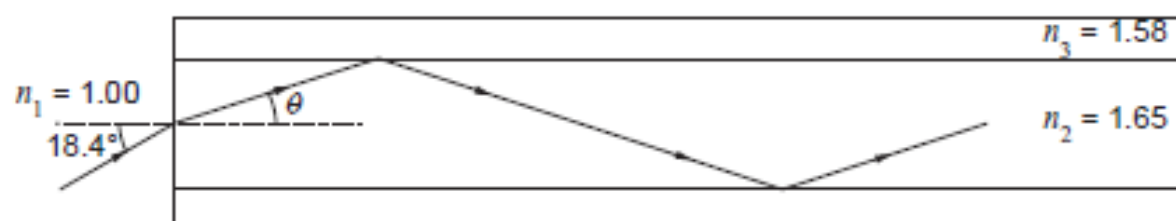


1. 2. A light ray enters an optical fibre as shown.



- (a) Show that the angle θ is approximately 10° .

[2]

.....

.....

.....

- (b) Deduce whether or not this light will propagate along the length of the optical fibre with total internal reflection as shown.

[4]

.....

.....

.....

.....

.....

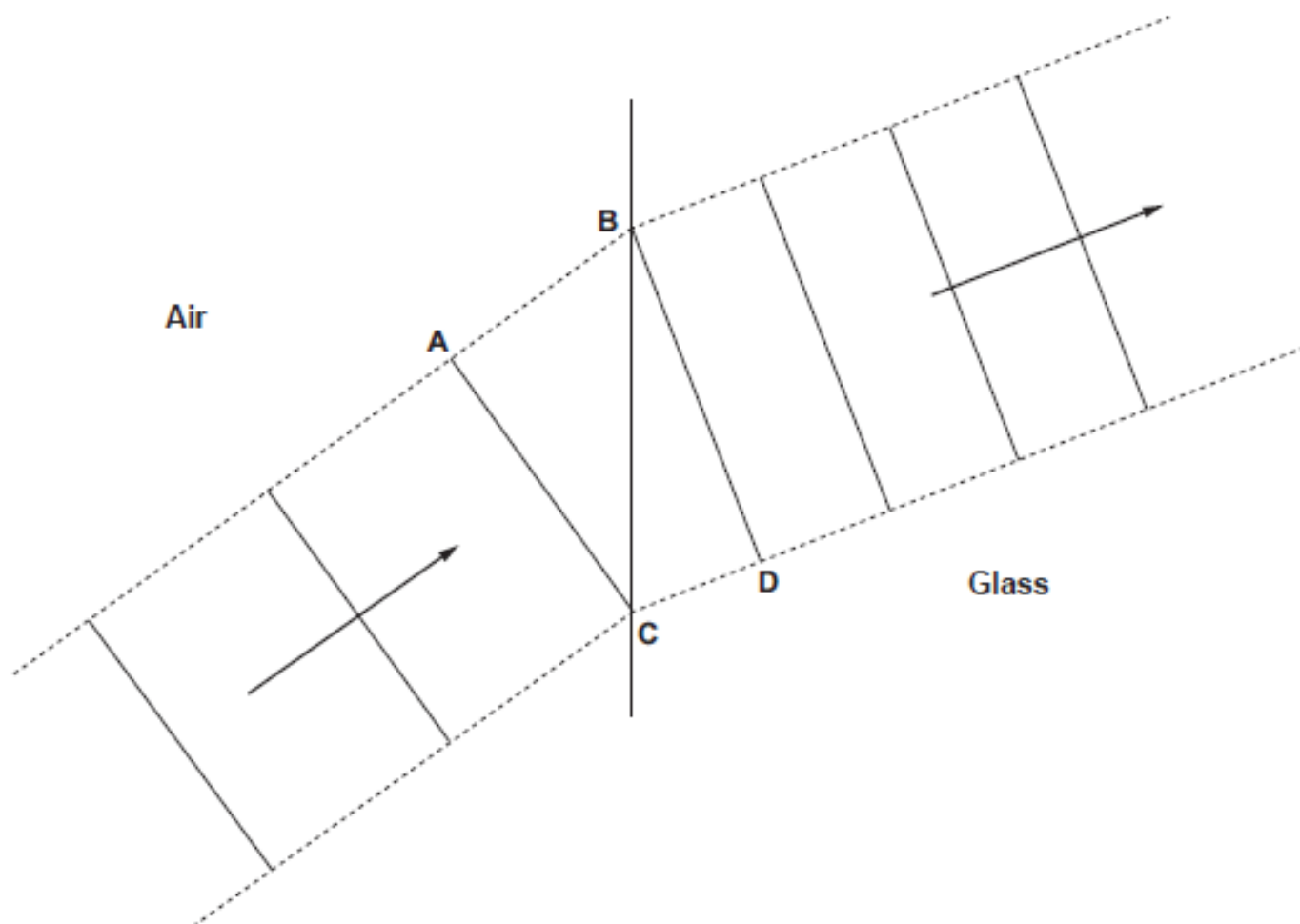
.....

.....

.....

2.

3. A light beam travelling in air hits a boundary with glass. The diagram shows wavefronts on the light beams in the air and in the glass.



- (a) State what is meant by refraction and use the diagram to explain why refraction occurs. [3]

.....

.....

.....

.....

.....

.....

(b) By measuring appropriate lengths from the diagram calculate the speed of light in the glass. [3]

.....

.....

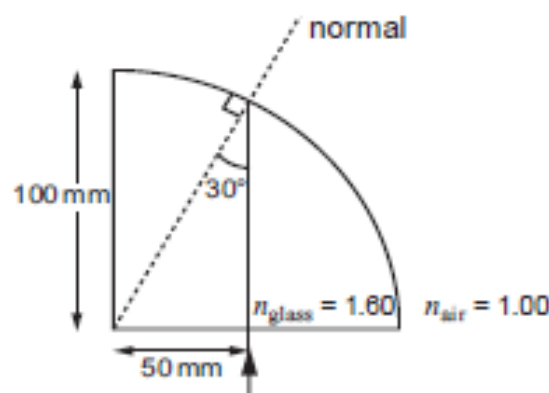
.....

.....

.....

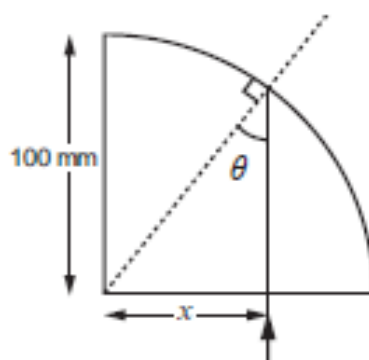
.....

3. 7. (a) (i) A narrow beam of light enters a glass block of quarter-circle cross-section, as shown. The refractive index of the glass is 1.60.



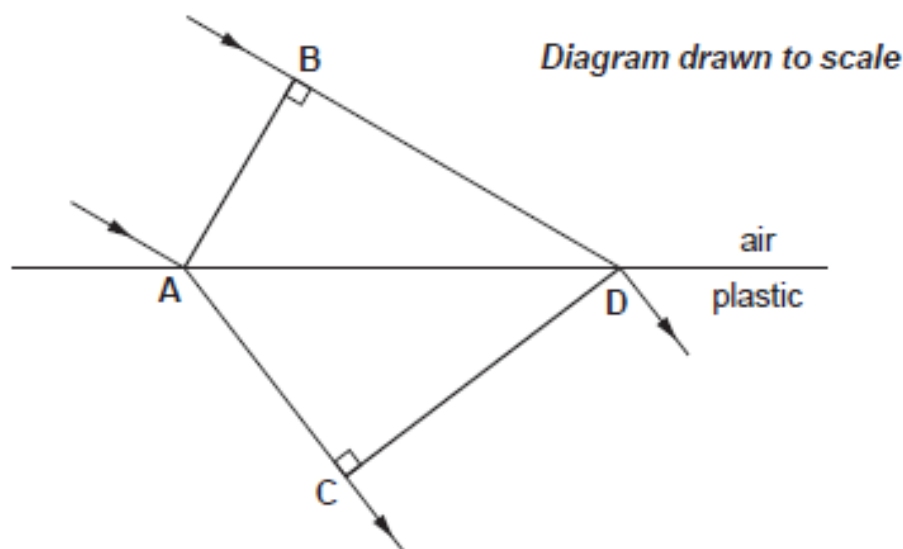
Calculate the angle of refraction into the air at the curved surface and carefully sketch the refracted beam on the diagram. [Use of a protractor is not required.][3]

- (ii) Calculate the largest distance, x , along the bottom face of the block, at which the beam can enter the block normally, for it to emerge from the curved face. You should refer to the angle θ in your calculation. [3]



4.

7. (a) The diagram (real size) shows a beam of light passing from air into a clear plastic. AB is a wavefront about to enter the plastic, and CD is its position a short time later.



- (i) Determine the speed of light in the plastic using measurements made with a ruler from the diagram, and taking the speed of light in air to be equal to its speed in a vacuum. Show your working clearly. [3]

.....

.....

.....

.....

.....

- (ii) Calculate the refractive index of the plastic. [1]

.....

.....

.....

- (b) In a multimode fibre of length 120.00 m, the length of the longest possible (zig-zag) route for light to travel successfully is 120.90 m. The refractive index of the fibre core is 1.520. Very short pulses of light are sent into one end of the fibre at intervals of 4.0 ns.
- (i) Evaluate whether or not overlap (or overtaking) of pulses will occur before the pulses have reached the other end of the fibre. [3]

.....

.....

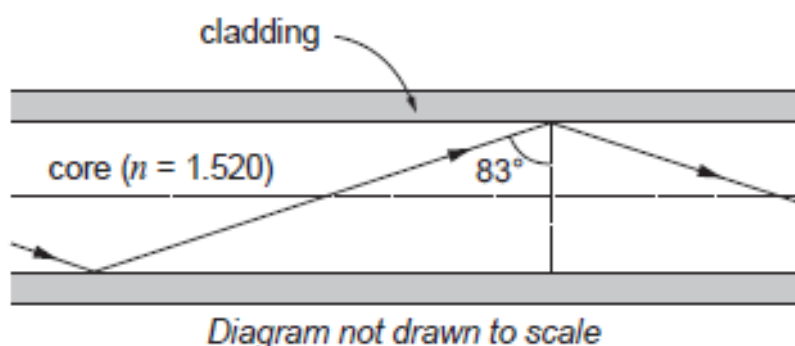
.....

.....

.....

.....

- (ii) Part of the longest possible successful zig-zag route is shown below.



- Calculate the refractive index of the cladding. [2]

.....

.....

.....

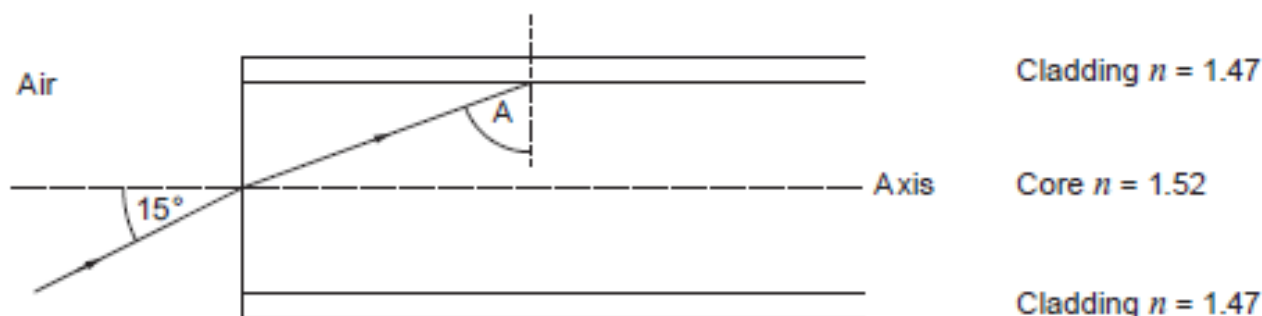
.....

.....

.....

5.

6. (a) A multimode optical fibre has a core made of glass of refractive index 1.52. The cladding is made of a material with refractive index 1.47.



- (i) Calculate the critical angle for the core-cladding boundary. [2]

.....

.....

.....

- (ii) A beam of light enters the optical fibre from air at an angle of 15° as shown. Calculate angle A. [3]

.....

.....

.....

.....

.....

- (iii) A technician states that the beam of light entering the fibre from air at an angle of 15° will not travel down the optical fibre. Evaluate whether the technician is correct. [2]

.....

.....

.....

- (b) Calculate the time taken for the light to travel along the axis of a straight optical fibre of length 15 km. [3]

.....

.....

.....

.....

.....

- (c) (i) State how the paths of light in monomode and multimode optical fibres differ. [1]

.....

.....

- (ii) Explain the advantage of monomode optical fibres over multimode optical fibres for communicating a rapid sequence of data encoded as light pulses. [3]

.....

.....

.....

.....

.....

.....

Read through the following article carefully.

Freely adapted from:

The Physics of Optical Fibres
By Justino Luis Moreno

Paragraph

Basically, an optical fibre is just a piece of glass along which you send light. A similar procedure was first demonstrated not with glass but with water flowing from a spout in 1840 by scientists Daniel Colladon and Jacques Babinet. Babinet later published his work in an article entitled "On the reflections of a ray of light inside a parabolic liquid stream". This effect can be reproduced quite easily in a school lab using the apparatus shown in Figure 1.

1

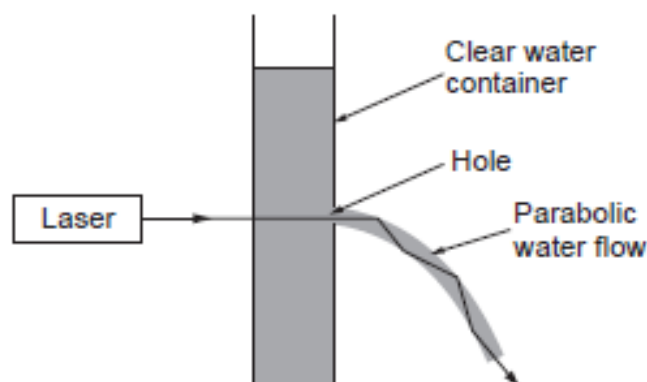


Figure 1

Although this set up is pleasing to the eye and is the basis of some water features, it isn't much use for international telecommunication! A standard optical fibre is shown in Figure 2 along with a ray of light entering it.

2

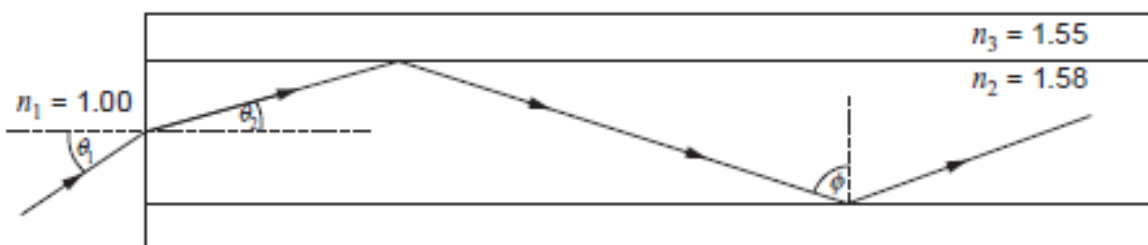


Figure 2

This ray of light is repeatedly reflected along the length of the optical fibre. If the entrance angle (θ_1) is small enough then an effect called total internal reflection (TIR) means that the light is completely reflected each time resulting in no light escaping as it travels along the optical fibre. The physicists in charge of designing these things can prove that the minimum value angle ϕ can have for TIR to take place is given by the equation:

3

$$\phi = \sin^{-1}\left(\frac{n_3}{n_2}\right)$$

This angle is around 80° for the optical fibre shown. The minimum angle for ϕ means that there is a maximum angle for θ_1 . This gives an acceptance cone where the input light gets propagated without loss. A quick bit of geometry shows you that the exit angle is the same as the entry angle so that when light exits it produces an almost perfect cone shaped beam with a circular cross-section as can be seen in Figure 3.

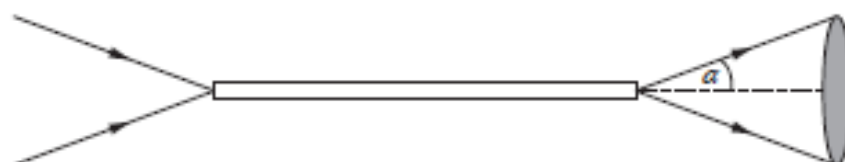


Figure 3

An important term in optical fibre technology is maximum bit rate. Since each pulse represents a bit of data, this is the highest frequency of pulses that can be sent down an optical fibre before the pulses start to overlap and become indistinguishable from each other. A monomode optical fibre cable of length 80 km can comfortably have a maximum bit rate of 10 Gbs^{-1} . This means that 10^{10} pulses can pass along its length every second without overlapping. A typical telephone conversation requires around 10 kbs^{-1} meaning that one monomode optical fibre cable can carry a million telephone conversations simultaneously. High definition TV requires a much higher bit rate and a 10 Gbs^{-1} fibre will only handle around 2 000 high definition TV signals.

One of the most important factors that limit data transfer in optical fibres is multimode dispersion. This, put simply, is to do with the entrance cone of light in Figure 3. There is a range of distances that the pulses have to travel because there are a variety of angles at which they can travel along the fibre. The pulses then become spread out and indistinct, ruining the digital signal. Multimode dispersion is eliminated by using monomode optical fibre cables which have very thin cores. As a rule, monomode fibres have a core diameter of around $8 \mu\text{m}$. This means that the core is less than 10 wavelengths thick so that the light stops behaving like rays. For monomode fibres there is only one propagation direction – along the axis.

Another drawback of sending signals down long lengths of optical fibres is that some of the light is either scattered or absorbed by the glass molecules themselves (an effect known as attenuation). Although no light escapes the fibre due to TIR there are other losses involved and these are usually summarised by using a decibel (dB) scale. This scale is defined by saying that a 10 dB decrease (-10 dB) in power is when the power has dropped to 10% of its input value. A loss of -20 dB then corresponds to a drop to 1% power and -30 dB is a drop to 0.1% power. The following table shows the relationship between dB values and power ratio:

dB	Power ratio $\left(\frac{P}{P_0}\right)$
-5	0.316
-10	0.100
-15	0.032
-20	0.010

Table 1

The losses of optical fibres are usually quoted in the unit dB/km and some modern optical fibres can have values as low as 0.01 dB/km. Hence, each km of cable loses 0.01 dB meaning that you can use 1 000 km before your signal is down to 10% strength. Optical fibres have come a long way since they were born in a fountain of light nearly 200 years ago. They stretch out (literally) to all areas of the world bringing light, sound and broadband wherever they go. Technical advances mean that data can be sent at a rate of 1.05×10^{15} pulses per second over a distance of 50 km with only one monomode optical fibre. Nonetheless, the technology has its limitations of which attenuation and multimode dispersion are but two.

(e) Rhys makes the following claim:

"A multimode optical fibre that can transfer data at a maximum bit rate of 500 Mb s^{-1} over a distance of 1 km would be able to transfer data at a maximum rate of 50 Mb s^{-1} over a distance of 10 km."

Discuss whether or not Rhys's claim is valid (paragraph 5 & 6).

[3]

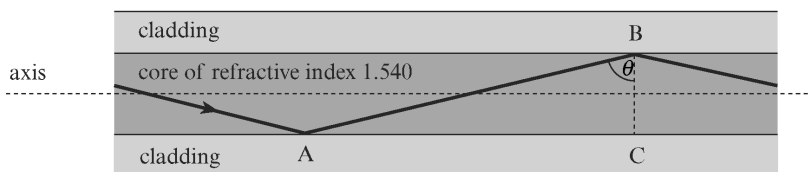
(f) A certain type of optical fibre has an attenuation of 0.8 dB/km. When the signal decreases to 6% of its original intensity it must be amplified or the signal will be lost. An engineer intends to install these optical fibres in lengths of 20 km before each amplifier. Determine whether or not this is an appropriate length of optical fibre to use (see paragraph 7 and Table 1).

[3]

(g) Aled claims that a core diameter of around $13 \mu\text{m}$ is thin enough for a monomode optical fibre because a wavelength in air of $1.3 \mu\text{m}$ is usually used in communications. Rhian claims that this is nonsense because the wavelength in the optical fibre is changed due to its refractive index. Justify by including a calculation who is correct (paragraph 6). [4]

7.

The diagram shows a path which light can take along a ‘thick’ (multimode) optical fibre.



- (a) The smallest angle θ at which *total internal reflection* can take place is 77° . Calculate the *refractive index* of the cladding. [2]

.....

.....

.....

- (b) (i) Calculate the time it takes light to travel along 2.0 km of the fibre if it travels through the core **in a straight line parallel to the axis of the fibre**. [3]

.....

.....

.....

- (ii) (I) Show that for $\theta = 77^\circ$, the length of AB is 1.026 times greater than the length of AC (see diagram). [1]

.....

.....

- (II) Hence calculate the **extra** time it takes for light to travel 2.0 km along the fibre via the zigzag path (i.e. for $\theta = 77^\circ$). [2]

.....

.....

.....

- (iii) Without further calculation explain how this difference in times limits the rate at which data (encoded in the light) can be sent through 2.0 km of the fibre. [2]

.....

.....

.....

8.

- (a) (i) Insert the correct symbol (< or = or >) to compare the *speeds* (v), *frequencies* (f) and *wavelengths* (λ) of a monochromatic light beam as it passes from air to glass.

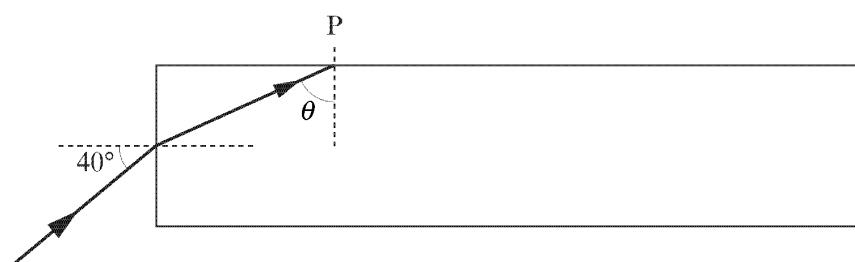
v_{air} v_{glass} , f_{air} f_{glass} , λ_{air} λ_{glass} . [2]

- (ii) Justify your choice of symbol for the case of the frequencies. [Your justification should not require use of the equation $v = f\lambda$.] [1]

.....

.....

- (b) The diagram shows a narrow beam of light entering a solid cuboid (block) of glass of refractive index 1.52, surrounded by air (of refractive index 1.00).



- (i) Show clearly that $\theta = 65^\circ$. [3]

.....

.....

.....

- (ii) Show that the beam will not emerge into the air at point P. [2]

.....

.....

.....

(iii) (I) Carefully complete the path of the beam, showing it eventually emerging into the air and travelling through the air. [1]

(II) Indicate clearly on the diagram sections of the **whole** path which are parallel to each other. [2]

(c) In a multimode fibre, light travels at a range of angles **to the fibre axis**. Explain why, for clear communication of rapid streams of data, the range of angles should be restricted so that even the greatest value of the angle is very small. [2]

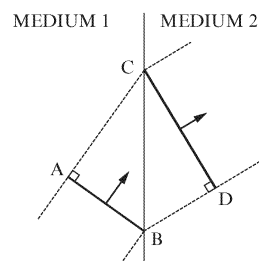
.....

.....

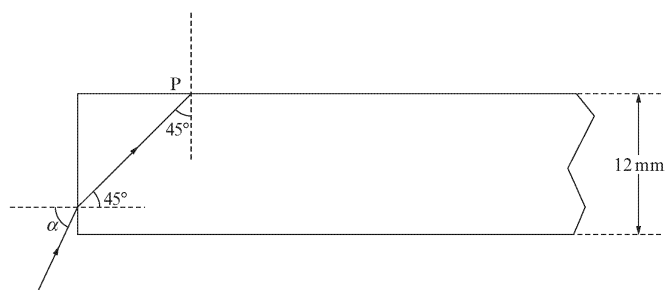
.....

.....

- (a) Explain, in terms of waves, why *refraction* occurs. Refer to the diagram below in your answer. [Mathematics is not needed.] [3]



- (b) A laser beam is directed on to the end-face of a rod of clear plastic of refractive index 1.33, surrounded by air (refractive index 1.00).



- (i) Calculate the angle α .

[2]

- (ii) At P, 90% of the light power is refracted out into the air, and 10% is reflected.

- (I) **Draw** carefully on the diagram above the paths of the light refracted and reflected at P. The reflected ray need extend no further than the bottom of the rod. [2]

- (II) Estimate how far the reflected light travels along the rod **from P** before the power drops to a millionth of the power of the beam incident on P. [Consider successive reflections.] [3]

.....

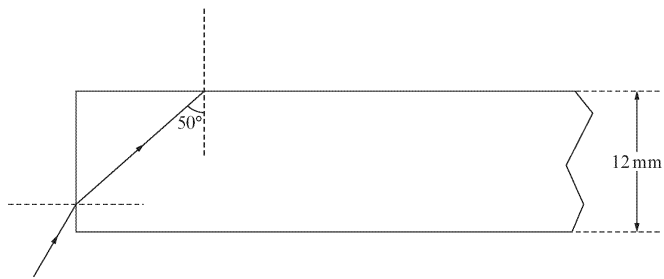
.....

.....

.....

.....

- (c) The angle of the laser beam is changed as shown.



- (i) By first calculating the critical angle, explain why the laser beam now travels along the rod with no loss of power at reflections. [2]

.....

.....

.....

- (ii) Give the full name of the type of reflection occurring. [1]

.....

10.

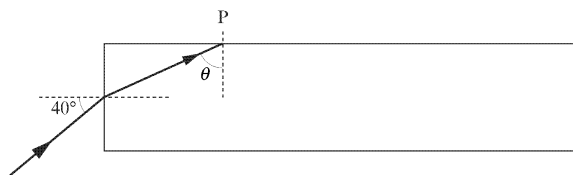
- (a) (i) Insert the correct symbol (< or = or >) to compare the *speeds* (v), *frequencies* (f) and *wavelengths* (λ) of a monochromatic light beam as it passes from air to glass.

v_{air} v_{glass} , f_{air} f_{glass} , λ_{air} λ_{glass} . [2]

- (ii) Justify your choice of symbol for the case of the frequencies. [Your justification should not require use of the equation $v = f\lambda$.] [1]

.....

- (b) The diagram shows a narrow beam of light entering a solid cuboid (block) of glass of refractive index 1.52, surrounded by air (of refractive index 1.00).



- (i) Show clearly that $\theta = 65^\circ$. [3]

.....

- (ii) Show that the beam will not emerge into the air at point P. [2]

.....

- (iii) (I) Carefully complete the path of the beam, showing it eventually emerging into the air and travelling through the air. [1]

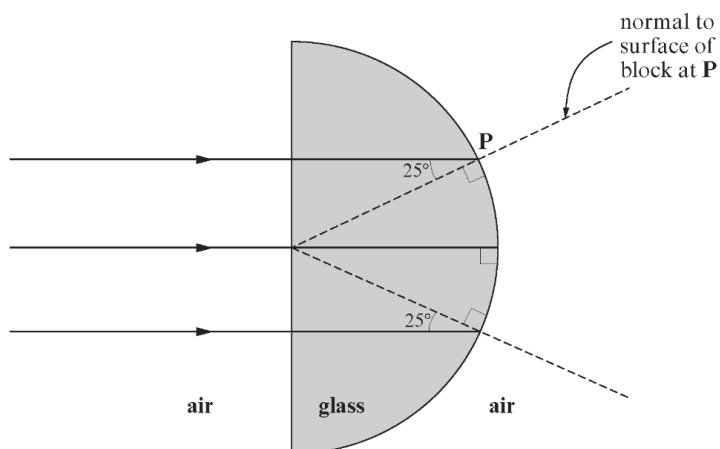
- (II) Indicate clearly on the diagram sections of the **whole** path which are parallel to each other. [2]

- (c) In a multimode fibre, light travels at a range of angles **to the fibre axis**. Explain why, for clear communication of rapid streams of data, the range of angles should be restricted so that even the greatest value of the angle is very small. [2]

.....

11.

- (a) (i) The diagram shows three beams of light travelling through a glass block of semicircular cross-section and refractive index, n , of 1.58. The block is surrounded by air (refractive index 1.00).



- (I) Sketch, on the diagram above, the paths of all three beams when they emerge into the air from the curved surface of the block. [2]
- (II) Calculate the angle to the normal at which the top beam emerges into the air at P. [2]

.....

.....

.....

.....

- (ii) (I) Show by calculation that a beam of light striking the curved surface at **Q** (see diagram alongside) will not re-enter the air at **Q**. [2]

.....

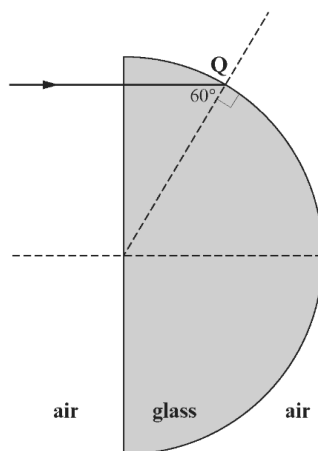
.....

.....

.....

.....

.....



- (II) **Continue** carefully on the diagram the path of the beam until it re-emerges into the air. [2]

- (b) (i) State how the core of a *monomode* optical fibre differs from that in a multimode fibre. [1]

.....

.....

- (ii) How do the paths of light in monomode and multimode fibres differ? [1]

.....

.....

.....

- (iii) Explain the advantage of monomode fibres over multimode fibres for communicating a rapid sequence of data encoded as light pulses. [3]

.....

.....

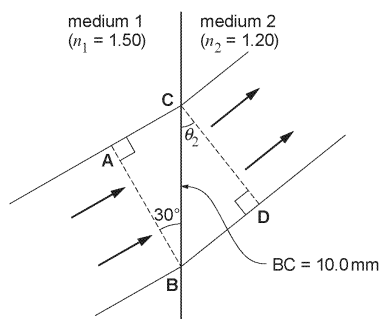
.....

.....

.....

.....

4. (a) A beam of light passes from medium 1, of refractive index $n_1 = 1.50$, into medium 2, of refractive index $n_2 = 1.20$.



- (i) Calculate the speeds of light in the two media. [1]

medium 1

.....

medium 2

.....

- (ii) Show clearly that the end, A, of wavefront AB will take $2.5 \times 10^{-11} \text{ s}$ to reach the boundary at C. [Note that distance BC = 10.0 mm .] [2]

.....

.....

.....

- (iii) While A is travelling to C, the end, B, of wavefront AB travels to D, through medium 2. Calculate the distance BD and hence the angle θ_2 . [2]

.....

.....

.....

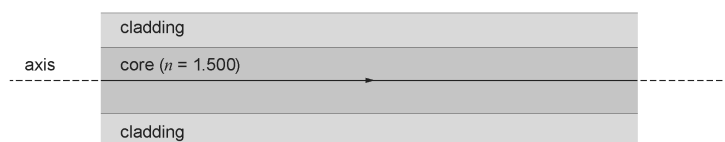
- (iv) Check your value of θ_2 using a refraction equation involving n_1 and n_2 . [2]

.....

.....

.....

- (b) A diagram of an optical fibre is given.



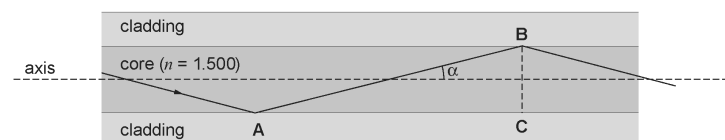
- (i) Show clearly that a light pulse travelling along the axis of the fibre takes $8.0\mu\text{s}$ to travel through 1.6km of fibre. [2]

.....

.....

.....

- (ii) The greatest angle, α , to the axis at which light can travel through the core without escaping is 14° . Calculate the refractive index of the cladding. [3]



.....

.....

.....

.....

.....

- (iii) Calculate the **difference** in times taken for a pulse to travel through 1.6km of fibre by the routes in (b)(i) and (b)(ii). [2]

.....

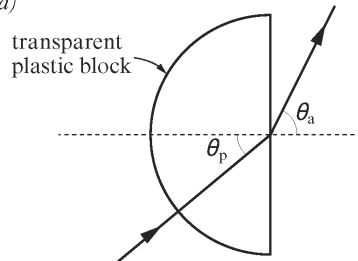
.....

.....

.....

13.

(a)

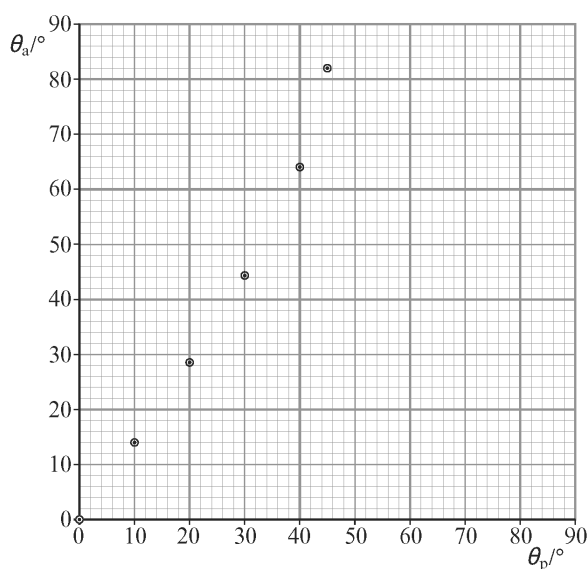


A student traces the path of a narrow beam of light through a transparent plastic block, and measures the angles θ_a and θ_p (see diagram). She repeats the measurements for various chosen values of θ_p , and her results are plotted below.

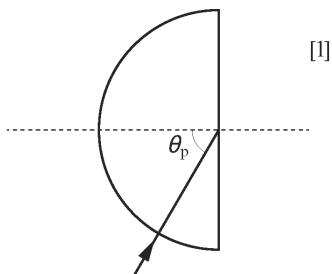
(i) Draw a curve of best fit. [1]

(ii) Without calculation, use the graph to obtain a value for the *critical angle* of the plastic.

Critical angle = [1]



(iii) Carefully continue the light path on the diagram, to show what would happen if the student had selected an angle θ_p which was greater than the critical angle.



- (iv) Use data from any one of the plotted points to calculate a value for the refractive index, n , of the plastic. [2]

.....

.....

.....

- (v) (I) Describe the line of best fit you would expect if $\sin \theta_a$ were plotted on the vertical, 'y', axis against $\sin \theta_p$. [2]

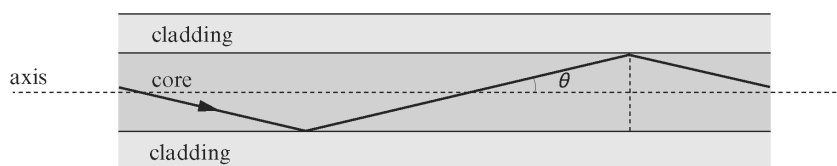
.....

.....

- (II) Briefly, how would you find n from this graph? [1]

.....

- (b) A multimode optical fibre has a core of refractive index 1.530 and a cladding of refractive index 1.520.



- (i) Calculate the *critical angle* for the boundary between the core and the cladding. [2]

.....

.....

- (ii) Hence determine the maximum angle, θ , between a light path and the axis of the fibre (see diagram) if the light is to travel for a long distance through the fibre. [1]

- (iii) Explain why it is an advantage for this angle to be small if data are being transmitted. [2]

.....

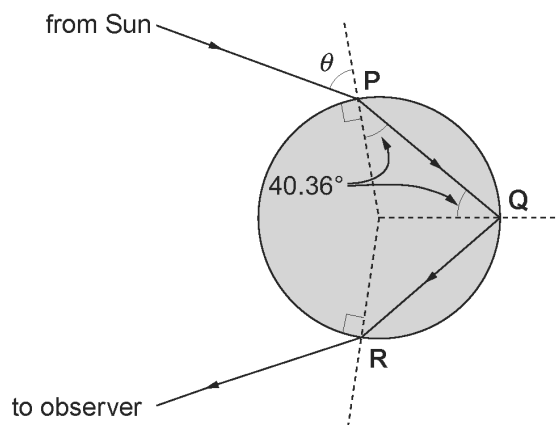
.....

.....

.....

14.

- (a) Rainbows form when sunlight is refracted and reflected by raindrops. The diagram shows the path of red light (of wavelength 700 nm) through a raindrop when a rainbow is observed.



- (i) The refractive index of water (for light of this wavelength) is 1.331. Calculate the angle of incidence, θ , at P. [Refractive index of air = 1.000.] [2]

.....

.....

.....

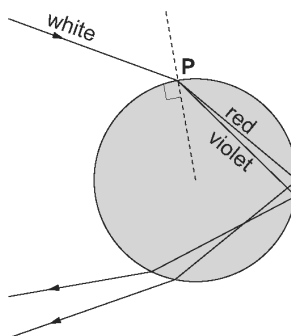
- (ii) Is the internal reflection at Q a case of *total* internal reflection? Give your reasoning clearly. [2]

.....

.....

.....

- (iii) The diagram below shows the paths (difference exaggerated) of violet and red light through the raindrop. The paths are different because different wavelengths of light travel through water at slightly different speeds.



By comparing the refraction of the red and the violet light at P, explain which colour, violet or red, travels more slowly through water. [2]

.....

.....

.....

(b) Light takes $1.75\ \mu\text{s}$ to travel through 360 m of multimode fibre by the quickest route through the core.

- (i) Show that the refractive index of the core is approximately 1.5, giving your own answer to 3 significant figures. [2]

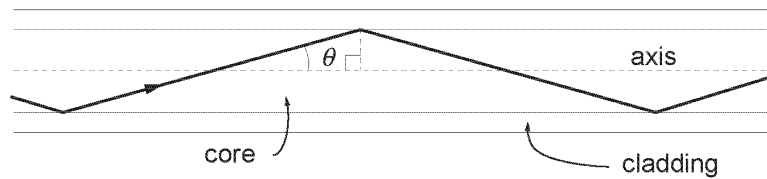
.....

.....

.....

.....

- (ii) The greatest angle, θ , to the axis at which light can propagate with total internal reflection is 15° .



Calculate the refractive index of the **cladding**. [3]

.....

.....

.....

- (iii) Although total internal reflection occurs for any angle smaller than 15° to the axis, the accurate transmission of data encoded as a rapid stream of pulses is more likely if the paths are restricted to a maximum angle much lower than 15° . Explain why. [3]

.....

.....

.....

.....