Module 4 Electrons, Waves & Photons

Unit 4 Waves

4.4 Waves

This section provides knowledge and understanding of wave properties, electromagnetic waves, superposition and stationary waves. The wavelength of visible light is too small to be measured directly using a ruler. However, superposition experiments can be done in the laboratory to determine wavelength of visible light using a laser and a double slit.

There are opportunities to discuss how the double-slit experiment demonstrated the wave-like behaviour of light (HSW7).

The breadth of the topic covering sound waves and the electromagnetic spectrum provides scope for learners to appreciate the wide ranging applications of waves and their properties. (HSW1, 2, 5, 8, 9, 12)
Module 2 – Foundations of physics

2.1 Physical quantities and units
2.2 Making measurements and analysing data
2.3 Nature of quantities

Module 3 – Forces and motion

3.1 Motion
3.2 Forces in action
3.3 Work, energy and power
3.4 Materials
3.5 Newton’s laws of motion and momentum

Module 4 – Electrons, waves and photons

4.1 Charge and current
4.2 Energy, power and resistance
4.3 Electrical circuits
4.4 Waves
4.5 Quantum physics
4.4 Waves

- 4.4.1 Wave Motion
- 4.4.2 Electromagnetic Waves
- 4.4.3 Superposition
- 4.4.4 Stationary Waves
4.4.1 Wave Motion

4.4.1 Wave motion

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) progressive waves; longitudinal and transverse waves

(b) (i) displacement, amplitude, wavelength, period, phase difference, frequency and speed of a wave

(ii) techniques and procedures used to use an oscilloscope to determine frequency

(c) the equation \( f = \frac{1}{T} \)

(d) the wave equation \( v = f\lambda \)

(e) graphical representations of transverse and longitudinal waves

(f) (i) reflection, refraction, polarisation and diffraction of all waves

(ii) techniques and procedures used to demonstrate wave effects using a ripple tank

(iii) techniques and procedures used to observe polarising effects using microwaves and light

(g) intensity of a progressive wave; \( I = \frac{p}{A} \); intensity \( \propto (amplitude)^2 \).
What are some of the words used to describe waves?
Progressive Waves

• An oscillation that can travel from one place to another.
  – Some need matter to travel through (sound).
  – Some can travel through a vacuum (light).

• Progressive waves transfer energy but not matter.
  – Matter particles oscillate about a fixed point.

• As the oscillating matter particles are pulled from their original equilibrium position, they experience a restoring force which pushes them back again.
Transverse Wave

Longitudinal Wave
Two types of Progressive Waves

• Transverse waves
  – Oscillations are perpendicular to the direction of energy transfer.
  – Waves have peaks & troughs.
  – Eg. Electromagnetic waves, ripples on water, S-waves from earthquakes.
Transverse Waves
Two types of Progressive Waves

• Longitudinal waves
  – Oscillations are parallel to the direction of energy transfer.
  – Waves have compressions & rarefactions.
  – Eg. Sound, P-waves from earthquakes.
Longitudinal Waves

Compression

Rarefaction

Wave length
# Wave Equations - Terminology

<table>
<thead>
<tr>
<th>Term</th>
<th>Symbol</th>
<th>Unit</th>
<th>Definition</th>
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<tbody>
<tr>
<td>displacement</td>
<td>$s$</td>
<td>m</td>
<td>distance from the equilibrium position in a particular direction; a vector, so it can have either a positive or a negative value</td>
</tr>
<tr>
<td>amplitude</td>
<td>$A$</td>
<td>m</td>
<td>maximum displacement from the equilibrium position (can be positive or negative)</td>
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<td>wavelength</td>
<td>$\lambda$</td>
<td>m</td>
<td>minimum distance between two points in phase on adjacent waves, for example, the distance from one peak to the next or from one compression to the next</td>
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<tr>
<td>period of oscillation</td>
<td>$T$</td>
<td>s</td>
<td>the time taken for one oscillation or time taken for wave to move one whole wavelength past a given point</td>
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<tr>
<td>frequency</td>
<td>$f$</td>
<td>Hz</td>
<td>the number of wavelengths passing a given point per unit time</td>
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<tr>
<td>wave speed</td>
<td>$v$ (or $c$)</td>
<td>m s$^{-1}$</td>
<td>the distance travelled by the wave per unit time</td>
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The Wave Equations

\[ v = f \lambda \]

Where:

- \( v \) = Velocity (wave speed), ms\(^{-1}\)
- \( f \) = Frequency (No of waves per second), Hz
- \( \lambda \) = Wavelength, m

\[ f = \frac{1}{T} \]

- \( f \) = Frequency (No of waves per second), Hz
- \( T \) = Period of Oscillation, s

So:

\[ v = \frac{\lambda}{T} \]
How can we represent waves visually?
Displacement – Distance Graphs

- Used to measure Amplitude and wavelength for both types of wave.
- Think about displacement of a slinky at different distances from your hand.
Phase Difference

• The difference between the displacements of two particles on a wave (or on different waves).

• Often measured in degrees (or radians).

• $360^\circ$ ($2\pi$ radians) represents one complete cycle.
Phase Differences

Phase shift = 90 degrees
A is ahead of B
(A "leads" B)

Phase shift = 90 degrees
B is ahead of A
(B "leads" A)

Phase shift = 180 degrees
A and B waveforms are mirror-images of each other

Phase shift = 0 degrees
A and B waveforms are in perfect step with each other
Displacement – Time Graphs

- Used to measure Amplitude and Period for both types of wave.
Longitudinal waves can also be represented this way.
What’s the difference between reflection, refraction & diffraction?
Reflection

- When a wave changes direction at a boundary between two different media, with the wave remaining in the original medium.
Reflection of circular waves
Refraction

- When a wave changes direction as it changes speed when it passes from one medium to another.

Refraction affects the wavelength but not frequency, so the wave speed is changed.
Diffraction

- Waves spread out as they pass through a gap or travel around an obstacle.
  - Speed, wavelength and frequency of the wave all stay constant during diffraction.

- The degree of diffraction depends on the relative size of the gap and the wavelength.
  - Diffraction is much greater when the gap is the same size as the wavelength.
Diffraction around obstacles

- The longer the wavelength, the greater the diffraction.

The obstacle is longer than the wavelength, so there is little diffraction.
Polarisation

• As transverse waves travel their oscillations occur at a variety of directions.
• Polarised waves all oscillate in the same direction.
  – This confines the waves to a single plane.
  – The plane contains the direction of oscillations and the direction of energy transfer.
  – We say the waves have been plane polarised.
• Longitudinal waves have oscillations which are already limited to one plane so cannot be polarised.
Spot the spelling mistake
Why does the intensity of light reduce with distance travelled?
Intensity

• The radiant power passing through a surface per unit area.

• Units of intensity: Watts per square metre (Wm$^{-2}$)

\[ I = \frac{P}{A} \]
Intensity v Distance

- When a wave radiates out from a source in all directions its intensity will vary with the distance travelled.

- How?
Intensity v Distance

• For a point source of light, energy radiates in all directions.

• The intensity of light at different distances is proportional to $1/r^2$ where $r$ is the distance from source to observer.

This relationship is called the inverse square law.
Intensity v Distance

- The total radiant power of the source is spread over the surface of a sphere.

\[ I = \frac{P}{A} \]

- Doubling the distance reduces the intensity by a factor of 4 \((2^2)\).
Intensity v Amplitude

- Intensity of water waves also drops as they radiate outwards.
- The height (amplitude) of the ripple decreases with distance travelled.

- Amplitude is proportional to speed of the oscillating particles. Particle speed is related to Energy by:

\[ E_K = \frac{1}{2} mv^2 \]
### 4.4.1 Wave Motion (review)

#### Learning outcomes

- **Learners should be able to demonstrate and apply their knowledge and understanding of:**

  (a) progressive waves; longitudinal and transverse waves

  (b) **(i)** displacement, amplitude, wavelength, period, phase difference, frequency and speed of a wave

  **(ii)** techniques and procedures used to use an oscilloscope to determine frequency

  (c) the equation \( f = \frac{1}{T} \)

  (d) the wave equation \( v = f \lambda \)

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4.4.2 Electromagnetic Waves

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) electromagnetic spectrum; properties of electromagnetic waves

(b) orders of magnitude of wavelengths of the principal radiations from radio waves to gamma rays

(c) plane polarised waves; polarisation of electromagnetic waves

(d) (i) refraction of light; refractive index; \( n = \frac{c}{v} \); \( n \sin \theta = \text{constant at a boundary where} \theta \text{ is the angle to the normal} \)

(ii) techniques and procedures used to investigate refraction and total internal reflection of light using ray boxes, including transparent rectangular and semi-circular blocks

(e) critical angle; \( \sin C = \frac{1}{n} \); total internal reflection for light.
What are electromagnetic waves
The Electromagnetic Spectrum

- Gamma ray
- X-ray
- Ultraviolet
- Visible
- Infrared
- Microwave
- Radio
Electromagnetic waves

• Transverse waves.
• Can travel through a vacuum.
• No particles to oscillate

• EM waves can be imagined as oscillating electric & magnetic fields at right angles to each other.
EM Spectrum

As the song goes, EM waves are classified according to their wavelengths.
Properties of EM Waves

• Can be
  – Reflected
  – Refracted
  – Diffracted
  – Plane polarised

• All EM waves travel at the same speed in a vacuum (the speed of light, c, 3.00x10^8 ms^{-1})
What is the wavelength of radio 1 broadcasts?

- Frequency: 99.1 MHz

\[ \nu = f \lambda \]
\[ c = f \lambda \]

\[ \lambda = \frac{c}{f} = \frac{3.00 \times 10^8}{9.91 \times 10^7} = 3.03m \]
Polarisation of EM Waves

• Naturally occurring EM waves are unpolarised.
  – The EM fields oscillate in random directions.

• Filters can be used to polarise the waves.
A second filter can prevent all waves.
Refractive Index

- Light is refracted by different amounts by different materials at a boundary.

- The angle of refraction depends on the change in wave speed as the light crosses a boundary.

- Each material has a property called a refractive index.

\[ n = \frac{c}{v} \]

Where:
- \( n \) = refractive index of a material
- \( c \) = speed of light in a vacuum
- \( v \) = speed of light through the material
What is the speed of light through glass?

\[ n = \frac{c}{v} \]

\[ v = \frac{c}{n} \]

\[ v = \frac{3.00 \times 10^8}{1.52} = 1.97 \times 10^8 \]
Refraction Law

• For a specific boundary, the ratio between the two refractive indices equals the ratio between the sines of the refractive angles.

\[ \frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1} \]

So,

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

And,

\[ n \sin \theta = \text{Constant, } k \]
Total Internal Reflection

• Occurs when light strikes a boundary with a large enough angle to the normal:

  – Light must be travelling through the medium with the higher refractive index.
    • Eg, from water to air not the other way round.

  – The angle at which light hits the boundary must be above a critical angle.
    • This angle depends on the refractive indices of the media.
Total Internal Reflection

\[ n_w \sin \theta_w = n_a \sin \theta_a \]

\[ n_w \sin C = n_a \sin 90 \]

\[ n_w \sin C = 1 \times 1 \]

Using this equation, we can calculate the critical angle (C) from the refractive indices:

\[ \sin C = \frac{1}{n_w} \]
Determining Refractive Index from Critical Angle

- Practical

\[ n_g \sin C = n_a \sin 90 \]

\[ n_g = \frac{1}{\sin C} \]
4.4.2 Electromagnetic Waves (review)

4.4.2 Electromagnetic waves

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) electromagnetic spectrum; properties of electromagnetic waves

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(e) critical angle; \( \sin \theta = \frac{1}{n} \); total internal reflection for light.
4.4.3 Superposition

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) (i) the principle of superposition of waves
(ii) techniques and procedures used for superposition experiments using sound, light and microwaves

(b) graphical methods to illustrate the principle of superposition

(c) interference, coherence, path difference and phase difference

(d) constructive interference and destructive interference in terms of path difference and phase difference

(e) two-source interference with sound and microwaves

(f) Young double-slit experiment using visible light

(g) (i) \[ \lambda = \frac{ax}{D} \] for all waves where \( a \ll D \)
(ii) techniques and procedures used to determine the wavelength of light using (1) a double-slit, and (2) a diffraction grating.
What happens when waves collide?
Superposition

• When 2 waves of the same type meet, they can pass through each other.

• Where they overlap they superpose, with the resultant displacement equal to the sum of the displacement of the individual waves.

• Remember that displacement is a vector quantity so the superposed wave may have a higher or lower resultant displacement than the original.
Interference

• Similar to superposition.

• A superposition of progressive waves.

• Here the waves are continuous rather than single pulses.
Constructive interference

Destructive interference
How does interference affect intensity?

• Since, intensity = (amplitude)$^2$
  – Constructive interference will increase the amplitude and so increase the intensity of the wave.
    • Light will become brighter
    • Sound will become louder
  – Destructive waves have the opposite effect.
Are all interference patterns the same?
• Look at the interference pattern between these waves.

• These superposed waves are either interfering constructively or destructively but the pattern is changing.

• Because the waves have different frequencies and varying phase differences.
What happens when two sources have the same frequency and a constant phase difference?

- Here the two waves show a stable interference pattern.

- These waves are said to be coherent – they have the same frequency and so have a constant phase difference.
Path Difference

• Waves emitted from two different but coherent sources interfere with a series of maxima and minima.
  – At the maxima they interfere constructively.
  – At the minima they interfere destructively.

• Maxima and minima are caused because even though the two waves start off in phase, they travel different distances to reach a certain point and may end up either in phase or in antiphase.

• These different distances are called path differences.
Show the maxima and minima

Crest

Trough

s₁ s₂
Maxima Minima

m = path difference in wavelengths
Interference of sound

- Set sig gen to 1kHz
- Set speakers 0.5m apart
- Plot interference pattern using masking tape on table.
Newton thought light was made of particles. Young showed light to be a wave...
Young’s Double Slit Experiment

Light / dark maxima & minima are called fringes.
Calculating wavelength of light

Figure 2: The geometry of a typical double-slit experiment

\[ a = \text{separation between the two slits} \]
\[ D = \text{Distance between slits and a distant screen, } D \gg a. \]
\[ x = \text{Distance between fringe central maxima and 1}\text{st order maxima.} \]
Calculating wavelength of light

Since:
D is much greater than a.

So:
The two shaded triangles are practically congruent.
\( \theta_1 \) and \( \theta_2 \) are practically the same and are very small.
The path difference (\( S_1 \) to P) is therefore equal to 1 whole wavelength.

\[
\sin \theta_1 = \frac{\lambda}{a} = \tan \theta_2 = \frac{x}{D} \quad \text{So} \quad \frac{\lambda}{a} = \frac{x}{D} \quad \text{So} \quad \lambda = \frac{ax}{D}
\]
Limitations of \( \lambda = \frac{ax}{D} \)

- The equation only applies when D is much greater than a.
### 4.4.3 Superposition (review)

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4.4.4 Stationary Waves

**Learning outcomes**

*Learners should be able to demonstrate and apply their knowledge and understanding of:*

(a) stationary (standing) waves using microwaves, stretched strings and air columns

(b) graphical representations of a stationary wave

(c) similarities and the differences between stationary and progressive waves

(d) nodes and antinodes

(e) (i) stationary wave patterns for a stretched string and air columns in closed and open tubes

(ii) techniques and procedures used to determine the speed of sound in air by formation of stationary waves in a resonance tube

(f) the idea that the separation between adjacent nodes (or antinodes) is equal to \( \lambda/2 \), where \( \lambda \) is the wavelength of the progressive wave

(g) fundamental mode of vibration (1st harmonic); harmonics.
What is a stationary wave?
Stationary waves

- Stationary waves (or standing waves) are not single waves at all.

- They are superposed progressive waves which have the same frequency travelling in opposite directions.
Forming stationary waves

Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.
• The simplest stationary wave pattern as shown here, consists of a point of no displacement at both ends, called nodes and a point of maximum amplitude midway between the adjacent nodes, called anti nodes.
• This is called the first harmonic on a string.
• *Distance between adjacent nodes* = ½λ
• If the frequency of the waves along the ropes from either end is raised steadily, the pattern from the previous diagram disappears and a new pattern is observed with two equal loops along the rope.

• Frequency is double that of the first figure, but now half the wavelength.

• This is because the distance from one node to another is = half a wavelength.

• Length of the rope is equal to one full wavelength.
What’s actually happening?

- The red wave is reflected off the fixed end to become the blue wave.
- The green wave is the resultant (what we see).

Figure 4: A stationary wave (in green) is the resultant of two progressive waves travelling in opposite directions (red to the right, blue to the left).
Comparing stationary waves & progressive waves

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<tr>
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<th>Progressive wave</th>
<th>Stationary wave</th>
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<td>energy transfer</td>
<td>energy transferred in the direction of the wave</td>
<td>no net energy transfer</td>
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<td>wavelength</td>
<td>minimum distance between two adjacent points oscillating in phase, for example, the distance between two peaks or two compressions</td>
<td>twice the distance between adjacent nodes (or antinodes) is equal to the wavelength of the progressive waves that created the stationary wave</td>
</tr>
<tr>
<td>phase differences</td>
<td>the phase changes across one complete cycle of the wave</td>
<td>all parts of the wave between a pair of nodes are in phase, and on different sides of a node they are in antiphase</td>
</tr>
<tr>
<td>amplitude</td>
<td>all parts of the wave have the same amplitude (assuming no energy is lost to the surroundings)</td>
<td>maximum amplitude occurs at the antinode then drops to zero at the node</td>
</tr>
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</table>
What are harmonics? I thought this was to do with music?
Harmonics

• If a string is stretched between 2 points the points act as nodes.
• When the string is plucked a wave travels along the string and reflects off the end, creating two waves travelling in opposite directions.
• The wave vibrates in its fundamental mode and at the fundamental frequency, $f_0$.

Wavelength is double the length of the string.
Higher harmonics

- Since $v = f \lambda$, as frequency increases wavelength will decrease.
- Shorter wavelengths will also fit exactly between the nodes.
- These are the harmonics where the frequency is an integer multiple of the fundamental frequency.
How do Stationary waves behave in open & closed tubes?
Ever played the pan pipes?

- These pipes are closed at one end.
- Blowing across the top creates a stationary longitudinal wave inside which reflects off the bottom.
- The length of the pipe determines the wavelength of the wave.
Representing sound waves

- Sound waves are longitudinal waves
  - But they can still be represented graphically.
Stationary sound waves

- Stationary waves can be represented as:

![Stationary sound waves diagram]
Harmonics in closed tube sound waves

- For a stationary wave to form in a closed tube there must be a node at the closed end and an antinode at the open end.
- The wavelength is then determined by the length of the tube.
- Frequencies are always odd multiples of the fundamental frequency ($3f_0$, $5f_0$, etc)

![Diagram of harmonics in a closed tube](image)
Harmonics in open tube sound waves

• With open tubes, a standing wave must have an antinode at both ends.
• Harmonics are possible at all integer multiples of the fundamental wavelength.
Practical

• Calculating the speed of sound in air using a resonance tube

Holding a tuning fork above a tube closed at one end can form a stationary wave inside the tube. The air vibrates at the same frequency as the tuning fork. If the frequency of the tuning fork is at the fundamental frequency for the air column, the sound becomes loud as the air inside the tube resonates.

In the apparatus in Figure 4 the length of the tube can be changed by raising and lowering it in the water. When the frequency of the tuning fork matches $f_0$, the length of the tube above water $L$ must be equal to $\frac{1}{4} \lambda$ (see Figure 3). The speed of sound in air can be calculated using $v = f\lambda = f \times 4L$, where $f$ is the frequency of the tuning fork.

\[ \text{Figure 4} \quad \text{The top end of the tube is open. The level of water determines the position of the closed end of this tube.} \]
### 4.4.4 Stationary Waves (review)

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Complete!