3.3 Waves

AQA 7408 · Calculator allowed · about 225 minutes · Write-in edition

Total Marks

Name: _____ Date: ____ / ____ / _____

Answer ALL questions. Show all your working.

1 An optical fibre used in telecommunications has a core of refractive index 1.52, surrounded by cladding of refractive index 1.45. Use the Physics Equations Sheet.

(a) Calculate the critical angle for light travelling from the core towards the cladding, using $\sin(\theta_c) = n2/n1$. **(3)**

(b) The speed of light in a vacuum is $c = 3.00 \times 10^8$ m/s. Use $n = c/v$ to calculate the speed of light in the fibre core. **(2)**

(c) State the condition on the angle of incidence, at the core-cladding boundary, required for total internal reflection (and hence for the fibre to guide light along its length). **(2)**

(d) State one further condition, in terms of the refractive indices of the core and cladding, that must be satisfied for total internal reflection to be possible at all at this boundary. **(1)**

(e) Optical fibres used for long-distance telecommunications suffer from signal degradation. Discuss the physical causes of this degradation and explain how the design of the fibre and the transmitted signal can be adapted to reduce its effects. **(6)**

(Total for Question 1 is 14 marks)

2 Required practical: a student sets up a stretched string of length 0.80 m between a vibration generator and a pulley, with a mass hung over the pulley to provide tension. The mass per unit length of the string is 4.0×10^{-4} kg/m. Use the Physics Equations Sheet. Take $g = 9.81$ m/s^2. Use $v = \sqrt{T/\mu}$, where T is the tension in the string and μ is the mass per unit length.

(a) A mass of 250 g is hung from the string. Calculate the tension T in the string. **(2)**

(b) Calculate the speed of the transverse wave on the string. **(3)**

(c) The string vibrates in its fundamental mode as a standing wave, with the string length of 0.80 m equal to half a wavelength. Calculate the frequency of the vibration generator needed to produce this fundamental standing wave. **(3)**

(d) The student then increases the tension in the string by hanging a heavier mass, while keeping the string length and the number of antinodes the same. Explain the effect this has on the frequency needed to maintain a standing wave pattern with the same number of antinodes. **(3)**

(e) State what is meant by a 'node' and by an 'antinode' on a stationary (standing) wave. **(2)**

(Total for Question 2 is 13 marks)

3 Required practical: a monochromatic light source of wavelength 589 nm (from a sodium lamp) shines through a pair of double slits separated by 0.40 mm, producing an interference pattern on a screen 2.50 m from the slits. Use the equation $w = (\lambda \times D)/s$, where w is the fringe spacing, D is the slit-to-screen distance and s is the slit separation.

(a) Calculate the fringe spacing, w, observed on the screen. **(3)**

(b) Show that about 14 bright fringes would be seen across a central 5.0 cm width of the screen. **(3)**

(c) State two conditions necessary for the light passing through the two slits to produce a stable, observable interference pattern. **(2)**

(d) State what is meant by the 'path difference' between two waves arriving at a point. **(1)**

(e) The sodium lamp is replaced with a red laser of longer wavelength, with the slit separation and screen distance unchanged. State and explain the effect on the fringe spacing. **(2)**

(Total for Question 3 is 11 marks)

4 A microwave transmitter emits plane-polarised microwaves towards a receiver. A metal grille, which acts as a polarising filter for microwaves, is placed between the transmitter and the receiver.

(a) State what is meant by a transverse wave being 'plane polarised'. **(1)**

(b) The grille is initially oriented so the receiver detects a maximum signal. Predict and explain what happens to the signal detected as the grille is slowly rotated through 90 degrees (about the axis along which the microwaves travel). **(3)**

(c) State one everyday application of polarising filters, and briefly explain how polarisation is used in this application. **(2)**

(d) Sound waves cannot be polarised. Use this fact to justify that sound waves must be longitudinal rather than transverse. **(2)**

(Total for Question 4 is 8 marks)

5 Two loudspeakers, A and B, are connected to the same signal generator so that they emit coherent sound waves of wavelength 0.680 m. A listener walks along a line parallel to the speakers and detects a series of loud and quiet points.

(a) State what is meant by two sources being coherent. **(1)**

(b) At a particular point, the path difference between the sound from speaker A and from speaker B is 2.04 m. Determine whether the listener hears a loud point (constructive interference) or a quiet point (destructive interference) at this position, showing your reasoning. **(3)**

(c) Explain why this experiment would not produce a stable interference pattern if speakers A and B were instead connected to two separate, independent signal generators of the same nominal frequency. **(2)**

(d) The wavelength of the sound is changed to 0.850 m by adjusting the frequency of the signal generator, with the speed of sound remaining 340 m/s. Use $v = f \times \lambda$ to calculate the new frequency of the signal generator. **(2)**

(Total for Question 5 is 8 marks)

6 Required practical: a resonance tube, closed at one end, is used to measure the speed of sound. A tuning fork of frequency 512 Hz is held above the open end, and the air column length is increased from zero until the first resonance (loudest sound) is heard, at a length of 0.158 m. For a closed pipe at first resonance, $L = \lambda/4$.

(a) Calculate the wavelength of the sound in the tube at this first resonance. **(2)**

(b) Use $v = f \times \lambda$ to calculate the speed of sound in air found in this experiment. **(2)**

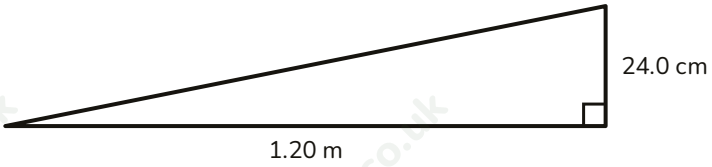
(c) A second resonance is found at a greater air column length. Using $L = (3 \times \lambda)/4$ for this second resonance, calculate the length at which it occurs. **(2)**

(d) State what is meant by 'resonance' occurring in the air column of the tube. **(1)**

(e) The student repeats the experiment several times and finds the measured speed of sound varies between 320 and 328 m/s, whereas the accepted value at room temperature is 343 m/s. Evaluate possible sources of error in this method and suggest improvements that could be made to obtain a more accurate value for the speed of sound. **(6)**

(Total for Question 6 is 13 marks)

7 Required practical: a student directs a laser beam through a diffraction grating with 300 lines per mm onto a screen 1.20 m away. The first-order maximum is observed at a distance of 24.0 cm from the central (zeroth-order) maximum on the screen. Use $d \sin(\theta) = n \times \lambda$, where d is the grating spacing.



(a) Calculate the grating spacing, d, in metres. **(2)**

(b) Using the small right-angled triangle formed by the screen distance and the position of the first-order maximum, calculate the angle θ for the first-order maximum. **(3)**

(c) Calculate the wavelength of the laser light, using $d \sin(\theta) = n \times \lambda$ with $n = 1$. **(3)**

(d) State one advantage of using a diffraction grating, rather than a double slit, to determine the wavelength of light. **(1)**

(e) The student then uses a grating with 600 lines per mm instead of 300 lines per mm, keeping the laser and the screen distance the same. Explain, without further calculation, how the position of the first-order maximum on the screen would change. **(2)**

(Total for Question 7 is 11 marks)

8 Standing waves on a string. A guitar string of length 0.65 m has mass per unit length 1.2×10^{-3} kg/m and is under a tension of 145 N.

(a) Calculate the speed of a transverse wave on the string. **(3)**

(b) The string vibrates in its fundamental mode. Calculate the fundamental frequency. **(2)**

(c) The string is then made to vibrate at its third harmonic. Calculate this frequency and state the number of antinodes present on the string. **(2)**

(Total for Question 8 is 7 marks)

9 A diffraction grating with 600 lines per mm is illuminated normally with light of wavelength 632.8 nm from a helium-neon laser.

(a) Calculate the grating spacing d in metres. **(1)**

(b) Calculate the angle at which the first-order maximum is observed. **(3)**

(c) Determine the highest order of diffraction maximum that can be observed with this grating and this wavelength, showing your reasoning. **(3)**

(Total for Question 9 is 7 marks)

10 A point source emits sound waves uniformly in all directions. At a distance of 2.0 m from the source, the intensity of the sound is 4.5×10^{-3} W/m^2.

(a) State how the intensity of sound from a point source varies with distance from the source. **(1)**

(b) Calculate the intensity of the sound at a distance of 6.0 m from the source. **(3)**

(c) Using the relationship between intensity and amplitude, calculate the ratio of the wave amplitude at 6.0 m to the amplitude at 2.0 m. **(3)**

(Total for Question 10 is 7 marks)

11 A student measures the wavelength of a laser using two independent methods. Method 1: a double-slit arrangement with slit separation $s = 2.5 \times 10^{-4}$ m and slit-to-screen distance D = 3.00 m, giving a measured fringe spacing $w = 7.60 \times 10^{-3}$ m, using $w = (\lambda \times D)/s$. Method 2: a diffraction grating with 600 lines per mm, using $d \sin(\theta) = n \times \lambda$.

(a) Calculate the wavelength obtained from the double-slit method (Method 1). **(2)**

(b) The student estimates the percentage uncertainty in the measured fringe spacing w to be 3.0%, with the percentage uncertainties in s and D negligible in comparison. Calculate the absolute uncertainty in the wavelength found in part (a). **(3)**

(c) The diffraction grating (Method 2) is then used with the same laser. Calculate the angle of the second-order (n = 2) maximum, using the wavelength found in part (a). **(3)**

(d) State one advantage of averaging fringe widths measured across ten fringe spacings, rather than measuring a single fringe spacing, when determining w. **(1)**

(e) Evaluate which of the two methods (double slit or diffraction grating) is likely to give the more precise value of the wavelength, using your understanding of the experimental measurements involved. **(3)**

(Total for Question 11 is 12 marks)

12 A wind instrument is modelled as a pipe of length 0.60 m, open at both ends. For a pipe open at both ends, stationary waves form when the pipe length is a whole number of half wavelengths: $L = n \times (\lambda/2)$, where $n = 1, 2, 3 \ldots$ The speed of sound in air depends on temperature according to $v = 331 + 0.60 \times \theta$, where θ is the temperature in degrees Celsius and v is in m/s.

(a) State what is meant by the 'fundamental frequency' of a stationary wave system such as this pipe. **(1)**

(b) Calculate the speed of sound in the pipe when the air temperature is 18°C. **(2)**

(c) Calculate the frequency of the fundamental (n = 1) note produced by the pipe at this temperature. **(3)**

(d) Calculate the frequency of the third harmonic (n = 3) at this temperature. **(2)**

(e) On a cold day the temperature drops to -5°C. Show that the fundamental frequency of the pipe changes by less than 5%, compared with its value at 18°C, assuming the pipe length does not change. **(4)**

(Total for Question 12 is 12 marks)

13 Interference and diffraction experiments, such as Young's double-slit experiment and diffraction through a grating, provide strong evidence for the wave nature of light. However, the photoelectric effect, in which electrons are only emitted from a metal surface above a threshold frequency of incident light regardless of its intensity, cannot be explained by a purely wave-based model and instead supports a photon (particle) model of light. Evaluate how evidence from wave phenomena and evidence from the photoelectric effect together support the modern view that light exhibits wave-particle duality, referring to specific features of each type of evidence in your answer.

(Total for Question 13 is 6 marks)

14 Young's double-slit experiment. A laser illuminates two slits of separation 0.45 mm. The resulting fringe pattern is observed on a screen 1.85 m from the slits. The fringe spacing is measured as 2.28 mm.

(a) Calculate the wavelength of the laser light, giving your answer in nm to 3 significant figures. **(4)**

(b) The fringe spacing was measured to ± 0.05 mm, the slit separation to ± 0.01 mm and the slit-to-screen distance to ± 0.02 m. Calculate the percentage uncertainty in the calculated wavelength. **(3)**

(c) Use your answers to (a) and (b) to state the wavelength with its absolute uncertainty, to an appropriate number of significant figures. **(2)**

(Total for Question 14 is 9 marks)

15 Unpolarised light of intensity 840 W/m^2 is incident on a polarising filter, then on a second polarising filter whose transmission axis is at 35 degrees to the first.

(a) Calculate the intensity of light transmitted through both filters. **(4)**

(b) Calculate the angle between the transmission axes of the two filters that would be needed to reduce the intensity after the second filter to 10% of the intensity leaving the first filter. **(3)**

(Total for Question 15 is 7 marks)

16 REQUIRED PRACTICAL. A student determines the speed of sound in air using a signal generator, a loudspeaker and two microphones connected to a double-beam oscilloscope. The loudspeaker is driven at a fixed frequency of 2500 Hz. One microphone is fixed; the second is moved directly away from the loudspeaker along the line joining them until the two oscilloscope traces are back in phase for the eighth time. The total distance moved by the second microphone is measured as 1.056 m.

(a) Explain why the student measures the total distance moved for eight complete cycles back into phase, rather than measuring the distance for just one wavelength. **(2)**

(b) Calculate the wavelength of the sound wave. **(2)**

(c) Calculate the speed of sound in air from this result. **(2)**

(d) The ruler used to measure the 1.056 m distance has an uncertainty of ± 1 mm, and the frequency of the signal generator has a negligible uncertainty. Calculate the percentage uncertainty and hence the absolute uncertainty in the calculated speed of sound. **(3)**

(e) The accepted speed of sound in air at 20°C is 343 m/s. Suggest two reasons why the student's calculated value is lower than this. **(2)**

(Total for Question 16 is 11 marks)

Mark scheme · 3.3 Waves

Question 1

(a) correct substitution: $\sin(\theta_c) = 1.45/1.52$ **M1**

(a) = 0.954 (awrt), and takes inverse sine **M1**

(a) 72.5 degrees (awrt 72.4-72.6 degrees) **A1**

(a) Answer: 72.5 degrees

(b) correct rearrangement and substitution: $v = (3.00 \times 10^8)/1.52$ **M1**

(b) 1.97×10^8 m/s (awrt, cao) **A1**

(b) Answer: 1.97×10^8 m/s

(c) the angle of incidence must be greater than the critical angle (greater than 72.5 degrees, ft from (a)) **B1**

(c) this condition must be met at every reflection along the length of the fibre, so the light stays confined within the core oe **B1**

(c) Answer: The angle of incidence must exceed the critical angle (greater than 72.5 degrees) at every reflection along the fibre.

(d) the light must be travelling from a medium of higher refractive index (the core) into a medium of lower refractive index (the cladding) oe **B1**

(d) Answer: Light must travel from the higher refractive index medium (core) towards the lower refractive index medium (cladding).

(e) **L3** Coherent discussion of at least two distinct causes of degradation (e.g. absorption/attenuation and one form of dispersion), each with a clearly linked, valid method of reducing its effect. **5-6**

(e) **L2** Identifies at least one or two causes of degradation, with some explanation of solutions, though links between cause and solution may be incomplete. **3-4**

(e) **L1** Basic, general statements (e.g. 'the signal gets weaker') without detailed physical cause or a clearly linked improvement. **1-2**

(e) **L0** No creditable content. **0**

(e) Indicative content:

- Absorption: impurities in the fibre material absorb some of the light energy, causing attenuation (a gradual loss of signal amplitude/intensity) along the length of the fibre; using very pure glass reduces absorption.
- Modal dispersion: light rays entering the core at different angles travel different path lengths (and take different times) along the fibre, causing a pulse of light to broaden and, over long distances, overlap with neighbouring pulses; this is reduced by using a very narrow core (a single-mode/monomode fibre) so only one path is possible.
- Material (chromatic) dispersion: different wavelengths within a pulse travel at slightly different speeds in the fibre, because refractive index depends on wavelength, again causing pulse broadening; this is reduced by using a light source with a very narrow range of wavelengths (e.g. a laser rather than an LED).
- Regenerating (amplifying and reshaping) the signal at intervals along its length, using repeater stations, restores its strength and pulse shape before degradation makes the signal unreadable.

(e) Answer: Credit awarded via levels of response using the indicative content (absorption/attenuation, modal dispersion, material dispersion, and their corresponding solutions).

Question 2

(a) $T = mg = 0.250 \times 9.81$ **M1**

(a) 2.45 N (awrt 2.4-2.5 N) **A1**

(a) Answer: 2.45 N

(b) correct substitution: $v = \sqrt{2.4525/4.0 \times 10^{-4}}$ **M1**

(b) evaluates ratio inside the square root: 6131 (awrt) **M1**

(b) 78.3 m/s (awrt 78-79 m/s, ft from (a)) **A1**

(b) Answer: 78.3 m/s

(c) wavelength = $2 \times 0.80 = 1.60$ m **M1**

(c) correct substitution: $f = v/\lambda = 78.3/1.60$ **M1**

(c) 48.9 Hz (awrt 48-49 Hz, ft from (b)) **A1**

(c) Answer: 48.9 Hz

(d) increasing the tension T increases the wave speed v, since $v = \sqrt{T/\μ}$ **B1**

(d) the wavelength is unchanged, since the string length and number of antinodes are the same **B1**

(d) since $f = v/\lambda$ and λ is unchanged, an increase in v means the frequency needed increases oe **B1**

(d) Answer: The frequency needed increases, because increasing the tension increases the wave speed while the wavelength (fixed by the string length and mode) stays the same.

(e) a node is a point on the wave with zero (permanently no) displacement/amplitude **B1**

(e) an antinode is a point on the wave with maximum amplitude of oscillation **B1**

(e) Answer: Node: point of zero displacement/amplitude. Antinode: point of maximum amplitude.

Question 3

(a) converts units correctly: $\lambda = 589 \times 10^{-9}$ m, s = 0.40×10^{-3} m — **M1**

(a) correct substitution: $w = (589 \times 10^{-9} \times 2.50)/(0.40 \times 10^{-3})$ — **M1**

(a) 3.68×10^{-3} m (awrt 3.7 mm) — **A1**

(a) Answer: 3.68 mm (3.68×10^{-3} m)

(b) converts width to metres: 5.0 cm = 0.050 m — **M1**

(b) number of fringes = $0.050/(3.68 \times 10^{-3})$ — **M1**

(b) = 13.6, so about 14 bright fringes fit across the width (cso, ft from (a)) — **A1**

(b) Answer: About 14 bright fringes.

(c) the two sources (slits) must be coherent (constant phase difference) oe — **B1**

(c) the light from the two slits must have the same frequency/wavelength (and be monochromatic, of similar amplitude) oe — **B1**

(c) Answer: Coherence (constant phase difference); same frequency/wavelength.

(d) the extra distance travelled by one wave compared with the other, from the sources to that point oe — **B1**

(d) Answer: The extra distance travelled by one wave compared with the other, to reach the same point.

(e) the fringe spacing increases — **B1**

(e) since $w = (\lambda \times D)/s$, with D and s unchanged, a larger λ gives a larger w oe — **B1**

(e) Answer: The fringe spacing increases, because w is directly proportional to wavelength when D and s are fixed.

Question 4

(a) the oscillations of the wave occur in one plane only, which contains the direction of propagation oe — **B1**

(a) Answer: The oscillations occur in only one plane, which contains the direction of travel of the wave.

(b) the detected signal (amplitude/intensity) decreases as the grille is rotated — **B1**

(b) the signal falls to (a) minimum/zero once the grille has been rotated through 90 degrees — **B1**

(b) the grille only allows through the component of the oscillation aligned with its transmission direction, and this component reduces to zero at 90 degrees oe — **B1**

(b) Answer: The signal decreases steadily and falls to a minimum (zero) at 90 degrees, because only the component of oscillation aligned with the grille's transmission direction is allowed through.

(c) named application, e.g. polaroid sunglasses, LCD screens, or aligning a radio/TV aerial with a transmitter — **B1**

(c) valid explanation linked to the named application, e.g. sunglasses absorb the (partially) polarised glare reflected from horizontal surfaces such as water or a road oe — **B1**

(c) Answer: Example: polaroid sunglasses, which absorb the horizontally polarised glare reflected from surfaces such as water or wet roads.

(d) only transverse waves can be polarised, because polarisation requires restricting the oscillation direction (perpendicular to propagation) to a single plane — **B1**

(d) since sound cannot be polarised, it cannot be transverse, so it must be longitudinal oe — **B1**

(d) Answer: Since only transverse waves can be polarised, and sound cannot be polarised, sound must be a longitudinal wave.

Question 5

(a) sources with the same frequency and a constant phase difference oe — **B1**

(a) Answer: Sources of the same frequency with a constant phase difference.

(b) divides path difference by wavelength: 2.04/0.680 — **M1**

(b) = 3.0, a whole number of wavelengths — **A1**

(b) conclusion: constructive interference (a loud point), since the path difference is a whole number of wavelengths oe — **A1**

(b) Answer: Loud point (constructive interference), since 2.04/0.680 = 3.0 exactly.

(c) the two sources would no longer be coherent, as independent generators cannot maintain a constant phase difference oe — **B1**

(c) the positions of the loud and quiet points would therefore shift continuously/randomly over time, so no stable pattern would be observed oe — **B1**

(c) Answer: The sources would not be coherent, since independent generators drift in phase relative to each other, so the loud and quiet points would shift constantly and no stable pattern would form.

(d) correct substitution: f = 340/0.850 — **M1**

(d) 400 Hz (cao) — **A1**

(d) Answer: 400 Hz

Question 6

(a) $\lambda = 4 \times L = 4 \times 0.158$ **M1**

(a) 0.632 m (cao) **A1**

(a) Answer: 0.632 m

(b) correct substitution: $v = 512 \times 0.632$ **M1**

(b) 324 m/s (awrt 323-324 m/s, ft from (a)) **A1**

(b) Answer: 324 m/s

(c) correct substitution: $L = (3 \times 0.632)/4$ **M1**

(c) 0.474 m (awrt, ft from (a)) **A1**

(c) Answer: 0.474 m

(d) the air column vibrates with maximum amplitude, forming a stationary wave, when driven at (one of) its natural frequencies oe **B1**

(d) Answer: The air column vibrates with maximum amplitude (forming a stationary wave) when driven at one of its natural frequencies.

(e) **L3** Detailed, coherent evaluation of multiple sources of error (including at least one systematic and one random error), each clearly linked to a valid, practical improvement. Physics used accurately throughout. **5-6**

(e) **L2** Sound evaluation of some sources of error, with improvements suggested, though links between error and improvement may be incomplete or only partially explained. **3-4**

(e) **L1** Basic, general statements about accuracy or error, with limited explanation and little or no clear link to this specific experiment. **1-2**

(e) **L0** No creditable content. **0**

(e) Indicative content:

- There is a systematic error (end correction): the antinode at the open end of the tube actually occurs slightly beyond the tube opening, so the measured length L underestimates the true resonating length, giving a systematic underestimate of the wavelength and speed.
- This end correction can be reduced/eliminated by finding a second (or higher) resonance and using the difference between resonant lengths (which is always half a wavelength) rather than a single length measurement.
- Judging the exact position of resonance (loudest sound) by ear is imprecise and introduces random error; a microphone and oscilloscope, or a data logger with a sound sensor, could be used to detect the maximum amplitude more objectively and precisely.
- The speed of sound depends on air temperature; if room temperature was not measured or was different from the assumed value, this would cause a systematic difference from the accepted value of 343 m/s.
- Repeating the length measurement several times at each resonance and averaging reduces the effect of random error in judging the resonance position.
- Using a signal generator and loudspeaker instead of a tuning fork would allow a wider range of precise, known frequencies to be tested, improving the reliability of the method.

(e) Answer: Credit awarded via levels of response using the indicative content (end correction, resonance judgement, temperature effects, repeats/averaging, use of sensors/data logger).

Question 7

(a) $d = 1/300$ mm $= 3.33 \times 10^{-3}$ mm **M1**

(a) 3.33×10^{-6} m (awrt, cao) **A1**

(a) Answer: 3.33×10^{-6} m

(b) $\tan(\theta) = x/L = 0.240/1.20$ **M1**

(b) = 0.200, and takes inverse tan **M1**

(b) 11.3 degrees (awrt 11.2-11.3 degrees) **A1**

(b) Answer: 11.3 degrees

(c) sin(11.3 degrees) = 0.196 (awrt) **M1**

(c) correct rearrangement and substitution: $\lambda = (3.33 \times 10^{-6} \times 0.196)/1$ **M1**

(c) 6.5×10^{-7} m (awrt 650-655 nm, ft from (a) and (b)) **A1**

(c) Answer: 6.5×10^{-7} m (about 654 nm)

(d) the grating produces sharper/narrower and brighter maxima than a double slit, allowing the angle (and hence wavelength) to be measured more precisely oe **B1**

(d) Answer: A diffraction grating produces sharper, brighter maxima, allowing a more precise measurement of the angle and hence the wavelength.

(e) the grating spacing d halves (there are twice as many lines per mm) **B1**

(e) since $\sin(\theta) = (n \times \lambda)/d$, a smaller d gives a larger $\sin(\theta)$ and hence a larger angle, so the first-order maximum moves further from the centre oe **B1**

(e) Answer: The first-order maximum moves further from the centre, because halving d roughly doubles sin(θ), increasing the diffraction angle.

Question 8

(a) quote $v = \sqrt{T / \μ}$ **M1**

(a) substitute $v = \sqrt{145 / 1.2 \times 10^{-3}}$ **M1**

(a) v = 348 m/s (accept 347-348) cao **A1**

(a) Answer: 348 m/s

(b) use $f = v / 2L$ with L = 0.65 m and v from (a) **M1**

(b) f = 267 Hz (accept 266-268) cao **A1**

(b) Answer: 267 Hz

(c) f3 = 3 x f1 = 802 Hz (accept 799-804 following through from (b)) **A1**

(c) 3 antinodes (and 4 nodes) oe **B1**

(c) Answer: f3 = 802 Hz; 3 antinodes.

Question 9

(a) $d = 1 / (600 \times 10^3) = 1.67 \times 10^{-6}$ m cao **B1**

(a) Answer: 1.67×10^{-6} m

(b) quote $d \sin(\theta) = n \lambda$ with n = 1 **M1**

(b) substitute $\sin(\theta) = 632.8 \times 10^{-9} / 1.67 \times 10^{-6}$ **M1**

(b) θ = 22.3 degrees cao **A1**

(b) Answer: 22.3 degrees

(c) recognise the maximum order occurs when $\sin(\theta) = 1$, so $n(max) = d / \lambda$ **M1**

(c) calculate $d / \lambda = 1.67 \times 10^{-6} / 632.8 \times 10^{-9} = 2.63$ **M1**

(c) n = 2 is the highest order observed, since n = 3 would require $\sin(\theta) = 1.14$ which is impossible cao **A1**

(c) Answer: n = 2

Question 10

(a) intensity is inversely proportional to the square of the distance from the source (inverse square law) oe **B1**

(a) Answer: Intensity is inversely proportional to the square of the distance from the source.

(b) use I2 = I1 x $(r1/r2)^2$ **M1**

(b) substitute I2 = 4.5 x 10^{-3} x $(2.0/6.0)^2$ **M1**

(b) I2 = 5.0 x 10^{-4} W/m^2 cao **A1**

(b) Answer: 5.0 x 10^{-4} W/m^2

(c) quote I proportional to A^2, so A2/A1 = $\sqrt{I2/I1}$ **M1**

(c) substitute A2/A1 = $\sqrt{5.0 \times 10^{-4} / 4.5 \times 10^{-3}}$ **M1**

(c) A2 : A1 = 1 : 3 (ratio = 0.333) cao **A1**

(c) Answer: A2 : A1 = 1 : 3

Question 11

(a) correct substitution: λ = (w x s)/D = (7.60 x 10^{-3} x 2.5 x 10^{-4})/3.00 **M1**

(a) 6.33 x 10^{-7} m (awrt 633 nm, cao) **A1**

(a) Answer: 6.33 x 10^{-7} m (633 nm)

(b) recognises that since λ = w x s/D and the uncertainties in s and D are negligible, the percentage uncertainty in λ equals the percentage uncertainty in w (3.0%) **M1**

(b) calculates 3.0% of the wavelength found in (a): 0.030 x 6.33 x 10^{-7} **M1**

(b) ± 1.9 x 10^{-8} m (awrt, ft from (a)) **A1**

(b) Answer: ± 1.9 x 10^{-8} m (about ± 19 nm)

(c) d = 1/600 mm = 1.67 x 10^{-6} m **M1**

(c) correct substitution: sin(θ) = (2 x 6.33 x 10^{-7})/(1.67 x 10^{-6}) **M1**

(c) 49.5 degrees (awrt 49.4-49.6 degrees, ft from (a)) **A1**

(c) Answer: 49.5 degrees

(d) it reduces the percentage (random) uncertainty in w, since any fixed error in locating the fringe edges is divided by the number of fringe widths spanned oe **B1**

(d) Answer: It reduces the percentage uncertainty in the fringe spacing, since a fixed measurement error is spread over many fringe widths.

(e) the diffraction grating is likely to give the more precise value, because it produces sharper and brighter maxima than a double slit oe **B1**

(e) double-slit fringes are dimmer and wider, making it harder to judge the exact centre of each fringe precisely, increasing the random uncertainty in w oe **B1**

(e) valid overall conclusion linking this to a smaller percentage uncertainty in the wavelength obtained from the grating method oe **B1**

(e) Answer: The diffraction grating method is likely to be more precise, since its sharp, bright maxima allow the angle to be measured more precisely than the wider, dimmer double-slit fringes.

Question 12

(a) the lowest frequency (n = 1) at which a stationary wave pattern can be formed in the system oe **B1**

(a) Answer: The lowest frequency (n = 1) at which a stationary wave can be formed in the pipe.

(b) correct substitution: v = 331 + 0.60 x 18 **M1**

(b) 342 m/s (awrt, cao) **A1**

(b) Answer: 342 m/s

(c) wavelength = 2 x L/n = 2 x 0.60/1 = 1.20 m **M1**

(c) correct substitution: f = v/λ = 341.8/1.20 **M1**

(c) 285 Hz (awrt 284-285 Hz, ft from (b)) **A1**

(c) Answer: 285 Hz

(d) recognises harmonics of an open-open pipe are integer multiples of the fundamental: f3 = 3 x f1, or recalculates wavelength = 2 x 0.60/3 = 0.40 m **M1**

(d) 855 Hz (awrt 854-855 Hz, ft from (c)) **A1**

(d) Answer: 855 Hz

(e) v at -5°C = 331 + 0.60 x (-5) = 328 m/s **M1**

(e) f1 at -5°C = 328/1.20 = 273 Hz (awrt) **M1**

(e) percentage change = (284.8 - 273.3)/284.8 x 100 **M1**

(e) = 4.0%, which is less than 5% (cso) **A1**

(e) Answer: The fundamental frequency changes by about 4.0%, which is less than 5%, confirming the statement.

Question 13

Level 3 Detailed and well-linked evaluation that correctly explains how interference and diffraction require superposition of waves (path difference, constructive/destructive interference) and could not occur for classical particles, AND explains why the photoelectric effect (existence of a threshold frequency, instantaneous emission, and kinetic energy of electrons depending on frequency not intensity) cannot be explained by a wave model but is explained by discrete photons of energy E = hf. Reaches a clear, justified conclusion that light must be treated as having both wave and particle character (wave-particle duality), used in different contexts. **5-6**

Level 2 Correctly describes at least one piece of wave evidence and at least one feature of the photoelectric effect, with some explanation of why each supports its respective model, but the argument linking them to a duality conclusion is only partially developed or contains minor inaccuracies. **3-4**

Level 1 Basic or one-sided answer: describes either wave evidence or photon evidence in isolation, with little or no attempt to connect the two forms of evidence or reach a conclusion about duality. **1-2**

Indicative content:

- Wave evidence: interference and diffraction require superposition of waves and depend on path difference; regions of constructive and destructive interference (bright and dark fringes) can only be explained if light behaves as a wave.
- A stream of classical particles would not produce a stable interference pattern with alternating maxima and minima; the wave model correctly predicts fringe spacing from wavelength, slit separation and distance to screen.
- Photoelectric evidence: emission of electrons occurs only above a threshold frequency, independent of intensity, and emission is effectively instantaneous even at very low intensity.
- A wave model predicts that energy should accumulate over time at any frequency given sufficient intensity, eventually releasing electrons; this is not observed, so the wave model fails here.
- The photon model (E = hf) explains the threshold frequency as the minimum photon energy needed to overcome the work function, and explains why increasing intensity (more photons) increases the rate of emission but not the maximum kinetic energy of each photoelectron, which depends only on frequency.
- Conclusion: light must be described using both models depending on the phenomenon being explained (wave-particle duality); neither a purely wave model nor a purely particle model alone accounts for all observed behaviour of light.

Question 14

(a) quote fringe spacing $w = \lambda D / a$ **M1**

(a) rearrange to $\lambda = w a / D$ **M1**

(a) substitute $\lambda = (2.28 \times 10^{-3} \times 4.5 \times 10^{-4}) / 1.85$ **M1**

(a) $\lambda = 555$ nm cao **A1**

(a) Answer: 555 nm

(b) calculate each percentage uncertainty: w = 0.05/2.28 x 100 = 2.19%, a = 0.01/0.45 x 100 = 2.22%, D = 0.02/1.85 x 100 = 1.08% **M1**

(b) recognise that for a product/quotient the percentage uncertainties are added **M1**

(b) total percentage uncertainty = 5.5% cao **A1**

(b) Answer: 5.5%

(c) absolute uncertainty = 5.5% of 555 nm = 30 nm (accept 30-31) **M1**

(c) $\lambda = (555 \pm 30)$ nm cao, uncertainty to 1-2 sig figs **A1**

(c) Answer: (555 ± 30) nm

Question 15

(a) recognise the first filter transmits half the unpolarised intensity: $I1 = 840/2 = 420$ W/m^2 **M1**

(a) quote Malus's law $I = I1 \cos^2(\theta)$ **M1**

(a) substitute $I = 420 \times \cos^2(35 \text{ degrees})$ **M1**

(a) $I = 282$ W/m^2 (accept 280-283) cao **A1**

(a) Answer: 282 W/m^2

(b) set $\cos^2(\theta) = 0.10$ **M1**

(b) $\theta = \arccos(\sqrt{0.10})$ **M1**

(b) $\theta = 71.6$ degrees cao **A1**

(b) Answer: 71.6 degrees

Question 16

(a) measuring across several wavelengths and dividing by the number of wavelengths means the absolute uncertainty in the ruler reading is spread over a much larger distance **B1**

(a) this reduces the percentage uncertainty in the value obtained for a single wavelength, compared with measuring just one wavelength directly oe **B1**

(a) Answer: Measuring across eight wavelengths and dividing by 8 spreads the fixed absolute uncertainty of the ruler over a much larger measured distance, reducing the percentage uncertainty in the wavelength.

(b) wavelength = total distance / number of wavelengths = 1.056 / 8 **M1**

(b) λ = 0.132 m cao **A1**

(b) Answer: 0.132 m

(c) use v = f λ = 2500 x 0.132 **M1**

(c) v = 330 m/s cao **A1**

(c) Answer: 330 m/s

(d) percentage uncertainty in distance = (0.001/1.056) x 100 = 0.095% **M1**

(d) since frequency uncertainty is negligible, this is also the percentage uncertainty in the speed **M1**

(d) absolute uncertainty = (0.095/100) x 330 = 0.31 m/s, so v = (330.0 ± 0.3) m/s cao **A1**

(d) Answer: ± 0.3 m/s

(e) the speed of sound in air increases with temperature, so the laboratory air was likely at a lower temperature than 20°C oe **B1**

(e) alternatively, a systematic error such as the student misjudging when the traces were exactly back in phase (a small consistent offset in the distance measured) would also explain a discrepancy oe **B1**

(e) Answer: The laboratory air was probably at a temperature below 20°C, since the speed of sound in air increases with temperature; a systematic timing/alignment error in judging when the traces were exactly in phase is also a plausible cause.