Cambridge

IGCSE

Physics

CODE: (9702)

Chapter 14 and Chapter 15

Practical circuits and waves

Chapter 14: Superposition of waves

Chapter 13 explores the production of waves and the difference between longitudinal and transverse waves. It then discusses the interaction between two or more waves at a point in space. Unlike **particles**, waves pass through each other without affecting each other. When two waves meet, they combine, with the displacements of the two waves adding together. The resultant displacement is determined by adding the displacements of the two waves at different positions.

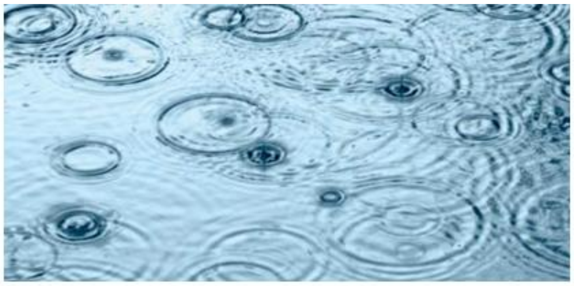

Figure 14.2 Here we see ripples produced when drops of water fall into a swimming pool. The ripples overlap to produce a complex pattern of crests and troughs.

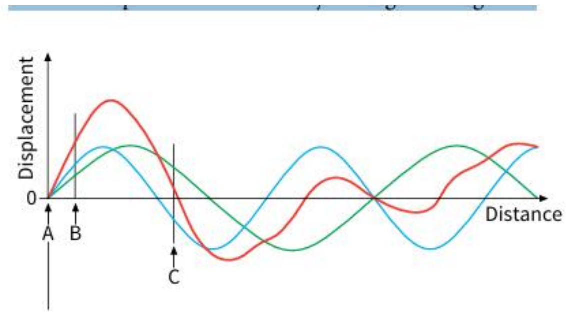

Figure 14.3 Adding two waves by the principle of superposition – the red line is the resultant wave.

The idea that we can find the resultant of two waves which meet at a point simply by adding up the displacements at each point is called the principle of superposition of waves. This principle can be applied to more than two waves and also to all types of waves. A statement of the **principle of superposition** is shown below:

When two or more waves meet at a point, the resultant displacement is the algebraic sum of the displacements of the individual waves.

Diffraction of waves

Diffraction is the spreading of a wave as it passes through a gap or around an edge. It is easy to observe and investigate diffraction effects using water waves, as shown in Box 14.1.

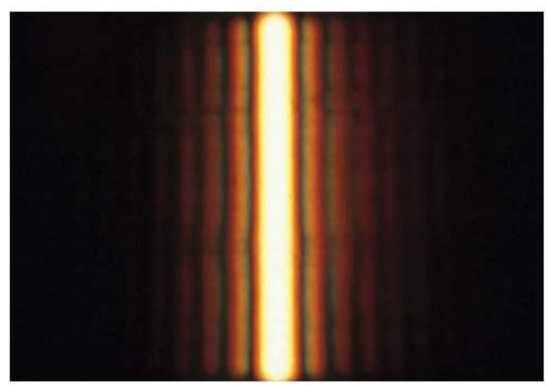

Figure 14.5 Light is diffracted as it passes through a slit.

Diffraction of sound and light

Diffraction effects are most noticeable when waves pass through a gap with a width equal to their wavelength. Sound waves, with wavelengths from a few millimetres to a few meters, can be easily observed due to their diffractivity. Visible light, with shorter wavelengths, is not diffracted by doorways due to their larger gap width. However, diffraction can be observed by passing light through a narrow slit or hole, as seen in laser light smearing onto a screen.

Diffraction of radio and microwaves

Radio waves have wavelengths of a kilometer and 10 cm, diffracted by hills and buildings. Microwaves, used by mobile phones, have shorter wavelengths and travel in straight lines. Cars require external radio aerials to diffract longer wavelengths, while FM signals can be picked up weakly, while AM signals cannot.

Explaining diffraction

Diffraction is a wave effect explained by the principle of superposition. When a plane ripple reaches a gap in a barrier, each moving point creates new ripples, which can be calculated using the principle of superposition. In some directions, the ripples add, while in others, they cancel out.

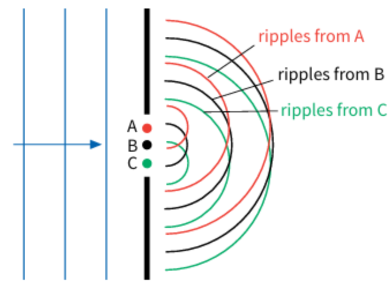

Figure 14.10 Ripples from all points across the gap contribute to the pattern in the space beyond.

Interference

Adding waves of different wavelengths and amplitudes results in complex waves. We can find some interesting effects if we consider what happens when two waves of the same wavelength overlap at a point. Again, we will use the principle of superposition to explain what we observe.

Explaining interference

Figure 14.14 shows how interference arises. The loudspeakers in Figure 14.11 (Box 14.2) are emitting waves that are in phase because both are connected to the same signal generator.

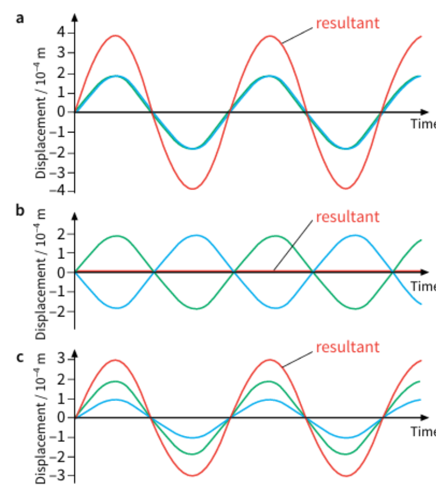

Figure 14.14 Adding waves by the principle of superposition. Blue and green waves of the same amplitude may give **a** constructive or **b** destructive interference, according to the phase difference between them. **c** Waves of different amplitudes can also interfere constructively.

Where two waves arrive at a point in phase with one another so that they add up, we call this effect **constructive interference**. Where they cancel out, the effect is known as **destructive interference.**

How can we explain the interference pattern observed in a ripple tank (Box 14.2)? Look at Figure 14.15 and compare it to Figure 14.13. Figure 14.15 shows two sets of waves

These conditions apply to all waves (water waves, light, microwaves, radio waves, sound, etc.) that show interference effects. In the equations below, n stands for any integer (any whole number, including zero).

- For **constructive interference** the path difference is a whole number of wavelengths:

  path difference $= 0, \lambda, 2\lambda, 3\lambda$, etc.

  or path difference $= n\lambda$
- For **destructive interference** the path difference is an odd number of half wavelengths:

  path difference $= \frac{1}{2}\lambda, 1\frac{1}{2}\lambda, 2\frac{1}{2}\lambda$, etc.

  or path difference $= (n + \frac{1}{2})\lambda$

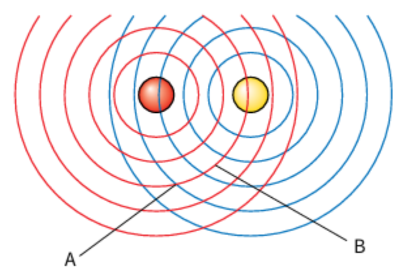

Figure 14.15 The result of interference depends on the path difference between the two waves.

Coherence

We are surrounded by various types of waves, including light, infrared radiation, radio waves, and sound. However, we don't always observe interference patterns, and specialized equipment is needed to measure these effects. In everyday life, we can observe interference effects like haloes around streetlamps or the Moon. To measure these effects, we need specially arranged conditions, as seen in a demonstration with loudspeakers.

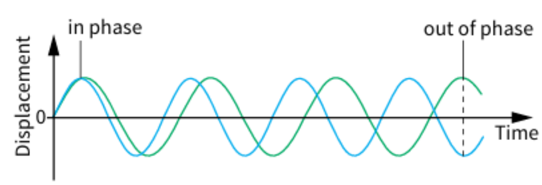

Figure 14.18 Waves of slightly different wavelengths (and therefore frequencies) move in and out of phase with one another.

We say that they act as two coherent sources of sound waves (coherent means sticking together). Coherent sources emit waves that have a **constant phase difference**

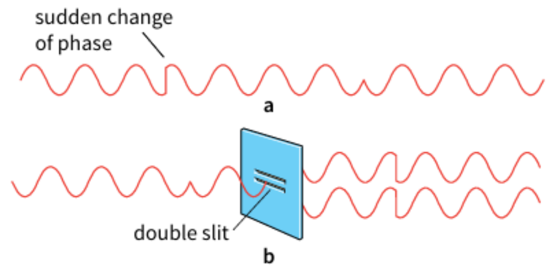

Figure 14.19 Waves must be coherent if they are to produce a clear interference pattern.

The laser experiment involved two lasers producing identical frequency and wavelength of light. To observe interference, a single laser was divided into two slits, which act as coherent sources of light. These slits are always in phase, ensuring a constant phase difference between them. Without these sources, the interference pattern would be too fast for our eyes to detect, resulting in a uniform light band.

The Young double-slit experiment

Now we will take a close look at a famous experiment which Thomas Young performed in 1801. He used this experiment to show the wave nature of light. A beam of light is shone on a pair of parallel slits placed at right angles to the beam.

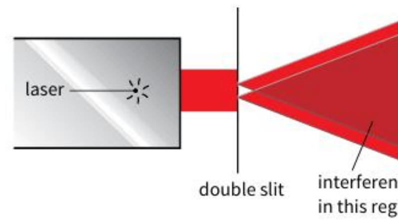

Figure 14.20 Interference occurs where diffracted beams from the two slits overlap.

Explaining the experiment

In order to observe interference, we need two sets of waves. The sources of the waves must be coherent – the phase difference between the waves emitted at the sources must remain constant

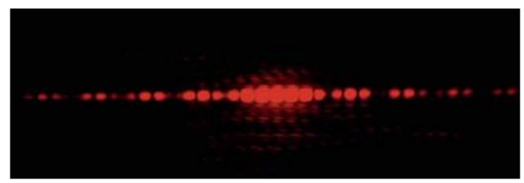

Figure 14.21 Interference fringes obtained using a laser and a double slit.

Point A

Point A, opposite the slits midpoint, receives two light rays from slit 1 and slit 2, resulting in zero path difference. Assuming phase, they will interfere constructively, causing a bright fringe at A, indicating their phase difference.

Point B,

Point B, at the midpoint of the first dark fringe, receives two rays of light from each slit. As they travel further than the other, they become in antiphase, causing a half-wavelength path difference, resulting in destructive interference.

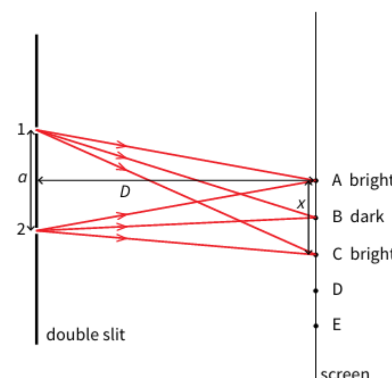

Figure 14.22 Rays from the two slits travel different distances to reach the screen.

Point C

This point is the midpoint of the next bright fringe, with AB = BC. Again, ray 1 has travelled further than ray 2; this time, it has travelled an extra distance equal to a whole wavelength λ.

The complete interference pattern (Figure 14.21) can be explained in this way.

Determining wavelength λ

The double-slit experiment can be used to determine the wavelength λ of light. The following three quantities have to be measured:

■ ■ Slit separation a – This is the distance between the centres of the slits, which is the distance between slits 1 and 2 in Figure 14.22.

■ ■ Fringe separation x – This is the distance between the centres of adjacent bright (or dark) fringes, which is the distance AC in Figure 14.22.

■ ■ Slit-to-screen distance D – This is the distance from the midpoint of the slits to the central fringe on the screen

Once these three quantities have been measured, the wavelength λ of the light can be found using the relationship:

$$\lambda = \frac{ax}{D}$$

Diffraction gratings

A transmission diffraction grating is a large number of lines on a slide that diffract light, producing interference fringes when shone through. A reflection diffraction grating, like the shiny surface of a CD or DVD, reflects and diffuses light, producing coloured bands. These lines carry digital information and are reflected on the surface, creating a pattern of interference fringes.

Figure 14.24 A CD acts as a reflection diffraction grating. White light is reflected and diffracted at its surface, producing a display of spectral colours.

Observing diffraction with a transmission grating

The fringes are also referred to as maxima. The central fringe is called the zeroth-order maximum, the next fringe is the first-order maximum, and so on. The pattern is symmetrical, so there are two first-order maxima, two second-order **maxima**, and so on.

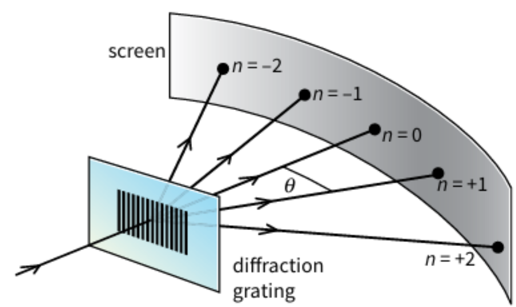

Figure 14.25 The diffracted beams form a symmetrical pattern on either side of the undiffracted central beam.

Explaining the experiment

The principle of light passing through multiple slits results in overlapping beams of light that interfere with one another. To achieve constructive interference, all beams must be in phase. The zeroth-order maximum occurs in the straight-through direction, where rays travel parallel to one another and in phase. The first-order maximum forms when all rays must be in phase. Rays 1 and 2 travel the smallest distance, while ray 3 travels two extra wavelengths and is in phase with rays 1 and 2.

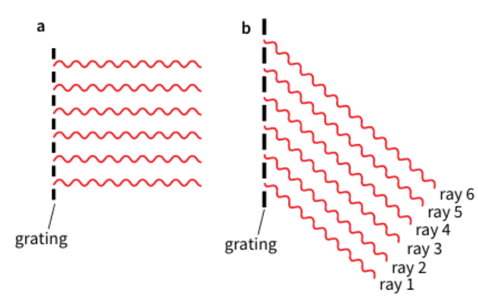

Figure 14.26 **a** Waves from each slit are in phase in the straight-through direction. **b** In the direction of the first-order maximum, the waves are in phase, but each one has travelled one wavelength further than the one below it.

Determining wavelength λ with a grating

By measuring the angles at which the maxima occur, we can determine the wavelength of the incident light. Th e wavelength λ of the monochromatic light is related to the angle θ by: d sin θ = nλ

Diffracting white light

On either side, a series of spectra appear, with violet closest to the centre and red furthest away. We can see why different wavelengths their maxima at different angles have if we rearrange the equation d sin θ = nλ to give:

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

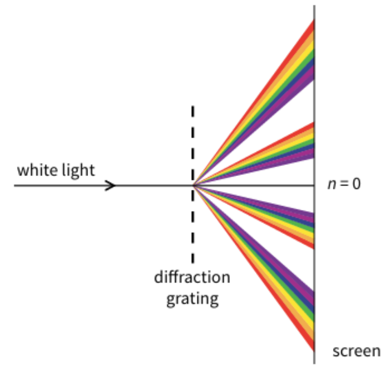

Figure 14.27 A diffraction grating is a simple way of separating white light into its constituent wavelengths.

Chapter 15: Stationary waves

From moving to stationary

The waves we have considered so far in Chapters 13 and 14 have been progressive waves; they start from a source and travel outwards, transferring energy from one place to another. A second important class of waves is stationary waves (standing waves).

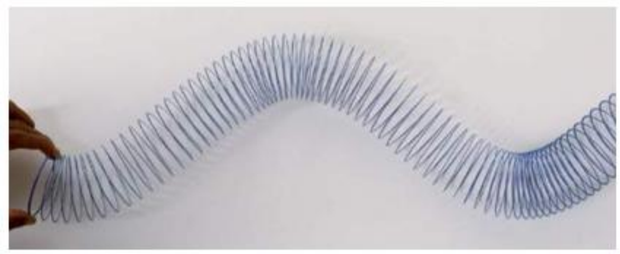

Figure 15.2 A slinky spring is used to generate a stationary wave pattern.

To create interesting patterns, move the spring end with the right frequency, and the pattern disappears with slight increase or decrease in shaking frequency.

Nodes and antinodes

A stationary wave on a long spring is represented by a series of loops separated by nodes. The wave profile is not traveling along the spring's length, making it a standing wave. The phase difference between nodes is 180°, causing adjacent loop sections to move in antiphase, half a cycle out of phase with one another.

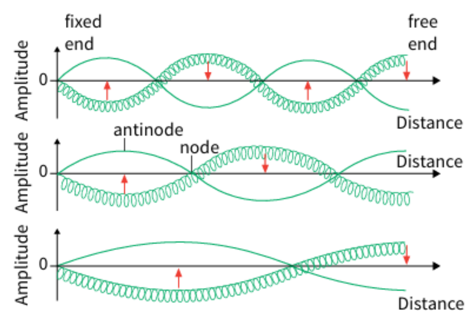

Figure 15.3 Different stationary wave patterns are possible, depending on the frequency of vibration.

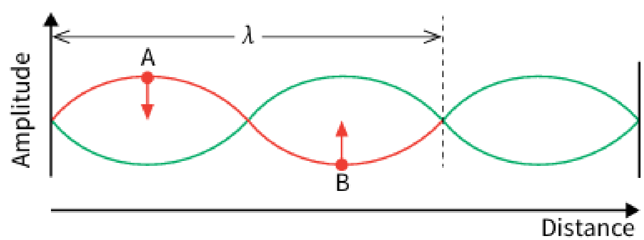

Figure 15.4 The fixed ends of a long spring must be nodes in the stationary wave pattern.

Formation of stationary waves

A stationary wave is formed whenever two progressive waves of the same amplitude and wavelength, travelling in opposite directions, superpose. Figure 15.5 uses a displacement–distance graph (s–x) to illustrate the formation of a stationary wave along a long spring (or a stretched length of string):

■ ■ At time t = 0, the progressive waves travelling to the left and right are in phase. The waves combine constructively, giving an amplitude twice that of each wave.

- After a time equal to one-quarter of a period ($t = \frac{T}{4}$), each wave has travelled a distance of one quarter of a wavelength to the left or right. Consequently, the two waves are in antiphase (phase difference = 180°). The waves combine **destructively**, giving zero displacement.
- After a time equal to one-half of a period ($t = \frac{T}{2}$), the two waves are back in phase again. They once again combine **constructively**.
- After a time equal to three-quarters of a period ($t = \frac{3T}{4}$), the waves are in antiphase again. They combine **destructively**, with the resultant wave showing zero displacement.
- After a time equal to one whole period ($t = T$), the waves combine **constructively**. The profile of the spring is as it was at $t = 0$.

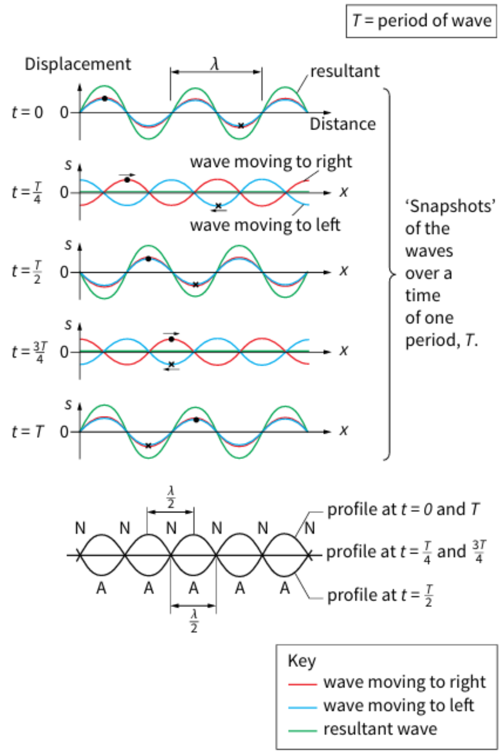

Figure 15.5 The blue-coloured wave is moving to the left and the red-coloured wave to the right. The **principle of superposition** of waves is used to determine the resultant displacement. The profile of the long spring is shown in green.

A closer inspection of the graphs in Figure 15.5 shows that the separation between adjacent nodes or antinodes is related to the wavelength λ of the progressive wave. The important conclusions are:

$$\text{separation between two adjacent nodes (or between two adjacent antinodes)} = \frac{\lambda}{2}$$

$$\text{separation between adjacent node and antinode} = \frac{\lambda}{4}$$

The wavelength λ of **any** progressive wave can be determined from the separation between neighbouring nodes or antinodes of the resulting standing wave pattern. (This separation is $= \frac{\lambda}{2}$.) This can then be used to determine either the speed v of the progressive wave or its frequency f by using the wave equation:

$$v = f\lambda$$

It is worth noting that a stationary wave does not travel and therefore has no speed. It does not transfer energy between two points like a progressive wave. Table 15.1 shows some of the key features of a progressive wave and its stationary wave.

	Progressive wave	Stationary wave
wavelength	λ	λ
frequency	f	f
speed	v	zero

Table 15.1 A summary of progressive and stationary waves.

Stationary waves and musical instruments

When the string is plucked half-way along its length, it vibrates with an antinode at its midpoint. This is known as the **fundamental mode of vibration** of the string. The **fundamental frequency** is the **minimum frequency** of a standing wave for a given system or arrangement.

Figure 15.13 When a guitar string is plucked, the vibrations of the strings continue for some time afterwards. Here you can clearly see a node close to the end of each string.

Harmonic sounds are produced by vibrating the air column in wind instruments, resulting in a note with a frequency twice the fundamental frequency. The note can be altered by changing the air column length or exposing holes for more free vibration. The musician's skill lies in stimulating the string or air column to produce a desired mixture of frequencies, with harmonic frequency always being a multiple of the fundamental frequency.

Determining the wavelength and speed of sound

Since we know that adjacent nodes (or antinodes) of a stationary wave are separated by half a wavelength, we can use this fact to determine the wavelength λ of a progressive wave. If we also know the frequency f of the waves, we can f ind their speed v using the wave equation v = f λ

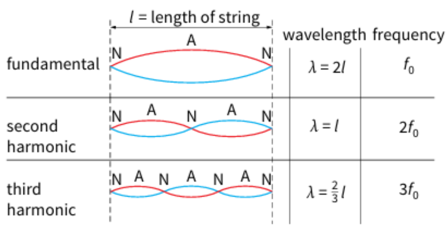

Figure 15.14 Some of the possible stationary waves for a fixed string of length l. The frequency of the harmonics is a multiple of the fundamental frequency f_0.

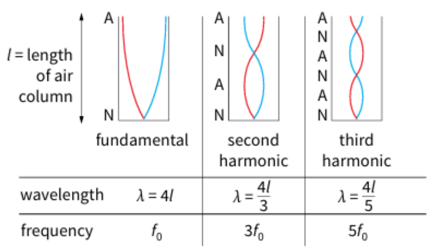

Figure 15.15 Some of the possible stationary waves for an air column, closed at one end. The frequency of each harmonic is an odd multiple of the fundamental frequency f_0.

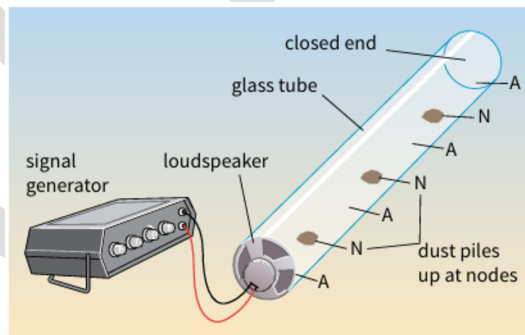

Figure 15.16 Kundt's dust tube can be used to determine the speed of sound.

Revision questions

1. (a) For a progressive wave, state what is meant by wavelength.

....

.... [1]

(b) A light wave from a laser has a wavelength of 460nm in a vacuum.
Calculate the period of the wave.

period = ... s [3]

(c) The light from the laser is incident normally on a diffraction grating.
Describe the diffraction of the light waves at the grating.

....

....

.... [2]

(d) A diffraction grating is used with different wavelengths of visible light. The angle θ of the fourth-order maximum from the zero-order (central) maximum is measured for each wavelength. The variation with wavelength λ of sinθ is shown in Fig. 4.1.

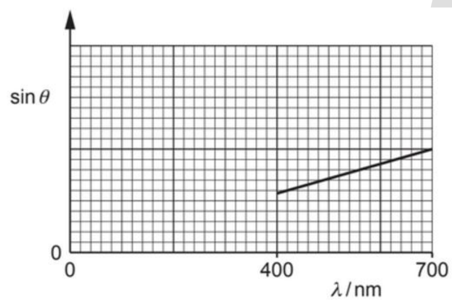

Fig. 4.1

(i) The gradient of the graph is G.
Determine an expression, in terms of G, for the distance d between the centres of two

adjacent slits in the diffraction grating.

d = ...

(ii) On Fig. 4.1, sketch a graph to show the results that would be obtained for the second-order maxima.

2.

(a) State the principle of superposition. [2]

(b) A transmitter produces microwaves that travel in air towards a metal plate, as shown in Fig. 4.1.

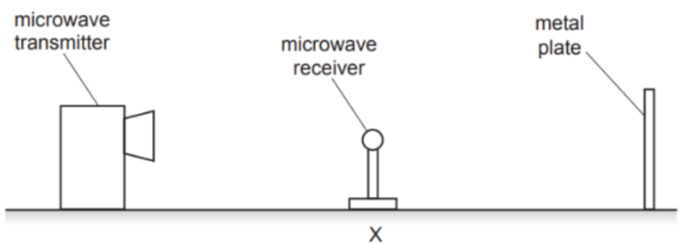

Fig. 4.1

The microwaves have a wavelength of 0.040m. A stationary wave is formed between the transmitter and the plate.

(i) Explain the function of the metal plate. [1]

(ii) Calculate the frequency, in GHz, of the microwaves.

frequency = ... GHz [3]

(iii) A microwave receiver is initially placed at position X where it detects an intensity minimum. The receiver is then slowly moved away from X directly towards the plate.

1. Determine the shortest distance from X of the receiver when it detects another intensity minimum.

2. Determine the number of intensity maxima that are detected by the receiver as it moves from X to a position that is 9.1cm away from X.

number = ...

[2]

3.

(a) By reference to the direction of transfer of energy, state what is meant by a longitudinal wave. [1]

(b) A vehicle travels at constant speed around a wide circular track. It continuously sounds its horn, which emits a single note of frequency 1.2kHz. An observer is a large distance away from the track, as shown in the view from above in Fig. 4.1.

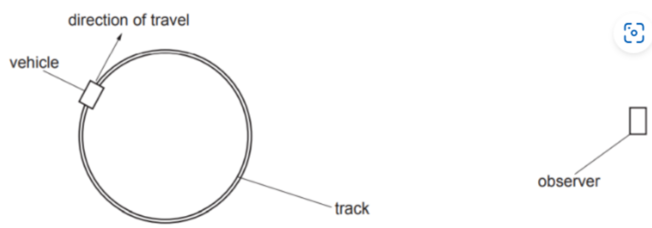

Fig. 4.1 (not to scale)

Fig. 4.2 shows the variation with time of the frequency *f* of the sound of the horn that is detected by the observer. The time taken for the vehicle to travel once around the track is *T*.

Fig. 4.2 shows the variation with time of the frequency *f* of the sound of the horn that is detected by the observer. The time taken for the vehicle to travel once around the track is *T*.

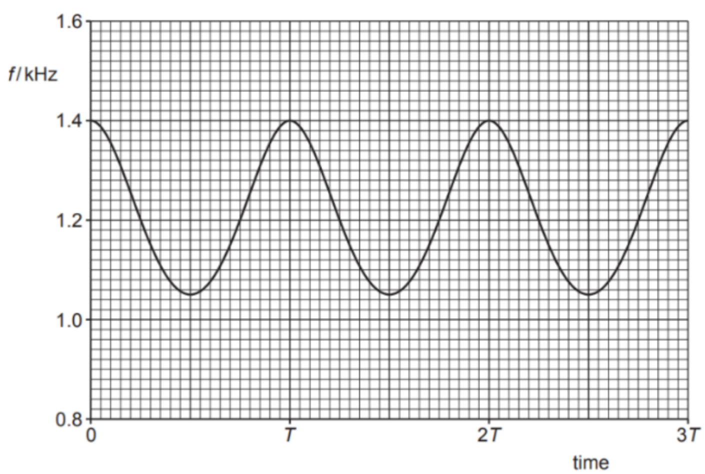

Fig. 4.2

(i) Explain why the frequency of the sound detected by the observer is sometimes above and sometimes below 1.2kHz. [2]

(ii) State the name of the phenomenon in **(b)(i)**. [1]

(iii) On Fig. 4.1, mark with a letter X the position of the vehicle when it emitted the sound that is detected at time T. [1]

(iv) On Fig. 4.1, mark with a letter Y the position of the vehicle when it emitted the sound that is detected at time $\frac{9T}{4}$ [1]

c) The speed of the sound in the air is 320ms^{-1}.

Use Fig. 4.2 to determine the speed of the vehicle in (**b**).

speed = ... ms^{-1} [3]

[Total: 9]

4.

(a) (i) By reference to the direction of propagation of energy, state what is meant by a longitudinal wave.
(ii) State the principle of superposition.

(b) The wavelength of light from a laser is determined using the apparatus shown in Fig. 4.1.

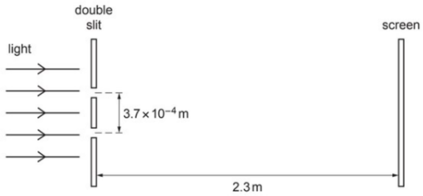

Fig. 4.1 (not to scale)

The light from the laser is incident normally on the plane of the double slit. The separation of the two slits is 3.7×10^{-4}m. The screen is parallel to the plane of the double slit. The distance between the screen and the double slit is 2.3m. A pattern of bright fringes and dark fringes is seen on the screen. The separation of adjacent bright fringes on the screen is 4.3×10^{-3}m.

(i) Calculate the wavelength, in nm, of the light.
wavelength = ... nm

(ii) The intensity of the light passing through each slit was initially the same. The intensity of the light through one of the slits is now reduced.

Compare the appearance of the fringes before and after the change of intensity.

5.

(a) (i) State the conditions required for the formation of a stationary wave.

.... [2]

(ii) State the phase difference between any two vibrating particles in a stationary wave between two adjacent nodes.

phase difference = ...° [1]

(b) A motorcycle is travelling at 13.0 m/s along a straight road. The rider of the motorcycle sees a pedestrian standing in the road directly ahead and operates a horn to emit a warning sound.
The pedestrian hears the warning sound from the horn at a frequency of 543Hz. The speed of the sound in the air is 334 m/s.

(i) Calculate the frequency, to three significant figures, of the sound emitted by the horn.

frequency = ... Hz [2]

(ii) The motorcycle rider passes the stationary pedestrian and then moves directly away from her. As the rider moves away, he operates the horn for a second time. The pedestrian now hears sound that is increasing in frequency.

State the variation, if any, in the speed of the motorcycle when the rider operates the horn for the second time... [1]

(c) A beam of vertically polarised monochromatic light is incident normally on a polarising filter, as shown in Fig. 5.1.

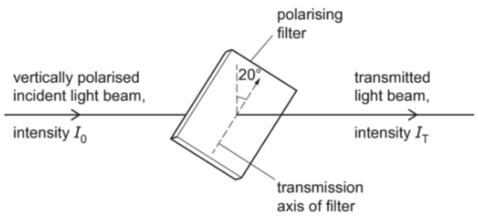

Fig. 5.1

The filter is positioned with its transmission axis at an angle of 20° to the vertical. The incident light has intensity I_0 and the transmitted light has intensity I_T.

(i) By considering the ratio $\frac{I_T}{I_0}$ calculate the ratio $\frac{\text{amplitude of transmitted light}}{\text{amplitude of incident light}}$.

Show your working. ratio = ... [3]

(ii) The filter is now rotated, about the direction of the light beam, from its starting position shown in Fig. 5.1. The direction of rotation is such that the angle of the transmission axis to the vertical initially increases.

Calculate the minimum angle through which the filter must be rotated so that the intensity of the transmitted light returns to the value that it had when the filter was at its starting position.

6.

A long rope is held under tension between two points A and B. Point A is made to vibrate vertically and a wave is sent down the rope towards B as shown in Fig. 5.1.

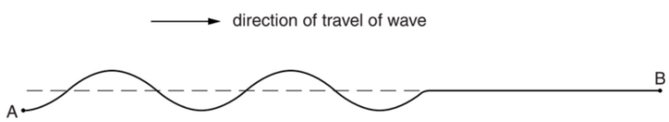

Fig. 5.1 (not to scale)

The time for one oscillation of point A on the rope is 0.20 s. The point A moves a distance of 80 mm during one oscillation. The wave on the rope has a wavelength of 1.5 m.

(a) (i) Explain the term displacement for the wave on the rope.

(ii) Calculate, for the wave on the rope,

1. the amplitude,

amplitude = ... mm [1]

2. the speed.

speed = ... m/ s[3]

(b) On Fig. 5.1, draw the wave pattern on the rope at a time 0.050 s later than that shown.[2]

(c) State and explain whether the waves on the rope are

(i) progressive or stationary,

7.

A source of radio waves sends a pulse towards a reflector. The pulse returns from the reflector and is detected at the same point as the source. The emitted and reflected pulses are recorded on a cathode-ray oscilloscope (c.r.o.) as shown in Fig. 2.1.

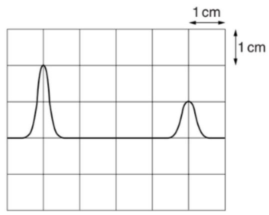

Fig. 2.1

The time-base setting is $0.20\mu s cm^{-1}$.

(a) Using Fig. 2.1, determine the distance between the source and the reflector.

distance = ... m [4]

(b) Determine the time-base setting required to produce the same separation of pulses on the c.r.o. when sound waves are used instead of radio waves.

The speed of sound is 300 m/ s.

8.

(a) (i) State the conditions required for the formation of a stationary wave.

.... [2]

(ii) State the phase difference between any two vibrating particles in a stationary wave between two adjacent nodes.

phase difference = ...° [1]

(b) A motorcycle is travelling at 13.0 m/s along a straight road. The rider of the motorcycle sees a pedestrian standing in the road directly ahead and operates a horn to emit a warning sound.

The pedestrian hears the warning sound from the horn at a frequency of 543Hz. The speed of the sound in the air is 334 m/s.

(i) Calculate the frequency, to three significant figures, of the sound emitted by the horn.

frequency = ... Hz [2]

(ii) The motorcycle rider passes the stationary pedestrian and then moves directly away from her. As the rider moves away, he operates the horn for a second time. The pedestrian now hears sound that is increasing in frequency.

State the variation, if any, in the speed of the motorcycle when the rider operates the horn for the second time... [1]

(c) A beam of vertically polarised monochromatic light is incident normally on a polarising filter, as shown in Fig. 5.1.

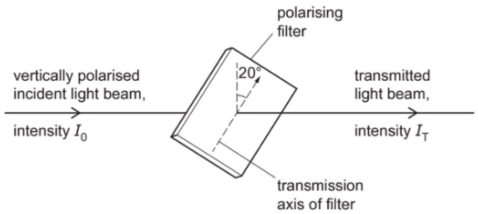

Fig. 5.1

The filter is positioned with its transmission axis at an angle of 20° to the vertical. The incident light has intensity I_0 and the transmitted light has intensity I_T.

(i) By considering the ratio $\frac{I_T}{I_0}$ calculate the ratio $\frac{\text{amplitude of transmitted light}}{\text{amplitude of incident light}}$.

Show your working. ratio = ... [3]

(ii) The filter is now rotated, about the direction of the light beam, from its starting position shown in Fig. 5.1. The direction of rotation is such that the angle of the transmission axis to the vertical initially increases.

Calculate the minimum angle through which the filter must be rotated so that the intensity of the transmitted light returns to the value that it had when the filter was at its starting position.