 15 kHz to gamma rays of frequencies $10^{24}$ Hz, all of which travel in air or a vacuum at a speed of $3 \times 10^8$ m s$^{-1}$.

# THE ELECTROMAGNETIC SPECTRUM 15.8

**NOVEL CHALLENGE**

You are listening to a radio broadcast of a live orchestral concert in London 20 000 km away. *Would you hear it before or after a person at the rear of the concert hall 50 m away from the orchestra? (Sound travels at about 330 m s$^{-1}$.)*

## Radio and television waves

Radio waves make up one of the biggest groups of waves in the electromagnetic spectrum. They are produced by the oscillations (the acceleration and deceleration) of electrons. The uses of radio waves are widespread: they are used in radio and television broadcasting as well as for communications. AM radio waves have a very long wavelength of several hundred metres and therefore are easily diffracted around buildings. FM radio waves are much shorter (several metres) and diffraction of these is noticeable as buildings are much larger than the wavelengths. Therefore FM reception would be weaker on the side of the building not facing the station. You may have noticed this difference as you drive through town. The good thing about FM radio waves, though, is that they are of much higher energy than AM waves and can penetrate into underground car parks better so you do not lose reception as easily.

UHF (ultra-high frequency, therefore short wavelength) TV wavelengths are only fractions of a metre long and therefore are not diffracted by buildings. TV antennae have to point towards the stations. TV waves, being very short, can also be reflected from objects; in particular, aircraft passing overhead. This could result in waves arriving at your home both directly from the station and reflected from the aircraft. Since this results in a path difference, interference could result in distortion or pulsating images on your TV set when an aircraft passes overhead. Reflection off nearby hills produces a weak delayed signal, which results in 'ghosting'.

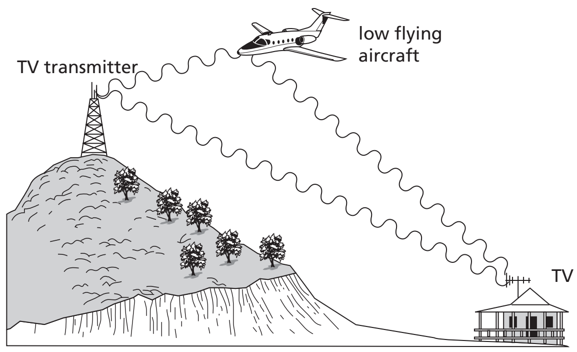



**Figure 15.23**
The interference of TV waves from the transmitter and those reflected from low flying aircraft can cause distortion on TV sets.

Short wave radio signals of about tens of metres long can be reflected from the ionosphere (a layer in the atmosphere). By bouncing these waves off the ionosphere messages can be sent around the world.

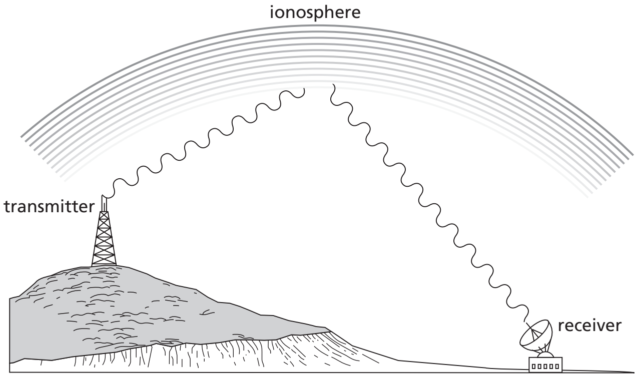



**Figure 15.24**
Short wave radio transmissions reflect from the ionosphere thus being able to be received around the world.

Table 15.5 gives a summary of the variety of radio waves and their uses.

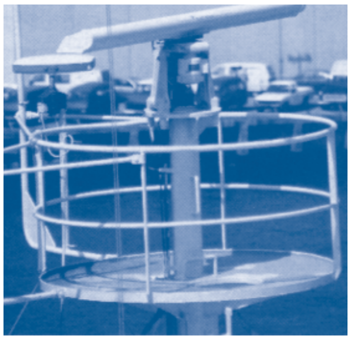
## Table 15.5 THE FREQUENCY AND WAVELENGTH OF VARIOUS RADIO WAVES

| TYPE OF RADIO WAVE | WAVELENGTH RANGE | FREQUENCY RANGE | USE |
|---|---|---|---|
| Long waves | 600 m – 20 km | 15 kHz – 500 kHz | communications |
| Medium waves | 100 m – 600 m | 500 kHz – 3 MHz | AM radio |
| Short waves | 10 m – 100 m | 3 MHz – 30 MHz | AM radio, communications |
| VHF (very high frequency) | 1 m – 10 m | 30 MHz – 300 MHz | FM radio |
| UHF (ultra-high frequency) | 0.1 m – 1 m | 300 MHz – 3000 MHz | television |

**INVESTIGATING**

You can hear popcorn popping from the outside of a microwave oven. *If the sound can get out, why can't the dangerous microwaves get out?*

**Photo 15.6**
A microwave radar system.



## Microwaves and radar

Microwaves have shorter wavelengths than radio waves. Because of this they can penetrate the ionosphere and can be reflected by smaller objects. They therefore have been used in communication and radar systems. They can be sent to satellites, which retransmit them to ground stations around the world.

Since they can be reflected by small objects they are used in radar systems. **Radar** was a term coined by the British in the mid-1930s as an abbreviation of 'radio direction and ranging'. The possibility of using radio waves (wavelength 10 cm to 10 m) reflected back from aircraft and other metal objects such as ships and submarines attracted much attention in Britain, America, Germany and France in the 1930s. However, it was the pioneering work of British government research physicist Professor Sir Robert Watson-Watt that led to its successful deployment in the defence of Britain's coastline. By March 1936, radar stations were being erected all along the south coast, using 10 m wavelength radio waves to detect German aircraft at distances of up to 100 km. It was found that the best reflections came from objects approximately equal in size to the wavelength.

Although 10 m radar could detect large metal objects such as planes, ships and submarines, it was useless for detecting submerged submarines where only the small *schnorkel* (air intake) was above the surface. The invention in 1940 of the cavity magnetron (now used in microwave ovens) changed all that. It could produce radar with a wavelength of 10 cm, making objects as small as 10 cm visible from as much as 10 km away. In a strange twist of fate, Watson-Watt was caught speeding in a police radar trap on a visit to the USA in 1954.

A radar system consists of a transmitter, an aerial, and a receiver. Pulses are transmitted via the aerial, which rotates on its axis to scan the surroundings for reflected signals, which are heard as an echo. The distance and direction of the objects reflecting the pulses can thus be calculated.

Shorter microwaves of about 0.1 mm produce considerable heat. They do this by causing the particles of matter they penetrate to vibrate faster, resulting in the matter heating up. They are thus used in microwave ovens where they are especially suitable for vibrating water molecules in foods. You may have noticed that when food is cooked in a microwave oven the food itself gets very hot but the plate does not get nearly as hot as in a conventional oven.

**NOVEL CHALLENGE**

A microwave oven doesn't heat evenly. It's hot in the centre, cooler a bit further out and hot again near the edge. This is due to standing waves being produced, and producing nodes and antinodes. *If the frequency of microwaves in an oven is 2.45 GHz, calculate the wavelength in centimetres and then draw a wave diagram to show this uneven heating.*

## Infrared waves

Infrared waves have wavelengths between microwaves and visible light of approximately 0.010 mm. These cannot be detected by the human eye but can be detected by phototransistors and special infrared-sensitive photographic film. All hot bodies emit infrared radiation. Below 500°C, bodies emit only infrared radiation; above 500°C they emit some visible light as well. (Infrared waves and heat effects have been discussed in Chapter 12.) The infrared radiation heating effect is also used in infrared lamps to help overcome injury and to heat and dry objects such as paint on cars during manufacture.

As well as those applications mentioned in Chapter 12 — medical, military and satellite detection applications — infrared waves are also used in alarm systems. As infrared waves cannot be seen, intruders do not notice when they break a beam of the waves and set off the alarm. Self-opening doors of shops work on the same principle.

## Ultraviolet waves

Ultraviolet (above violet) waves, or radiation, are those waves with shorter wavelengths than those of visible light — their wavelengths are between 100 nm and 400 nm. They are produced by very hot bodies such as the Sun as well as by electrical discharges through gases. Overdoses of UV radiation can cause sunburn, skin cancer and eye damage; however, luckily for us, most of this radiation from the Sun is absorbed by the ozone layer in the upper atmosphere. (Refer to Chapter 32.)

UV radiation carries more energy than visible light and can cause electrons to be ejected from metals when shone on them. Also, when it strikes some substances it causes the substances to emit visible light in a process called **fluorescence**.

Ultraviolet light is also used to detect cracks in materials and to sterilise objects.

## X-rays

X-rays are waves with even shorter wavelengths than ultraviolet waves. They have wavelengths of approximately 1.0 nm. They are produced by firing high-speed electrons at a metallic surface. The fast deceleration of these electrons produces X-rays. Because X-rays have great penetrating power through matter and affect photographic film they are used to 'see' through objects. X-ray photographs are a useful tool in medicine. They are also used to detect flaws in metallic structures and welds.

X-rays have high energy and are able to kill living cells. Because malignant cancerous tumours are more susceptible to X-rays than normal cells, controlled doses are used to kill the cancerous cells. Operators have to be careful not to give themselves too high a dose so they wear monitors to register the doses they receive and use lead aprons for protection.

## Gamma rays

Gamma rays, of wavelength 0.01 nm, have the shortest wavelength of all forms of electromagnetic radiation. Because they have such a short wavelength they are often not considered as waves. Wave properties of gamma radiation cannot easily be observed or detected. They are the most energetic and penetrating of all forms of electromagnetic radiation and require a thick sheet of lead or a concrete wall to stop them. They are emitted from radioactive nuclei — this will be covered more fully in Chapter 28. They too are used to treat cancers and have numerous other applications.

Table 15.6 summarises the types of electromagnetic waves, their uses, and detection methods.

**Table 15.6 TYPES, USES AND METHODS OF DETECTION OF ELECTROMAGNETIC WAVES**

| | RADIO | TV | MICROWAVES | INFRARED | VISIBLE | ULTRAVIOLET | X-RAYS | λ-RAYS |
|---|---|---|---|---|---|---|---|---|
| **Wavelength** | 0.1–10 m | 0.1–1 m | $10^{-1}$–$10^{-3}$ m | $10^{-3}$–$10^{-6}$ m | $2 \times 10^{-7}$–$7 \times 10^{-7}$ m | $10^{-7}$–$10^{-9}$ m | $10^{-9}$–$10^{-12}$ m | $10^{-11}$ m |
| **Use** | broadcasts | TV broadcasts | ovens, radar | scanning, drying paint, treating injuries, alarm systems | sight | flaw detection, sterilising objects | medicine, flaw detection | medicine, power stations |
| **Source** | radio transmitters | TV transmitters | | warm and hot objects | hot objects, fluorescent substances | very hot objects | X-ray tubes | radioactive substances |
| **Detector** | aerial with radio | aerial with TV set | | skin, thermometer, thermistor | eyes, photographic film, LDR | photographic film, skin | photographic film | Geiger–Muller tube |

## EI Activity 15.8 RADIO PHYSICS

Predict and justify the outcome of the following, and then try them. **(a)** Tune a small transistor radio in to a station and squat down with it in your lap (will the radio still pick up the broadcast?) **(b)** Instead, just wrap the radio in alfoil. **(c)** Tune a radio to a distant station at night and then turn it on in the morning without changing stations. If any of your predictions were wrong, explain the result.

## EI Activity 15.9 MICROWAVE COOKERY FOR PHYSICISTS

Ask your teacher to put the following into a microwave oven and to turn on 'high' for a few seconds (they are all pretty safe): **(a)** a small fluorescent bulb; **(b)** a neon pilot light; **(c)** two alfoil squares just touching at their corners; **(d)** a 100 W incandescent bulb; **(e)** some large squares of moist cobalt chloride paper (pink when wet, blue when dry); **(f)** a grape that you have prepared beforehand — cut it almost in half and peel it backwards so that each half is connected by a thin skin bridge. This is really spectacular. Don't do it at home; your mum won't be pleased.

# POLARISATION 15.9

**INVESTIGATING**

*Have you ever wondered what happens when you shine a laser through Polaroid? Is a laser polarised and so none gets through? If we had time we'd try it.*

Electromagnetic waves, as suggested by Maxwell, are a type of transverse wave composed of oscillating electric and magnetic fields. These transverse waves have components of electric and magnetic fields in all directions. When all components of the electric fields except for one are blocked the wave is said to be **plane polarised**. It is usually the electric field vector that defines the direction of polarisation.

A device that allows only one component of the electric field through is called a **polariser**. An example may explain this more simply; if a slinky spring is threaded through a slit in a wall as shown in Figure 15.25 and shaken in all directions, only those pulses that are in the same plane as the slit will get through; the rest will be blocked.

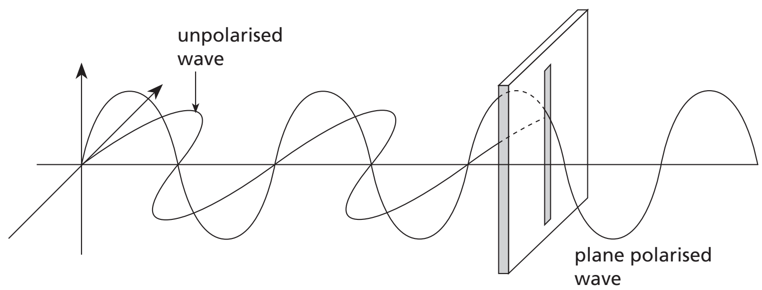



**Figure 15.25**
Polarisers allow only waves in the plane of the polariser to pass through.

'Polaroid' is the brand name of synthetic materials that have these polarising properties. They polarise light or allow light waves vibrating in one direction through. If a second piece of polaroid called an **analyser** is placed after the polariser, as shown in Figure 15.26, it is possible to block out all light from the source by rotating the analyser. If the plane of the analyser and the polariser line up then light will be seen. However, if they are at right angles no light will be transmitted through the analyser. Between these two extremes the amount of light transmitted will vary depending on the angle between the planes of the polariser and the analyser.

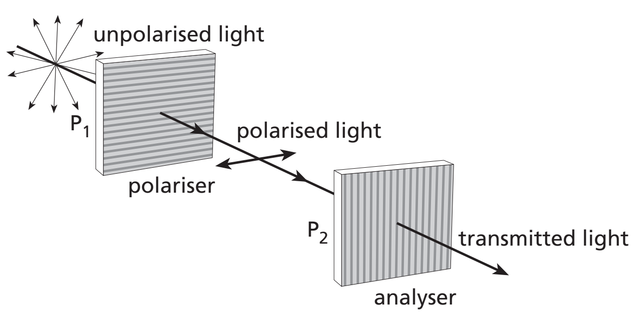
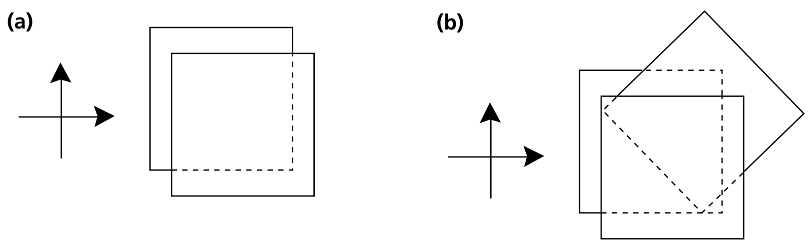



**Figure 15.26**
The angles between the polariser and the analyser determine the amount of light that is transmitted.

# Activity 15.10 SUNGLASSES

If you have an old pair of Polaroid sunglasses, pop the lenses out and place them together. When they are rotated as shown in Figure 15.27 the amount of light passing through will vary.

1 Cut one of the lenses in half — now you have three pieces.
2 Cross one pair so that they go black (Figure 15.27 **(a)**).
3 Slide the third one in at an angle and note what happens (Figure 15.27 **(b)**). How on earth can this happen?
4 Try it in front and behind the crossed polarisers. What happens?




**INVESTIGATING**

The nematic crystals used in liquid crystal displays (e.g. your calculator) melt like all crystals. Put your calculator in the sun and watch the display go black. *At what temperature did this happen?*

**Figure 15.27**
For Activity 15.10.

## Polaroid sunglasses

When wearing Polaroid sunglasses, annoying reflections from horizontal surfaces, such as shiny floors, wet roads, car bonnets, the ocean and the beach are eliminated. When sunlight reflects from these surfaces it becomes horizontally polarised because most of the other components are scattered. Polaroid sunglasses have their polarising plane vertical so as to block these reflections.

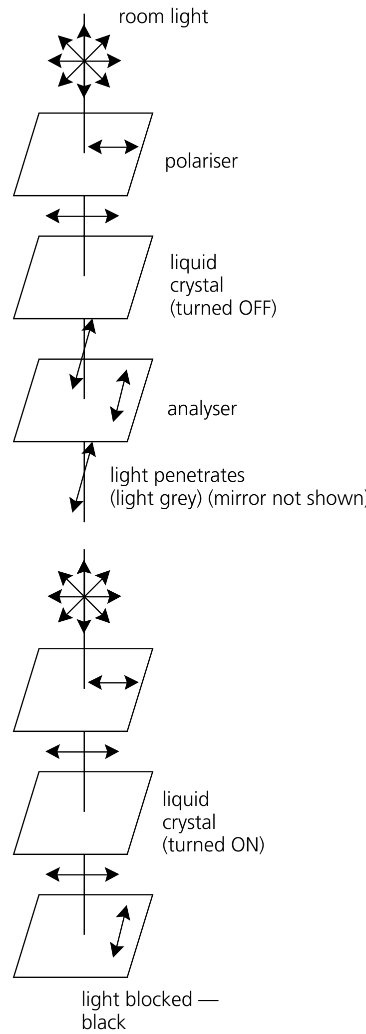
## Camera filters

To reduce the brightness of light entering a camera, photographers sometimes use Polaroid filters which have polarisers that can be rotated. Light intensity can be reduced by rotating one of the polarisers. By doing this instead of closing the aperture down, the depth of field of the lens is not affected. The polarising filter is also used to reduce unwanted reflections from glass or water surfaces.

## Liquid crystal display

The sort of display used in calculators and digital watches uses two pieces of Polaroid that are crossed. Room light passes through the top polariser, where it is then rotated through 90° by the liquid crystals before it strikes the bottom polariser. The bottom polariser is crossed with respect to the top polariser but because the liquid crystals have rotated the light through 90° the light passes through. Underneath the bottom layer is a mirror which reflects the room light back to the user. (See Figure 15.28.) When a voltage is applied to the crystals they stop rotating the light so it is blocked, and appears black. If you have a broken calculator check that it has Polaroid and mirrors in it.

**Figure 15.28**
Liquid crystal displays in calculators and digital watches use polarising filters. A voltage applied to the liquid controls the amount of light reflected back to the user.



## Practice questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

### Review — applying principles and problem solving

***16** State two properties of waves that are considered to be strictly wave characteristics.

***17** State the important characteristics of Young's experimental design that allowed the interference fringes to be observed.

****18** Light from a red laser of wavelength 620 nm is shone on a pair of parallel slits 0.10 mm apart. The interference pattern produced is incident on a screen 2.8 m from the slits.

- **(a)** Calculate the distance from the central maximum to the first-order nodal line in this pattern.
- **(b)** Calculate the distance to the third-order antinodal line.
- **(c)** What would happen to the pattern if the distance between the slits was reduced?
- **(d)** What would happen to the pattern if the slits and laser were moved toward the screen?
- **(e)** What would happen to the pattern if yellow light was used instead of red light?

****19** If Young's experiment was used to produce an interference pattern with X-rays (wavelength of 1.0 nm), what slit separation would be needed to make the second antinode 2.0 mm from the central maximum on a screen placed 2.0 m from the slits? (Is this feasible?)

***20** Green light of wavelength 510 nm is shone on a pair of slits placed 2.0 m from a screen. The distance between the slits is 0.20 mm.

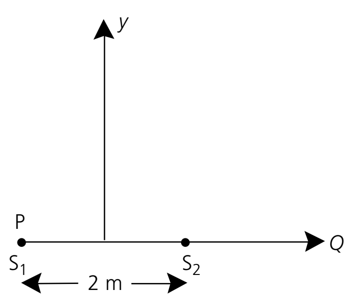
- **(a)** What is the distance from the central maximum to the third antinodal line?
- **(b)** What is the thickness of the central maximum?

***21** Students use a single slit to determine the wavelength of light produced by a laser. Light from the laser is incident on a slit of 1.0 mm width, and the interference pattern is observed on a screen 3.0 m from the laser. The first-order dark band appears 2.0 mm from the middle of the central maximum. What is the wavelength of light emitted by the laser?

***22** $S_1$ and $S_2$ are sources of VHF radio waves of wavelength 0.50 m. They are connected to the same generator and remain in phase.

- **(a)** If a detector of this radiation is moved from P to Q as shown in Figure 15.29 how far from P will the first minimum be detected?
- **(b)** Why does the detector register a maximum of intensity when it is 1.5 m from P?

**Figure 15.29**
For question 22.




***23** Blue light of wavelength 450 nm is incident on a pinhole of $2.0 \times 10^{-4}$ m diameter made in an opaque sheet and the resultant interference pattern is produced on a screen 2.5 m from the pinhole.

- **(a)** Describe the pattern produced on the screen.
- **(b)** What is the distance from the central maximum to the third bright line?
- **(c)** What is the diameter of the central maximum?

****24** A water film ($n$ = 1.33) in air is 320 nm thick. It is illuminated by white light at normal incidence. What colour of light occurs in the reflected interference pattern produced above the film?

***25** A thin film of refractive index 1.5, and $4.0 \times 10^{-5}$ cm thick, is surrounded by air and illuminated by white light normal to its surface. What wavelengths within the visible spectrum will be intensified in the reflected beam?

***26** Light of wavelength 680 nm in air illuminates at right angles two glass plates 12 cm long that touch at one end and are separated at the other end by a wire of 0.048 mm diameter. How many bright fringes will appear over the 12 cm length?

***27** **(a)** What is the speed in air of **(i)** red light of wavelength 620 nm; **(ii)** blue light of wavelength 470 nm; **(iii)** X-rays of wavelength 1.0 nm?
**(b)** Find the frequency of each of the above electromagnetic waves.
**(c)** What would be the frequency of these rays in water?

***28** List several pieces of evidence that support the theory that light is a wave.

***29** A radio station transmits at a frequency of 105 MHz. Calculate the wavelength of these radio waves.

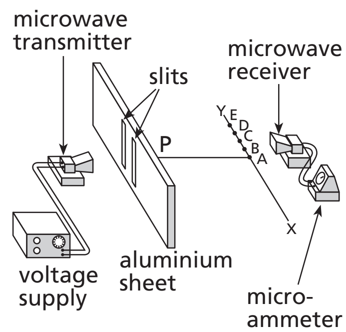
***30** A ship using a microwave radar system to detect distant aircraft receives 'echoes' back $5.0 \times 10^{-4}$ s after transmission of a radar pulse. Determine the distance to the aircraft.

***31** Weather satellites use infra-red detectors rather than visible light detectors. Explain the advantages of this.

****32** Microwaves can be used in the laboratory to show the interference of waves. The microwaves are transmitted by a microwave transmitter and received by a detector.

The microwave transmitter transmits on a frequency of $2.0 \times 10^{10}$ Hz. It is found that the maximum intensities occur at points A, C, and E, while minimum intensities occur at points D and B. The distance from A to D is found to be 1.5 m while the distance from P to A is 3 m. (Refer to Figure 15.30.)
**(a)** Calculate the wavelength of the microwaves used.
**(b)** What is the path difference from the two slits to point **(i)** D; **(ii)** C?
**(c)** Calculate the separation between the slits produced by the aluminium plates to produce this pattern.

**Figure 15.30**
For question 32.



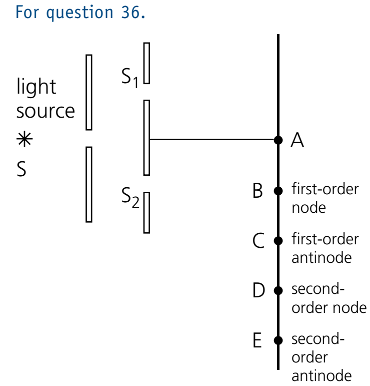

***33** Which category of wave is used for the following:
**(a)** reflecting from the ionosphere;
**(b)** communicating by retransmitting from satellites;
**(c)** producing heat for drying paint on cars;
**(d)** treating cancers;
**(e)** seeing objects;
**(f)** detecting cracks in welds;
**(g)** 'seeing' internal structures;
**(h)** operating radar systems;
**(i)** causing skin cancers?

***34** A radio station is transmitting carrier waves of 5.0 m wavelength. Is this likely to be an FM or an AM station?

***35** The categories of waves in the electromagnetic spectrum overlap. There is no distinct division between, say, X-rays and gamma rays. However, they are produced differently. Explain how they differ in their production.

****36** Figure 15.31 is a schematic diagram of Young's double-slit experiment.
**(a)** What are the distances **(i)** $S_1A–S_2A$; **(ii)** $S_1B–S_2B$; **(iii)** $S_1E–S_2E$?
**(b)** What kind of interference occurs at **(i)** D; **(ii)** A?
**(c)** If the distance from A to D is 4.0 mm, the distance to the screen is 90 cm and the distance between the slits $S_1$, $S_2$ is 0.15 mm, find the wavelength of the light used.

**Figure 15.31**
For question 36.




***37** Choose two AM and two FM radio stations. On what frequencies do they transmit? Calculate the wavelength of these radio waves.

***38** The new generation of compact discs can fit over two hours of music and video onto one disc but they need a much higher frequency laser to read the CD pits. Why do you think this is?

## Extension — complex, challenging and novel

***39 A parallel beam of light containing red light of wavelength 650 nm and orange light of wavelength 580 nm is shone on a diffraction grating containing 1000 lines per centimetre. Calculate the angular deviation of these two wavelengths in the second-order bright fringe.

***40 White light reflected at normal incidence from a soap film has, in the visible spectrum, an interference maximum that occurs for light of 600 nm wavelength and a minimum that occurs for light of 450 nm wavelength, with no minimums between these wavelengths. If $n$ = 1.33, what is the film thickness, assumed uniform?

***41 Monochromatic light falls normally on a thin film of oil that covers a glass plate. The wavelength of the source can be varied continuously. Complete destructive interference of the reflected light is observed for wavelengths of 500 and 700 nm and for no other wavelengths in between. If the index of refraction of the oil is 1.3 and that of glass is 1.5, find the thickness of the oil film.

***42 An oil tanker accidentally discharges oil onto the Great Barrier Reef. If the thickness of the oil film produced on the water was $5.0 \times 10^{-7}$ m what colour would the film appear? ($n_{oil}$ = 1.45.)

***43 An air wedge is made by placing a thin sheet of paper between the ends of a pair of glass slides. Red light of 650 nm is shone at right angles onto the surface of the slides. The bright bands in the interference pattern of reflected light are observed to be 0.40 mm apart. If the paper is 5.0 cm from the point of contact of the slides, what is the thickness of the paper?

***44 One method of measuring the thickness of a razor blade is by using double-slit interference. Design an experiment that would enable you to do this. (*Hint:* use two blades.)

**45 Answer true or false:

- **(a)** Light is a mixture of particles and waves.
- **(b)** Light waves and radio waves are not the same thing.
- **(c)** Microwaves have an extremely short wavelength.
- **(d)** The addition of all colours produces black.
- **(e)** Light exists in the crest of a wave and darkness in the trough.
- **(f)** Rays and wavefronts are the same thing.
- **(g)** Photons are just neutral electrons.