

1

A layer of liquid of refractive index 1.6 covers the horizontal flat surface of a glass block of refractive index 1.5. A ray of light strikes the boundary between them at an angle such that it travels along the boundary afterwards.

How does the ray strike the boundary?

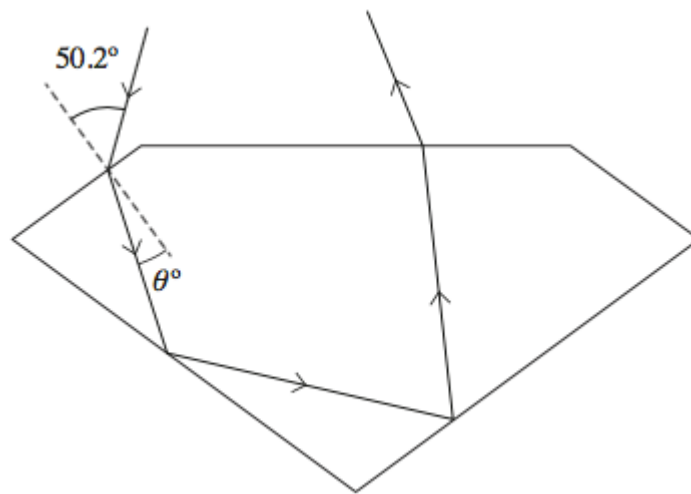
- A** it travels in glass at an angle of 70° to the boundary ☐
- B** it travels in glass at an angle of 20° to the boundary ☐
- C** it travels in the liquid at an angle of 70° to the boundary ☐
- D** it travels in the liquid at an angle of 20° to the boundary ☐

(Total 1 mark)

2

Diamond jewels sparkle because light that enters the diamond at different incident angles is reflected back to an observer. **Figure 1** shows the path of one of these incident rays through a diamond.

Figure 1



- (a) (i) Calculate the critical angle for diamond.

Refractive index of diamond = 2.42

critical angle = _____ degree

(2)

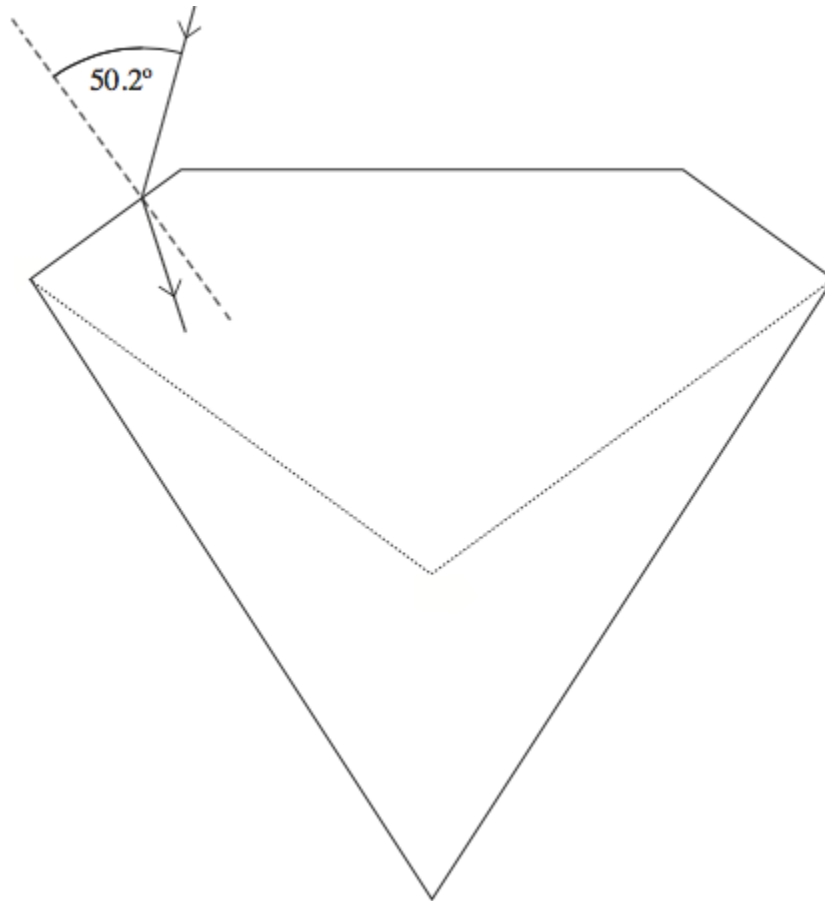
- (ii) The ray shown in **Figure 1** enters at an angle of incidence of 50.2° . Calculate the angle of refraction θ .

$\theta =$ _____ degree

(2)

- (iii) The angles of a diamond are chosen to maximise the amount of light reflected. **Figure 2** shows a diamond with different angles to that of a normally shaped diamond. The dotted lines show the normal shape of a diamond.

Figure 2



Draw on **Figure 2** the path of the ray until it leaves the diamond.

(2)

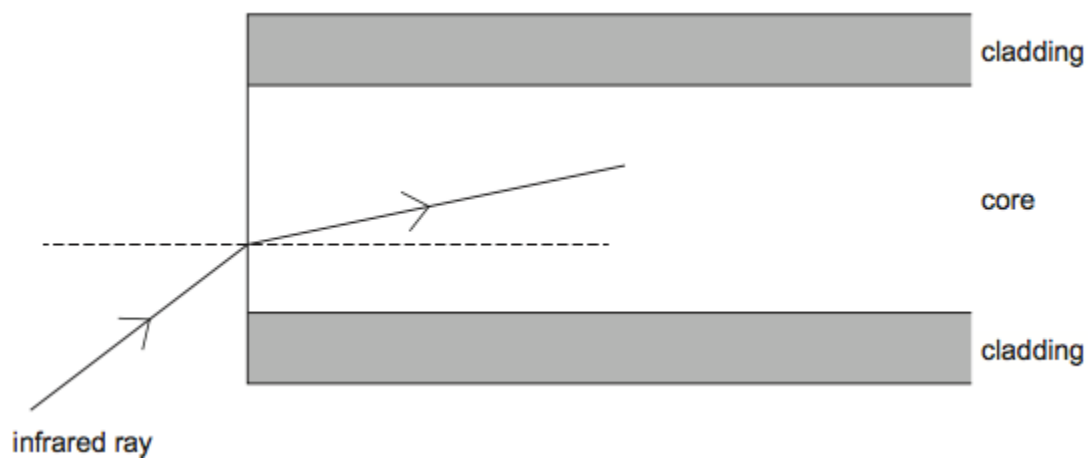
- (iv) Moissanite is a transparent material with a refractive index of 2.67.

Discuss whether this material, if made to the diamond shape shown in **Figure 1**, would reflect light back more or less than diamond.

(2)

- (b) **Figure 3** shows an infrared ray entering an optical fibre. The refractive index of the core is 1.55 at infrared frequencies.

Figure 3



- (i) Calculate the speed at which infrared radiation travels in the core.

speed = _____ m s⁻¹

(1)

- (ii) The wavelength of this infrared radiation is 1300 nm in air.
Calculate the wavelength of infrared in the core.

wavelength = _____ m

(2)

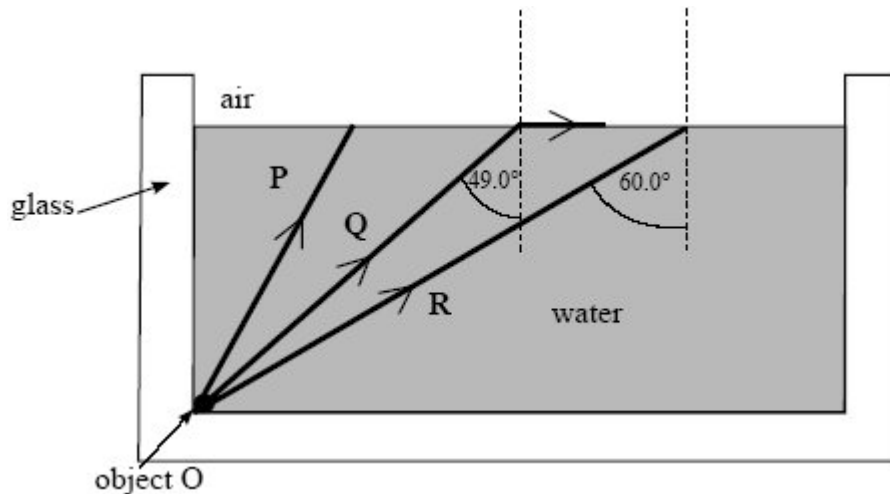
- (iii) State **one** reason for surrounding the core with cladding.

(1)

(Total 12 marks)

3

The diagram below shows a rectangular glass fish tank containing water. Three light rays, **P**, **Q** and **R** from the same point on a small object **O** at the bottom of the tank are shown.



- (a) (i) Light ray **Q** is refracted along the water-air surface. The angle of incidence of light ray **Q** at the water surface is 49.0° . Calculate the refractive index of the water. Give your answer to an appropriate number of significant figures.

Answer _____

(1)

- (ii) Draw on the diagram above the path of light ray **P** from the water-air surface.

(3)

(b) In the diagram above, the angle of incidence of light ray **R** at the water-air surface is 60.0° .

(i) Explain why this light ray is totally internally reflected at the water surface.

(2)

(ii) Draw the path of light ray **R** from the water surface and explain whether or not **R** enters the glass at the right-hand side of the tank.

the refractive index of the glass = 1.50

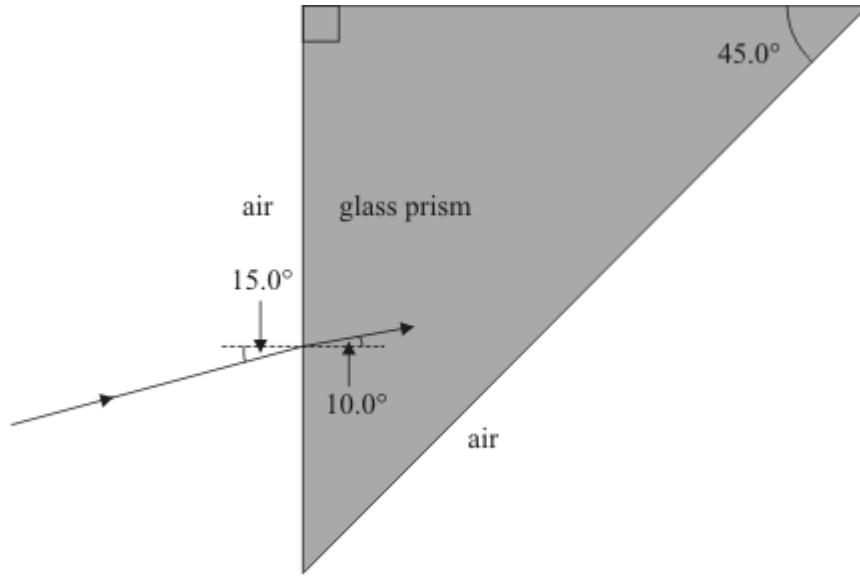
(4)

(Total 10 marks)

4

A ray of light passes from air into a glass prism as shown in **Figure 1**.

Figure 1



- (a) Confirm, by calculation, that the refractive index of the glass from which the prism was made is 1.49.

(1)

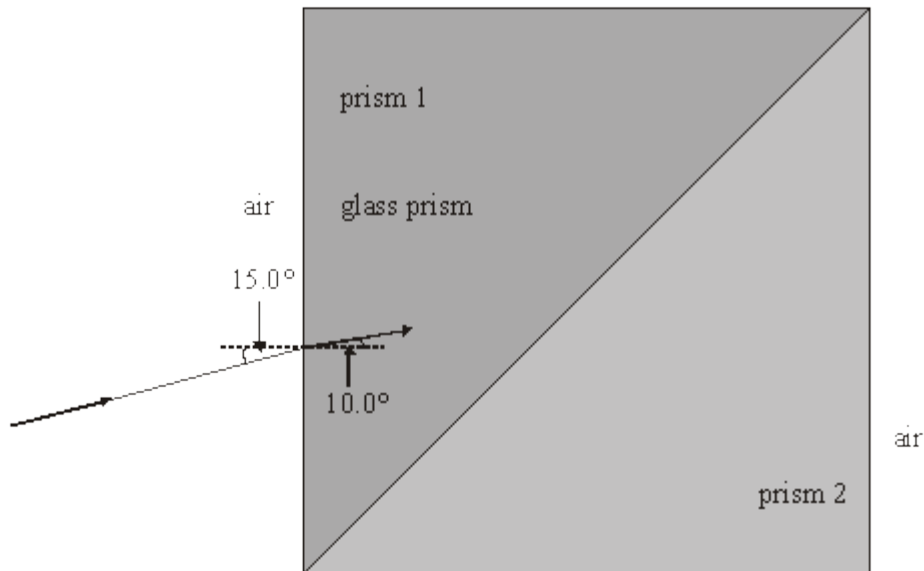
- (b) On **Figure 1**, draw the continuation of the path of the ray of light until it emerges back into the air. Write on **Figure 1** the values of the angles between the ray and any normals you have drawn.

the critical angle from glass to air is less than 45°

(2)

- (c) A second prism, prism 2, made from transparent material of refractive index 1.37 is placed firmly against the original prism, prism 1, to form a cube as shown in **Figure 2**.

Figure 2



- (i) The ray strikes the boundary between the prisms. Calculate the angle of refraction of the ray in prism 2.

- (ii) Calculate the speed of light in prism 2.

- (iii) Draw a path the ray could follow to emerge from prism 2 into the air.

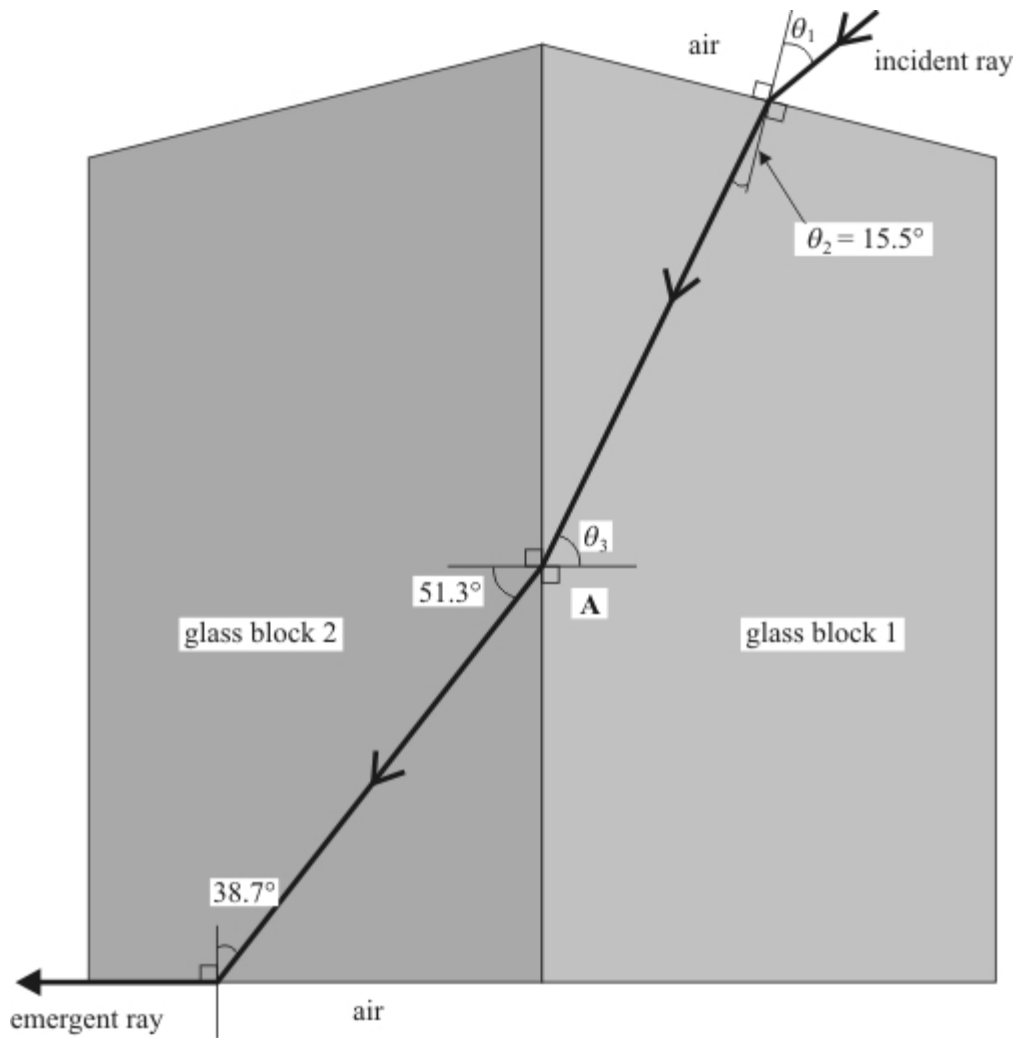
(7)

(Total 10 marks)

5

The figure below shows a ray of light passing from air into glass at the top face of glass block 1 and emerging along the bottom face of glass block 2.

refractive index of the glass in block 1 = 1.45



(a) Calculate

(i) the incident angle θ_1 ,

(ii) the refractive index of the glass in block 2,

(iii) the angle θ_3 by considering the refraction at point **A**.

(7)

(b) In which of the two blocks of glass will the speed of light be greater?

Explain your reasoning.

(2)

(c) Using a ruler, draw the path of a ray partially reflected at **A** on the figure above. Continue the ray to show it emerging into the air. No calculations are expected.

(2)

(Total 11 marks)

6

Figure 1 shows a cross-section through a rectangular light-emitting diode (LED). When current passes through the LED, light is emitted from the semiconductor material at P and passes through the transparent material and into the air at Q.

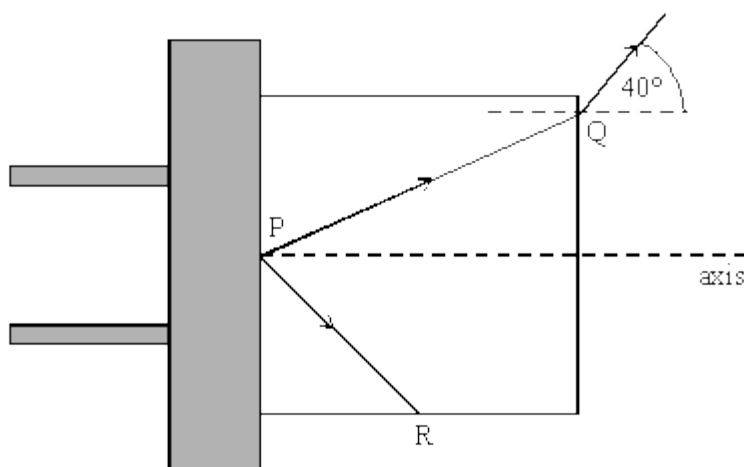


Figure 1

- (a) (i) The refractive index of the transparent material of the LED is 1.5. Calculate the critical angle of this material when the LED is in air.

- (ii) **Figure 1** shows a light ray PQ incident on the surface at Q. Calculate the angle of incidence of this light ray at Q if the angle of refraction is 40° .

- (iii) **Figure 1** also shows a second light ray PR incident at R at an angle of incidence of 45° . Use **Figure 1** to explain why this light ray cannot escape into the air.

- (b) The LED in part (a) is used to send pulses of light down two straight optical fibres of the same refractive index as the transparent material of the LED. The fibres are placed end-on with the LED, as shown in **Figure 2**. Optical fibre 1 is positioned at Q and the other at S directly opposite P.

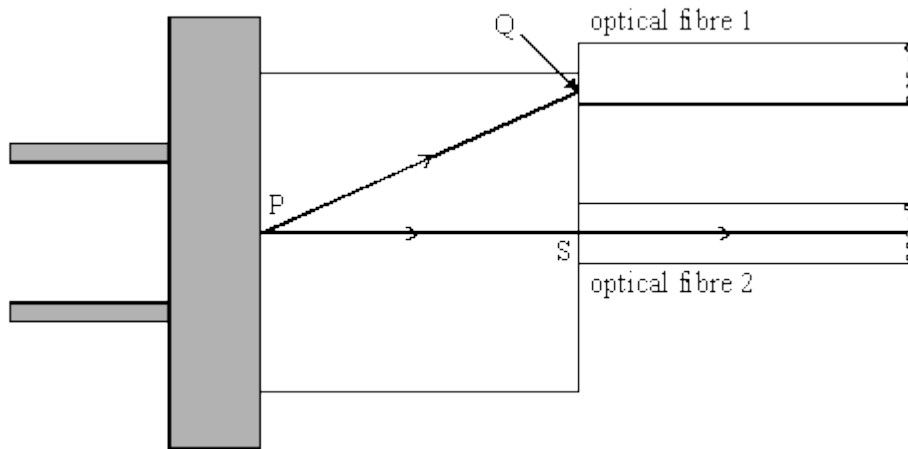


Figure 2

- (i) Continue the path of the light ray PQ into and along the optical fibre.
- (ii) Compare the times taken for pulses of light to travel along the same length of each fibre.

Give a reason for your answer.

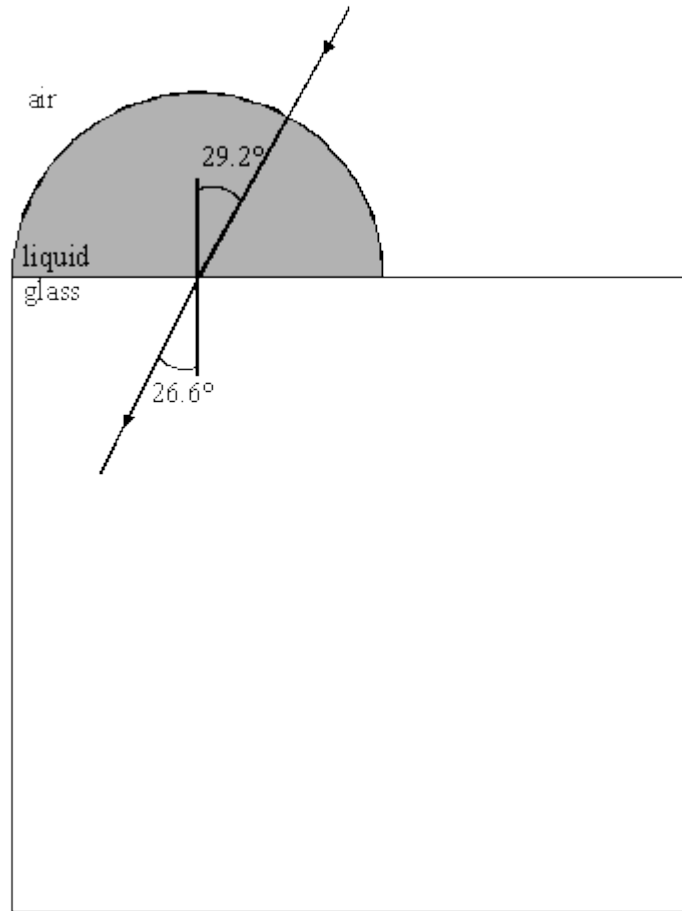
(3)

(Total 10 marks)

7

The diagram below shows a liquid droplet placed on a cube of glass. A ray of light from air, incident normally on to the droplet, continues in a straight line and is refracted at the liquid to glass boundary as shown.

refractive index of the glass = 1.45



(a) Calculate the speed of light

(i) in the glass,

(ii) in the liquid droplet.

- (b) Calculate the refractive index of the liquid.

(2)

- (c) On the diagram above, complete the path of the ray showing it emerge from the glass cube into the air.

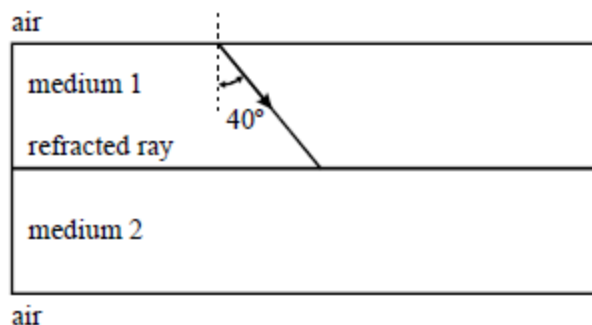
No further calculations are required.

(2)

(Total 7 marks)

8

A glass plate surrounded by air is made up of two parallel sided sheets of glass in perfect contact as shown in the figure. Medium 1, the top sheet of glass, has a smaller refractive index than medium 2.



- (a) A ray of light in air is incident on the top sheet of glass and is refracted at an angle of 40° as shown in the figure. At the boundary between medium 1 and medium 2 some light is transmitted and the remainder reflected.

On the figure, sketch without calculation, the following:

- (i) the path followed by the transmitted ray showing it entering from the air at the top and emerging into the air at the bottom;
- (ii) the path followed by the reflected ray showing it emerging from medium 1 into the air.

(4)

(b) The refractive index of medium 1 is 1.35 and that of medium 2 is 1.65.

(i) Calculate the angle of incidence where the ray enters medium 1 from the air.

(ii) Calculate the angle of refraction at the boundary between medium 1 and medium 2.

(5)

(c) Total internal reflection will not occur for any ray incident in medium 1 at the boundary with medium 2.

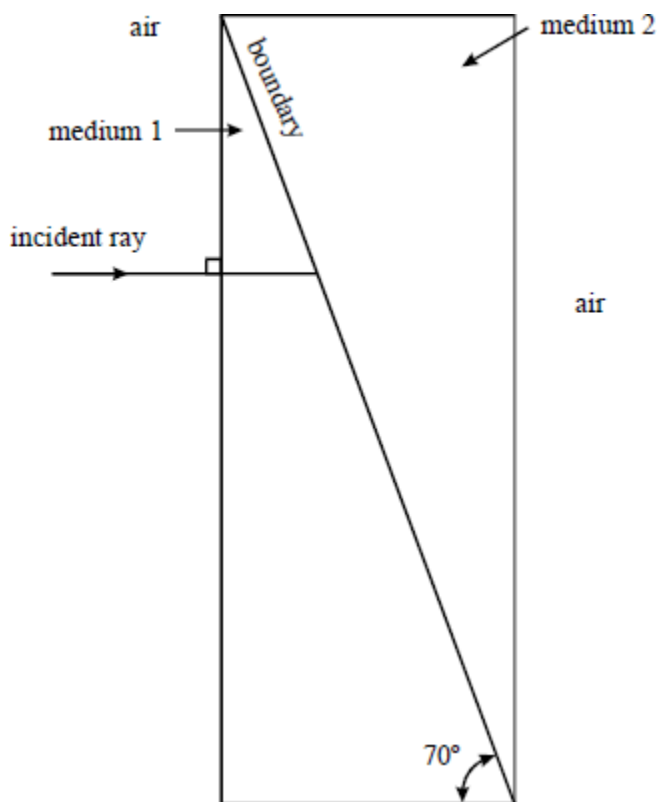
Explain, without calculation, why this statement is true.

(1)

(Total 10 marks)

9

Two prisms made from different glass are placed in perfect contact to form a rectangular block surrounded by air as shown. Medium 1 has a smaller refractive index than medium 2.



- (a) A ray of light in air is incident normally on medium 1 as shown. At the boundary between medium 1 and medium 2 some light is transmitted and the remainder reflected.
- Sketch, without calculation, the path followed by the refracted ray as it enters medium 2 and then emerges into the air.
 - Sketch, without calculation, the path followed by the reflected ray showing it emerging from medium 1 into the air.

(4)

- (b) The refractive index of medium 1 is 1.40 and that of medium 2 is 1.60.

- Give the angle of incidence at the boundary between medium 1 and medium 2.

- Calculate the angle of refraction at this boundary.

(4)

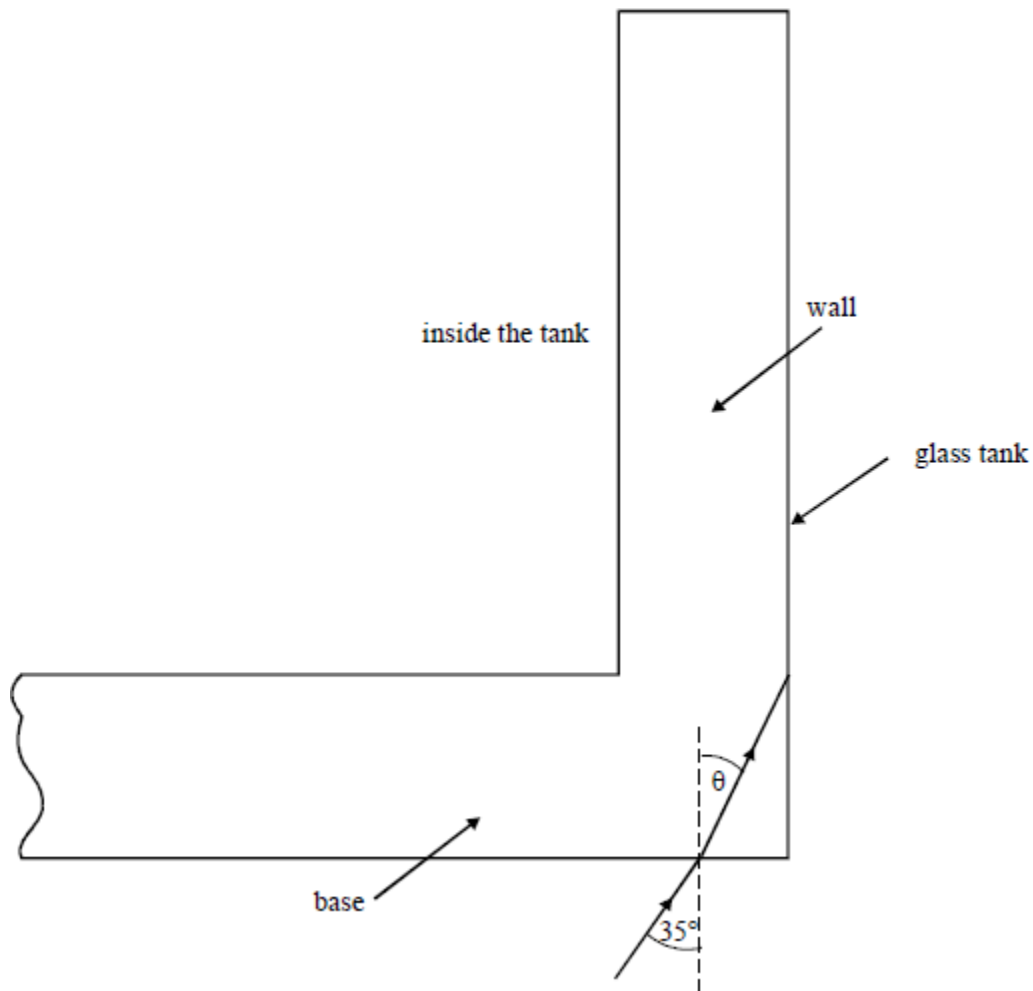
(c) Calculate the critical angle for a ray passing from medium 2 into the air.

(2)

(Total 10 marks)

10

The diagram shows a cross-section of one wall and part of the base of an empty fish tank, viewed from the side. It is made from glass of refractive index 1.5. A ray of light travelling in air is incident on the base at an angle of 35° as shown.



- (a) Calculate the angle θ .

(2)

- (b) (i) Calculate the critical angle for the glass-air interface.

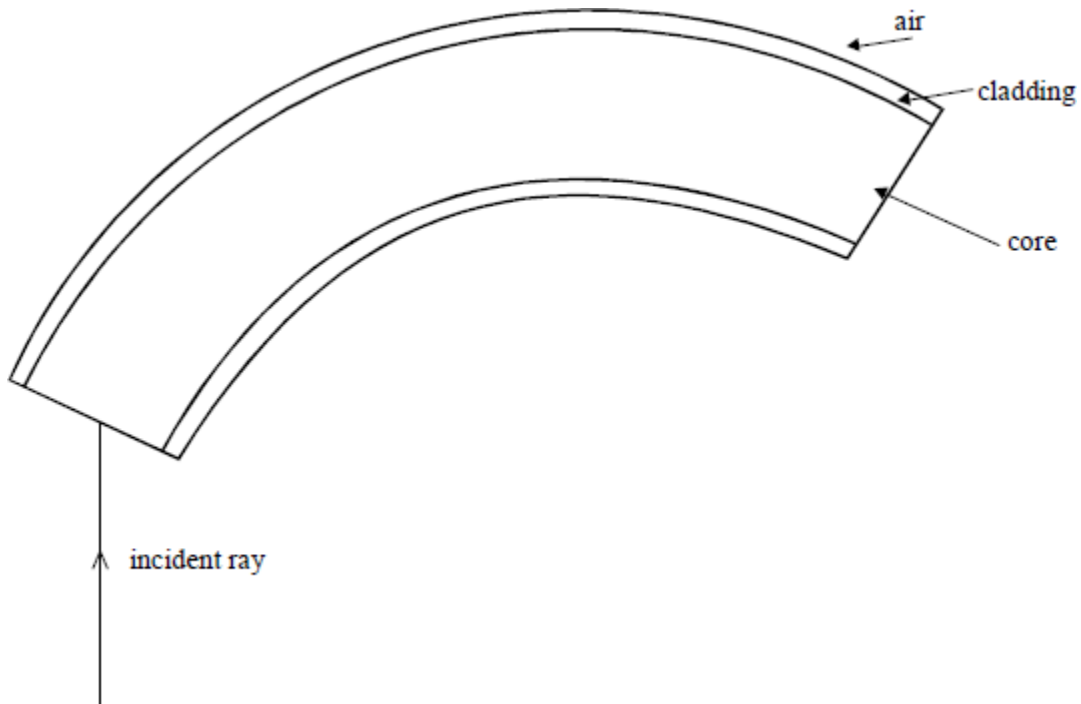
- (ii) Hence, draw on the diagram the continuation of the path of the ray through the glass wall and out into the air. Mark in the values of all angles of incidence, refraction and reflection.

(6)

(Total 8 marks)

11

- (a) The diagram shows a 'step index' optical fibre. A ray of monochromatic light, in the plane of the paper, is incident in air on the end face of the optical fibre as shown in the diagram.



- (i) Draw on the diagram the complete path followed by the ray until it emerges at the far end.
- (ii) Name the process which occurs as the ray enters the end of the optical fibre.

- (iii) The core has a refractive index of 1.50, clad in a material of refractive index 1.45. Calculate the critical angle of incidence at the core-cladding interface.

(7)

- (b) (i) Give **one** reason why a cladding material is used in an optical fibre.

- (ii) In part (a)(iii), the cladding material has a refractive index of 1.45. Explain why it would be advantageous to use cladding material of refractive index less than 1.45.

(3)

- (c) State **one** use of optical fibres.

(1)

(Total 11 marks)

12

Figures 1 and 2 each show a ray of light incident on a water-air boundary. **A**, **B**, **C** and **D** show ray directions at the interface.

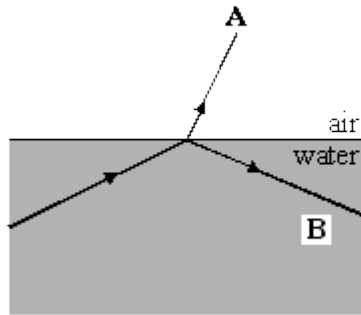


Figure 1

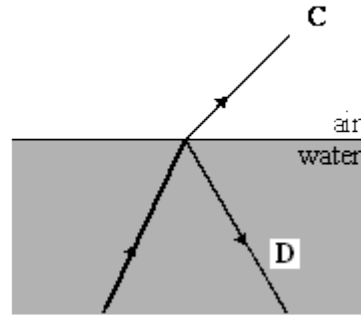


Figure 2

- (a) Circle the letter below that corresponds to a direction in which a ray **cannot** occur.

A **B** **C** **D**

(1)

- (b) Circle the letter below that corresponds to the direction of the faintest ray.

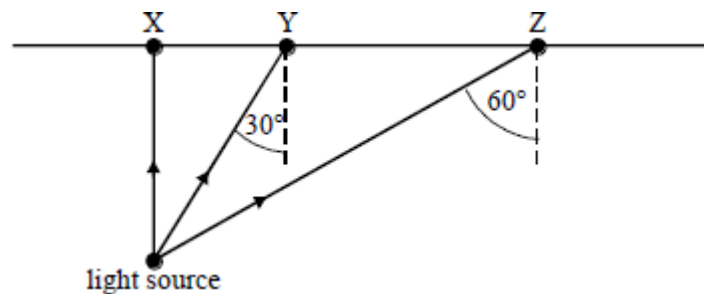
A **B** **C** **D**

(1)

(Total 2 marks)

13

A small intense light source is 1.5 m below the surface of the water in a large swimming pool, as shown in the diagram.



- (a) Complete the paths of rays from the light source which strike the water surface at X, Y and Z.

- (b) Calculate the diameter of the disc through which light emerges from the surface of the water.

speed of light in water = $2.25 \times 10^8 \text{ m s}^{-1}$

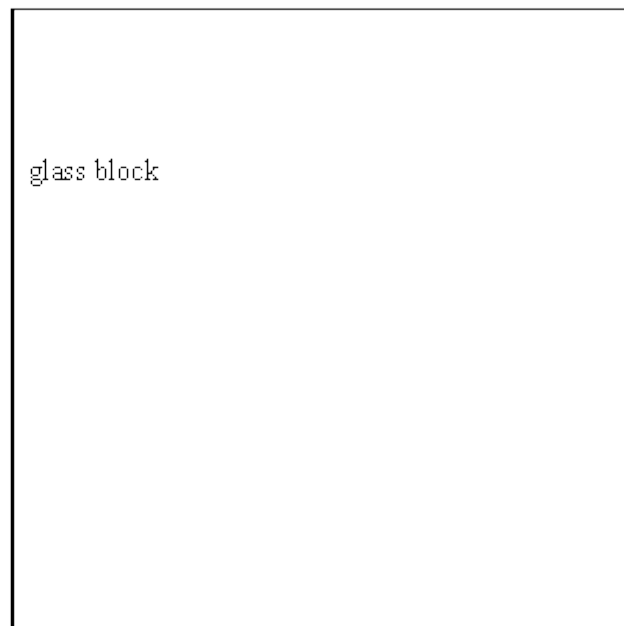
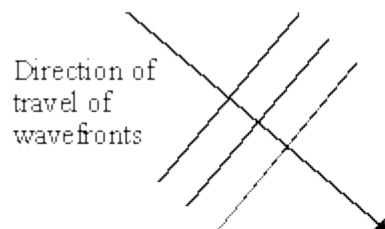
speed of light in air = $3.00 \times 10^8 \text{ m s}^{-1}$

(Total 7 marks)

14

The diagram below shows three wavefronts of light directed towards a glass block in the air. The direction of travel of these wavefronts is also shown.

Complete the diagram to show the position of these three wavefronts after partial reflection and refraction at the surface of the glass block.



(Total 3 marks)

Mark schemes

1

D

[1]

2

(a) (i) $\sin C = 1/n = 1/2.42 \checkmark (= 0.413)$

$C = 24.4^\circ \checkmark$ (allow 2 or more sig figs)

Answer only gains both marks

2

(ii) $\sin \theta_{\text{dia}} = \sin \theta_{\text{air}} / n = \sin 50.2 / 2.42 \checkmark (= 0.317)$

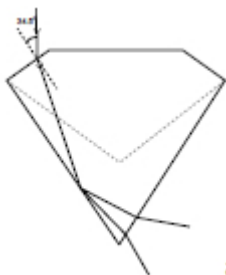
$\theta_{\text{dia}} = 18.5^\circ \checkmark$ (allow 2 or more sig figs)

Answer only gains both marks

Answer can be 18° or 19° depending on rounding

2

- (iii) TIR shown at bottom left surface $\checkmark$ (If the reflected ray were extended it would pass through the writing below the diagram between the 'i' in 'it' and the full stop at the end of 'diamond'.) ray leaves bottom right surface either with an increased emergent angle or straight though if hitting normally $\checkmark$
(The second mark is consequential on gaining the first mark)



acceptable emergent rays

2

- (iv) it has smaller critical angle / critical angle is 22°
allowing more / same number / greater chance / increased probability of TIR's occurring

greater/same sparkle $\checkmark\checkmark$ max 2

'reflect more' is insufficient for a mark

2

(b) (i) $c_{\text{core}} = c_{\text{air}} / n = 3.00 \times 10^8 / 1.55 = 1.9 \times 10^8 \text{ (ms}^{-1}\text{)} \checkmark (1.94 \times 10^8 \text{ ms}^{-1})$

1 sig fig is not acceptable if no other answer is given

1

(ii) $(n = c_{\text{air}} / c_{\text{core}} = f \lambda_{\text{air}} / f \lambda_{\text{core}} = \lambda_{\text{air}} / \lambda_{\text{core}})$

$\lambda_{\text{core}} = \lambda_{\text{air}} / n$ or $1300 \times (10^{-9}) / 1.55$ ✓

$= 8.4 \times 10^{-7} \text{ (m)}$ ✓ $(8.39 \times 10^{-7} \text{ m or } 839 \text{ nm})$

The first mark is for the equation or substitution ignoring powers of 10 errors

1st mark can be gained from calculating the frequency ($f = 3.0 \times 10^8 / 1300 \times 10^{-9} = 2.3 \times 10^{14} \text{ (Hz)}$ which then can be used to find the the wavelength

Using this method the answer can range between $8.4 \times 10^{-7} \rightarrow 8.7 \times 10^{-7} \text{ (m)}$ and consider ecf's from (b)(i)

2

(iii) protects the core (from scratches etc)

prevents crosstalk / stops signal crossing from one fibre to another / increases critical angle / reduces pulse broadening / reduces smearing / prevents multipath dispersion allows fibre to be supported / touched (without losing light)

✓any one point

Preventing signal loss is not enough for the mark.

1

[12]

3

(a) (i) (refractive index of water = $1/\sin 49.0$) = **1.33** (not 1.3 or 1.325) **(1)**

(ii) ray P shown in the air to right of vertical **(1)**

refracted away from the normal in the correct direction **(1)**

correct partial reflection shown **(1)**

4

(b) (i) **critical angle** for water-air boundary = 49.0°
or angle of (incidence of) Q is θ_c **(1)**

the angle of incidence (of R) exceeds the critical angle **(1)**

(ii) the figure shows that R undergoes TIR at water surface and strikes the glass side **(1)**

angle of incidence at glass side = 30° **(1)**

R enters the glass and refracts towards the normal **(1)**

because $n_g > n_w$ **(1)** (or water is optically less dense than glass)

(calculates angle = 26.2° gets last two marks)

6

[10]

4

(a) $n = \left(\frac{\sin \theta_1}{\sin \theta_2} \right) = \frac{\sin 15.0^\circ}{\sin 10.0^\circ} \text{ (1) } (= 1.49)$

1

- (b) TIR on hypotenuse **and** refraction at top surface **(1)**
 55°, 10° and 15° all marked correctly **(1)**

2

(c) (i) use of $n_1 \sin \theta_1 = n_2 \sin \theta_2$ and $n_1 \sin \theta_1 = n_2 \sin \theta_2$

[or $n_1 \sin \theta_1 = n_2 \sin \theta_2$] **(1)**

$1.49 \sin 55^\circ = 1.37 \sin \theta_2$ **(1)**

$\theta_2 = 63^\circ$ **(1)**

(ii) (use of $n = \frac{c_1}{c_2}$) gives $1.37 = \frac{3.0 \times 10^8}{c_2}$ **(1)**

$c_2 = 2.2 \times 10^8 \text{ ms}^{-1}$ **(1)**

$(2.19 \times 10^8 \text{ ms}^{-1})$

- (iii) refraction at boundary between prisms, refracted away from normal **(1)**

emerging ray (r.h. vertical face) refracting away from normal **(1)**

7

[10]**5**

(a) (i) (use of $n = \frac{\sin \theta_1}{\sin \theta_2}$ gives) $1.45 = \frac{\sin \theta_1}{\sin 15.5^\circ}$ **(1)**

$\theta_1 = 22.8^\circ$ **(1)**

$$(ii) \quad n = \frac{1}{\sin \theta_c} \quad (1)$$

$$n = \left(\frac{1}{\sin 38.7^\circ} \right) = 1.6(0) \quad (1)$$

$$\text{use of } n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad \text{and} \quad n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (1)$$

$$[\text{or } n_1 \sin \theta_1 = n_2 \sin \theta_2]$$

$$1.45 \sin \theta_3 = 1.60 \sin 51.3 \quad (1)$$

$$\theta_3 = 59.4^\circ \quad (1)$$

(allow C.E. for value of n from (ii))

7

(b) block 1 **(1)** (requires some explanation)

$$\text{reference to } \frac{\sin \theta_1}{\sin \theta_2} = \frac{c_1}{c_2} \quad (1)$$

[or statement such as light refracts/bends towards normal as it enters a denser/higher refractive index material, or block 1 has lower refractive index]

2

(c) reflection at boundary with $i = r$ **(1)**

refraction (at bottom surface) bending away from normal **(1)**

2

[11]

6

$$(a) \quad (i) \quad \sin c = \frac{1}{1.5} \quad (1)$$

$$c = 42^\circ \quad (1) \quad (41.8^\circ)$$

$$(ii) \quad 1.5 \sin i = \sin 40 \quad (1)$$

$$i = 25^\circ \quad (1) \quad (25.4^\circ) \quad (\text{use of } c = 41.8^\circ \text{ gives } i = 26.4^\circ)$$

(iii) total internal reflection at R **(1)**

further total internal reflection below Q **(1)**

further total internal reflection **(1)**

7

- (b) (i) light ray enters fibre without refraction **(1)**
total internal reflection at fibre/air surface **(1)**
- (ii) pulse in fibre 1 takes longer because it travels across the fibre
as well as along it **(1)**

3

[10]

7

- (a) (i) (use of $n = \frac{c_1}{c_2}$ gives) $c_{\text{glass}} = \times \left(= \frac{3.00 \times 10^8}{1.45} \right)$
 $= 2.07 \times 10^8 \text{ m s}^{-1}$ **(1)**
- (ii) use of $\frac{\sin \theta_1}{\sin \theta_2} = \frac{c_1}{c_2}$ **(1)**
- $$c_{\text{liquid}} = \frac{2.07 \times 10^8 \times \sin 29.2^\circ}{\sin 26.6^\circ} = 2.26 \times 10^8 \text{ m s}^{-1}$$
- (1)**
-
- (allow C.E. for values of
- c_{glass}
- from (i))

3

- (b) use of $\frac{n_2}{n_1} = \frac{c_1}{c_2}$

$$\text{to give } n_{\text{liquid}} = \frac{1.45 \times 2.07 \times 10^8}{2.26 \times 10^8} = 1.33$$
 (1)

$$\left[\text{or } n_1 = \frac{c_1}{c_{\text{liquid}}} = \frac{3 \times 10^8}{2.26 \times 10^8} = 1.33 \right] \quad (\text{allow C.E. for value of } c_{\text{liquid}})$$

$$[\text{or use } {}_1n_2 = \frac{n_2}{n_1} = \frac{\sin \theta_1}{\sin \theta_2} \text{ to give correct answer}]$$

2

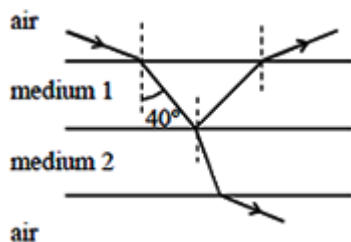
- (c) diagram to show :
total internal reflection on the vertical surface **(1)**
refraction at bottom surface with angle in air greater
than that in the liquid (29.2°) **(1)**

2

[7]

8

- (a)



- (i) incident angle $> 40^\circ$ **(1)**
 angle of refraction into medium 2 $< 40^\circ$ **(1)**
 emergent ray with correct refraction **(1)**
- (ii) reflection at boundary between media with $i \approx r$ **(1)**
 (hence) emergent ray at approximately same angle as incident ray
 and showing correct refraction **(1)**

max 4

(b) (i) (use of ${}_1n_2 = \frac{\sin \theta_1}{\sin \theta_2}$ gives) $1.35 = \frac{\sin \theta_1}{\sin 40}$ **(1)**
 $\theta_1 = 60(2)^\circ$ **(1)**

(ii) (use of ${}_1n_2 = \frac{n_2}{n_1} = \frac{\sin \theta_1}{\sin \theta_2}$ gives) $\frac{1.65}{1.35} = \frac{\sin 40}{\sin \theta_2}$ **(1) (1)**
 $\theta = 31.7^\circ$ **(1)**

5

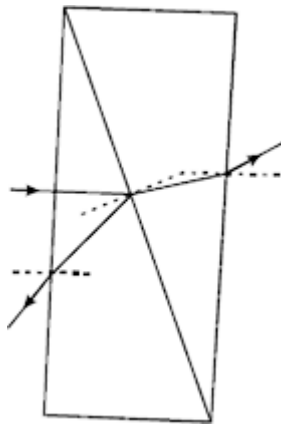
- (c) (total internal reflection) only occurs when light goes
 from a higher to a lower refractive index
 [or goes from a more dense to a less dense medium/material] **(1)**

1

[10]

9

(a)



Ray diagram to show:

- (i) refraction towards normal at boundary **(1)**
 emerging ray refracted away from normal **(1)**
- (ii) reflection at boundary with $i \approx r$
 emerging ray refracted away from normal **(1)**

4

(b) (i) 20° (1)

(ii) ${}_1n_2 = \frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}$ (1)

$$\frac{1.60}{1.40} = \frac{\sin 20^\circ}{\sin \theta} \quad (1)$$

$$\theta_2 = 17.4^\circ \quad (1)$$

4

(c) $(\sin \theta_c = 1/n \text{ gives}) \quad \sin \theta_c = 1/1.60$ (1)

$$= \theta_c = 38.7^\circ \quad (1)$$

2

[10]

10

(a) $({}_1n_2 = \frac{\sin \theta_1}{\sin \theta_2} \text{ gives}) \quad 1.5 = \frac{\sin 35^\circ}{\sin \theta}$ (1)

$$\theta = 22^\circ \quad (1) \quad (22.48^\circ)$$

(2)

(b) (i) $(\sin \theta_c = 1/n \text{ gives}) \quad \sin \theta_c = \frac{1}{1.5}$ (1)

$$\theta_c = 42^\circ \quad (1) \quad (41.8^\circ)$$

- (ii) ray diagram to show:
one total internal reflection (1)
with one angle of reflection marked as 68° (1)
correct refraction of ray on exit from top surface with 35° marked (1)
angle of incidence of 22° marked at point of exit (1)

(6)

[8]

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(a) (i) diagram to show: (1)

ray refracted towards normal (1)

total internal reflection at core-cladding interface (1)

$i = r$ indicated (1)

ray continues whole length of fibre and emerges, without errors (1)

(ii) refraction (1)

(iii) use of $n_2 = \frac{\sin \theta_1}{\sin \theta_2}$ gives $\frac{n_2}{n_1} = \frac{\sin \theta_1}{\sin \theta_2}$ (1)

$$\frac{1.54}{1.45} = \frac{1}{\sin \theta_2} \quad (1)$$

$$\theta_C (= \theta_2) = 75.2^\circ \quad (1)$$

[or $\sin \theta_C = 1/n$ gives $\sin \theta_C = n_{\text{clad}}/n_{\text{core}}$ (1)

$$\sin \theta_C = 1.45/1.50 \quad (1)$$

$$\theta_C = 75.2^\circ (1)]$$

(max 7)

(b) (i) to protect outer surface of the core (1)

(ii) greater acceptance angle (1)

enables more light to be collected

(or smaller critical angle makes escape less likely) (1)

(3)

(c) endoscopy or communications (1)

(1)

[11]

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(a) A

B1

(b) D

B1

[2]

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(a) ray straight through at X (1)

ray refracted at $>30^\circ$ at Y (1)

ray totally internally reflected at Z (1)

(b) $\frac{\sin \theta_{\text{water}}}{\sin \theta_{\text{air}}} = \frac{c_{\text{water}}}{c_{\text{air}}} \left[\text{or} = \frac{2.55 \times 10^8}{3.00 \times 10^8} \right]$

at critical angle $\sin \theta_{\text{air}} = 1$ (1)

$\sin \theta_{\text{water}} = 0.75$, $\theta_{\text{water}} = 48.6^\circ$ (1)

radius = $1.5 \tan 48.6^\circ$ (1) = 1.7m, $\therefore$ diameter = 3.4m (1)

[7]

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reflection wavefront direction sensible

B1

refraction wavefront direction sensible

B1

one pair of wavefronts correctly spaced

B1

[3]