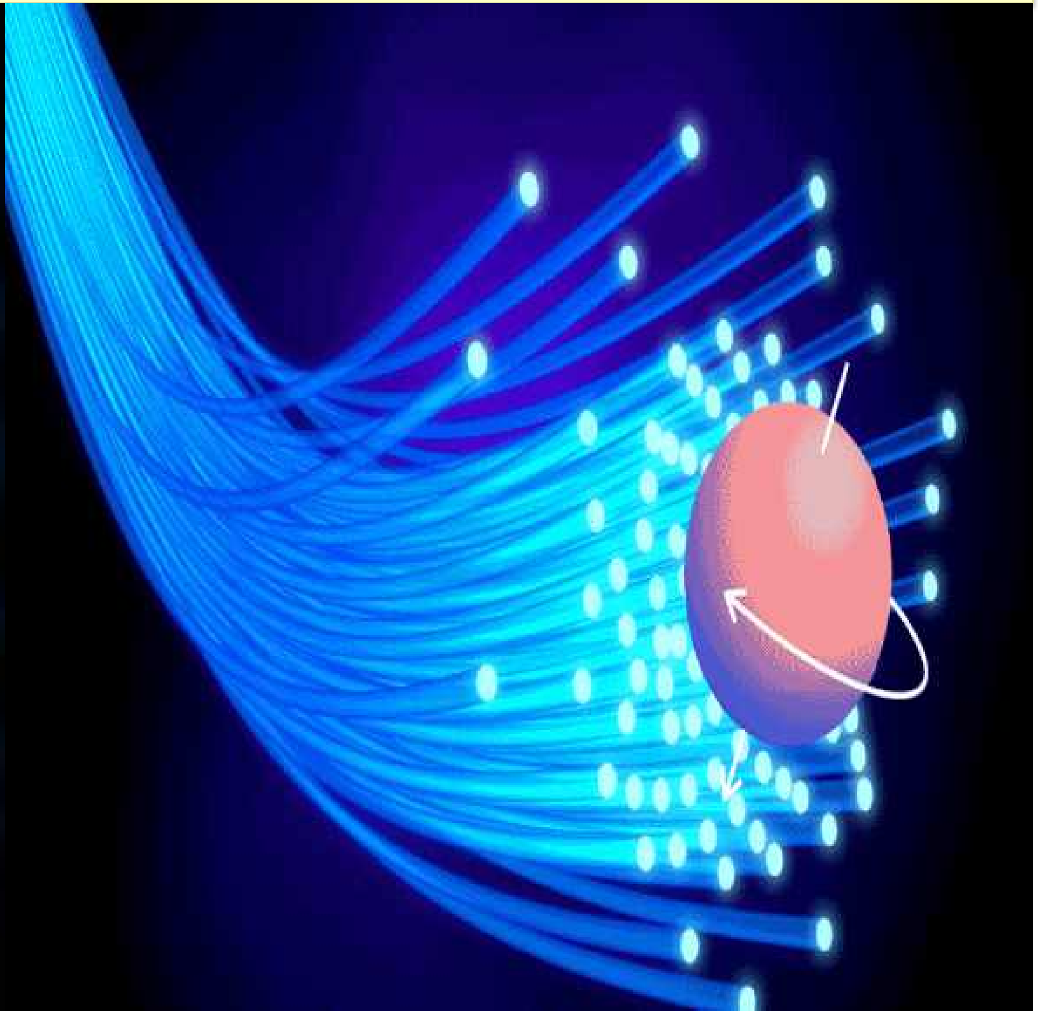
Lecture -26

Fibre Optics

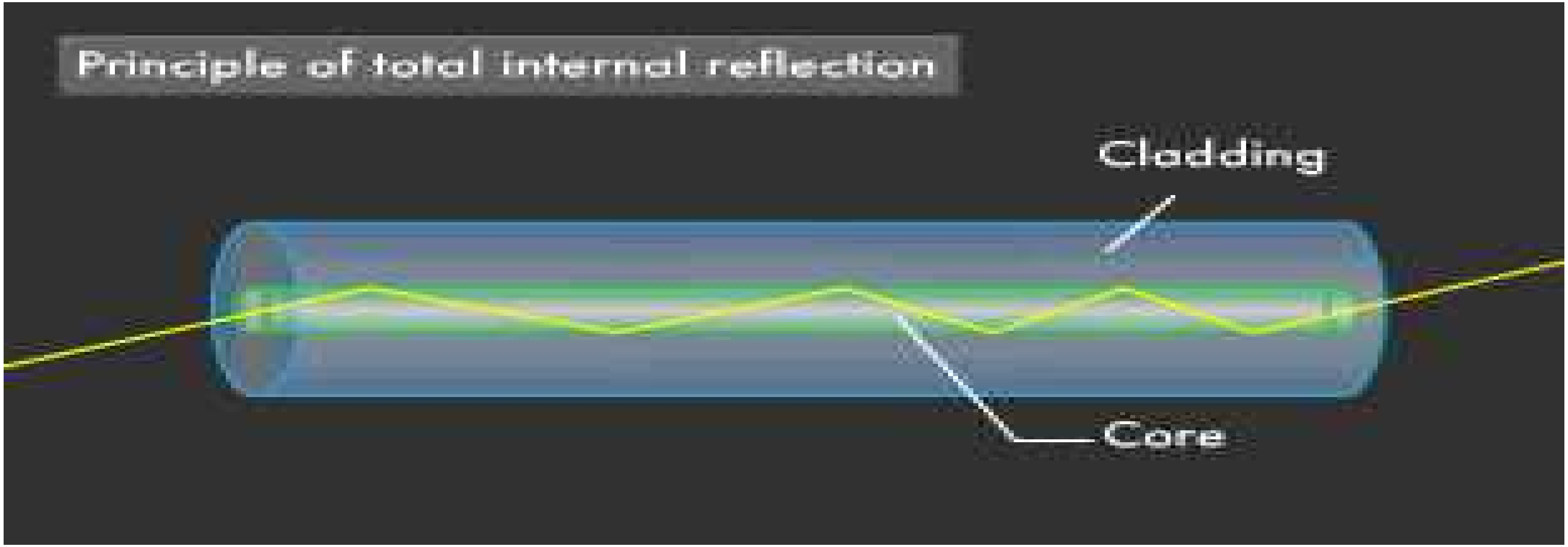


Contents

- Fibre optics
- Total internal reflection (TIR)
- Classification of fibre

Fibre optics

Fibre optics is the technology used to transmit information in the form of light pulses through strands of fibre, made of glass or plastic over long distances.

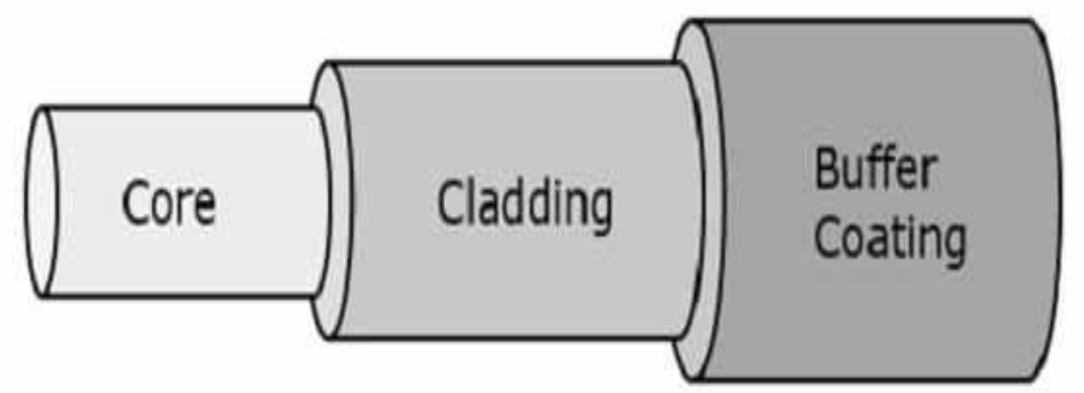


With the help of well labeled diagram, name the components of an optical fibre. **[2015-16, 2020-21]**

Structure: It consists of three parts:

(a) Core **(b)** Cladding **(c)** Buffer coating (Sheath)

(a) Core: It is innermost part of the fibre surrounded by a second layer, called cladding. The refractive index of core is slightly more than the cladding.



(b) Cladding: The optical properties different from core.

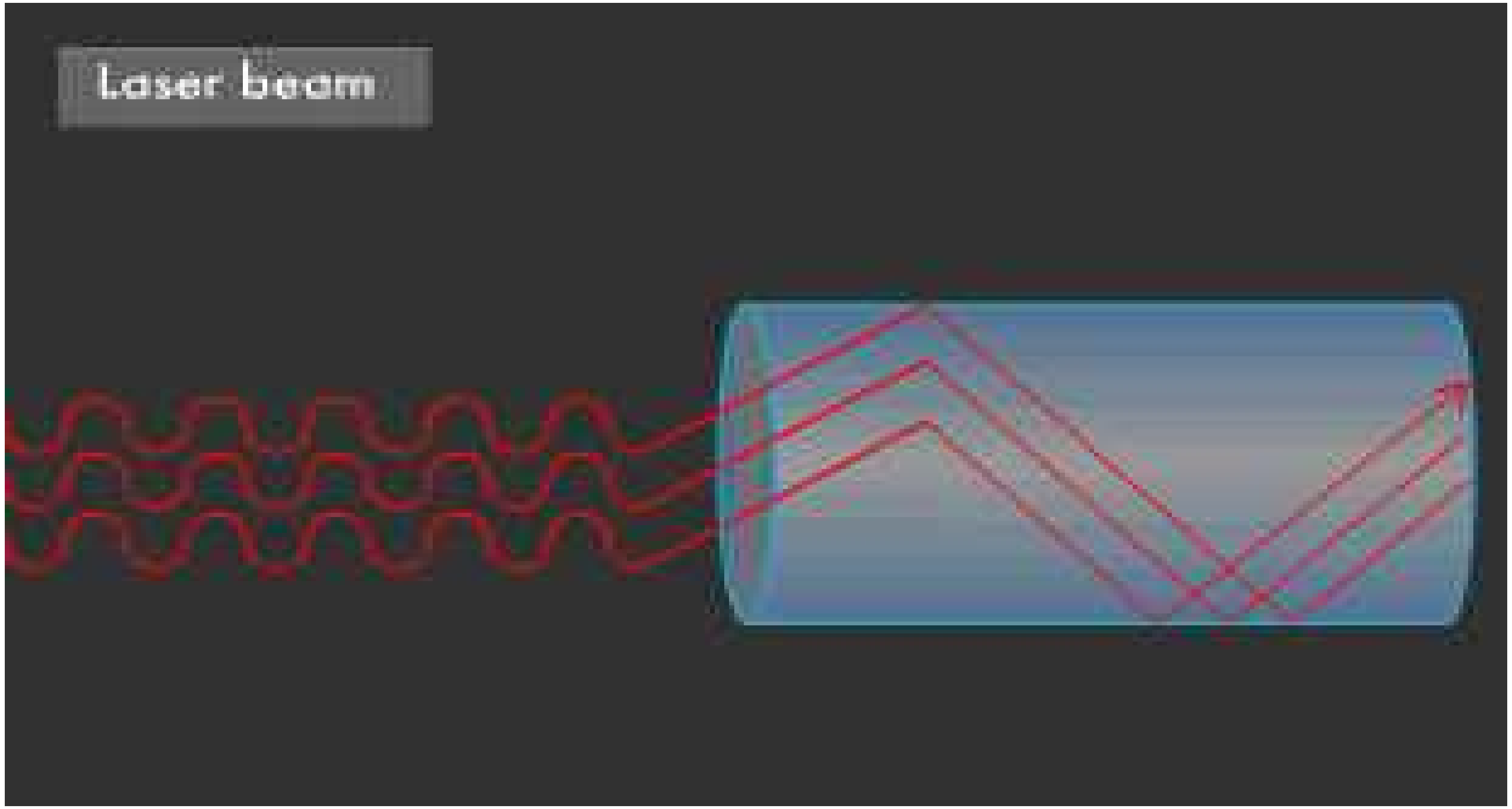
(c) Buffer coating (sheath) : It is the outermost layer of the fibre which protects the fibre from crashing, contaminations and moisture.

What is the principle of operation of an optical fibre?

[2018 - 19]

Principle of optical fibre (Propagation mechanism):

The optical fibre is based on the principle of total internal reflection (TIR).



What are the conditions in optical fibre for total internal reflection?

Condition for TIR in optical fibre

1. The refractive index of the core material (μ_1) must be slightly higher than that of cladding (μ_2).

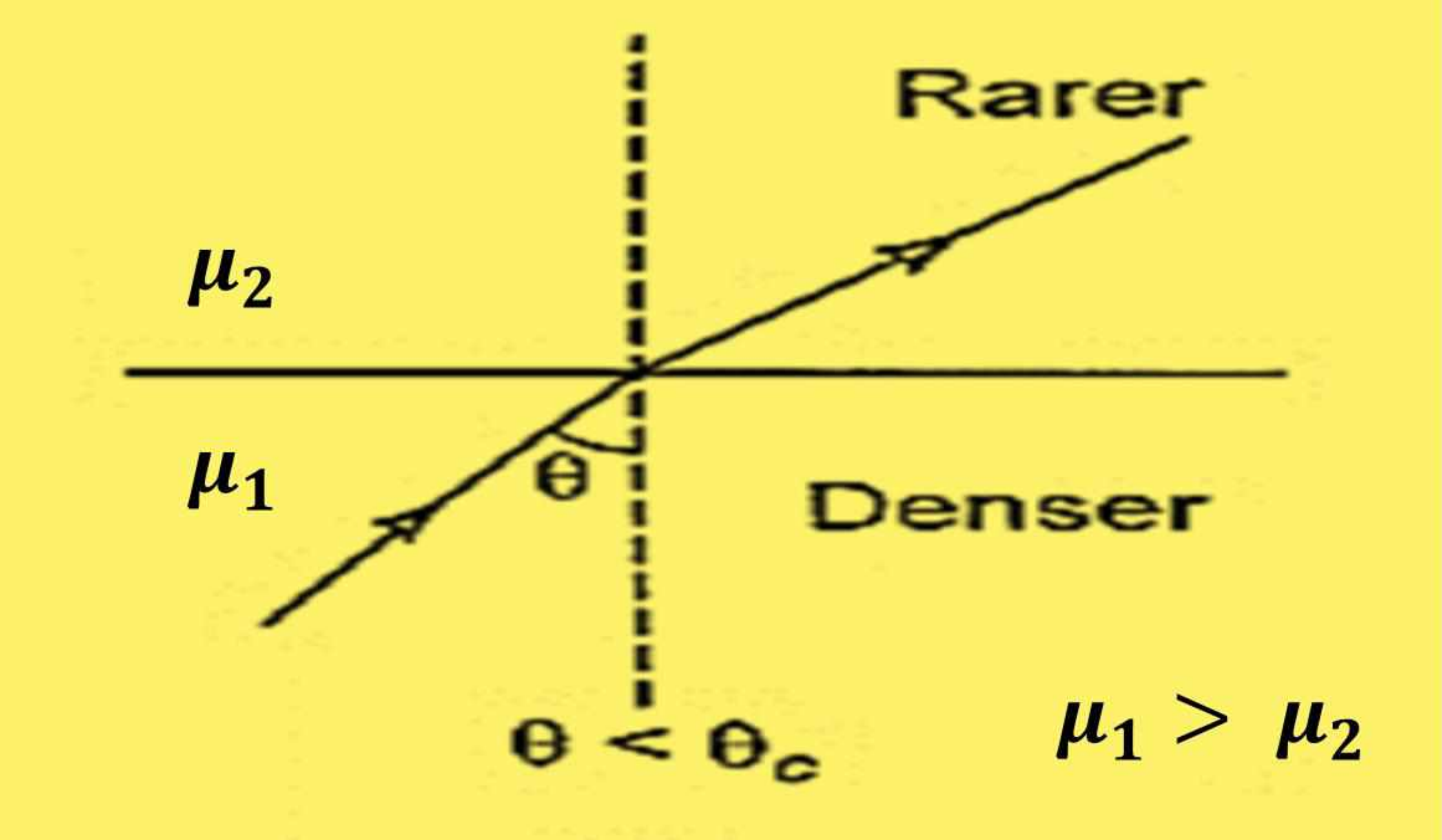
2. At the core-cladding interface, the angle of incidence θ (between the incident ray and normal to the surface) must be greater than critical angle (θ_c). This is defined as

$$\sin \theta_c = \frac{\mu_{cladding}}{\mu_{core}}$$

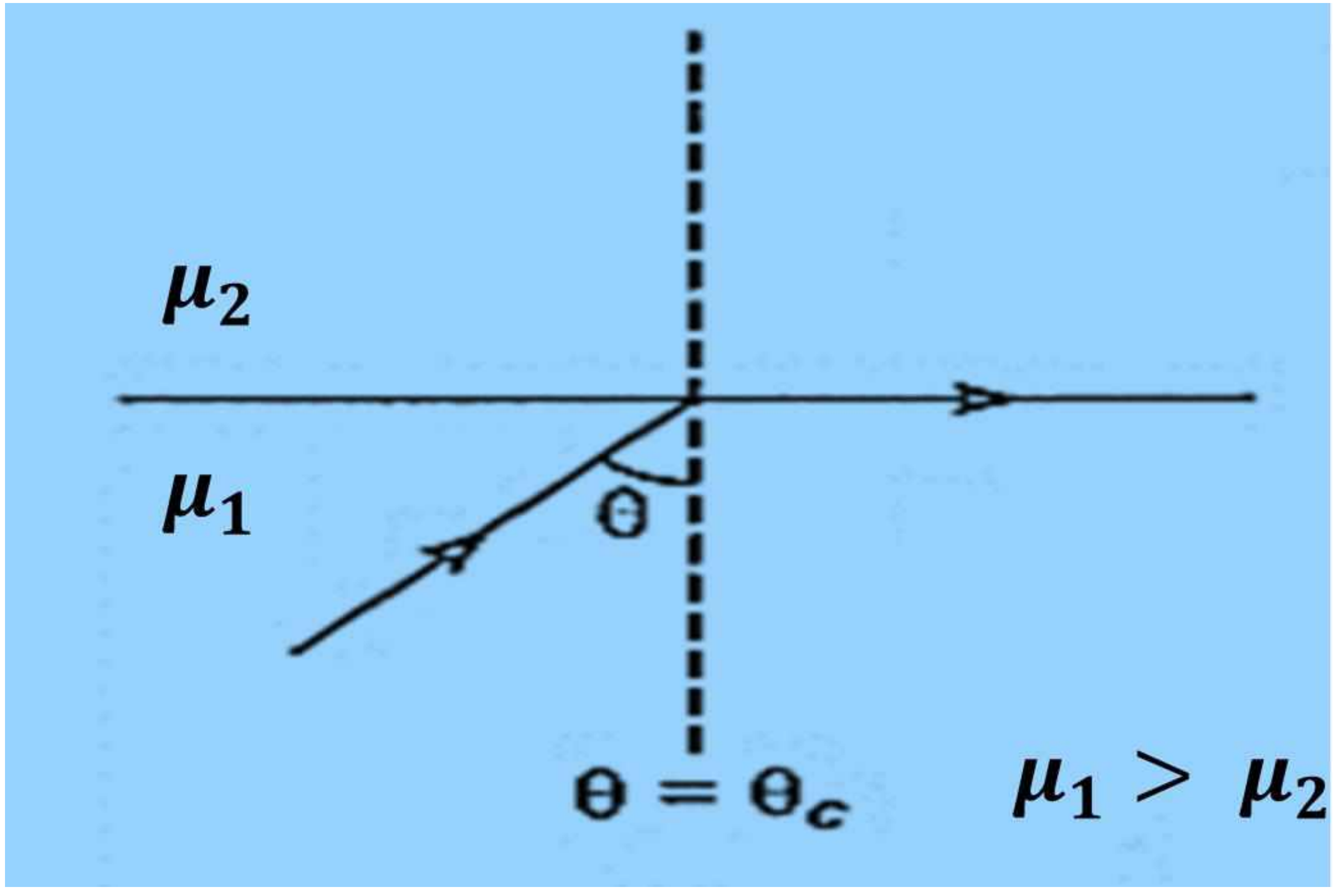
What do you mean by total internal reflection?

Total Internal Reflection

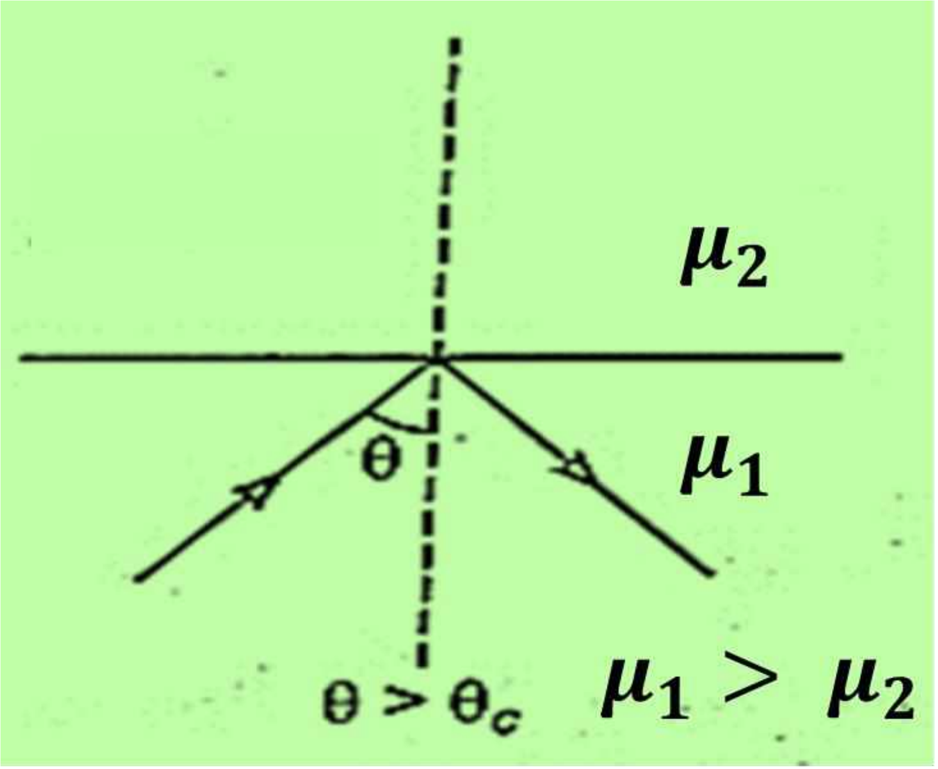
(a) When the angle of incidence (say $\boldsymbol{\theta}$) is less than critical angle $\boldsymbol{\theta}_{\mathbf{c}}$, then the ray is refracted in rarer medium as shown in figure.

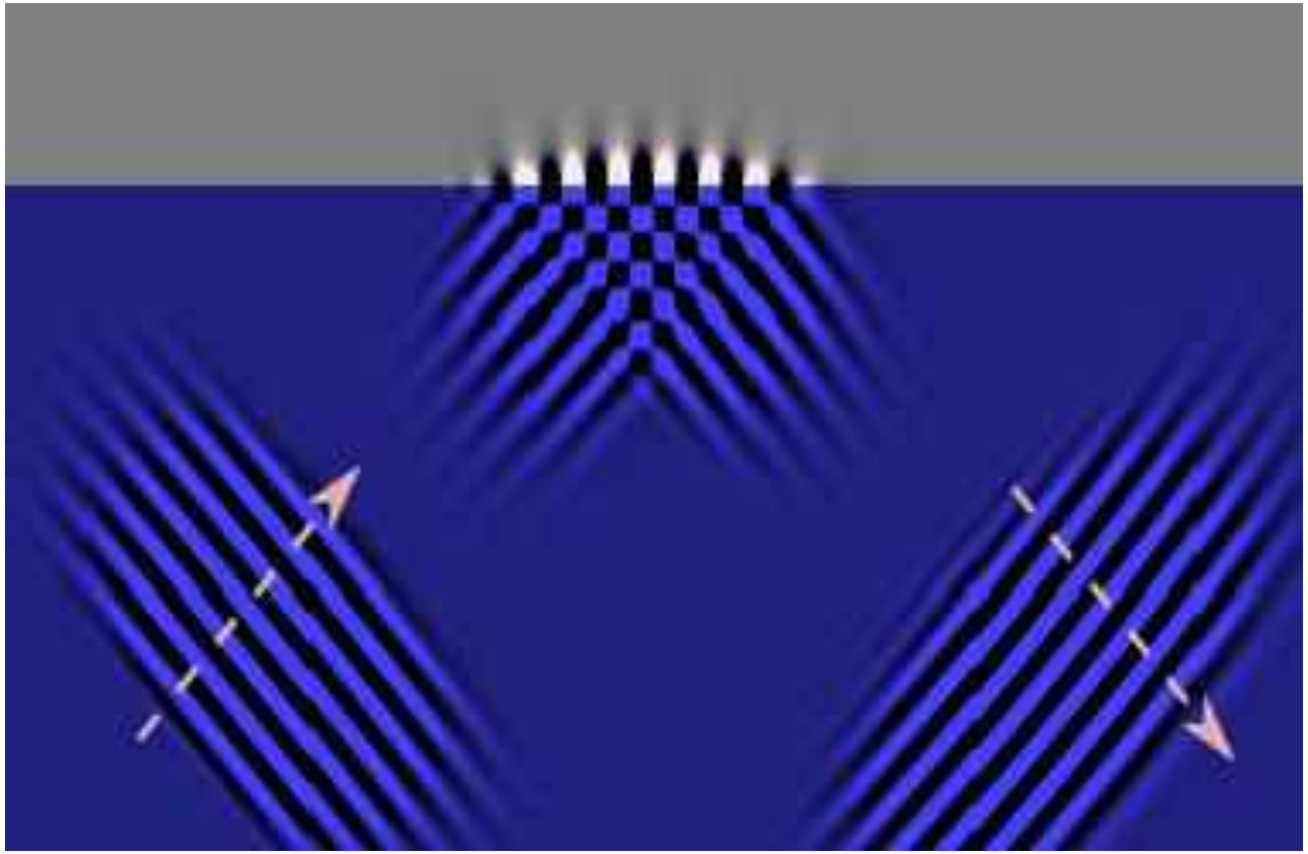


b) For a particular angle of incidence, the refracted ray just grazes the interface between the two media as shown in figure. This angle of incidence is called critical angle.



c) When the angle of incidence is further increased ($\boldsymbol{\theta} > \boldsymbol{\theta}_c$), the ray is reflected back in the same medium. This phenomenon is called as **total internal reflection**.





What do you understand by an optical fibre and discuss its classifications?

[2015 - 16, 2018 - 19]

or

Discuss the structure of an optical fibre. What are various types of optical fibre? Explain their advantages and disadvantages. [2015 - 16, 2018 - 19]

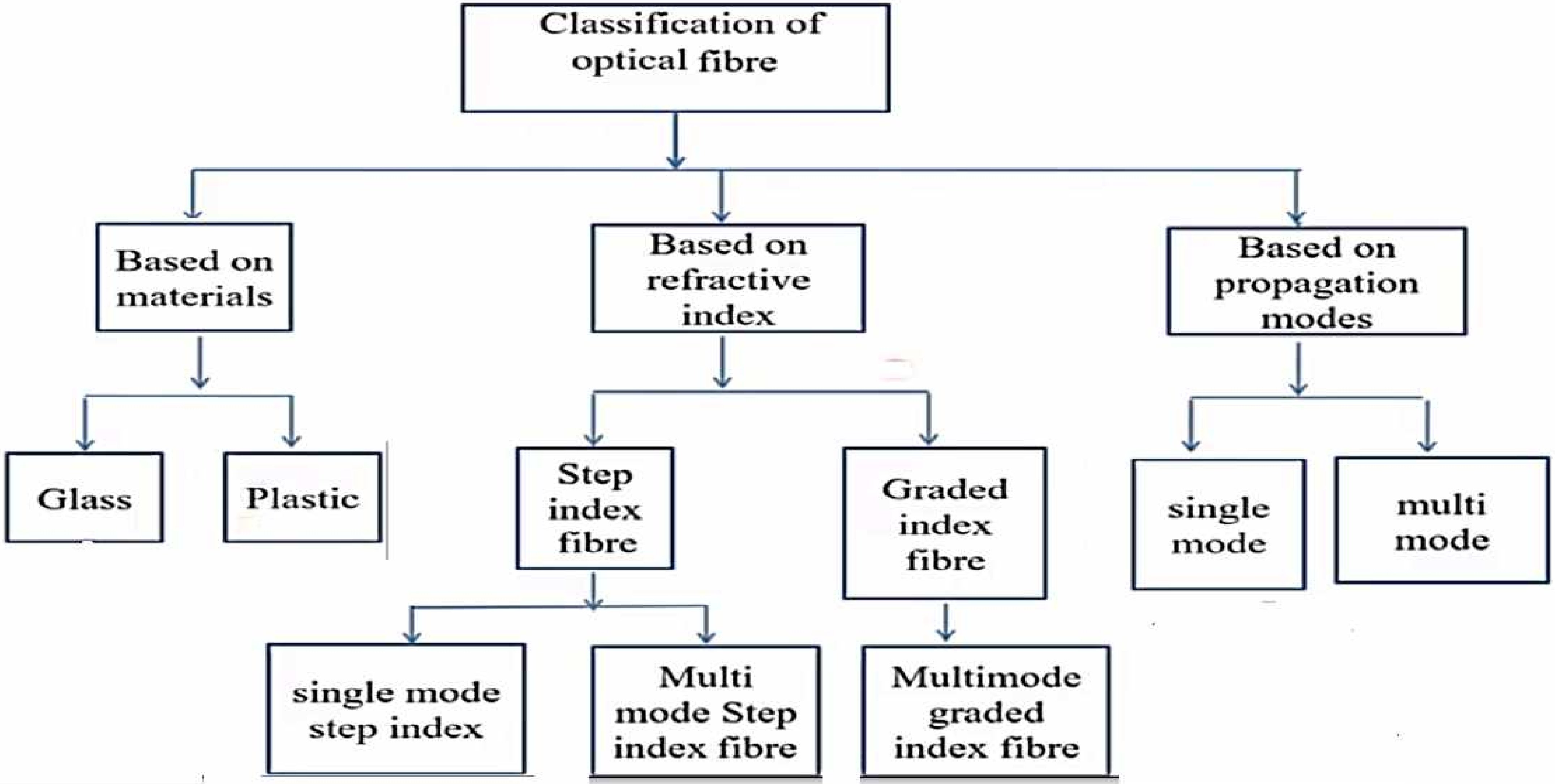
Optical fibre

Optical fibre is very thin and flexible medium having a cylindrical shape. It is used for transportation of optical energy (light energy) from one point to another. It is made up of glass or plastic.

Types of optical fibre

The optical fibres are classified into three types based on

(a) Materials
(b) Number of modes
(c) Refractive index


Classification of optical fibre
Based on materials
Based on refractive index
Based on propagation modes
Glass
Plastic
Step index fibre
Graded index fibre
single mode
multi mode
single mode step index
Multi mode Step index fibre
Multimode graded index fibre

Classification based on materials

1. Glass fibre

When the optical fibre is made up of mixture of metal oxides and silica glasses, then it is called glass fibre.

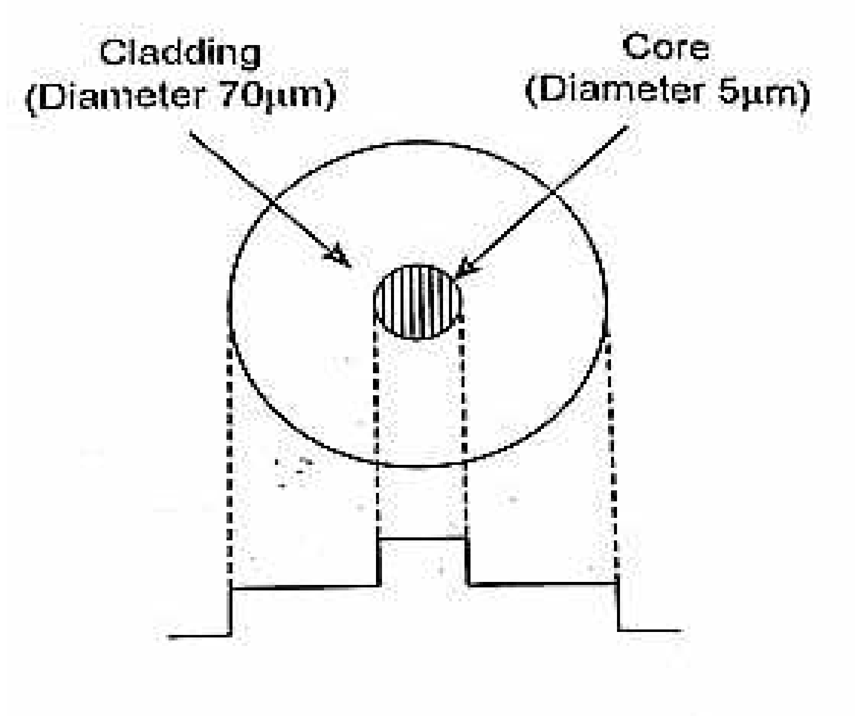
2. Plastic fibre

When the fibres are made up of plastics, then it is called plastic fibre.

Classification based on number of modes

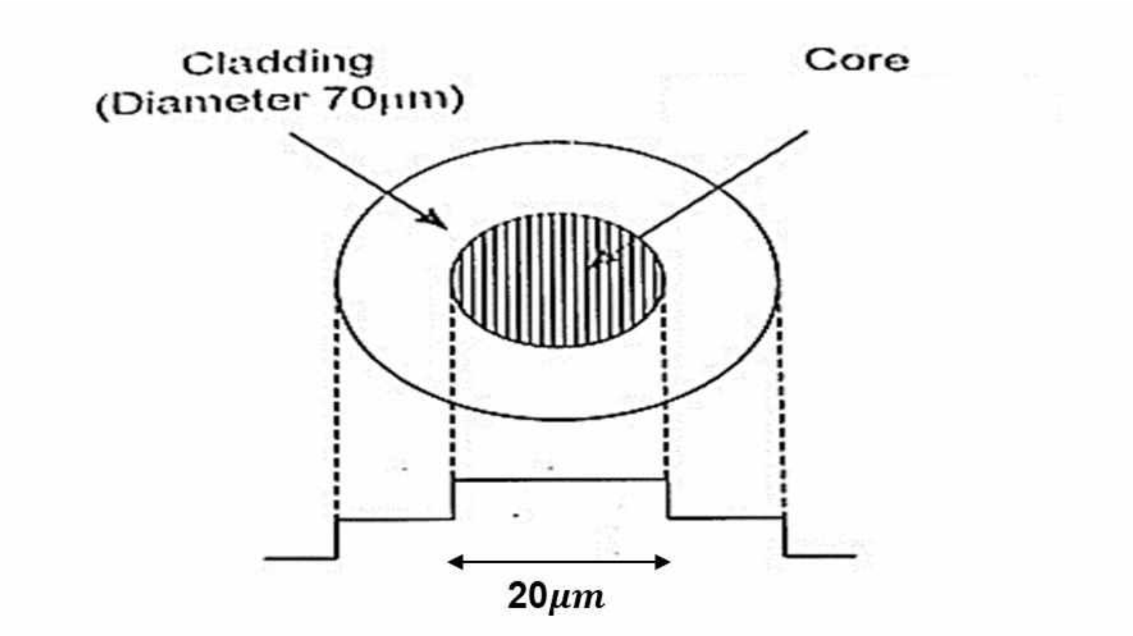
1. **Single mode fibre (SMF)**

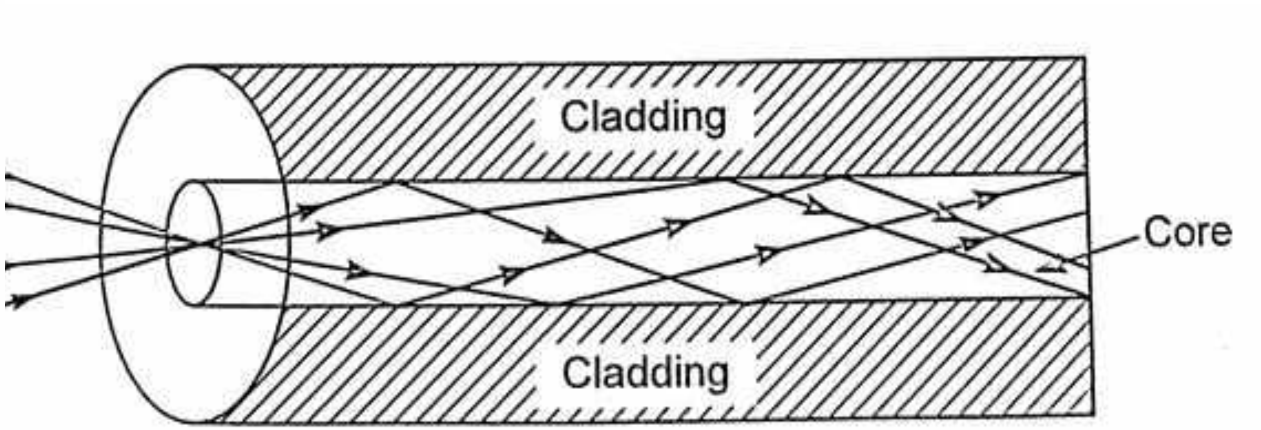
The single mode fibre is shown in fig. It has smaller core diameter (5-10 μm) and high cladding diameter (50 - 70 μm).



2. Multi-mode fibre

The Multi-mode fibre is shown in fig. It has larger core diameter than single mode fibre. The core diameter is 20-100 μm and that of cladding is 70-125μm. Multi-mode fibre allows a large number of modes for the light rays travelling through it.





Classification based on refractive index

I. Step index optical fibre

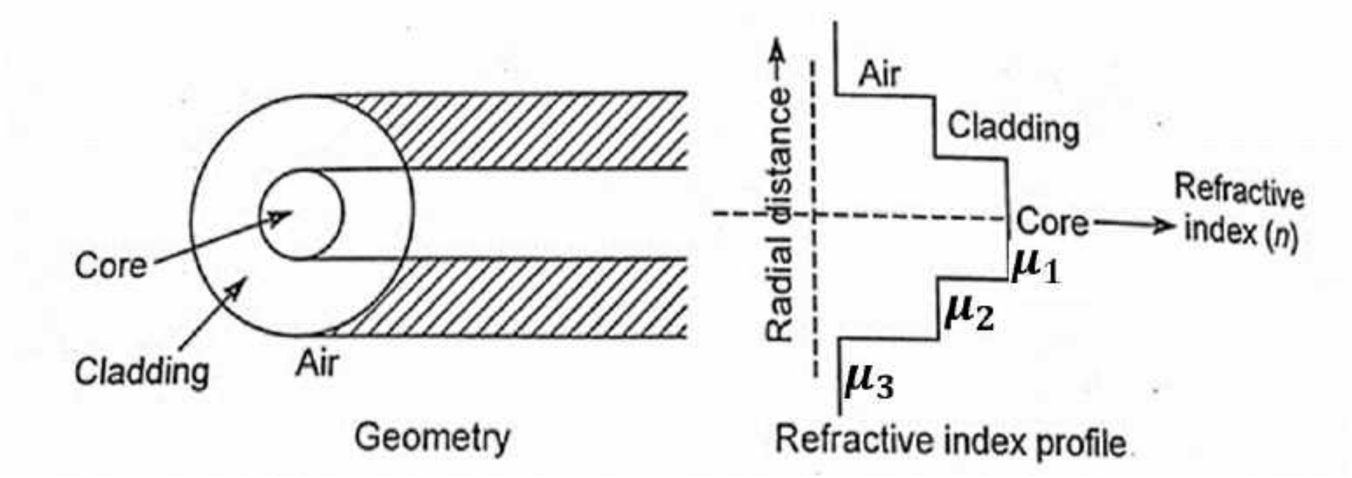
- When the refractive indices of core, cladding and air in optical fibre vary step by step, then the fibre is known as step index fibre.
- Core has a uniform refractive index (μ_1) and the cladding has also a uniform refractive index (μ_2), i.e. $\mu_1 > \mu_2$.
- Based on refractive index and number of modes, the step index fibres can further be classified into following two types:

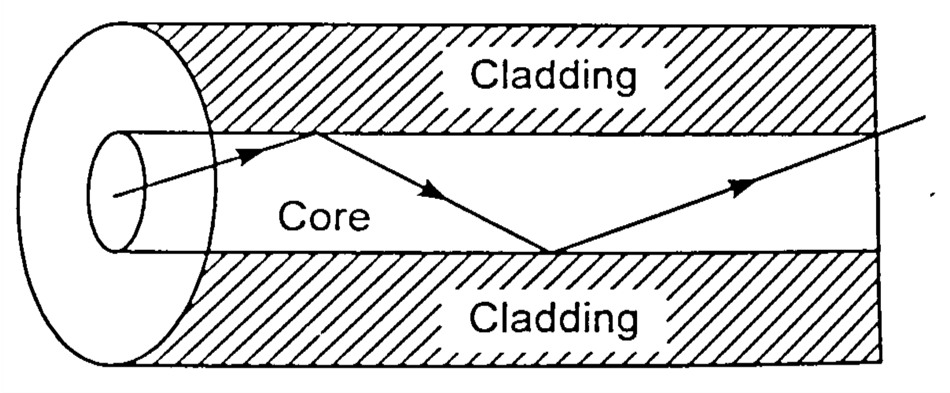
(i) Step index single mode fibre

(ii) Multi mode step index fibre

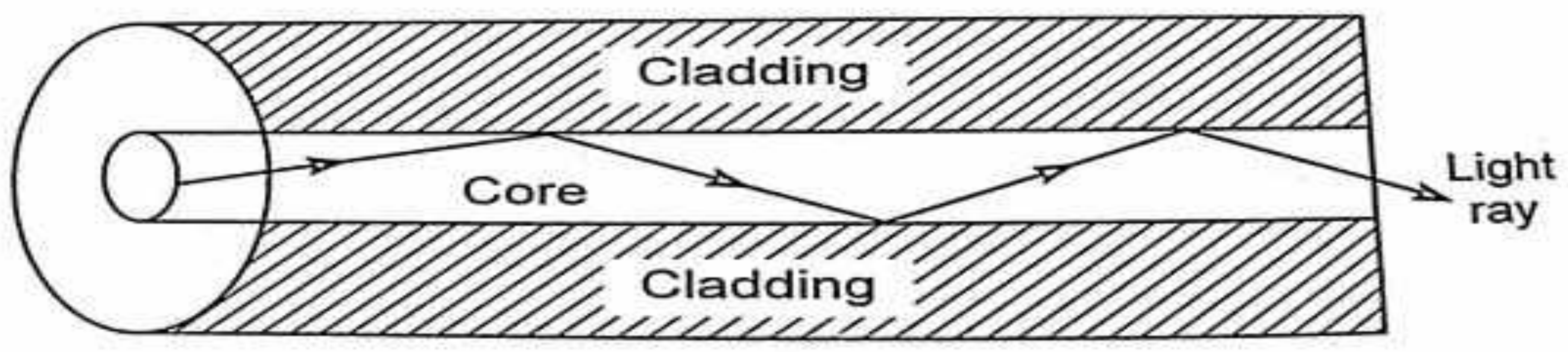
(i) Step - index single mode fibre

- Step-index single mode fibre has a core diameter of 5 to 10 μm and an external diameter of cladding of 50 to 125 μm. The core has higher uniform refractive index value than uniform refractive index of cladding.





Characteristics:

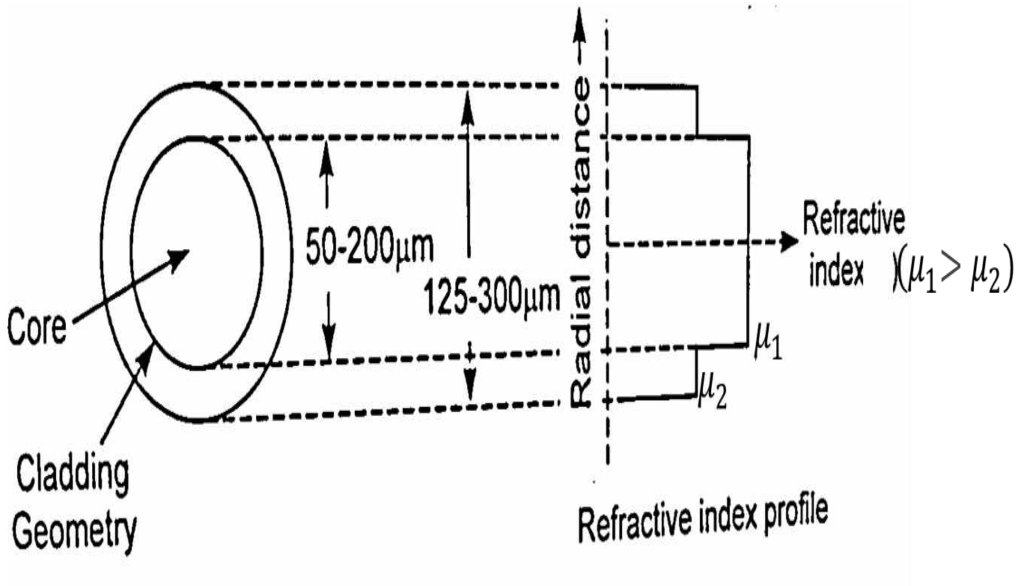


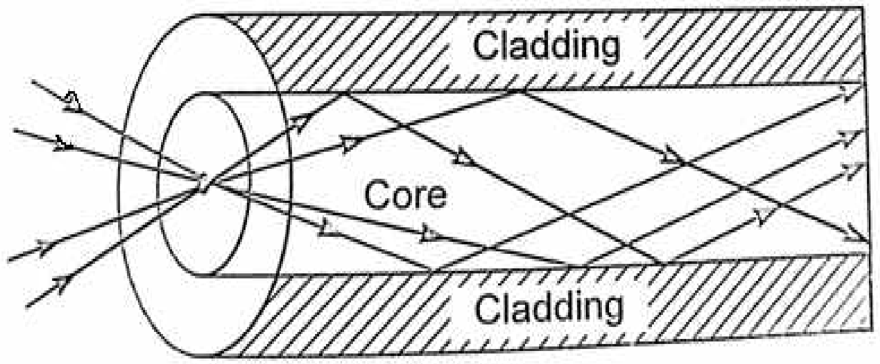
a) The single mode fibre can support only one mode of propagation.
b) Suitable for long distance communication such as telephone lines.
c) Fabrication is very difficult and costly

(ii) Step index multi-mode fibre

- In step index multi-mode fibre, the core has a much larger diameter; therefore more number of modes of propagation of light can be possible.

- A typical step-index multimode fibre has a core diameter of 50 to 200 μm and an external diameter of cladding 125 to 300μm. It has a core material with uniform refractive index and a cladding material of lesser refractive index than that of core.



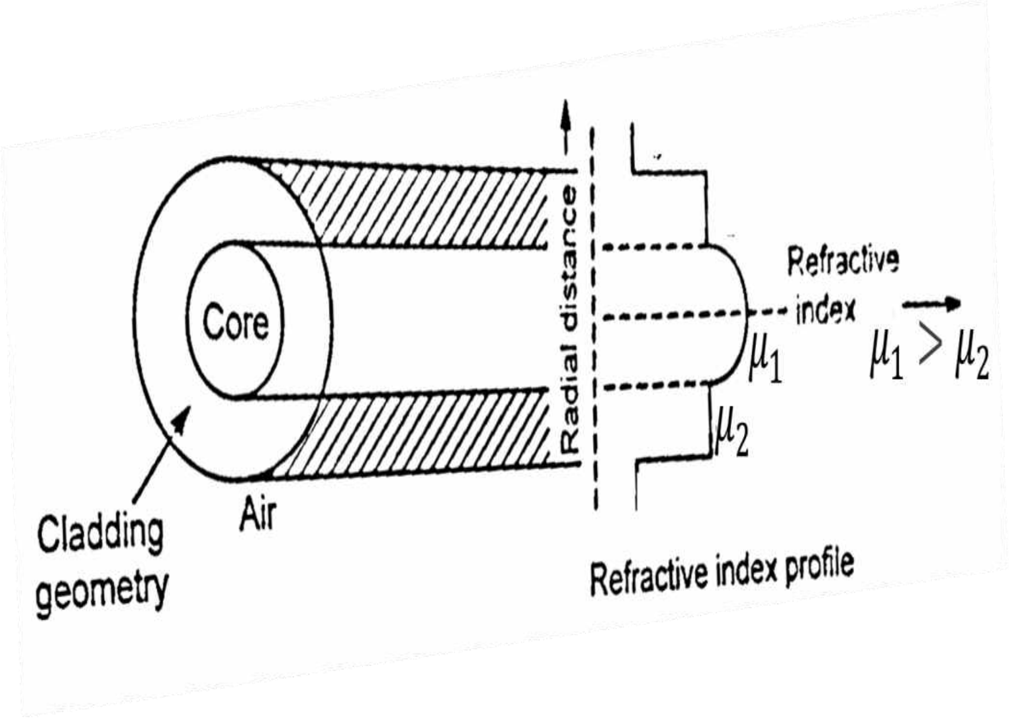


Characteristics:

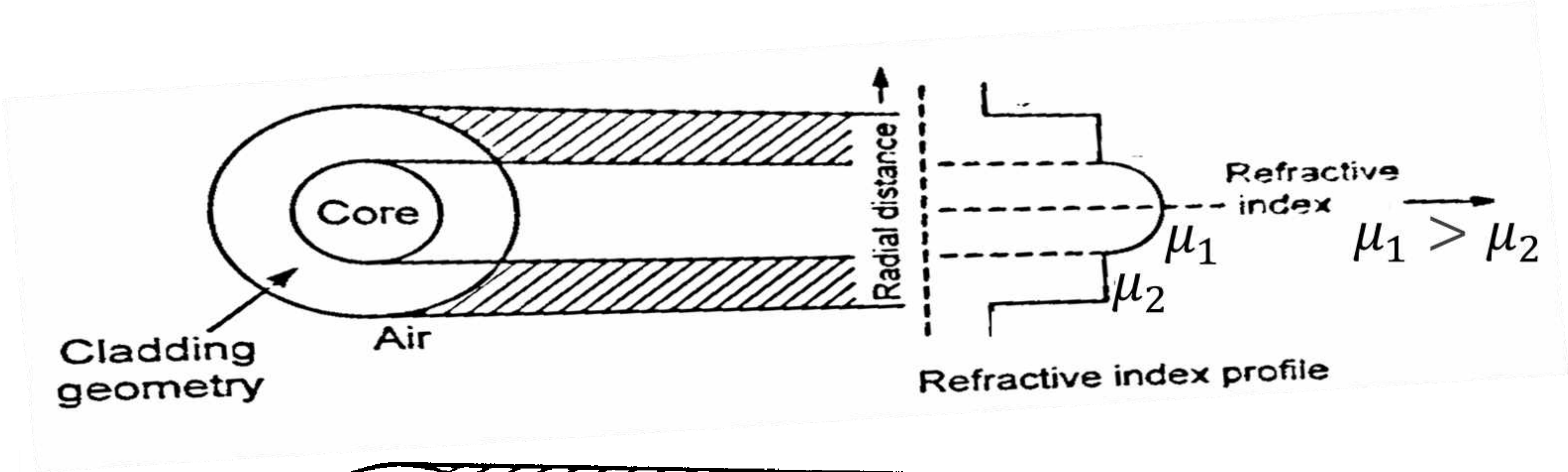
a) The multimode can support a number of modes.
b) Propagation of light is easy.
c) The fabrication is less difficult than single mode fibre.
d) The fibre is not costly.
e) Not suitable for long distances communication.

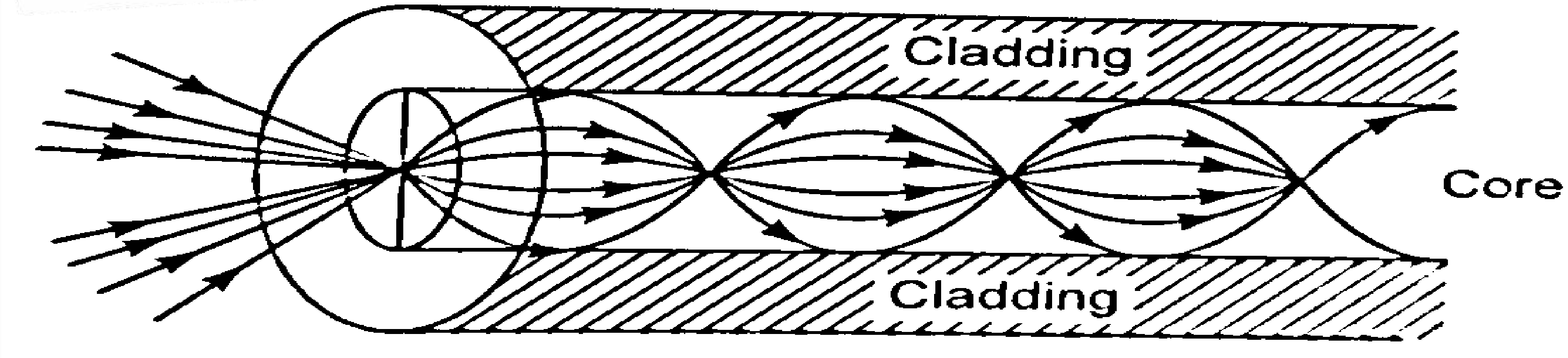
II. Graded- index optical fibre

- *If the core has a non-uniform refractive index that gradually decreases from the center towards the core-cladding interface, the fibre is called a graded-index fibre. The cladding has uniform refractive index.*
- The core and cladding diameters are about 50 $\mu m - 70\ \mu m$ respectively in case of multimode fibre.



- The light rays propagate through it in the form of skew rays or helical rays. **They do not cross the fibre axis at any time and are propagating around the fibre axis in helical or spiral manner.**





Step index multimode fibre		
S. No.	**Advantages**	**Disadvantages**
1.	Relatively easy to manufacture.	Lower bandwidth.
2.	Cheaper than other types.	High dispersion.
3.	Larger layer NA (numerical aperture)	Smearing of signal pulse.
4.	They have longer life times than laser diodes.	

Graded index fibre		
S.No.	**Advantages**	**Disadvantages**
1.	Dispersion is low.	Expensive
2.	Bandwidth is greater than step-index multimode fibre.	Very difficult to manufacture.
3.	Easy to couple with optical source.	

Discuss the merits and demerits of single (mono) mode fibre over multimode counterpart.

1. No dispersion in single mode fibre during propagation while more dispersion in multimode fibre.

2. It propagates the signal for long distances while multimode is used for shorter distance.

3. There is less attenuation in single mode fibre compare to multimode fibre.

What are the differences between single mode fibre and multimode fibre?

S.No.	Single mode fibre	Multimode fibre
1.	Only one mode can propagate through the fibre.	A large number of modes or paths for the light rays may pass through the fibre.
2.	The core has smaller diameter and difference in refractive index of core and cladding is very small.	The core diameter is large and the refractive index difference between core and cladding is larger than single mode fibre.

3.	There is no dispersion i.e., degradation of signal during travel in fibre.	There is more dispersion, i.e., degradation of signal due to multimode.
4.	Fabrication is difficult and costly.	Fabrication is less difficult and not costly.
5.	The fibre can carry information to longer distances.	Information can be carried to shorter distances only.

What is the condition for number of modes in single and multimode optical fibre. **[2019 - 20]**

The condition for number of modes in single and multimode fibre are designed by V-number (cut-off parameter)

$$V = \frac{2\pi a}{\lambda_0}\sqrt{{\mu_1}^2 - {\mu_2}^2} = \frac{2\pi a}{\lambda_0}(NA)$$

$$If\ \ V \leq 2.405\ \rightarrow Single\ mode\ fibre$$

$$V > 2.405\ \rightarrow Multi\ mode\ fibre$$

V-number increases with numerical aperture and diameter of the core

a: Radius of the core;

λ_0: Operating wavelength of light wave

μ_1: Refractive index of core material;

μ_2: Refractive index of cladding material;

NA: Numerical aperture

Fibre Optics

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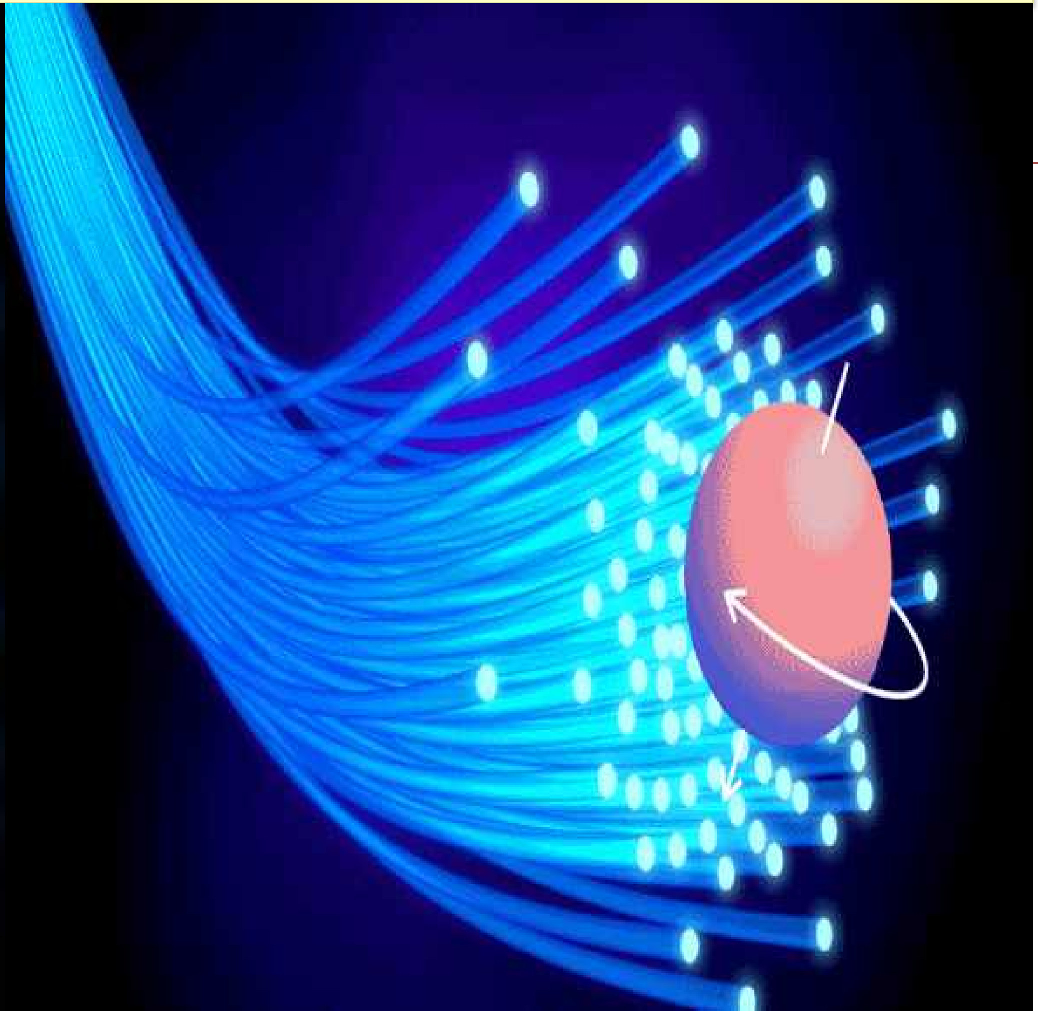


GROUP OF INSTITUTIONS

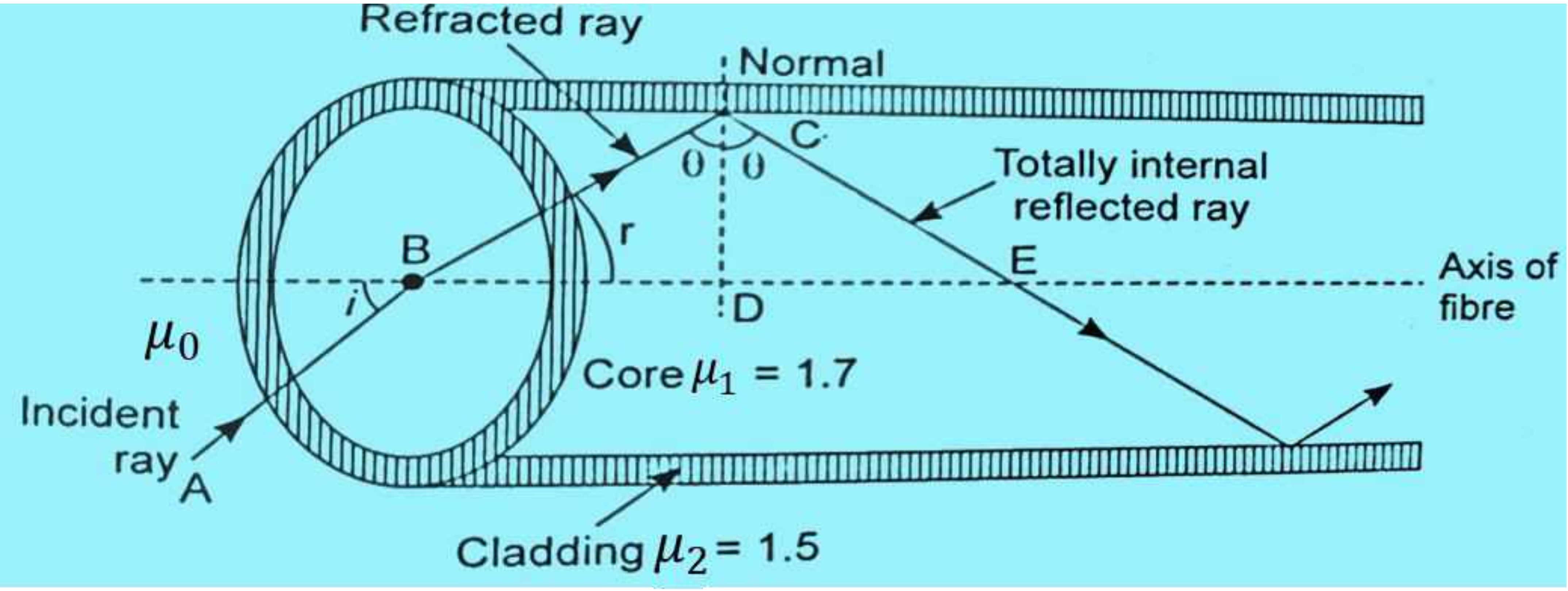
Contents

- Critical angle
- Acceptance angle
- Acceptance cone
- Numerical aperture
- Attenuation coefficient

What do you mean by critical angle, acceptance angle, acceptance cone and numerical aperture? Derive expression for them. [2015 - 2016]

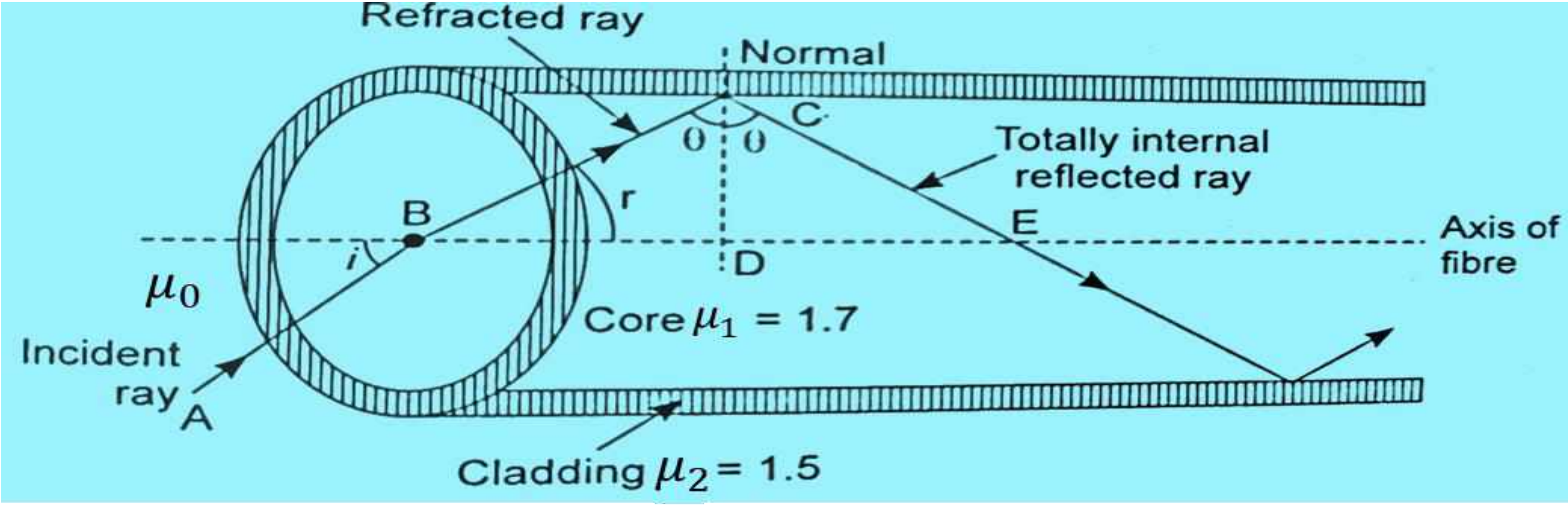
Critical angle

Critical angle is a particular incident angle in denser medium for which refraction angle will be 90 degree in rarer medium.

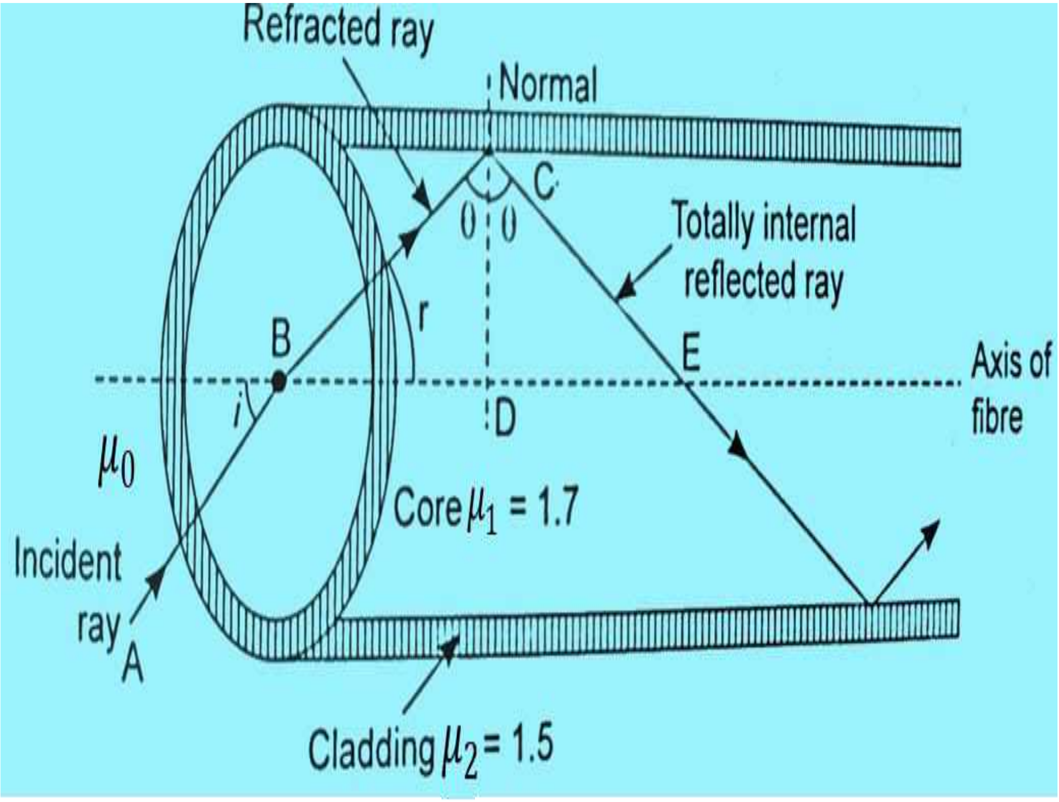


Acceptance angle

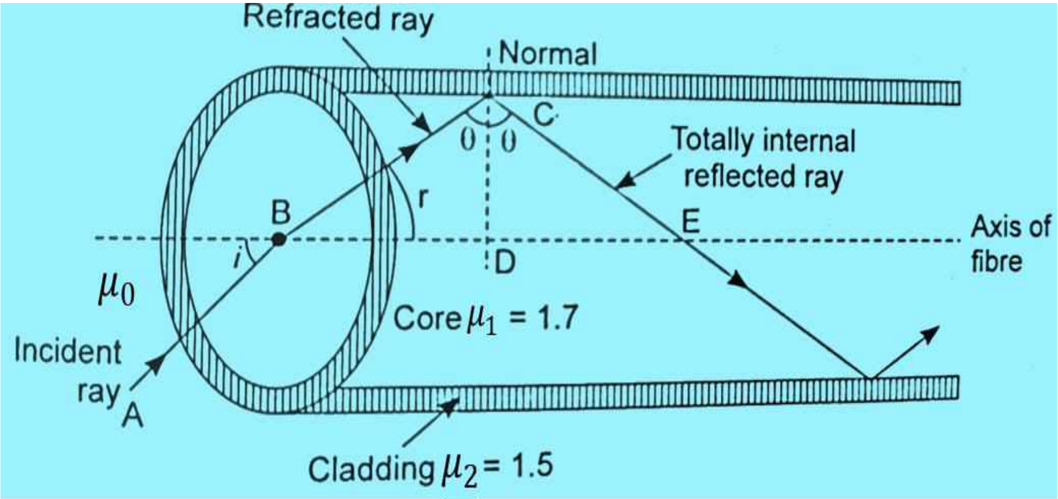
Acceptance angle is the maximum angle that incident light ray can make with the fibre axis, so that light ray will propagate through the fibre by total internal reflection within the core.



- Consider a cylindrical fibre cable, refractive index of core μ_1 *and* cladding refractive index μ_2 , where $\mu_1 > \mu_2$.
- Let μ_0 be the refractive index of the medium from which the light ray enters into the fibre.Alight ray AB enter into the fibre at an angle i to the axis of fibre.
- The ray refracts at an angle r and strikes the core-cladding interface at an angle θ.



- When angle i increases , r will increase and θ will decrease.
- When θ angle is greater than critical angle θ_c, then light ray will stay within the core of fibre.



Applying Snell's law of refraction at the point of entry of the ray AB into the core,

$$\mu_0 \sin i = \mu_1 \sin r \qquad \text{..........(1)}$$

From ΔBCD,

$$r = 180 - (90 + \theta)$$

$$= (90 - \theta)$$

or $\sin r = sin(90 - \theta)$

$$\sin r = \cos\theta \quad .....(2)$$

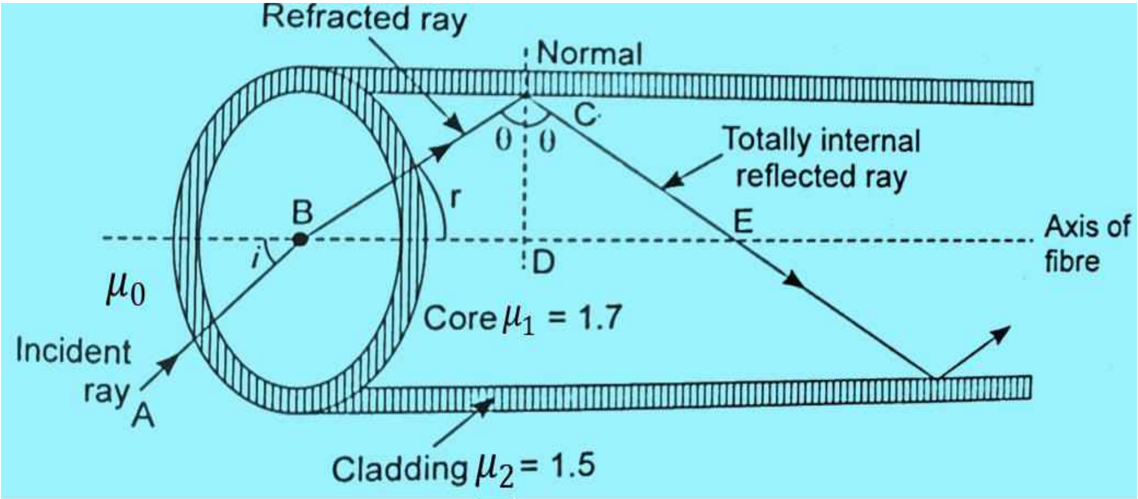
Now from eq. (1) & (2)

$$\mu_0 \sin i = \mu_1 \cos\theta \quad ....(3)$$

For maintaining $\theta \geq \theta_c$ (critical angle) for TIR then angle of incident iwill be i_{max} . Applying this condition in eq. (3) we get

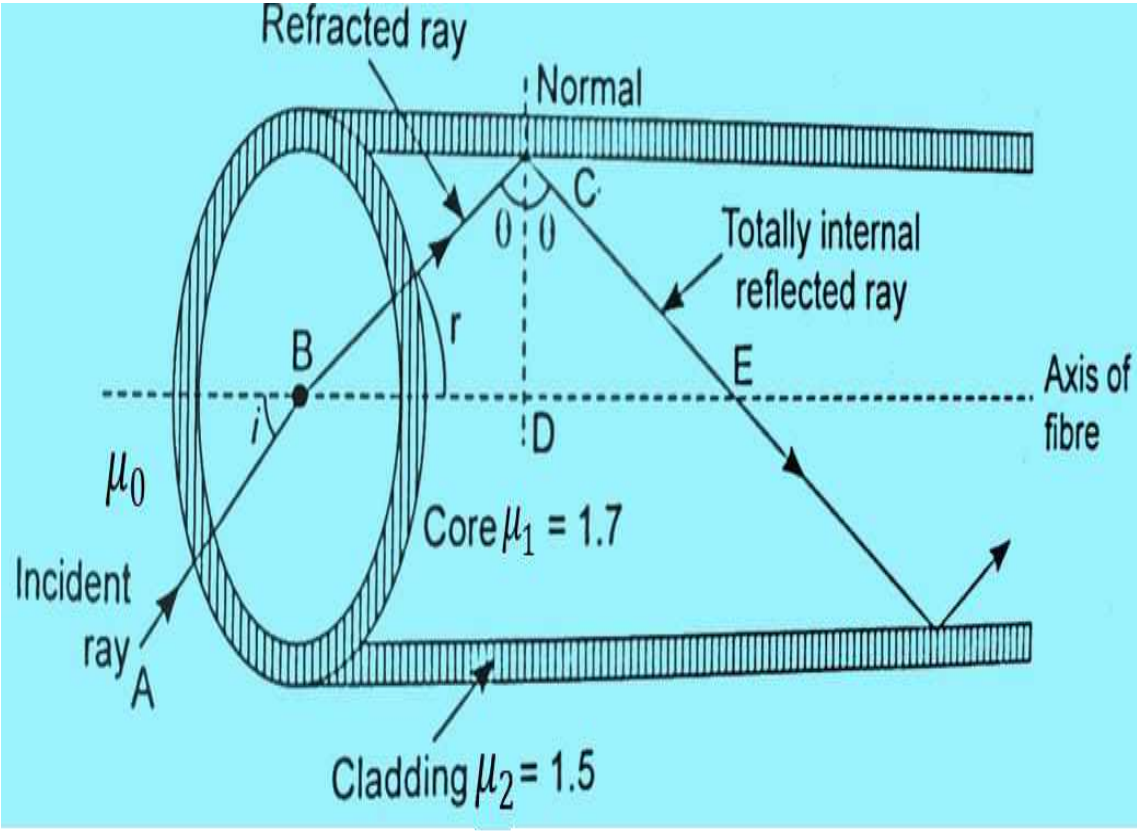
$$\sin i_{max} = \frac{\mu_1}{\mu_0} \cos\theta_c ....(4)$$

We know that, $\sin\theta_c = \frac{\mu_2}{\mu_1}$



$$\cos\theta_c = \sqrt{1 - sin^2\theta_c} = \sqrt{1 - \frac{{\mu_2}^2}{{\mu_1}^2}}$$

$$\cos\theta_c = \sqrt{\frac{{\mu_1}^2 - {\mu_2}^2}{{\mu_1}^2}} = \frac{\sqrt{{\mu_1}^2 - {\mu_2}^2}}{\mu_1} \quad ....(5)$$



From eq. (4), we have

$$\sin i_{max} = \frac{\mu_1}{\mu_0} \times \frac{\sqrt{{\mu_1}^2 - {\mu_2}^2}}{\mu_1}$$

$$= \frac{\sqrt{{\mu_1}^2 - {\mu_2}^2}}{\mu_0} \quad ....(6)$$

$$i_{max} = \sin^{-1}\frac{\sqrt{{\mu_1}^2-{\mu_2}^2}}{\mu_0} \quad ....(7)$$

For air medium, $\mu_0 = 1$

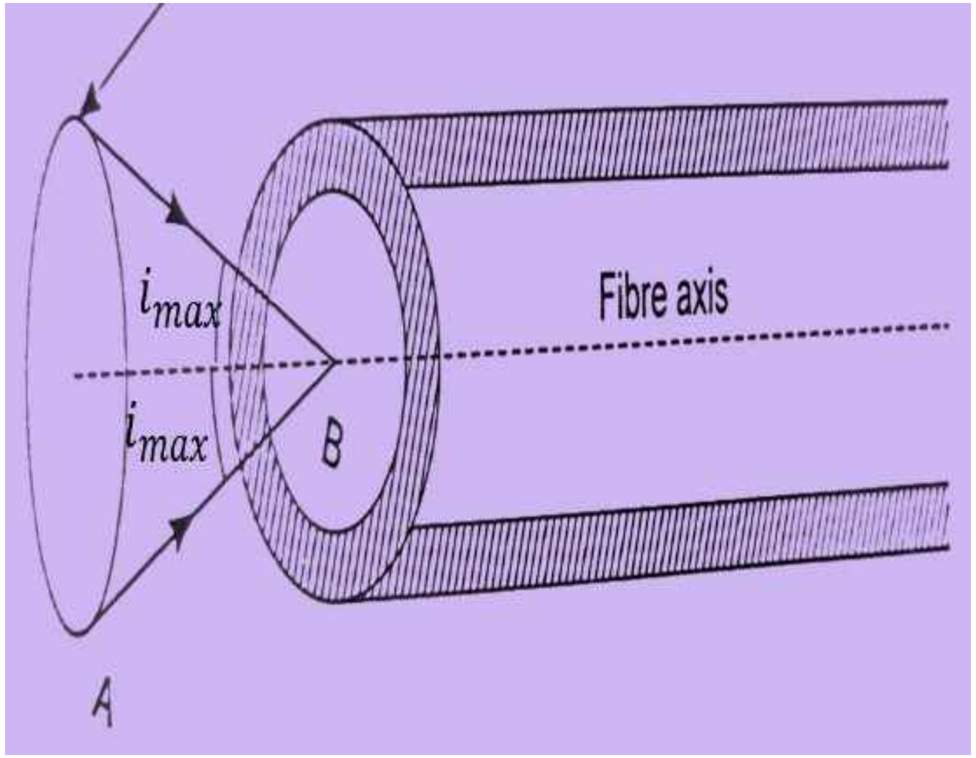
Then **acceptance angle,**

$$i_{max} = \sin^{-1}\sqrt{{\mu_1}^2 - {\mu_2}^2} \quad ..(8)$$

Acceptance cone

If all possible direction of acceptance angle are considered at same time, we get a cone corresponding to the surface known as acceptance cone.

$$Acceptance\ cone = 2\, i_{max}$$

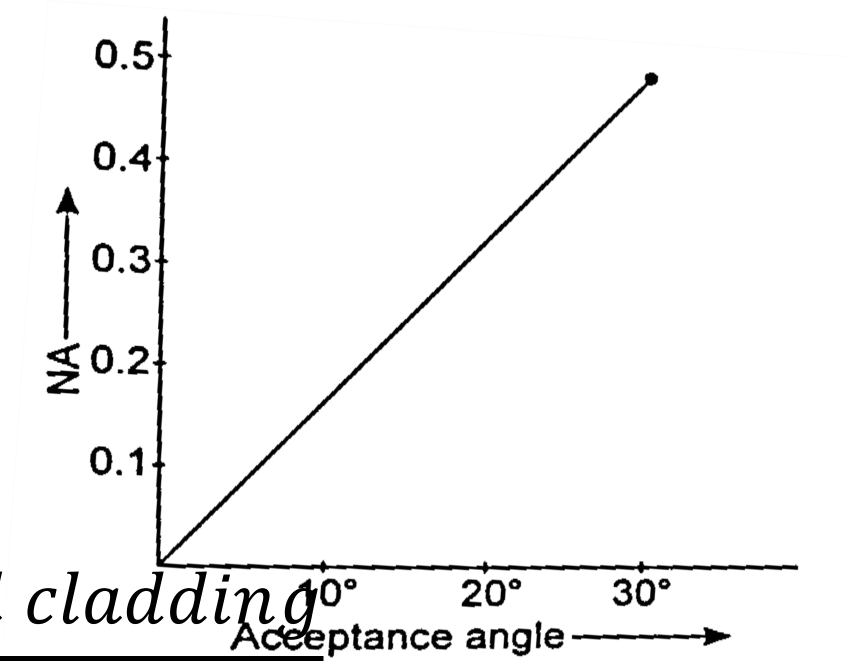


Numerical aperture:

Numerical aperture determines the light gathering ability of the fibre. This is also called the merit of the optical fibre. So, it is a measure of amount of light that can be accepted by the fibre. This is also defined as the sine of acceptance angle.

$$\text{NA} = \sin i_{max}$$

$$\text{NA} = \sqrt{{\mu_1}^2 - {\mu_2}^2} \qquad \ldots.(1)$$



The numerical aperture (NA) may also be evaluated in terms of relative refractive index difference Δ defined as,

$$\Delta = \frac{Refractive\ index\ difference\ between\ core\ and\ cladding}{Refractive\ index\ of\ core\ of\ optical\ fiber}$$

$$\Delta = \frac{\mu_1 - \mu_2}{\mu_1}$$

$$\Delta = 1 - \frac{\mu_2}{\ldots}$$

$$\frac{\mu_2}{\mu_1} = (1\text{-}\Delta) \qquad \ldots\ldots\ldots\ldots(2)$$

$$\text{NA} = \sqrt{{\mu_1}^2 - {\mu_2}^2}$$

$$= \mu_1\sqrt{1 - \frac{{\mu_2}^2}{{\mu_1}^2}} \qquad \ldots\ldots\ldots(3)$$

Now from eq. (2) and (3), we get

$$\text{NA} = \mu_1\sqrt{[1 - (1 - \triangle)^2]}$$

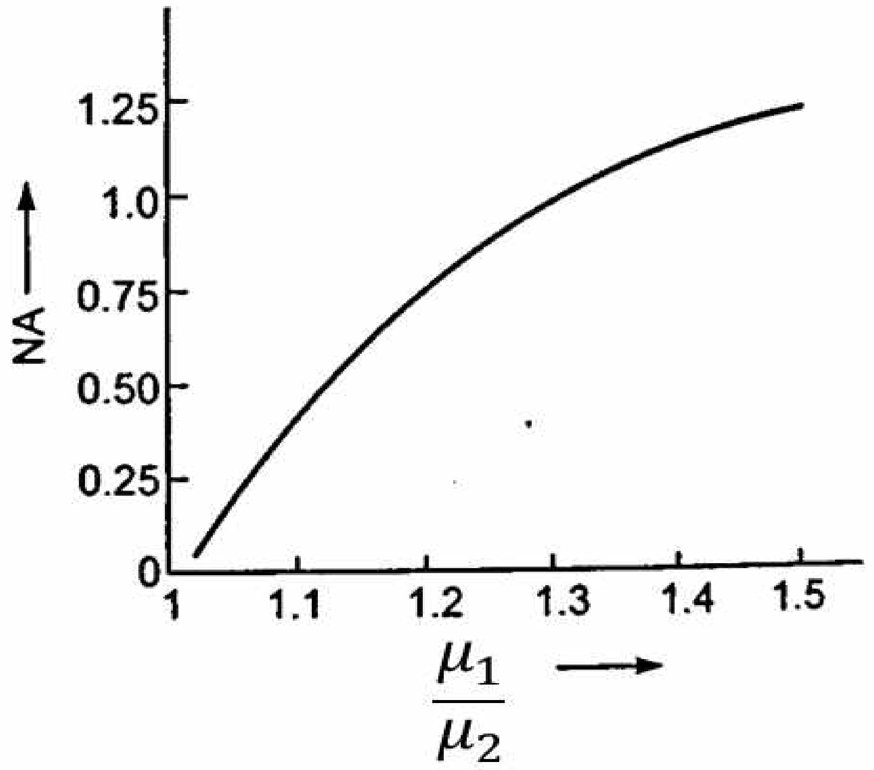
$$= \mu_1\sqrt{[2\triangle - \triangle^2]} \qquad \ldots\ldots.(4)$$

The core – cladding refractive index difference is very small due to which $\triangle^2$ is very small.

Hence:

$$NA = \mu_0\sqrt{(2\,\triangle)}$$

** Numerical aperture increases when the ratio $\left(\frac{\mu_1}{\mu_2}\right)$ increases.



What do you understand by attenuation in an optical fibre?

[2015 - 16, 2016 - 17, 2020 - 21]

Attenuation of optical signal in fibre

- When signals guided through an optical fibre, the reduction in amplitude or intensity of light signal is called attenuation or total loss.
- The losses are measured in decibel (dB) and attenuation is measured in dB/km.
- If P_i and P_o are the power of optical signal at input and output ends of fibre cable having length L, then we have

$$P_0 = P_i e^{-\alpha L}$$

or $$\alpha = -\frac{10}{L}\, log_{10}\left(\frac{P_0}{P_i}\right) \text{ in dB/km}$$

where α is known as attenuation coefficient.

****Attenuation is caused by absorption, scattering and bending losses.**

Fibre Optics

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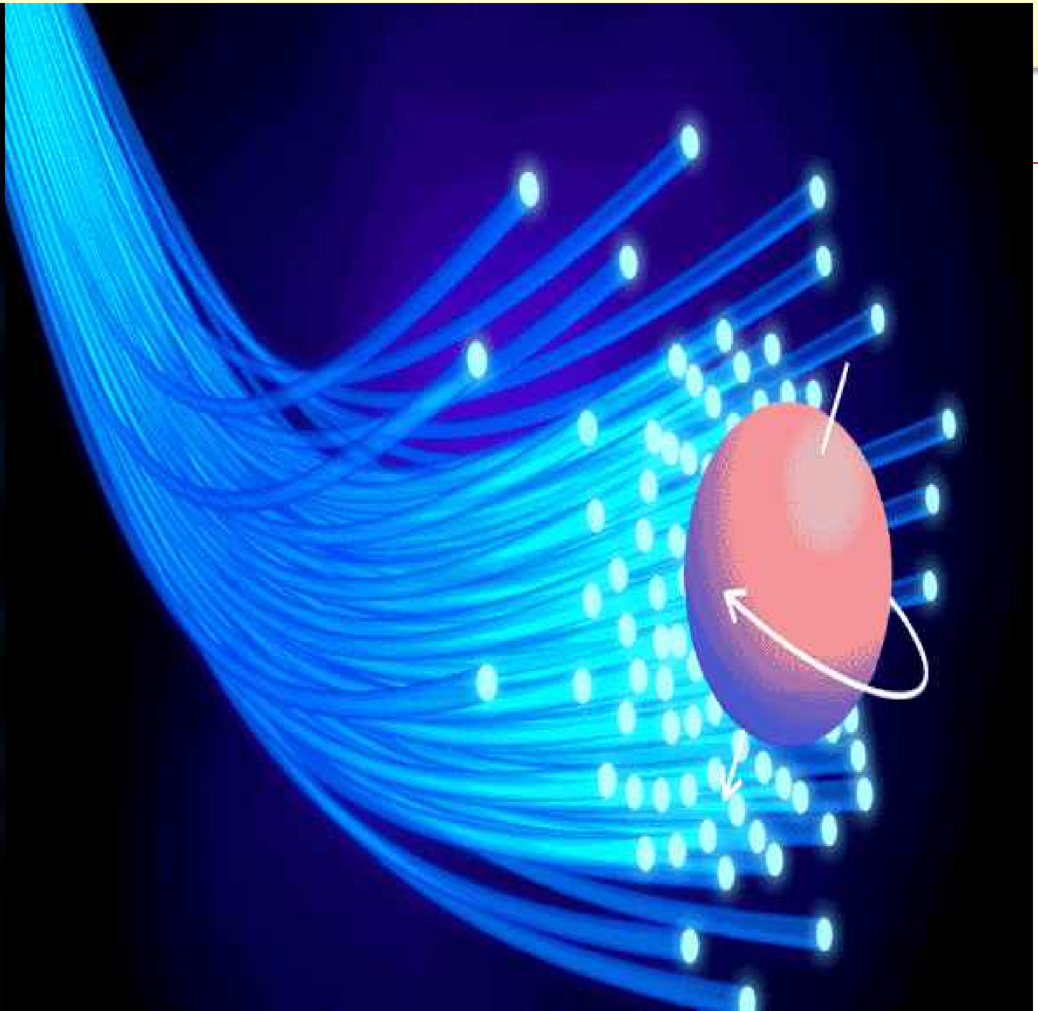


GROUP OF INSTITUTIONS

Contents

- Losses in optical fibre
- Dispersion

Discuss various types of losses in optical fibre. [2016-17]

Losses in optical fibre

There are three main losses which are responsible for attenuation in signal.

(1) Absorption loss

(2) Scattering loss

(3) Waveguide loss

(1) Absorption loss:

Absorption is a major cause of signal loss in an optical fiber during the propagation of signals. Absorption in optical fiber is due to following reasons.

a) Imperfections in the atomic structure of the fiber material

b) The intrinsic or basic fiber-material properties

c) The extrinsic (presence of impurities) fiber-material properties

(a) **Imperfections in the atomic structure -** Imperfections in the atomic structure induce absorption by the presence of missing molecules or oxygen defects. Absorption is also induced by the diffusion of hydrogen molecules into the glass fiber. Intrinsic and extrinsic material properties are the main cause of absorption.

(b) **Intrinsic absorption -** Intrinsic absorption is caused by basic fiber - material properties. If an optical fiber were absolutely pure, with no imperfections or impurities, then all absorption would be intrinsic. Intrinsic absorption sets the minimal level of absorption.

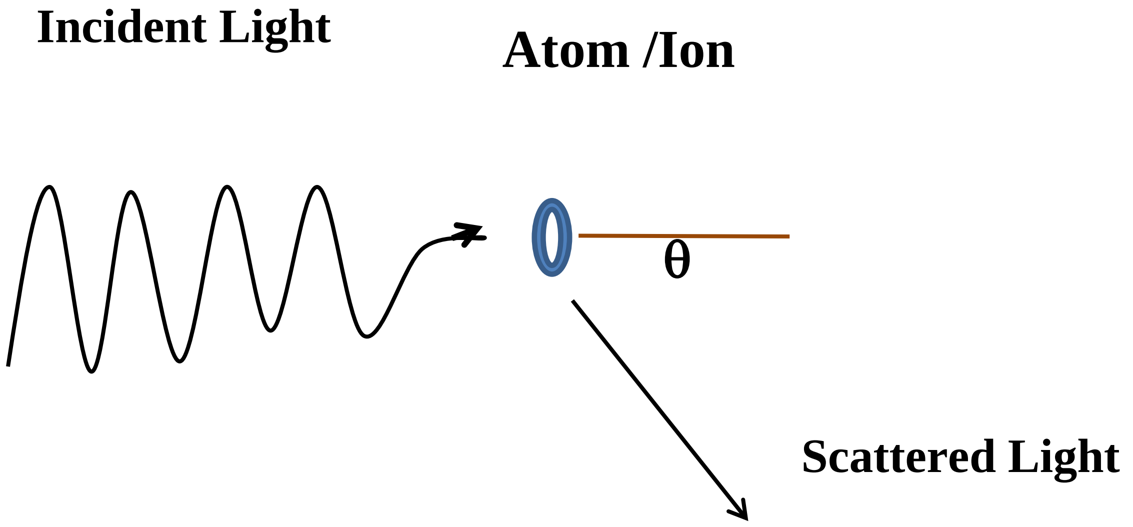
(c) Extrinsic absorption - Extrinsic absorption is caused by impurities introduced into the fiber material. Trace metal impurities such as iron, nickel, and chromium are introduced into the fiber during fabrication. Extrinsic absorption is caused by the electronic transition of these metal ions from one energy level to another.

(2) Scattering Loss

In order to change the refractive index of core of fibre, chemical impurities (atoms/ions) are added. Moreover, unwanted chemical impurities remain present in fibre during fabrication process.

- These chemical impurities act as scattering centers for light wave and responsible for signal loss.

- It has been observed that Rayleigh scattering loss is inversely proportional to the fourth power of the wavelength of incident light.



$$Scattering\ Loss \propto \frac{1}{\lambda^4}$$

**It is obvious that a optical signal of shorter wavelength suffers more scattering loss than light of longer wavelength. Hence, communication is avoided in shorter wavelengths region such as UV and Visible range.

(3) Waveguide loss

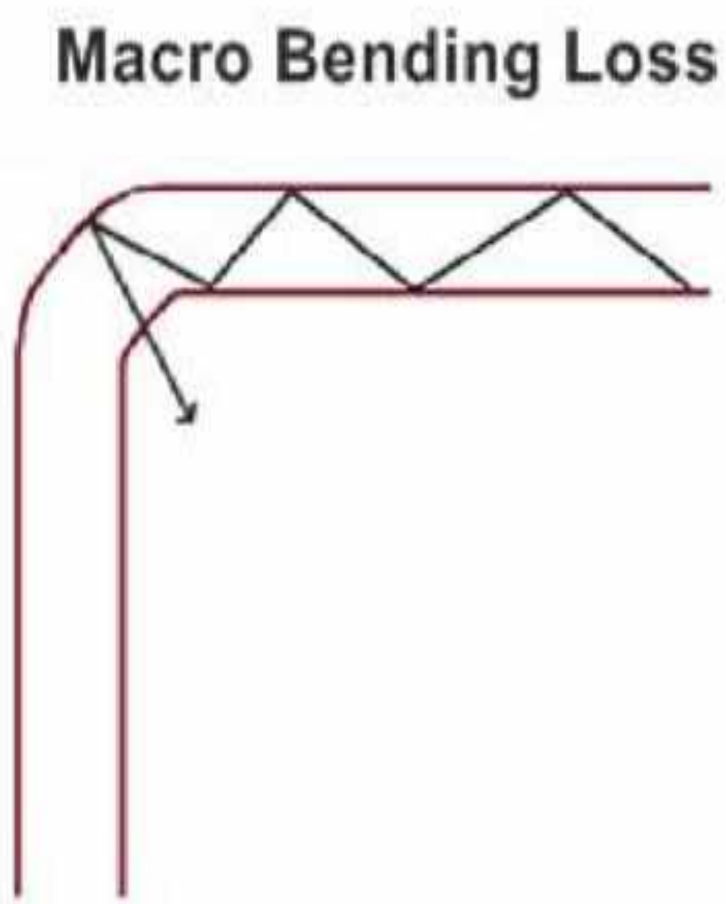
These are called extrinsic losses and can be minimized by taking care during fibre designing and fabrication.

a. **Macro bending loss and Micro bending** – cause local stresses in core.
b. **Presence of unwanted chemical impurities -** cause variation in local density.
c. **Non uniform core radius** – causes unwanted guided modes of light.
d. **Connecting issues in fibres -** cause leakage of optical signal.
e. **Axial distortion -** cause imperfection at core - cladding interface.

Bending loss : **Bending of the fibre also causes attenuation. There are two types of bending loss.**

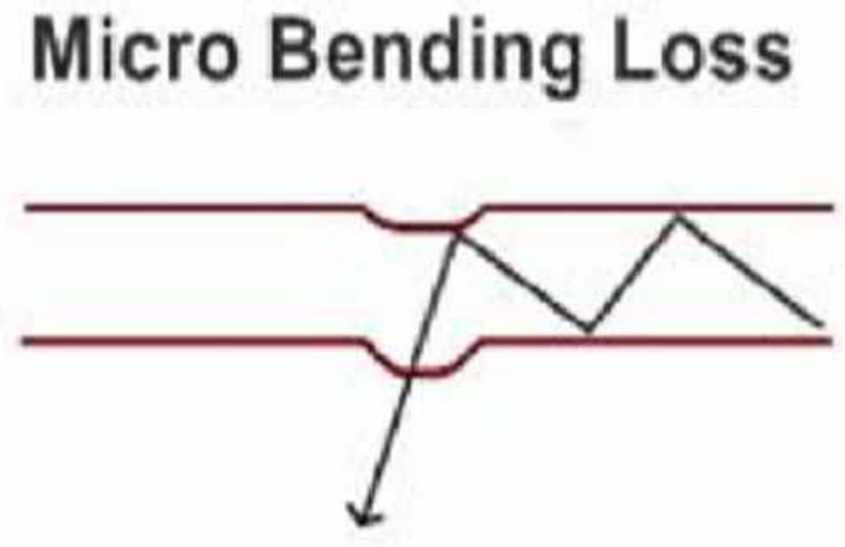
(a) Macro-bending loss:

The curvature of the bend is much larger than fibre diameter. As the radius of curvature decreases, the loss increases exponentially until it reaches at a certain critical radius.



(b) Micro-bending loss:

Micro-bending loss is a loss due to small bending in which either the core or cladding undergoes the slight bends at its surface. It is also occur due to the manufacturing defects in the core.



What do you understand by dispersion in an optical fibre? [2017-18]

Dispersion in an optical fibre

There are three main mechanism responsible for dispersion in fibre.

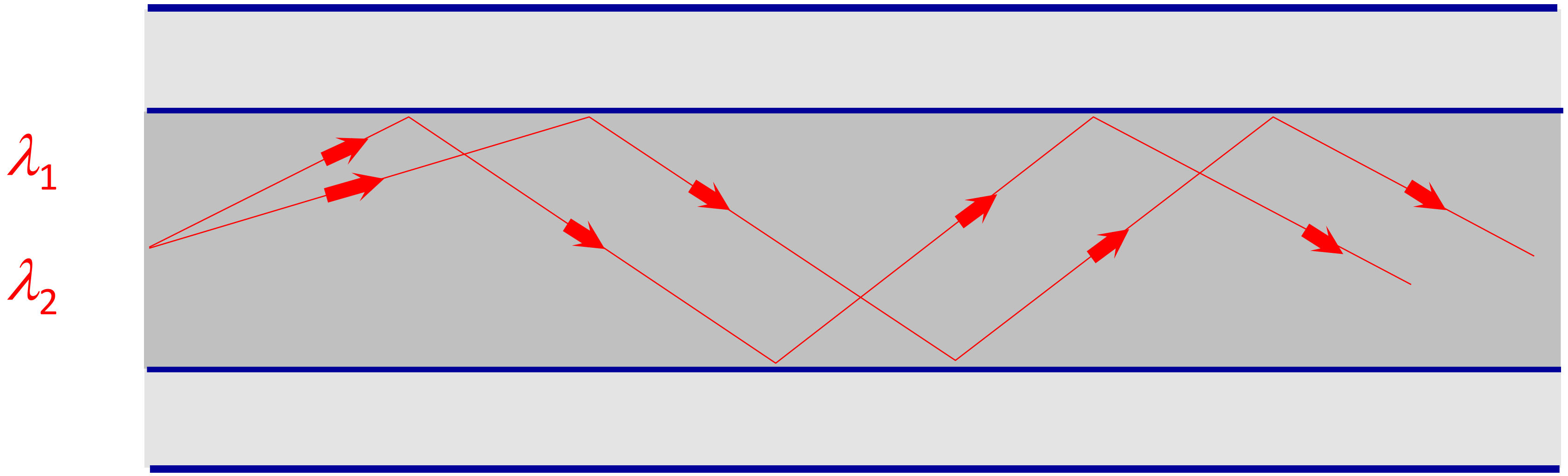
(1) Intermodal Dispersion or Multimode Dispersion

(2) Intramodal Dispersion or Material Dispersion

(3) Waveguide Dispersion

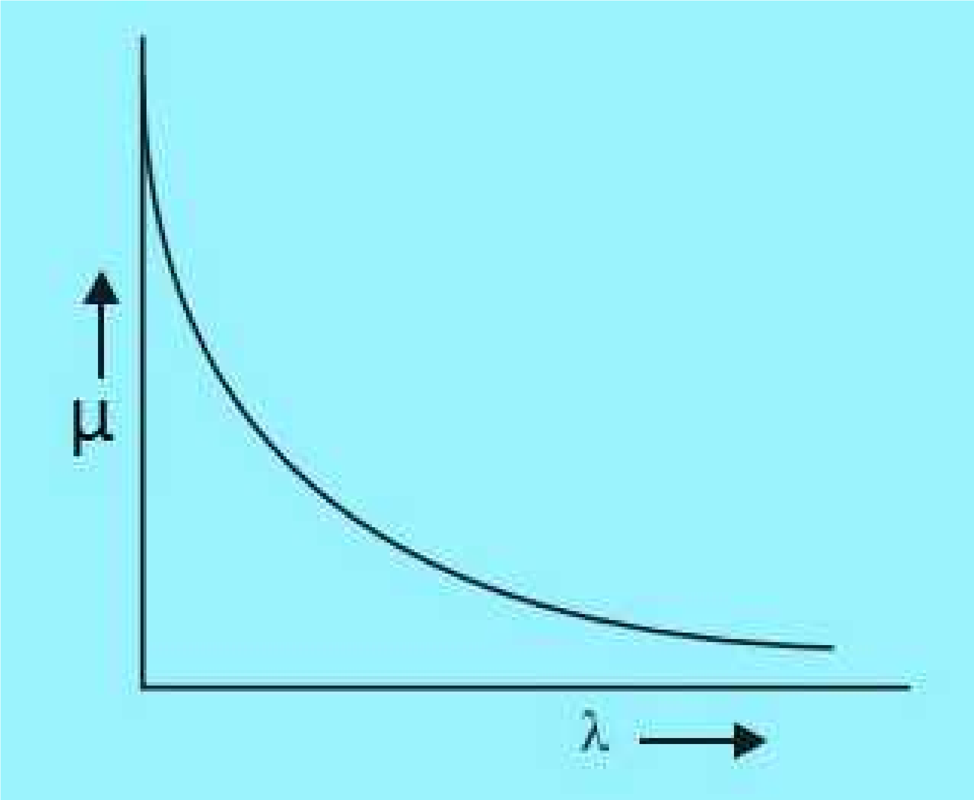
(1) Intermodal dispersion or multimode dispersion

- This kind of dispersion arises because different guided modes of light travel with different velocities in fibre.
- Light of different wavelengths follow different paths and take different time. It means that these modes do not reach at the output end of fibre at the same time and therefore pulse gets broadened.



(2) Intramodal dispersion or material dispersion

- This type of dispersion arises due to material of fibre.
- The refractive index of core - material varies with wavelength of light wavesi.e. same fibre material offers different refractive index to light waves of different wavelengths.
- Hence, the light of different wavelengths travel with different velocities.



$$\mu = \frac{B}{\lambda} + \frac{C}{\lambda^2} + \frac{D}{\lambda^4} \approx \frac{B}{\lambda}$$

$$\mathrm{v} = \frac{c}{\mu}$$

**The shorter wavelength wave travel slower than the longer wavelength wave. Consequently, a narrow pulse containing different light waves gets broadened as it travels along the core of fibre.

(3) Waveguide dispersion

It arises due to fibre design like core of radius etc. This dispersion limits the band width of optical signal. The designing parameters of a fibre are related with its V number as:

$$V = \frac{2\pi a}{\lambda_0}\sqrt{{n_1}^2 - {n_2}^2} = \frac{2\pi a}{\lambda_0}(NA)$$

a : Radius of the core

λ_0 : Operating wavelength of light wave

n_1 : Refractive index of core material

n_2 : Refractive index of cladding material

*If V$\leq 2.405 \rightarrow It\ supports\ single\ mode\ fibre$
V>2.405 →*It supports multimode fibre.*

*Higher the value of NA and larger the diameter give rise to the undesired modes of light. However, single mode fibres are dispersion - less or dispersion free because of the smaller diameter of core and minimum value of NA of the fibre.

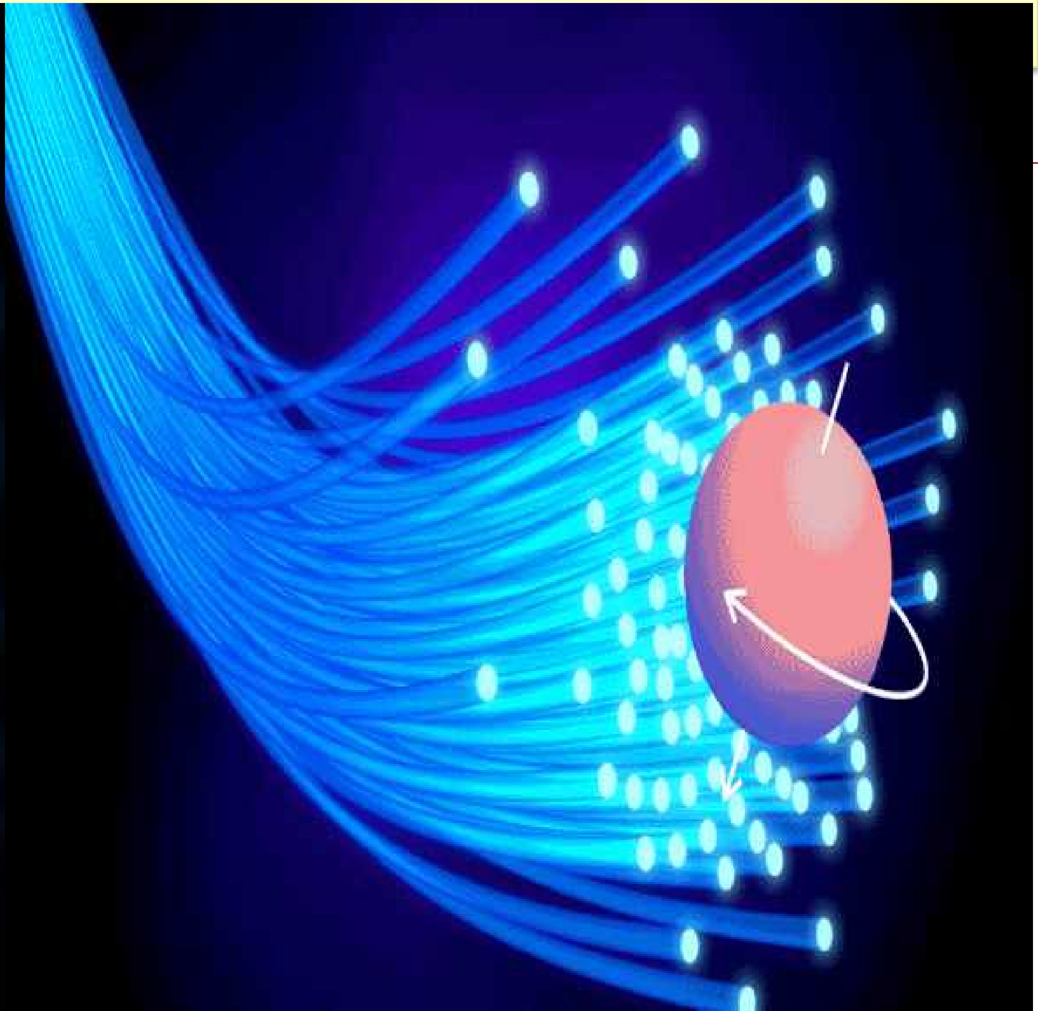
* Number of guided waves or modes in multimode fibres are

$$M = \frac{V^2}{2} \quad \text{Step index multi-mode fibre}$$

$$M = \frac{V^2}{4} \quad \text{for Graded index multi-mode fibre}$$

Fibre Optics

Lecture -29



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Contents

- **Numericals**

A step index fibre has core refractive index 1.468, cladding refractive index 1.462. Compute the maximum radius allowed for a fibre, if it supported only one mode at a wavelength 1300 nm. [2015-16]

$$V = \frac{2\pi a}{\lambda_0}\sqrt{\mu_1{}^2 - \mu_2{}^2}$$

$$V = \frac{2 \times 3.14 \times a}{1300 \times 10^{-9}}\sqrt{(1.468)^2 - (1.462)^2}$$

$$a = \frac{2.405 \times 1300 \times 10^{-9}}{2 \times 3.14 \times \sqrt{(1.468)^2 - (1.462)^2}}$$

$$a = 3.76 \times 10^{-6}\ m$$

$$\boldsymbol{a = 3.76\ \mu\mathrm{m}}$$

A communication system uses a 25 km long fibre having a loss of 2.5 dB/km. The input power is 2500 μW, compute the output power. **[2017-18]**

The loss per km is given by

$$dB = -\frac{10}{L}\ log_{10}\left(\frac{P_0}{P_i}\right)$$

$$2.5 = -\frac{10}{25}\ log_{10}\left(\frac{P_0}{2500\times10^{-6}}\right)$$

$$\frac{P_0}{2500\ \mu W} = Antilog\left(\frac{2.5 \times 25}{10}\right)$$

$$P_0 = 5.62 \times 10^{-7} \times 2500\mu W$$

$$\boldsymbol{P_0 = 0.0014\ \mu W}$$

Calculate the numerical aperture and the acceptance angle and the critical angle of the fibre from the following data: $\boldsymbol{\mu_{core} = 1.48}$ **and** $\boldsymbol{\mu_{cladding} = 1.46}$. **[2018-19, 2016-17]**

(I) Numerical aperture: $NA = \sqrt{(\mu_1)^2 - (\mu_2)^2}$

$$= \sqrt{(1.48)^2 - (1.46)^2}$$

$$\boldsymbol{NA} = \mathbf{0.24249}$$

(II) Acceptance angle:

$$\sin i_{max} = NA$$

$$i_{max} = \sin^{-1}(NA)$$

$$i_{max} = \sin^{-1}(0.24249)$$

$$\boldsymbol{i_{max} = 14.03°}$$

(III) Critical angle

$$\sin\theta_c = \frac{\mu_2}{\mu_1}$$

$$\theta_c = \sin^{-1}(\frac{\mu_2}{\mu_1})$$

$$\theta_c = \sin^{-1}(\frac{1.46}{1.48})$$

$$\boldsymbol{\theta_c = 80.57°}$$

Calculate the angle of acceptance of a given optical fiber, if the refractive indices of the core and cladding are 1.563 and 1.498 respectively.

We know that, $\sin i_{max} = \sqrt{{\mu_1}^2 - {\mu_2}^2}$

$$\sin i_{max} = \sqrt{(1.563)^2 - (1.498)^2} = 0.446$$

$$i_{max} = \sin^{-1}(0.446)$$

$$\boldsymbol{i_{max} = 26.49^0}$$

Calculate the numerical aperture, acceptance angle and critical angle of the fiber the following data: $n_1 = 1.50$ and $n_2 = 1.45$.

(2009-10, 2012-13)

We know that $\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.50 - 1.45}{1.50} = 0.033$

Numerical Aperture, $NA = n_1\sqrt{2\Delta}$

$$NA = 1.50\sqrt{2 \times 0.033} = \mathbf{0.385}$$

Acceptance angle, $i_{max} = \sin^{-1}(NA)$

$$\sin^{-1}(0.385) = \mathbf{22.64^0}$$

Using Snell's law,

$$\sin\theta_c = \frac{n_2}{n_1} = \frac{1.45}{1.50}$$

$$\theta_c = \sin^{-1}\left(\frac{1.45}{1.50}\right)$$

$$\boldsymbol{\theta_c} = \mathbf{75.16^0}$$

The optical power, after propagating through a fiber that is 500 m long is reduced to 25% of its original value. Calculate the fiber loss is dB/km.

The loss per km is given by

$$dB = -\frac{10}{L}\ log_{10}\left(\frac{P_0}{P_i}\right)$$

$$dB = -\frac{10}{1/2}\ log_{10}\left(\frac{25}{100}\right)$$

$$= \quad -20\ (log\ 25 - log\ 100)$$

$$= \quad -20\ (1.3979 - 2)$$

$$dB = \mathbf{12.042\ dB/km}$$

Thank you