3.3 Waves

3.3.1 Progressive and Stationary Waves

3.3.1.1 Progressive Waves

Content

- Oscillation of the particles of the medium;
  - amplitude, frequency, wavelength, speed, phase, phase difference, \( c=\lambda f \),\[ f=1/T. \]
- Phase difference may be measured as angles (radians and degrees) or as fractions of a cycle.

Opportunities for Skills Development

- Laboratory experiment to determine the speed of sound in free air using direct timing or standing waves with a graphical analysis.

Oscillation of particles in a medium with characteristics

Definitions;

A progressive wave is a wave that transfers energy from one point to another...

Without transferring material / (causing permanent displacement of the medium)

- **Amplitude**: Maximum displacement of a wave from its equilibrium position, measured in metres, m.
- **Frequency**: The number of waves passing a given point each second, measured in Hertz, Hz.
- **Wavelength**: The length of one complete cycle of a wave e.g. distance from crest to crest, or shortest distance between two particles oscillating in phase. This is also measured in metres.
- **Speed**: Speed of a wave \( c \) is equal to \( f\lambda \), measured in ms\(^{-1}\).
- **Phase**: The fraction of a wave cycle that has elapsed relative to a given origin.
- **Phase Difference**: It is the difference in the fraction of cycle that has elapsed between two waves, measured in radians, rad.
Phase Difference

Phase difference can be measured as angles in both degrees and radians, or just as fractions of a cycle.

One cycle is equal to 360° or 2π, so you can describe the relationship between two crests as either being 360°/2π out of phase, or that they are in phase as there is one wavelength difference between the two points. Furthermore, if you have a particle in equilibrium and another particle at a crest ¼ of a wavelength away, you can say it is 90° or π/2 out of phase.
3.3.1.2 **Longitudinal and Transverse Waves**

**Content**

- Nature of longitudinal and transverse waves.
- Examples to include: sound, electromagnetic waves, and waves on a string.
- Students will be expected to know the direction of displacement of particles/fields relative to the direction of energy propagation and that all electromagnetic waves travel at the same speed within a vacuum.
- Polarisation as evidence for the nature of transverse waves.
- Applications of polarisers to include Polaroid material and the alignment of aerials for transmission and reception.
- Malus’s Law will not be expected.

**Opportunities for Skills Development**

- Students can investigate the factors that determine the speed of a water wave.

**Longitudinal and Transverse Waves**

**Longitudinal Waves:** The energy transfer in the wave travels parallel to the direction of propagation of the wave.

**Transverse Wave:** Energy transfer occurs perpendicular to direction of propagation of the wave.

**Examples of Longitudinal and Transverse Waves**

Examples of Transverse Waves; Electromagnetic Waves*, Waves on a string.
Examples of Longitudinal Waves; Sound Waves, Seismic Waves.

* All Electromagnetic Waves travel at the same speed in a vacuum (Light, UV, Gamma etc.)

**Polarisation**

Polarisation is a phenomenon exclusive to transverse waves. Polarisation is evidence of transverse nature as transverse waves can oscillate in any plane, and polarisation is the process in which the waves are made to oscillate in one plane only. This can be demonstrated in the diagram below.

This is basically done by passing the waves through a grid so that only waves in the correct plane can pass through.
Applications of Polarisation

It is used in polaroid glasses, where it attempts to reduce the amount of light reaching the eye by polarising the light. Also it can be taken into account when transmitting and receiving waves, an aerial has to be aligned to the plane of the polarised waves for it to receive maximum signal.
Question:

2 Progressive waves are generated on a rope by vibrating vertically the end, P, in simple harmonic motion of amplitude 90 mm, as shown in Figure 1. The wavelength of the waves is 1.2 m and they travel along the rope at a speed of 3.6 m s$^{-1}$. Assume that the wave motion is not damped.

Figure 1

(a) Point Q is 0.4 m along the rope from P. Describe the motion of Q in as much detail as you can and state how it differs from the motion of P. Where possible, give quantitative values in your answer.

You may be awarded additional marks to those shown in brackets for the quality of written communication in your answer.

Answer:

<table>
<thead>
<tr>
<th>Question 2</th>
<th>Q2 Jun 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>vibrates or oscillates or moves in shm ✓ vibration/oscillation is vertical/perpendicular to wave propagation direction ✓</td>
</tr>
<tr>
<td></td>
<td>frequency ($=\frac{c}{\lambda}$) = 3.0 (Hz) ✓ (or same as P)</td>
</tr>
<tr>
<td></td>
<td>amplitude = 90 (mm) ✓ (or same as P)</td>
</tr>
<tr>
<td></td>
<td>Q has a phase lag on P ✓ (or vice versa)</td>
</tr>
<tr>
<td></td>
<td>phase difference of $\left(\frac{0.4}{1.2} \times 2\pi\right) = \frac{2\pi}{3}$ (rad) or 120° ✓</td>
</tr>
</tbody>
</table>
3.3.1.3. Principles of Superposition of Waves and Formation of Stationary Waves

Content

- Stationary waves
- Nodes and antinodes on a string
  \[ f = \frac{1}{2\pi} \sqrt{\frac{T}{\mu}} \] for first harmonic.
- The formation of stationary waves by two waves of the same frequency travelling in opposite directions.
- A graphical explanation of formation of stationary waves will be expected.
- Stationary waves formed on a string and those produced with microwaves and sound waves should be considered.
- Stationary waves on strings will be described in terms of harmonics. The terms fundamental (for first harmonic) and overtone will **not** be used.

Opportunities for Skills Development

- Students can investigate the factors that determine the frequency of stationary wave patterns of a stretched string.

Stationary Waves

Stationary waves are combination of two progressive waves moving in opposite directions, each having the same amplitude, frequency and wavelength. In a stationary wave the oscillations occur in a vertical plane, as opposed to particles moving left/right, so the particles oscillate between fixed points, called nodes. There is also no energy transfer, whereas in progressive waves you will get energy transferred from the source outwards. Only certain frequencies will cause the formation of a stationary wave, a given frequency will cause the first harmonic (1/2 wavelength), then if the string is bound by fixed points double this frequency will give the 2\(^{nd}\) harmonic (1 wavelength) and so on.

The phenomenon is caused as a result of interference, both constructive and destructive.

This is constructive interference, where two waves in phase will add up to form a wave of double the amplitude. The point of maximum displacement from this interference is called an antinode on a stationary wave.

When waves arrive out of phase (antiphase) they cancel each other out, causing destructive interference. This is basically a point of no displacement, called a node on a stationary wave, the nodes have fixed positions on the wave.
This figure shows a stationary wave, where constructive and destructive interference of two waves travelling with equal amplitude, frequency and wavelength in opposite directions, have superposed to form a stationary wave. This stationary wave has characteristic points of no displacement, and maximum displacement (nodes, and antinodes). These are formed as a result of the interference. The stationary wave is clearly bound by two fixed points, which causes the reflection of the wave, and thus the formation of the stationary wave.

$$f = \frac{1}{2L} \sqrt{\frac{T}{\mu}}$$ If we are asked to find the frequency, of a stationary wave we can use the equation given to the left, where $f = \text{frequency}$, $L = \text{length of the string}$, $T = \text{tension}$, and $\mu = \text{mass per unit length}$. This equation can be used for the first harmonic. This means that if, like in the picture above, there is a third harmonic, the length would be equal to $1/3$ of the total length, or half of the wavelength.

You may be asked to look at stationary waves on a string, stationary waves formed by microwaves, or sound waves. They are formed in the same way, and thus have the same characteristics.

The terms ‘fundamental’ which is used instead of first harmonic will not be used, and neither will overtone.

The videos below give a good explanation of stationary waves:

https://www.youtube.com/watch?v=MVFGQ8QZAJE&list=PLIDtvjFYT9NxoJ70Ns7Htg9UUm2gUPRP
AQA June 2011 Q7e

Question:

Explain how the wave theory of light accounts for the areas on the screen where the intensity is a minimum

Answer:

• Cancellation/waves cancel/destructive interference/destructive superposition
• (light from one slit meets light from the other) in antiphase (180 out of phase) or a path difference of \((n+1/2\lambda)\)

AQA Jan 2011 Unit 2 Q4

Figure 4 shows a stationary wave on a string. The string is tied onto a thin metal bar at A and fixed at B. A vibration generator causes the bar to oscillate at a chosen frequency.

![Figure 4](image)

Question:

Explain how a stationary wave is formed. Then describe the key features of the stationary wave shown in Figure 4.

The quality of your written answer will be assessed in this question.

Answer:

• 4 nodes where there is no movement/zero amplitude
• 3 antinodes where amplitude is maximum
• Wavelength 0.80 m
• End antinodes in phase/middle and ends in antiphase
• Between node and antinode, amplitude of oscillation increases
• Waves reflect off the clamp (and the rod)
• Waves travelling in opposite directions superpose/add/interfere
• Wave have same wavelength and frequency (similar amplitude)
• Always cancellation at nodes/always constructive superposition at antinodes
• Energy is not transferred along string
3.3.2 Refraction, Diffraction and Interference

3.3.2.1 Interference

Content

- Path difference. Coherence.
- Interference and diffraction using a laser as a source of monochromatic light.
- Young’s double-slit experiment: the use of two coherent sources or the use of a single source with double slits to produce an interference pattern.
- Fringe spacing, \( w = \frac{\lambda D}{s} \).
- Production of interference pattern using white light.
- Students are expected to show awareness of safety issues associated with using lasers.
- Students will not be required to explain how a laser works.
- Students will be expected to describe and explain interference produced with sound and electromagnetic waves.
- Appreciation that knowledge and understanding of nature of electromagnetic radiation has changed over time.

Opportunities for Skills Development

- Investigation of two-source interference with sound, light and microwave radiation

Path Difference and Coherence

Say two stones have been thrown into a pond nearby, and their paths have followed the ones that are shown on the diagram. If you took their first point of disturbance and marked the points \( s_1 \) and \( s_2 \), it’s clear that the waves from \( s_1 \) have arrived one full cycle earlier than \( s_2 \). Therefore, their path difference would be one wavelength. Path difference can be defined as the difference in path traversed by two waves, measured in terms of their wavelengths. Coherence of waves is when the phase difference/relationship of the two waves is constant, and their frequency is the same.
Interference and diffraction using a laser as a source of monochromatic light.

Monochromatic light is light that is of the same wavelength, for example light merely composed of one colour. Interference is a phenomenon whereby two waves will superpose to produce a resultant wave, either interfering constructively or destructively. Diffraction is where a wave will spread out after passing through a gap, the amount of diffraction depends on the size of the gap relative to the wavelength.

Lasers are highly monochromatic and almost perfectly parallel, so convex lenses can be used to focus the lasers onto a very fine spot. The beam power is then concentrated in a very small area.

Laser are also a very convenient source of coherent light, and so when using a laser to show double slit interference, you can just illuminate the double slits directly. So you don’t need to make the light pass through a single slit first as with non-laser light. Inside a laser, each emitted photon causes more photons to be emitted as it passes through the light-emitting substance. This means that photons are always in phase with each other, but in non-laser light sources the atoms emit photons at random, so there are random phase differences.

Young’s double-slit experiment: the use of two coherent sources or the use of a single source with double slits to produce an interference pattern.

For the double slit experiment, you can either use two coherent sources, or a single source with double slits as these both produce interference patterns. The interference pattern for a double slit diffraction can be seen below, the maxima have equal distances between them, and the same intensity. Sometimes the pattern can be illustrated as equally spaced maxima that progressively decrease in intensity. The fringe separation is equal to $w$.

![Double Slit](image)

The use of a single source with double slits can be seen below. The single slits diffract the wave so that it travels an equal distance to get to the next double slits, thus ensuring a constant phase difference. Thus when the two waves overlap after passing the double slits, they will overlap and interfere to produce the bright and dark fringes.
The other method is just simply to use two coherent sources that will interfere and produce a pattern. Coherence being where there is a constant phase difference and the same frequency.

**Fringe spacing, \( w = \lambda D/s \).**

Fringe spacing is equal to the wavelength (\( \lambda \)), multiplied by the distance to the screen (D), all divided by the separation of the sources (s). The derivation of this equation is shown below.

**Production of interference pattern using white light.**

White light contains visible light wavelengths from across the whole visible light spectrum, from the highest wavelengths of the reds, to the lower wavelengths of blue/violet. Therefore, its interference pattern is composed of a variety of different wavelengths that each have different points of maxima. The interference pattern contains a central fringe of white light, thus a mixture of all colours as they all form a maximum at \( n=0 \). Then because the different wavelengths will be diffracted by different amounts, as the distance d between the slits is a constant, then some will travel a further distance away from the central maximum. This happens to be red, which has the longest wavelength and so will diffract the most so will be further away from the central maximum than say blue, whose wavelength is at the lower end of the visible light spectrum.
The picture below shows if you were to look at the actual colours produced on a screen from the interference of white light vs monochromatic light. Clearly they both have a central maximum of a single colour, and they both lose intensity as you move from the central maximum. However the white light clearly shows a dispersion of different colours, whereas the monochromatic light is obviously only one colour.

Students are expected to show awareness of safety issues associated with using lasers.

Lasers are particularly dangerous if aimed at the eyes, as they can damage the retina. Lasers send out such concentrated beams of light that they can damage the retina. The retina is vital in converting focused images into neural messages to the brain for visual recognition, therefore is damaged can be cause blindness. Thus laser beams should always be directed away from the eye.

Students will not be required to explain how a laser works.

Students will be expected to describe and explain interference produced with sound and electromagnetic waves.

Appreciation that knowledge and understanding of nature of electromagnetic radiation has changed over time.

Newton told us that visible light (electromagnetic radiation) was a stream of microscopic particles called corpuscles. However, these corpuscles could not explain interference or diffraction effects, thus the view of light as a wave was adopted. Then, Einstein discovered that in fact light did behave as a particle, and came in little packets of energy called photons. And so now we understand that light has a wave-particle duality.

If you are interested in reading more on this topic, then visit http://scienceblogs.com/builtinfacts/2010/03/31/a-brief-history-of-light/
Figure 9 shows a laser emitting blue light directed at a single slit, where the slit width is greater than the wavelength of the light. The intensity graph for the diffracted blue light is shown.

The laser is replaced by a laser emitting red light.

On the axes shown in Figure 9, sketch the intensity graph for a laser emitting red light.

- Red light will have a wider base as it diffracts more (longer wavelength)
‘State and explain one precaution that should be taken when using laser light.’

One from

- Don’t shine towards a person
- Avoid (accidental) reflections
- Wear laser safety goggles
- ‘laser on’ warning light outside room
- Stand behind laser
- Other sensible suggestion

Then one for

- Eye / skin damage could occur

‘The red laser light is replaced by a non-laser source emitting white light.

Describe how the appearance of the pattern would change.’

- Central white (fringe)
- Each/every/all subsidiary maxima are composed of a spectrum (clearly stated or implied)
- Each/every/all subsidiary maxima are composed of a spectrum (clearly stated or implied) and (subsidiary maxima) have violet (allow blue) nearest central maximum or red furthest from centre
- Fringe spacing less / maxima are wider / dark fringes are smaller (or not present)
AQA Jan 2011 Unit 2 Q3cde

**Question:**
Describe how the pattern would change if light of a longer wavelength was used (the diagram above shows the answer to the first question, ie the original pattern)

**Answer:**
Maxima further apart/central maximum wider/subsidiary maximum wider/maxima are wider

**Question:**
State two ways in which the appearance of the fringes would change if the slit was made narrower.

**Answer:**
- Lower intensity
- Wider separation

**Question:**
The laser is replaced with a lamp that produces a narrow beam of white light. Sketch and label the appearance of the fringes as you could see them on a screen.

**Answer:**
A small loudspeaker emitting sound of constant frequency is positioned a short distance above a long glass tube containing water. When water is allowed to run slowly out of the tube, the intensity of the sound heard increases whenever the length $l$ (shown in Figure 1) takes certain values.

(a) Explain these observations by reference to the physical principles involved.

You may be awarded marks for the quality of written communication in your answer.

Answer:

<table>
<thead>
<tr>
<th>Question 1</th>
<th>Q1 Jun 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td></td>
</tr>
<tr>
<td>reference to resonance ✓</td>
<td></td>
</tr>
<tr>
<td>air set into vibration at frequency of loudspeaker ✓</td>
<td></td>
</tr>
<tr>
<td>resonance when driving frequency = natural frequency of air column ✓</td>
<td></td>
</tr>
<tr>
<td>more than one mode of vibration ✓</td>
<td></td>
</tr>
<tr>
<td>stationary wave (in air column) ✓ (or reference to nodes and antinodes)</td>
<td></td>
</tr>
<tr>
<td>maximum amplitude vibration (or max energy transfer) at resonance ✓</td>
<td></td>
</tr>
</tbody>
</table>

[alternative answer to (a):
first two marks as above, remaining four marks for wave reflected from surface (of water) ✓
interference/superposition (between transmitted and reflected waves) ✓
maximum intensity when path difference is $n\lambda$ ✓
maxima (or minima) observed when $l$ changes by $\lambda/2$ ✓]

Max 4
With the loudspeaker emitting sound of frequency 480Hz, the effect described in part (a) is noticed first when \( l = 168 \text{mm} \). It next occurs when \( l = 523 \text{mm} \).

Use both values of \( l \) to calculate

**Question:**

The wavelength of the sound waves in the air column

**Answer:**

\[ \frac{\lambda}{2} = 523 - 168 = 355 \text{mm}. \text{ So } 355 \times 2 = 710 \text{mm} \]

**Question:**

The speed of the sound waves

**Answer:**

\[ c = f \lambda \text{ so } c = 480 \times 710 \times 10^{-3} = 340 \text{ m/s} \]
3.3.2.2 Diffraction

Content

- Appearance of the diffraction pattern from a single slit using monochromatic and white light.
- Qualitative treatment of the variation of the width of the central diffraction maximum with wavelength and slit width. The graph of intensity against angular separation is not required.
- Plane transmission diffraction grating at normal incidence.
- Derivation of $d \sin \theta = n \lambda$.
- Use of the spectrometer will not be tested.
- Applications of diffraction gratings.

Appearance of the diffraction pattern from a single slit using monochromatic and white light.

Diffraction through a Single Slit; This produces the interference pattern shown below. You get bright fringes followed by dark fringes. These are produced by constructive and destructive interference respectively, constructive interference where the waves arrive in phase, and destructive in antiphase. In other words, the constructive interference forms when there is a path difference of an integer, and destructive the opposite, i.e. 1 and 1.5. There is also a characteristic wider base with single slit diffraction, where the central maxima are double the width of the other maxima, and by far the brightest.
Qualitative treatment of the variation of the width of the central diffraction maximum with wavelength and slit width. The graph of intensity against angular separation is not required.

The greater the wavelength, the wider the fringes. Also, making the slit narrow makes the fringes wider.

**Plane transmission diffraction grating at normal incidence.**

**Diffraction Grating:** A series of narrow, parallel slits for example 500 slits per mm. When light shines on the grating, you get a series of bright lines. You get orders of maximum where \( m=0, m=1 \) etc. These are essentially the placing of the bright fringes, where the diffracted waves are constructively interfering. There is no path difference on the zero order maximum \( (m=0) \), as the waves arrive in phase and interfere constructively, with no path difference. The second order maximum \( (m=2) \) has a path difference of 1. This means that one wave has travelled one full cycle further than the other, however they are both in phase as they are the same proportion of a cycle in. Thus they interfere constructively again, to produce a bright fringe. This process is exactly the same for every maximum, however where there is no light present destructive interference of the waves is present. So between the maxima you get destructive interference, where the waves arrive with a path difference that is not an integer number of wavelengths. The waves therefore arrive out of phase, interfering destructively to produce a point of no light.

Diffraction gratings can be useful to separate out different colours, like in a hydrogen spectrum. The hydrogen gas in a thin tube is excited by an electrical discharge, releasing photons of light with different wavelengths. Thus you can use the diffraction grating to separate out these different wavelengths, and colours as you can see in the diagram above. Red light and blue light will diffract by different amounts as they have their own characteristic frequencies. This will give maxima at different points, allowing you to see the emission spectrum.

The above diagram shows a diffraction grating at normal incidence. The angle of diffraction between each transmitted beam and the central beam can be increased by using light of longer wavelength ie red instead of green, or a grating with closer slits.
Derivation of \( dsin\theta=n\lambda \)

The equation related to diffraction gratings is \( dsin\theta=n\lambda \), the derivation of this is shown below.

The number of slits per metre on the grating, \( N = 1/d \), where \( d \) is the grating spacing. Also, for a given order and wavelength, the smaller value of \( d \), the greater angle of diffraction. This can also be looked at as the larger number of slits per metre, the bigger the angle of diffraction.

Moreover, to find the maximum number of orders produced, substitute \( \theta = 90 \) into the equation, ie \( sin\theta = 1 \), then calculate \( n \) using \( n = d/\lambda \). The max number will be given by the resulting value of \( d/\lambda \) rounded down to the nearest whole number.

Use of the spectrometer will not be tested.
Applications of diffraction gratings.

A diffraction grating is used when attempting to separate light of different wavelengths with high resolution, for example it can be used in measuring atomic spectra, or the composition of a star.
AQA AS June 2016 7407

Question:

In a diffraction-grating experiment the maxima are produced on a screen. What causes the separation of the maxima of the diffraction pattern to decrease?

Answer:

A  using light with a longer wavelength
B  increasing the distance between the screen and grating
C  increasing the distance between the source and grating
D  using a grating with a greater slit separation

Answer is D
3.3.2.3 Refraction at a plane surface

Content

- Refractive index of a substance, \( n = \frac{c}{c_s} \)
- Students should recall that the refractive index of air is approximately 1.
- Snell’s law of refraction for a boundary \( n_1 \sin \theta_1 = n_2 \sin \theta_2 \)
- Total internal reflection
- Simple treatment of fibre optics including the function of the cladding.
- Optical fibres will be limited to step index only.
- Material and modal dispersion.
- Students are expected to understand the principles and consequences of pulse broadening and absorption.

**Refractive index of a substance, \( n = \frac{c}{c_s} \)**

Refraction occurs when light reaches a boundary between two different transparent substances. At the boundary the light will undergo a change in direction, as it will travel at different speeds within different substances depending on their refractive index. Light rays bend towards the normal when passing from air to glass, do not bend at all when passing along the normal, and bends towards the normal when passing into a denser substance. This is due to the change of speed when travelling in different substances, as when passing into a denser substance the rays will slow down, thus bend towards the normal.

When a light ray in air enters for example, glass, partial reflection will occur.

Furthermore, the **frequency** of waves does not change when refraction occurs.

**Students should recall that the refractive index of air is approximately 1.**

The refractive index of air is approximately 1 because light rays travel at approximately the speed of light in air (as opposed to full speed in a vacuum).

**Snell’s law of refraction for a boundary \( n_1 \sin \theta_1 = n_2 \sin \theta_2 \)**

Snell’s law states that \( n_1 \sin \theta_1 = n_2 \sin \theta_2 \), where \( n_1 \) is the refractive index of one substance, and \( \theta_1 \) is the angle of incidence/refraction depending on which side you take to be 1 or 2.

**Total internal reflection**

If the angle of incidence is increased to a certain value, called the critical angle, the light ray refracts along the boundary. If the angle is increased above this value, the light ray undergoes total internal reflection.

Total internal reflection requires two things to occur:

1. The incident substance has a larger refractive index than the other substance
2. The angle of incidence exceeds the critical angle
When the critical angle is reached, the angle of refraction is 90, so \( \sin 90 = 1 \) and you can rearrange \( n_1 \sin \theta_1 = n_2 \sin \theta_2 \) to get \( \sin \theta_c = \frac{n_2}{n_1} \), where \( \sin \theta_c \) is equal to the critical angle.

An example of total internal reflection is in diamonds. Diamonds sparkle when white light is shone on them because as the white light enters the diamond, it is split into the colours of the spectrum. Diamond has a very high refractive index so it separates out the colour more than other substances, also with a very low critical angle, a light ray in diamond may totally internally reflect many times before emerging. This means the colours spread out more.

**Simple treatment of fibre optics including the function of the cladding.**

Optical fibres have many uses, like in **endoscopes** which are used to see inside the body, and in communications to carry light signals.

In an optical fibre the light ray is totally internally reflected each time it reaches the fibre boundary. These fibres allow pulses of light entering at one end from a transmission signal, to the other end. Such fibres need to be highly transparent in order to reduce absorption of light as if the light was absorbed, the amplitude of the pulses would decrease progressively.

The fibres all contain a core surrounded by a layer of cladding with a lower refractive index to reduce light loss from the core. The cladding provides protection to the core to prevent scratching, which could cause loss of light. Also the cladding is of lower refractive index to ensure that TIR takes place.

TIR takes place at the core-cladding boundary, as without cladding, at a point where two fibres are in direct contact, light would cross from one fibre to the other. Thus the signals would reach the wrong target.

**Optical fibres will be limited to step index only.**

**Material and modal dispersion.**

The core needs to be very narrow in order to prevent **modal dispersion**. This is more prominent in wider cores because it means that light travelling along the axis of the core will travel a shorter distance than light undergoing total internal reflection. It causes pulse broadening as the pulses emerging are longer than they should be. On the contrary, **material dispersion** (sometimes called spectral dispersion) occurs when white light is used as opposed to monochromatic light. Different colours will travel at different speeds, ie blue travels slower than red in the fibre. This also results in pulse broadening, and so monochromatic light is used to prevent this.

**Students are expected to understand the principles and consequences of pulse broadening and absorption.**

Absorption results in a reduction of amplitude of the pulses, thus the core must be as transparent as possible. The result of pulse broadening is that different pulses could merge, resulting in a completely distorted final pulse.
‘Describe the structure of a step-index optical fibre outlining the purpose of the core and the cladding.’

- **The core is the transmission medium for EM waves to progress (by total internal reflection)**
- **Cladding provides lower refractive index** so that total internal reflection takes place
- And cladding offers protection of the boundary from scratching which could lead to light leaving the core.

‘A signal is to be transmitted along an optical fibre of length 1200 m. The signal consists of a square pulse of white light and this is transmitted along the centre of a fibre. The maximum and minimum wavelengths of the light are shown in Table 1.

Table 1

<table>
<thead>
<tr>
<th>Colour</th>
<th>Refractive index of fibre</th>
<th>Wavelength / nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>1.467</td>
<td>425</td>
</tr>
<tr>
<td>Red</td>
<td>1.459</td>
<td>660</td>
</tr>
</tbody>
</table>

Explain how the difference in refractive index results in a change in the pulse of white light by the time it leaves the fibre’

- Blue travels slower than red due to the greater refractive index
- So red reaches end before blue, leading to material pulse broadening

‘Discuss two changes that could be made to reduce the effect described in part 5.2.’

- Use of monochromatic source so speed of pulse is constant
- Use of shorter repeaters so that the pulse is reformed before significant pulse broadening has taken place.
- Use of monomode fibre to reduce multipath dispersion
**AQA June 2011 Q5e**

**Question:**

Figure 7 shows a pulse of monochromatic light (labelled X) that is transmitted a significant distance along the fibre. The shape of the pulse after travelling along the fibre is labelled Y. Explain why the pulse at Y has a lower amplitude and is longer than it is at X.

**Answer:**

- (reduced amplitude) due to absorption/energy loss (within the fibre)/attenuation/scattering (by the medium)/loss from fibre
- (pulse broadening caused by) multi-path (modal) dispersion/different rays/modes propagating at different angles/non axial rays take longer time to travel same distance along fibre as axial rays