Introduction to optical communication

by

Ahmed Abdulbari Jasim

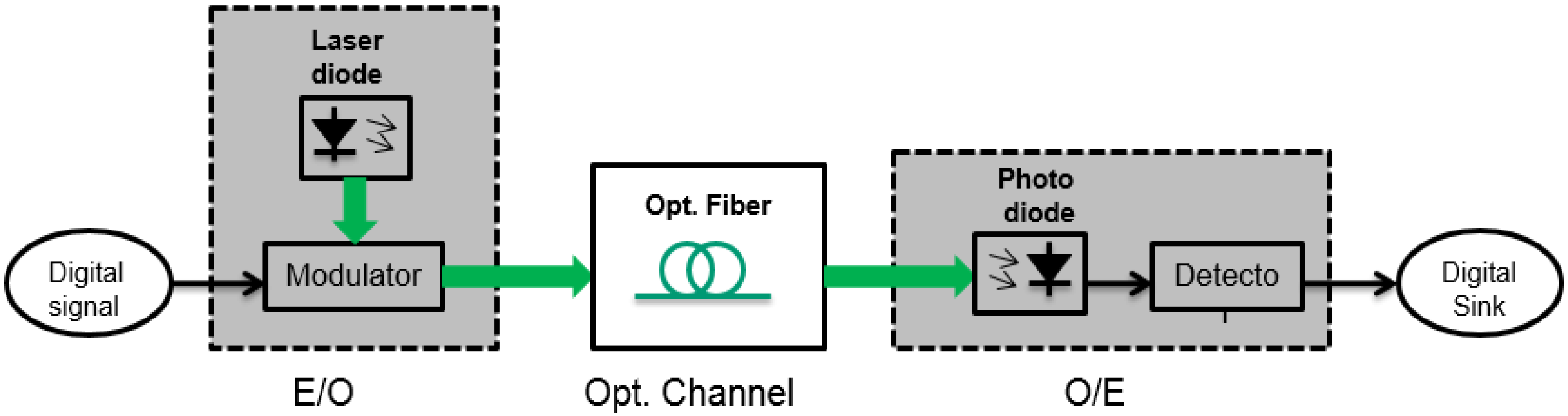
Communication Engineering Dept.
Faculty of Electronics Engineering
Ninevah University

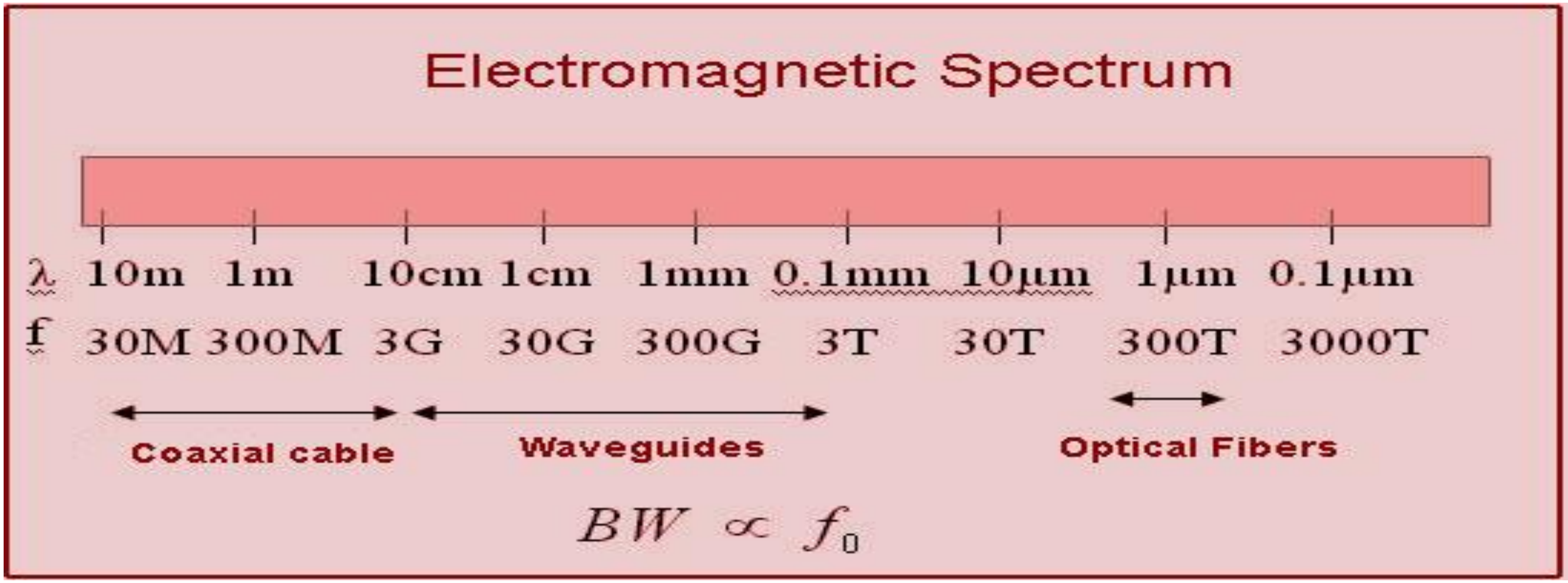
- Optical Communication is the most modern mode of wired communication.
- Optical communication is also the youngest mode of communication. However its capabilities supersede all other modes of communication.
- Before optical communication the most of the communication was in radio and microwave domain which has frequency range orders of magnitude lower than the optical for the electromagnetic spectrum.

Optical Communications System

- **Conventional communications system**

- **Optical communications system**



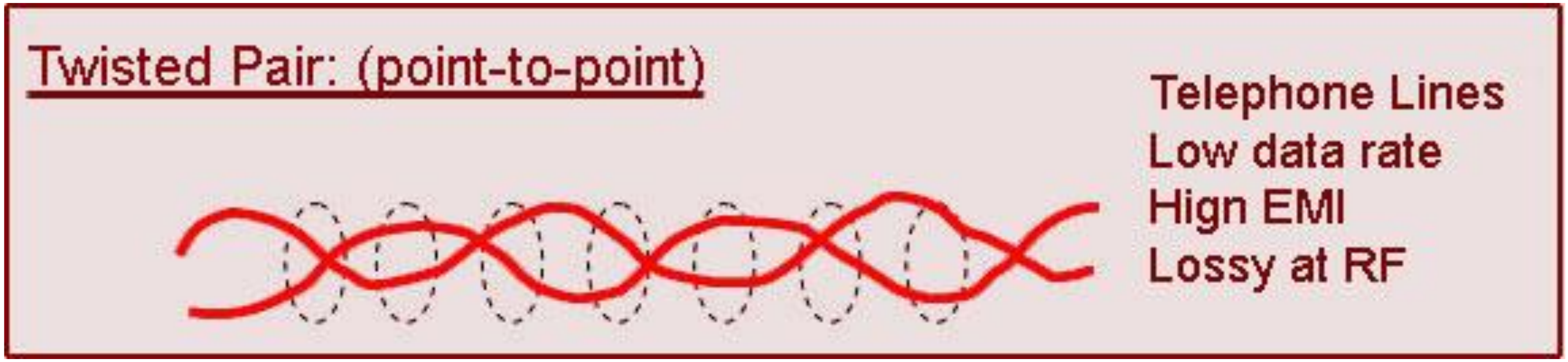


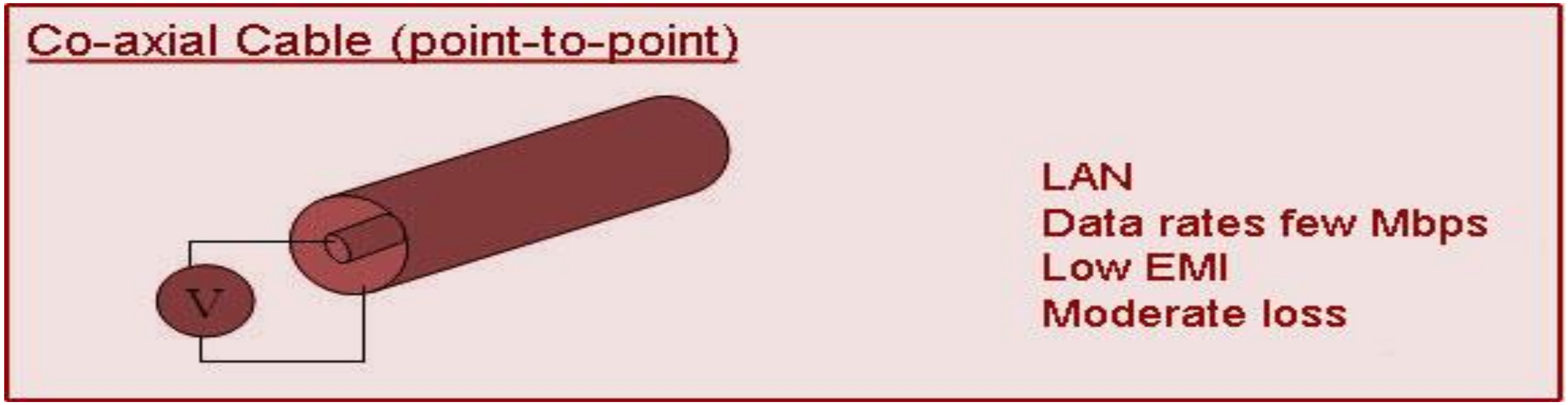
For good communication a system needs to have following things.
(1) **Bandwidh (BW)**
(2) **Good signal to noise ratio (SNR) i.e. low loss**

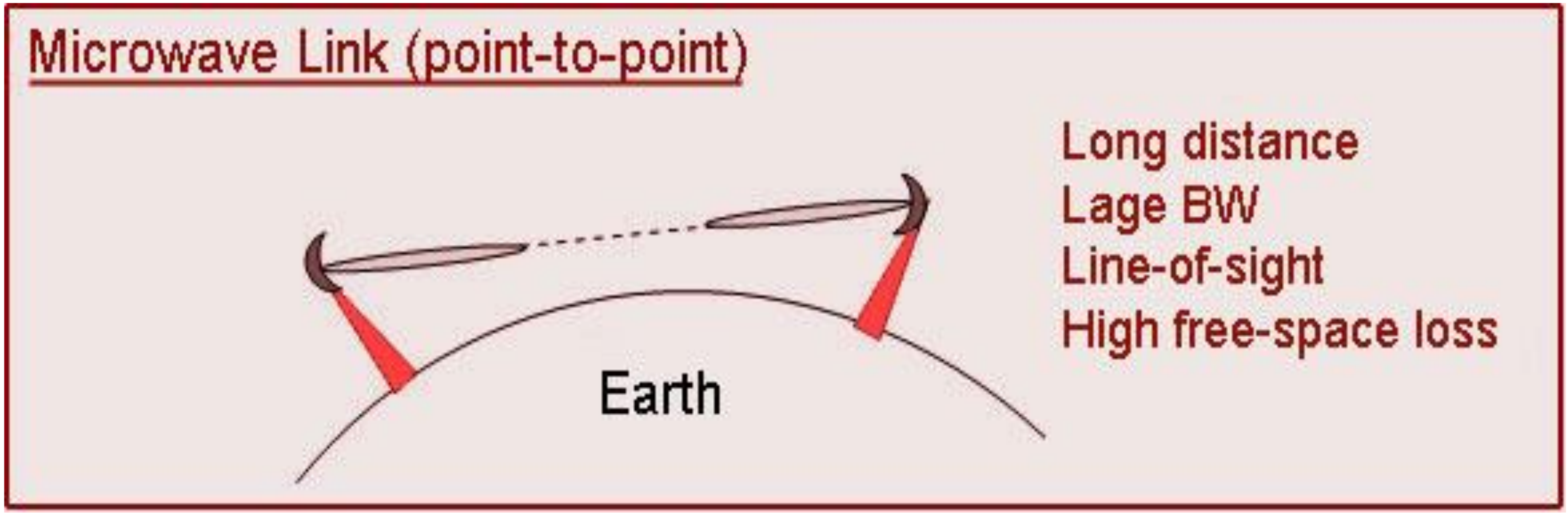
- Since the bandwidth of a system is more or less proportional to the frequency of operation, use of higher frequency facilitates larger BW.
- The BW at optical frequencies is expected to be 3 to 4 orders of magnitude higher than that at the microwave frequencies (1GHz to 100GHz).

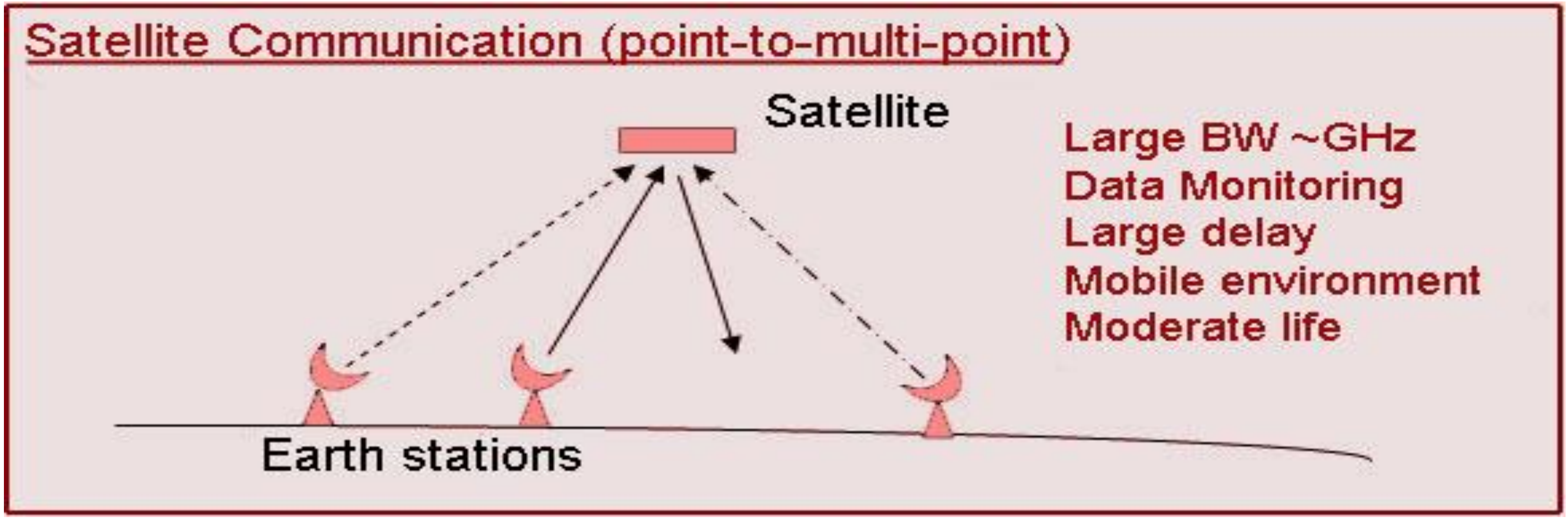
Transmission media Alternative to the Optical Communication

There are various wired and wireless media used for long and short distance communication. Their broad characteristics are summarized in the following.






Microwave Link (point-to-point)
Earth
Long distance
Lage BW
Line-of-sight
High free-space loss


Satellite Communication (point-to-multi-point)
Satellite
Earth stations
Large BW ~GHz
Data Monitoring
Large delay
Mobile environment
Moderate life

- The first two media have a very limited bandwidth.
- Microwave links and Satellite communication has comparable bandwidths as in principle their mode of operation is same but the spatial reach of satellite is far greater.
- Before Fiber optic communication became viable, satellite communication was the only choice for long distance communication.

Comparison of Satellite and Optical communication

Satellite vs Fiber Optics

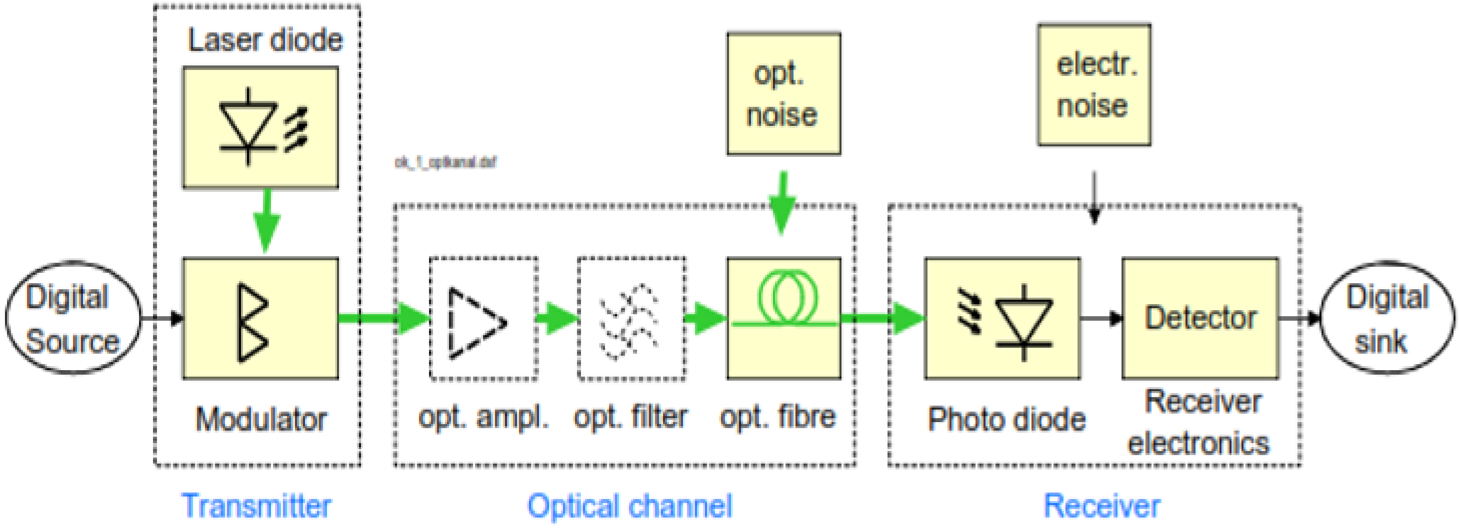
Satellite	**Fiber Optics**
Point to Multi-point	Point to point
BW ~ GHz	BW ~ THz
Maintenance free	Needs Maintenance
Short life ~7-8 Yr	Long life
No upgradeability	Upgradeable
Mobile, air, sea	On ground only

- The two modes of transmission have their own merits and limitations. The two can in fact play a complementary role. We therefore conclude that. Satellite and Optical communication will co-exist due their complementary nature.

Advantages of Optical Communication

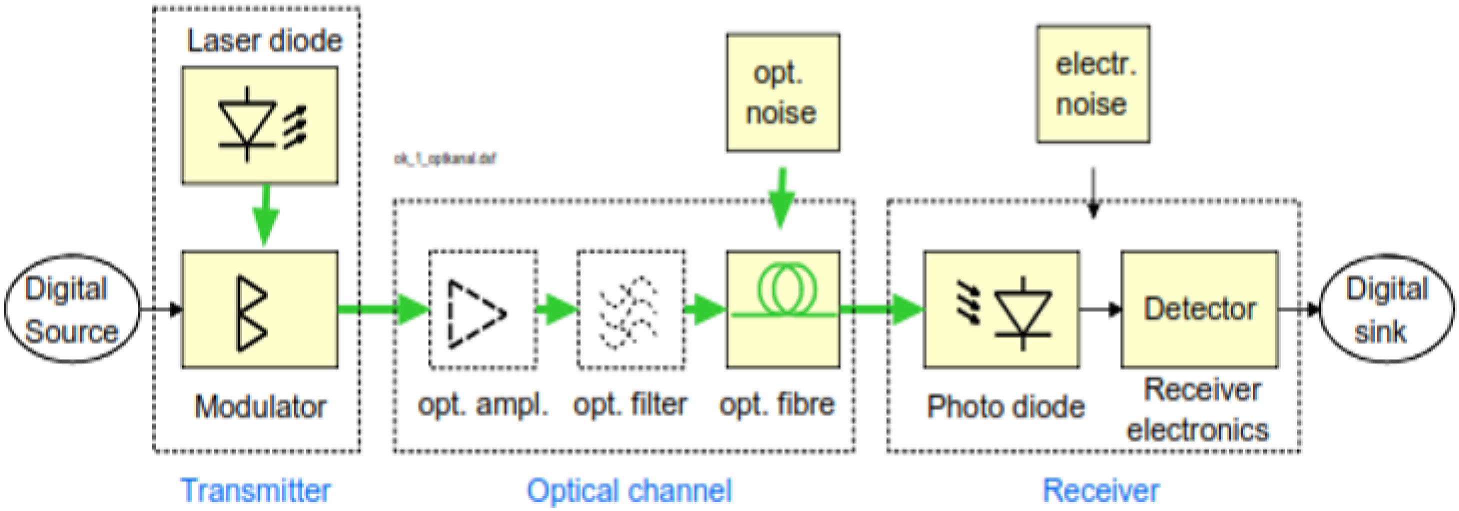
- Ultra high bandwidth (THz)
- Low loss (0.2 dB/Km)
- Low EMI
- Security of transmission
- Low manufacturing cost
- Low weight, low volume
- Point to Point Communication

General Block Diagram of Basic Optical Transmission System



Basic optical transmission link with transmitter, Channel and receiver. We have optical signals (thick, green) and electrical signals (thin, black). Optical signals are (sinusoidal) carrier at optical frequency (THz). Electrical signals represent the transmitted and received signals, which are associated with digital data modulation.

General Block Diagram of Basic Optical Transmission System



<u>Laser Diode</u>: produces nearly single frequency light with well defined wavelength = carrier signal at frequency $(f_c = C/\lambda_c)$. f_c in the range of several hundred THz (1 THz = 10^{12} Hz). The light wave, i.e. the electromagnetic wave is often simply called “electrical field”.

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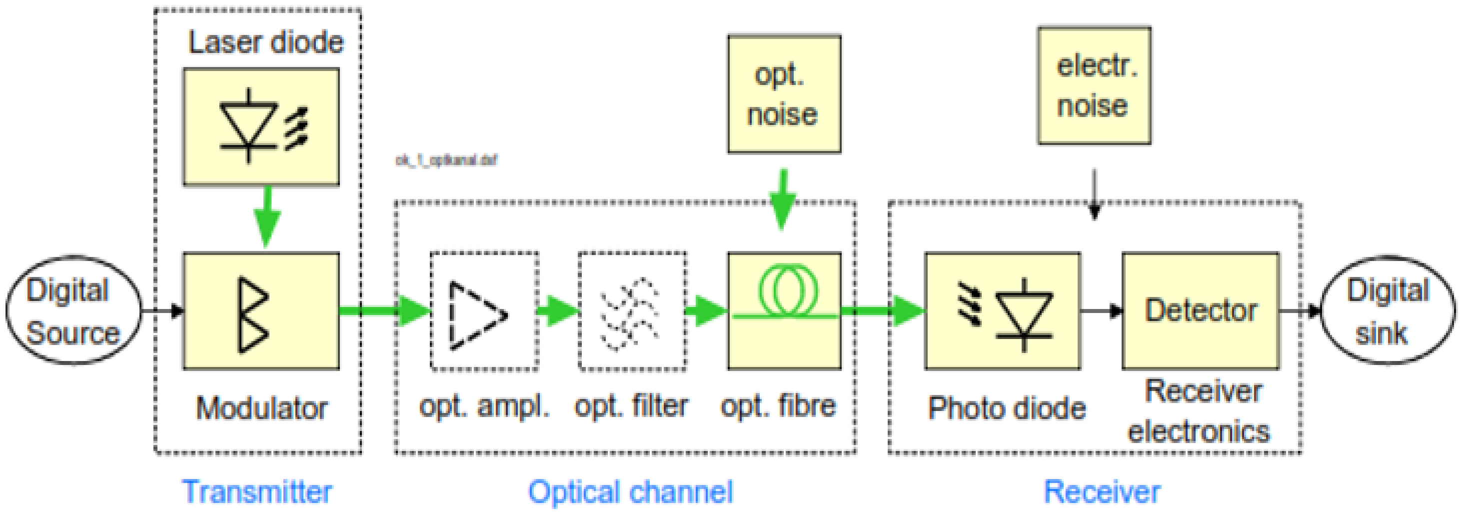
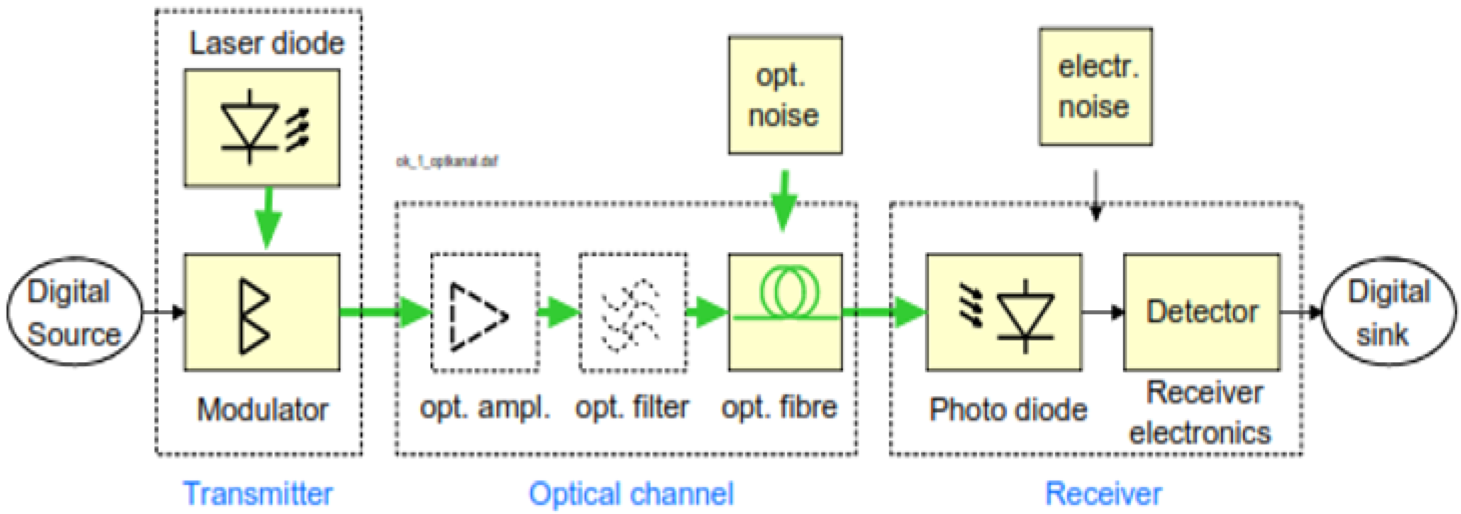


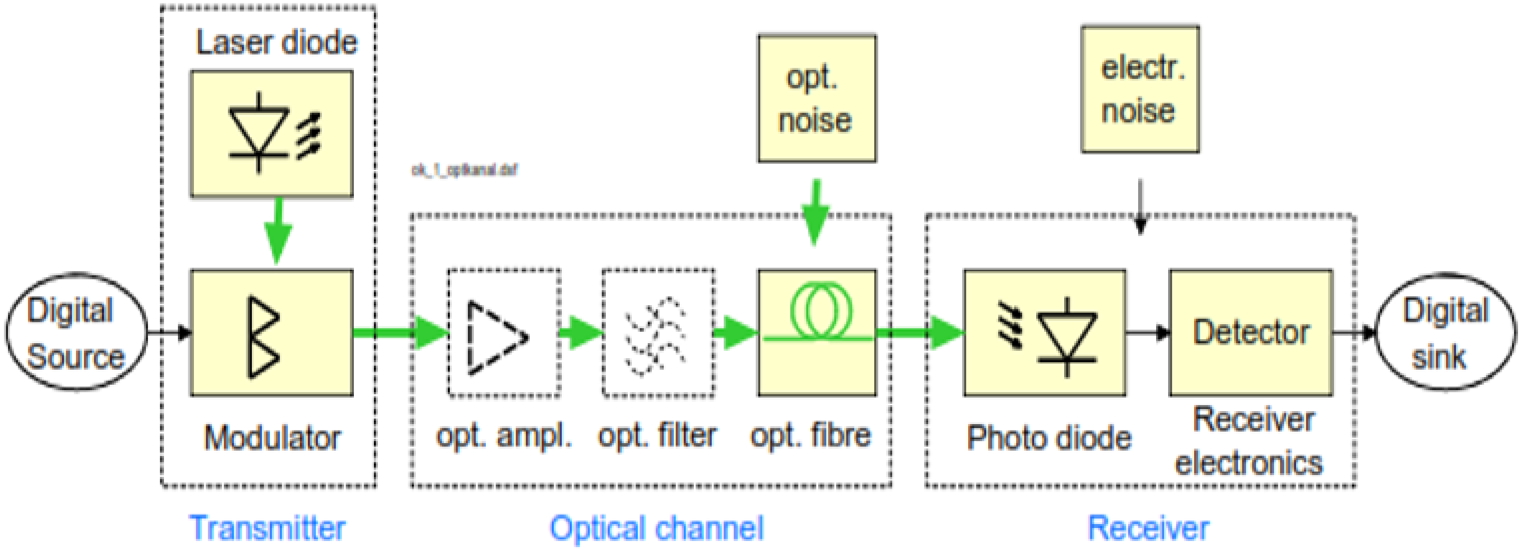
Modulator: Electrical-to-optical convertor in which the digital signal (electrical) is modulated on the carrier (here light). Most modulators have the capability to modulate the power of the light. I.e. the instantaneous optical power (=light intensity =$|E(t)|^2$) is proportional to the modulating data signal of e.g. 10 Gb/s. With binary signal "1"=light on, "0"=light nearly off (On-Off Keying and Intensity Modulation). Implementation, either *direct modulation* of laser diode forward current or by a separate *external modulator* (as shown above).

General Block Diagram of Basic Optical Transmission System



Optical fiber: Waveguide made of silica glass or plastic fiber used to guide the light wave. There are two types of fiber Single Mode Fiber (SMF) and Multi-Mode Fiber (MMF). Fiber has a *cladding* with diameter of 125 μm and *core* with diameter of 5..10 μm (SMF) or 50 μm (MMF). Core has slightly higher refractive index.

General Block Diagram of Basic Optical Transmission System



<u>Photo diode</u>: Optical-to-electrical conversion by detecting the power of the received signal (envelope detector). The received instantaneous light power results in a proportional electrical signal (photo current)

<u>Noise</u>: Is present in the optical domain (mainly from optical amplifier) as well as in the electrical domain (from electronics) and from photo diode itself (short noise)

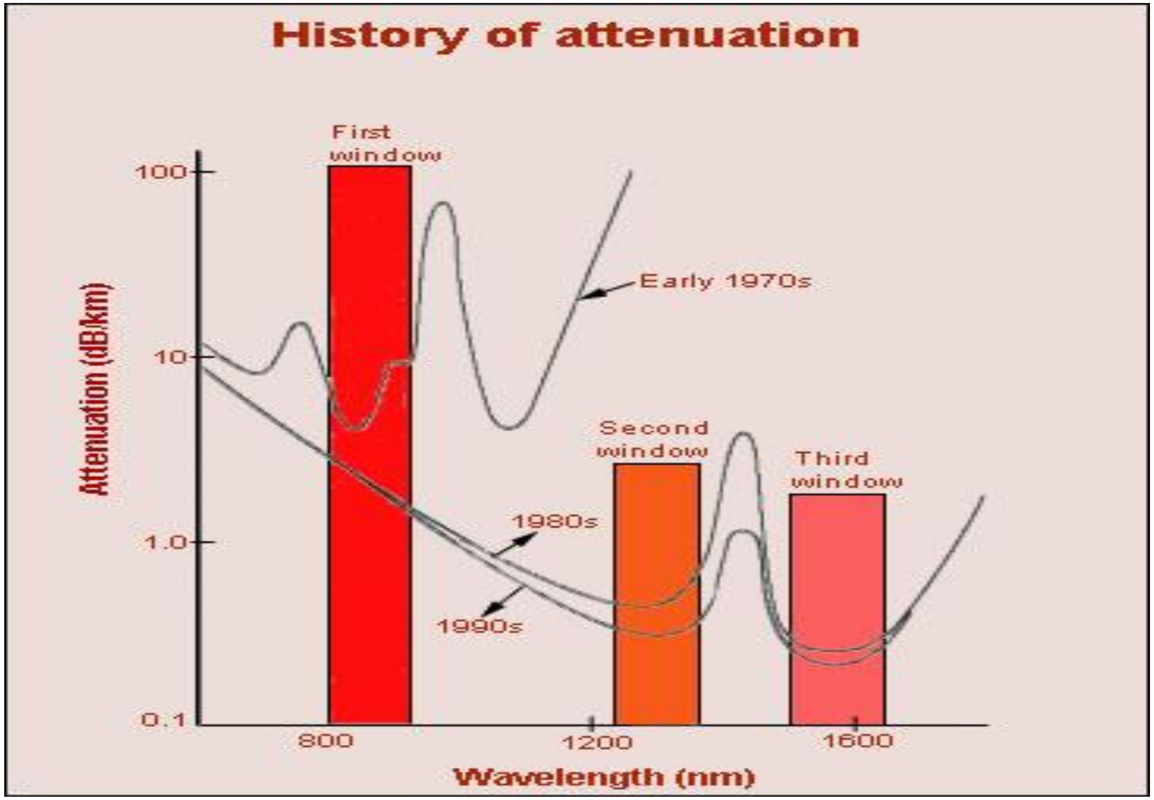
- Initially in early 1970s due to technology limitation, the optical fiber had a low loss window around 800nm. Also the semiconductor optical sources were made of GaAs which emitted light at 800nm. Due to compatibility of the medium properties and the sources, the optical communication started in **800nm band** so called the **'First window'** .

- As the glass purification technology improved, the true silica loss profile emerged in 1980s. The loss profile shows two low loss windows, one around 1300nm and other around 1550nm. In 1980s the optical communication shifted to **1300nm band** , so called the '**Second Window'** . This window is attractive as it can support the highest data rate due to lowest dispersion.

- In 1990s the communication was shifted to **1550nm** window, so called **'Third Window'** due to invention of the Erbium Doped Fiber Amplifier (EDFA). The EDFA can amplify light only in a narrow band around 1550nm. Also this window has intrinsically lowest loss of about **0.2 dB/Km** . This band has higher dispersion, meaning lower bandwidth. However, this problem has been solved by use of so called 'dispersion shifted fibers'.

- The optical transmission medium is the best in a sense that it has ultra wide bandwidth and very low attenuation.

- The attenuation history is given in the following Figure.



Both 1300nm and 1550nm band have approximately 100nm bandwidth each. The frequency bandwidth is related to the wavelength bandwidth as

$$\Delta f = \frac{c}{n\,\lambda^2}\Delta\lambda$$

- Where c is the velocity of light in vacuum, n is the refractive index of the medium, λ is the central wavelength of the band, and $\Delta\lambda$ is the wavelength bandwidth (also called **spectral width**).

- For 1550nm window, $\lambda = 1550nm$, and $\Delta\lambda \approx 100nm$. For silica optical fibers $n \approx 1.5$. We therefore get

$$\Delta f = \frac{3\times 10^{8}}{1.5\times(1550\times 10^{-9})^{2}}\times 100\times 10^{-9} = 8.3\times 10^{12} \quad Hz$$

So we have Approximately.

$$1\text{ nm spectral width} = 120\ GHz \qquad \text{at 1300nm}$$

$$1\text{ nm spectral width} = 80\ GHz \qquad \text{at 1550nm}$$

So , as **a rule of thumb** we can take for optical communication,

$$1 \text{ nm spectral width} \approx 100\ GHz$$

Basics of Light

Characteristics of light

- Intensity (Power per unit solid angle)
- Wavelength (Color)
- Spectral width (purity of color)
- Polarization

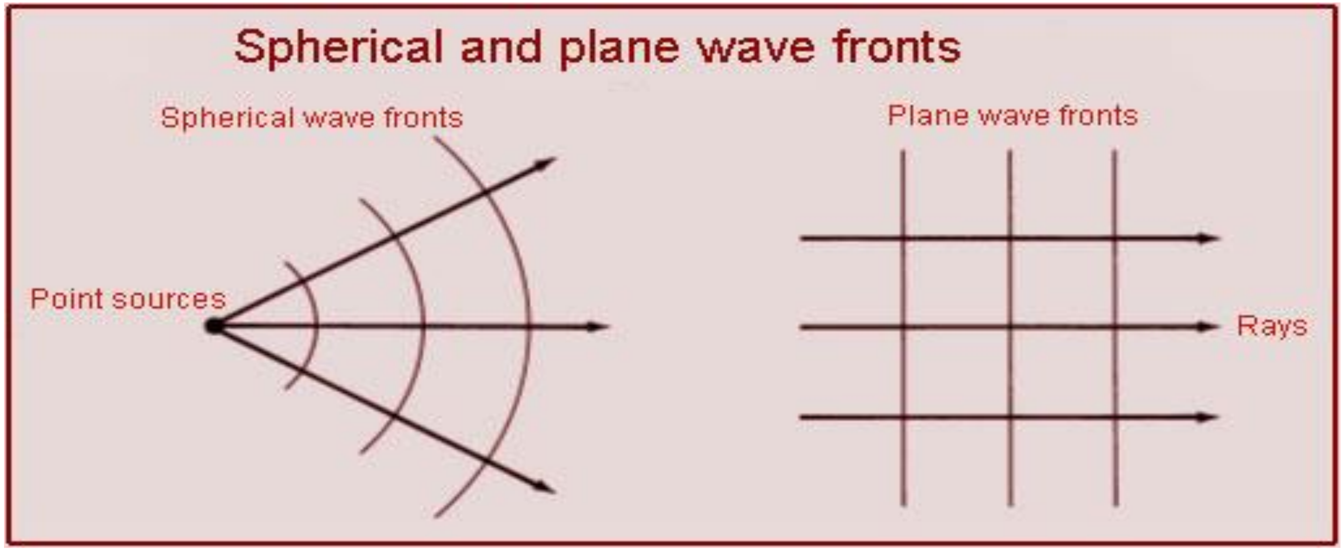
- Linear
- Circular
- Elliptical

The characteristics of light are summarized in the following. The first three parameters scalar characteristics of light whereas the last parameter, polarization, describes the vector nature of light.

The choice of wavelength depends upon the loss profile of the medium. For optical fiber the wavelength has to be 1300nm or 1550nm for low loss.

The spectral width has direct bearing on the data rate which the medium can support. Larger the spectral width, smaller is the data rate. A semiconductor laser typically has spectral width about 20 to 100 times less compared to LED. Consequently, laser based communication can support much higher data rates.

Spherical and plane wave fronts



- Light is an Electromagnetic wave.
- It consists wave fronts. The lines normal to the wave fronts are called the light rays.
- If the phase fronts are concentric spheres, the light is called a spherical wave, and if the phase fronts are parallel planes, the light is called a plane wave.
- For a plane waves the rays are parallel whereas for the spherical wave, the emerge from the center of the spheres.
- If the source is a finite distance, the appropriate model is the spherical wave model, and if the source is assumed to be at infinite distance, the plane wave model is appropriate.
- A plane wave can be represented by a wave function which is a composite function of space and time.

- Wave Function $\psi(x,t) = A\exp(\omega t - \beta x)$

A : Amplitude of the wave

ω : Angular frequency of the wave (rad/s)

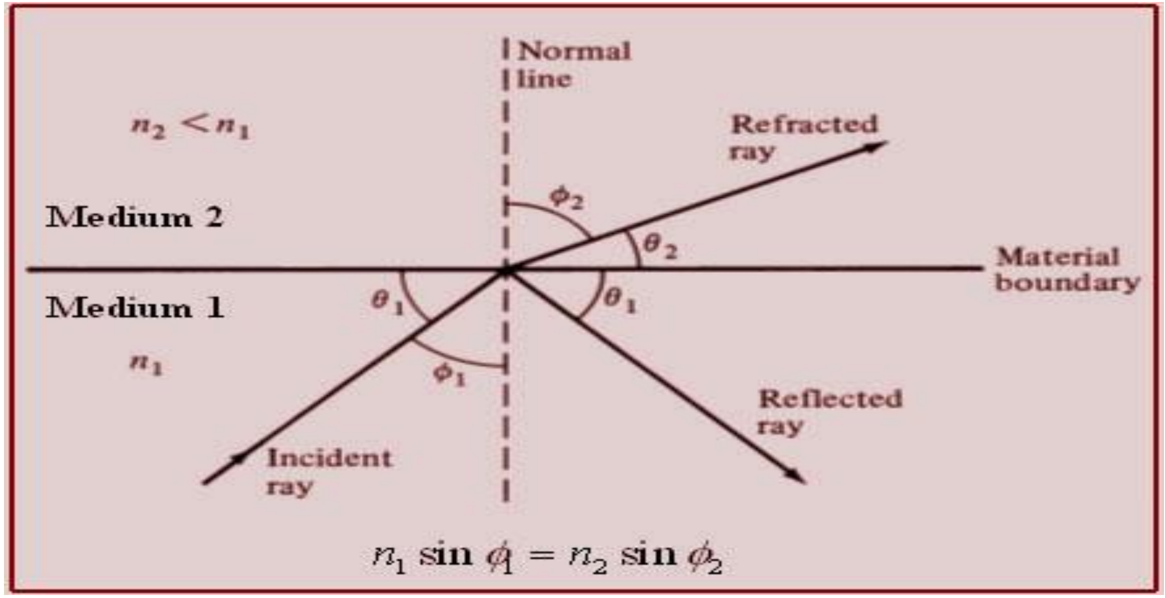
β : Phase constant (rad/m)

x : Distance

t : Time

Snell's Law

When light travels from one medium to other, it gets refracted. The relation between the angle of incidence and the angle of refraction is given by the Snell's law. The Snell's law is described in the following figure.



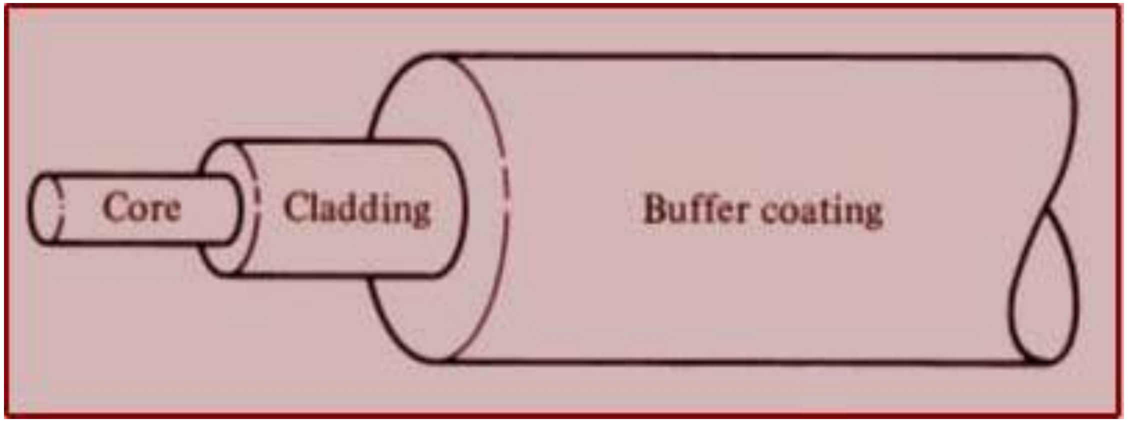
- If the angle of incidence, ϕ_1 is greater than the critical angle, ϕ_c given by

$$\phi_c = \sin^{-1}(n_2/n_1)$$

where n_1 and n_2 are the refractive indices of the two media as shown in Fig., then the light is **Total Internally reflected** in medium 1. There is no refracted ray in that case.

Basic Fiber Structure

- An optical fiber basically is a solid glass rod surrounded by concentric glass shell as shown in Fig



- The rod is called the **core** and is made of highly purified glass. Most of the light energy in confined to the core.
- The glass shell called **cladding.** The cladding shields optical fields so as not to get interfered by the outer layers of the fiber. The cladding is an essential part of an optical fiber.
- The cladding is surrounded by the buffer layers. These layers have no role in propagation of light. They are essentially there to provide the mechanical support to the glass fiber and to protect the fiber from external damage.

Application

- Long distance transmission at High capacity in WAN and MAN
- Fiber to the home (FTTH), Cable TV distribution systems (CATV)
- Replacement of electrical lines if EMI and RF problems (opt. cabling in cars, airplanes, ships, ……)
- "Fiber Radio" RF-signal feeding of mobile radio base stations
- Optical free space transmission

Thank you

Ray Model

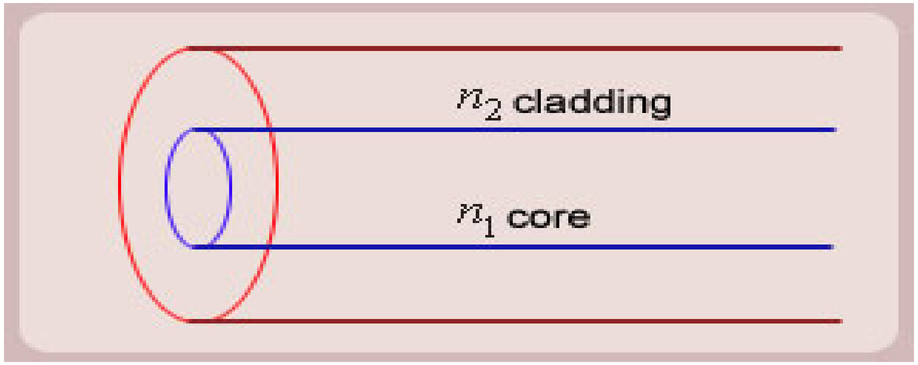
PROPAGATION OF LIGHT IN AN OPTICAL FIBER (RAY MODEL)

1.Optical fiber is basically a solid glass rod. The diameter of rod is so small that it looks like a fiber.

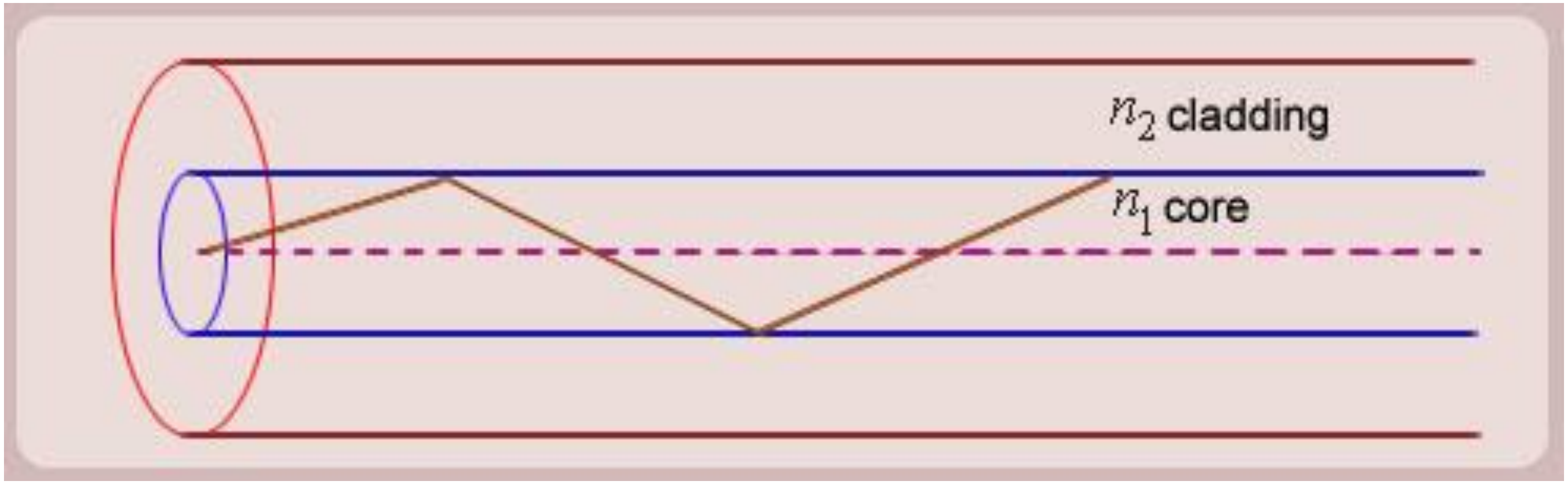
2. Optical fiber is a dielectric waveguide. The light travels like an electromagnetic wave inside the waveguide. The dielectric waveguide is different from a metallic waveguide which is used at microwave and millimeter wave frequencies.

3. In a metallic waveguide, there is a complete shielding of electromagnetic radiation but in an optical fiber the electromagnetic radiation is not just confined inside the fiber but also extends outside the fiber.

4. The light gets guided inside the structure, through the basic phenomenon of **total internal reflection** . This phenomenon occurs only when the refractive index of core is greater than the refractive index of cladding and so the cladding is made from glass of lower refractive index. By multiple total internal reflections at the core-cladding interface the light propagates throughout the fiber over very long distances with low attenuation.



For the light to propagate inside the fiber through total internal reflections at core-cladding interface, the refractive index of the core must be greater than the refractive index of the cladding. That is *n1>n2*



Refractive index

Refractive index of a medium is defined as the ratio of the velocity of light in vacuum to the velocity of light in that medium. It is denoted by n. Since refractive index is a ratio of two velocities, it is a pure number and has no unit.

$$\text{Refractive index of medium } (n_{(medium)}) = \frac{\textit{Velocity of light in vacuum } (c)}{\textit{Velocity of light in the medium } (v)}$$

For most media, n(medium) > 1, i.e. the velocity of light reduces from its value in vacuum. In fact, light travels fastest in vacuum and in any other medium it slows down. For example, the refractive index of material glass is about 1.5, i.e. light travels 1.5 times faster in vacuum than in glass. Similarly the refractive index of water is 1.33. In other words, refractive index of a medium indicates the factor by which the speed of light reduces in the medium.

SIMPLE RAY MODEL

For propagation of light inside the core there are two possibilities.

1. A light ray is launched in a plane containing the axis of the fiber. We can then see the light ray after total internal reflection travels in the same plane i.e., the ray is confined to the plane in which it was launched and never leave the plane. In this situation the rays will always cross the axis of the fiber. These are called the **Meridional rays.**

2. The other possibility is that the ray is not launched in a plane containing the axis of the fiber.

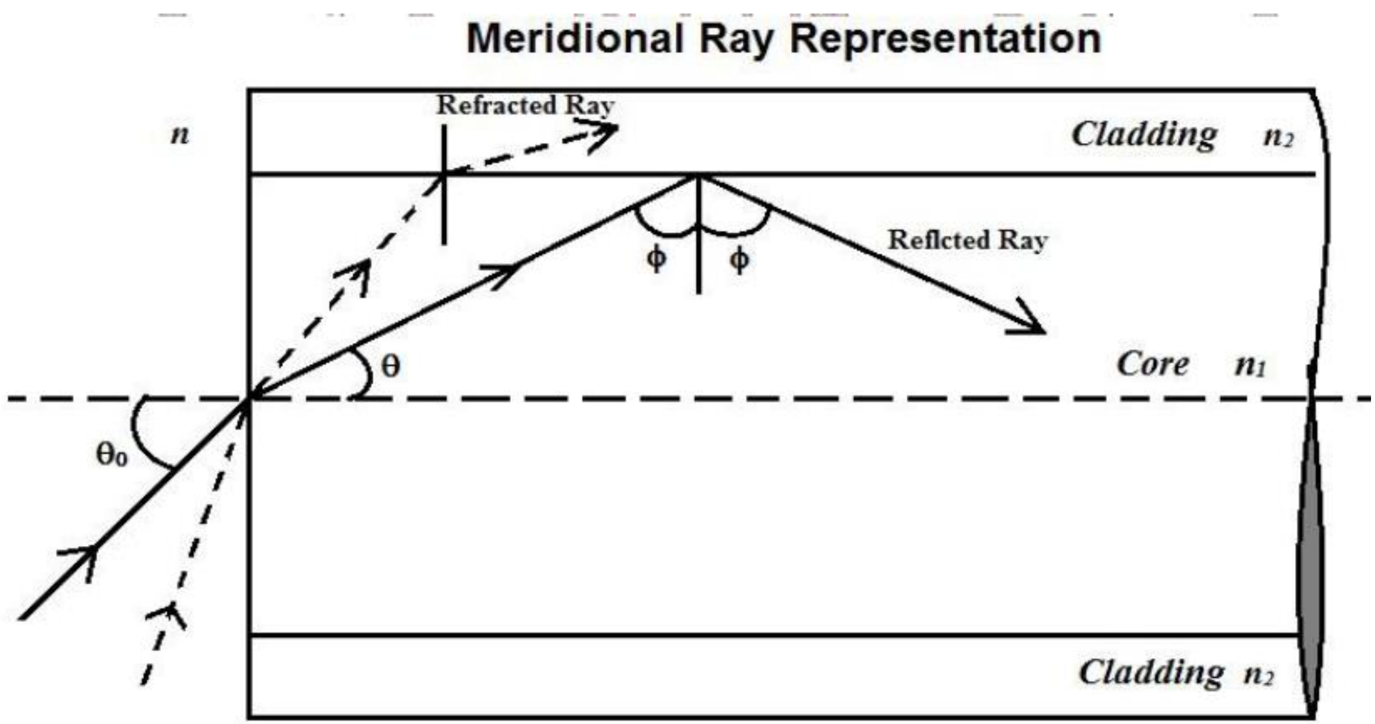
For example if the ray is launched at some angle such that it does not intersect the axis of the fiber, then after total internal reflection it will go to some other plane. We can see that in this situation the ray will never intersect the axis of the fiber. The ray essentially will spiral around the axis of fiber. These rays are called the **Skew rays.**

So it can be concluded that if the light is to propagate inside an optical fiber it could be through two types of rays

a) Meridional rays: The rays which always pass through the axis of fiber giving high optical intensity at the center of the core of the fiber.

b) Skew Rays : The rays which never intersect the axis of the fiber, giving low optical intensity at the center and high intensity towards the rim of the fiber.

Propagation of Meridional Rays



Let us consider figure above (Fig.3). A ray is launched from outside (air) at an angle θ_o from the axis of the fiber.

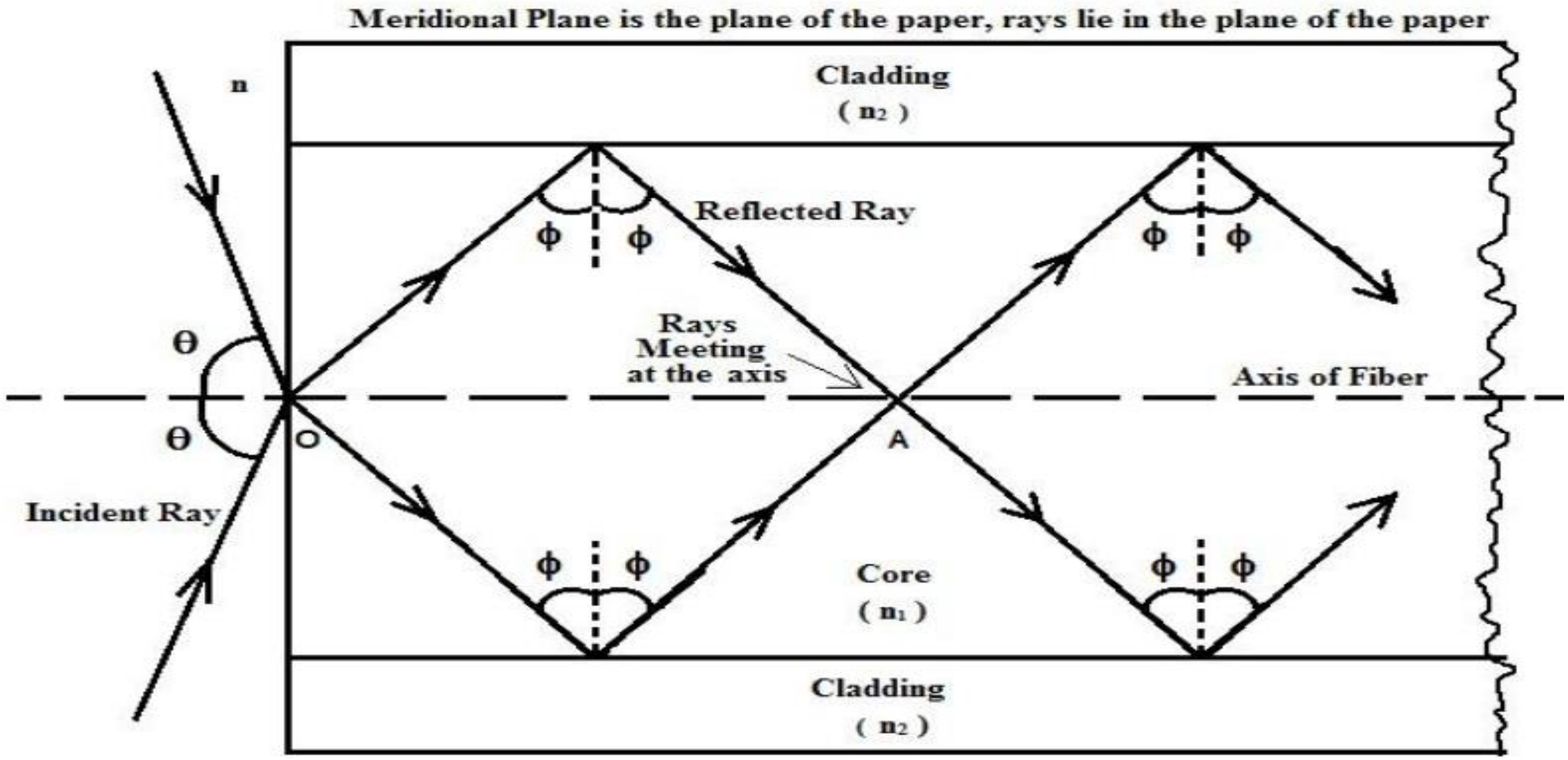
The question is, under what conditions the ray is ultimately guided inside the core due to total internal reflections at the core cladding boundary?

- There may be infinite number of planes that pass through the axis of the fiber and consequently there are an infinite number of meridional planes. This indirectly indicates that there are an infinite number of meridional rays too, which are incident on the tip of the fiber making an angle with the fiber-axis as shown in the previous figure.

- in practice there would be a bunch of rays that would be convergent at the same point. Meridional rays are classified into bound and unbound rays. The rays that undergo TIR inside the fiber core remain inside the core at all times along the propagation and are called as bound rays. The rays that fail to undergo TIR inside the core are lost into the cladding and are called unbound rays. The dotted ray shown in previous figure is an unbound meridional ray.

- These meridional rays which get totally internally reflected at the core-cladding boundary meet again at the axis of the optical fiber as shown in the next figure.

Since all the reflected rays meet at the same point a region of high optical intensity is generated at that point (point A in figure). Since these rays undergo multiple TIR at the core-cladding boundary, they meet repeatedly at the axis at regular intervals along the fiber. This causes multiple regions of maximum intensity along the axis of the fiber.



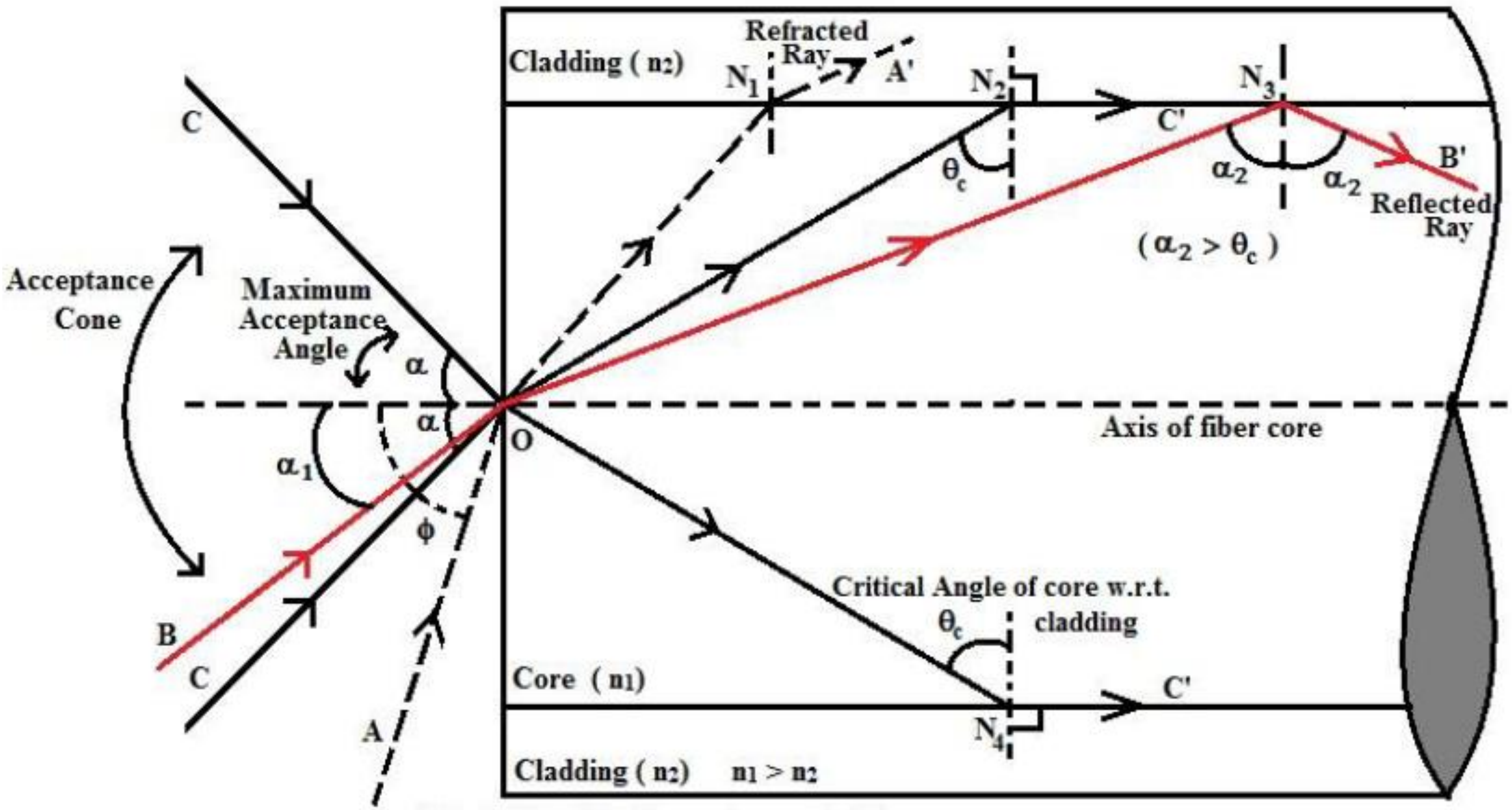
- In the next figure, The ray CO is launched into the fiber at such an angle ‘α’ that its refracted ray is incident at the core-cladding boundary at its critical angle ‘θc’.

- If any light ray is launched at an angle more than α then the refracted ray just refracts out to the cladding because the angle of incidence of its refracted ray at the core-cladding interface is less than the critical angle.

- Thus the angle α is indicative of the maximum possible angle of launching of a light ray that is accepted by the fiber. Consequently, the angle α is called the angle of acceptance of the fiber core.

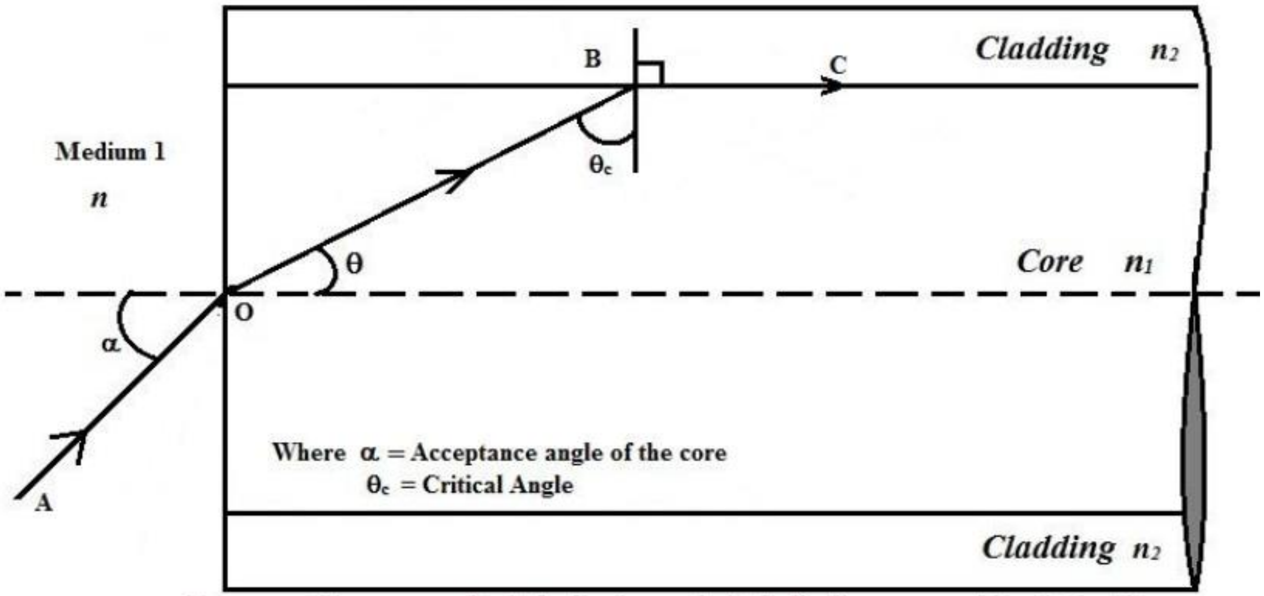
- Since the optical fiber is symmetrical about its axis, it is very clear that all the launched rays, which make an angle α with the axis, considered together, form a sort of a cone. This cone is called the acceptance cone of the fiber as shown in the next figure.

- Any launched ray that lies within this cone is accepted by the fiber and the light of this ray is guided along the fiber by virtue of multiple TIRs as shown by the red ray BO in the figure below.



NUMERICAL APERTURE OF OPTICAL FIBER

- An incident ray AO is incident from medium1 at the tip of the fiber making an angle α with the axis of the fiber, which is the acceptance angle of the fiber.
- The refracted ray for this incident ray in the core then is incident at the core-cladding interface at the critical angle θc of the core with respect to the cladding.
- The angle of refraction for critical angle of incidence is 90 degree.



Applying Snell's law at the medium1-core interface we get:

$$n \sin \alpha = n_1 \sin \theta$$

From the figure it is clear that $\theta = \frac{\pi}{2} - \theta_c$ and so substituting this in the above equation, we get:

$$\sin \alpha = \frac{n_1}{n} \cos \theta_c$$

From the basic trigonometric ratios, $\cos \theta_c = \sqrt{1 - \sin^2 \theta_c}$

Applying Snell's law at the core-cladding interface we get:

$$\sin \theta_c = \frac{n_2}{n_1} \quad \Rightarrow \cos \theta_c = \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2}$$

$$\boxed{\sin \alpha = \sqrt{\frac{n_1^2 - n_2^2}{n^2}}}$$

Since the initial medium 1 from which the light is launched is air most of the times, n = 1. The angle α is indicative of light accepting capability of the optical fiber.

Greater the value of α, more is the light accepted by the optical fiber. In other words, the optical fiber acts as some kind of aperture that accepts only some amount of the total light energy incident on it.

The light accepting efficiency of this aperture is thus indicated by **sin α** and hence this quantity is called as the numerical aperture (N.A.) of the optical fiber.

Thus for an optical fiber in air, with core refractive index n1 and cladding refractive index n2 and having an acceptance angle of α is given by

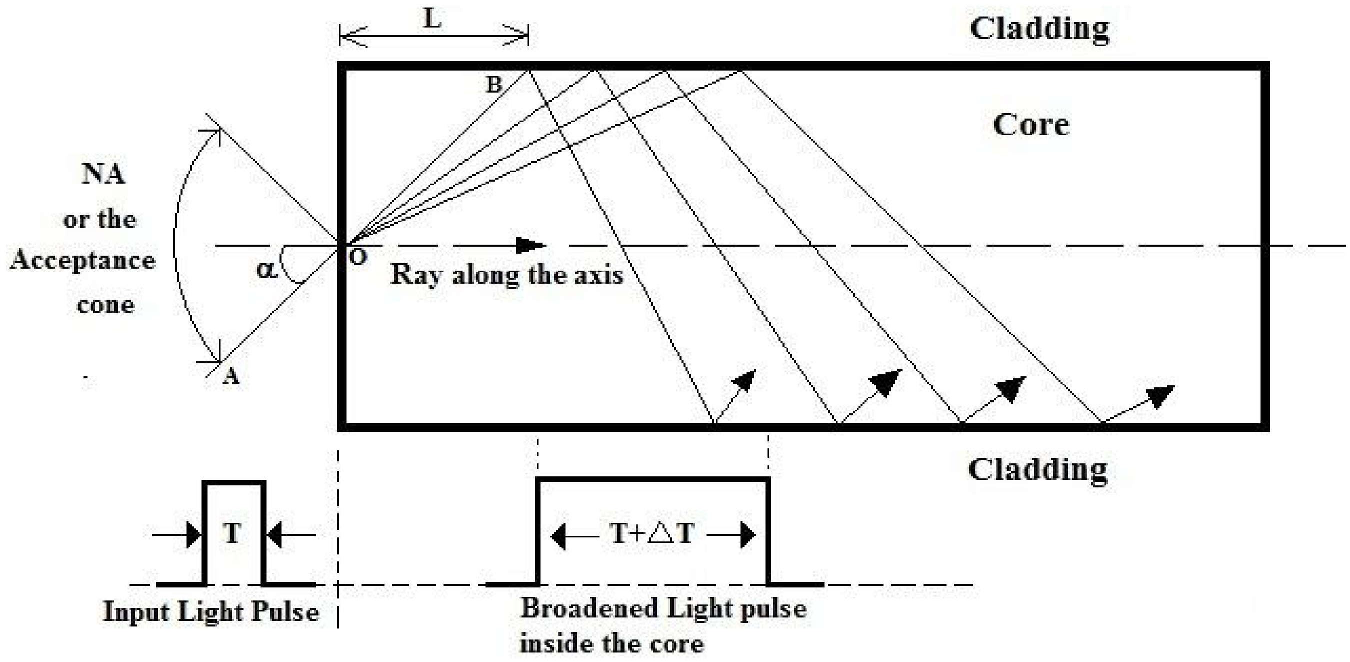
$$N.A. = \sin\alpha = \sqrt{n_1^2 - n_2^2}$$

So, for good launching efficiency, n_1^2 should be large compared to n_2^2. Since the material for the optical fiber has been chosen as glass, the refractive index of the core is practically fixed to about 1.5.

The only choice therefore we have is to reduce the refractive index of the cladding for good launching efficiency. Since $n_2 = 1$ (i.e., no cladding) is the minimum possible value, it suggests that the cladding is an undesirable feature. In the first look it then appears that the cladding is only for mechanical support.

DISPERSION

- The amount of light accepted by an optical fiber is only one of the parameters in optical communication. A more important parameter is the data rate which the fiber can handle since the primary purpose here is to send information from one point to another.
- In an optical fiber light is launched in the form of optical pulses to transmit the required information. Light energy launched into the fiber may be considered to travel in the form of numerous rays in accordance to the Ray-Model.
- These rays travel different paths inside the core of an optical fiber because different light rays are incident on the tip of the optical fiber at different angles within the acceptance cone itself.
- This causes different light rays in the acceptance cone to travel along different paths in the core of the optical fiber and accordingly take different time intervals to travel a given distance too, which leads to a phenomenon of pulse broadening inside the core of the optical fiber.
- Thus the pulse of light which might originally be of width T seconds now might be of $T+\Delta T$ seconds inside the fiber core. The next figure below depicts a pictorial description of how light pulse broadens inside the core of the fiber.



$$\Delta t = \frac{L}{\cos\theta_1'}\frac{n_1}{c} - \frac{L}{c}n_1$$

$$= \frac{Ln_1}{c}\left(\frac{1}{\cos\theta_1'} - 1\right)$$

$$= \frac{Ln_1}{c}\left(\frac{n_1}{n_2} - 1\right)$$

$$= \frac{Ln_1}{cn_2}(n_1 - n_2)$$

The amount of broadening is measured in terms of the increase in the pulse time width and is denoted by ΔT.

the value of ΔT is given by:

$$\Delta T = \frac{L}{c}\frac{n_1(n_1 - n_2)}{n_2}$$

where c is velocity of light. Since the core material is glass, $n_1 \approx 1.5$, and since $n_2 \le n_1$, it can lie between 1 and 1.5.

The ratio n_1 / n_2 then lies between 1 and 1.5 only. The time difference Δt per unit length therefore is more or less proportional to $(n_1 - n_2)$.

Δt per km $\propto (n_1 - n_2)$

The time difference Δt essentially is the measure of pulse broadening on the optical fiber.

limits the rate at which data can be transmitted along the fiber. This indirectly limits the bandwidth available on the fiber. Thus we can say that more the pulse broadening lower the bandwidth. That is:

$$Bandwidth\ (BW) = \frac{1}{\Delta T}$$

This phenomenon is called **DISPERSION** of an optical fiber. The dispersion (pulse broadening) has to be small since the data rate is inversely proportional to the pulse broadening. For high speed communication (high speed does not refer to the time taken by data to reach the destination but it refers to the number of bits per sec) the pulse broadening and hence the dispersion should be minimal.

For low dispersion ($n_1 - n_2$) should be as small as possible. So for an optical fiber the refractive index of core has to
be made as close to the refractive index of cladding as possible.

Thus for low ΔT values, the only option available with us is to decrease the value (n1–n2) or in other words, to increase the refractive index of the cladding n2.

3. Contradictory Requirement:

(a) For higher launching efficiency (higher NA), $n_1 - n_2$ should be **as large as possible** .

(b) For high data rate (bandwidth), $n_1 - n_2$ should be **as small as possible** .

The two are contradictory requirements.

Since data transfer rate is rather more important in communication, $n_1 - n_2$ is made as small as the fabrication technology permits.

So for all practical fibers, $\frac{n_1 - n_2}{n_1} \sim 10^{-2} - 10^{-3}$

Refractive index of the cladding differs from that of the core by only 0.1 to 1%.

- When the optical fiber is used for data communication, fibers with high values of n2 are used.

- If the cladding is removed, the value of n2 becomes 1 and the value of the above difference becomes about 0.5. The bandwidth corresponding to this value of n1-n2 is of the order of few Kilohertz, which is far worse than that of a normal twisted pair of wires.

- Thus cladding is an extremely important requirement for optical fiber when the bandwidth is the prime concern of the application and its refractive index is made as close to that of the core as the available technology permits, but not made equal.

- This is brought about by varying the amount of doping in a single glass rod. The differently doped regions have different refractive indices and serve as core and cladding of the optical fiber.

Different types of fibers:

1. STEP INDEX FIBER

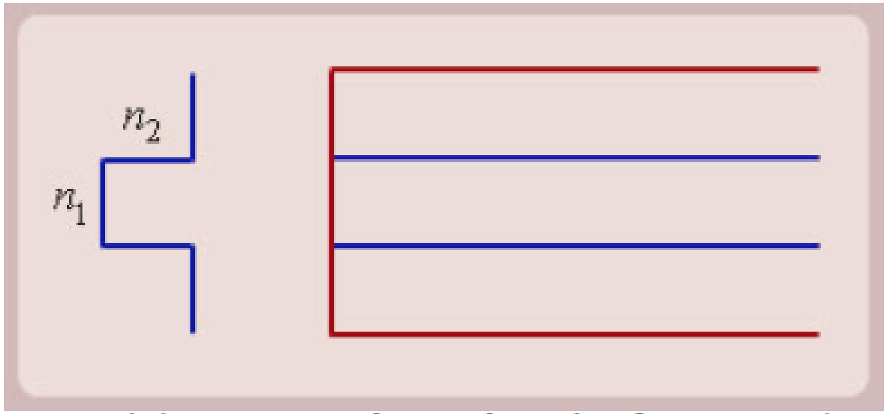


Figure (5): **Step Index Fiber** (Refractive index profile)

For this fiber the refractive index of the core is constant (see Fig 5). Since refractive index profile looks like a pulse or step, this kind of fiber is called the **STEP INDEX FIBER.** This structure is useful for analyzing propagation of light inside an optical fiber. Generally it is not used in practice because data transfer rate in this fiber is the lowest.

Just as a small exercise we can ask, what kind of pulse broadening occurs in a step index fiber if we do not use cladding?

Let us take 1Km of the optical fiber.
Since $n_1 = 1.5, n_2 = 1$ and $L = 1000m$,

$$\Delta t = \frac{L}{c} \cdot \frac{n_1}{n_2}(n_1 - n_2)$$

$$= \frac{10^3}{3 \times 10^8} \cdot \frac{1.5}{1}(1.5 - 1)$$

$$= .25 \times 10^{-5} \text{ sec}$$

Bandwidth $\approx \frac{1}{\Delta t} = \frac{1}{2.5 \times 10^{-6}} = 4 \times 10^5\ Hz$

So if we make a cladding-less optical fiber, its light launching efficiency is excellent but it has hardly any bandwidth. Even an electrical cable is better than the optical fiber.

Important Conclusion: The cladding is an essential part of an optical fiber. It does not just provide the mechanical support but increases the bandwidth of the fiber.

We can observe from the expression for pulse broadening that $\Delta t \propto L$ keeping all other parameters constant.

Since $BW \sim 1/\Delta t$, we get

$\Rightarrow$ BW $\times L = const$.

Important: We can trade in the bandwidth for the length and vice versa. That is, we can send low bit rate signals over long distances and high bit rate signals only over short distances.

2. GRADED INDEX FIBER

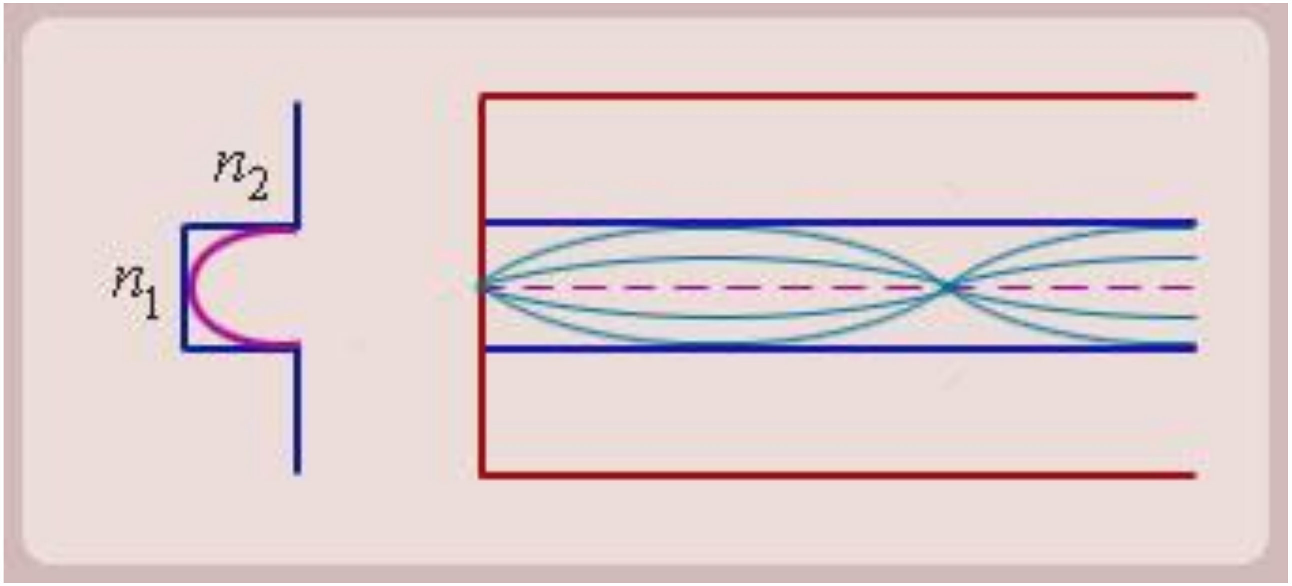
(a) In a step index fiber since the refractive index is constant inside the core, the velocity of all the rays is constant and hence there is travel time difference between different rays. If we develop a system where the rays which travel longer distances travel with higher velocities and the rays which travel shorter distances travel with lower velocities, the pulse spread on the fiber can be reduced and consequently the bandwidth can be increased.

(b) The ray which is at a higher angle, should speed up and the ray which is along the axis of the fiber should travel with the slowest possible velocity.

Since velocity is inversely proportional to the refractive index, it can be manipulated by changing the refractive index of the core. The refractive index of outer layers of the core should be smaller compared to that of the inner layers, so the rays that go in the outer layers, travel faster. So we find that for reducing dispersion, the refractive index at the center should be maximum and it should gradually decrease from the center to the core-cladding interface. The rays that go at higher angles speed up and the dispersion gets reduced.

In this fiber we grade the refractive index profile of the core and consequently it is called the **graded index fiber.**

A graded index fiber and the ray propagation is shown in the figure 6:



(c) If we taper the profile optimally, we get the dispersion reduction compared to that for a step index fiber, even by a factor of thousand. The data rate of a typical graded index fiber is typically 10 to 100 times higher compared to a step index fiber.

Therefore, in practice, even for LANs, we use GIF (Graded Index Fiber) instead of SIF (Step Index Fiber).

3. SINGLE MODE FIBER

The optical fiber in which only one ray travels along the axis of fiber is called the ***single mode optical fiber .***

Single mode optical fiber is the best amongst the three types of fibers, namely the step index fiber, GI fiber and the single mode fiber.

In a long distance communication, we use single mode optical fiber, whereas in LANs we generally use graded index optical fiber.

Note: For single mode optical fiber however we have to use a source like laser because the diameter of the fiber is very small and without a highly collimated beam, sufficient light can not be launched inside the fiber.

The three types of fibers have typical diameters as follows:

OPTICAL FIBERS CORE DIAMETER.

SM $5-10\mu m$

GRADED INDEX $50-60\mu m$

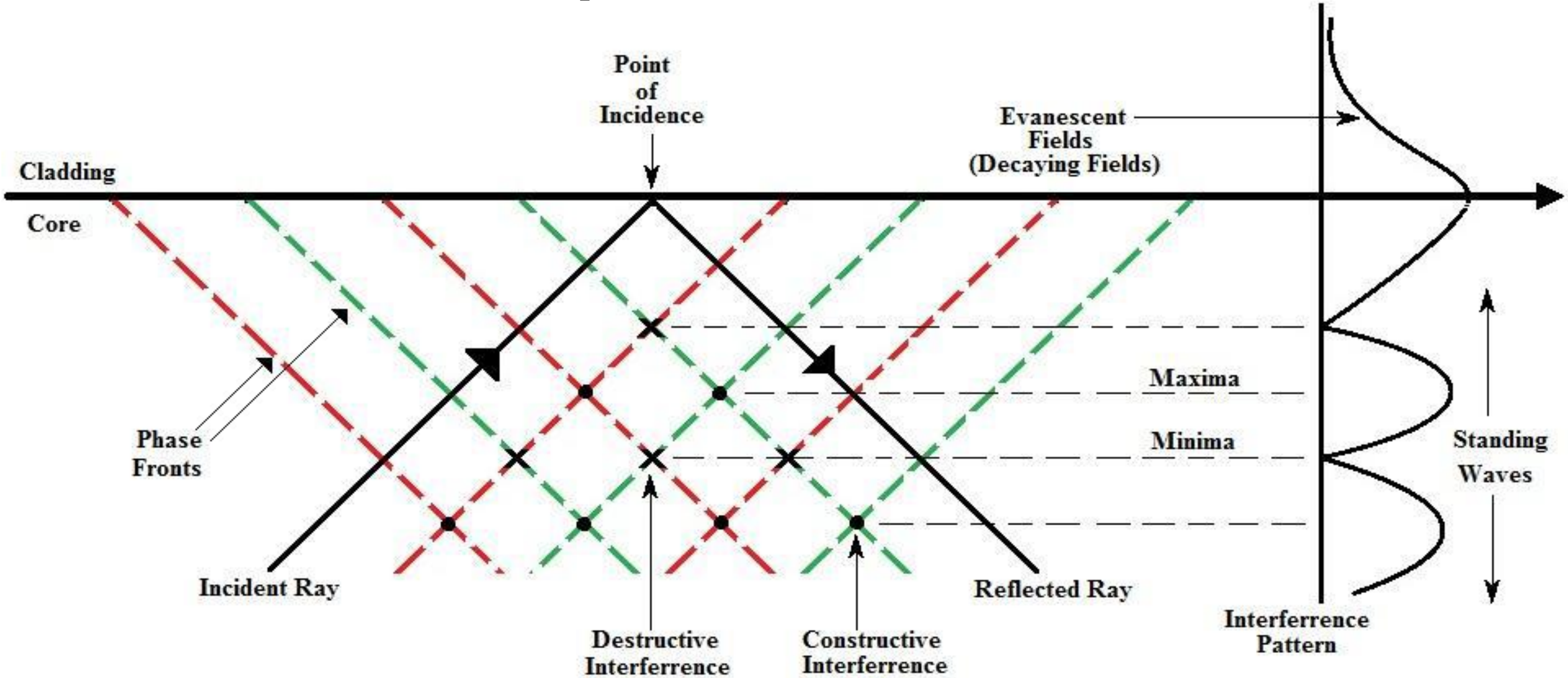
STEP INDEX $50-60\mu m$

Note: The Cladding Diameter for all types of fibers has been standardized to $125\mu m$

PHASE-FRONT (WAVE-FRONT) BASED STUDY OF TIR

Any light ray launched meridional within the acceptance cone will propagate along the fiber core by virtue of multiple total internal reflections at the core-cladding interface

Figure below shows the phenomenon of total internal reflection of a ray of light at the core-cladding boundary along with the wave-fronts of the incident and the reflected rays



- The distance between a red and a green wave-front corresponds to a phase difference of 180^o (π radians).

- The similar coloured wave-fronts have either 0^o or 360^o phase difference between them.

- Thus, when two similar coloured wave-fronts meet, they interfere constructively and dissimilar coloured wave-fronts interfere destructively.
-
- This is evident from the interference pattern that sets up in the core as shown in the previous figure.

- In the core, the interference between the incident and the reflected wave-fronts constitutes a standing wave pattern of varying light intensity with discrete maxima and minima in a direction normal to the core-cladding interface.

- If we refer to the electromagnetic wave theory of light, it shows that at total internal reflection, the light intensity inside the cladding is not completely zero. Instead, there exist some decaying fields in the cladding, which do not carry any power but support the total internal reflection phenomenon by satisfying the boundary conditions at the core-cladding interface.

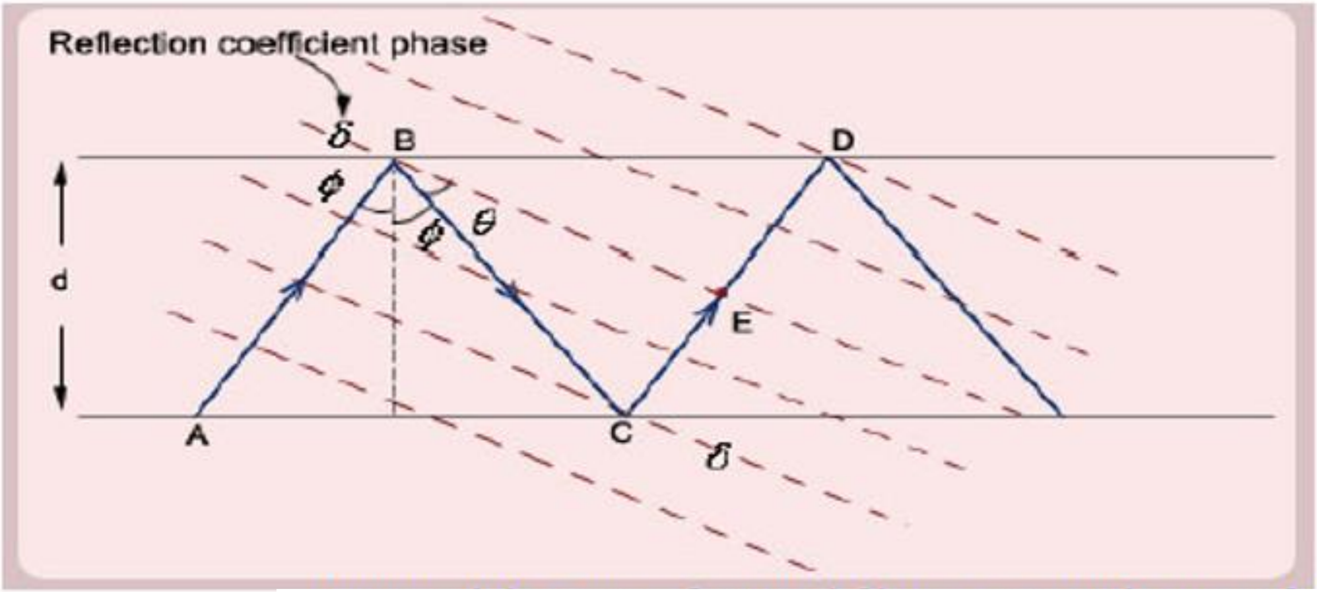
- These fields are called as evanescent fields.

- these fields decay down to a negligibly small value as we move away from the core-cladding boundary deeper into the cladding.

- Larger the value of the angle of incidence of the incident ray at the core-cladding boundary, sharper is the decay of the evanescent fields.

The light basically consists of wave fronts. A line perpendicular to a wave front is called the ray. Light is an electromagnetic wave and when we say it travels like a ray it is a collection of wavefronts which move.

Let us take an optical fiber with light rays propagating in it. The rays and the wave fronts which are perpendicular to the rays, are as shown in figure



Let us consider a phase front corresponding to the ray AB and passing through the point B. This phase front also meets the ray CD at point E. In other words, the phase of the ray at B (just before the reflection) is same as that of the ray at point E. That is to say that the phase change corresponding to the distance BCE added with the phase (δ) of the reflection coefficient at points B and C should be a multiple of 2π. This is what is called the condition for the constructive interference.

From simple geometric considerations we have

$$\theta + 2\phi = \pi / 2$$
$$BC = d \sec\phi$$
$$CE = BC \sin\theta = d \sec\phi . \sin(\pi/2 - 2\phi)$$
$$= d \sec\phi \cos 2\phi$$

phase change from B to E is

$$\Phi = \frac{2\pi}{\lambda} . n_1 (BC + CE) + 2\delta$$
$$= \frac{2\pi}{\lambda} n_1 \{d \sec\phi + d \sec\phi \cos 2\phi\} + 2\delta$$

For constructive interference the phase change should be multiple of 2π

$$\Rightarrow \Phi = 2m\pi$$

Simplifying equations we get a condition for sustained propagation of light rays inside the core as

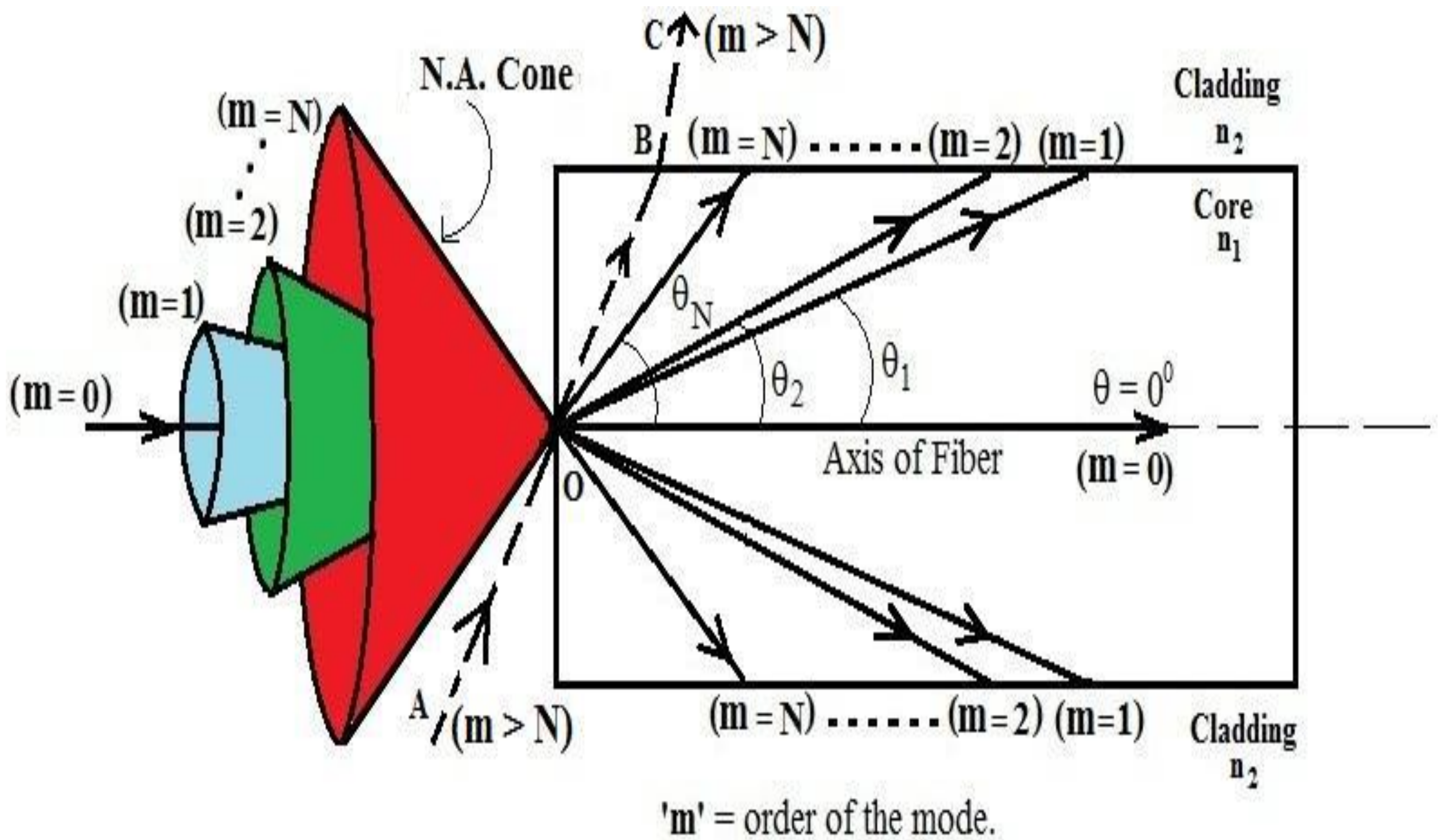
$$\boxed{\frac{2\pi n_1 d \cos\phi}{\lambda} + \delta = m\pi}$$

- The significance of the equation is that only those rays, which are incident on the tip of the fiber at angles such that their angle of refraction in the core satisfies equation can successfully travel along the fiber.

- If we concentrate on equation, we find that since ‘m’ can take only discrete integral values, the value of angle θ is also discrete. This suggests that there are only some discrete launching angles within the acceptance cone (N.A. cone) for which the rays can propagate inside the fiber core.

- the acceptance cone can no longer be assumed as a solid cone of rays, launched at all possible angles (smaller than acceptance angle), but has to be viewed as composed of discrete conical rings of rays which are launched at the tip of the fiber core at angles which satisfy the equation.

- This leads to further decrease in the light gathering efficiency of the optical fiber.
- Any ray that is not launched at these discrete angles will not propagate inside the optical fiber.
- This discretization in the values of launching angles lead to formation of what are called as **modes** in an optical fiber.


N.A. Cone
C (m > N)
B (m = N) ...... (m = 2) (m=1)
Cladding
n_2
Core
n_1
(m = N)
(m = 2)
(m=1)
(m = 0)
θ_N
θ_2
θ_1
$\theta = 0^0$
Axis of Fiber
(m = 0)
O
A (m > N)
(m = N) ...... (m = 2) (m=1)
Cladding
n_2
'm' = order of the mode.

Limitations of the Ray-model

(1) The ray model gives an impression that during total internal reflection the energy is confined to the core only. However,

it is not so. In reality the optical energy spreads in cladding also.

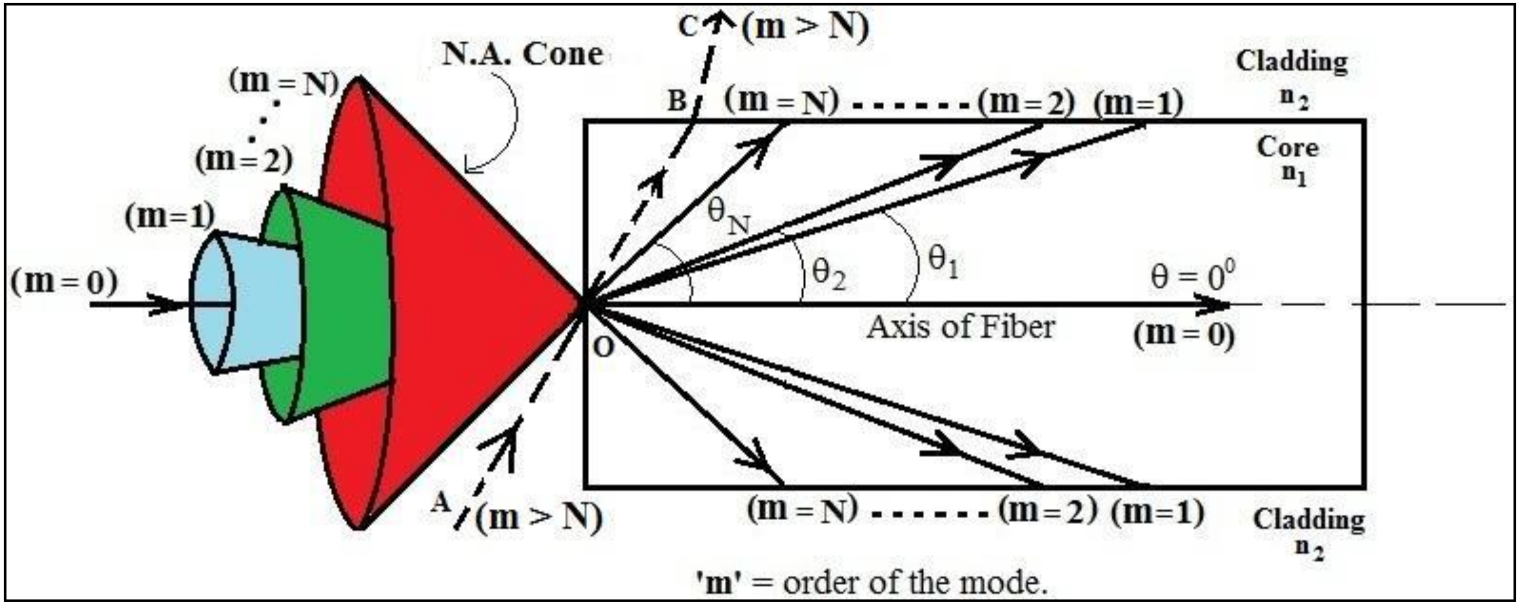
(2) The ray model does not speak of the discrete field patterns for propagation inside a fiber.

(3) The ray model breaks down when the core size becomes comparable to the wavelength of light. The ray model

therefore is not quite justified for a SM fiber.

The limitations of the Ray model are overcome in the wave model discussed in the next module.

Modal Propagation of Light in an Optical Fiber



The number of different values of ‘m’ signifies the number of different possible launching angles which can successfully propagate in the optical fiber core

The ray that is launched along the axis of the fiber propagates without any phase condition requirement to be satisfied and corresponds to the first mode of propagation, also called as the zero order mode of propagation. This is shown by m=0 in the figure above and few other modes are shown by their respective annular rings represented by different colours.

- There may be N possible modes of propagation for which the rays successfully travel along the fiber creating unique light intensity patterns around the axis of the core.

- However, one should carefully note here that, the number allowable values of ‘m’ depend on the acceptance angle of the optical fiber

- Any ray that is launched outside this cone does not propagate along the fiber although it might correspond to a particular mode

- This is shown in the figure above by the ray **AO.** This ray simply refracts out of the core because its angle of incidence at the core-cladding interface is smaller than the critical angle of the core with respect to the cladding

- the optical fiber too is selective in accepting only those rays which satisfy the basic phase conditions and the other rays are rejected by the fiber although they may lie within the acceptance cone of the fiber.

- Thus there are only a finite number of modes that are allowed in an optical fiber and the other modes are rejected.

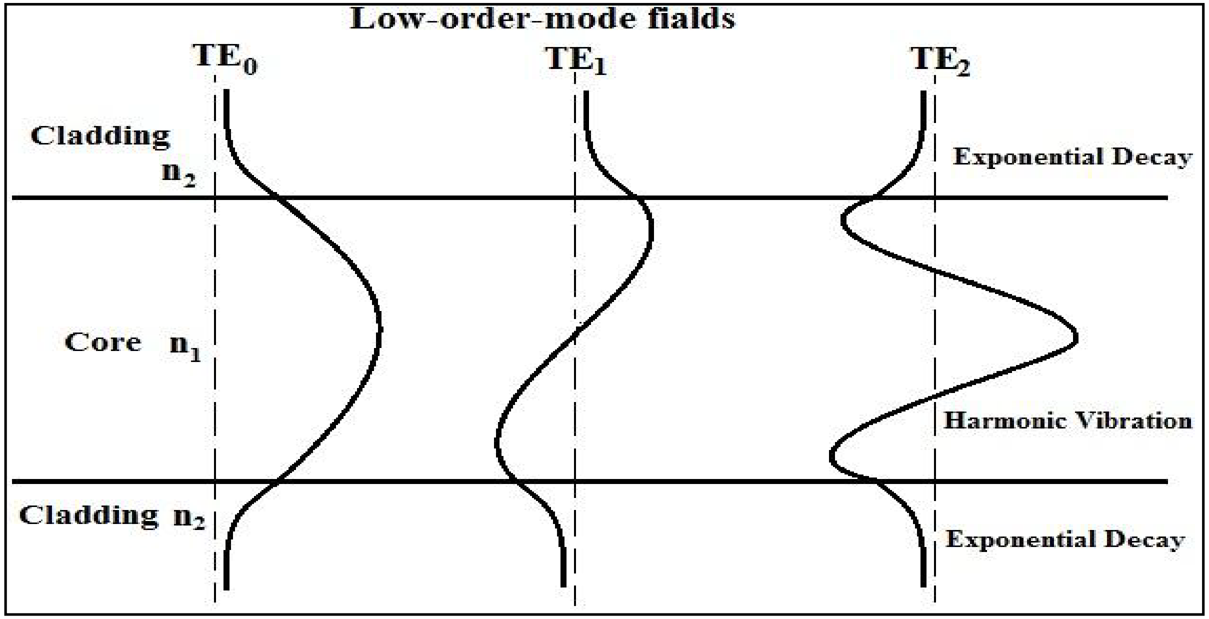
- This leads to a further decrease in the light accepting efficiency of fiber.
- Treating light a transverse electromagnetic wave

- when meridional rays propagate along the fiber, their electric and magnetic fields of all the rays superimpose to result in electric and magnetic field distribution

- Electric and Magnetic field distribution may be either transverse electric (TEx) or transverse magnetic (TMx).

- The propagation of skew rays, on the other hand, results in a particularly special form of modes which are neither TE nor TM in nature and are called as Hybrid modes.

- Rigorous analysis shows that hybrid mode is in fact the lowest order mode that can propagate in an optical fiber. Since hybrid mode is the lowest order mode, it can be analytically shown that the mode of the ray that propagates in the fiber along the axis is hybrid.



- For very low launching angles with respect to the axis of the fiber, the intensity pattern created is the one which is shown by TE0 in the above figure.

- There exists a maximum intensity region around the axis of the core and as we move towards the periphery of the core the fields start to decay.

- These fields eventually decay down to negligibly low value in the cladding.

- If the launching angle is increased further, we get the intensity patterns as that shown for TE1 and TE2 in the above figure.
- The subscript of TE in fact indicates the number of destructive interferences in the pattern where the field intensity crosses the zero level, or in other words, creates a optically dark area.
- So, for TE0 we have no dark area, for TE1 we have one dark area at the axis, for TE2 we have two dark areas and so on.
- This subscript is also termed as the index of the mode.
- The above discussion is also true for TM mode as well.

The ray-model of light showed us that launching angle of the light ray must be smaller than the acceptance angle of the optical fiber core.

However, the consideration of the wave-fronts showed us that this condition of the launching angle is not enough to ensure a successful propagation of light in an optical fiber.

The launching angle must be such that the angle of refraction of the launched ray into the fiber must satisfy the phase condition of equation below for sustained propagation inside the optical fiber core

$$\frac{2\pi n_1 d \sin\theta}{\lambda} + \delta = \pi m \quad (m=0,1,2,3,\ldots)$$

The different discrete values of the angle θ indirectly signify the different allowable launching angles of the light rays into the optical fiber. If we substitute the first value of m (i.e. m=0) in the above equation we get θ=0 degree.

Let us now substitute the next integral value of m to obtain the first order mode

$$\theta_1 = sin^{-1}\left\{\frac{\lambda(\pi-\delta)}{2\pi d n_1}\right\}$$

This value of θ1 signifies the first annular ring of rays that propagates inside the fiber. Similarly we may obtain the other modes that propagate in the fiber by subsequent substitution of the corresponding values of m until the condition $\theta \leq \alpha$ is reached, where α is the N.A. of the fiber core.

The pulse broadening is caused by the time delay in between the axially launched ray and the ray corresponding to the largest order mode possible in the optical fiber because it is the largest order mode that travels the longest path inside the fiber.

what if we do not allow any mode to get launched into the fiber except the axial ray

the propagation of next mode and the subsequent modes depends on many parameters

If we reduce the diameter of the core to a very low value such that $\theta 1$ exceeds the numerical aperture of the fiber core, then the rays corresponding to this $\theta 1$ cannot be launched into the fiber. Thus only the axial ray would be launched and any higher mode would not be launched into the fiber thereby reducing the pulse broadening effect to a negligibly low value.

These types of fibers which allow only a single mode of light to propagate inside them are called as Single Mode Optical Fibers (SMOF).

And the optical fibers which allow the propagation of multiple modes are called as Multimode Optical Fibers MMOF).

Thus it is obvious that SMOF have very low pulse broadening in comparison to MMOF and thus have higher bandwidths. But MMOF have higher N.A. than SMOF.

- One significant observation to note here is that though SMOF have high bandwidths, they have very low N.A. values, which makes it very difficult to launch light into a single mode optical fiber.

To overcome this issue:

- First of all, the source of light has to have a highly directional beam.(Laser)

- Secondly, the fiber core has to be carefully aligned to the source. The slightest disturbance to this arrangement would prevent any available light to enter the fiber even with a highly directional optical source.

Analysis of Wave-Model of Light

After determining the transverse components if we apply the boundary conditions, we form four simultaneous equations. But we have five unknown quantities to be determined which are

1) The arbitrary constants A, B, C and D that appear in the expressions for the field components.

2) The value of the phase constant β.

By eliminating the arbitrary constants. we obtain an equation which is called as the characteristic equation of a mode. We get

$$\left\{\frac{J'_{\nu}(ua)}{uJ_{\nu}(ua)}+\frac{K'_{\nu}(wa)}{wK_{\nu}(wa)}\right\}\left\{\beta_1^2\frac{J'_{\nu}(ua)}{uJ_{\nu}(ua)}+\beta_2^2\frac{K'_{\nu}(wa)}{wK_{\nu}(wa)}\right\}=\frac{\beta\nu}{a}\left\{\frac{1}{u^2}+\frac{1}{w^2}\right\}^2$$

Here,

$$J'_{\nu}(x)\equiv\frac{\partial}{\partial x}J_{\nu}(x) \quad \text{and} \quad K'_{\nu}(x)\equiv\frac{\partial}{\partial x}K_{\nu}(x)$$

The equation has been obtained after eliminating all the arbitrary components. Hence it is the general characteristic equation of any mode in the optical fiber.

It contains all the six components of the electric and the magnetic field because it is obtained by using all the boundary conditions together.

We know that if a mode possesses all the field components of electric and magnetic field, the mode is called a hybrid mode.

Therefore the characteristic equation is called the characteristic equation of hybrid modes. The quantities ‘u’ and ‘w’ are defined as:

$$u^2 = \omega^2 \mu \epsilon_1 - \beta^2$$

$$w^2 = \beta^2 - \omega^2 \mu \epsilon_2$$

the quantity 'v' is an integral constant. If we now assume the value of 'v' to be zero, it indicates a circularly symmetrical field. The variation of the field pattern in the azimuthal direction for v=0 is shown below:

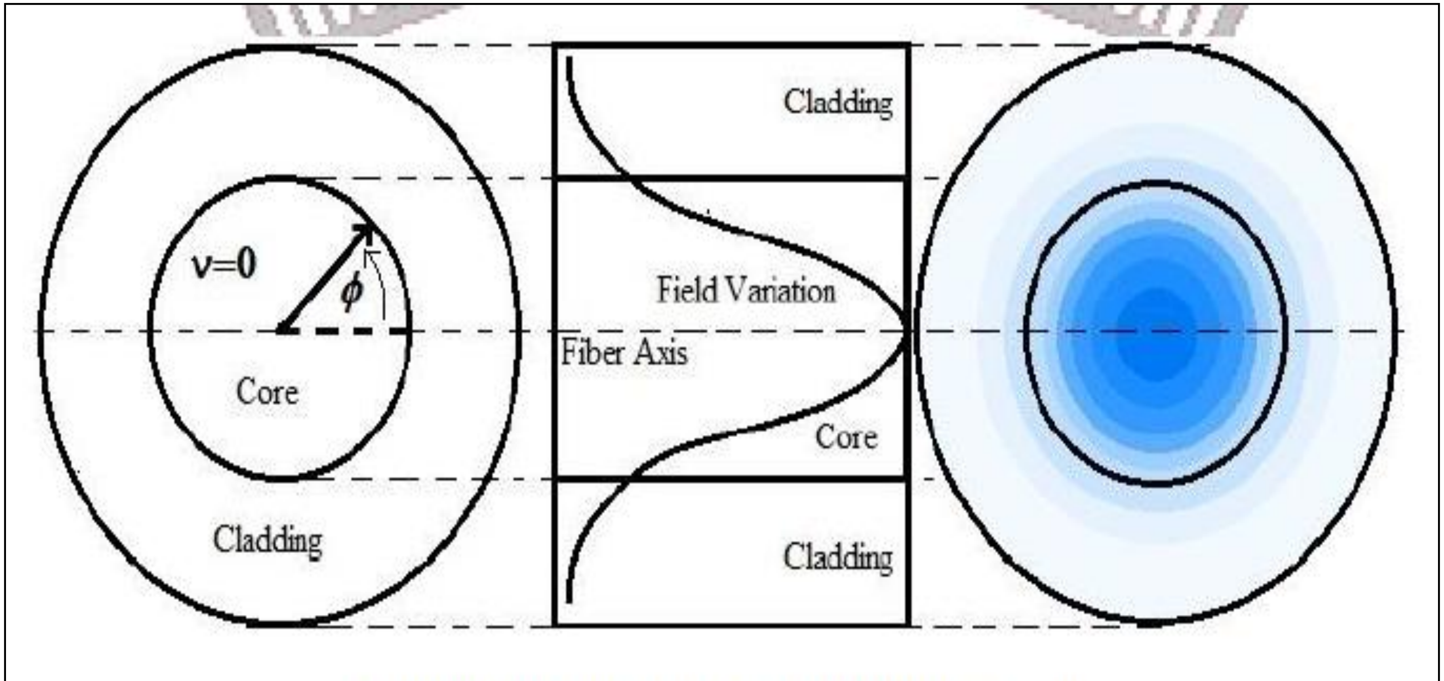


Figure 6.1: Light Intensity Pattern for ν=0

- The previous diagram shows that the fields are circularly symmetric in the azimuthal direction with a maximum intensity at the central region of the fiber and gradually decreasing towards the periphery of the core of the fiber.
- If we recall our discussion on the ray model of light, we find that maximum intensity at the axis is shown by meridional rays.
- That is why v=0 corresponds to meridional rays and any higher value of v corresponds to skew rays. Also, these field patterns have no maximum at the axis of the fiber because skew rays spiral around the axis and do not meet at the axis of the fiber.
- The intensity patterns corresponding to zero and higher values of v are shown in the next table

Type of Rays	Value of ν	Value of m	Intensity Pattern at fiber output
Meridional Rays	0	1	
	0	2	
	0	3	
Skew Rays	1	1	
	2	1	
	3	1	
	4	1	
	5	1	

Table 6.1: Light Intensity Patterns for different ν.

If we now substitute v=0 in the characteristic equation, the right hand side of the equation is zero and the resultant equation would be:

$$\left\{\frac{J'_0(ua)}{uJ_0(ua)}+\frac{K'_0(wa)}{wK_0(wa)}\right\}\left\{\beta_1^2\frac{J'_0(ua)}{uJ_0(ua)}+\beta_2^2\frac{K'_0(wa)}{wK_0(wa)}\right\}=0$$

The left hand side of the above equation is a product of two terms. So, to satisfy the equation either one or both has to be zero. Hence we have two solutions to the above equations. If we equate the first term to zero, it would signify the characteristic equation for Transverse Electric (TE) modes. On the other hand if the second term is equated to zero, it would signify the characteristic equation for Transverse Magnetic (TM) modes.

$$\left\{\frac{J'_0(ua)}{uJ_0(ua)}+\frac{K'_0(wa)}{wK_0(wa)}\right\}=0 \qquad \text{For TE modes}$$

$$\left\{\beta_1^2\frac{J'_0(ua)}{uJ_0(ua)}+\beta_2^2\frac{K'_0(wa)}{wK_0(wa)}\right\}=0 \qquad \text{For TM modes}$$

One important observation which was clear from the Ray-Model and is also now analytically proved by the wave-model is that TE and TM modes have field distributions which are always circularly symmetric about the axis of the fiber because they correspond to v=0.

Also, TE and TM modes correspond to meridional rays only, as we had seen in the ray model. Some of the modes corresponding to the meridional rays are shown in a previous table .

On the contrary, Hybrid Modes do not have circularly symmetric field distributions because they correspond to higher values of v.

This was also seen from the ray model that skew rays move spirally around the fiber axis and hence do not produce circularly symmetric light intensity patterns around the axis of the fiber.

Intensity patterns for some higher values of v are shown in the previous table.

The two previous equations have multiple solutions owing to the fact that J1(x) and J0(x) are oscillatory functions which cross zero multiple times.

Thus, depending on the value of ‘a’ in the argument of the Bessel function, the two equations may have ‘m’ different solutions. The value of ‘m’ signifies the $\boldsymbol{m^{th}}$ solution.

So, to designate a mode we have a combination of (v,m), in which v signifies the type of the intensity pattern and ‘m’ signifies the number of the solution designated.

For example TE_{01} signifies circularly symmetric field of the first solution of the characteristic equation 1 . Similarly TM_{02} signifies circularly symmetric field of the $\mathbf{2^{nd}}$ solution of equation 2.

As it is already obvious, the value of v for TE and TM would be always zero but they have multiple values of ‘m’ and each combination signifies an entirely different intensity patterns. Some of these patterns are shown in a previous Table.

Hybrid modes are also designated by the above combination (v,m), where the value of v=1,2,3……etc. The value of ‘m’ here signifies the $\boldsymbol{m^{th}}$ solution of the characteristic equation of the hybrid mode.

For example HE_{11}, HE_{21}, HE_{54} etc. are some of the hybrid modes. Few hybrid modes and their corresponding light intensity patterns are shown in the previous table.

The combination (v,m) helps us to identify a particular mode and its corresponding light intensity pattern.

Also, if the light intensity pattern is shown to us, we can predict the mode of the pattern just by knowing v and m.

The index v of the combination (v,m) represents the number of complete cycles of the field in the azimuthal plane and the index ‘m’ represents the number of zero crossings in the azimuthal direction.

For example, TE_{02} would result in an intensity pattern that would be circularly symmetric about the axis with maximum intensity at the centre of the fiber and there would be two concentric dark rings around the axis.

The field distribution and the light intensity pattern for TE_{01} mode has been shown in a previous figure. The different modes can be designated as shown below:

$$\mathbf{TE_{0m}} = TE_{01},\ TE_{02},\ TE_{03}\ldots$$

$$\mathbf{TM_{0m}} = TM_{01},\ TM_{02},\ TM_{03}\ldots$$

$$\mathbf{HE_{vm}} = HE_{12},\ HE_{23},\ HE_{51}\ldots$$

V-NUMBER OF OPTICAL FIBER

While discussing about the numerical aperture of an optical fiber we stated that the numerical aperture, which depends on the difference of the refractive index on the core and cladding, is a characteristic parameter of the optical fiber.

However, it was not clear from the statement that, the numerical aperture was also dependent on the radius (or diameter) of the core of the optical fiber. This was evident only when the ray model was discussed.

This means that the definition of the numerical aperture is not truly characteristic as it lacks one parameter which is the radius of the fiber core.

Let us now define a more fundamental and characteristic parameter of an optical fiber.

We introduced to parameters 'u' and 'w' during the analysis of the wave-model of light inside the optical fiber. These quantities are defined as:

$$u^2 = \omega^2 \mu \epsilon_1 - \beta^2 \quad (6.16)$$

$$w^2 = \beta^2 - \omega^2 \mu \epsilon_2 \quad (6.17)$$

If we add the two equations we get:

$$u^2 + w^2 = \omega^2 \mu \epsilon_1 - \omega^2 \mu \epsilon_2$$

$$= {\beta_1}^2 - {\beta_2}^2$$

We see that the sum is independent of β. If we now express the phase constants of the core and the cladding in terms of the phase constant in vacuum, we have:

$$u^2 + w^2 = {\beta_0}^2 {n_1}^2 - {\beta_0}^2 {n_2}^2 = {\beta_0}^2 ({n_1}^2 - {n_2}^2) \quad (6.18)$$

Let us now multiply both sides of equation (6.18) by a^2 (a=radius of the optical fiber) and assume $V^2 = a^2(u^2 + w^2)$. Thus we obtain:

$$V^2 = a^2\beta_0{}^2(n_1{}^2 - n_2{}^2)$$

$$\Rightarrow V^2 = a^2\left(\frac{\omega}{c}\right)^2(n_1{}^2 - n_2{}^2) \qquad \text{(Since } \beta_0 = \frac{\omega}{c}\text{)}$$

$$\Rightarrow \boxed{V = \frac{a\omega}{c}\sqrt{(n_1{}^2 - n_2{}^2)}} \qquad (6.19)$$

$$\Rightarrow V = \frac{2\pi f a}{c}\sqrt{(n_1{}^2 - n_2{}^2)}$$

$$\Rightarrow \boxed{V = \frac{2\pi a}{\lambda}(N.A.)} \qquad (6.20)$$

The V-number of an optical fiber is thus a more comprehensive and true characteristic parameter because it involves all the attributes that describe an optical fiber namely, core refractive index, cladding refractive index and the radius of the core.

The radius of the cladding is implicit since its diameter is standardized to 125µm in order to make it mechanically compatible to physical connectors available.

The V-number is also used to compare two optical fibers.

If we concentrate on equation (6.19), we find that, for a given radius, the V-number of an optical fiber is directly proportional to the frequency of the light. That is why the V-number is sometimes also referred to as the normalized frequency of the fiber.

During the solution of the wave equation, we saw that the range of β is given as:

$$\beta_2 < \beta < \beta_1$$

This could also be written as

$$n_2 < n_{effective} < n_1$$

If we look into the equation of 'u' and 'w', we find that for β≤ω2μϵ2, the value of 'w' no longer remains purely imaginary and hence the modified Bessel function can no longer be used for describing the behaviour of the fields in the cladding.

At this condition the light energy no longer remains guided inside the core of the fiber and it starts to leak to the cladding causing energy loss because in the cladding energy dies down very rapidly.

Beyond this cut-off condition there would not be any considerable modal propagation of light in the fiber because most of the energy would get lost in the cladding.

The value of β indicates the effective phase constant with which the light energy propagates inside an optical fiber.

If the value of β equals β2, it signifies that most of the light energy propagates through a medium with refractive index n2, which is the cladding.

On the contrary, if the value of β approaches β1, then most of the energy gets confined in the core. This observation now explains the physical visualisation of β lying between β1 and β2.

It suggests that in practical situation, where β lies between β1 and β2, a part of the light energy propagates through the core and a part of the light energy propagates in the cladding.

But light energy cannot travel together with two different phase constants.

This is because the light energy of the propagating mode is, sort of tied together by phase condition and boundary condition requirements.

Therefore, there has to exist some kind of a mutual treaty in terms of the phase constant so that the part of the light which travels through the core reduces its phase constant and that which travels through the cladding increases its phase constant in order for the light to propagate in unison with the same phase constant β, along the optical fiber.

Thus if this mutual phase constant β is very close to $\beta 1$ we can easily conclude that most of the energy is confined within the core of the optical fiber and very little energy propagates through the cladding.

Thus as the value of β approaches $\beta 1$ more and more light energy starts to get confined in the core, which is practically very desirable for data security.

So for sustained and well confined propagation of light energy in the core of the optical fiber β must be as greater than ω2με2 as possible and as near to β1 as possible. That is, the value of effective refractive index neff must be nearer to n1 and much larger than to n2.

The main goal of our analysis was to find out the relationship between the phase constant β and the angular frequency (ω) of light inside the optical fiber so that the characteristics of propagation of light such as phase and group velocities could be calculated from it by using the following

$$\text{Phase Velocity}\left(v_p\right)=\frac{\omega}{\beta} \qquad (6.21)$$

$$\text{Group Velocity}\left(v_g\right)=\frac{\partial\omega}{\partial\beta} \qquad (6.22)$$

From the equation (6.19) we have found a relationship between ω and the V-number of a fiber. Thus for a given fiber we can use the V-number of the fiber instead of ω for our analysis because there is a direct variation between these two quantities.

Similarly, for the phase constant β, we may define a quantity called the normalized phase constant 'b' in place of the absolute phase constant β. This new phase constant may be defined as

$$b = \frac{{n_{eff}}^2 - {n_2}^2}{{n_1}^2 - {n_2}^2} \approx \frac{n_{eff} - n_2}{n_1 - n_2} \qquad (6.23)$$

The effective index of propagation is given by, $n_{eff} = \frac{\beta}{(2\pi/\lambda)}$

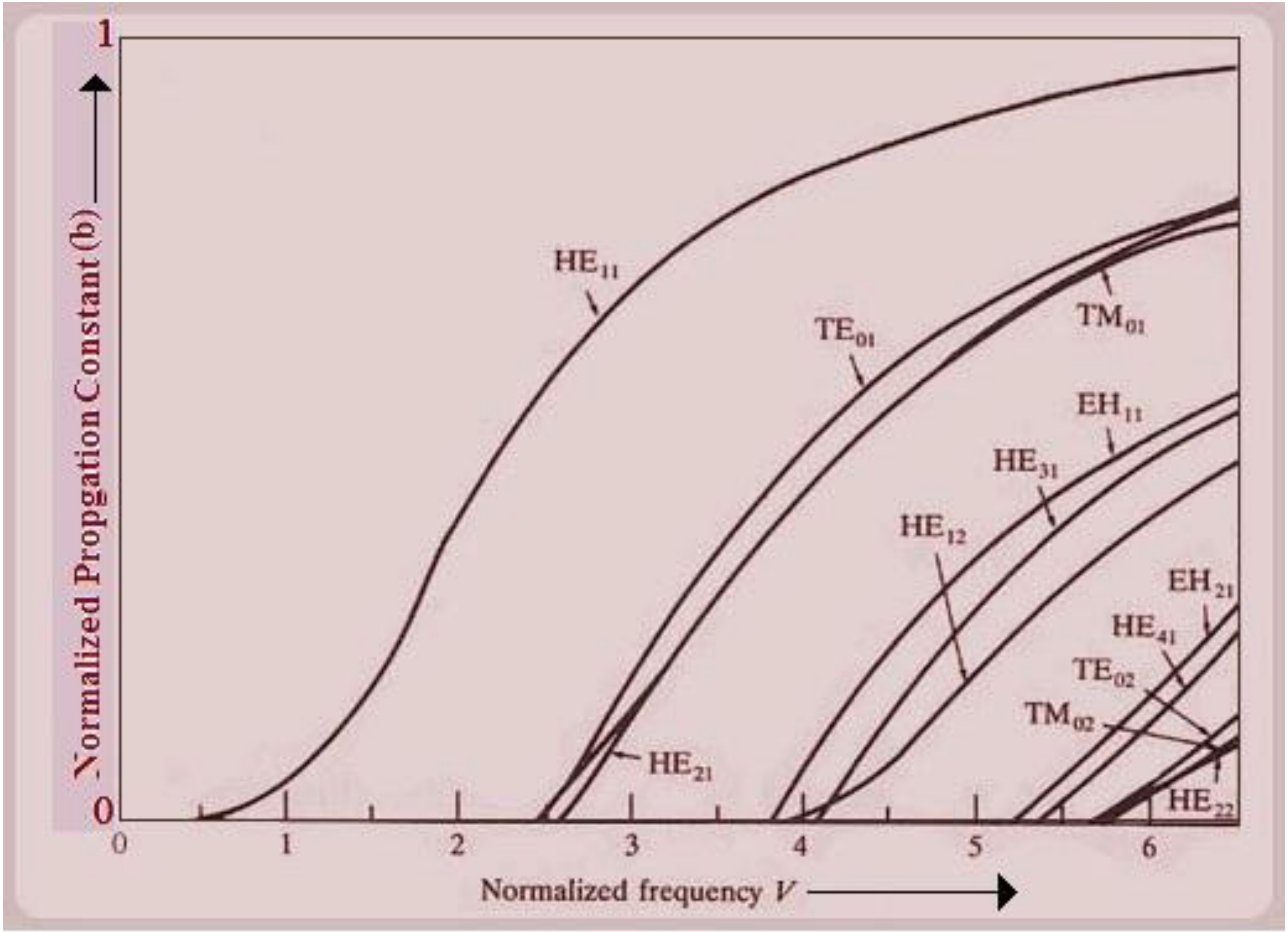
Thus the value of neff approaches n1 when β approaches β1 and it approaches n2 when β approaches cut=off (i.e. β2).

Correspondingly the value of the normalized phase constant ranges between (0, 1). That means, although the value of β ranges from β2 to β1, but the value of 'b' will always lie in (0, 1) irrespective of the mode of light. That is:

$$0<b<1$$

Thus instead of having a plot between ω and β, we may study the plot between V-number and the normalized propagation constant 'b'.

A plot of the normalized propagation constant 'b' versus the V-number of a given optical fiber is shown in the next slide:


Normalized Propgation Constant (b)
Normalized frequency V
1
0
0
1
2
3
4
5
6
HE11
TE01
TM01
EH11
HE31
HE12
HE21
EH21
HE41
TE02
TM02
HE22

It is clear that as the V-number of the fiber increases, all the graphs increase monotonically irrespective of core/cladding dimensions or properties. That is, for any optical fiber, if its V-number is increased, then the propagation constant corresponding to a particular mode also increases monotonically.

One observation here is that the HE11 is the mode which can propagate even at very low values of V-number. That is, it is the mode that successfully propagates even at very low frequencies.

However, if we consider the mode TE01, as shown in the graph, we find that this mode does not propagate until the V-number of the fiber exceeds a certain value, which is typically 2.4.

The value 2.4 is the first root of the J0(x) Bessel function. That is to say, the cut-offs of the different modes in the optical fibers are decided by the roots of the Bessel function.

Since the first root is 2.4, the V-number of the fiber should be greater than 2.4 for the dominant TE, TM or HE modes to propagate.

In other words, for a given fiber, the frequency should exceed a certain value. But the HE11 mode would inevitably propagate because its cut-off frequency is very low as shown in the graph.

Thus we observe something very interesting that, between V-number 0 and 2.4 only one mode propagates which is neither TE nor TM but is a hybrid mode.

In other words, the dominant mode of the fiber is a hybrid mode which has all the six components of the fields present. This is different from a metallic waveguide where the dominant mode is Transverse Electric.

Now, if we recall our discussion of the ray-model propagation of light, we find that the HE11 mode must correspond to the ray that travels along the axis of the optical fiber.

This is because it was the only ray which did not require any phase condition to be satisfied and it inevitably propagated along the axis of the fiber even if the core diameter was reduced to a very small value.

Here we have inherently deduced a quantitative condition for a fiber to be a single mode optical fiber.

That means if the V-number of the optical fiber is smaller than 2.4, the fiber will be a single mode optical fiber and if it is greater than 2.4 it will be a multimode optical fiber.

Each mode has a corresponding frequency .This frequency of the mode is called its cut-off frequency.

The V-number of an optical fiber is a very important characteristic parameter which is proportional to the frequency (or wavelength) of the propagating light.

In other words, for a particular mode to propagate inside the fiber, the V-number of the fiber must be greater than the V-number corresponding to the cut-off frequency of the mode.

For example, fibers having V-number lower than 2.4, allow only one mode, HE11 to propagate and no other mode can propagate in this fiber. Therefore such a fiber is called a single mode fiber.

In order to accommodate the higher order modes, the V-number of the fiber has to be increased.

Note that V-number of a fiber does not depend on the individual characteristics of the core or the cladding but depends on the characteristics of the core-cladding combination as a whole as is obvious from the expression below:

$$V = \frac{\omega a}{c}\sqrt{{n_1}^2 - {n_2}^2} = \frac{2\pi a}{\lambda}(N.A.) \qquad (7.1)$$

Here ω= Angular frequency of the mode.

a= Radius of the optical fiber.

n_1= Refractive Index of core.

n_2= Refractive Index of Cladding.

λ= Wavelength of the light.

N.A.= Numerical Aperture of the fiber.

Since the V-number of the optical fiber is proportional to the frequency, it is also called as the normalized frequency.

The curve between neff and the normalized frequency shows that for a particular mode to propagate, the V-number of the fiber corresponding to that mode must be greater than certain value which is the cut-off value for the mode.

Moreover, the propagation constant β for this mode has to be nearer to β1 and larger than β2 for the light energy of the mode to remain confined inside the core of the optical fiber.

Let us now have a quantitative analysis of the single mode operation in an optical fiber by considering some illustrative values as shown below. For a fiber to be single mode:

$$V \leq 2.4$$

If we substitute the expression for the V-number s in equation (7.1), we have

$$\frac{2\pi a}{\lambda}\sqrt{n_1{}^2 - n_2{}^2} \leq 2.4 \qquad (7.2)$$

Let us assume the value of the quantity $\sqrt{n_1{}^2 - n_2{}^2}$ be 0.1. Therefore we have:

$$\rightarrow 2\pi\left(\frac{a}{\lambda}\right)0.1 = 2.4$$

$$\rightarrow \left(\frac{a}{\lambda}\right) \approx \frac{2.4}{0.6}$$

$$\rightarrow \left(\frac{a}{\lambda}\right) \approx 4$$

Thus we see that, for a fiber having numerical aperture of 0.1, the radius should be less than 4 times of the wavelength.

Thus for the first window of optical communication (800 nm), a fiber would be single mode, if its radius is less than 3200nm or 3.2 μm.

For the second and the third windows, these values would approximately 5μm and 6μm respectively.

This was also obvious from the ray model that when the radius of the core is decreased considerably only one mode would propagate, thereby making it a single mode fiber.

This value of a radius is practically very small and hence, single mode optical fibers require special LASER kind of sources which have highly collimated beam of light.

let us now have a glimpse of the field distributions of a few modes. If we solve the field expressions for the modes, the electric fields of the first few modes inside the optical fiber are shown below:

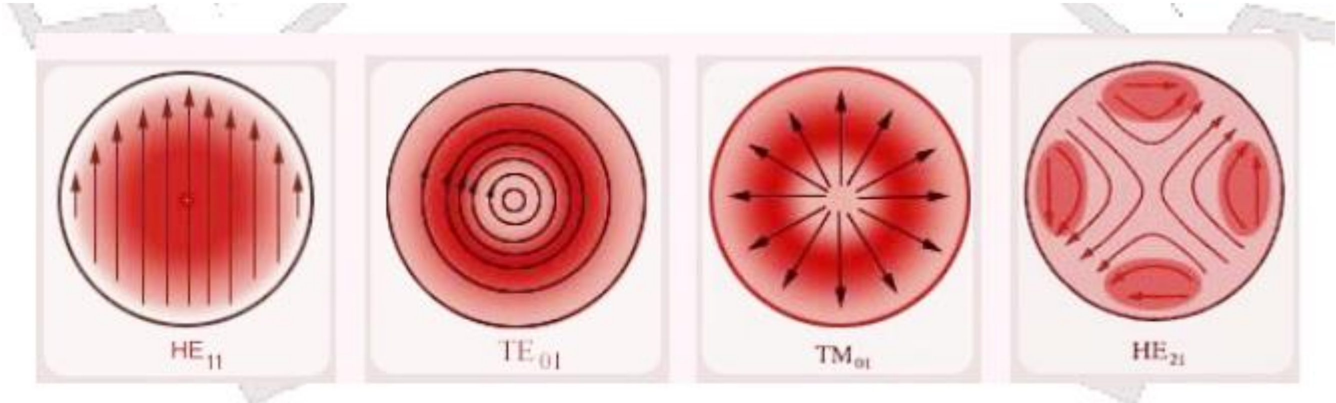


Figure 7.1: A few modes inside an optical fiber (V>2.4)

The HE11 mode is the lowest order mode that inevitably propagates inside an optical fiber.
As shown in the above figure, HE11 mode has an electric field which is always directed upwards with maximum amplitude at the axis and it decreases as we move radially outwards.
The TE01 and TM01 modes have circularly symmetric electric fields as we had already seen from our analysis and it is also obvious from the figure. These fields have a maximum electric field at the centre and it decreases as we move radially outwards.

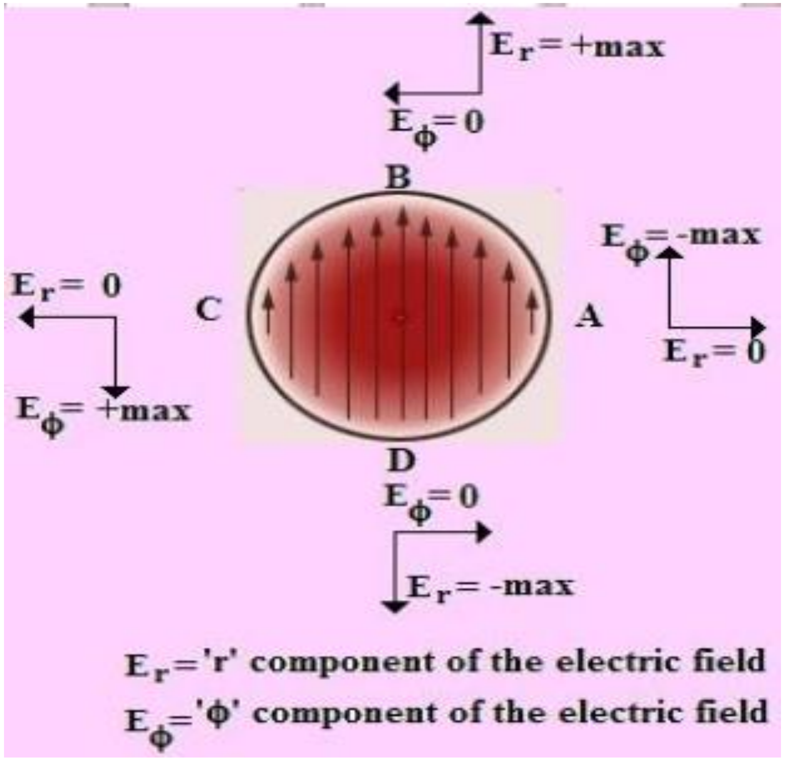
Let us now investigate how to identify the field pattern from the two subscripts written along with the mode, i.e. the ordered pair (v,m).

The value of 'v' indicates the behaviour of the field in the azimuthal plane, i.e. the variation of the field with respect to ϕ. In other words, it indicates the number of complete cycle variations in the ϕ plane.

The subscript 'm' dictates the number of zero-crossings, maxima and minima in the azimuthal plane. The number of zero-crossing is one less than the index 'm'.

From figure 7.1, it is clear that for the hybrid mode HE11 there is one complete cycle variation in the azimuthal plane for both Er and $E\phi$ components of the field and the field intensity has no zero crossings in the azimuthal plane though they are decreasing in nature.

This can be seen from the figure 7.2.



Similar observations can be made for the modes TE01, TM01 and HE21, and the field variations can be predicted from the knowledge of the two indices of the mode. For TE01 or TM01 modes, the fields are circularly symmetric about the axis of the fiber and have no zero crossings in the azimuth plane. This can be verified from the field pattern shown in the figure 7.1.

LINEARLY POLARIZED (LP) MODES

In earlier discussions, we have already been familiar with the fact that practical optical fibers keep their core refractive index (n1) very close to the cladding refractive index (n2) in order to achieve higher data rates.

In other words, the value of the quantity (n1-n2) is made very small, typically of the order of 10^{-3} to 10^{-4}. This requirement can also be deduced from equation (7.2) above.

If we substitute the value of the quantity under the radical sign to be large then we would have a very small value of the fiber radius 'a' which would be of no practical use as far as light launching efficiencies are concerned.

Therefore, for all practical optical fibers a quantity 'Δ' is defined as shown below:

$$\Delta \equiv \frac{n_1 - n_2}{n_1} \ll 1 \qquad (7.3)$$

The value of ‘Δ’ is very less than 1 because n1 is very close to n2 or in other words, (n1-n2) has a very small value as discussed above.

The assumption of Δ given by equation (7.3) is called as the weakly guiding approximation

When the difference between the core and cladding refractive indices becomes very small, there results a substantial amount of light energy that lies in the cladding. As this difference further decreases, more and more light energy spreads into the cladding.

In other words, the light guiding capability of the fiber gets weaker and the structure hence becomes weakly guiding in nature.

the fields in a practical optical fiber are almost transverse in nature and it can be shown that they are linearly polarized.

This means that the field patterns shown in figure 7.1 no longer remain so as far as direction is concerned.

That is, the fields do show the same intensity variation patterns but they all are now polarized linearly with the same linearity, i.e. all the fields have same polarization orientations.

These polarizations may be either vertical or horizontal as shown in the figure 7.3 below:

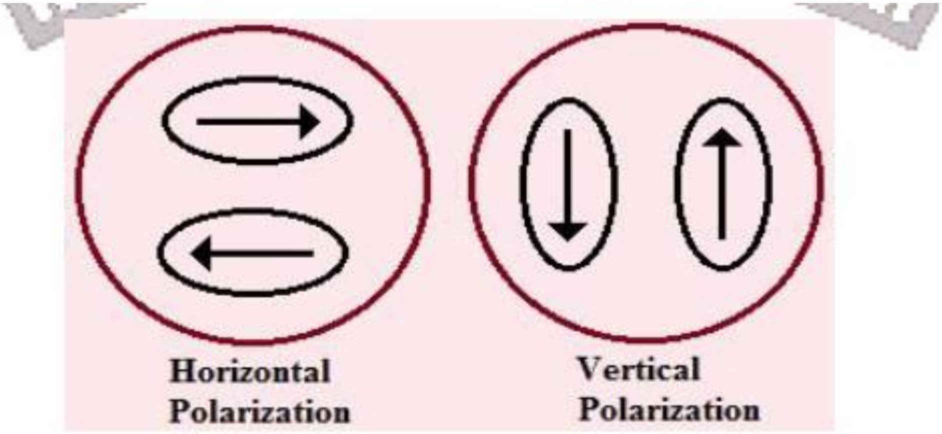


Figure 7.3: Polarizations of the Linearly Polarized modes

If we observe the b-V diagram of an optical fiber, we find that all the clusters of the modes higher than HE11 degenerate to form linearly polarized modes.

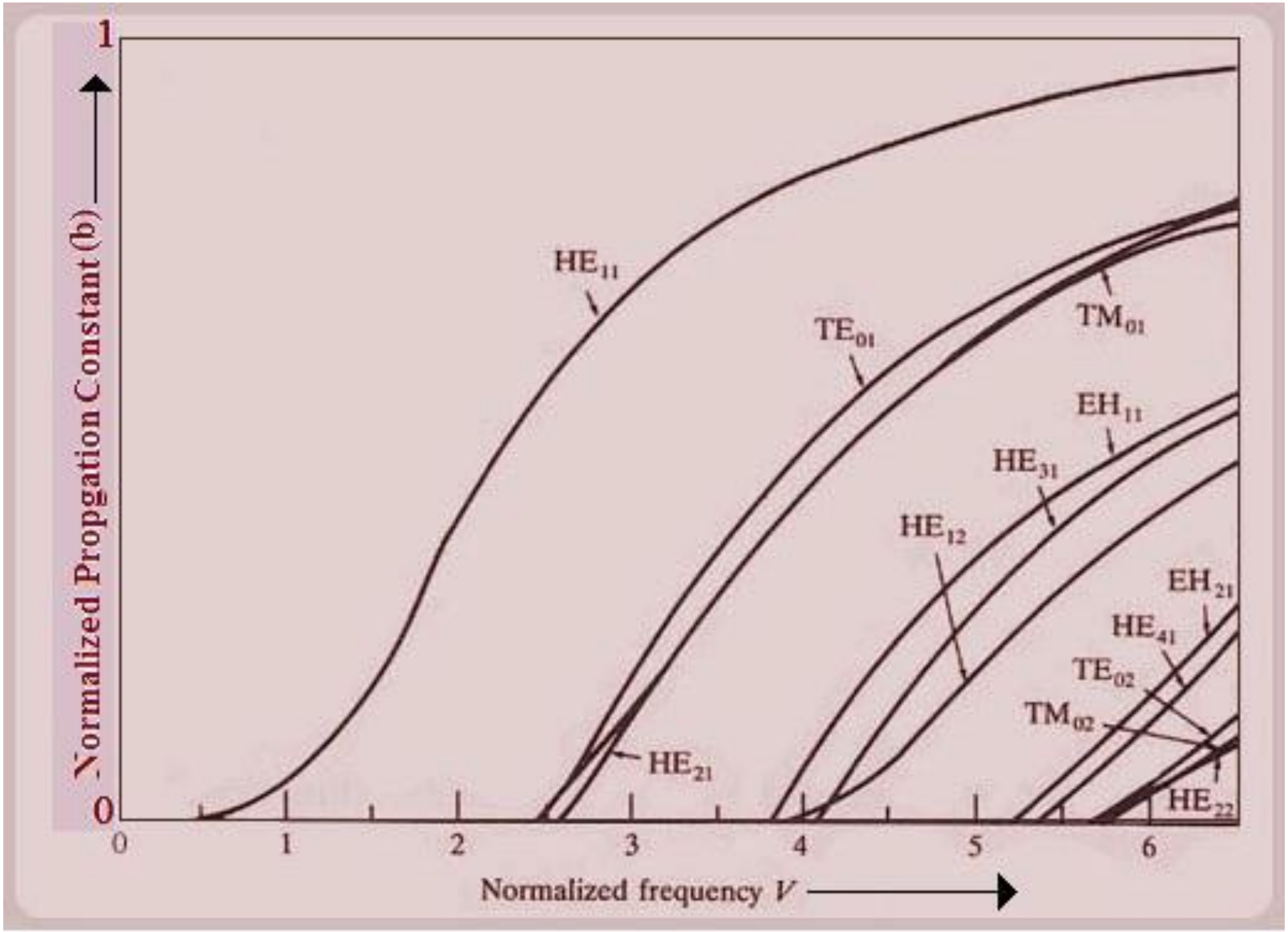
That is to say, as the value of n1 approaches n2, each of the higher mode clusters degenerate into a linearly polarized mode.

For example, the cluster TE01, TM01 and HE21 degenerate to form one single linearly polarized mode.

The dominant mode HE11 is already a linearly polarized mode as can be seen from figure 7.1.

In almost all practical optical fibers one would not find light propagating in the form of TE, TM or HE modes. Light propagates in the form of linearly polarized modes which are briefly called as LP modes

The TE, TM and HE modes thus remain only to academic investigations, because in practice light inside an optical fiber is almost linearly polarized.


1
0
Normalized Propogation Constant (b)
0
1
2
3
4
5
6
Normalized frequency V
HE11
TE01
TM01
EH11
HE31
HE12
EH21
HE41
TE02
TM02
HE21
HE22

Let us now have an understanding of the nomenclature and indices of the LP modes.

The HE11 mode in practical fibers is referred to as the LP01 mode. Note that the first index of the LP mode signifies the variation of light intensity in the azimuthal plane i.e. with respect to ϕ.

In case of HE modes the first index showed the field variations in the azimuthal plane and hence had the value 1 for the lowest order mode.

But in case of LP modes this index turns into 0 because once the direction of the field has been ascertained, the field intensity is constant at all ϕ for a given value of ‘r’.

The second index of the LP modes indicates the number of zero crossings in the light intensity pattern. The number of zero crossings is one less than the index. Hence LP01 mode has (1-1=0) no zero crossings in the intensity pattern, though the intensity decreases radially outwards.

Similarly, TE0m, TM0m and HE2m modes degenerate into LP1m modes.

In LP1m modes there would be one cycle variation in the light intensity in the azimuthal plane and the number of zero crossings would be (m-1).

Thus under the weakly guiding approximation, the dominant mode of propagation is the LP01 mode.

The next mode that propagates is the LP11 mode and in such a way all the consequent modes propagate.

Let us now discuss the first two LP modes, i.e. LP01 and LP11 modes.

These two modes are very important for long distance optical fiber communication.

LP01 mode propagates inevitably like the HE11 mode and the LP11 mode is used for dispersion compensation in the optical fiber.

The LP11 mode is created by degeneration of the three modes- TE01, TM01 and HE11.

Let us have a qualitative glimpse as to how this mode forms by the degeneration of the above three modes. Figure 7.5 below shows the different possible forms of creation of LP11:

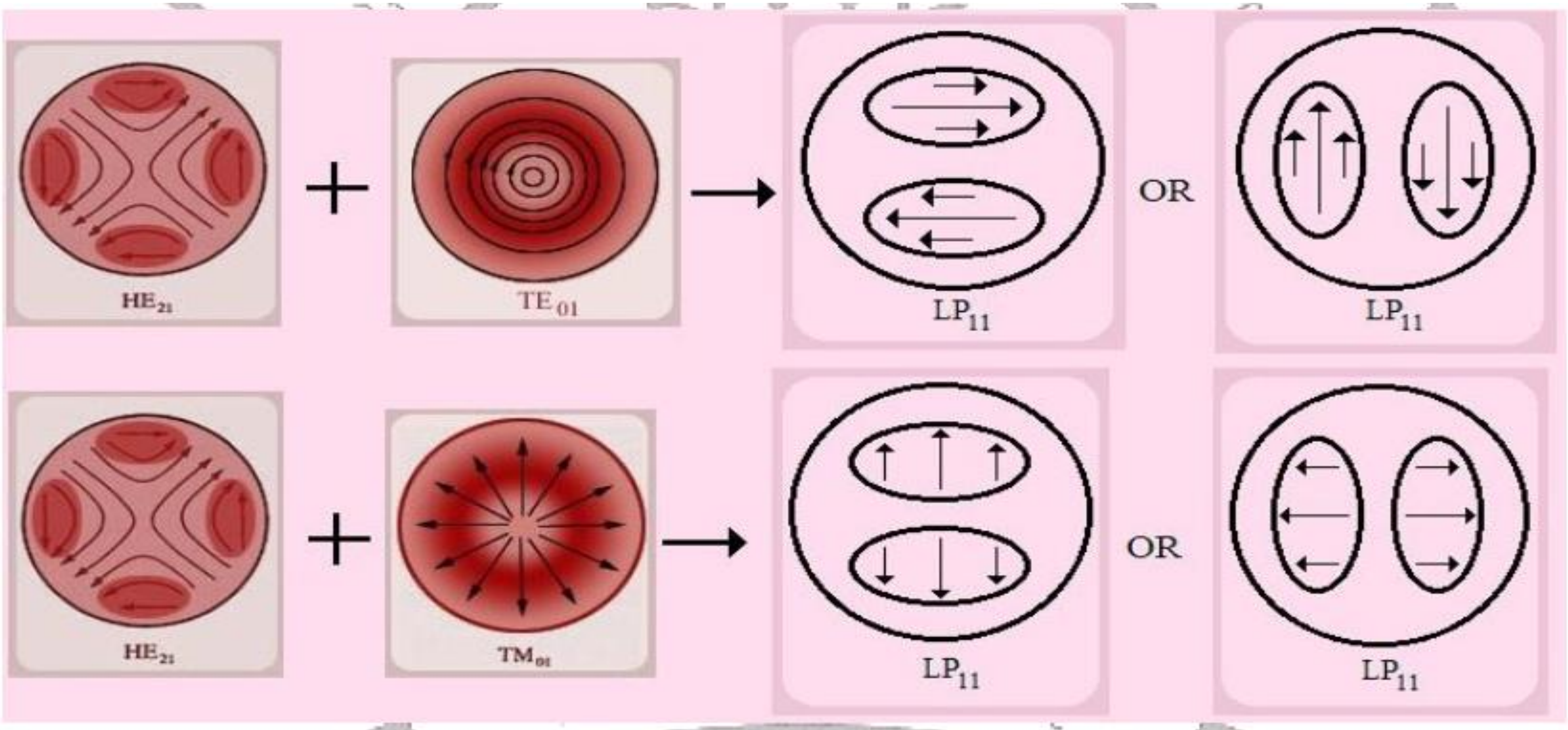


Figure 7.5: formation of LP_{11} mode from the TE_{01}, TM_{01} and HE_{21} modes.

As the figure suggests, there are four possible field patterns for the LP11 mode.

Thus when we speak of LP11 mode we inherently mean four possible field patterns having polarizations and intensity patterns given by figure 7.5.

Thus if light of arbitrary polarization when launched into an optical fiber has an excitation mode of LP11, the light propagating inside the fiber is in fact a combination of the four possible patterns of the LP11 mode propagating simultaneously inside the optical fiber.

Similar possibilities exist for the LP01 mode too. The only difference comes due to the circularly symmetric nature of the intensity pattern due to which any angular rotation of the pattern about the axis makes no difference in the intensity pattern but only has a change in the orientation of the polarization.

Therefore there are two possible orientations of polarization as shown in the figure 7.6.

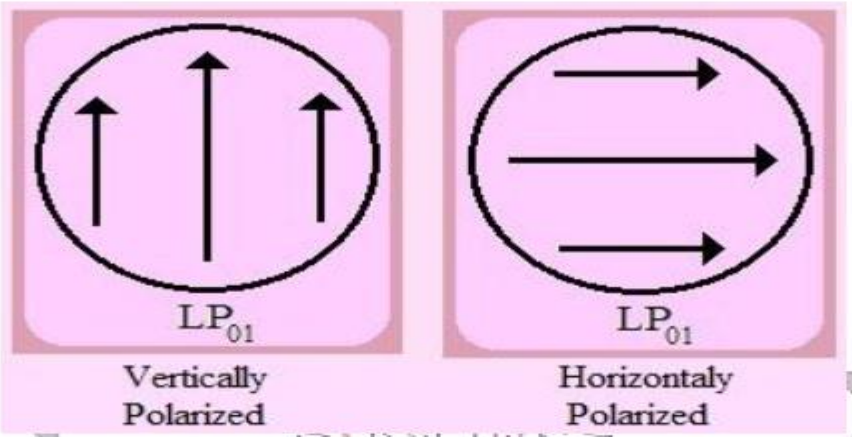


Figure 7.6: Possible field orientations of LP_{01} mode

Thus for LP01 mode there is degeneracy by factor of 2 and for LP11 mode there is degeneracy by a factor of 4.

Similarly if we calculate the degeneracies for each mode, when the number of modes in the fiber is very large, and sum up, then the number of modes that propagate inside the optical fiber is approximately given by:

$$M \approx \frac{V^2}{2} \qquad (7.4)$$

Here, M= number of modes, V= V-number of the optical fiber.

One must carefully note here that this approximation holds only when the V-number of the fiber is much greater than 1.

For example, if we consider a multimode optical fiber having V-number of 10, then there would be approximately 50 (=10^2/2) modes that can propagate inside the optical fiber.

Let us now have a look into the b-V diagram of an optical fiber in terms of the LP modes.

The LP modes are generated by a degeneration of the TE, TM and HE modes and hence the b-V diagram would now look like as shown below:

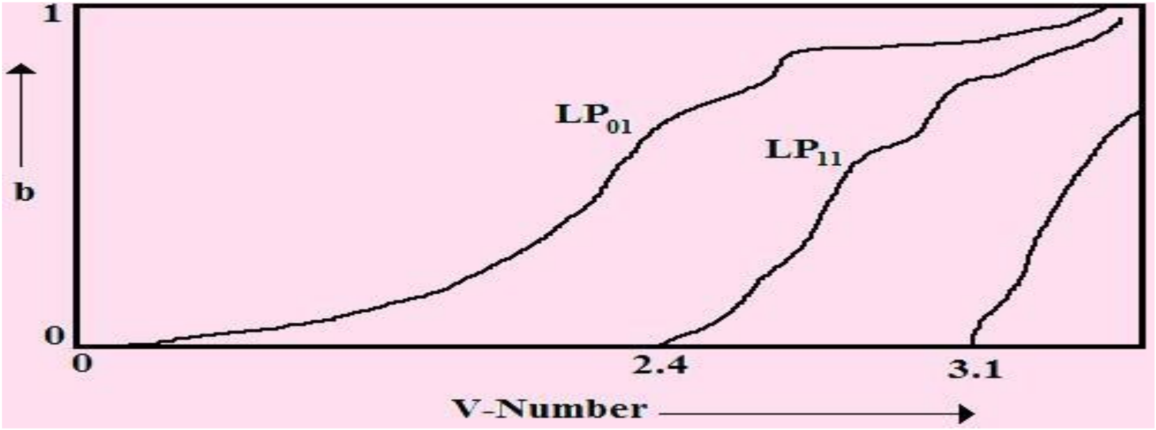


Figure 7.7: b-V curve of optical fiber in terms of LP modes.

For a weakly guiding optical fiber, figure 7.7 is the diagram which gives a relationship between the propagation constant β and the angular frequency ω of the optical fiber.

From the knowledge of this relationship, the phase velocities and the group velocities of the light propagation inside a fiber can be calculated using the formula given below:

$$Phase\ Velocity\ (v_p) = \frac{\omega}{\beta} \qquad (7.5)$$

$$Group\ Velocity\ (v_g) = \frac{\partial \omega}{\partial \beta} \qquad (7.6)$$

Any point on the graph indicates the propagation constant and frequency of the mode corresponding to the point and the inverse of the slope of the graph at that point indicates the group velocity of the mode.

Once the phase and the group velocities of the mode are numerically calculated from the b-V curve, further calculations such as distortion calculations for the mode can be performed for the mode.

Analysis of Signal Distortion in Optical Fiber

The spectral width of an optical source is defined as the range of wavelengths that the source emits around the main central wavelength for which it was designed.

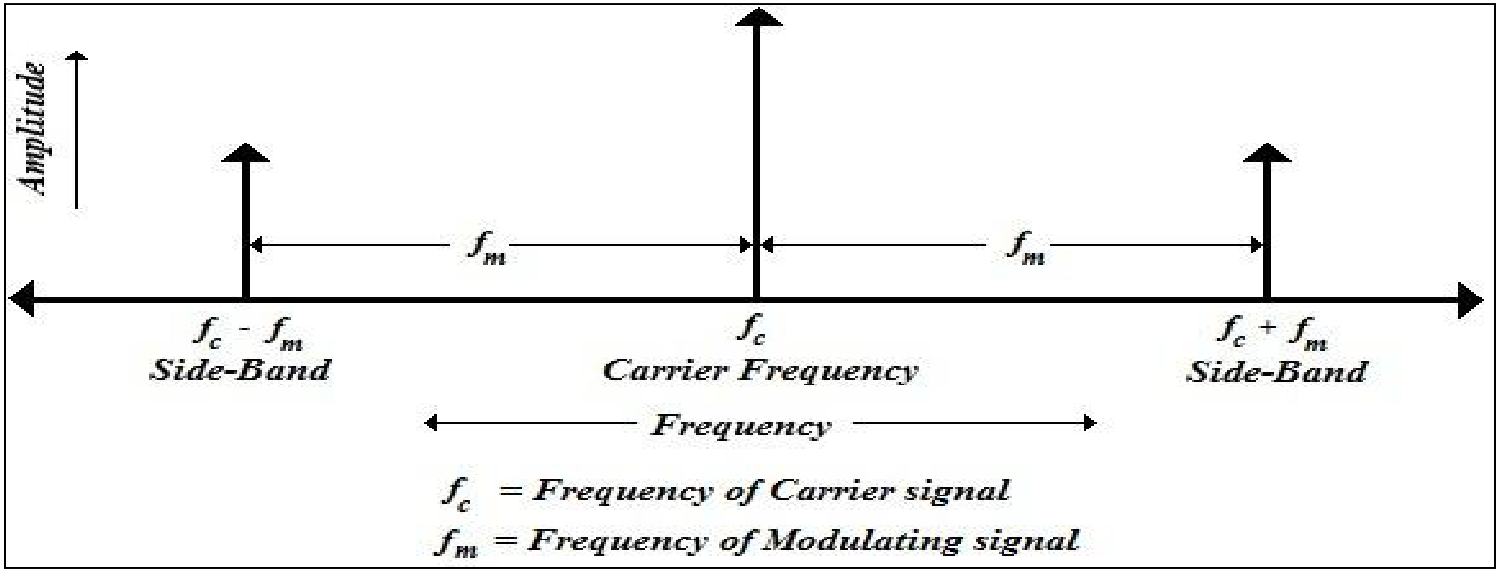
This range of wavelength is denoted by Δλ and can be calculated as given below:

$$\Delta f = \frac{c}{n\,\lambda^2}\Delta\lambda$$

In this relation ‘f’ and ‘λ’ are the frequency and wavelength respectively of the optical source and ‘Δf’ is the frequency domain equivalent of the spectral width of the source.

One of the fundamental differences between information transmission at radio frequencies and that in optical domain is that, at radio frequencies, the spectral width of the carrier signal is so small that it is neglected and the frequency spectrum of the carrier signal is represented by a delta function at the carrier frequency.

That is why when we consider amplitude modulated radio transmission; the spectrum of the modulated signal shows three sharp peak points represented by delta functions as shown in the figure below:



As the carrier frequency increases to the optical domain the spectral width of the carrier signal cannot be neglected.

That is why, in the optical domain, the carrier signal cannot be represented by a delta function as in case of radio carrier signal.

The spectrum of its carrier signal is like a distributed frequency function about the central frequency of the source for which the source was designed.

This situation is shown in the figure 8.2 below which shows the frequency domain equivalent of the carrier signal source output.

The output of a typical optical source like 1μm wavelength LASER, which has a spectral width of the order of 1nm, when fed to a Spectrum Analyser, shows an output as shown below in figure 8.2.

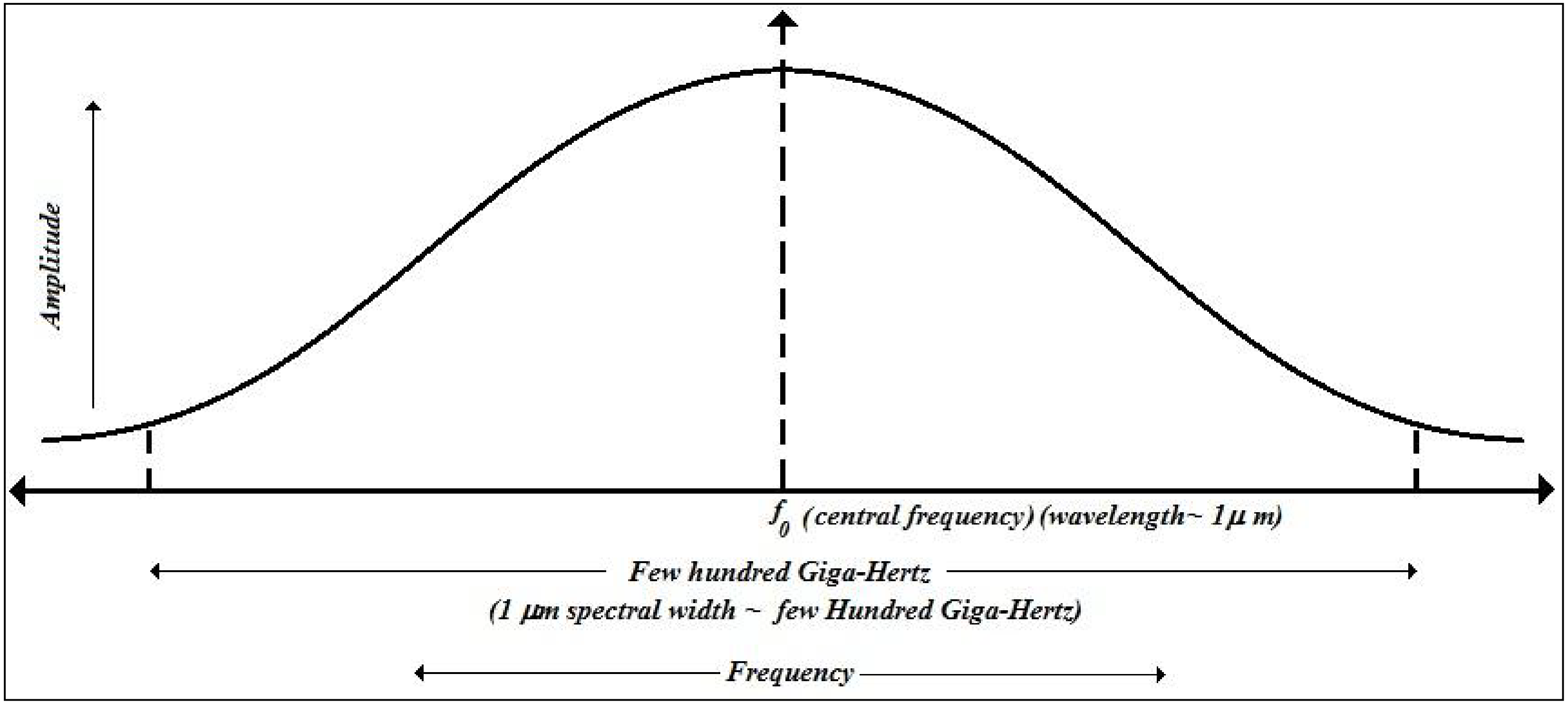


Figure 8.2: Frequency spectrum of the un-modulated optical carrier signal.

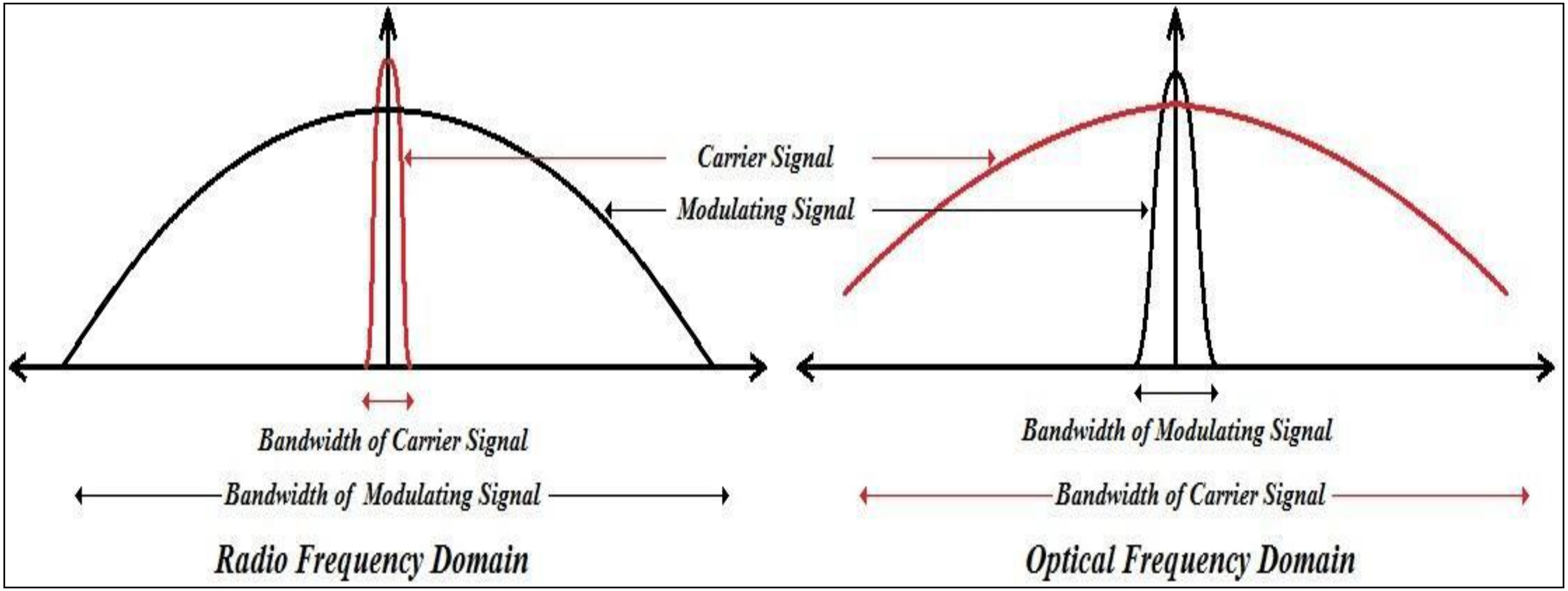


Figure 8.6: Frequency spectrum of carrier and modulating signals

In the analysis of a radio system, since the side bands in the modulated signal are clearly visible, both spectral domain as well as time domain techniques can be employed in the demodulation (detection) of radio frequency signals.

However, the scenario in the optical frequency domain is not so. Due to the wide spectral width of the carrier signal (as seen from the figure8.6) the spectral domain techniques cannot be used in demodulation of optical signals, and so time domain approach has be used to decode optically modulated carriers.

The only time domain modulation/demodulation scheme which does not require any knowledge about the frequency spectrum of the modulated signal, is the amplitude modulation/demodulation (with carrier).

This is because, for such a signal the modulating signal can be recovered from the modulated signal by simple envelope detection technique.

That is why optical communication system uses simple amplitude modulation/demodulation for data communications.

To visualise the distortion caused by the wide spectral width of the carrier signal we may assume the wide-band optical carrier to be actually composed of numerous narrow-band individual carrier signals of small bandwidths which are transmitted simultaneously. This would be clearer from the figure 8.7 below:

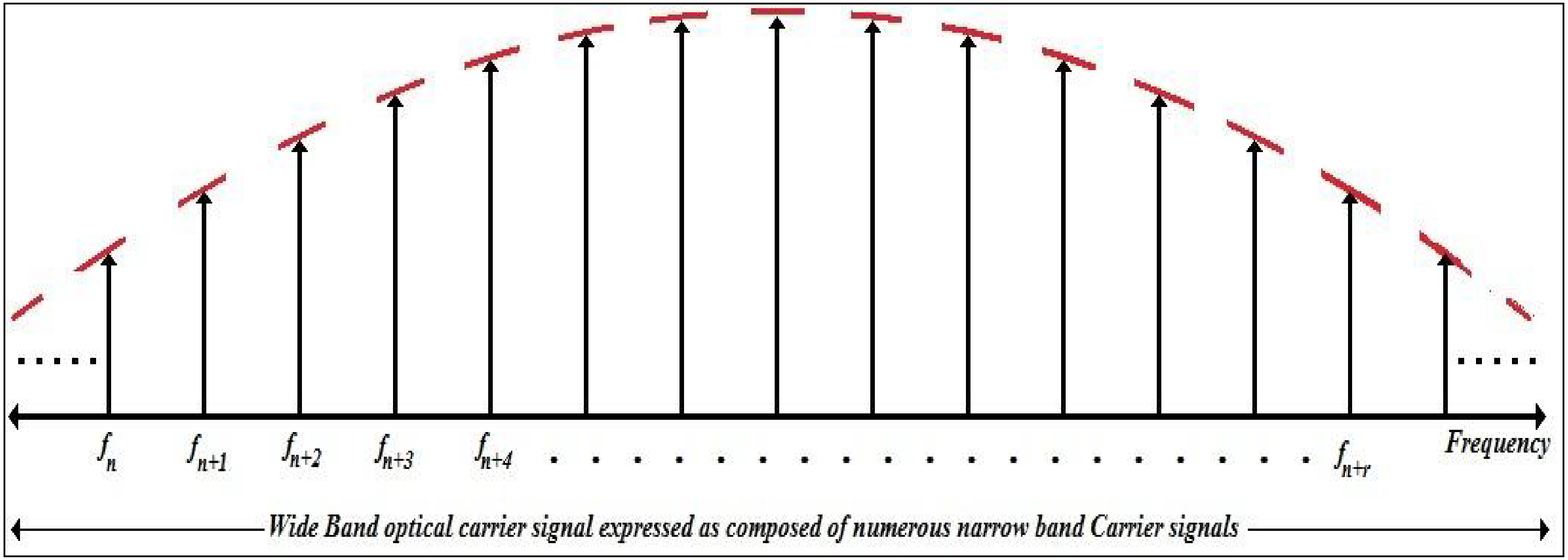


Figure 8.7: Optical Carrier expressed in terms of numerous narrowband carriers.

The task now is to modulate this composite carrier signal according to the modulating signal.

In other words, we have to change the envelope of this wideband carrier signal according to our modulating signal.

Each narrow-band carrier is modulated by the modulating frequency '*fm*' and all these modulated carriers are simultaneously transmitted.

This situation can be visualised as a simultaneous or parallel transmission of numerous individual amplitude modulated signals having different carrier frequencies.

Each of these signals has its individual side bands, but all such different sidebands are completely merged together and no individual side bands are visible.

From the b-V diagram of an optical fiber, we can observe that propagation constant is a non-linear function of frequency. This means that different wavelengths (or frequencies) in an optical fiber travel with different speeds.

Hence, all carrier signals that compose the wide band optical carrier signal, each travel with its corresponding speed and also the information which it carries.

Since the modulating signal is same for all the carriers, same information takes different times to travel a given length of fiber; or more specifically, the same pulse takes different times to reach the output of a given length of optical fiber causing an effective pulse broadening. And this is what is called as the material or the intra-modal dispersion.

Thus, larger the spectral width of the optical carrier signal more is the dispersion or pulse broadening. In other words we can say that pulse broadening is related to the spectral width of the carrier signal.

If the optical carrier signal shown in figure 8.7 is now amplitude modulated by a pulse and observed in the time domain, we would observe a situation that is depicted in figure 8.8.

Just before the modulated optical carrier signal pulse enters the optical fiber core (i.e. at t0) it may be considered to be composed of a number of pulses which effectively are the individually modulated carrier pulses in the wide-band carrier signal, all modulated to the their corresponding indices.

When this carrier signal pulse enters the optical fiber core, the process of pulse broadening due to intra-modal or material dispersion starts and the pulses start separating out from each other as shown in the figure 8.8.

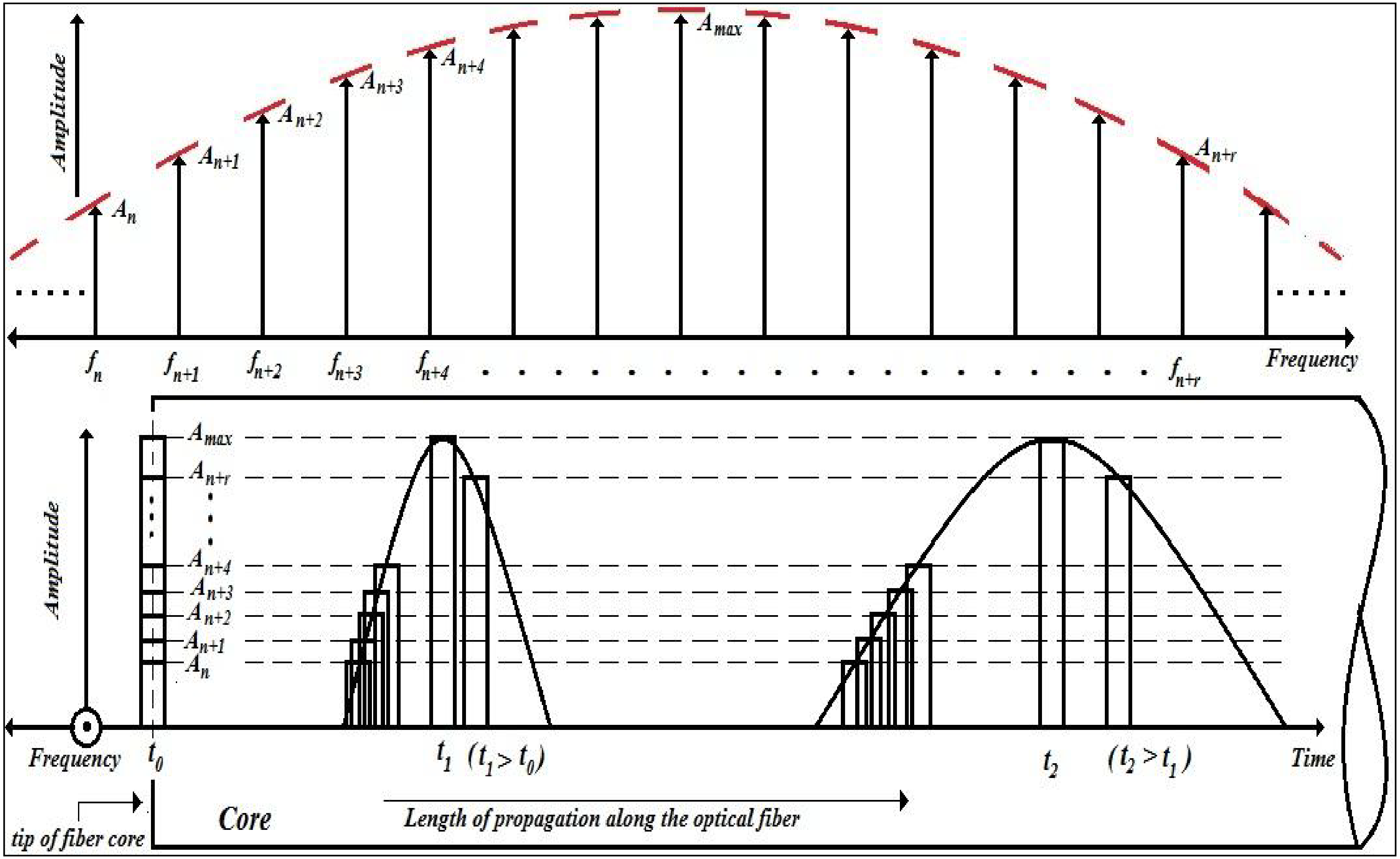


Figure 8.8: Pulse broadening effect

the amplitude of the pulse correspond to the fi^{th} frequency component in the optical carrier signal.

The $fn+r^{th}$ pulse travels faster than the fn^{th} pulse and hence separates out faster as shown in the figure above.

The question now is that what would the effective shape of the pulse inside the fiber core be?

The answer is the shape of the pulse inside the optical fiber core would just be a projection of the shape of the carrier spectrum at t_0 and hence would be dominated by the shape of the frequency spectrum of the carrier signal.

Therefore, the carrier spectrum now decides the effective shape of the modulated pulse.

The bandwidth required in optical communication is decided by carrier frequency whereas in radio-frequency communication, the band-width requirement is determined by modulating signal (which according to Nyquist's theorem was two times of the maximum frequency component in the modulating signal) irrespective of whatever the carrier frequency used.

Thus in an optical communication system the pulse broadening depends mainly on two aspects:

1- the spectral width of the carrier signal.
2- the distance travelled by the pulse inside the optical fiber core.

Also the bandwidth requirement and the shape of the pulse is determined by the spectrum of the carrier signal.

The group velocity of the group of pulses of light (in figure 8.8) inside the optical fiber is defined by:

$$Group\,Velocity, v_g = \frac{\partial \omega}{\partial \beta} = 2\pi c \frac{\partial}{\partial \beta}(1/\lambda) \qquad (8.2)$$

Hence, the group delay per unit length is given as,

$$t_g = \frac{1}{v_g} \qquad (8.3)$$

This equation then helps us to calculate the effective pulse broadening which is the delay between the first and the last pulse. Hence, the pulse broadening can be written as:

$$\tau_g = \frac{dt_g}{d\lambda}\sigma_\lambda = \frac{\sigma_\lambda}{2\pi c}\left\{2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right\} \qquad (8.4)$$

Here 'σ_λ' is the spectral width of the source and 'c' is the velocity of light. We can now formally define the dispersion as the pulse broadening per unit distance per unit spectral width of the source. It is denoted by 'D' and has a unit of (pico-second/kilometre/nanometre). That is

$$D = \frac{dt_g}{d\lambda} = \frac{\tau_g}{\sigma_\lambda} = \frac{1}{2\pi c}\left\{2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right\} \qquad (8.5)$$

Distortion in the optical fiber

When an optical signal is transmitted on an optical fiber, the signal is distorted owing to two phenomena. These phenomena are known as dispersion and attenuation.

The following diagram shows the constituents of each phenomenon that contribute to the distortion of optical signal in the optical fiber.

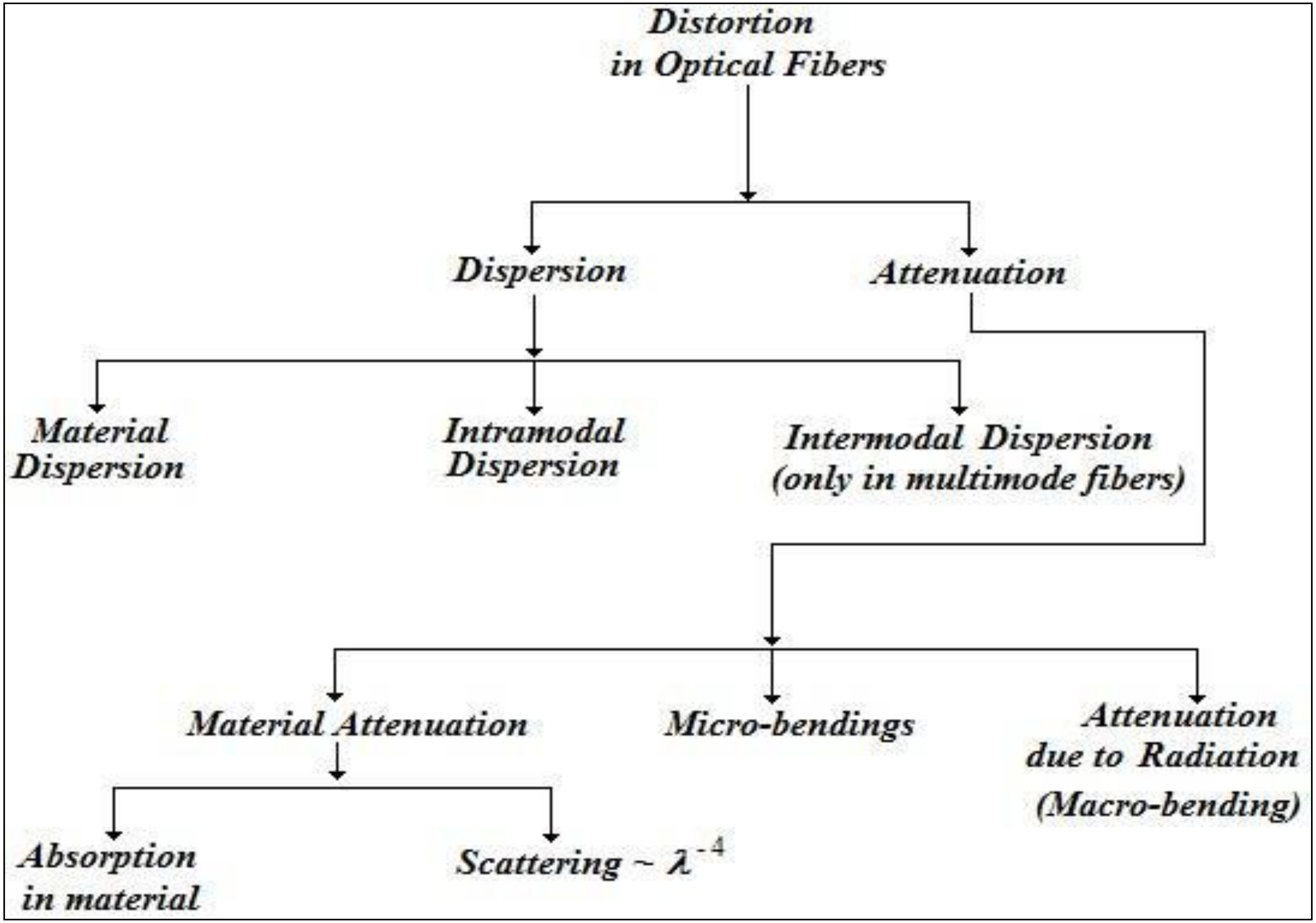


Figure 8.8: Constituents causing Distortion in Optical Fibers

When light is launched into an optical fiber in the form of a light pulse, the pulse energy propagates by different paths which lead to the broadening of the actual time-width of the pulse.

This phenomenon is called as dispersion and has already been discussed.

Dispersion may be due to material properties and imperfections too.

It may also be to pulse broadening within a single mode which is referred to as intra-modal. Intra-modal dispersion occurs in single mode fibers too on account of its finite bandwidth.

The dispersion caused by multipath propagation of light energy is referred to as inter-modal dispersion and has already been discussed. Inter-modal dispersion does not occur in single mode fibers.

Another cause of signal distortion in optical fibers is the attenuation of the optical signal inside the optical fibers.

Attenuation can occur due to material absorption properties too.

During manufacture process of the optical fiber, some imperfections called as micro-centres are created inside the optical fibers which have dimensions of the order of λ^{-4}.

These micro-centres lead to scattering of light inside the optical fibers and as a result the light signal is attenuated.

When optical fiber cables are laid for communication, most often, it is not possible to align them in perfect straight lines and some bends remain here and there.

These micro-bends lead to spurious leakage of light energy causing loss of optical energy. Such leakages can also be witnessed within the laboratory by deliberately bending the optical fiber into which light is launched.

When fibers are laid in the form of large arcs or ‘macro-bends’, another phenomenon referred to as radiation creeps in causing loss of light energy and thus leading to attenuation of the optical signal within the optical fiber.

Let us now try to visualize the dispersion in an optical fiber. Figure 8.9 below shows two light pulses, launched into an optical fiber, which propagate as a function of time.

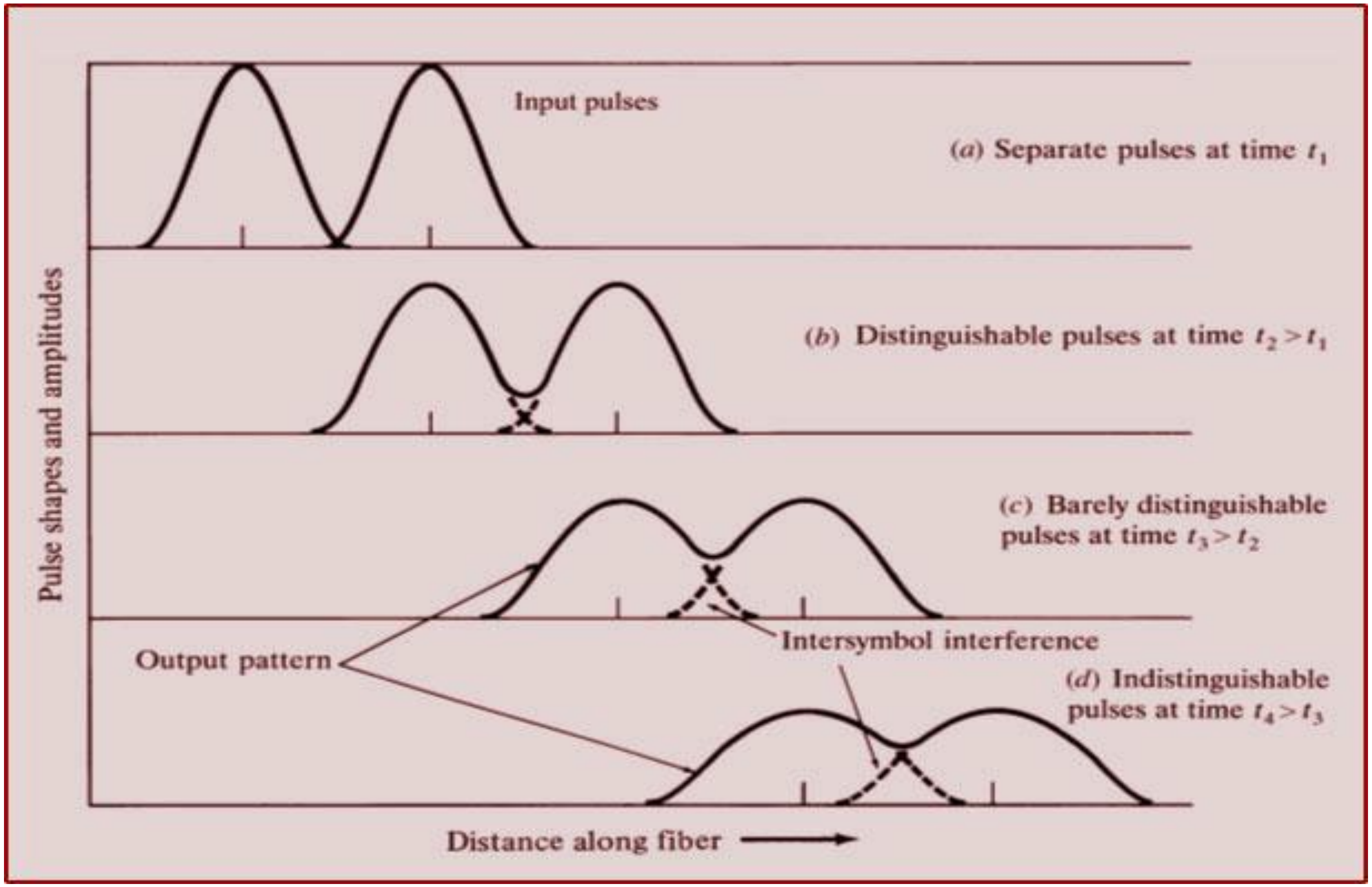


Figure 8.9: Pulse broadening in an optical fiber

As is obvious from the previous figure, as the pulses progress inside the fiber they start to overlap and the effective pulse width broadens.

Since the light energy has to be conserved inside the fiber, the amplitude of the pulse reduces as a result of this broadening.

This overlapping or merging of adjacent pulses is also sometimes referred to as inter-symbol interference (ISI).

Thus distortion occurs in the data transmission due to this pulse broadening inside the optical fiber.

After considerable overlapping, it would be difficult to even predict the presence of two distinct pulses.

Before this happens, we have to regenerate the pulses which are done by optical repeaters.

The pulse broadening effect poses some kind of a restriction on the maximum length of fiber that can be used without repeaters.

If a transmission is made beyond this length, the pulse broadening will not allow any useful output to be detected at the receiver end.

So when light pulses propagate in an optical fiber, two significant effects take place:

1- the pulse broadens
2- the peak amplitude of the pulse reduces as a result of this broadening.

Since at the detecting end we do not integrate the pulse over the pulse width but just sample the output at regular intervals of time, the Signal-to-Noise ratio also gets affected due to the distortion.

Any of the sources of dispersion mentioned in figure 8.8 can be calculated by considering the others to be negligible small and then after calculating similarly for all the other sources, just add them linearly to get the net dispersion in the optical fiber.

Dispersion in Single Mode Optical Fiber.

1-material dispersion

For calculating material dispersion, we assume that the optical fiber is an infinite medium and there is no wave guiding of light in the material of the optical fiber and the refractive index of the material is a function of the wavelength as we have already seen from the b-V diagram.

phase constant of the light would be that of a transverse electromagnetic wave, which is given by

$$\beta = \frac{2\pi}{\lambda} n(\lambda)$$

Here n(λ) is function which depicts the refractive index variation with respect to wavelength.

To find an expression for dispersion, we have to first calculate the group delay. Group delay can be calculated by differentiating equation (8.6) with respect to angular frequency 'ω'.

$$t_g = \frac{d\beta}{d\omega} \tag{8.7}$$

Now, by differentiating equation (8.7) with respect to the wavelength we would get the resultant expression for the material dispersion as:

$$D_{material} = \frac{dt_g}{d\lambda} = -\frac{\lambda}{c}\frac{d^2 n(\lambda)}{d\lambda^2} \tag{8.8}$$

From equation (8.8) , we see that the material dispersion is directly proportional to the wavelength as well as to the second derivative of the refractive index function.

If we plot an experimentally calculated graph of the refractive index as a function of wavelength for the material glass, we would get a plot as shown in figure 8.9.

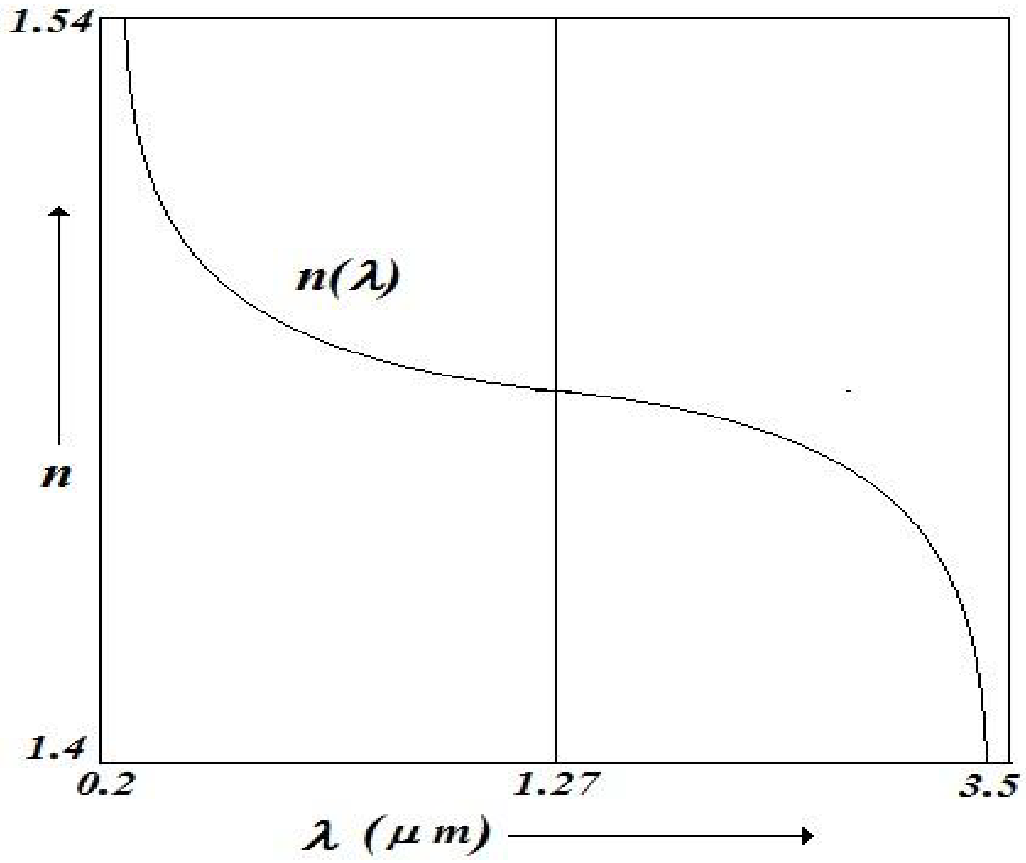


Figure 8.9: Variation of Refractive index with wavelength

The graph shows that the refractive index of glass decreases as the wavelength of light increases, but this decrease is non-linear and has a change of curvature at an wavelength of about 1.27μm (1270 nm).

The wavelength 1270nm has a special importance, not only that the curvature of graph changes at this wavelength but also the second derivative of the curve at this wavelength is zero.

This means that if we use light of 1270 nm in the optical fiber we would get either very low or even no material dispersion and hence would have the highest possible data rate for communication.

The material dispersions corresponding to different windows of optical communication is tabulated in the next slide:

Wavelength (λ) (nm)	$D_{material}$ (ps/Km/nm)
850	85
1310	0.1
1550	-20

As we can see from the table, initial optical communications were very dispersive with dispersions ranging as high as 85 ps/Km/nm.

In the second window the dispersion value is very low and so the 1310 nm window has some special importance.

The third window of operation has a dispersion of -20ps/Km/nm. The significance of the negative sign would be illuminated later.

So it is preferable to perform optical communications in the 1270nm wavelength or to keep the operating wavelength as close to it as possible in order to have minimum distortion and high data rates.

In the above table we see that, for wavelength of about 1550nm, the material dispersion value goes negative.

negative sign means longer wavelengths (or lower frequencies) travel with higher velocities as compared to the shorter wavelengths (or higher frequencies).

On the contrary, positive sign, thus, indicates that shorter wavelengths (or higher frequencies) travel faster than the longer wavelengths (lower frequencies).

From this discussion, the sign of the material dispersion does not matter because both the signs indicate pulse broadening.

That is why, we generally use the absolute value of the material dispersion in our calculations.

2- waveguide dispersion

The b-V diagram of optical fiber suggests that the variation of propagation constant with frequency is not linear and so we can expect that there would be some kind of dispersion created due to this wave-guiding nature of the optical fiber.

$$Normalized\ propagation\ Constant,\ b = \frac{\beta^2 - \beta_2{}^2}{\beta_1{}^2 - \beta_2{}^2} \qquad (9.3)$$

$$D_{wg} = -\frac{n_2\Delta}{c}\frac{V}{\lambda}\frac{d^2}{dV^2}(bV)$$

the b-V diagram of an optical fiber has no analytical expression from which the second derivative (which is required in equation 9.14) can be calculated. So the above equation has to be solved numerically

To find out the operating wavelength range for minimum dispersion, which again has to be approached and solved numerically from the b-V diagram. If we do so, we observe the following facts:

At 800nm, $D_{material} >> D_{wg}$

At 1300nm $D_{material} << D_{wg}$

D_{wg} peaks around a V-number of 1.2

So if we want to operate at a minimum dispersion range, either this range has to be much higher than V-number 1.2 or it has to be much lower than V-number 1.2.

if we operate at a range much lower than 1.2, it causes considerable reduction in V-number which in turn leads to unacceptably low launching efficiencies.

In addition, there is a limitation that the V-number of operation cannot exceed 2.4. Otherwise the optical fiber would no longer remain a single mode optical fiber.

Hence to reduce waveguide dispersion, we must operate at V-number as close as possible to 2.4 but neither greater nor equal to it.

the dispersion here is not so reduced that it can be acknowledged, but is almost 20% of the peak which would occur at V=1.2.

The total dispersion in the single mode optical fiber is thus the sum of the material dispersion and the waveguide dispersion. We call the total dispersion as the **chromatic dispersion** of the optical fiber.

Chromatic Dispersion= Material Dispersion+ Waveguide Dispersion.

Material dispersion is a property of the glass as a material and will always exist irrespective of the structure of the optical fiber.

So, the material dispersion in an optical fiber cannot be varied.

The only quantity that is a structure dependent quantity is the waveguide dispersion.

Waveguide dispersion depends upon the radius, numerical aperture etc.

Hence by altering these parameters, we can manipulate the waveguide dispersion which in turn manipulates the chromatic dispersion.

If we now plot a curve indicating the total dispersion in a single mode optical fiber, we would find a curve as shown in the figure 9.1.

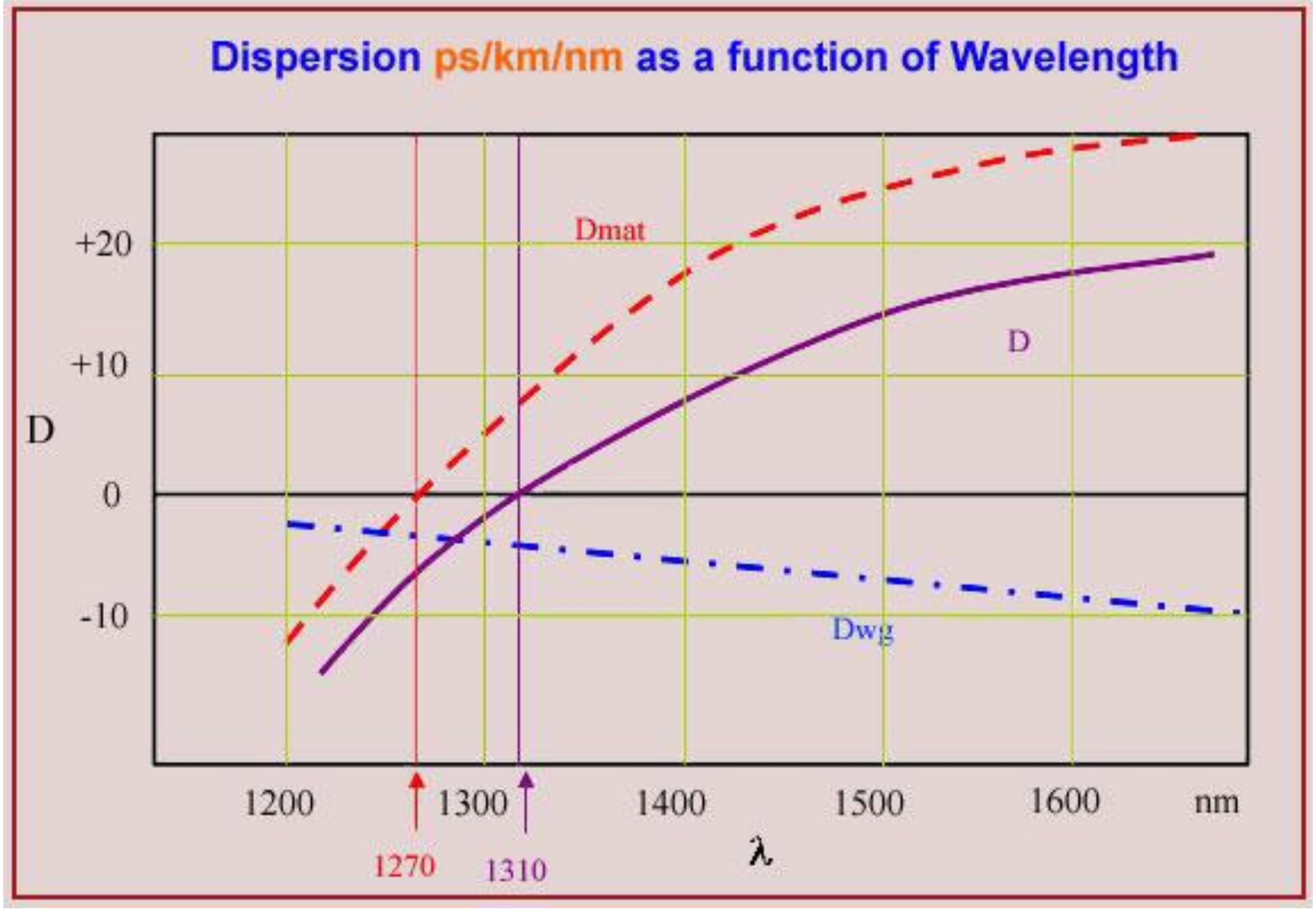


Figure 9.1: Total Dispersion in a single mode optical fiber.

that material dispersion of glass goes to zero at a wavelength of about 1270nm.

This situation is now can be clearly seen from the cure of the material dispersion in the figure 9.1.

If we observe the total dispersion curve shown in the previous figure, we see that it crosses zero at a wavelength of about 1310nm.

Thus if a single mode optical fiber is operated at a wavelength of about 1310nm, the total dispersion in this fiber would be almost zero at this wavelength of operation.

The word ‘almost’ is used because when the fiber is operated at around 1310nm wavelength, the incident light does not contain only a single wavelength of 1310nm but consists of a small band of wavelengths centred around 1310nm.

These wavelengths would have their own corresponding dispersions and hence the total dispersion will not be zero although it might be very small.

In other words, at an operating wavelength of around 1310nm, the single mode optical fiber would support very large bandwidth or very high data rates.

If this operating wavelength is shifted to 1550nm, the dispersion in the fiber is very large and consequently the bandwidths and the data rates are low at 1550nm operation.

Primarily this was the reason for the 1310nm optical window to be the most immediately accepted window of operation in optical communication.

Attenuation in optical fiber

There are many sources of attenuations that may occur inside an optical fiber. Material absorption, scattering, micro and macro bending losses, etc.

Material absorption is a intrinsic property of a material to absorb light of one or more wavelengths and hence this property of glass may cause some amount of attenuation in the signal as it propagates along the optical fiber.

The more significant loss is the scattering loss which causes greater loss of optical power from the optical signal.

During the manufacturing process of the optical fiber, there remain tiny regions inside the optical fiber which have refractive index different than the medium in which they lie.

These types of tiny regions are called micro-centres and are responsible for the scattering of light.

The dimensions of these micro-centres are much smaller compared to the wavelength of the light and they scatter the light as shown in the figure 9.2

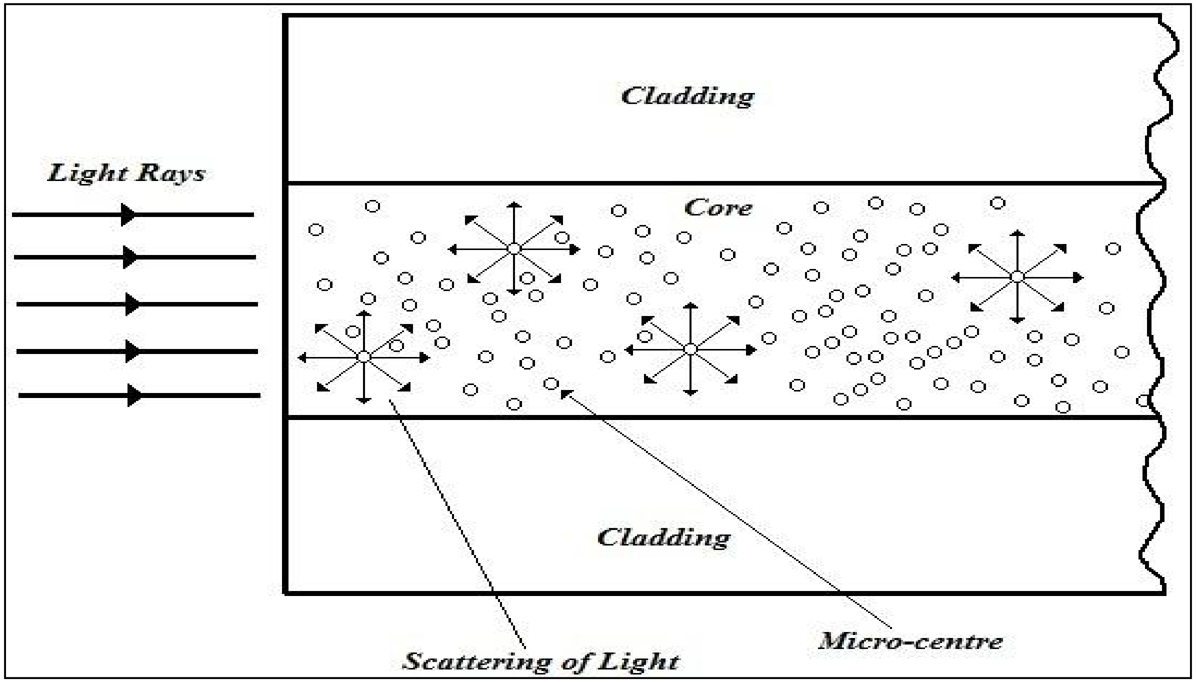


Figure 9.2: Rayleigh Scattering in Optical Fiber

This causes the light to get scattered almost in the same way as the scattering of atmospheric microwave signals by rain-drops.

This type of scattering is called as Rayleigh scattering.

Due to Rayleigh scattering, a very small amount of light is lost and as a result the light signal is attenuated.

This loss of light is called as the scattering loss.

Rayleigh scattering is a very strong function of the wavelength as it varies indirectly to λ4, where λ is the wavelength of light.

This means that, if we double the wavelength of operation, the Rayleigh scattering loss would reduce by a factor of 16 (i.e. 24).

Close observation would reveal that this might be the reason behind the low loss characteristic of the optical fiber at 1550nm as compared to 800nm (as seen in figure 2.1) because the ration between the two wavelengths is almost double.

If we plot the Rayleigh scattering loss as function of wavelength, we would obtain a curve as shown in figure 9.3.

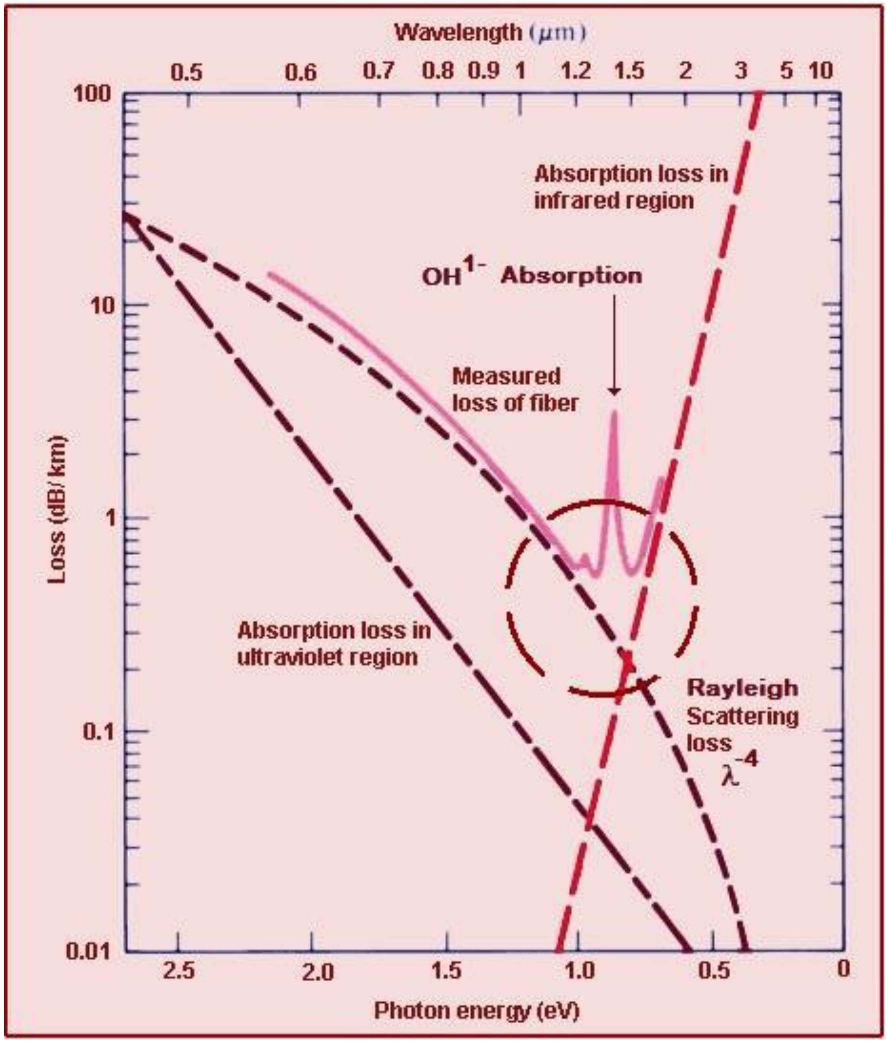


Figure 9.3: Rayleigh Scattering Loss in optical fiber

The previous figure clearly shows the trend in which the scattering loss decreases as the wavelength of operation increases.

However for glass, there is another type of loss which is termed as the infrared-loss which occurs due to the intrinsically bad conductivity of glass to infrared wavelengths.

This loss is a rapidly increasing function of wavelength.

So any infrared wavelength gets rapidly attenuated inside glass.

This loss of glass is also shown in the above figure.

So as we move our wavelength of operation more towards the infrared region, the loss profile of glass gets dominated by the infrared loss of glass.

This transfer from a Rayleigh scattering loss to a infrared loss in the loss profile of glass creates a valley like region in the overall loss profile of glass.

This region is indicated by the region inside the circle in the previous figure

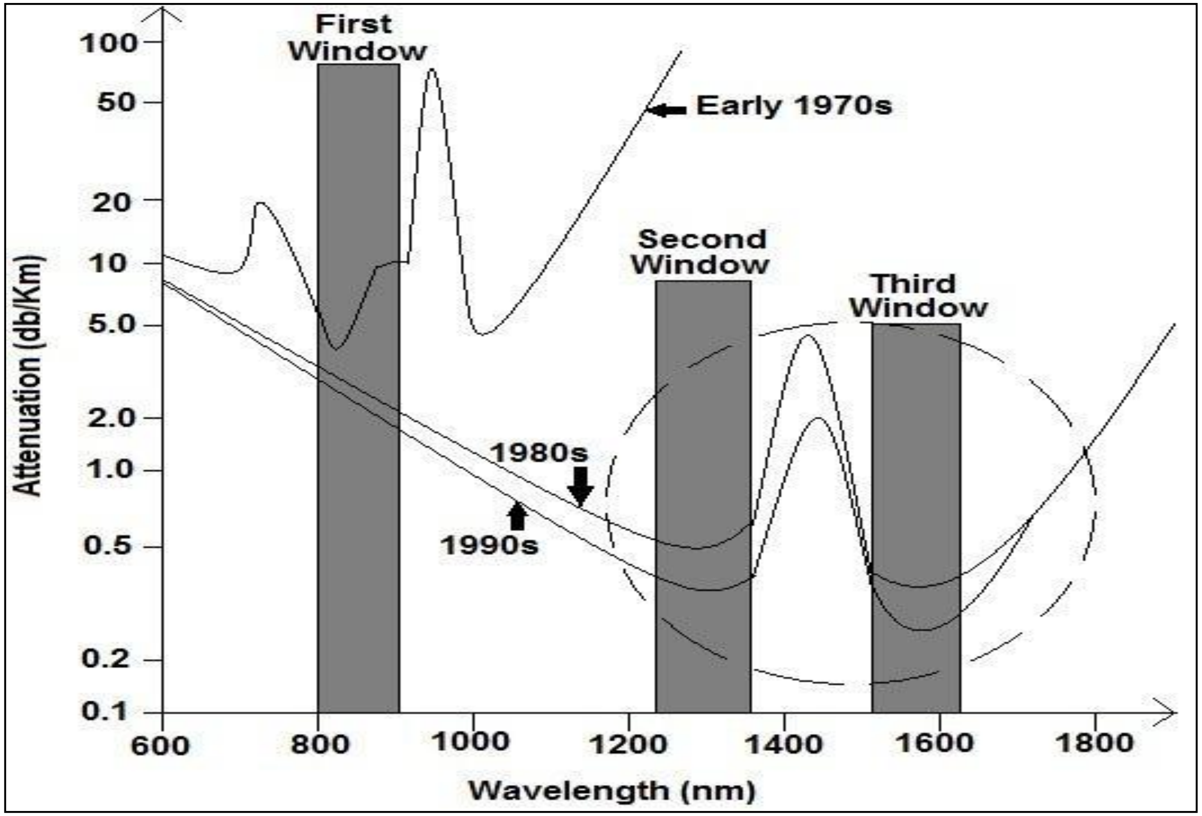
During the process of purification glass, some water molecules remain inside glass even after glass has been carefully purified.

However purification and manufacturing technologies have been considerably improved and modified to reduce these absorption peaks to a considerably low level.

the loss profile of glass causing two different windows of optical communication.

This is the peak that appeared in the loss profile of glass between 1300nm and 1500nm.

If we magnify the region inside the circle, we would fine the following curve which we had already studied as figure 2.1.



The material absorption and the scattering losses are due to intrinsic properties of glass and hence would always remain in the optical fiber even in the ideal condition when the fiber is not laid into the system.

There are two other sources which are not due to intrinsic nature of glass. These losses are due to deformations produced in the optical fiber while laying the fiber for application.

This deformation may be microscopic or even macroscopic.

Microscopic deformations are referred to as micro-bending and the loss is called as micro-bending loss.

The other type of loss is called as macro-bending loss.

Micro bending loss in a fiber can be caused even by a slight application of pressure onto the fiber by the hand while holding the fiber.

Micro-bending causes the critical angle condition to be invalid for the propagating rays and hence these rays refract out of the fiber as shown in the figure.

This causes loss of light energy and leads to attenuation of the light signal.

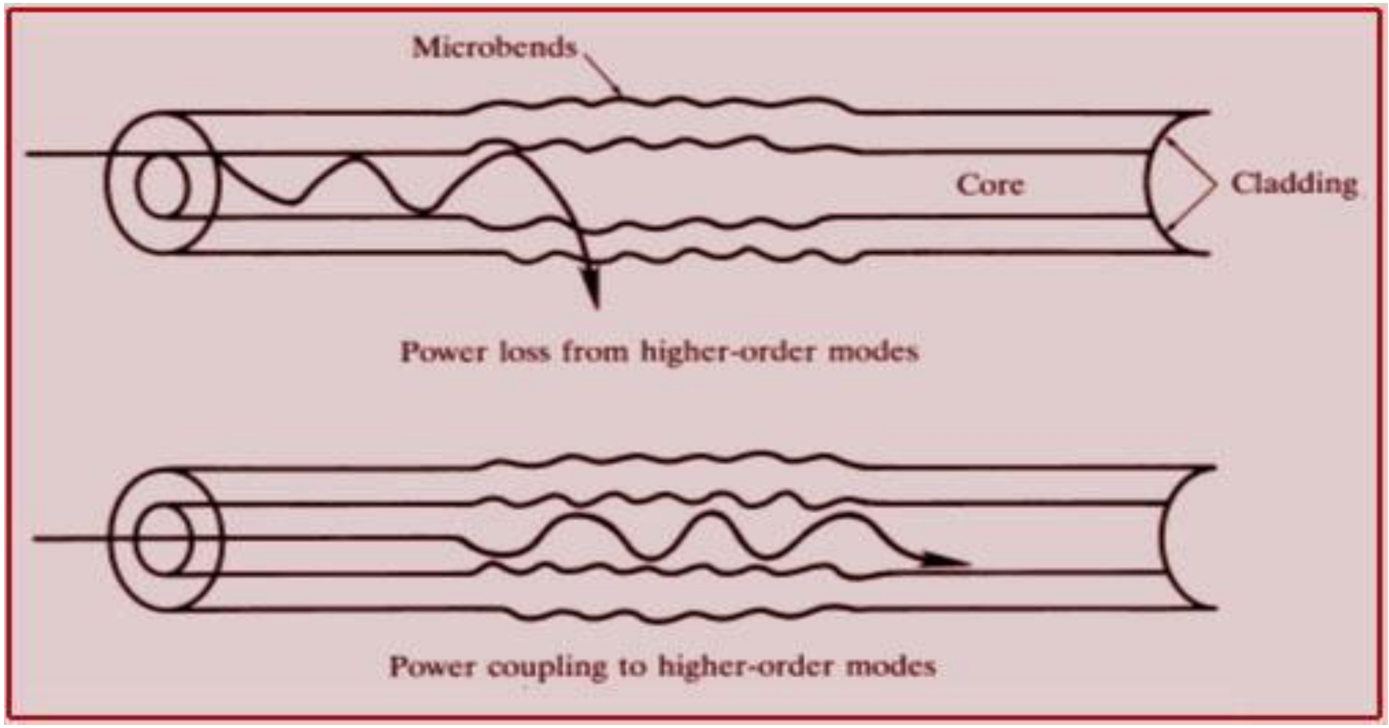


Figure 9.5: Micro Bending in Optical Fibers

When an optical fiber is subjected to a gentle bend over a large arch, light energy in the fiber starts to leak out of the optical fiber.

This phenomenon is known as the macro-bending loss or the radiation loss in an optical fiber.

In practice, fibers get deformed when laid into the system due to variety of reasons.

In a straight fiber, the wave-fronts of the light energy propagating inside the fiber are parallel to each other and normal to the direction of propagation as shown in the figure below.

when the optical fiber is gently bent over a large arch, the wave-fronts are no more parallel to each other and as a result, different points on a particular wave-front require different velocities.

These velocities go on increasing as we move outwards along a particular wave-front (say from A to B).

Therefore, some light energy is radiated out of the fiber causing loss of total light energy. This effect increases if the bend is sharper

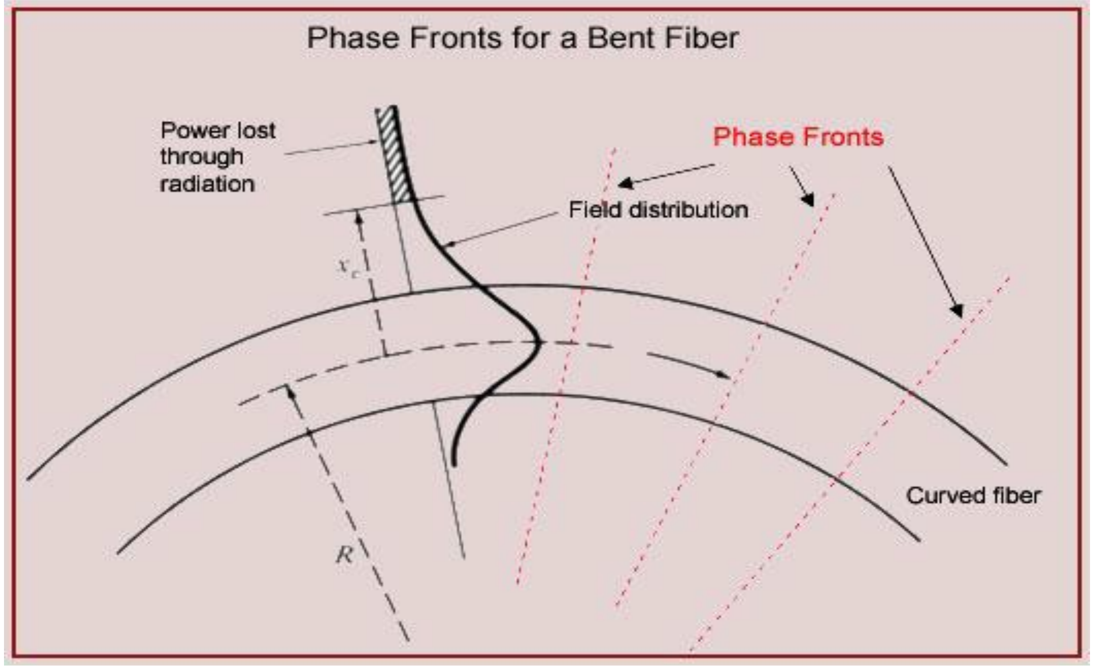


Figure 10.3: Radiated power on a bent optical fiber.

That is why, while laying optical fibers, one should be careful of not allowing any sharp bends or loops to be developed in the laid fibers in order to avoid radiation loss.

Presence of light inside the fiber can be ascertained by gently bending the optical fiber which would cause a leakage of light from the optical fiber due to radiation loss thereby confirming the presence of light in the optical fiber.

This causes a reduction in the signal security.

However, in practical optical fibers, this danger is averted by providing opaque sheaths over bare optical fibers which do not allow any radiated light to be tapped.

This causes great difficulty in information tapping and hence provides great signal security.

At operating wavelengths of about 1310nm the dispersion is almost zero whereas the loss figure is high, but at operating wavelengths of about 1550nm the dispersion is higher whereas the loss is lower.

Hence we now have two operating options available with us to choose from.

Either we choose to operate at high data rates with higher loss at 1310nm or we choose to operate at lower data rates at lower loss at 1550nm.

However, the characteristic of a good communication system requires a system that has both low loss as well as a large bandwidth.

In our case we find that we can only have either large bandwidth with higher loss or smaller bandwidth with lower loss.

The development in technology have made it possible to manipulate the total dispersion in an optical fiber in such a way that we no longer are in problem.

So, by altering the different fiber parameters such as the refractive index profile, fiber radius, etc. we can actually manipulate the dispersion profile of the optical fiber.

This flexibility induces an interrogation in the mind as to whether the zero dispersion point at 1310nm could be shifted to 1550nm.

The reason behind this shifting is the low loss characteristics of the optical fiber at 1550nm coupled with the availability of a large bandwidth.

The fiber manufacture technology now helps us in precise design of optical fibers as per requirements and using such sophisticated technology the zero dispersion point has been shifted to almost 1550nm.

These new type of optical fibers are hence called dispersion-shifted (DS) optical fibers.

The dispersion profile of these fibers is shown in the figure 10.4.

The figure shows the initial 1310nm optimized optical fiber and also the dispersion shifted optical fiber dispersion profile.

This is done by favorably manipulating the refractive index profile and size of the fiber so as to change the waveguide dispersion profile so that the total dispersion profile, which actually is the sum of the material and the waveguide dispersion shifts altogether.

This is the kind of optical fiber that is used in the modern optical communication system because this fiber gives both the advantages of a large bandwidth as well as low loss.

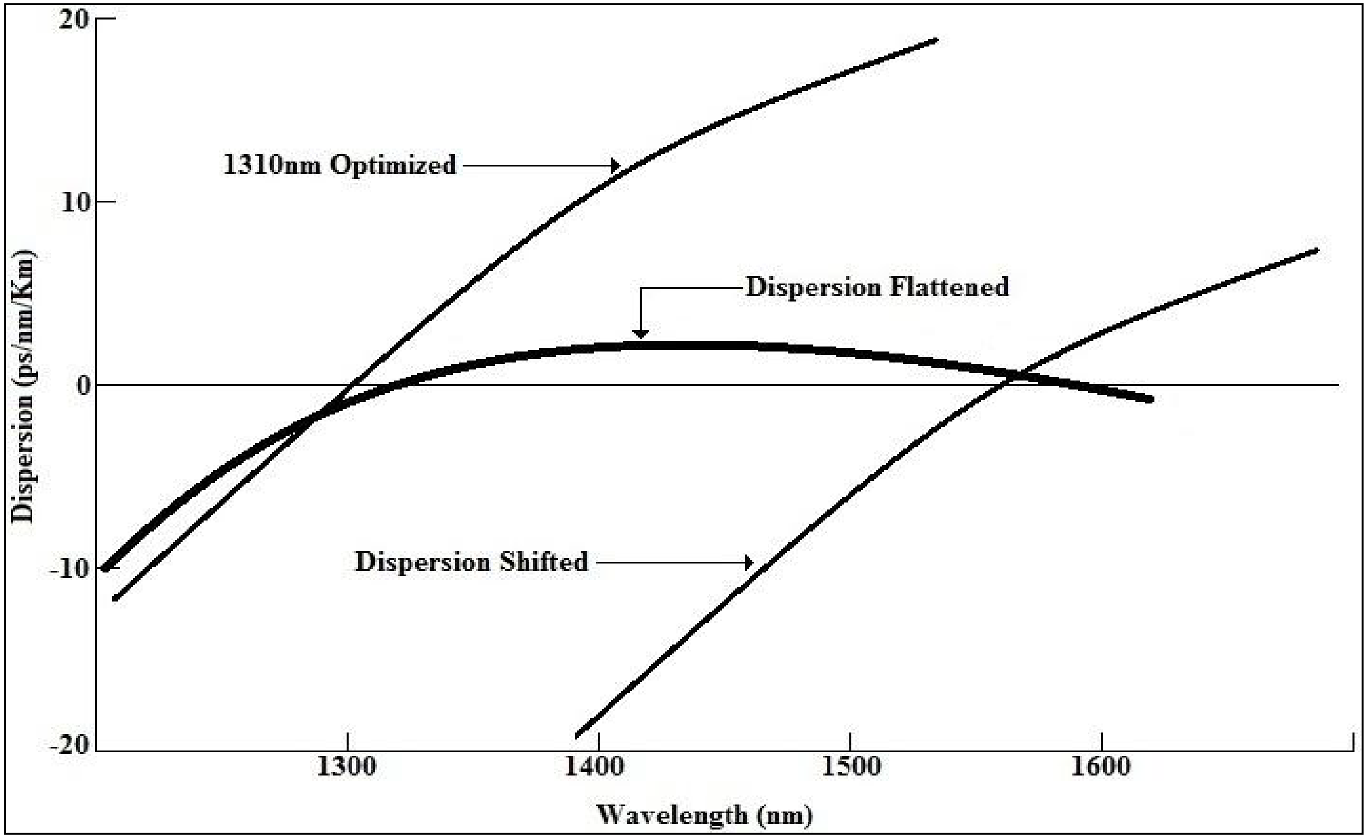


Figure 10.4: Dispersion Profile of a Single Mode Dispersion Shifted Fibers