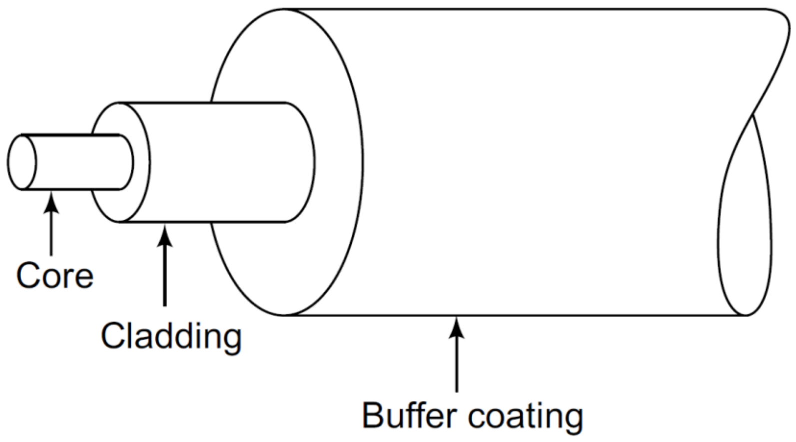
Fiber Optics

Optical Fiber

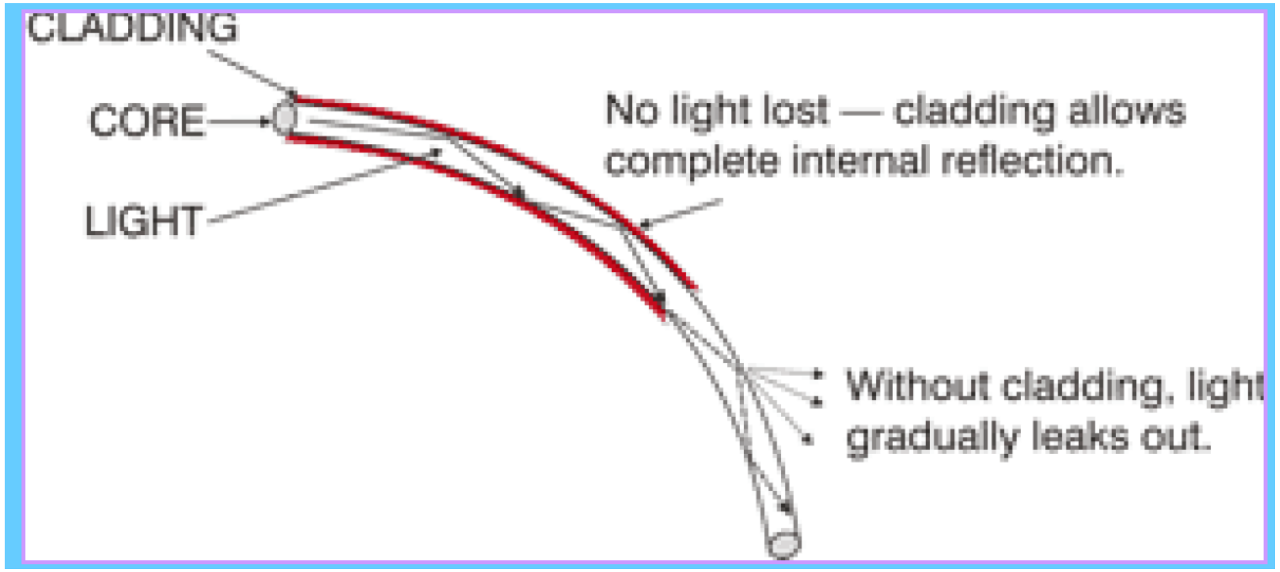
An optical fiber is a long cylindrical dielectric waveguide, usually of circular cross-section, transparent to light over the operating wavelength.

Fiber structure



- ❑ A single solid dielectric of two concentric layers.
- ❑ Inner layer – Core of radius ‘a’ and refractive index “n_1”
- ❑ Outer layer – Cladding refractive index “n_2“
- ❑ $n_2 < n_1$ (condition necessary for TIR)

Light Propagation through Optical Fiber



For light propagation through the fiber, the conditions for total internal reflection (TIR) should be met at the core-cladding interface

Optical Fiber Wave guiding

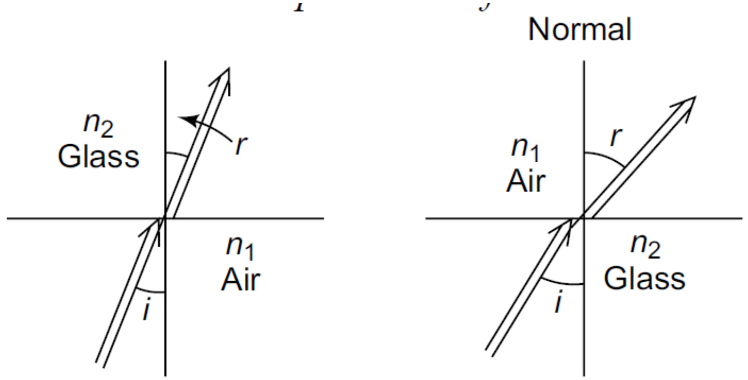
- To understand transmission mechanisms of optical fibers with dimensions approximating to those of a human hair;

- Necessary to consider the optical waveguiding of a cylindrical glass fiber.

- Fiber acts as an open optical waveguide –may be analyzed using simple ray theory –Geometric Optics

- Not sufficient when considering all types of optical fibers
- Electromagnetic Mode Theory for Complete Picture

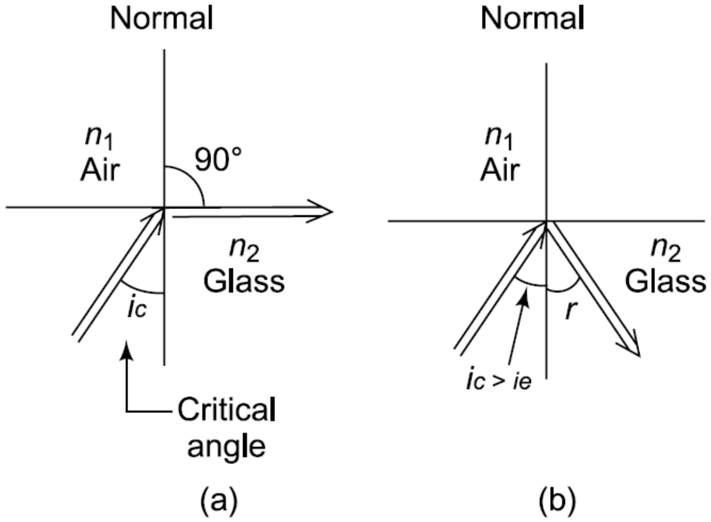
Snell's Law in Refraction



$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1} \quad \text{i.e.,} \qquad \text{i.e., } n_1 \sin i = n_2 \sin r$$

where n_2 is the refractive index of the second medium (glass) and n_1 is the refractive index of the first medium (air). This is known as *Snell's law*.

Fig. 2.2 Phenomenon of refraction: (*A*) Refracted ray bends towards normal and $\angle r < \angle i$ (*B*) Refracted ray bends away from normal and $\angle r > \angle ik$.

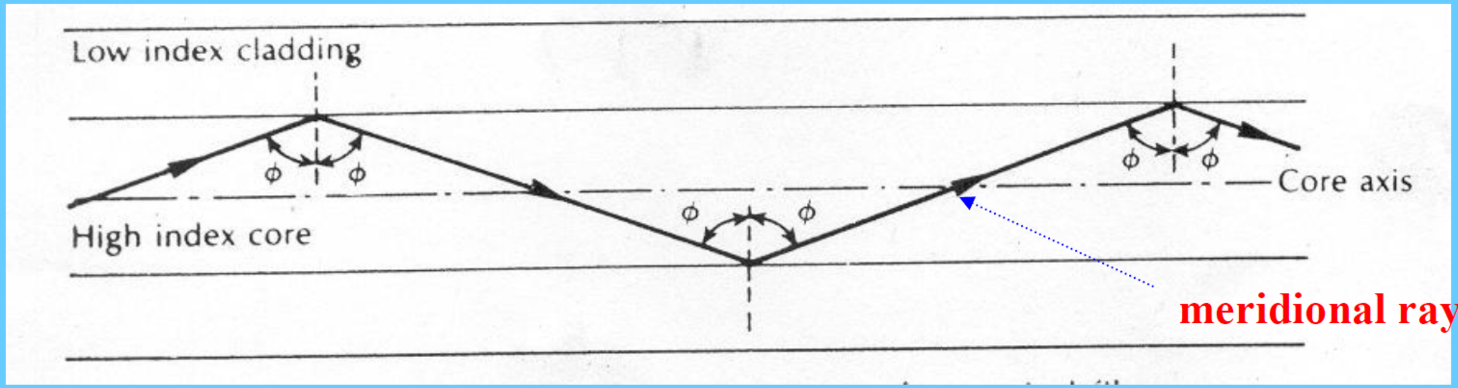


When a ray of light travelling from denser to rarer medium, incident on the surface greater than the critical angle, then it is totally reflected back

Fig. 2.3 (a) Whenever a ray of light has $\angle r = 90°$, then $\angle i_c$ is called critical angle.
(b) At an angle greater than critical angle, there is no refraction but internal reflection.

Total Internal Reflection

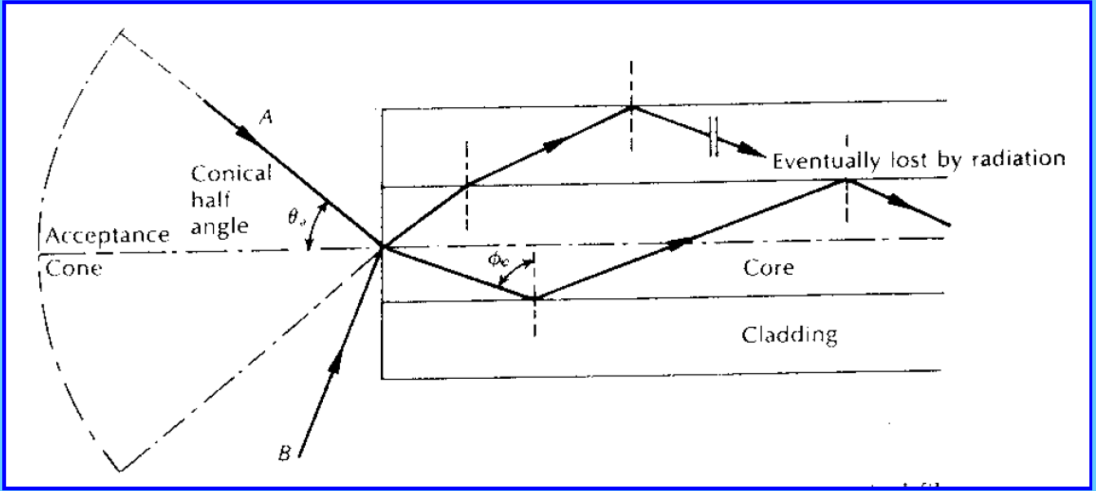
- Value of critical angle (ϕ_C); $\sin \phi_C = n_2/n_1$
  - At angle of incidence greater than critical angle, the light is reflected back into the originating dielectric medium (TIR) with high efficiency ($\approx$ 99.9%)



Transmission of light ray in a perfect optical fiber

ACCEPTANCE ANGLE

- Not all rays entering the fiber core will continue to be propagated down its length
- Only rays with sufficiently shallow grazing angle (i.e. angle to the normal > ϕ_C) at the core-cladding interface are transmitted by TIR.



➢ Any ray incident into fiber core at angle > θ_a will be transmitted to core-cladding interface at an angle < ϕ_C and will not follow TIR.
$\Rightarrow$ ***Lost (case B)***

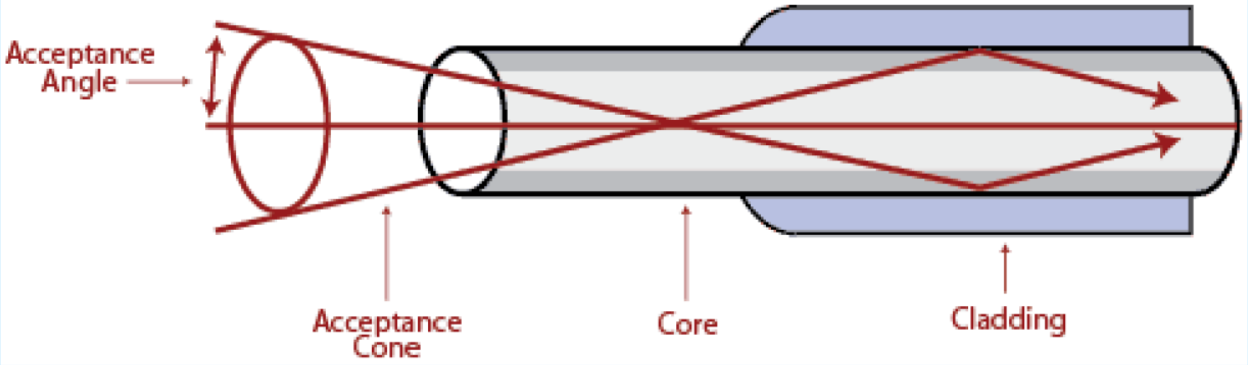
It is the maximum angle of a ray hitting the fiber core which allows the incident light to be guided by the core.

Acceptance angle θ_0:

$$\theta_0 = \sin^{-1}\left(\sqrt{\mu_1^2 - \mu_2^2}\right)$$

Acceptance Cone

❖ For rays to be transmitted by TIR within the fiber core, they must be incident on the fiber core within an acceptance cone defined by the ***conical half angle*** "θ_a" .



☞ 'θ_a' is the maximum angle to the axis at which light may enter the fiber in order to be propagated

$\Rightarrow$ **Acceptance angle** for the fiber

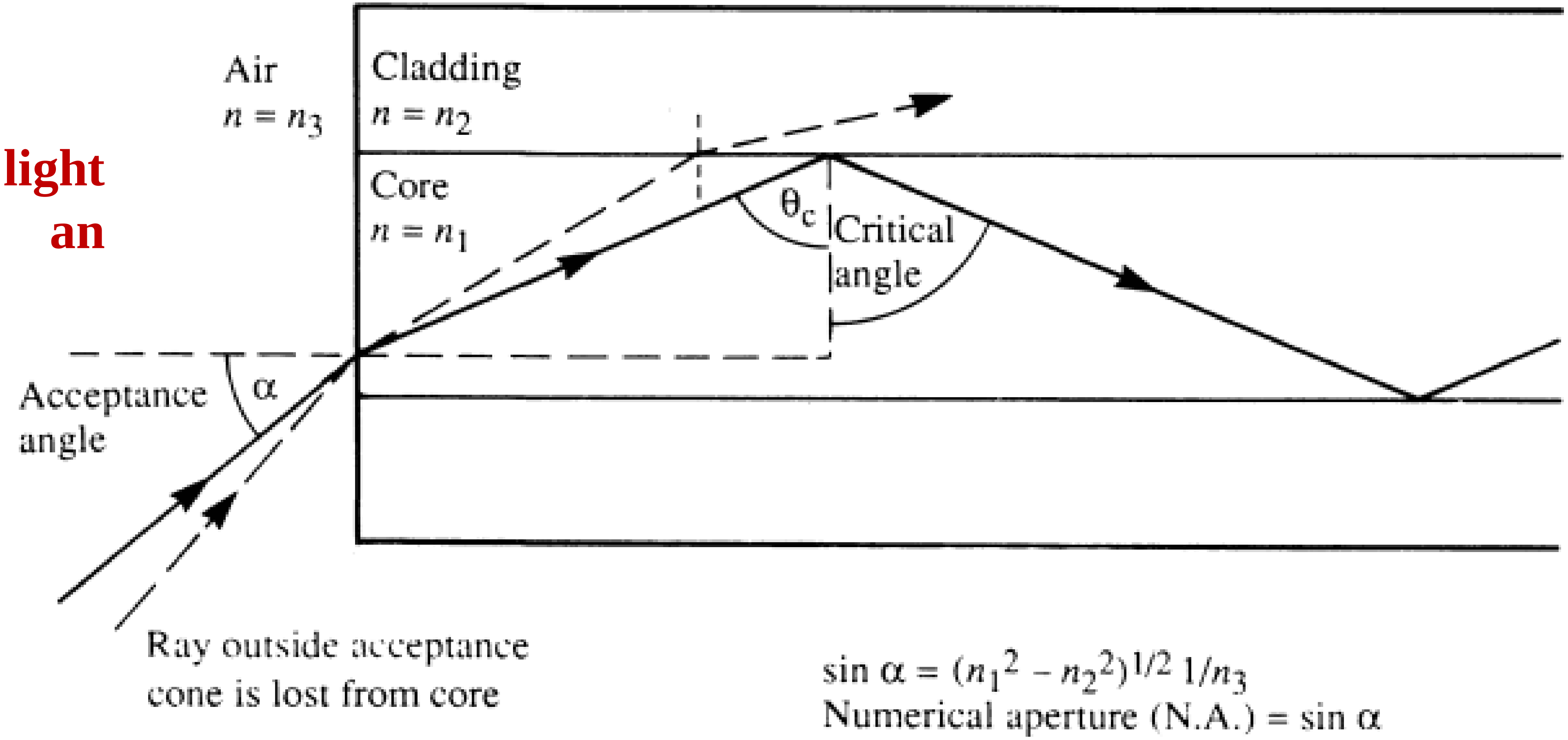
Numerical Aperture (NA)

A very useful parameter : measure of light collecting ability of fiber.

Larger the magnitude of NA, greater the amount of light accepted by the fiber from the external source

N.A. = Sinα

It tells how much light is gathered by an optical fibre



NA varies from 0.12-0.20 for SMFs and 0.20-0.50 for MMFs

Fractional refractive index change

Numerical Aperture Definition

The numerical aperture (NA) is defined as the sine of the acceptance angle.

$$\therefore \qquad NA = \sin i_m$$

$$NA = \sqrt{n_1^2 - n_2^2}$$

$$n_1^2 - n_2^2 = (n_1 + n_2)(n_1 - n_2)$$

$$= \left(\frac{n_1 + n_2}{2}\right)\left(\frac{n_1 + n_2}{n_1}\right).2n_1$$

approximate $\dfrac{n_1 + n_2}{2} \approx n_1$

$$\therefore \qquad (n_1^2 - n_2^2) = 2n_1^2 \Delta$$

$$\therefore \qquad NA = n_1 \sqrt{2\Delta} \rightarrow \Delta = \left(\frac{n_1 - n_2}{n_1}\right)$$

= fractional refractive index change.

Δ has to be + ve as $n_1 > n_2$. In order to guide light rays effectively through a fibre $\Delta << 1$.

Typically Δ is of the order of 0.01.

Numerical aperture determines the light gathering ability of the fibre. It is a measure of the amount of light that can be accepted by a fibre.

The **V number** determines the fraction of the optical power in a certain mode which is confined to the fiber core.

Since the **V-number** of the optical fiber is proportional to the **frequency**, it is also **called** as the **normalized frequency**. of the amount of energy in the mode that lies in the core and the cladding. Thus we see that, for a fiber having numerical aperture of 0.1, the radius should be less than 4 times of the wavelength.

V-Number

- Normalized Frequency, V may be expressed in terms of NA and Δ, as

$$V = \frac{2\pi}{\lambda} a(NA) = \frac{2\pi}{\lambda} a\, n_1 (2\Delta)^{\frac{1}{2}}$$

- Normalized frequency is a dimensionless parameter and simply called ***V-number*** or ***value of the fiber***.
- It combines in a very useful manner the information about three parameters, **a**, **Δ** and **λ**.
- Limiting parameter for single and multimode propagation in optical fiber.

$\Rightarrow V \leq 2.405$ for SM operation

A normalized frequency parameter, which determines the number of modes of a step-index fiber.

TYPES OF OPTICAL FIBRES

There are two types of optical fibres

1. SMF
2. MMF

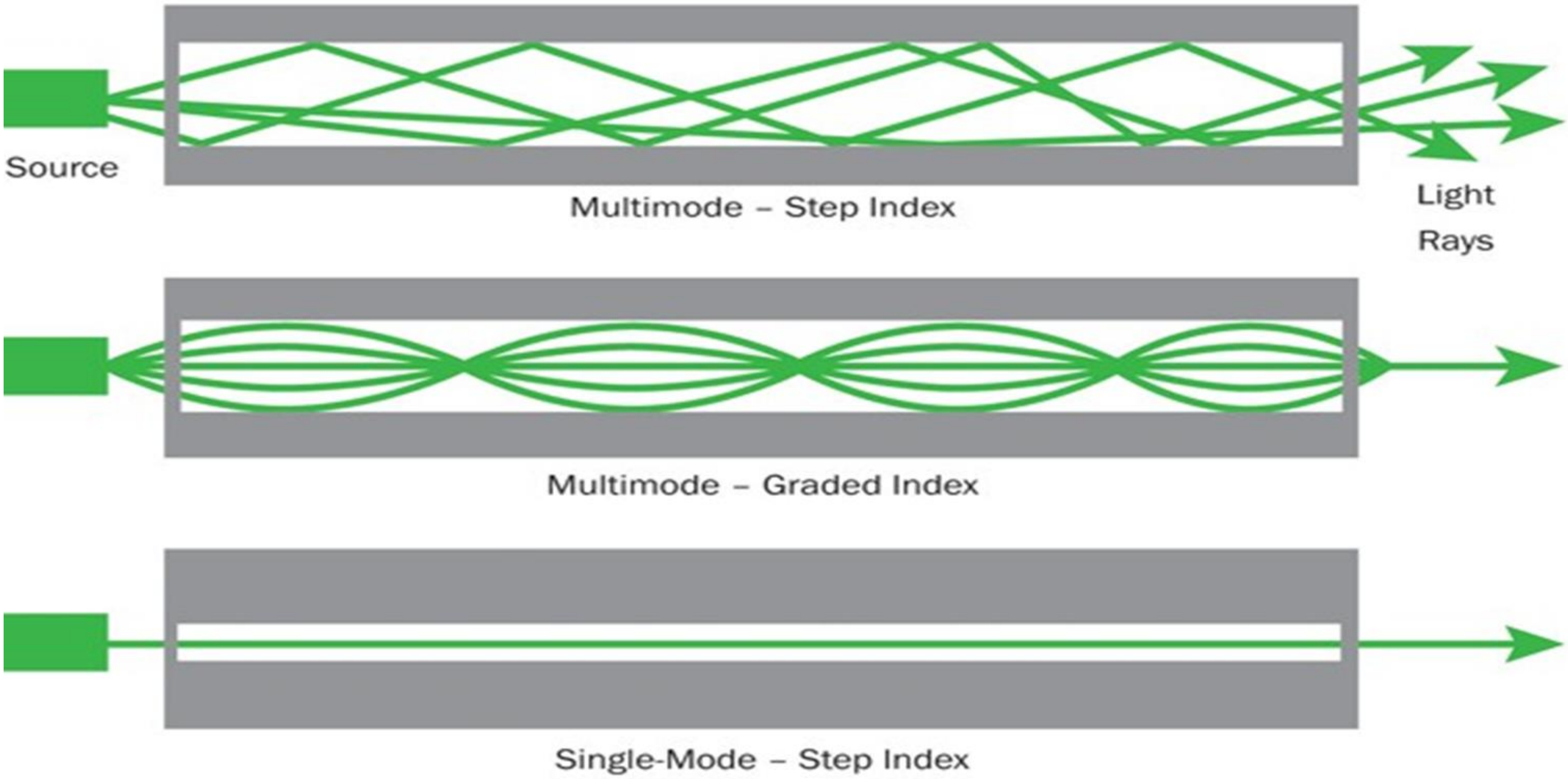
A single mode fibre has a smaller core diameter and can support only one mode of propagation.

On the other hand, a multimode fibre has a larger core diameter and supports a number of modes.

Multimode fibres are further distinguished on the basis of index-profile.

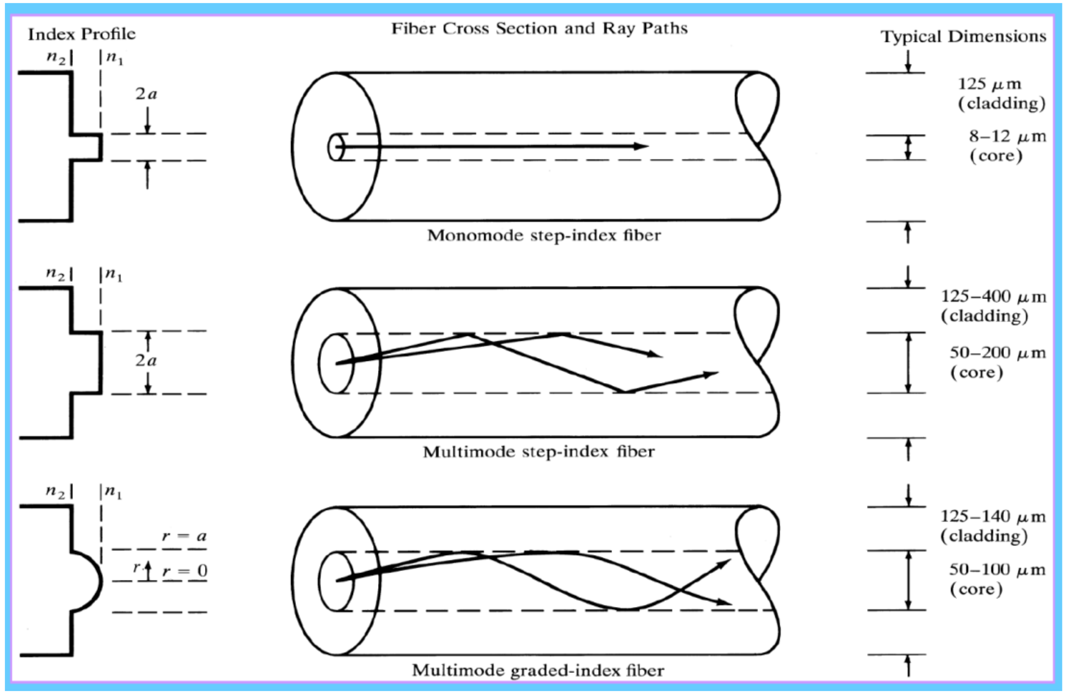
A multimode fibre can be either a step index type or graded index GRIN type. Single mode fibre is usually a step index type.

Multimode and Single-Mode Light Propagation



Single Mode Step Index Fibre

A SM step index fibre has a very fine thin core of uniform refractive index of a higher value which is surrounded by a cladding of lower refractive index. The refractive index changes abruptly at the core cladding boundary because of which it is known as step index fibre.



Multimode Mode Step Index Fibre

A multimode step index fibre is very much similar to the single mode step index fibre except that its core is of bigger diameter. A typical fibre has a core diameter of 100 mm. Light follows zigzag paths inside the fibre. Many such zigzag paths of propagation are permitted in a MMF.

Multimode Graded Index Fibre

A graded index fibre is a multimode fibre with a core consisting of concentric layers of different refractive indices therefore the refractive index of the core varies with distance from the fibre axis. It has high value at the centre and falls off with increasing radial distance from the axis.

Comparison between Single Mode and Multimode Fibres

Single Mode	Multimode
1. It supports only one mode of of propagation.	1. It supports a large number of modes propagation
2. It has very small core diameter of the order of 5 to 10 μm.	2. It has larger core diameter of the order of 50 to 150 μm.
3. Transmission losses are very small.	3. Transmission losses are more.
4. It has higher bandwidth.	4. It has lower bandwidth.
5. It requires laser diode as source of light.	5. It can work with LED also.
6. It is used for long distance	6. It is used for short distance communication.
7. It is by default step index fibre.	7. It can be step index or graded index fibre.
8. Mostly it is made up of glass.	8. It is made preferably from plastic.

Comparison between Step Index and Graded Index Fibres

Step Index Fibre	Graded Index Fibre
1. Refractive index is uniform fort the core and suddenly charges at core cladding boundary.	1. Refractive index of core is not uniform. It is maximum along the axis of core and decreases towards core cladding boundary.
2. Pulse distortion is present.	2. Pulse distortion is minimum.
3. It can be single mode or multimode.	3. It is only multimode.
4. It can be manufactured easily.	4. Manufacturing is not easy.
5. It has high numerical aperture.	5. It has low numerical aperture.
6. Attenuation is higher.	6. Attenuation is lower.
7. It offers lower bandwidth.	7. It offers higher bandwidth.
8. Reflection losses are present.	8. Reflection losses are absent.

Application Areas

- **Single mode fibers**: Mostly Step index type
  - Ideally suited for high bandwidth, very long-haul applications using single-mode ILD sources; **Telecommunication, MANs**

- **Multimode fibers** : Step index, Graded index
  - **Step Index Fibers**: Best suited for short-haul, limited bandwidth and relatively low cost applications.
  - **Graded Index Fibers**: Best suited for medium-haul, medium to high bandwidth applications using incoherent and coherent sources (LEDs and ILDs); LANs

Loses in Fiber Optics

- Attenuation
- Dispersion-intermodal
- Intramodal
- Bend loss-micro macro scattering losses
- Absorption

Loses in Fiber Optics

Attenuation

- An optical signal propagating through a fibre will get progressively attenuated.
- The signal attenuation is defined as the ratio of the optical output power from a fibre of length L to the i/p power.
- It is expressed in decibel per kilometer dB/km.

$$\propto = \frac{10}{L} \log \frac{P_i}{P_0}$$

Dispersion

- A light pulse launched into a fibre decreases in the fibre. It also spreads during its travel. The pulse received at the output is wider than input pulse.
- The pulse becomes distorted as it is propagated through the fibre.
- Such a distortion arises due to dispersion effects. Dispersion is typically measured in nano seconds per kilometer (ns/km).

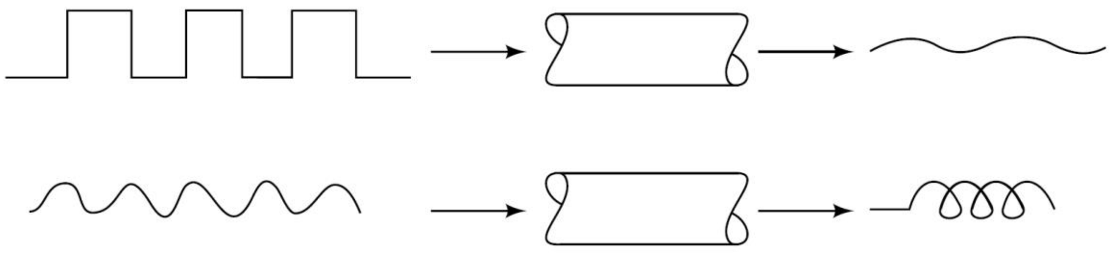
There are three mechanisms which contribute to the distortion of the light pulse in a fibre. They are known as:

i. Material dispersion

ii. Wave guide dispersion

iii. Intermodal dispersion

Broadening of the signal due to dispersion



Material Dispersion

Light waves of different wavelengths travel at different speeds in a medium. The short wavelength waves travel slower than long wavelength waves. Consequently, narrow pulses of light tend to broaden as they travel down the optical fibre. This is known as material dispersion.

Wave Guide Dispersion

Wave guide dispersion arises from the guiding properties of the fibre. The effective refractive index for any mode varies with wavelength, which causes pulse spreading just like the variation in refractive index does.

Intermodal Dispersion

A ray of light launched into a fibre follows different zigzag paths. When numerous modes are propagating in a fibre, they travel with different net velocities with respect to fibre axis. Parts of the wave arrive at the output before other parts leading to a spread of the input pulse. This is known as intermodal dispersion. It does not depend on the spectral width of the source.

other Fibre losses

The losses occurring in optical fibre (glass fibres) may be mainly attributed to three mechanisms, namely, absorption, Rayleigh scattering and geometric effects.

Absorption

Even highly pure glass absorbs light in specific wavelength regions. Strong electronic absorption occurs at UV lengths, while vibrational absorption occurs at IR wavelength from 7 to 12 mm. These absorption losses are inherent property of the glass itself and is called intrinsic absorption. However, intrinsic losses are insignificant where fibre systems operate at present.

Rayleigh Scattering

Glass is a disordered structure having local microscopic variations in density which in turn causes local variations in refractive index. Light propagation through such a structure suffers scattering losses. It is known as Rayleigh scattering loss. Because Rayleigh scattering is proportional to λ^4 it becomes important at lower wavelength. Thus, loss is proportional $1/\lambda^4$.

Geometric effects

These are fibre losses introduced during manufacturing processes. Irregularities in fibre dimensions may arise in the drawing process, in coating and cabling process or in the installation process.

Merits of optical Fibre

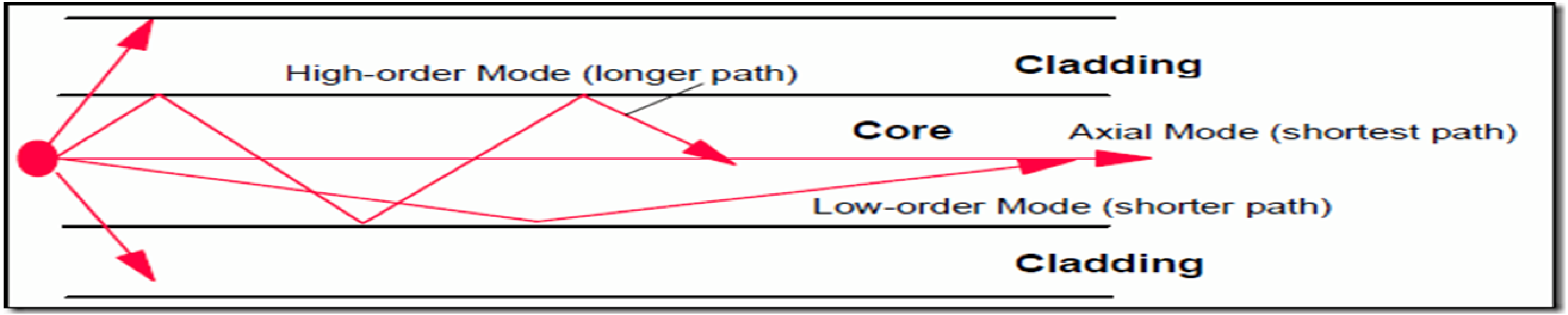
- Optical fibres are cheaper
- Optical fibres are small in size, light in weight, flexible and mechanically Strong
- Optical fibres are not hazardous
- Optical fibres are immune to EMI and RFI
- Optical fibres reduce cross-talk possibility
- Optical fibres have a wider bandwidth

While a telephone cable composed of 900 pairs of wire can handle 10,000 calls, 1 mm fibre cable can transmit 50,000 calls Thus, fibres have ability to carry large amounts of information.

- Optical fibres have low loss per unit length

Intermodal dispersion

- **Intermodal dispersion deals with the path (mode) of each light ray. Most transmitters emit many different modes. Some of these light rays will travel straight through the center of the fiber (axial mode) while others will repeatedly bounce off the cladding/core boundary to zigzag their way along the waveguide, as illustrated below. The modes that enter at sharp angles are called high-order modes. These modes take much longer to travel through the fiber than the low-order modes and therefore contribute to modal dispersion. One way to reduce modal dispersion is to use graded-index fiber.**



- Material dispersion
- Wave guide dispersion

Material dispersion is caused by the wavelength dependence of the refractive index on the fiber core material, while the waveguide dispersion occurs due to dependence of the mode propagation constant on the fiber parameters (core radius, and difference between refractive indexes in fiber core and fiber cladding) and signal wavelength. Material dispersion contributes to group delay distortion, along with waveguide delay distortion, differential mode delay, and multimode group delay spread.