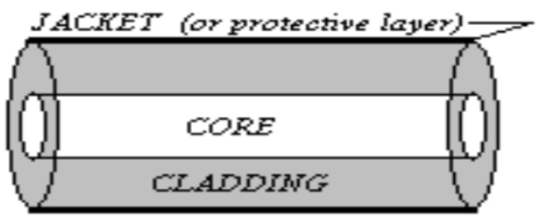
OPTICAL FIBERS

Optical fibers are thin flexible, strand of glass or plastic which guide the light waves to propagate along curved path by the principle of total internal reflection.

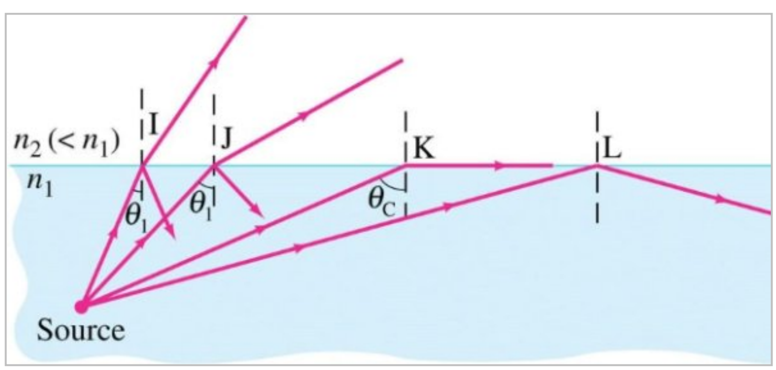
Structure of optical fiber

It consists of three coaxial regions. The innermost light guiding region is known as the Core. It is surrounded by a coaxial middle region known as the cladding. This layer serves to confine the light to the core. Core and cladding are made up of transparent dielectric materials like glass and plastic. The refractive index of cladding is always lower than that of the core. The outermost region is called as sheath or buffer. This protects the cladding and core from abrasions, contamination and moisture. The sheath also increases the mechanical strength of the fiber.



Principle of optical fibers: Basic principle of transmission of light through an optical fibre is total internal reflection.

Total internal reflection- When light travels from denser to rarer medium and angle of incidence in the denser medium is greater than critical angle for the pair of media, the light gets reflected back in the denser medium. This phenomenon is known as total internal reflection.

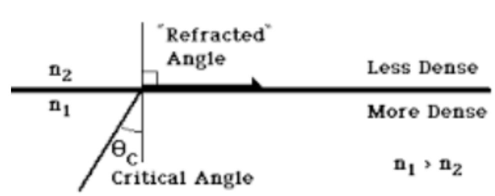


Critical angle- The angle of incidence in the denser medium for which angle of refraction in the rarer medium is 90^0, is called critical angle for the pair of media.

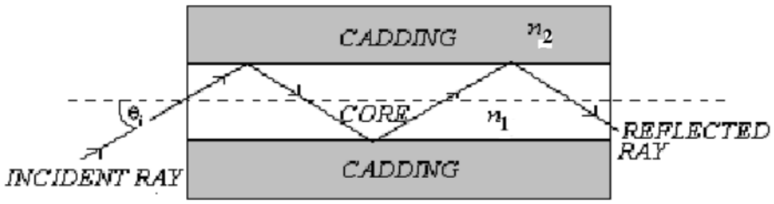
$$n_1 \sin\theta_c = n_2 \sin 90^0$$

or

$$\sin\theta_c = \frac{n_2 \sin 90^0}{n_1} = \frac{n_2}{n_1}$$



Optical fiber consists of core and cladding where core material refractive index is more than the refractive index of the cladding material.



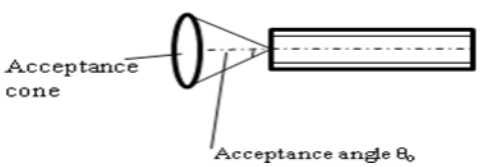
n_1 → R.I. of core, n_2 → R.I. of cladding. Such that $n_1 > n_2$.
When light is made to incident at the one end of core, for a particular angle of incidence θo (less than acceptance angle) the light ray will undergo total internal refraction at the boundary of core and cladding.

Acceptance angle. (θo)

It is the maximum allowed angle that a light ray can have relative to the axis of fiber for transmission through fiber i.e. It is that angle of incidence made by light ray at the one end of the core of an optical fiber measured with respect to the axis of fiber, for which refracted ray inside the core grazes the interface or boundary between core and cladding. For any other angle of incidence θ_i < θo, light ray undergoes total internal reflection and it propagates through the optical fiber with multiple internal reflection.

For any other angle of incidence greater than the acceptance angle i.e., θ_i > θo light ray entering the fiber refracts out of the core and cladding and thus escapes out of the optical fiber without total internal reflection.

Acceptance cone-It is the cone in which the light incident at acceptance angle or less than the acceptance angle can propagate through the fibre after total internal reflection.



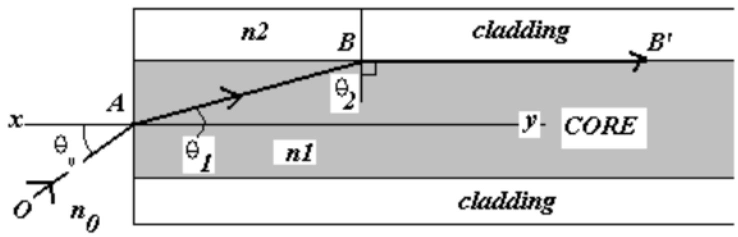
Numerical Aperture (N.A).

It is a measure of light gathering capacity of the optical fibre. It is defined as the sine of acceptance angle.

i.e. **NA = sin θ_o**

<u>Expression for numerical aperture and condition for propagation:</u>

Let, n_o be the R.I. of medium in which optical fiber is placed.
n_1 be the R.I. of core medium and n_2 be the R.I. of cladding medium such that, $n_1 > n_2 > n_o$.



Let OA be the light ray incident on one end of the core at A, with angle of incidence θ_o (measured with respect to axis of the fiber XY).
Let AB be the refracted ray with angle of refraction θ_1 in the core.

Let θ_2 be the angle of incidence made by ray AB at B on the boundary-separating core and cladding such that θ_2 is the critical angle for pair of media core and cladding.

As we have assumed θ_2 is the critical angle, AB ray refracts along the boundary separating core and cladding as BB'.
Applying Snell's law ($n_i \sin\theta_i = n_r \sin\theta_r$) for the refraction at A,
We get,

$$n_o \sin\theta_o = n_1 \sin\theta_1 \qquad (1)$$

Similarly applying Snell's law for the refraction at B,
We get,

$$n_1 \sin\theta_2 = n_2 \sin 90^o = n_2$$

from geometry $\theta_2 = 90-\theta_1$,
therefore $n_1 \cos\theta_1 = n_2$

$$\cos\theta_1 = \frac{n_2}{n_1} \qquad (2)$$

From eq (1) $\sin\theta_o = \dfrac{n_1 \sin\theta_1}{n_0}$

$$= \frac{n_1}{n_0}\sqrt{1-\cos^2\theta_1}$$

$$= \frac{n_1}{n_0}\sqrt{1-\frac{n_2^2}{n_1^2}}$$

Therefore $\sin\theta_0 = \dfrac{\sqrt{n_1^2 - n_2^2}}{n_0}$

Here $\boldsymbol{\theta_o}$ is called acceptance angle and $\mathbf{sin\theta_o}$ is called **numerical aperture** which is measure of light gathering capability of an optical fiber.

There fore

$$\text{Numerical Aperture(N.A)} = \sin\theta_o = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

&

$$\text{Acceptance angle} = \theta_o = \sin^{-1}\left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right)$$

If the surrounding medium is air,

Then $n_o = 1$

Therefore, $\sin\theta_0 = \sqrt{n_1^2 - n_2^2}$

From the expression for Numerical aperture

$$N.A. = \sqrt{n_1^2 - n_2^2}$$

It is clear that only for the angle of acceptance satisfying $\sin\theta_0 = \sqrt{n_1^2 - n_2^2}$, the light ray will undergo refraction in such way that refracted ray will be within the core of the fiber. If θ_i, is the angle of incidence at one end of the core of an optical fiber such that θ_i is less than θ_o, then θ_2 becomes more than the critical angle at B as a result of which the ray undergoes total internal reflection at the boundary separating the core and cladding.

Condition of propagation:

The ray will propagate through the fiber if the angle of incidence $\theta_i \leq \theta_o$

or $\sin\theta_i \leq \sin\theta_o \leq NA$

$\theta_i \leq \sin^{-1}(NA)$

Fractional index change (Δ)

It is the ratio of the difference in refractive indices of core and cladding to the refractive index of core of an optical fiber.

$$\Delta = \frac{n_1 - n_2}{n_1}$$

Relation between N.A and fractional index change (Δ).

$$NA = \frac{\sqrt{n_1^2 - n_2^2}}{n_o} = \frac{\sqrt{(n_1 + n_2)(n_1 - n_2)}}{n_o}$$

$$= \frac{\sqrt{(n_1 + n_2)(\frac{n_1 - n_2}{n_1})n_1}}{n_o}$$

Since $n_1 \approx n_2$, we can write $(n_1 + n_2) \approx 2n_1$

Therefore $NA = \frac{\sqrt{2n_1.\Delta n_1}}{n_o} \approx \frac{n_1\sqrt{2\Delta}}{n_o}$

Modes of propagation in an optical fiber

Modes can be visualized as possible number of paths for light rays in optical fiber. Geometrically these modes can be treated as light rays propagating through the optical fiber. Single mode fiber allows only one path for the propagation where as multimode fiber allows more than one path and each mode can be used as one channel for communication.

V- number (or) Normalized frequency:

The number of modes sustained in an optical fiber depends on radius of the core, refractive index of core(n_1)and cladding (n_2) and wavelength of light used, which can be calculated by parameter called V- number given by is,

$$\mathbf{V}= \frac{\pi d}{\lambda}\,\mathbf{(NA)} = \frac{\pi d}{\lambda}\,\frac{\sqrt{n_1^2-n_2^2}}{n_0}$$

where d= core diameter, λ= the wavelength of light propagating in the fiber.

The number of modes supported by the fiber, $\mathbf{N} \cong \frac{V^2}{2}$

Refractive index profile: The graph showing the variation of refractive index with respect to radial distance from the axis of fiber is called the refractive index profile.

Types of optical fibers

Optical fibers mainly have been classified according to their refractive index profile as

1. Step index single mode fiber.
2. Step index multimode fiber.
3. Graded index multimode fibers.

Fig (1)

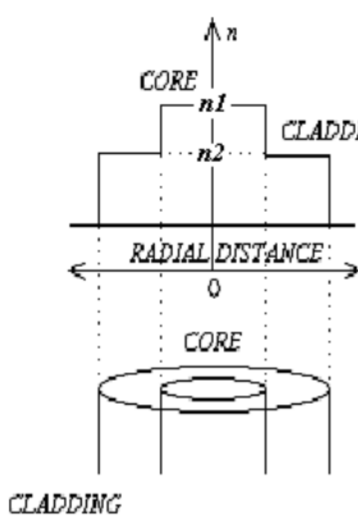
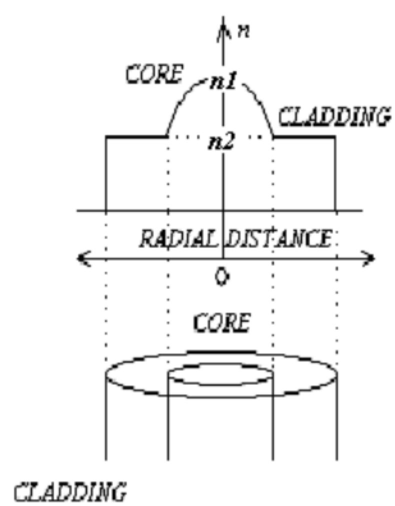


Fig (2)



Step index fibers

Fig (1) shows R.I. profile of step index fiber where R.I. profile appears like a step. The refractive indices of the core and cladding vary like a step and so it called as step index fiber. It has constant higher value of refractive index of core and constant lower value of refractive index of cladding. The light rays propagating through it are in the form of **meridional rays** which will cross the fiber axis during every reflection at the core-cladding boundary and are propagating in a zig-zag manner. The variation of refractive index of a step index fiber as a function of radial distance can be mathematically represented as

$n(r)=n_1$ [r<a, inside core]

$=n_2$ [r>a, in cladding]

Step index fibers can be divided as **Step index single mode fiber and Step index multi-mode fiber.**

Step index single mode fiber

A single mode fiber is one in which light follows a single path for the propagation through the core. These fibers will have the core diameter of the order of 8 to 10 μm and cladding diameter of the order of 60 to 70 μm. Because of narrow core only zeroth order mode is allowed in a single mode as shown in fig.

Characteristics of single mode step index fiber

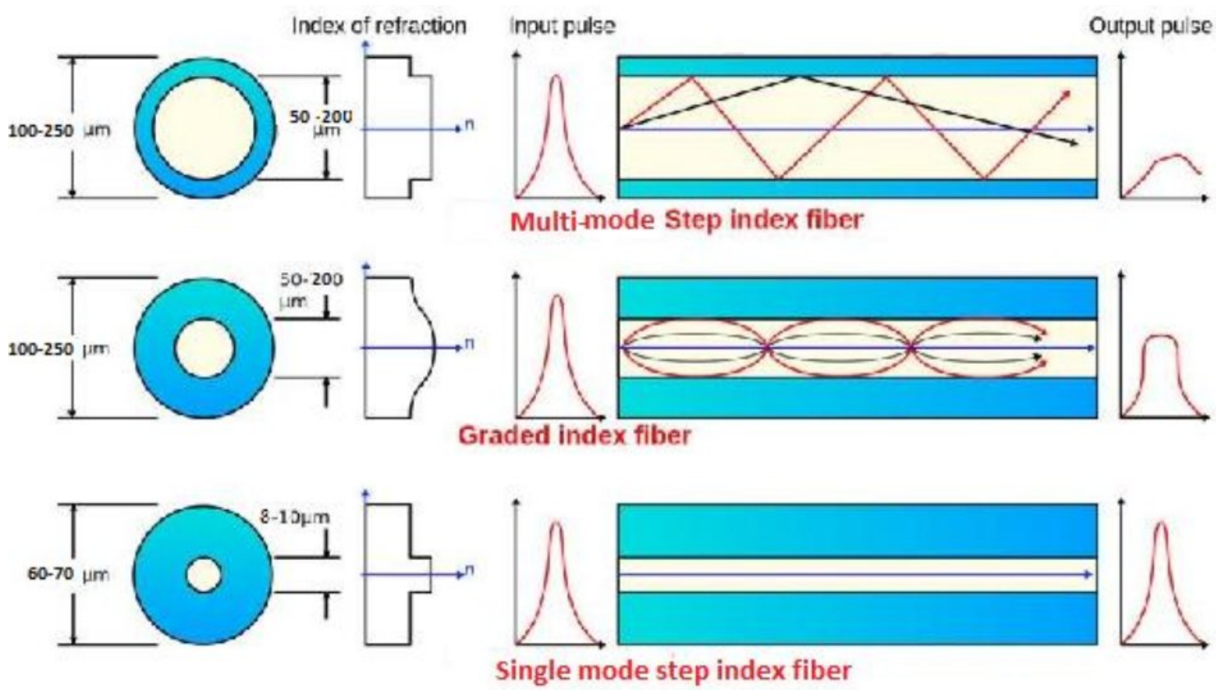
1. It has small core diameter.
2. It has high bandwidth.
3. It has small numerical aperture around 0.02.
4. It has less attenuation.

Advantages

It has very high capacity. Nearly 80% of the fibers are of step index single mode.

Fabrication of fibers, Launching of light into single mode fibers and joining of two fibers are very difficult.

They need lasers as a source and are used in long distance communications. **They find application in submarine cable systems.**



Step index multi-mode fiber

Multimode fiber is one in which light follows many path (more than one) through the core for the propagation. These fibers will have core diameter of the order 50 to 200 μm and cladding diameter of 100 to 250 μm. Due to large core diameter it can support large number of modes as shown in fig.

Characteristics of Multimode step index fiber

1. It has high core diameter.
2. It has low band width.
3. It has high numerical aperture around 0.3.
4. They suffer from intermodal dispersion so attenuation is more.

Advantages

1. They are easier to manufacture.
2. They have simple circuitry.

LED or Laser can be used as a source. Fabrication, Launching of light into fiber and joining of two fibers are easy in these fibers so they are cheap. **They are used as data links for communication purposes which has lower bandwidth requirements.**

Light propagation in step index fibers is by multiple total internal reflections. In multimode step index fibers, there is a time delay between different pulses of lower order modes and high order modes travelling along different paths as shown in fig. Hence the pulse received at the other end is broadened. This is known as intermodal dispersion. This imposes limitation on the separation between pulses and reduces the transmission rate and capacity. To overcome this problem, graded index fibers are used.

Graded Index fibers

Fig (2) shows R.I. profile of graded index fiber where refractive index of core is not constant but decreases as we move away from the axis of the core. But refractive index of cladding remains constant and its value is less than the core's refractive index. As there is continuous variation in the refractive index of the core, light propagates through refraction of light following a curved path as shown in figure below. The variation of refractive index of core with radius in a graded index fiber as a function of radial distance can be mathematically represented as

$$n(r) = \begin{bmatrix} n_1\sqrt{1-2\Delta\left(\dfrac{r}{a}\right)^{\alpha}}, & r < a \quad inside\ core \\ n_2, \quad r > a \quad in\ cladding \end{bmatrix},$$

where α is a dimensionless parameter which defines the shape of the index profile and 'a' is radius of core.

The light rays travel along the region of lower refractive index faster as compared to light travelling in the region of high refractive index, hence all the pulses of signals will reach at the other end of fiber simultaneously. Thus the problem of intermodal dispersion can be reduced to a large extent and attenuation is less in graded index fiber. Light rays propagating through it are in the form of **skew rays** (or) helical rays which will not cross the fiber axis at any time and are propagating around the fiber axis in a helical (or) spiral manner as shown in fig. (3).

Characteristics of graded index multimode fibers

1. It is a high quality fiber.
2. It has moderate bandwidth and capacity.
3. It has small numerical aperture.
4. It has low attenuation.

Advantage

LED or Laser can be used as a source for GRIN multimode fibers. It is most expensive of all. It is easier to splice and interconnect. But these fibers are free from intermodal dispersion. **It's typical application is in telephone trunk between central offices.**

Dispersion

The spreading of an optical pulse as it travels inside the core of an optical fiber is called dispersion. It is expressed in units of ns/km

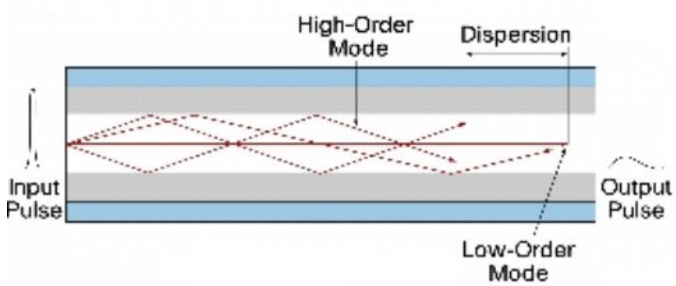
Types of dispersion

1) Intermodal dispersion

2) Intramodal dispersion

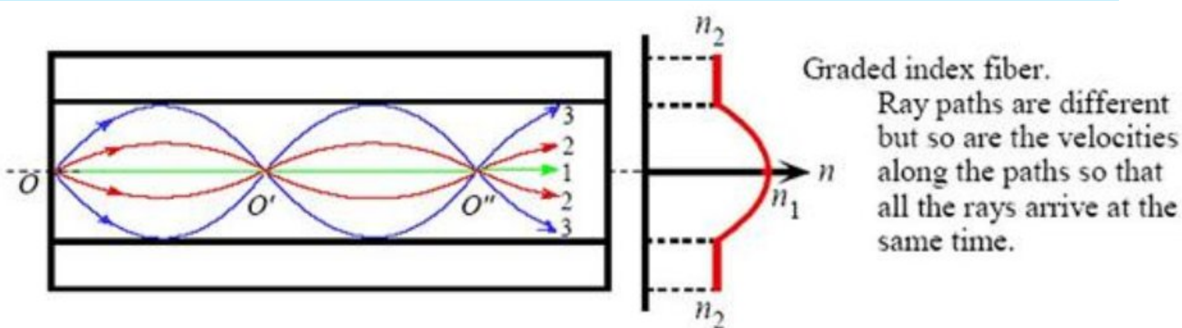
1) Intermodal dispersion

When light travels in the step-index multimode fiber, each ray is reflected many times. The higher order modes travel longer distance than the lower order modes to reach the end of fiber. Hence higher order modes arrive later than the lower order and pulses broaden causing signal distortion. The path length of the zeroth order (along the axis of fiber) is the shortest among the allowed modes.



Therefore the part of the input energy that takes this mode arrives at the receiving end earliest compared to those which take higher order modes. This type of distortion is known as intermodal dispersion.

In graded index fiber light ray travel at different speeds in different parts of the fiber because refractive index varies across the core. The rays near the outer edge of core travel faster than the rays in the centre of the core and arrive at the end of the fiber at approximately at the same time.



2) Intramodal dispersion

Intramodal dispersion is again divided into two parts

(i) Material dispersion

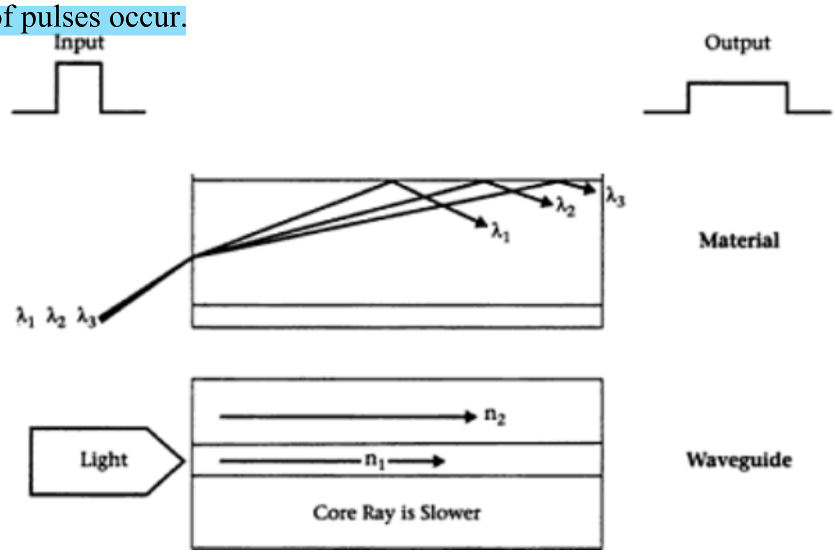
(ii) Waveguide dispersion

i) Material dispersion

A light pulse is a wave packet, composed of a group of components of different wavelengths. The different wavelength components will travel at different speeds along the fiber.. The short wavelengths travel slower than long wavelengths. Consequently, pulses of light tend to broaden as they travel down the fiber. It is often called the chromatic dispersion. Material dispersion occurs in all type of fibers.

ii) Waveguide dispersion

Waveguide dispersion arises from guiding properties of the fiber. It occurs in single mode fibers. It is caused by the different refractive indices of the core and cladding of an optical fiber. Regardless of the nature of the light source and optical fiber, some light travels in the cladding as well. The light propagating in the cladding travels faster than the light confined to the core and hence, broadening of pulses occur.



In a multimode step index fiber, all three pulse spreading mechanism exist simultaneously. In case of step index single mode fiber only material and waveguide dispersion exist.

Attenuation

Attenuation is the loss of power suffered by an optical signal as it travels down the optical fiber is called as attenuation.

It is expressed in terms of attenuation coefficient.

Attenuation coefficient $$\alpha = -\frac{10}{L}\log_{10}\left[\frac{P_{out}}{P_{in}}\right]$$

Generally α is expressed in decibel/km (dB/km),

where **L** is the length of the fiber in **km**, $\mathbf{P_{out}}$ is output power and $\mathbf{P_{in}}$ is input power in Watt.

The losses or attenuation may be due to light absorption, scattering and extensive fiber bends. These loss mechanisms can be explained as follows.

(1) Absorption losses.

Absorption losses occur due to absorption of photons associated with signal by the fiber material.

Intrinsic Absorption-In silica fibers SiO_2 is the main constituent which can absorb part of the optical signals and is called intrinsic absorption. Along with intrinsic absorption, there may be impurity absorption.

Extrinsic Absorption-Generally impurities present are transition metal ions, OH (hydroxyl) ions which will absorb photons during the propagation of light signals.

However by reducing impurity concentrations during the fabrication of fibers, we can reduce impurity absorption but intrinsic absorption cannot be avoided which sets the lowest limit for absorption loss. However limit is found to be of the order of 0.01 db / km. For plastic fiber this loss is high.

(2)**Scattering losses.**

Scattering losses occur due to inhomogeneities and structural defects present in the fiber.

Rayleigh Scattering: While the signals travel in the fiber, the photons may be scattered because of sharp changes in refractive index values inside the glass over distances that are small compared to wavelength of light. These regions of dimensions less than the wavelength of light acts as a scattering agents, as a result of which photon changes its direction and can escape out of the fiber without undergoing total internal reflection and thus loss in optical signals occurs.

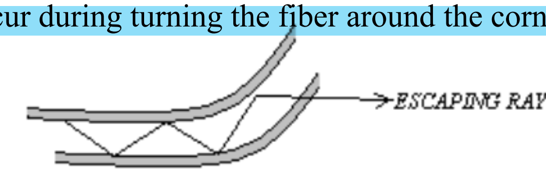
This kind of scattering is called Rayleigh's scattering and the rate of scattering is inversely proportional to fourth power of light wavelength used. To reduce this type of scattering losses generally lights of longer wavelengths will be used for communication purpose.

Mie scattering- Non perfect cylindrical structure of the fiber and imperfections like irregularities in the core-cladding interface diameter fluctuations, trapped gases bubbles, unreacted starting materials etc. may create scattering which is termed as Mie scattering.

(3)Bending losses.

Bending loss or radiative loss occurs due to bending of a fiber. There are two types in bending one is macroscopic bending and the other one is microscopic bending.

Macroscopic bends: refers to bends having radius that are much larger compared to the fiber diameter which occur during turning the fiber around the corner while laying it.

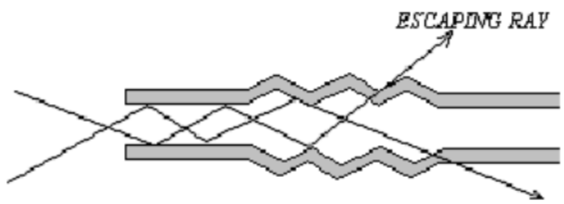


MACROSCOPIC BEND

Light ray encountering this sharp bend fails to get total internally reflected due to change in angle of incidence at the boundary separating core and cladding. This kind of losses can be avoided by avoiding sharp bends in the fibers during installation.

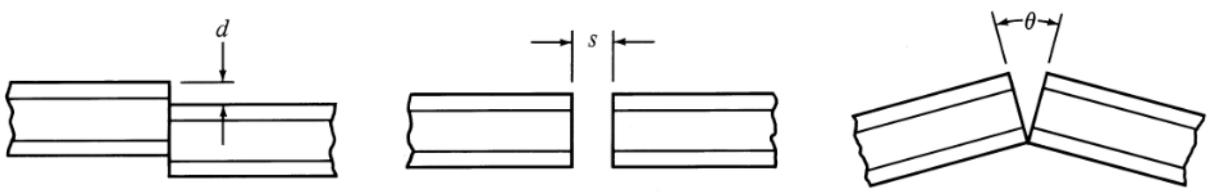
Microscopic bends:

These losses refer to repetitive small scale fluctuations in the linearity of the fiber axis due to non-uniformities in the manufacturing the fiber or due to the non-uniform lateral pressures created during the cabling of the fibers. The micro bends cause irregular reflections and some of them then leak through the fiber. Wrapping or coating compressible jackets over the fiber so that external pressure effects in fiber can be avoided, can minimize signal losses due to geometric losses.



microscopic bends

(4) Splicing or coupling losses For some applications, the optical fibers have to be laid over very large distances then it becomes necessary to interconnect two fibers which are usually of kilometer length. When the fibers are interconnected, losses occur due to mechanical misalignment. This is called splicing or coupling losses.



(*a*) Lateral (axial) (*b*) Longitudinal (end separation) (*c*) Angular