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3.5 Refraction

PHYSICS

AQA A Level Revision Notes

3.5 Refraction

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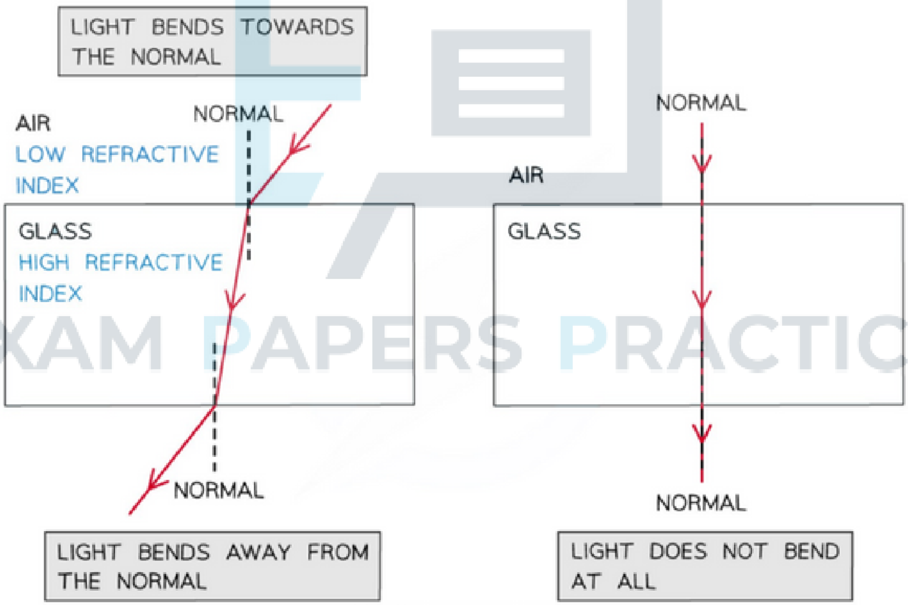
Refractive Index

- Refraction occurs when light passes a boundary between two different transparent media
- At the boundary, the rays of light undergo a **change in direction**
- The direction is taken as the angle from a hypothetical line called the normal
    - This line is perpendicular to the surface of the boundaries and is represented by a straight dotted line
- The change in direction depends on which media the light rays pass between:
    - From air to glass (less dense to more dense): light bends **towards** the normal
    - From glass to air (more dense to less dense): light bends **away** from the normal
    - When passing along the normal (perpendicular) the light **does not bend** at all



Refraction of light through a glass block

- The change in direction occurs due to the change in speed when travelling in different substances
    - When light passes into a denser substance the rays will **slow down**, hence they bend towards the normal

- The only properties that change during refraction are speed and wavelength – the frequency of waves **does not change**
    - Technically the intensity and amplitude of the wave also decreases slightly upon refraction since a small portion of the wave also reflects but this is not as noticeable as the change in speed and wavelength

Calculating Refractive Index

- The refractive index, *n*, is a property of a material which measures how much light slows down when passing through it

$$n = \frac{c}{c_s}$$

- Where:
    - c = the speed of light in a vacuum (m s^{-1})
    - c_s = the speed of light in a substance (m s^{-1})

- Light travels at different speeds within different substances depending on their refractive index
    - A material with a high refractive index is called **optically dense**, such material causes light to travel **slower**

- Since the speed of light in a substance will always be less than the speed of light in a vacuum, the value of the n is **always greater than 1**
- In calculations, the refractive index of air can be taken to be approximately 1
    - This is because light does not slow down significantly when travelling through air (as opposed to travelling through a vacuum)

Exam Tip

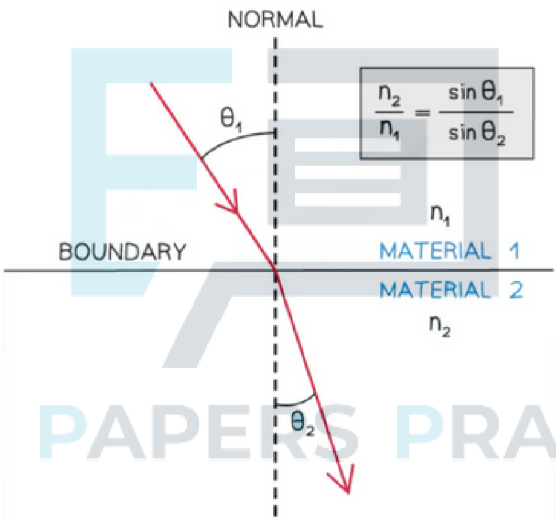
Always double-check if your calculations for the refractive index are greater than 1. Otherwise, something has definitely gone wrong in your calculation!The refractive index of air will not be given in the question. Always assume that $n_{air} = 1$

Snell's Law

- Snell's law relates the angle of incidence to the angle of refraction, it is given by:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

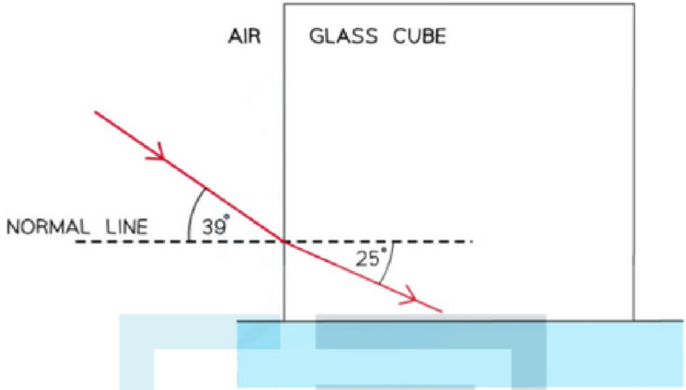
- Where:
  - n_1 = the refractive index of material 1
  - n_2 = the refractive index of material 2
  - θ_1 = the angle of incidence of the ray in material 1
  - θ_2 = the angle of refraction of the ray in material 2



- θ_1 and θ_2 are always taken from the **normal**
- Material 1 is always the material in which the ray goes through **first**
- Material 2 is always the material in which the ray goes through **second**

Worked Example

A light ray is directed at a vertical face of a glass cube. The angle of incidence at the vertical face is 39° and the angle of refraction is 25° as shown in the diagram.



Show that the refractive index of the glass is about 1.5.

Step 1: Write down the known quantities

- Refractive index of air, $n_1 = 1$
- Refractive index of glass = n_2
- Angle of incidence, $\theta_1 = 39°$
- Angle of refraction, $\theta_2 = 25°$

Step 2: Write out Snell's Law

$$\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}$$

Step 3: Calculate the refractive index of glass

$$n_2 = \frac{\sin 39}{\sin 25} = 1.489 = 1.5 \text{ (2 s.f.)}$$

- Note that in a "show that" question, the answer should be to at least one more significant figure than the value given in the question

Exam Tip

Always check that the angle of incidence and refraction are the angles between the normal and the light ray. If the angle between the light ray and the boundary is calculated instead, calculate 90 – θ (since the normal is perpendicular to the boundary) to get the correct angle

Total Internal Reflection

- As the angle of incidence is increased, the angle of refraction also increases until it gets closer to 90°
- When the angle of refraction is exactly 90° the light is refracted along the boundary
  - At this point, the angle of incidence is known as the **critical angle** θ_c
- This angle can be found using the formula:

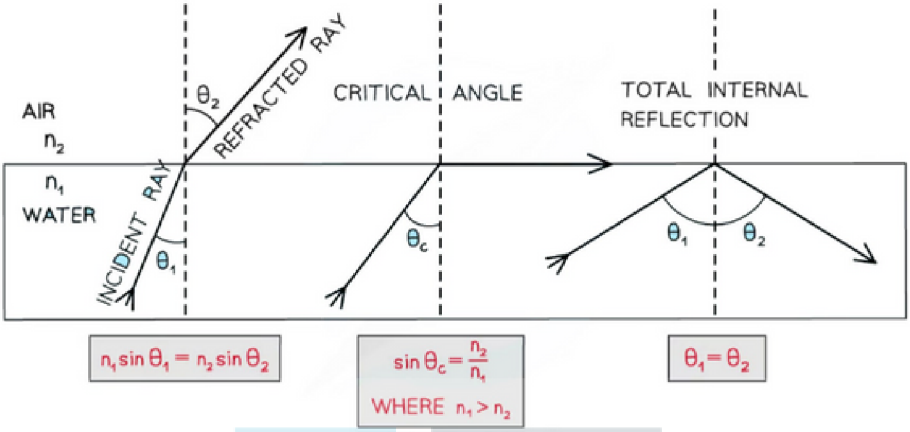
$$\sin \theta_c = \frac{n_2}{n_1}$$

- This can easily be derived from Snell's law where:
  - $\theta_1 = \theta_c$
  - $\theta_2 = 90°$
  - $n_1 > n_2$

- Total internal reflection (TIR) occurs when:

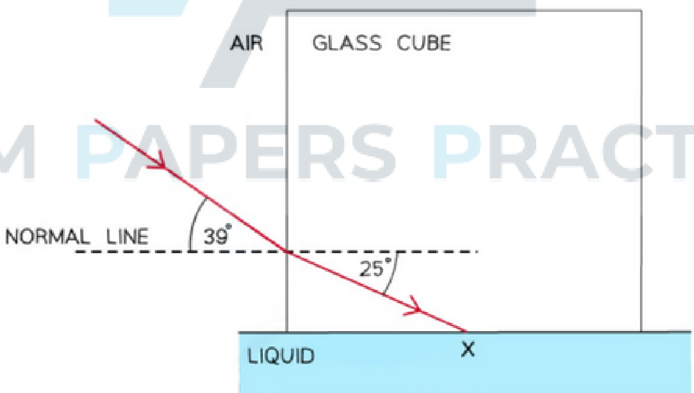
The angle of incidence is greater than the critical angle and the incident refractive index n_1 is greater than the refractive index of the material at the boundary n_2

- Therefore, the **two** conditions for total internal reflection are:
  - The angle of incidence > the critical angle
  - The refractive index n_1 is greater than the refractive index n_2



Worked Example

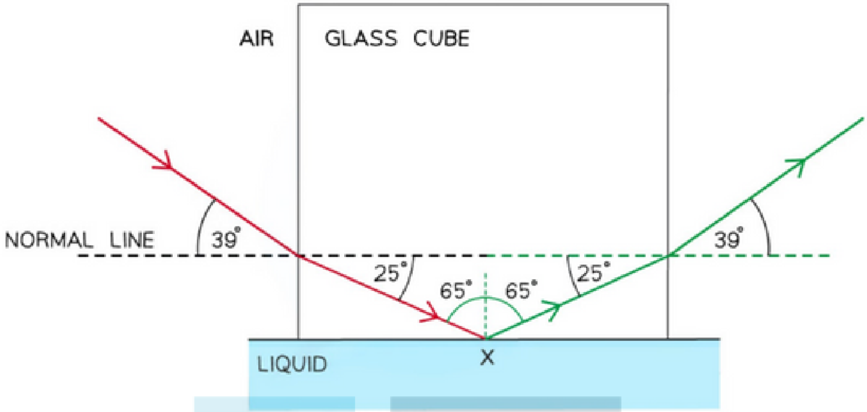
A glass cube is held in contact with a liquid and a light ray is directed at the vertical face of the cube. When the angle of incidence at the vertical face is 39° and the angle of refraction is 25° as shown in the diagram, the light ray is totally internally reflected at **X** for the first time.



(i) Complete the diagram to show the path of the ray beyond **X** to the air and calculate the critical angle for the glass-liquid boundary.

(ii) Calculate the refractive index of the liquid.

(i)



Step 1: Draw the reflected angle at the glass-liquid boundary

- When a light ray is reflected, the angle of incidence = angle of reflection
- Therefore, the angle of incidence (or reflection) is 90° – 25° = 65°

Step 2: Draw the refracted angle at the glass-air boundary

- At the glass-air boundary, the light ray refracts **away** from the normal when the ray leaves to air (as air is less dense)
- Due to the reflection, the light rays are symmetrical on either side of the glass (39°)

Step 3: Calculate the critical angle for the glass-liquid boundary

- The question states the ray is "totally internally reflected for the first time" meaning that this is the **smallest** angle at which TIR occurs
- Therefore, 65° is the critical angle

(ii)**Step 1: Write down the known quantities**

- Refractive index of glass, n_1 = 1.489 (from previous worked example)
- Refractive index of liquid = n_2
- Angle of incidence / critical angle, $\theta_1 = \theta_c$ = 65°
- Angle of refraction, θ_2 = 90°

Step 2: Write out Snell's Law or the equation for critical angle

$$\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2} \quad \text{or} \quad \sin\theta_c = \frac{n_2}{n_1}$$

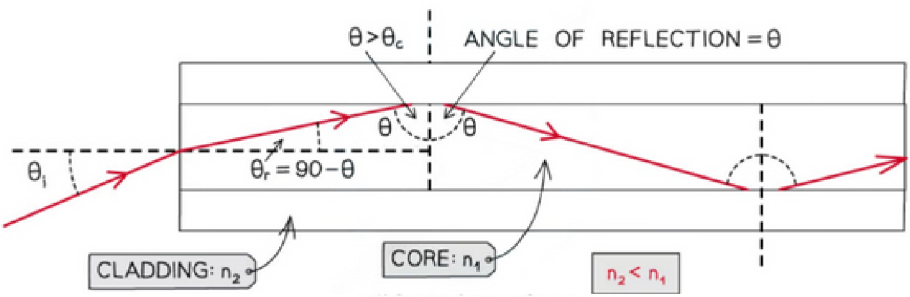
Step 3: Calculate the refractive index of the liquid

$$n_2 = \frac{\sin 65}{\sin 90} \times 1.489 = 1.35 \text{ (3 s.f.)}$$

3.5.3 Fibre Optics

Fibre Optics

- Fibre optics utilise the phenomenon of total internal reflection to send high speed light signals over large distances
- These have many important uses, including:
  - Communications, such as telephone and internet transmission
  - Medical imaging, such as endoscopes



A light ray is totally internally reflected down an optical fibre

- There are three main components that make up optical fibres:
  - An optically dense **core**, such as plastic or glass
  - A lower optical density **cladding** surrounding the core
  - An **outer sheath**

- Since the refractive index of the core is **more** than the refractive index of the cladding, this allows TIR to occur
  - $n_{cladding} < n_{core}$

- The outer sheath:
  - Prevents physical damage to the fibre
  - Strengthens the fibre
  - Protects the fibre from the outside from scratches

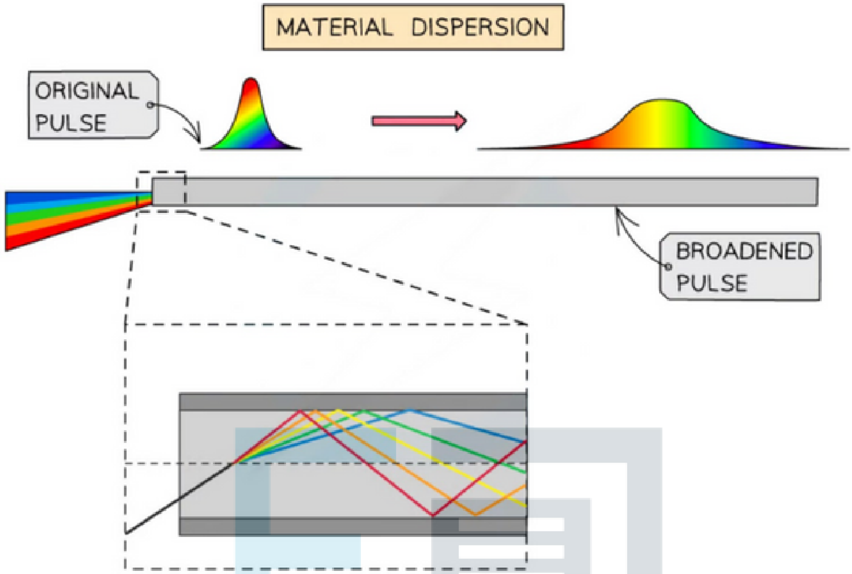
- The cladding is also required because:
  - It protects the core from damage
  - It prevents signal degradation through light escaping the core, which can cause information from the signal to be lost
  - It keeps signals secure and maintains the quality of the original signal
  - It prevents scratching of the core
  - It keeps the core away from adjacent fibre cores hence preventing crossover of information to other fibres
  - It provides the fibre with strength and prevents breakage given that the core needs to be very thin

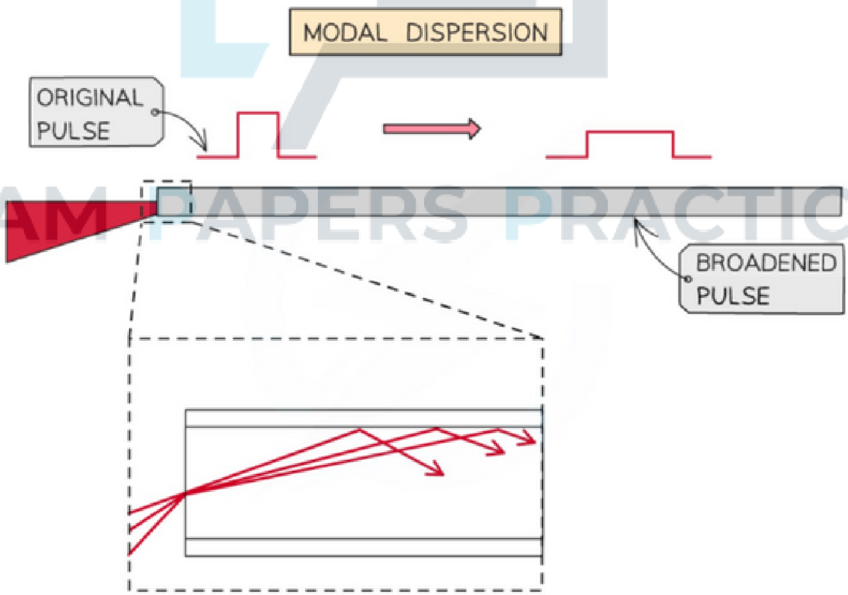
Material & Modal Dispersion

- Material dispersion, or spectral dispersion, occurs when **white light** is used instead of monochromatic light
- This is because different wavelengths of light travel at different speeds
  - Blue light travels **slower** than red light due to the greater refractive index
  - Therefore, the red light reaches the end before the blue light

- This results in **pulse broadening**, and to prevent this, monochromatic light must be used
- Modal dispersion occurs when the light pulses in the optical fibre spread out due to the **different angles** of incidence in the original pulse
- This is more prominent in wider cores as the light travelling along the axis of the core travels a shorter distance than light undergoing total internal reflection at the core-cladding boundaries
  - To prevent modal dispersion, the core needs to be very **narrow**

- This also causes **pulse broadening** as the pulses emerging are longer than they should be


MATERIAL DISPERSION
ORIGINAL PULSE
BROADENED PULSE

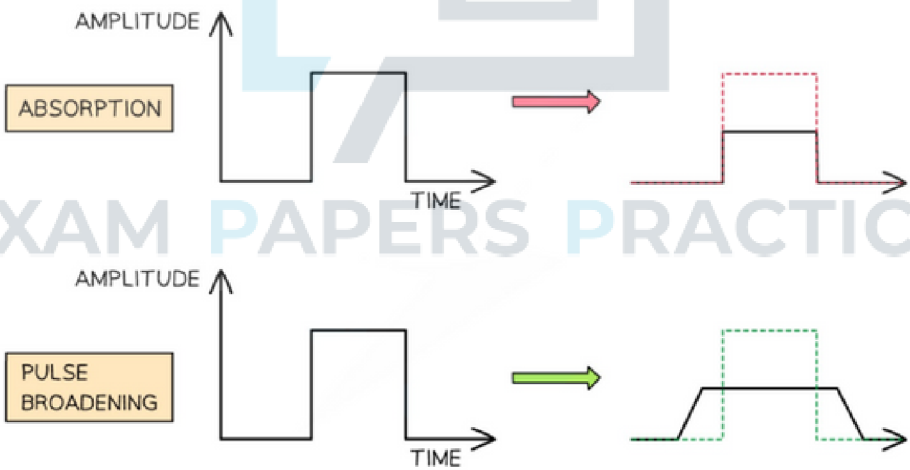

MODAL DISPERSION
ORIGINAL PULSE
BROADENED PULSE

- The **advantages** of using a narrow core are:
  - Less light is lost by refraction out of the core
  - There is a smaller change in angle between each reflection, so the angle of incidence is less likely to fall below the critical angle
  - Less overlapping pulses hence reduction of modal dispersion
  - The quality of the signal will be better and less distorted
  - The signal will be transferred quicker leading to improved data and information transfer

Pulse Broadening & Absorption

- Absorption occurs when
  - Part of the signal's energy is absorbed by the fibre
  - The signal is attenuated by the core

- This reduces the **amplitude** of the signal, which can lead to a **loss of information**
- Pulse broadening is caused by **modal and material dispersion**
- The consequence of pulse broadening is that different pulses could merge, resulting in a completely **distorted final pulse**



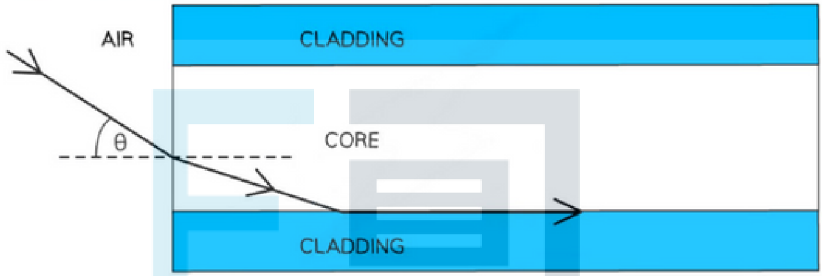
Reducing Pulse Broadening & Absorption

- To reduce absorption:
  - Use a core which is extremely transparent
  - Use of optical fibre **repeaters** so that the pulse is regenerated before significant absorption has taken place

- To reduce pulse broadening:
  - Make the core as **narrow** as possible to reduce the possible differences in path length of the signal
  - Use of a **monochromatic** source so the speed of the pulse is constant
  - Use of optical fibre **repeaters** so that the pulse is regenerated before significant pulse broadening has taken place
  - Use of single-mode fibre to reduce multipath modal dispersion

Worked Example

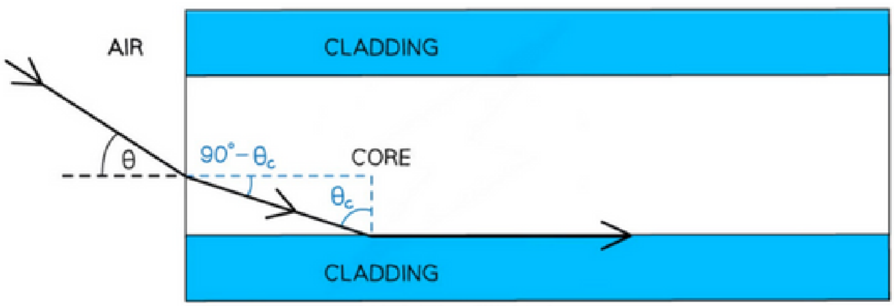
A cross-sectional view of a step-index optical fibre is shown in the diagram.



The ray of light enters the end of the fibre and refracts along the core-cladding boundaryCalculate the angle of incidence, θ, of the ray at the point of entry to the fibre.

The speed of light in the core is 2.027×10^8 m s^{-1}

The speed of light in the cladding is 2.055×10^8 m s^{-1}



Step 1: Calculate the refractive indices of the cladding and the core

$$\text{Refractive index, } n = \frac{c}{c_s}$$

$$\text{Refractive index of core, } n_1 = \frac{3.00 \times 10^8}{2.027 \times 10^8} = 1.48$$

$$\text{Refractive index of cladding, } n_2 = \frac{3.00 \times 10^8}{2.055 \times 10^8} = 1.46$$

Step 2: Calculate the critical angle

$$\sin \theta_c = \frac{n_2}{n_1} = \frac{c_1}{c_2}$$

$$\theta_c = \sin^{-1}\left(\frac{1.46}{1.48}\right) = 80.6°$$

or

$$\theta_c = \sin^{-1}\left(\frac{2.027 \times 10^8}{2.055 \times 10^8}\right) = 80.5°$$

Step 3: Calculate the angle of refraction

- Forming a right-angled triangle, as shown in the diagram:
- The angle of refraction, $\theta_r = 90 - \theta_c = 90° - 80.5° = 9.5°$

Step 4: Write out Snell's law and list the known quantities

$$\frac{n_2}{n_1} = \frac{\sin \theta}{\sin \theta_r}$$

- Where:
  - Refractive index of air, $n_1 = 1$
  - Refractive index of core, $n_2 = 1.48$
  - Angle of incidence = θ
  - Angle of refraction, $\theta_r = 9.5°$

Step 5: Rearrange and calculate the angle of incidence

$$\sin \theta = n_2 \sin \theta_r$$

$$\sin \theta = 1.48 \times \sin 9.5 = 0.2443$$

$$\theta = \sin^{-1} (0.2443) = 14.1°$$