Module 2 Unit 3

OPTICAL FIBRES

(As per SVU-R2020 Scheme & Syllabus)

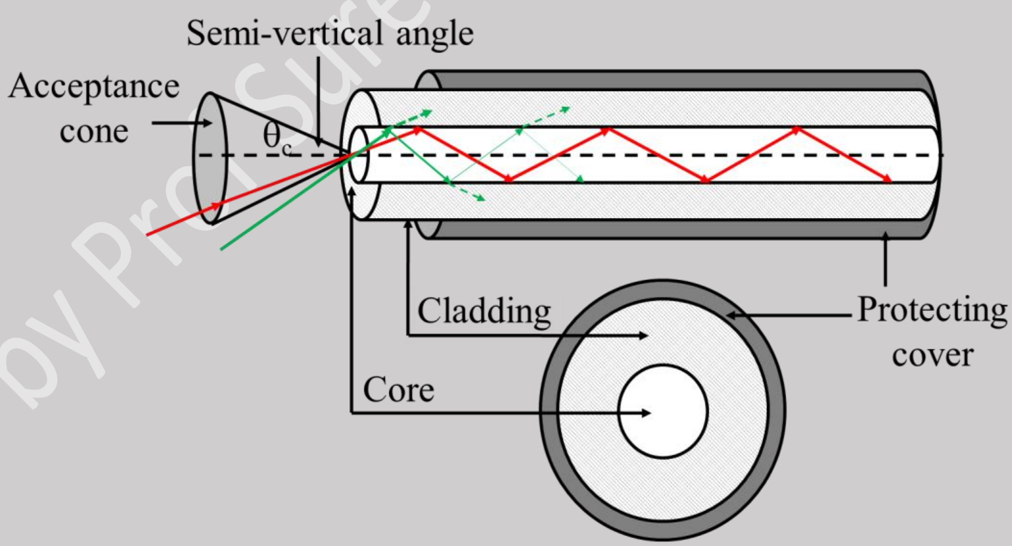
- **Introduction**

Our globe is physically connected by means of optical fibres. Worth to mention, the "online" mode of work is impossible without optical fibres. Since when the Standard Telecom Labs of England announced optical fibres with low transmission losses, there has been phenomenal grown in the fibre optics applications in the last 50 years. At present, optical fibres offer the safest, cheapest, fastest and highest capacity data transfer media. Apart from their use in communications, optical fibres find applications in other fields like surgery, defence and sensors.

- **Basic information about optical fibres**

Optical fibres are glass or plastic solid threads (not hollow like capillary), which are designed to propagate light typically in the IR region. Their main function is to accept and transmit as much light as possible along their length. The principle on which, optical fibres work is called as "total internal reflection".

An optical fibre basically consists of two coaxial regions called the (inner) "core" and the (outer) "cladding". Usually these regions cannot be visually distinguished from each other since the only difference between them being that of refractive index and that is too, very small (on the order of 0.01 to 0.1). The core diameter varies from 5 to 125 µm while the cladding diameter is usually 25 to 500 µm.



An optical fibre possesses an "acceptance cone", which is a measure of its light gathering capacity. It basically indicates that if rays of light from a source fall within this cone, then only they would undergo total internal reflection. Optical fibres are characterized by two important parameters called the "numerical aperture" and the "normalised frequency" or "V-number".

- **Advantages of Optical Fibres**

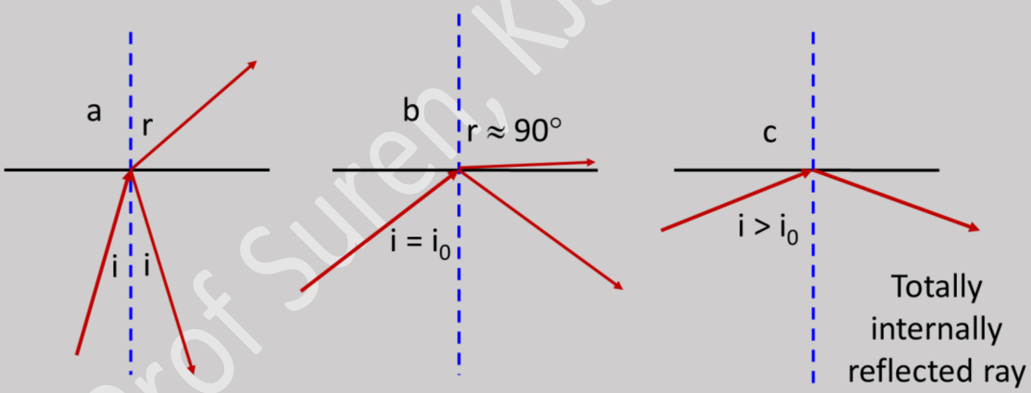
1) Cheaper, smaller, lighter, durable, chemically stable and mechanically flexible.
2) Safer, immune to stray EM signals, reduced cross-links, noise-free.
3) High bandwidth, very high data speeds.
4) Lower losses.

- **Principle of operation – Total Internal Reflection**

This is the basic principle on which, any optical fibre works. It is explained with the help of following diagrams. Consider a ray of light going from a region of higher refractive (say n_1) index towards a region of lower refractive index (say n_2). Let “i" be the angle of incidence and “r” be the angle of refraction. The ray would deflect away from the normal as $n_2 < n1$ and obviously, r < i. Apart from partial reflection, there would be in general, partial refraction (or transmission) also. Now, if we increase the angle of incidence, the angle of refraction will also go on increasing and there would be some critical value of the angle of incidence say $i = i_0$ for which, the refracted ray moves almost parallel to the interface as shown. This angle of incidence is called “critical angle of incidence”. At this angle,

$\sin(\mathrm{i}) = \frac{\mathrm{n}_2}{\mathrm{n}_1}$.

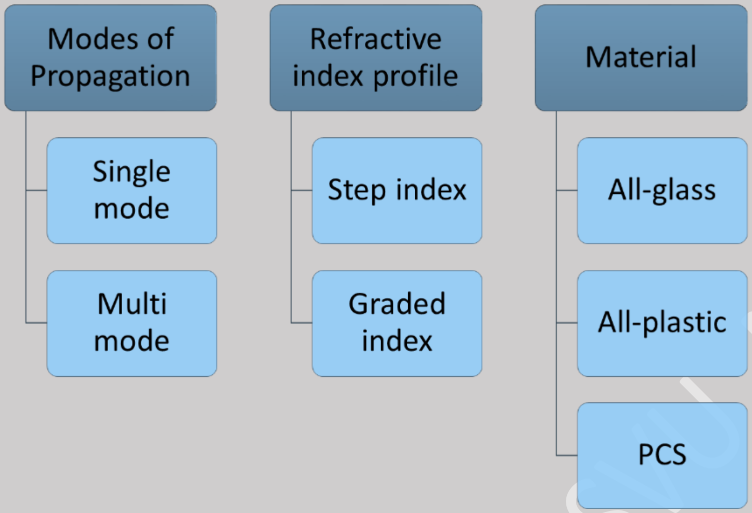
light traveling from denser medium to rarer medium



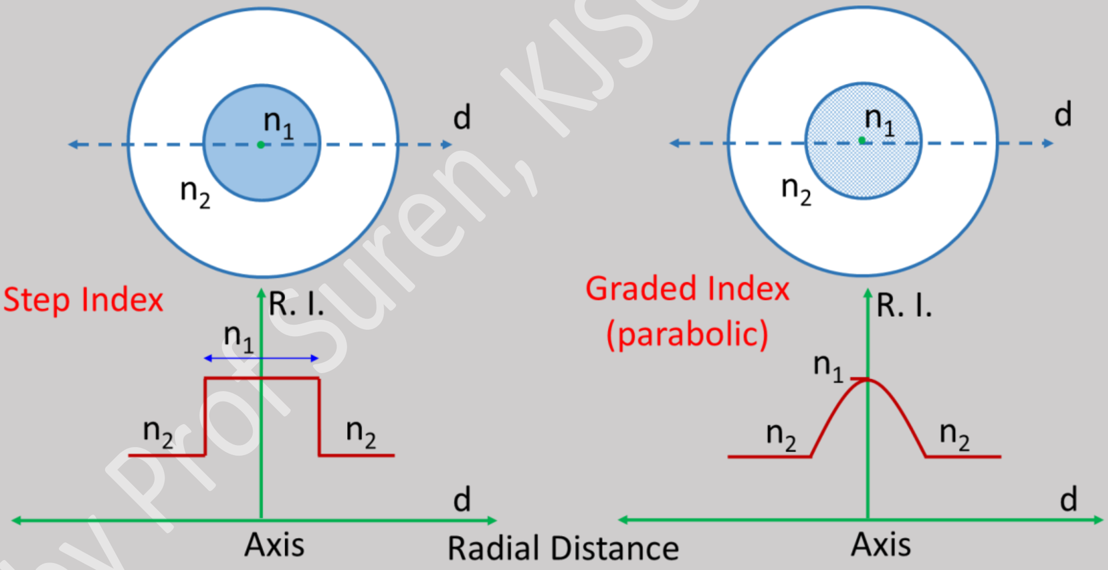
If we increase i further, there would be no transmission and complete reflection occurs. The ray is said to undergo total internal reflection (TIR). It occurs when a ray of light moving through a denser medium, falls on the surface of rarer medium at critical angle or above. In an optical fibre, the core is the denser medium and cladding being the rarer medium. The fibre supports passage of rays of light remaining in the core region and undergoing successive total internal reflections.

- **Types of Optical Fibres**

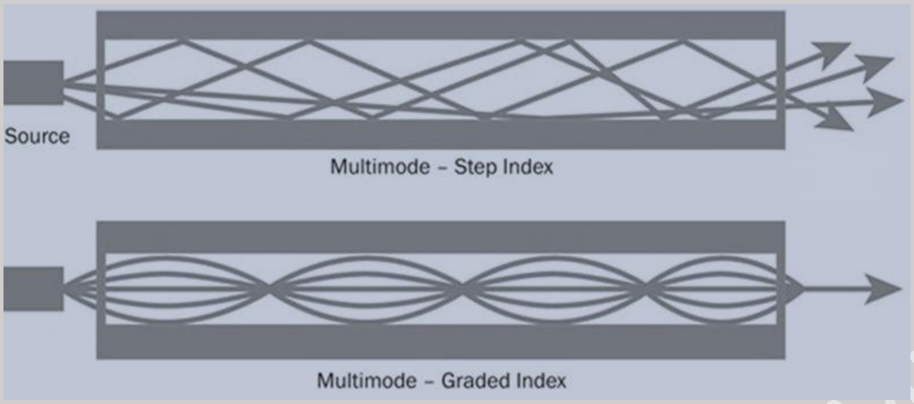
Depending upon applications, optical fibres are classified into single mode (SM) and multimode (MM) fibres. In simple context, modes refer to total number of allowed paths inside the core. Multimode fibres are further classified into step index (SI) and grade index (GRIN) fibres. In SI fibre, RI of core is uniform and changes abruptly at the core-cladding interface while in GRIN fibre, RI varies gradually within the core region from axis of fibre towards core-cladding interface. The graded index fibre can be graded in a linear, parabolic or in a staircase manner. Another classification is based on material used for fibre. All these classifications are summarized in following diagram.



The variation of refractive index with distance often called as "refractive index profile" for SI and GRIN optical fibres is shown in figure below:



The paths traversed by rays of light through different types of optical fibres are shown in following figure:



- **Single mode v/s. multimode**

Single mode	Multimode
Supports only axial modes	Supports axial and non-axial modes
Core diameter is small (5-10 μm)	Core diameter is larger (50-100 μm)
It works with only laser diode sources	It works with LED as well as laser diode sources
It offers lowest attenuation losses	It has higher attenuation than single mode fibres
Waveguide dispersion is limiting parameter	Waveguide dispersion is insignificant
Used for very long distance applications	Used for short to medium distance applications
It has only step index profile	It can have step and graded index profile
It is made from glass	It is made from glass or plastic

- **Step index v/s. graded index (Multimode)**

Step index (Multimode)	Graded index (Multimode)
RI of core is uniform	RI of core is gradually lowered
Suffers from pulse distortion	Pulse distortion effect is overcome by RI grading
Offers lower bandwidth	Offers higher bandwidth
Numerical aperture is higher	Numerical aperture is lower
Reflection losses are present	Reflection losses are minimal
Attenuation is higher	Attenuation is lower
They can be single mode or multimode	They are only multimode
Easier manufacturing process	Complex manufacturing process

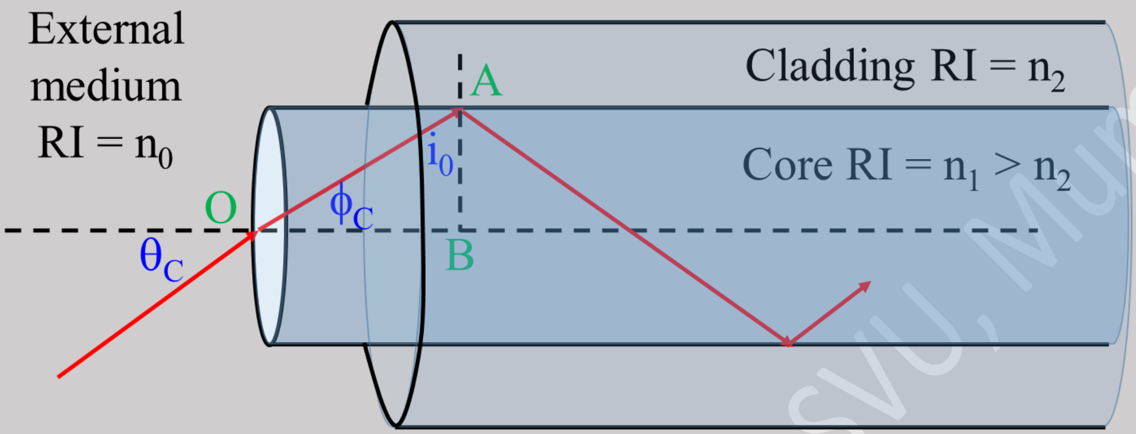
- **Numerical Aperture (NA)**

The numerical aperture of an optical fibre is a measure of amount of light that can be accepted by the fibre. In other words, it is the light gathering capacity of an optical fibre. The acceptance cone indicates limiting cone through which, light from a source must fall in order to undergo total internal reflection inside the fibre. It is a cone having semi-vertical angle θ_0 as shown in the same figure. The numerical aperture is the sine of this angle at the critical value for which, the condition of total internal reflection is satisfied. Thus,

Numerical Aperture i.e. $\mathrm{NA} = \sin\theta_C$.

The necessary condition for TIR is: $i \leq i_0$ and $\theta \geq \theta_C$

Let us have an expression for this NA. We consider a ray of light launched into the fibre (core) and it is moving towards the core-cladding boundary. It is incident at the boundary making critical angle i_0 so that it is totally internally reflected. Prior to this, let the ray makes angle θ_C at the external medium-core interface. Refer to following figure.



For external medium-core interface, in general, θ is the angle of incidence and ϕ is the angle of refraction. Applying Snell's law,

$$\frac{\sin\theta}{\sin\varphi} = \frac{n_1}{n_0} \quad \therefore n_0 \sin\theta = n_1 \sin\varphi$$

At $\theta = \theta_C$, let $\varphi = \varphi_C$ $\therefore n_0 \sin\theta_C = n_1 \sin\varphi_C$ Step (1).

When this ray is incident at the core-cladding interface, i is the angle of incidence and r is the angle of refraction. Applying Snell's law, we have in general,

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1} \quad \therefore n_1 \sin i = n_2 \sin r$$

But, at $\theta = \theta_C$, $i = i_0$ and $r = 90°$.

$\therefore n_1 \sin i_0 = n_2 \sin 90 \Rightarrow \sin i_0 = \frac{n_2}{n_1}$ Step (2).

In ΔAOB, $\sin\varphi_C = \cos(90 - \varphi_C) = \cos i_0 = \sqrt{1 - \sin^2 i_0}$

From step (1), $n_0 \sin\theta_C = n_1 \sin\varphi_C = n_1\sqrt{1 - \sin^2 i_0}$

Using step (2), $n_0 \sin\theta_C = n_1\sqrt{1 - \sin^2 i_0} = n_1\sqrt{1 - \frac{n_2^2}{n_1^2}} = \sqrt{n_1^2 - n_2^2}$

But the quantity $n_0 \sin\theta_C$ is the Numerical Aperture. Thus, we get,

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

Note: For ray incident from air, $n_0 = 1$.

For optical fibres, it is a common practice to express the numerical aperture in more simplified form as $NA \approx n_1\sqrt{2\Delta}$

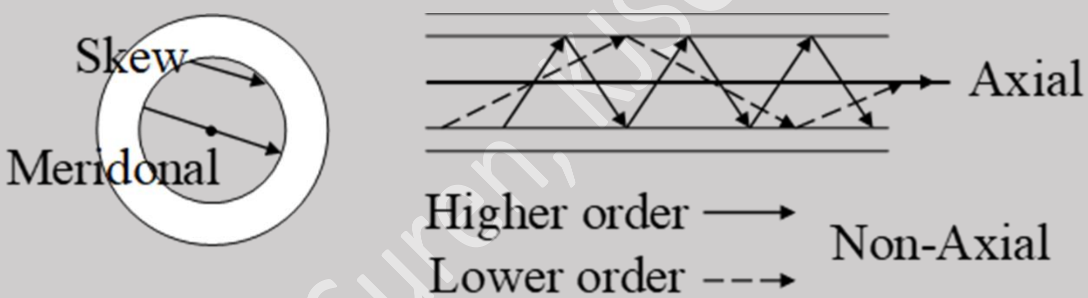
Where, Δ is known as fractional refractive index difference and it is defined as $\Delta = \frac{n_1 - n_2}{n_2}$.

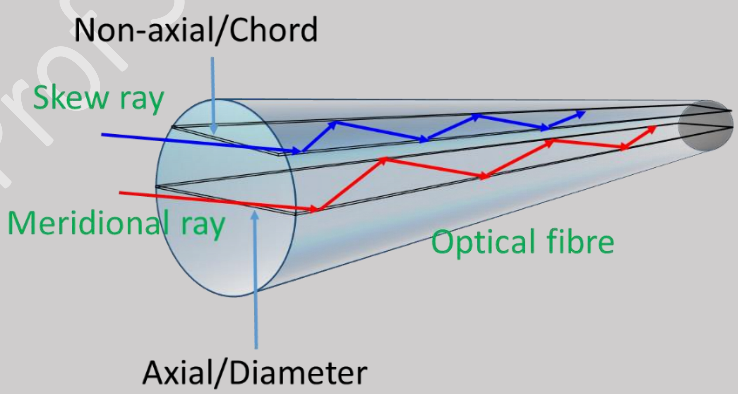
- **Modes of Propagation**

In simple context, a mode of propagation refers to the allowed path for a ray of light inside optical fibre. Although the basic condition of total internal reflection is satisfied, the fibre does not support all the rays falling within the cone of acceptance. It fibre allows only certain selective paths. They are dependent upon the ratio of wavelength of light to and diameter of the core region. These allowed paths of rays of light are known as modes of propagation.

The allowed directions for rays of light can be axial i.e. light propagating along or parallel to the axis of fibre or non-axial i.e. light undergoing successive internal reflections. Accordingly, the rays are called axial ray or axial mode and zigzag ray or non-axial mode respectively. The non-axial mode can further be meridional or skew. A meridional ray follows a zigzag path crossing the axis while a skew ray follows a zigzag path and does not cross the axis. Various possible modes of propagation are represented in following figure:

In a deeper sense, the optical fibre serves as waveguide for light waves of certain wavelength passing through. In order to satisfy the electromagnetic boundary conditions inside a waveguide for electromagnetic waves, certain conditions demand that depending upon the ratio d / λ, where, d is the core diameter and λ is the wavelength of light, the light waves are in phase only along certain directions with respect to axis of fibre so that they reinforce each other. These directions along which, light waves are in phase are called as modes.





- **V-Number and number of allowed modes of propagation**

An optical fibre is characterized by another important parameter called as the V-number or normalized frequency. It is given by,

$$V = \frac{2\pi a}{\lambda} \times NA$$

Where, "a" is the radius of core, λ is the wavelength of light and NA is the numerical aperture.

The maximum number of modes supported by the fibre is given by,

$N_m = \frac{V^2}{2}$; For multimode step index

$= \frac{V^2}{4}$; For multimode graded index (parabolic)

Further from electromagnetic theory, it follows that for V < 2.405, the fibre works as single mode fibre i.e. it supports only axial modes

- **Attenuation in optical fibres**

Although optical fibres are potentially far more superior than any other means of communications such as metallic cables (twisted pair, coaxial or BNC, wireless communication etc), they also suffer from some practical problems such as attenuation. Attenuation is the loss of signal while it is propagating in the form of light waves through an optical fibre.

Attenuation is measured in a decibel scale (dB), which is a logarithmic scale. The attenuation coefficient is given by,

$$\alpha = \frac{1}{L} 10 \log\left(\frac{P_{in}}{P_{out}}\right) /m$$ **Note:** usually expressed in dB/km

There may be various reasons for this loss but their collective effect is a measure of attenuation. Normally, attenuation is expressed in dB/km. Optical fibres have typically an attenuation of 0.1-0.2 dB/km as compared to copper cables which offer 2-3 dB/km at the best. Following are the major contributors to attenuation of signal through optical fibre:

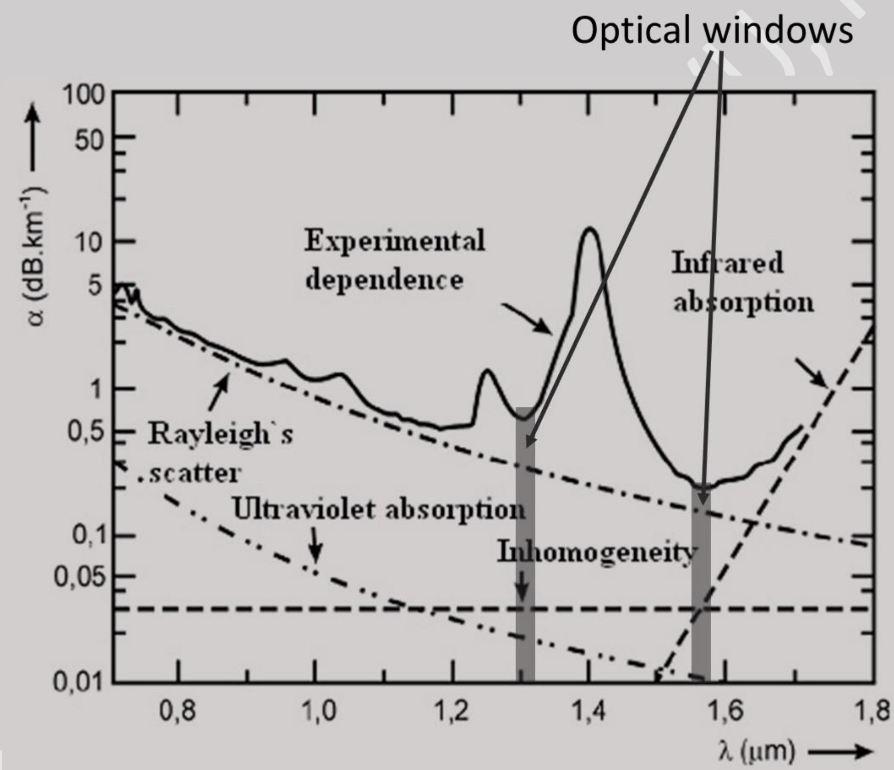
1) **Absorption:** There are two types of absorption agents: intrinsic and impurities. The absorption of light energy by material of the fibre i.e. glass or plastic itself is known as intrinsic absorption. Glass has two strong absorption ranges from 0.1 to 0.3 μm (UV range) and 7 to 12 μm (IR range). These are terms as electronic absorption and molecular vibrational absorption respectively. Plastic fibres have much higher absorption range and thus offer higher attenuation. However, impurities are chief contributors to absorption. These impurities can be minimized but it is impossible to remove them completely. Some impurities such as OH^- radicals mix up during the fibre manufacturing process itself. Other impurities such as Cu, Ni, Cr, V and Mn are also responsible for heavy absorption losses.

2) **Rayleigh scattering:** It occurs because of light passing through a medium having non-uniform distribution of mass and density. The amount of scattering is proportional to $1/\lambda^4$ where, λ is the wavelength of light. Optical fibres are made from glass or plastics. Both these media are

disordered (amorphous) structures and have local microscopic variations in density which it tern caused local variations in refractive index.

3) **Geometric effects:** They occur due to manufacturing defects such as irregularity in fibre dimensions (core and cladding diameters), stress developed due to fibre coating and cabling process, bends, kinks while installation etc. Geometric effect also includes bending losses. If a fibre in bent into a loop, the signal is attenuated due to loss of critical angle for part of incident light and it is known as bending loss.

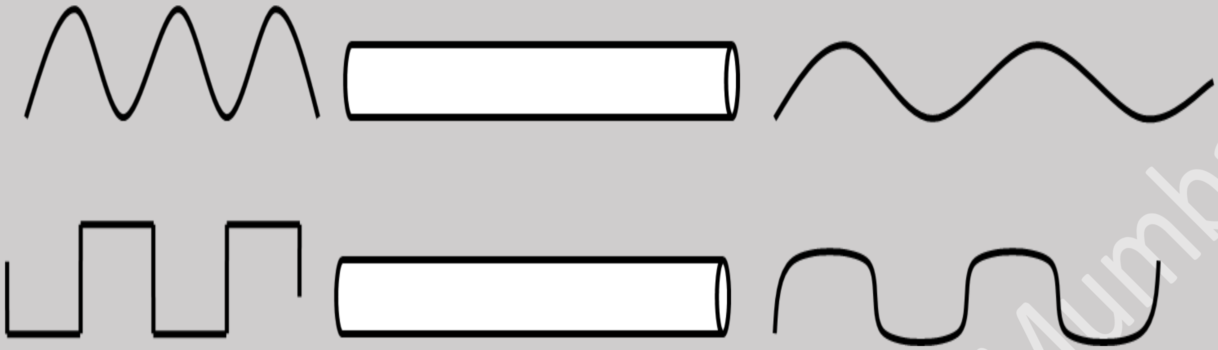
- **Optical window:**



The net attenuation as a function of wavelength is a result of many factors. It is shown in following figure, where the lossess are plotted from practically measured data. Both, the absorption and scattering losses are major contributors to attenuation plot. It can be seen that the net attenuation is lower in two ranges of wavelengths: around 1.3 μm and around 1.55 μm. these small ranges of wavelengths are called optical windows. Most of the LEDs or laser diodes are designed to emit in these ranges so that light undergo minimum attenuation.

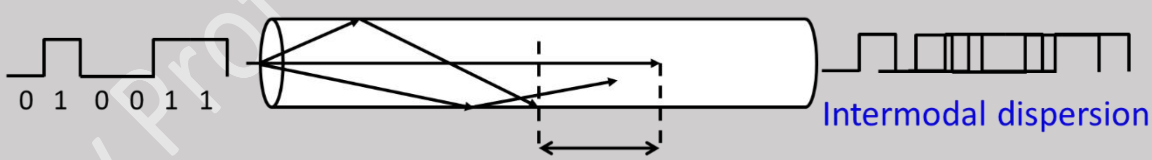
Note: There was another window defined, which is centred at 0.85 μm. It was in use earlier but today, the most preferred wavelength is 1.55 μm)

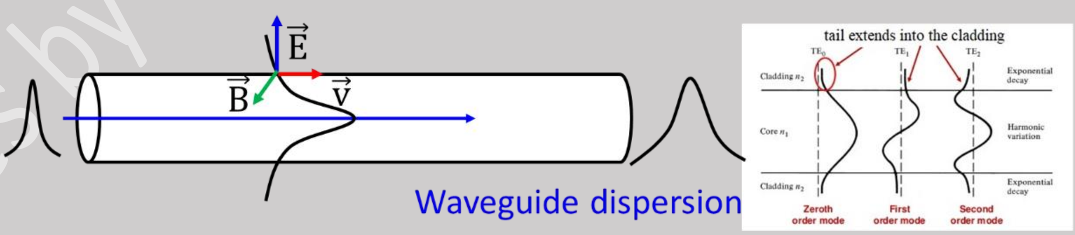
- **Dispersion in optical fibres**



Any practical optical fibre suffers from another problem – dispersion. It refers to the broadening of pulse as light travels through an optical fibre. The original waveform is distorted due to dispersion of light. It is measured in ns/km. This problem is typical of optical fibres only. There are three mechanisms those lead to bad signal due to dispersion of light.

1) **Material dispersion**: Glass or plastic used for optical fibre is a dispersive medium. It results in different wavelength components moving at different speeds through the fibre. Due to this, for light from some source such as an LED which consists of different wavelengths, the shorter wavelength component travels slower than the longer wavelength component and the light pulse tends to broaden. This type of dispersion depends upon the spectral width of the source. Material dispersion can be greatly reduced by using laser sources. However, use of laser diodes is not always desirable as laser circuits are costlier than LED circuits.

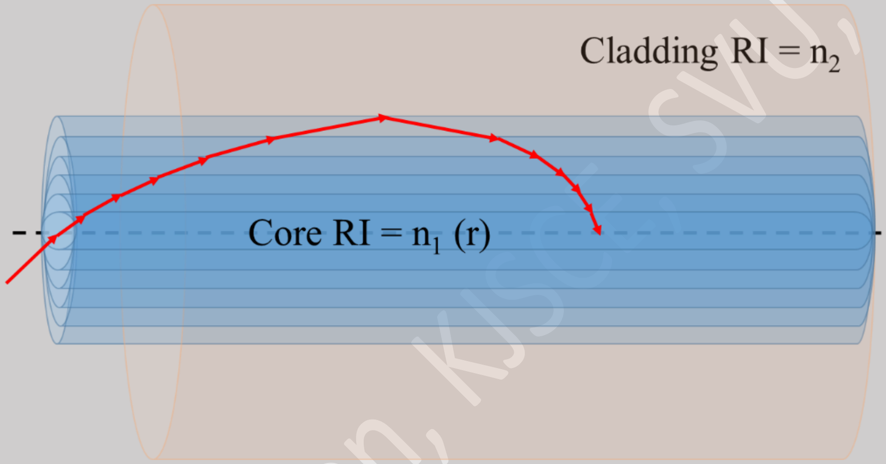




2) **Waveguide dispersion:** Although the ray of light is totally internally reflected, part of light energy penetrates into the cladding region. This happens as the traveling wave is an electromagnetic wave nd the medium in which it travels is a dielectric. So there is an induced electric field in the

cladding. Now as the wave propagates further, part of light penetrated into the cladding region travels little faster than the main part, which is confined to the core region. This leads to what is called as waveguide dispersion. This kind of problem is significant in a single mode fibre as the core diameter is extremely small.

3) Inter-modal dispersion: As different modes are directed along different directions, the time taken by different modes to cover a certain distance in optical fibre is different. The axial ray would take the least time while non-axial rays (zigzag rays) would take longer time. This problem occurs particularly in step index multimode fibre. As axial ray moves straight, it covers a longer lineal distance whereas the non-axial rays move in a zigzag manner and cover a shorter lineal distance depending upon their angle. Thus, after some time interval, all the modes do not come together at a point and their synchronization is lost.



This problem is overcome in graded index fibres by linearly varying the refractive index of core. The ray trajectory is shown in figure above. The refractive index is maximum at the axis and decreases towards the cladding. The axial ray has a shorter linear distance to cover but it travels with the lowest speed as it moves through a region of highest refractive index. A non-axial ray has to cover a longer linear distance but as it moves towards cladding, its speed increases due to reduction in the refractive index. Thus, longer distance is compensated by higher speed and al the modes remain synchronous.

Note: dispersion in fibres is usually expressed in ns/km or ps/km.

The intermodal dispersion is given by

$\tau_i = \frac{n_1 L}{c}\Delta$ for SI fibre and $\tau_i = \frac{n_2 L}{2c}\Delta^2$ for GRIN fibre (parabolic profile)

Here, L is length of fibre and c is speed of light

The total dispersion (without waveguide dispersion) is given by

$\tau = \sqrt{\tau_i^2 + \tau_m^2}$, where τ_m is material dispersion.

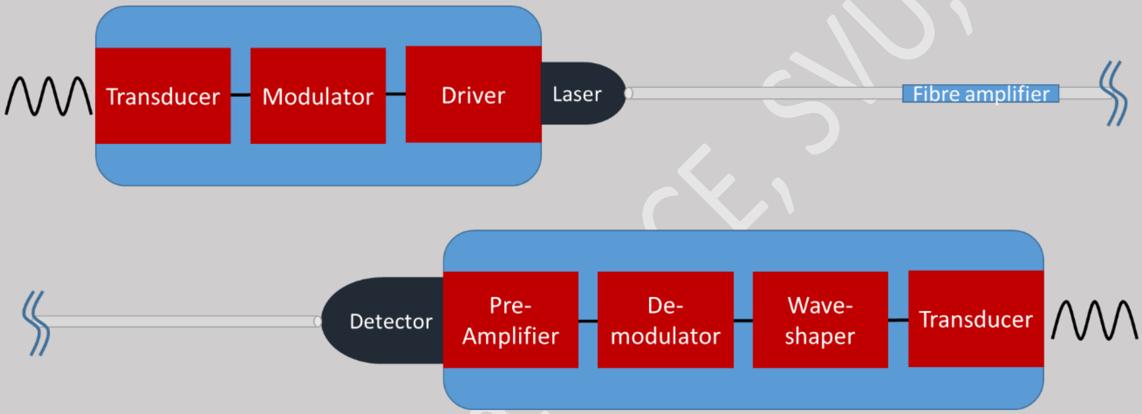
The maximum data speed or "bit rate" is given theoretically by

$B \approx \frac{0.7}{\tau}$ bits/sec

SUPPLEMENTARY

- **Application in Telecommunication**

This is the main application area of optical fibres. Traditionally, telecommunications systems use radio frequencies or microwaves for transmission through a communication channel. For wireless communications, different antennas are used. Optical fibres offer great advantages in terms of higher bandwidth, lower losses, cheaper and safer mode of communications. Today, a giant network of optical fibre cables running throughout the globe connects the entire world (physically). There are optical fibre cables submerged deep in oceans. One such fibre optic link connects India (via Mumbai) to the rest of the world. A typical optical fibre communication system consists of transmitter unit, receiver unit and channel or waveguide i.e. the optical fibre cable. In addition, it may involve a repeater unit also.



1) **Transmitter unit:** Normally, it consists of two modules the electrical data generator and the optical converter. The input data may be in any form; a music note, a photograph etc. It is first converted into an equivalent electric pulse with proper modulation of the signal. For this, normally a high frequency carrier wave is generated. Two forms of modulation are possible: analogue and digital. Digital modulation is more commonly used in fibre optic communication where, the signal is coded using discrete bits. The driver circuit converts this coded electrical signal into optical form. An LED or a Laser diode is the actual converter.

2) **Receiver unit:** This also consists of minimum two modules. The data in the form of light brought through the optical fibre cable is connected to a photo detector. It is normally off but when light is incident on it, it generates a small current pulse. This pulse is very small (in microamperes) and often requires amplification to a predetermined value. Then, there may be a wave-shaper circuit to retain the form of the original signal.

3) **Repeater unit, optical fibres and couplers:** The signal in the form of light suffers from attenuation and distortion. Therefore, repeater units are required at regular intervals to redesign the signal in both, amplitude and waveform. The optical fibres used may be of different variety: single mode, step index or graded index (multimode) depending upon the type, amount of data, quality requirements and environment. The optical couplers are crucial parts of the system. Special design is required to connect a fibre-source, fibre-detector and many-to-one or one-to-many fibres.
