AQA AS Refraction, Total Internal Reflection and Optical Fibres solutions

Matching solutions and teaching prompts for the class review

Specification points covered

• 3.3.2.3(a) Refractive index $n = c/c_s$. • 3.3.2.3(b) Air has refractive index approximately 1. • 3.3.2.3(c) Refraction at a plane boundary and Snell's law. • 3.3.2.3(d) Critical angle and total internal reflection.	• 3.3.2.3(e) Optical-fibre core and cladding. • 3.3.2.3(f) Step-index optical fibres. • 3.3.2.3(g) Material and modal dispersion. • 3.3.2.3(h) Pulse broadening and absorption.

Teaching focus

Keep frequency, speed and wavelength distinct at a boundary.
Insist that attenuation and dispersion are diagnosed from different observations.

1. Entering the fibre

1. A subsea data cable uses monochromatic light of vacuum wavelength 1.55 µm in a glass core of refractive index 1.50. Calculate (a) the speed of the light in the core, (b) its frequency and (c) its wavelength in the core. [3 marks]

Answer / mark points: Speed = $c/n = 3.00 \times 10^8/1.50 = 2.00 \times 10^8$ m s^{-1}. Frequency is unchanged on entering glass: $f = c/\lambda_0 = 3.00 \times 10^8/(1.55 \times 10^{-6}) = 1.94 \times 10^{14}$ Hz. Wavelength in the core = $v/f = 1.03 \times 10^{-6}$ m = 1.03 µm.

Teacher prompt / common error: Frequency stays the same at a boundary; speed and wavelength change.

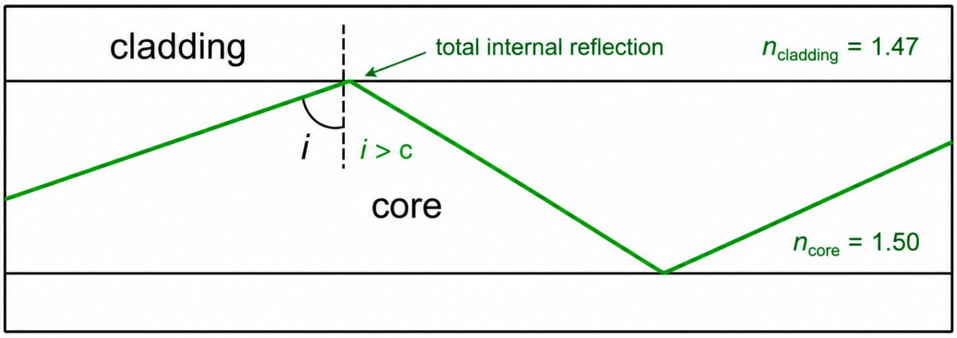
2. A test ray enters the glass core from air at an angle of incidence of 35.0°. Calculate the angle of refraction in the core. [2 marks]

Answer / mark points: Using $n_1 \sin\theta_1 = n_2 \sin\theta_2$ with $n_{air} = 1.00$: $\sin r = \sin 35.0°/1.50$, so $r = 22.5°$.

Teacher prompt / common error: Angles in Snell's law are measured from the normal, not the surface.

2. Confining the ray

3. The figure shows a ray in the step-index fibre. State both conditions needed for total internal reflection at the core–cladding boundary and explain why the refractive index of the core must be greater than that of the cladding. **[3 marks]**



Answer / mark points: The ray must travel from the higher-index core towards the lower-index cladding, and its angle of incidence to the normal must be greater than the critical angle. A lower cladding index makes a critical angle possible and keeps the ray confined to the core by total internal reflection.	
Teacher prompt / common error: Both the direction of travel and i > c are required.	

4. The refractive indices of the core and cladding are 1.50 and 1.47 respectively. Calculate the critical angle at their boundary. **[2 marks]**

Answer / mark points: sin c = $n_{cladding}/n_{core}$ = 1.47/1.50 = 0.980, so c = 78.5°.	
Teacher prompt / common error: Use the cladding index over the core index so that sin c is below one.	

5. Hence determine the greatest angle that a ray inside the core can make with the fibre axis and still undergo total internal reflection. **[2 marks]**

Answer / mark points: The angle to the fibre axis is complementary to the incidence angle. The limiting value is 90.0° - 78.5° = 11.5°. For total internal reflection the actual angle must be less than this limiting value.	
Teacher prompt / common error: The ray angle to the axis is not the incidence angle; they are complementary.	

3. Sending a data pulse

6. The repaired section is 80.0 km long. Calculate the travel time of a light pulse through it. Assume the light travels along the fibre axis and the core refractive index is 1.50. [2 marks]

Answer / mark points: t = distance/speed = nL/c = (1.50 × 80.0 × 10^3)/(3.00 × 10^8) = 4.00 × 10^{-4} s = 0.400 ms.
Teacher prompt / common error: Convert kilometres to metres and use the speed in the medium.

7. An input pulse has duration 3.0 ns and the received pulse has duration 8.0 ns. State what is meant by pulse broadening and explain why it limits the maximum data rate. [3 marks]

Answer / mark points: Pulse broadening is the increase in pulse duration, here from 3.0 ns to 8.0 ns. Wider neighbouring pulses can overlap at the receiver, making binary pulses harder to distinguish. A longer time separation is then required, so the maximum bit rate is lower.
Teacher prompt / common error: Do not describe a lower amplitude as pulse broadening.

8. Explain how modal dispersion causes pulse broadening in a step-index fibre and why reducing the difference between the core and cladding refractive indices reduces this effect. [3 marks]

Answer / mark points: Different ray paths or modes travel different distances through the core, so they arrive at different times. A smaller index difference reduces the range of accepted ray directions or path lengths, reducing the spread of arrival times.
Teacher prompt / common error: Modal dispersion is a spread of path lengths or arrival times, not absorption.

4. Diagnosing signal quality

9. Explain how material dispersion broadens a pulse. State one change to the source that reduces material dispersion. [3 marks]

Answer / mark points: A real pulse contains a range of wavelengths. The refractive index, and therefore the wave speed, depends on wavelength, so different wavelength components arrive at different times. Use a source with a narrower wavelength range, such as a suitable laser.

Teacher prompt / common error: Material dispersion needs a range of wavelengths and wavelength-dependent speed.

10. The optical power falls as the pulse travels along the cable. Explain what is meant by absorption and why an amplifier or repeater may be needed on a long link. [2 marks]

Answer / mark points: Absorption transfers optical energy to the fibre material, reducing pulse power or amplitude. A long link may attenuate the signal below the receiver threshold, so a repeater or optical amplifier restores a usable signal.

Teacher prompt / common error: Energy is transferred from the optical signal; it is not destroyed.

11. Three replacement fibres are tested over 80.0 km. Fibre A: attenuation 0.20 dB km^{-1}, modal broadening 0.050 ns km^{-1}. Fibre B: 0.28 dB km^{-1}, 0.015 ns km^{-1}. Fibre C: 0.16 dB km^{-1}, 0.090 ns km^{-1}. The link requires total attenuation no greater than 20 dB and modal broadening no greater than 5.0 ns. Calculate both totals for each fibre and select the only suitable fibre. [4 marks]

Answer / mark points: A: attenuation = 0.20 × 80.0 = 16 dB; broadening = 0.050 × 80.0 = 4.0 ns. B: 22.4 dB and 1.2 ns. C: 12.8 dB and 7.2 ns. Only A meets both limits, so select fibre A.

Teacher prompt / common error: Test both engineering limits. The lowest attenuation alone is not enough.

5. Commissioning the link

12. A refractometer sends light from glass of refractive index 1.52 into a liquid. The angle of incidence in the glass is 50.0° and the angle of refraction in the liquid is 68.0°. Calculate the refractive index of the liquid. [3 marks]

Answer / mark points: At the boundary, 1.52 sin 50.0° = n_{liquid} sin 68.0°. Therefore n_{liquid} = 1.52 sin 50.0°/sin 68.0° = 1.26.

Teacher prompt / common error: Keep the incident and refracted media in the correct order.

13. After installation, the received pulses are both weaker and wider than the transmitted pulses. Write a structured diagnosis of the link. Distinguish absorption from pulse broadening, identify plausible causes involving connectors, bends, modal dispersion and material dispersion, and describe measurements or changes that would test and correct the faults. [6 marks]

Answer / mark points: Award one mark for each linked point, to six: weak pulses indicate attenuation, not dispersion; excess connector loss, contamination, absorption or a tight bend can reduce received power; compare transmitted and received power or loss per kilometre and inspect sections/connectors; wide pulses indicate dispersion; multiple ray paths cause modal dispersion and a wavelength spread causes material dispersion; compare pulse width or arrival-time spread, use a narrower-spectrum source and a fibre with reduced modal dispersion, then retest. Credit a coherent alternative diagnostic sequence.

Teacher prompt / common error: Use separate evidence and tests for attenuation and dispersion before recommending a repair.

Language and method check

Award independent, creditworthy physics steps; do not award extra marks for repeated statements.
Accept equivalent methods when the physical reasoning, units and final precision remain consistent.