OPTICAL COMMUNICATIONS

UNIT I: Overview of Optical Fiber Communication

Historical Development: In 1880 Alexander Graham Bell and his assistant Charles Sumner Tainter created a very early precursor to fiber optic communications, the photophone at Bell's Volta Laboratory in Washington. Bell considered it his most important invension. The device allowed for the transmission of sound on a beam of light. On June, 3, 1880, Bell conducted the world's first wireless telephone transmission between two buildings some 213 meters apart. Due to its use of an atmospheric transmission medium, the photophone would not prove practical until advances in laser and optical fiber technologies permitted the secure transport of light. The photophone's first practical use came in military communication systems many decades later.

In 1954 Harold Hopkins and Narinder Singh Kapany showed that rolled fiber glass allowed light to be transmitted. Initially it was considered that the light can ~~traverse~~ traverse in only straight medium.

In 1963 Jun-ichi Nishizawa, a Japanese scientist at Tochoku University, proposed the use of optical fibers for communications. Nishizawa invented the PIN diode and the static induction transistor, both of which contributed to the development of optical fiber communications.

In 1966 Charles K. Kao and George Hockham at STC Laboratories showed that the losses of 1000 dB/km in existing glass (compared to 5-10 dB/km in coaxial cable) were due to contaminants which could potentially be removed.

Optical fiber was successfully developed in 1970 by Corning Glassworks, with attenuation low enough for communication purposes (about 20 dB/Km) and at the same time GaAs Semiconductor lasers were developed that were compact and therefore suitable for transmitting light through fiber optic cables for long distances.

In 1973, optelecom, Inc, co-founded by the inventor of the laser, Gordon Gould, received a contract from APA for the first optical communication systems. Developed for Army Missile command in Huntsville, Alabama, it was a laser on the ground and spout of optical fiber played out by missile transmit a modulated signal over five kilometers.

First Generation: (Graded-index fibers)

Year implemented : 1980
Bit rate : 45 Mb/s
Repeater spacing : 10 Km
Operating wavelength : 0.8 μm
Semiconductor : GaAs

Second Generation (Single-mode fibers)

Year implemented : 1985
Bit rate : 100 Mb/s to 1.7 Gb/s
Repeater spacing : 50 km
operating wavelength : 1.3 μm
semiconductor : InGaAsP

Third Generation (single-mode lasers)

Year implemented : 1990
Bit rate : 10 Gb/s
Repeater spacing : 100 Km
operating wavelength : 1.55 μm

Fourth Generation (optical amplifiers)

Year implemented : 1996

Bit rate : 10 Tb/s

Repeater spacing : > 10,000 Km

operating wavelength : 1.45μm to 1.62μm

Fifth Generation (Raman amplification)

Year implemented : 2002

Bit rate : 40 Gb/s to 160 Gb/s

Repeater spacing : 24,000 km to 35,000 km

Operating wavelength : 1.53μm to 1.57μm

Need of Fiber optic Communication

Fiber optic communication system has emerged as most important communication system. Compared to traditional system because of following requirements

1. Transmission loss : In long haul transmission system, there is need of low loss transmission medium.
2. Compact system : There is need of compact and least weight transmitters and receivers
3. Long span : There is need of increased span of transmission
4. Data rate : There is need of increased bit rate for data transmission.

General Optical Fiber communication System

An optical fiber communication is similar in basic concept to any type of communication system. A block schematic of general communication system is shown in fig 1. The communication system consists of a transmitter or modulator linked to the information source, the transmission medium and a receiver or demodulator at the destination point. In electrical communications the information source provides an electrical signal desired from the message signal, which is not electrical (eg sound), to a transmitter comprising electrical and electronic components converts the signal in to a suitable form for propagation over the transmission medium.

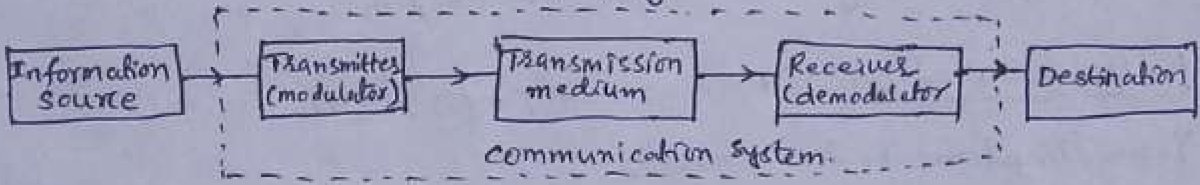

fig 1. General communication system

The transmission medium consists of a pair of wires, a coaxial cable or a radio link through free space down which the signal is transmitted to the receiver, where it is transformed in to the original electrical information signal (demodulated) before being passed to the destination. In any transmission medium the signal is attenuated or suffers loss and is subject to degradation due to contamination by random signals and noise, as well as possible distortions imposed by mechanisms with in the medium itself. Therefore, in any communication system there is a maximum permitted distance between the transmitter and receiver. There is a need of installation of repeaters or line amplifiers at intervals, both to remove signal distortion and to increase signal level before transmission is continued down the link.

The optical fiber communication system is shown in fig 2.

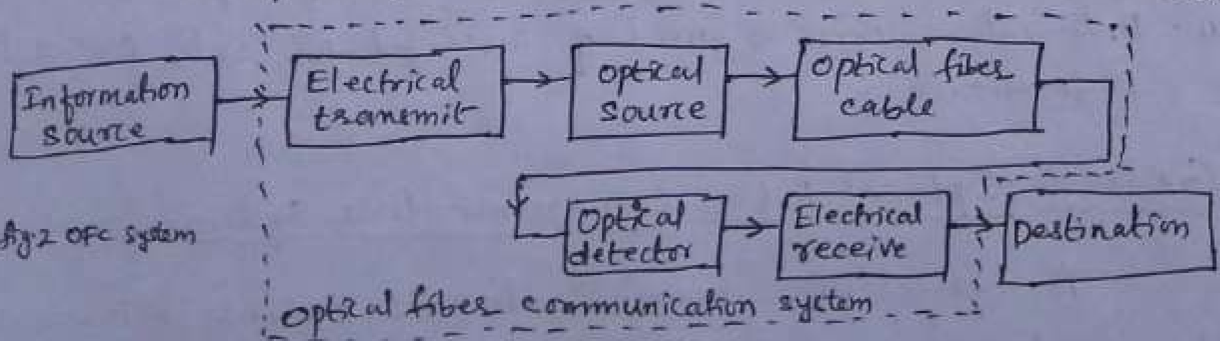

fig 2 OFC system

The information source provides an electrical signal to a transmitter, which drives an optical source to give modulation of the lightwave carrier. The optical source provides the electrical-optical conversion may be either a semiconductor or light emitting diode (LED).

The transmission medium consists of an optical fiber cable and the receiver consists of an optical detector which drives a further electrical stage and hence provides demodulation of optical carrier. photodiodes, photo transistors and photoconductors are utilized for the detection of the optical signal and the optical electrical conversion. The optical carrier may be modulated using either an analog or digital signal.

The block schematic of a typical digital optical fiber link shown in fig 3.

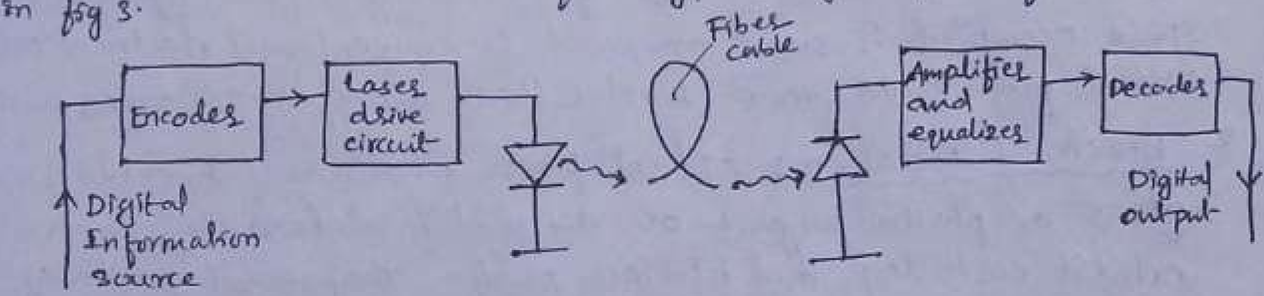

fig.3 A digital optical fiber link using a semiconductor laser source and an avalanche photodiode (APD) detector.

The input digital signal from the information source is suitably encoded for optical transmission. The laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal. Hence a digital optical signal is lanched in to the optical fiber cable. The avalanche photodiode (APD) detector is followed by a front-end amplifier and equalizer or filter to provide gain as well as linear signal processing and noise bandwidth reduction. Finally, the signal obtained is decoded to give the original digital information.

Difference in analog and digital modulation of the optical carrier: Analog modulation involves the variation of the light emitted from the optical source in a continuous manner. With digital modulation, discrete changes in the light intensity are obtained. Analog modulation with an optical fiber communication system is less efficient, requiring a far higher signal to noise ratio at the receiver than digital modulation. Analog optical fiber communication links are generally limited to shorter distances and lower bandwidths than digital link.

Advantages of optical fiber communications

1. Enormous potential bandwidth: Information carrying capacity of transmission system is directly proportional to carrier frequency of transmitted signals. The optical carrier frequency in the range of 10^{13} to 10^{16} Hz which yields a for greater potential transmission bandwidth than metallic cable systems.

2. Small size and weight: Size of fiber ranges from 10μm to 50μm space occupied is small compared to conventional electrical cables. optical fibers are much lighter than corresponding copper cables.

3. Electrical Isolation: optical fibers which are fabricated from glass or plastic polymer are electrical insulators. they do not exhibit earth loop and interface problems. They do not pick any electromagnetic wave or high current lightening. Also suitable in explosive environments.

4. Immunity to interference & cross talk: optical fibers form a dielectric waveguide and therefore free from electromagnetic interference (EMI), radiofrequency interference (RFI), or switching transients giving electromagnetic pulses (EMP). Hence the operation of OFC system is unaffected by transmission through an electrically noisy environment. And cross talk is negligible, even when many fibers are cabled together.

5. signal security: The light from optical fibers does not radiate significantly and therefore they provide a high degree of signal security.

6. Low transmission Loss: Fiber optic cables very less signal attenuation over long distances. Typically it is less than 1 dB/km. Due to usage of ultra low loss fibers it is loss less transmission.

7. Ruggedness and flexibility: Fiber cable can be easily bent or twisted without damaging it. The fiber cables are superior in terms of handling, installation, storage, transportation, maintenance, strength and durability.

8. System reliability and ease of maintenance: Low loss property of optical fibes cables which seduces the sequirement for intes-modiate sepeaters or line amplifiess to boost the transmitted signal strength.

9. Potential low cost: cost of fibes optic system is less compased to any others system.

Disadvantages of optical fibes communication:

1. Lack of Bandwidth Demand: It is economical only when the entise bandwidth is fully utilized.
2. Difficulty in splicing: The ~~siz~~ small size of fibes cable and cables cseates difficulties with splicing and forming connectors.
3. complex testing procedure: Due to small size of fibers, testing procedure tends to be more complex.
4. High investment cost: The initial cost of installation is very high compared to all others systems.

Applications of optical fibes communications:

Applications of optical fibes communications include tele-communications, data communications, video control and protection switching, sensors and powes applications.

1. public network applications: provides vasiety of applications for OFC system like trunk network, junction network, submesged plans
2. Military applications: used in military mobiles such as aiscraft, ships and tanks
3. civil applications: These transmission techniques utilized on sailways and along pipe, electric powes lines.
4. consumes applications: major application is within automative electronic
5. Industsial applications:

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6. optical sensor systems: It can be employed for monitoring and telemetry in industrial environments.

7. Local area networks: OFC technology is finding applications with LANs to meet the on-site requirements of large commercial organizations.

Optical fiber waveguides

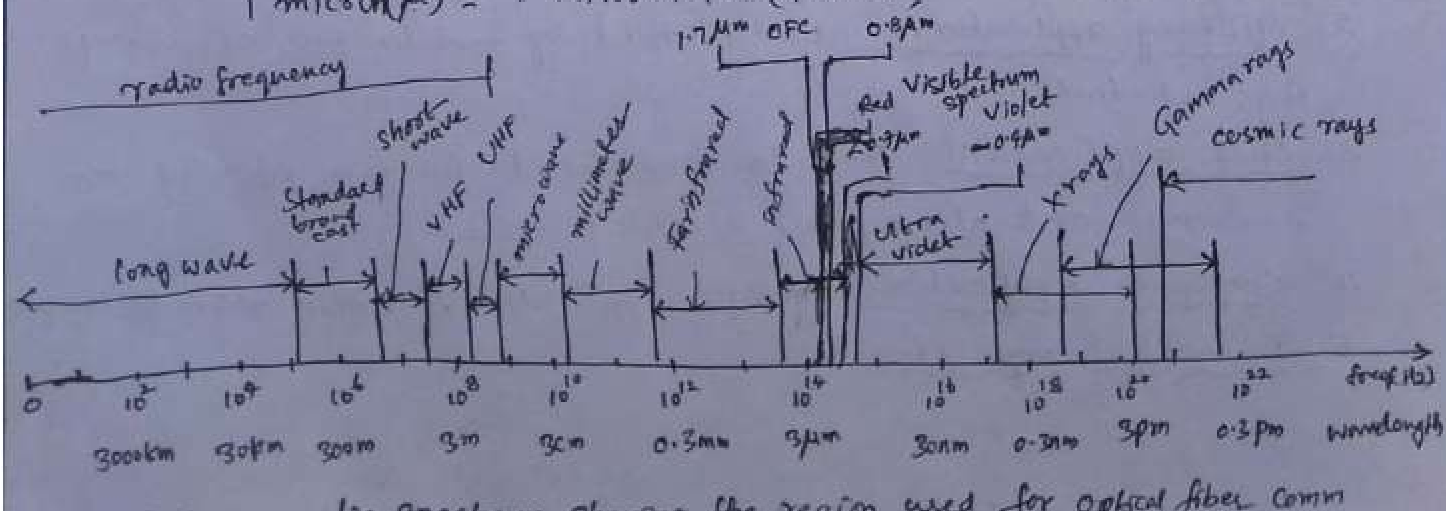
In free space light travels at its maximum possible speed i.e 3×10^8 m/s or 186×10^3 miles/sec. When light travels through a material it exhibits certain behaviour explained by laws of reflection and refraction.

Electromagnetic spectrum: The radio waves and light are electromagnetic waves. The rate at which they alternate in polarity is called their frequency(f) measured in (Hz). The speed of electromagnetic wave (c) in free space is approximately 3×10^8 m/s. The distance travelled during each cycle is called as wavelength(λ).

$$\text{Wavelength } (\lambda) = \frac{\text{Speed of light}}{\text{Frequency}} = \frac{c}{f}$$

In fiber optics, it is more convenient to use the wavelength of light instead of the frequency with light frequencies, wavelength is often stated in microns or nanometers.

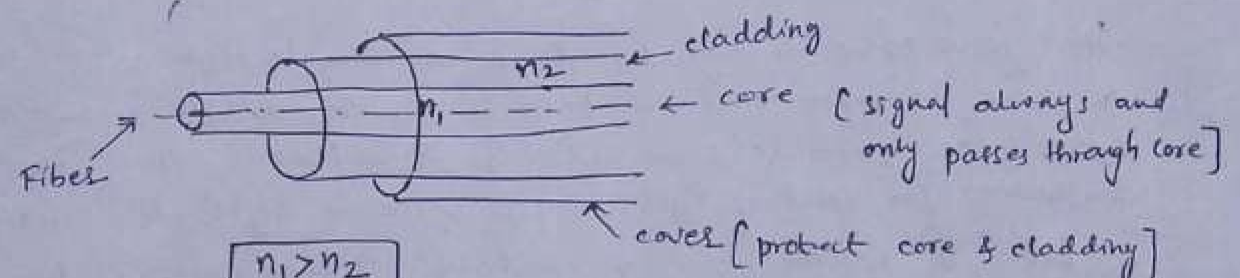
1 micron(μ) = 1 micrometer (1×10^{-6}) 1 nano(n) = 10^{-9} meter



the electromagnetic spectrum showing the region used for optical fiber comm

Fiber optics uses visible and infrared light. Infrared light covers a fairly wide range of wavelengths and is generally used for all fiber optic communications. Visible light is normally used for very short range transmission using a plastic fiber.

Structure of optical fiber :



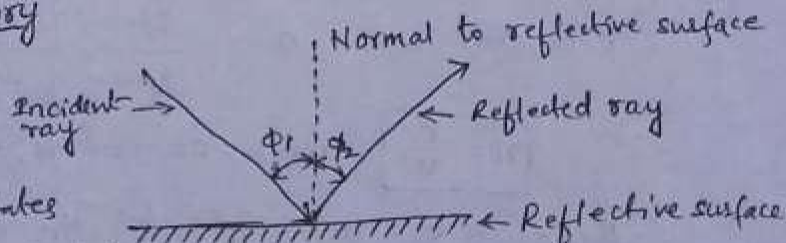
$\boxed{n_1 > n_2}$

The most commonly used optical fiber is single solid di-electric cylinder of radius a and index of refraction n_1. The cylinder is known as the core of the fiber. A solid die electric material surrounds the core, which is called as cladding. Cladding has a refractive index n_2 which is less than n_1.

cladding helps in - ① Reducing scattering losses ② Adds mechanical strength to the fiber ③ Protects the core from absorbing unwanted surface contaminants.

Ray Transmission Theory

Reflection :

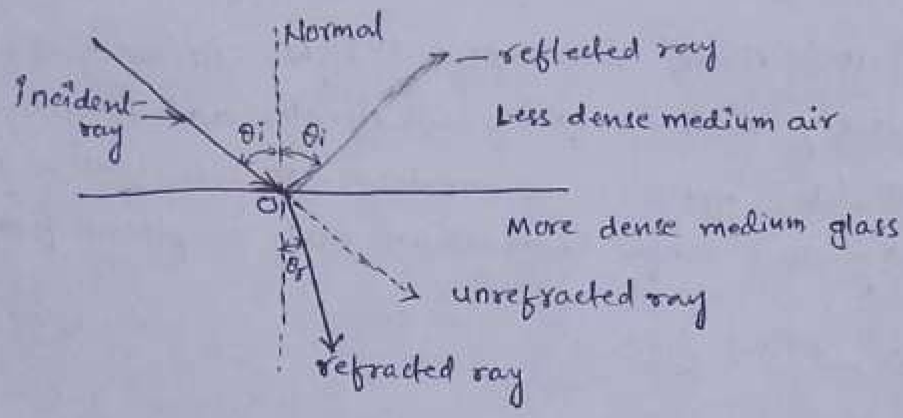


The law of reflection states that, when a light ray is incident upon a reflective surface at some incident angle ϕ_1 from imaginary perpendicular normal, the ray will be reflected from the surface at some angle ϕ_2 from normal which is equal to the angle of incidence.

$\boxed{\text{Law of reflection } \angle\phi_1 = \angle\phi_2}$

Refraction : When light ray passes from one medium to another medium i.e the light ray changes its direction at interface. Refraction occurs whenever density of medium changes.

The refraction can also be observed at air and glass interface



When wave passes through less dense medium to higher dense medium, the wave is refracted (bent) towards the normal. The refraction (bending) takes place because light travels at different speed in different mediums. The speed of light in free space is higher than in water or glass.

Let 'O' be the point of incidence. Dotted line indicates Normal line to the interface.

θ_i = Angle of incidence = Angle of reflection [∵ law of reflection]

θ_r = Angle of refraction.

Refractive Index (n): The amount of refraction or bending that occurs at the interface of two materials of different densities is usually expressed as refractive index of two materials. Refractive index is also known as index of refraction.

It is defined as the ratio of the velocity of light in free space to the velocity of light of the dielectric material (any optically transparent material)

$$\text{Refractive index } n = \frac{\text{speed of light in air}}{\text{speed of light in medium}}$$

$\boxed{n = \frac{c}{v}}$ where $c = 3 \times 10^8$ m/s, v = velocity of light in any medium

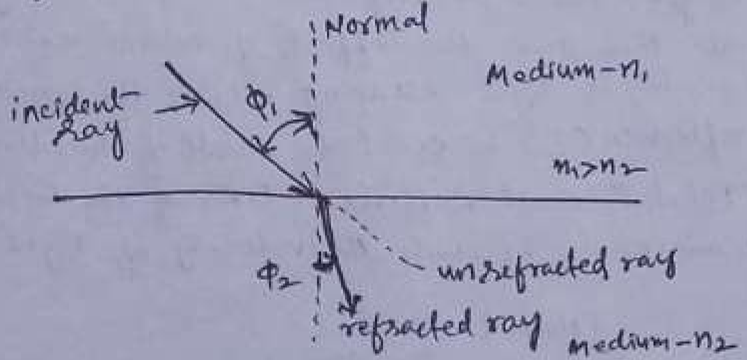
Refractive index indicates the amount of bending (refraction) at the interface of two different mediums / materials

Material Name	Refractive Index n
Air	1
Glass	1.5
Diamond	2
Silicon [Si]	3.5
GaAs	3.7
AlGaAs	3.9

Snell's law: Snell's law states that how light ray reacts when it meets the interface of two media having different indexes of refraction. Let the two medias have refractive indexes n_1 and n_2 where $n_1 > n_2$. ϕ_1 be the angle of incident and ϕ_2 be angle of refraction. Then according to snell's law, a relationship exists between the refractive index of both materials given by.

$$\boxed{n_1 \sin\phi_1 = n_2 \sin\phi_2}$$

The refractive index model for snell's law is shown in fig.



The refracted wave will be towards the normal when $n_1 < n_2$ and will away from it when $n_1 > n_2$

$$\boxed{\frac{n_1}{n_2} = \frac{\sin\phi_2}{\sin\phi_1}}$$

The ratio of refractive index of two mediums is inversely proportional to the refractive and incident angles.

As refractive index $n_1 = \frac{c}{v_1}$ and $n_2 = \frac{c}{v_2}$

$$\frac{c/v_1}{c/v_2} = \frac{\sin\phi_2}{\sin\phi_1} \Rightarrow \boxed{\frac{v_2}{v_1} = \frac{\sin\phi_2}{\sin\phi_1}}$$

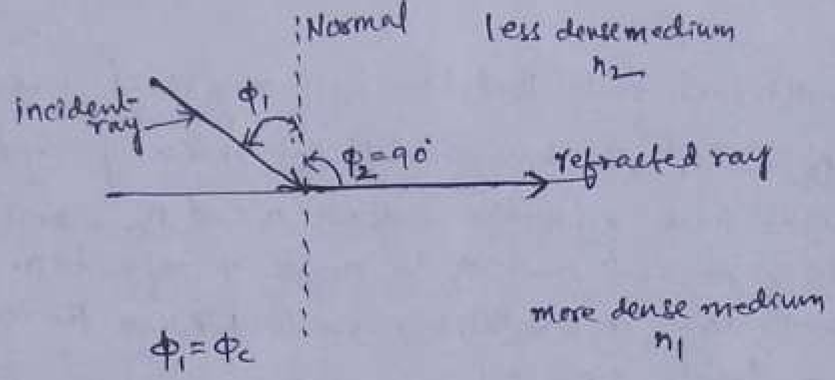
Critical angle (ϕ_c): When the angle of incidence (ϕ_1) is progressively increased, there will be progressive increase of refractive angle (ϕ_2). At some condition (ϕ_1) the refractive angle (ϕ_2) becomes 90° to the normal. When this happens the refracted light ray travels along the interface. The angle of incidence (ϕ_1) at the point at which the refractive angle (ϕ_2) becomes 90° is called the critical angle and denoted by ϕ_c.

Hence at critical angle $\phi_1 = \phi_c$ and $\phi_2 = 90^\circ$

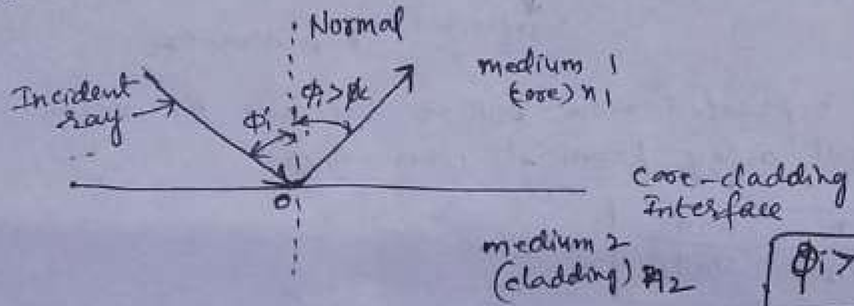
using Snell's law $n_1 \sin\phi_1 = n_2 \sin\phi_2$

$\sin\phi_c = \frac{n_2}{n_1} \sin 90^\circ \quad \because \sin 90^\circ = 1 \quad \therefore \sin\phi_c = \frac{n_2}{n_1}$

critical angle $\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$



<u>Total Internal Reflection (TIR)</u>: When the incident angle is increased beyond the critical angle, the light ray does not pass through the interface in to the other medium. This gives the effect of mirror exist at the interface with no possibility of light escaping outside the medium. In this condition angle of reflection (ϕ_2) is equal to angle of incidence (ϕ_i). This action is called as Total Internal Reflection (TIR) of the beam. TIR can be observed only in materials in which the velocity of light is less than in air.



$\boxed{\phi_i > \phi_c}$

(P) A light ray is incident from medium-1 to medium-2. If the refractive indices of medium-1 and medium-2 are 1.5 and 1.36 respectively, then determine the angle of refraction for an angle of incidence of 30°

sol: Medium-1 $n_1 = 1.5$ Medium-2 $n_2 = 1.36$

Angle of incidence $\phi_1 = 30°$

Snell's law $n_1 \sin\phi_1 = n_2 \sin\phi_2$

$1.5 \sin 30° = 1.36 \sin\phi_2 \Rightarrow \sin\phi_2 = \frac{1.5}{1.36} \sin 30°$

$\sin\phi_2 = 0.55147 \Rightarrow \phi_2 = 33.46°$ from normal.

(P) A light ray is incident from glass to air. Calculate the critical angle (ϕ_c).

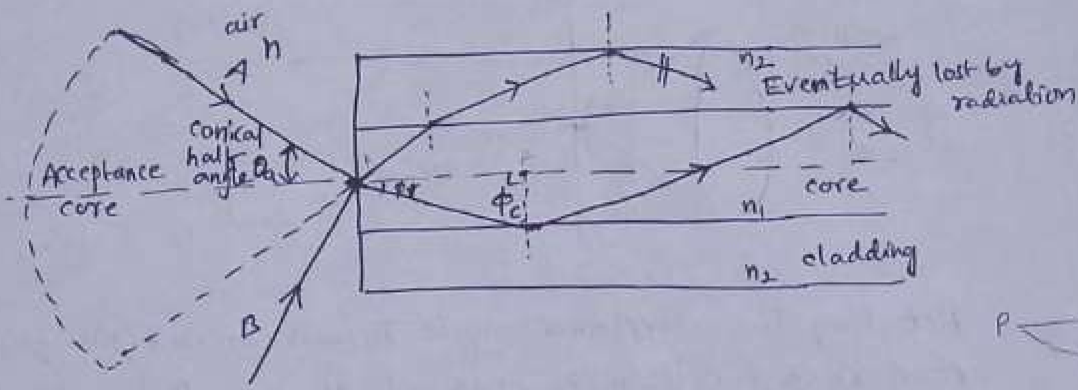
Sol: Refractive index of glass $n_1 = 1.5$, Refractive index of air $n_2 = 1.0$

$\sin\phi_1 = \frac{n_2}{n_1} \sin\phi_2 \Rightarrow \sin\phi_c = \frac{n_2}{n_1} \sin 90°$

$\sin(\phi_c) = \left(\frac{1.0}{1.5}\right) \times 1 = 0.67 \Rightarrow \phi_c = \sin^{-1} 0.67$

$\phi_c = 41.81°$

Acceptance Angle (θ_a)



It is the angle at which light ray must enter the optical fiber to undergo total internal reflection (TIR). Fig illustrates meridional ray 'A' at the critical angle ϕ_c which enters the fiber core at an angle θ_a to the fiber axis & is refracted at the air-core interface before transmission to core-cladding interface at critical angle. The incident ray B at an angle greater than θ_a is refracted in to cladding & lost by radiation. Hence 'θ_a' is the maximum angle to the axis at which light may enter the fiber in order to be propagated and is often referred to as the acceptance angle for the fiber.

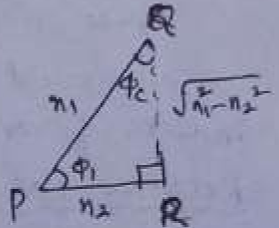
Applying snell's law to external incident angle

$$n \sin\theta_a = n_1 \sin\phi_1 \qquad \text{But } \phi_1 = 90^\circ - \phi_c$$

$$n \sin\theta_a = n_1 \cos\phi_c \qquad \sin\phi_1 = \sin(90^\circ - \phi_c) = \cos\phi_c$$

$$\sin\theta_a = \frac{n_1}{n}\cos\phi_c$$

Applying phythagorean theorem to Δ PQR



$$\cos\phi_c = \frac{\sqrt{n_1^2-n_2^2}}{n_1}$$

$$\sin\theta_a = \frac{n_1}{n}\left[\frac{\sqrt{n_1^2-n_2^2}}{n_1}\right]$$

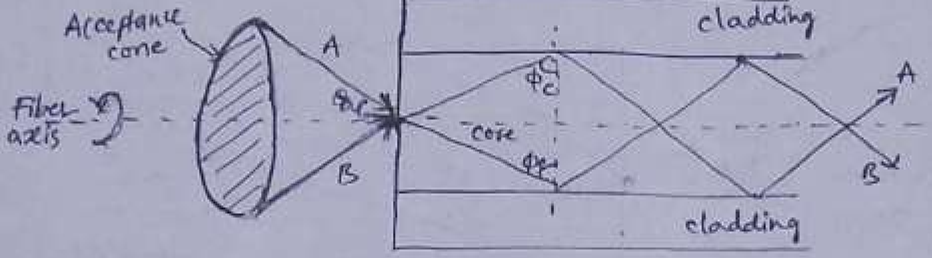
$$\sin\theta_a = \frac{\sqrt{n_1^2-n_2^2}}{n}$$

$$\theta_a = \sin^{-1}\left[\frac{\sqrt{n_1^2-n_2^2}}{n}\right]$$

The maximum value of external incidence angle for which light will propagate in the fiber. When the light ray enters the fibers from an air medium $n=1$. The above equation reduces to $\theta_{a(max)} = \sin^{-1}\left(\sqrt{n_1^2-n_2^2}\right)$

The angle θ_a is called as acceptance angle and $\theta_{a(max)}$ defines the maximum angle in which the light ray may incident on fiber to propagate down the fiber.

Acceptance cone:



Rotating the acceptance angle $\theta_{a(max)}$ around the fiber axis, a cone shaped pattern is obtained, It is called as acceptance cone of the fiber input. The cone of acceptance is the angle within which the light is accepted into the core and is able to travel along the fiber. The launching of light wave becomes easier for large acceptance cone. Total cone angle $= 2\theta_a$.

Numerical Aperture (NA):

The Numerical Aperture (NA) of a fiber is a figure of merit which represents the light gathering capacity. Larger the numerical Aperture, the greater the amount of light accepted by fiber. The acceptance angle also determines how much light is able to be enter the fiber and hence there is relation between the numerical aperture and the cone of acceptance.

Numerical aperture (NA) $= \sin\theta_{a(max)}$

$NA = \frac{\sqrt{n_1^2-n_2^2}}{n} \Rightarrow NA = \sqrt{n_1^2-n_2^2}$ for air $n=1$

$\therefore NA = \sqrt{n_{core}^2 - n_{cladding}^2}$

Hence acceptance angle $= \sin^{-1} NA$

Numerical aperture is effectively dependent only an refractive indices of core and cladding material.

Relative Refractive Index Difference (Δ): Relative refractive index difference between core and cladding refractive indices (n_1 & n_2) is given by

$\boxed{\Delta = \frac{n_1^2-n_2^2}{2n_1^2}}$ $n_1 =$ R-I of core

$n_2 =$ R-I of cladding

Relation between NA and Relative Refractive index difference (Δ):

we know that $NA = \sqrt{n_1^2-n_2^2} \Rightarrow NA^2 = n_1^2-n_2^2$

$\therefore$ Relative refractive index difference Δ is $\therefore \Delta = \frac{NA^2}{2n_1^2}$

$NA^2 = 2n_1^2\Delta \Rightarrow \boxed{NA = n_1\sqrt{2\Delta}}$

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(P) Calculate the numerical aperture and acceptance angle for a fiber angle of which $n_{core} = 1.5$ and $n_{cladding} = 1.48$. The launching takes place from air.

Sol. $NA = \sqrt{n_{core}^2 - n_{cladding}^2} = \sqrt{1.5^2 - 1.48^2}$

$NA = 0.244$

Acceptance angle $= \sin^{-1}\sqrt{n_{core}^2 - n_{cladding}^2} = \sin^{-1} NA$

$= \sin^{-1} 0.244$

$\underline{\theta_a = 14.12^\circ}$

J2007 (P) Light travelling in an air strikes a glass plate at an angle $\phi_1 = 33^\circ$, where ϕ_1 is measured between the incoming ray and glass surface, Upon striking the glass, part of the beam is reflected and part is refracted. If the refracted and reflected beams makes an angle of 90° with each other, what is the refractive index of the glass? what is the critical angle for the glass?

Sol: Given that $\phi_1 = 33^\circ$ and $\phi_2 = 90^\circ$

Assume refractive index of air $= 1$

According to snell's law

$n_1 \sin\phi_1 = n_2 \sin\phi_2$

Suppose n_1 is refractive index of glass

n_2 is refractive index of air $= 1$

$n_2 \sin\phi_2 = n_1 \sin\phi_1$

$$n_1 = \frac{n_2 \sin\phi_2}{\sin\phi_1} = \frac{\sin 90^\circ}{\sin\phi_1} = \frac{\sin 90^\circ}{\sin 33^\circ} = 1.836$$

Refractive index of glass $n_1 = 1.836$

From defination of critical angle, $\phi_2 = 90^\circ$ and $\phi_1 = \phi_c$

$\sin\phi_c = \frac{n_2}{n_1}\sin 90^\circ \Rightarrow \sin\phi_c = \frac{1}{1.836}\sin 90^\circ = 0.54$

$\therefore$ critical angle $\phi_c = \sin^{-1}(0.54) = \underline{32.68^\circ}$

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A 2010 (P) A silica optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.50 and a cladding refractive index of 1.47. Determine

a) the critical angle at the core-cladding interface

b) The NA for the fiber c) The acceptance angle in air for the fiber

Sol: The critical angle ϕ_c at the core cladding interface is given by

a) $\phi_c = \sin^{-1} \frac{n_2}{n_1} = \sin^{-1}\left(\frac{1.47}{1.50}\right) = 78.5^\circ$ $\boxed{\phi_c = 78.5}$

b) The Numerical Aperture is given by

$$NA = (n_1^2 - n_2^2)^{1/2} = (1.50^2 - 1.47^2)^{1/2} = (2.25 - 2.16)^{1/2} = 0.30$$

$\boxed{NA = 0.30}$

c) The acceptance angle in air 'θ_a' is given by

$$\theta_a = \sin^{-1} NA = \sin^{-1} 0.30 = 17.4^\circ$$

$\boxed{\theta_a = 17.4^\circ}$

2011 (P) A typical relative refractive index difference for an optical fiber designed for long distance transmission is 1%. Estimate the NA and the solid acceptance angle in air for the fiber when the core index is 1.46. Further, calculate the critical angle at the core-cladding interface within the fiber. It may be assumed that the concepts of geometric optics hold for the fiber.

Sol: $\Delta = 0.01$

$$NA = n_1\sqrt{2\Delta} = 1.46\,(0.02)^{1/2} = 0.21$$

For small angles the solid acceptance angle in air ξ is given by

$$\xi = \pi\theta_a^2 = \pi \sin^2\theta_a = \pi (NA)^2 = \pi(0.04) = 0.13$$

The relative refractive index difference Δ gives

$$\Delta = \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1}$$

Hence $\frac{n_2}{n_1} = 1 - \Delta = 1 - 0.01 = 0.99$

The critical angle at the core-cladding interface is

$$\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1} 0.99 = 81.9^\circ$$

$\theta_a = \sin^{-1}\boxed{\frac{n_1^2 - n_2^2}{n_0}}$
for air

$\theta_a = \sin^{-1}\sqrt{n_1^2 - n_2^2}$

$\sin\theta_a = \sqrt{n_1^2 - n_2^2}$

$\sin^2\theta_a = n_1^2 - n_2^2$

$\sin^2\theta_a = NA$

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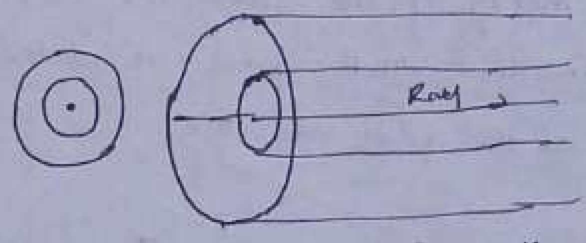
Types of Rays :

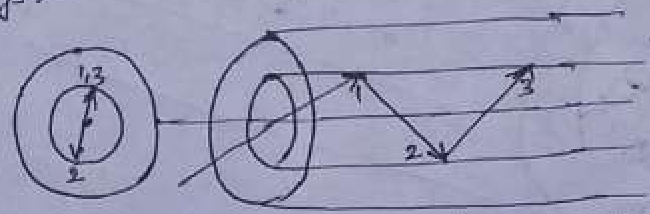
If the rays are launched within core of acceptance can be successfully propagated along the fiber. But the exact path of the ray is determined by the position and angle of ray at which it strikes the core. There exists three types of rays Axial rays, Meridional rays & skew rays

i) Axial rays :-



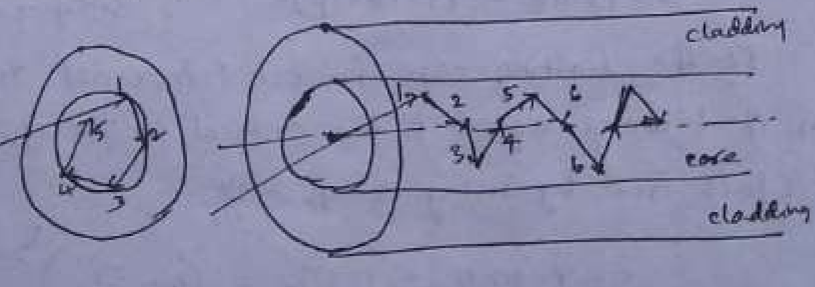
The axial ray travels along the axis of the fiber and stays at the fiber axis all the time.

ii) Meridional Rays :-



The meridional ray enters the core and passes through its axis. When the core surface is parallel, it will always be reflected to pass through the enter.

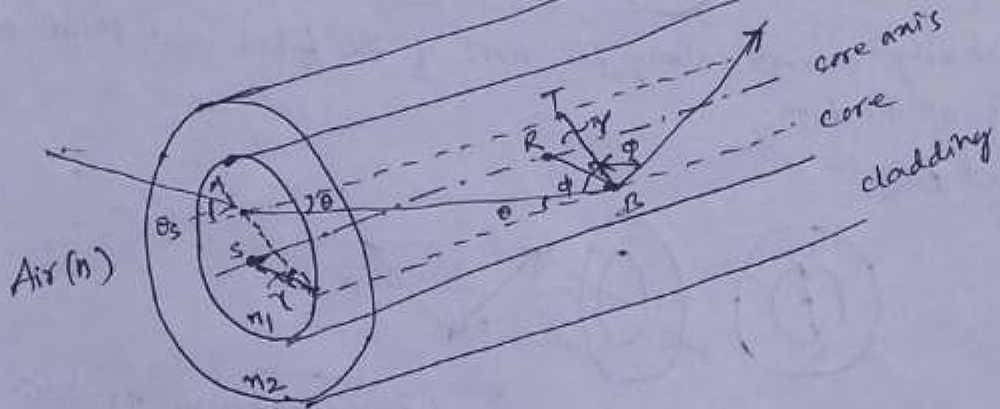
iii) Skew Rays : The skew ray does not pass through the center. The skew ray reflects off from the core cladding boundaries and again bounces around the outside of the core. It takes somewhat similar shape of spiral or helical path.



skew rays are not confined to a particular plane so they cannot be tracked easily. Analysing the meridional rays is sufficient for the purpose of result, rather than skew rays, because skew rays leads to greater power loss. The acceptance angle of skew rays is larger than the acceptance angle of meridian rays. skew rays are often used in the calculation of light acceptance in an optical fiber. The addition of skew rays increases the the amount of light capacity of a fiber.

The addition of skew rays also increases the ~~of~~ amount of loss in a fiber. A large number of skew rays that are trapped in the fiber core considered to be leaky rays.

In order to calculate the acceptance angle for a skew ray it is necessary to define the direction of the ray in two perpendicular planes. The geometry of the situation is shown in fig. Where a skew ray is shown incident on the fiber core at the point 'A' at angle 'θ_s' to the normal at the fiber end face



when considering the ray between 'A' and 'B', it is neccessary to resolve the direction of the ray path 'AB' to the core radius at the point B are in the same plane, this is simply $\cos\phi$.

Hence, the reflection at point 'B' at an angle 'ϕ' may be given by

$$\cos\gamma \sin\theta = \cos\phi$$

$$\cos\gamma \sin\theta = (1-\sin^2\phi)^{1/2} \qquad \because \sin^2\phi + \cos^2\phi = 1$$

If the limiting case for total internal reflection is now considered, then ϕ becomes equal to the critical angle ϕ_c for the core-cladding interface and by using $\sin\phi_c = \frac{n_2}{n_1}$.

$$\cos\gamma \sin\theta \leq \cos\phi_c = \left(1 - \frac{n_2^2}{n_1^2}\right)^{1/2}$$

Furthermore, using Snell's law at point 'A' then

$$n_0 \sin\theta_a = n_1 \sin\theta$$

where θ_a - the maximum input axial angle for meridional rays.

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θ_{as} represents the maximum input axial angle for skew rays

$$\sin\theta_{as} = \frac{n_1}{n_0}\frac{\cos\phi_c}{\cos\gamma} = \frac{n_1}{n\cos\gamma}\left(1-\frac{n_2^2}{n_1^2}\right)^{1/2}$$

where θ_{as} Thus acceptance angle for skew rays

$$n\sin\theta_{as}\cdot\cos\gamma = (n_1^2-n_2^2)^{1/2} = NA$$

and in the case of the fiber in air ($n=1$)

$$\sin\theta_{as}\cos\gamma = NA$$

$$\sin\theta_{as} = \frac{NA}{\cos\gamma}$$

$$\therefore \boxed{\theta_{as} = \sin^{-1}\left(\frac{NA}{\cos\gamma}\right)}$$

where $\theta_{as} \rightarrow$ acceptance angle for skew rays

$NA \rightarrow$ Numerical aperture

(P) An optical fiber in air has an NA of 0.4. compare the acceptance angle for meridional rays with that of skew rays which change direction by 100° at each reflection.

Sol. The acceptance angle for meridional rays is given by

$$\theta_a = \sin^{-1} NA$$

$\because n=1$

$$= \sin^{-1}(0.4)$$

$$\theta_a = 23.6^\circ$$

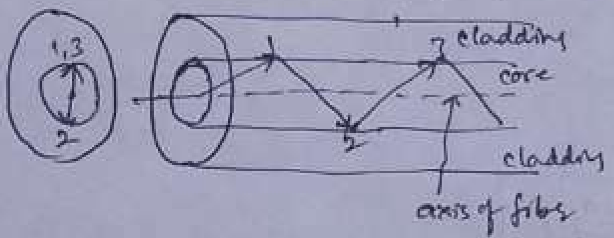
The skew rays change direction by 100° $\Rightarrow 2\gamma$ at each reflection therefore $\gamma = 50^\circ$ Hence the acceptance angle for skew rays is

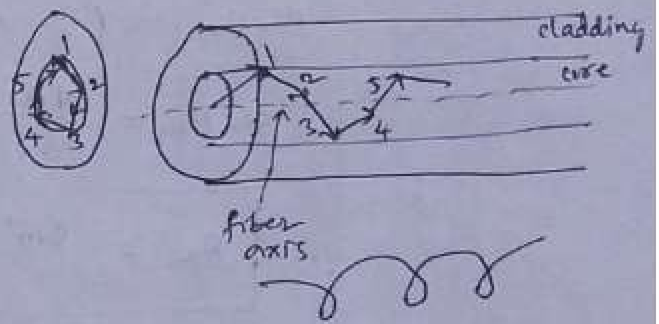
$$\theta_{as} = \sin^{-1}\left(\frac{NA}{\cos\gamma}\right)$$

$$= \sin^{-1}\left(\frac{0.4}{\cos 50}\right)$$

$$\theta_{as} = 38.5^\circ$$

Meridional Ray	Skew Ray
→ It is confined in a single plane	→ It is not confined in single plane
→ It always pass through fiber axis after each reflection	→ it does not passes through fiber axis after each reflection.
→ it follows ZigZag path	→ It follows helical path
→ tracking of ray is easy	→ tracking of ray is difficult
→ It can be explained by ray theory	→ It can be explained by mode theory





(P) The relative refractive index difference between the core axis and the cladding of a graded index fiber is 0.7% when the refractive index at the core axis is 1.45. Estimate values for the numerical aperture of the fiber along the axis when the index profile is assumed to be triangular.

Sol:

$\Delta = 0.7\% \Rightarrow \frac{0.7}{100} = 0.007$

$n_1 = 1.45$, $NA = n_1\sqrt{2\Delta} = 1.45\sqrt{(2\times0.007)}$

$NA = 0.1715$

(P) A multimode graded index fiber has an acceptance angle in air of 8°. Estimate the relative refractive index difference between the core axis and the cladding when the refractive index at the core axis is 1.52.

Sol:

$\theta_a = 8^\circ \quad n_1 = 1.52$

$\theta_a = \sin^{-1}\sqrt{n_1^2 - n_2^2} \Rightarrow \sin\theta_a = \sqrt{n_1^2 - n_2^2}$

$\sin 8^\circ = \sqrt{n_1^2 - n_2^2} \Rightarrow NA = 0.14$

$$\Delta = \frac{NA^2}{2n_1^2} = \frac{0.14^2}{2\times(1.52)^2}$$

$\Delta = 0.00424$

Cylindrical fiber

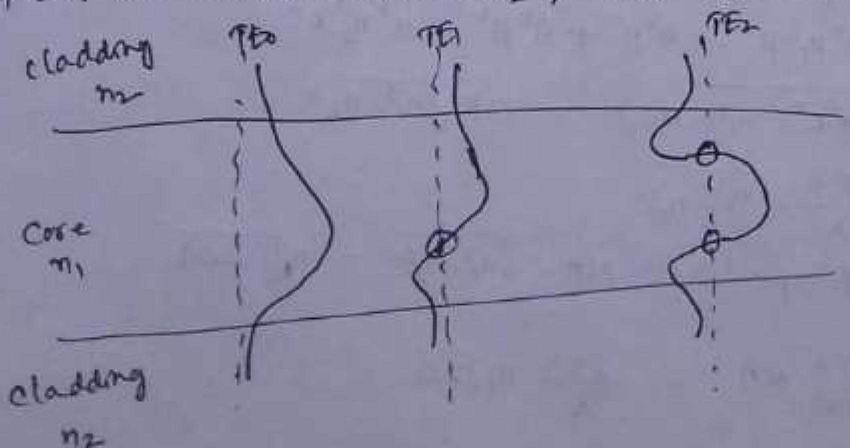
Modes: To analyze the optical fiber propagation mechanisms within a fiber, Maxwell's equations are to solve subject to the cylindrical boundary conditions at core-cladding interface. The core cladding boundary conditions lead to coupling of electric and magnetic field components resulting in hybrid modes. Depending on the larger E-field or H-field, the hybrid modes are HE or EH modes. The two lowest order modes are HE_{11} and TE_{01}. The order states the number of field zeros across the guide. The electric fields are not completely confined within the core. ie they do not go to zero at core-cladding interface and extends in to the cladding.

The low order mode confines the electric field near the axis of the fiber core and there is less penetration in to the cladding. while high order mode distribute the field towards the edge of the core fiber and penetration in to the cladding. therefore cladding modes also appear resulting in power loss. In leaky modes the fields are confined partially in the fiber core attenuated as they propagate along the fiber length due to radiation and tunnel effect. Therefore in order to mode remain unguided, the propagation factor β must satisfy the condition

$$n_2 k < \beta < n_1 k$$

where n_1 = Refractive index of fiber core
n_2 = " " " cladding
k = propagation constant $= \frac{2\pi}{\lambda}$

The cladding is used to prevent scattering loss that results from core material discontinuities. cladding also improves the mechanical strength of fiber core and reduces surface contamination. plastic cladding is commonly used. Materials used for fabrication of optical fibers are silicon dioxide (SiO_2), boric oxide-silica.



order of mode is equals to field crossing zero across guide. Field partially goes in to cladding. Field harmonically crossing across guide (core). For lower modes fields are highly concentrated at centre and lightly in cladding. For higher modes, fields are highly penetrated to cladding region. Cladding modes will be suppressed by a lossy coating which covers fiber.

lossy modes, it is partially confined to fiber. Power will be radiated out of fiber due to tunnel effect. This mode will disappear after few cm distance. propagation condition $n_2k < \beta < n_1k$

V Number of optical fiber or Normalized freq of fiber

Normalized frequency is a dimensionless parameter and some times it is also called as V number. It gives relation among three design variables of the fiber core radius (a), relative refractive index (Δ) and operating wavelength (λ)

$$V = \sqrt{U^2 + W^2}$$ where U = Radial propagation constant, W = cladding decay parameter

Radial propagation constant defined as

$$U = a\sqrt{n_1^2k^2 - \beta^2}$$ where a = Radius of core, n_1 = Refractive index of core, $k = 2\pi/\lambda$, β = propagation constant

cladding decay parameter is given as

$$W = a\sqrt{\beta^2 - n_2^2k^2}$$ where n_2 = Refractive index of cladding

So, V number will be

$$V = \sqrt{a^2(n_1^2k^2 - \beta^2) + a^2(\beta^2 - n_2^2k^2)}$$

$$= \sqrt{a^2n_1^2k^2 - a^2\beta^2 + a^2\beta^2 - a^2n_2^2k^2}$$

$$= \sqrt{a^2k^2(n_1^2 - n_2^2)} = ak\sqrt{n_1^2 - n_2^2}$$

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$$

Numerical aperture $NA = \sqrt{n_1^2 - n_2^2} = n_1\sqrt{(2\Delta)}$

$$V = \frac{2\pi a}{\lambda} NA = \frac{2\pi a}{\lambda} n_1\sqrt{2\Delta}$$

The total number of modes in a multimode fiber is given by

$$M = \frac{1}{2}\left(\frac{2\pi a}{\lambda}\right)^2 (n_1^2 - n_2^2)$$

$$= \frac{1}{2}\left[\frac{2\pi a}{\lambda} NA\right]^2 = \frac{(V)^2}{2}$$

$$\boxed{M = \frac{1}{2}\left[\frac{\pi d}{\lambda} \cdot NA\right]^2}$$ where d = core diameter

<u>mode coupling</u> :- waveguide perturbations such as deviations of the fiber axis from straightness, variations in the core diameter, irregularities at the core-cladding interface and refractive index variations may change the propagation characteristics of the fiber. These will have the effect of coupling energy travelling in one mode to another depending on the specific perturbation.

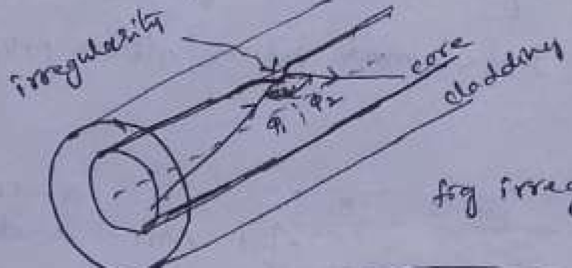


fig irregularity at core-cladding interface

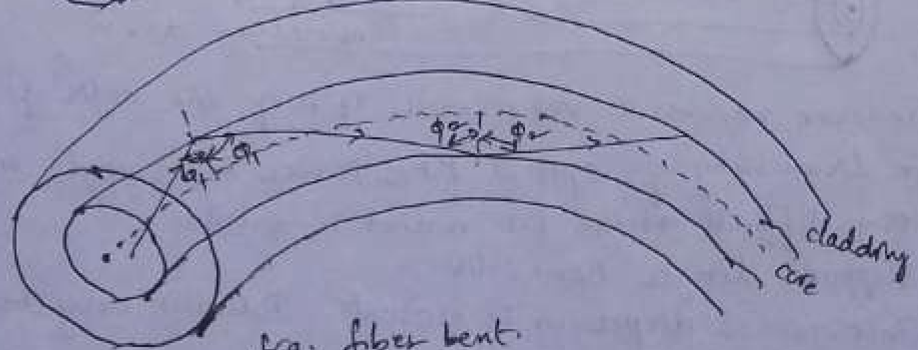


fig. fiber bent.

Ray theory gives the understanding of this phenomenon as shown in fig. which illustrates two types of perturbation. It may be observed that in both cases the ray no longer maintains the same angle with the axis. In electromagnetic wave theory this corresponds to a change in the propagation mode for the light. Thus individual modes do not normally propagate through out the length of the fiber without large energy transfers to adjacent modes, even when the fiber is exceptionally good quality and is not strained or bent by its surroundings. This mode conversion is known as mode coupling or mixing.

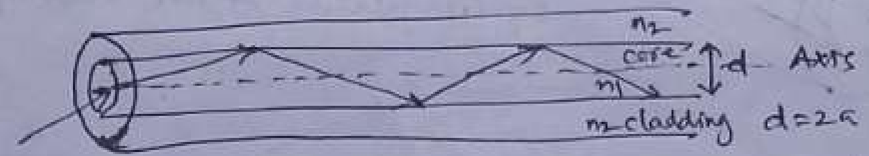
Mode coupling affects the transmission properties of fibers in several important ways, a major one being in relation to the dispersive properties of fibers over long distances.

Modes of Fibers

Fiber cables can also be classified as per their mode. Light rays propagate as an electromagnetic wave along the fiber. The two components, the electric field and magnetic field form patterns across the fiber. these pattern are called modes of transmission. The mode of a fiber refers to the number of paths for the light rays within the cable. According to modes optical fibers can be classified in to two types. ① Single mode fibres ② Multimode fiber

In simple words Mode refers → Number of paths.

① **Single mode fibers:-** Single mode fibers allows propagation of light ray only one path.



a – core radius
d – diameter of core

→ The core radius is very small. It is of the order of 10μm.

→ The launching of optical fiber power in to single mode fiber is very difficult as the core radius is small.

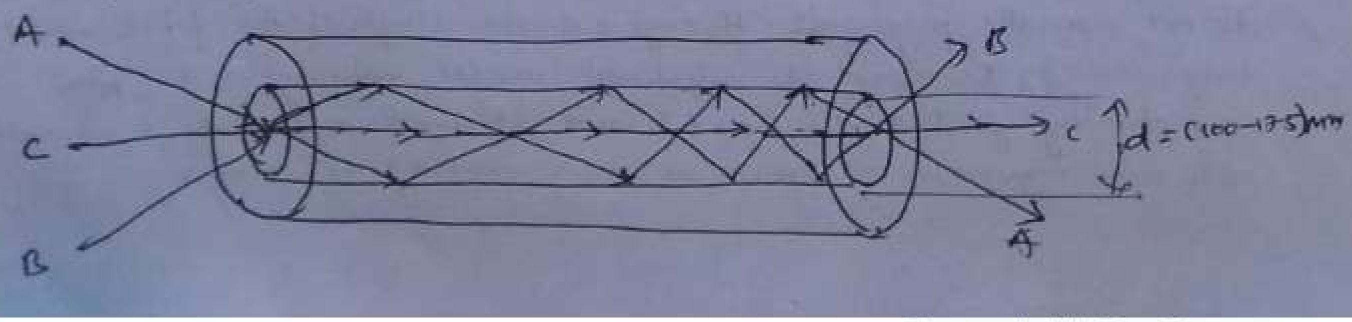
→ supports longer Bandwidth

→ Intermodal dispersion is absent. Ideally very low loss

→ Used for long distance communication

→ optical source used must be LASER

② **Multimode Fibers:** Multimode fiber allows propagation of light ray by multiple paths. ie multiple ligh rays are carried simultaneously through the multimode fiber core as shown in fig. Multimode fiber has a much larger diameter compared to single mode fiber. Its typical value (100-175)μm These fibers suffers from Intermodal dispersion

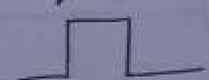


Comparison between stepindex single mode & multimode fibers

Single mode fiber	Multimode fiber
1. core ~~radius~~ diameter 2 to 10 μm is small [$a \simeq 10 \mu m$]	1. core diameter is greater than single mode. Step index: 50 μm to 400 μm. Graded index: 30 to 100 μm
2. Cladding diameter 125 μm	2. cladding diameter. Step index: 125 to 500 μm. Graded index: 100 to 150 μm
3. propagation of only fundamental mode	3. Multimode propagate
4. No intermodal dispersion	4. Greater intermodal dispersion
5. optical source is LASER	5. optical source is LED
6. Supports larger Bandwidth	6. Supports lesser Bandwidth.
7. Used for long distance comm	7. Used for short distance comm
8. less expensive	8. More expensive

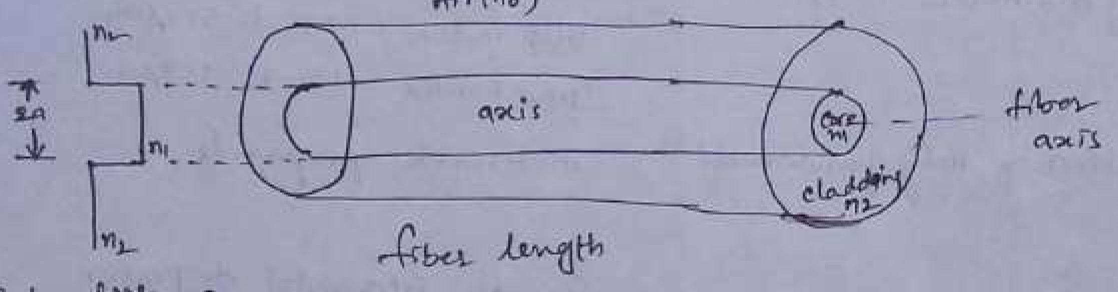
Fiber profile: A fiber is characterised by its profile and by its core and cladding diameters. One way of classifying the fiber cables is according to the index profile at fiber. The index profile is a graphical representation of value of refractive index across the core diameter.

There are two basic types of index profiles

i) step index fiber 

ii) Graded index fiber 

Step index fiber: The step index fiber is a cylindrical waveguide core with central or inner core has a uniform refractive index n_1 and the core is surrounded by outer cladding with uniform refractive index of n_2. The cladding refractive index (n_2) is less than the core refractive index (n_1). But there is an abrupt change in the refractive index (n_1) at the core-cladding interface. Refractive index profile of step indexed optical fiber is shown in fig.



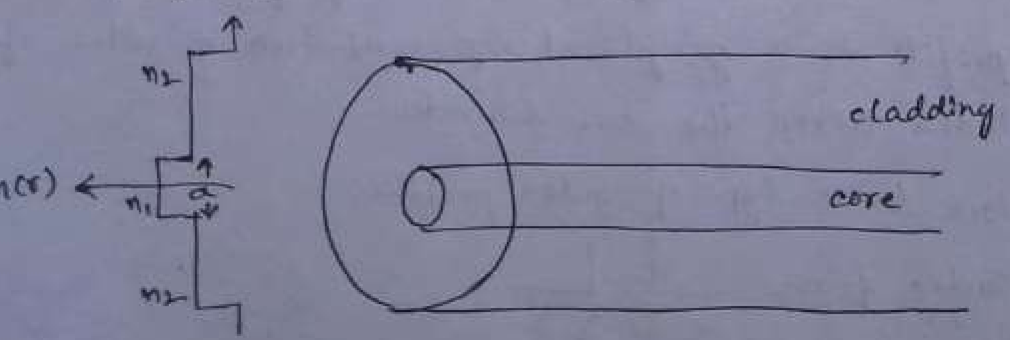
The propagation of light wave with in the core of step index fiber takes the path of meridional ray i.e ray follows a zig zag path of straight line segments. The bending (refraction) takes place only of core - cladding interface. Ray of light travels at constant velocity ($v = \frac{c}{n_1}$). Data transmission is slow

The refractive index profile is defined as

$$n(r) = \begin{cases} n_1 & \text{when } r < a \text{ (core)} \\ n_2 & \text{when } r \geq a \text{ (cladding)} \end{cases}$$

Depending on numbers of modes step index fibers are classified in to a) Single mode step index fiber b) Multimode step index fiber

a) Single mode step index fiber:



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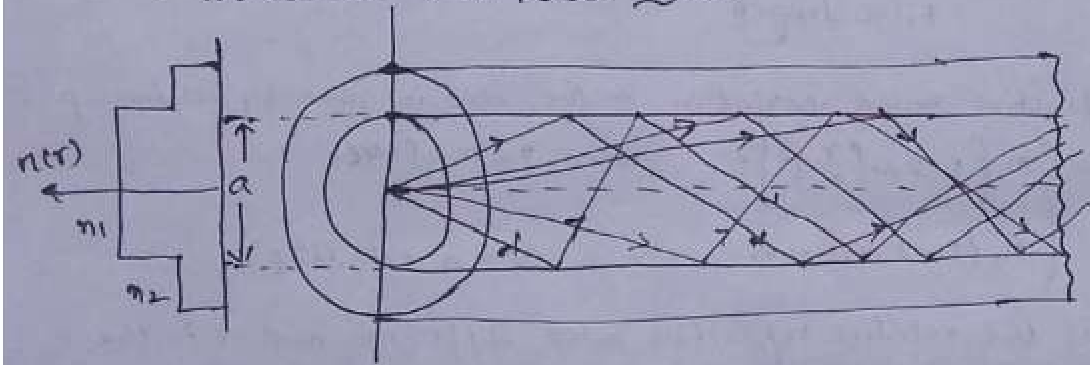
Single mode stepindex fiber has a central core that is sufficiently small so that there is essentially only one path for light ray through the cable. The light rays propagated in the fiber through reflections. Typical core sizes are 2 to 15 μm. Single mode fiber is also known as fundamental or monomode fiber. Single mode fiber will permit only one mode to propagate and does not suffer from mode delay differences. The core fiber of a single mode fiber is very narrow compared to the wavelength of light being used.

The disadvantages of this type of cable is that because of extremely small size inter connection of cables and interfacing with source is difficult. The refractive index of glass decreases with optical wavelength, the light velocity will also be wavelength dependent. Thus light from an optical transmitter will have definite spectral width.

b) Multimode Step index fiber:

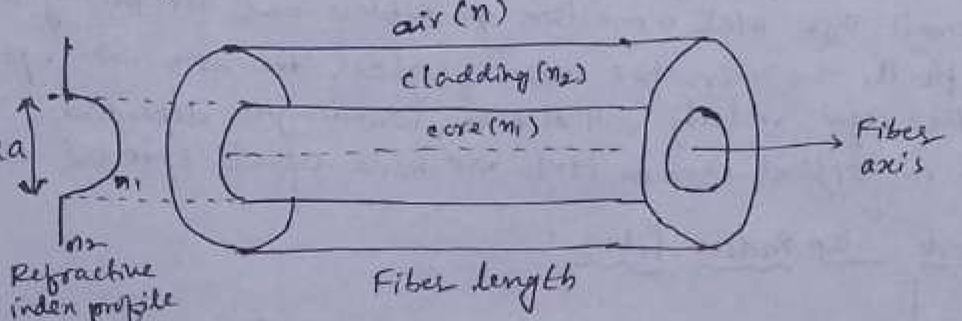


Multimode step index fiber is most widely used type. It is easy to manufacture. The light rays are propagated down. The core is zigzag manner. There are many paths that a light ray may follow during the propagation using total internal reflection. Light rays passing through the fiber are continuously reflected off. The glass cladding towards the centre of the core at different angles and lengths, limiting overall bandwidth. In multimode stepindex fiber considerable dispersion may occur due to differing group velocities of the propagating modes. The total number of guided modes or mode volume M_s for a step index fiber is related to the V value for the fiber by approximate expression $M_s = \frac{V^2}{2}$

which allows an estimate of the number of guided modes propagating in a particular multimode stepindex fiber.

Graded Index Fibers [GRIN - Fibers]:

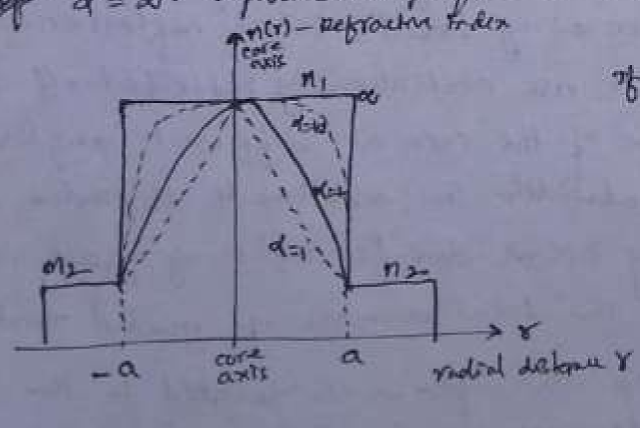
The graded index fiber has a core made from many layers of glass. In the graded index fibers the refractive index is not uniform within the core, it is highest at the center and decreases smoothly and continuously with distance towards the cladding. In graded index fiber the light waves are bent by refraction towards the core axis and they follow the curved path down the fiber length. This results because of change in refractive index as moved away from the center of the core.



The refractive index variation in the core is given by relationship

$$n(r) = \begin{cases} n_1\left[1-2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]^{\frac{1}{2}} & \text{when } r < a \text{ (core)} \\ n_1(1-2\Delta)^{\frac{1}{2}} \simeq n_2 & \text{" } r \geq a \text{ (cladding)} \end{cases}$$

where Δ is the relative refractive index difference and α is the profile parameter which gives the characteristic refractive index profile of fiber core. Expressing the refractive index profile of the fiber core as a variation of α allows representation of the step index profile when $\alpha = \infty$. a parabolic profile when $\alpha = 2$ and a triangular profile when $\alpha = 1$.



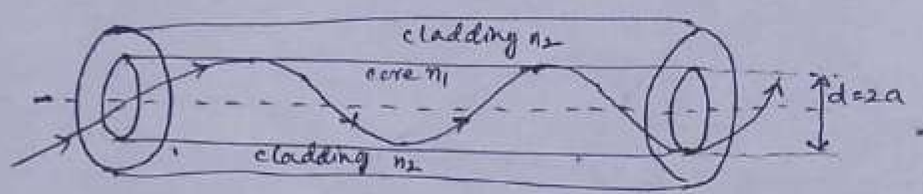
If $\alpha = \infty$ R-I profile is of step index profile
$\alpha = 2$ R-I " is parabolic
$\alpha = 1$ " " is triangular.

Depending on the number of modes, Graded index fibers are classified into

a) Single mode Graded Index fiber
b) Multi mode Graded Index fiber.

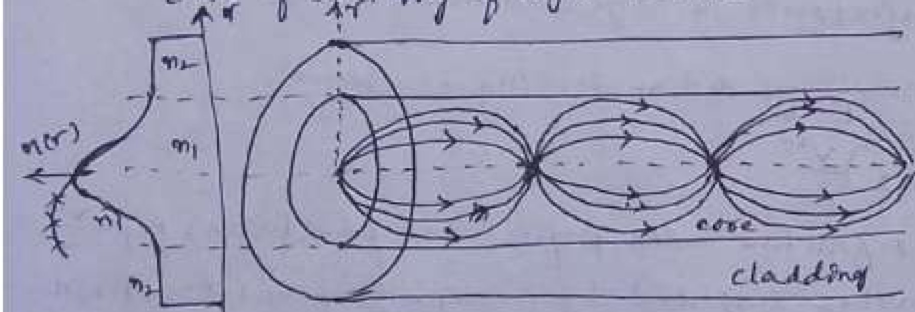
a) Single mode Graded Index Fibers:

It supports single mode propagation. Ray propagates in helical path. Light ray is called skew ray as shown in fig.



b) Multi mode Graded Index Fiber:

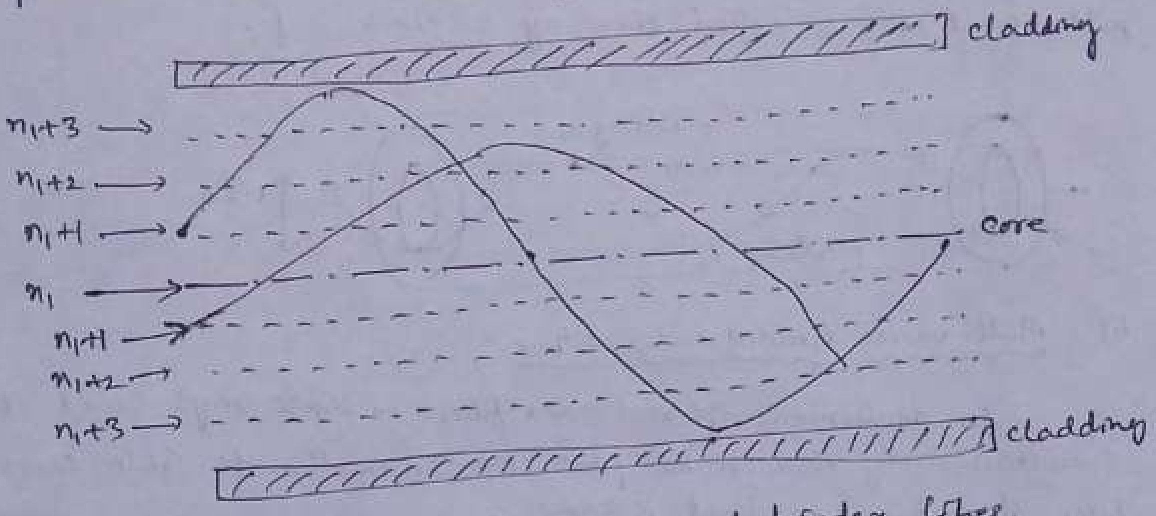
In multimode, graded index fiber multiple rays can be transmitted simultaneously through the fiber core. In multimode GRIN fibers the exit time of each ray of light is same.



The core size of multimode graded index fiber cable is varying from 50 to 100 μm range. The light ray is propagated through the refraction. The light ray enters the fiber at many different angles. As the light propagates across the core toward the centre it is intersecting a less dense to more dense medium. Therefore the light rays are being constantly refracted and ray is bending continuously. This cable is mostly used for long distance communication. The light rays no longer follow straight lines, they follow serpentine path being gradually bent back towards the center by the continuously declining refractive index. The modes travelling in a straight line are in higher refractive index. So they travel slower than the serpentine modes. this reduces the arrival time disparity because all modes arrive at about the same time.

As shown in fig. The light rays running close to the fiber axis with shorter path length. will have a lower velocity because they pass through a region with a high refractive index. Rays on core edges offers reduced refractive index, hence travel more faster than axial rays and cause the light components to take same -

amount of time to travel the length of fiber, thus minimizing dispersion losses. (intermodal dispersion).



Light trajectories in a graded index fiber

The total number of guided modes M_g is given by

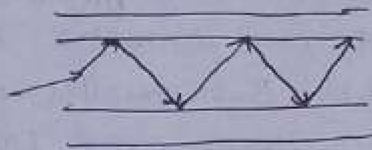
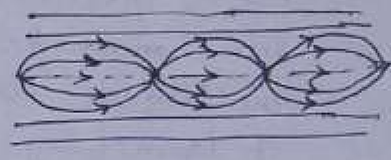
$$M_g = \left(\frac{\alpha}{\alpha+2}\right)\frac{V^2}{2}$$

For a parabolic refractive index profile core fiber ($\alpha=2$) $M_g \approx \frac{V^2}{4}$ which is half the number supported by a step index fiber ($\alpha=\infty$) with the same V value.

Standard fibers

Sr. No	Fiber type	cladding diameter (μm)	core diameter (μm)	Δ	Applications.
1	Single mode (8/125)	125	8	0.1% to 0.2%	1. Long distance 2. High data rate
2	Multimode (50/125)	125	50	1% to 2%	1. Short distance 2. Low data rate
3	Multimode (62.5/125)	125	62.5	1% to 2%	LAN
4	Multimode (100/140)	140	100	1% to 2%	LAN

Comparision of step index and Graded index fibers:

parameter	step index fiber	Graded index fiber
1. Data rate	slow	higher
2. coupling efficiency	higher	lower
3. Ray path	By total internal reflection 	travels in Oscillatory fashion 
4. Index Variation	$\Delta = \frac{n_1 - n_2}{n_1}$	$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$
5. Numerical Aperture	remains same	changes continuously with distance from fiber axis
6. Material used	Normally plastic or glass is preferred	only glass is preferred.
7. Bandwidth efficiency	10 - 20 MHz/km	1 GHz/km
8. pulse spreading	more	less
9. Attenuation of light	less typically 0.34 dB/km at 1.3 μm	more 0.6 to 1 dB/km at 1.3 μm
10 light source	LED	LED, Lasers
11 Applications	subscriber local network communication	Local and wide area networks

Single mode fibers:

The advantage of the propagation of a single mode within an optical fiber is that the signal dispersion caused by the delay differences between different modes in a multimode fiber is avoided. Multimode stepindex fibers cannot be used for single mode propagation due to difficulties in maintaing single mode operation. Therefore the transmission of a single mode fiber is designed to allow propagation in one mode only, while all other modes are attenuated by leakage or absorption

For single mode operation, only fundamental LP_{01} mode may exist. The single mode propagation of LP_{01} mode in step index fiber is possible over the range $0 \le V < 2.405$. The cut off normalized frequency in step index occurs at $V_c = 2.405$. The normalized frequency for the fiber can be adjusted within the range by reducing core radius and refractive index difference < 1%. In order to obtain single mode operation with maximum V number (2.4), the single mode fiber must have smaller core diameter than the equivalent multimode step index fiber. But smaller core diameter has problem of launching light in to fiber, joing fibers and reduced relative refractive index difference. Graded index fiber can also be used for single mode operation with some special fiber design. The cutoff value of normalized frequency Vc in single mode operation for a graded index fiber is given by

$$\boxed{V_c = 2.405\left(1+\frac{2}{\alpha}\right)^{1/2}}$$

cut off Wavelength (λ_c):

The effective cut off wavelength λ_c is defined as the largest wavelength at which higher order (LP_{11}) mode power relative to the fundamental mode (LP_{01}) power is reduced to 0.1 dB. The range of cutoff wavelength to avoid modal noise and dispersion problems is 1100 to 1280 nm (1.1 to 1.28 μm) for single mode fiber at 1.3 μm.

The cutoff wavelength λ_c can be computed from expression of normalized freq.

$$V = \frac{2\pi a}{\lambda}(NA) = \frac{2\pi a}{\lambda} n_1\sqrt{2\Delta} \Rightarrow \lambda = \frac{2\pi a}{V} n_1\sqrt{2\Delta}$$

$$\lambda_c = \frac{2\pi a}{V_c} n_1\sqrt{2\Delta}$$ where V_c - cutoff normalized freq.

λ_c is the wavelength above which a particular fiber becomes single mode. For same fiber dividing λ_c by λ we get the relation as

$$\frac{\lambda_c}{\lambda} = \frac{V}{V_c} \Rightarrow \lambda_c = \frac{V\cdot\lambda}{V_c}$$

For step index fiber $V_c = 2.405$ then

$$\boxed{\lambda_c = \frac{V\lambda}{2.405}}$$

Mode Field diameter (MFD) & Spot Size:

For single mode fibers operating near the cutoff wavelength λ_c, the field can be approximated by "Gaussian Distribution". In single mode optical fiber light ray propagates as a single gaussian pulse along the length of fiber with maximum intensity at the center of fiber core. Fig shows the electric field distribution $E(r)$ as a function of radial distance from fiber axis

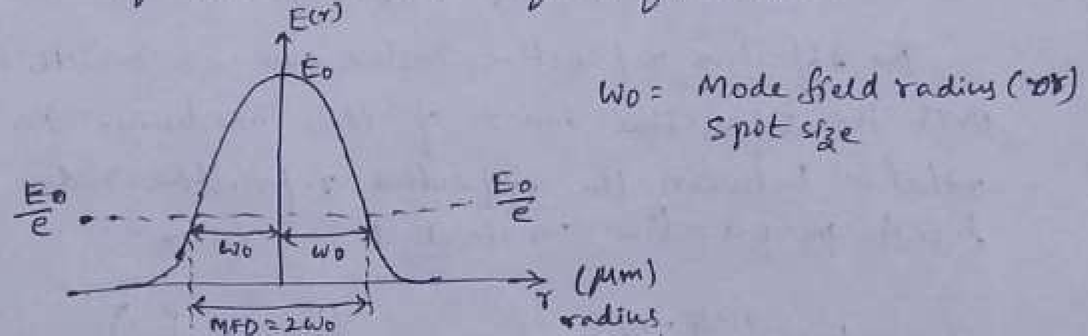


Fig. Mode field diameter representation.

The spot size $\omega_0 = \frac{MFD}{2}$

Mode field diameter is the distance between the opposite field amplitude points, where the field intensity is $(\frac{1}{e})$ times the maximum field intensity (E_0). Mode field diameter (MFD) is twice the spot size (ω_0). $\boxed{MFD = 2\omega_0}$

For many refractive index profiles and at typical operating wavelengths the MFD is slightly larger than the single mode fiber core diameter.

Effective Refractive Index:

The rate of change of phase of the fundamental LP_{01} mode propagating along a straight fiber is determined by the phase propagation constant β. It is directly related to the wavelength of the LP_{01} mode λ_{01} by the factor 2π, since β gives the increases in phase angle per unit length.

Hence $\beta\lambda_{01} = 2\pi$, $\lambda_{01} = \frac{2\pi}{\beta}$

It is convenient to define an effective refractive index for single mode fiber, some times referred to as a phase index or normalized phase change coefficient n_{eff}, by the ratio of the propagation constant of the fundamental mode to that of the vaccume propagation constant $\boxed{n_{eff} = \frac{\beta}{K}}$

Hence the wavelength of the fundamental mode λ_{01}, is smaller than the vaccum wavelength by the factor $\frac{1}{n_{eff}}$ where $\boxed{\lambda_{01} = \frac{\lambda}{n_{eff}}}$

The effective refractive index can be considered as an average over the refractive index of this medium. In addition a relation between the effective refractive index and the normalized propagation constant b as given

$$b \simeq \frac{n_{eff} - n_2}{n_1 - n_2} \qquad \left(n_{eff} = \frac{\beta}{K}\right)$$

The dimensionless parameter b which varies between 0 & 1 is particularly useful in the theory of single mode fibers because the relative refractive index difference is very small giving only a small range for β.

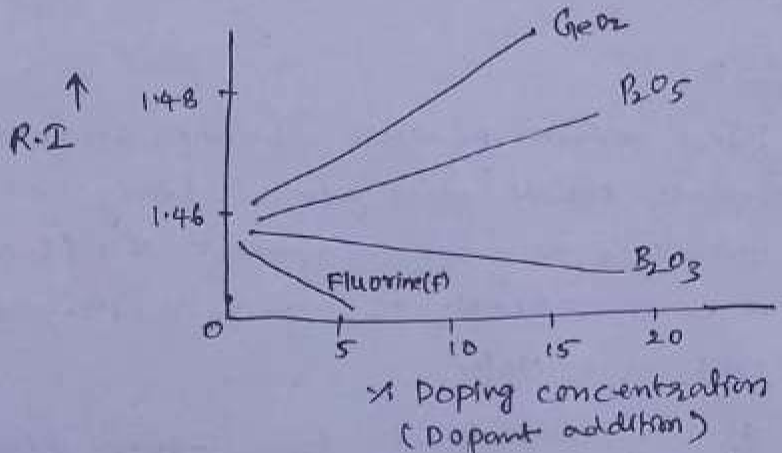
Fiber Materials: In seleting materials for optical fibers, the following requirements must be satisfied.

1) It must be possible to make long, thin and flexible fibers from materials.
2) The material must be transparent at a particular optical wavelength in order for the fiber to guide light efficiently.
3) physically compatible materials that have slightly different refractive indices for the core and cladding must be available.

Materials that satisfy these requirements are glasses & plastics. Most of the fibers are made up of glass consisting of either silica(SiO_2) or silicate. High loss glass fibers are used for short transmission distances and low loss glass fibers are used for long distance applications. Plastic fibers are less used because of their higher attenuation than glass fibers but they have greater mechanical strength.

Glass Fibers :

Glass is made by fusing mixtures of selenides (or) sulfides of metal oxides. The most common oxide is silica (SiO_2) whose refractive index is 1.458 at 850 nm. To produce two similar materials that have slightly different indices of refraction for the core and cladding, either fluorine or various oxides (referred to as dopants), such as B_2O_3, GeO_2 or P_2O_5 are added to the silica.



As shown in fig. The addition of dopants GeO_2 or P_2O_5 increases the refractive index, where as doping the silica with Fluorine (F) and B_2O_3 decreases it. One important criteria is that the refractive index of core is greater than that of the cladding.

Few fiber compositions are given as

composition	core	cladding
1	$GeO_2 - SiO_2$	SiO_2
2	$P_2O_5 - SiO_2$	SiO_2
3	SiO_2	$B_2O_3 - SiO_2$
4	$GeO_2 - B_2O_3 - SiO_2$	$B_2O_3 - SiO_2$

The principal raw material for silica is high purity sand. Glass composed of pure silica is referred to as either silica glass or fused silica or vitreous silica.

Some desirable properties of silica are

i) Resistance to deformation even at high temperature.
ii) High resistance to breakage from thermal shocks.
iii) Good chemical durability
iv) High transparency in both the visible and infrared regions.

The Glass fibers can be classified as to

i) Halide glass fibers   ii) Active glass fibers
iii) chalgenide glass fibers

i) Halide Glass Fibers:

A halide glass fiber contains fluorine, chlorine, bromine and iodine. The most common Halide glass fiber is heavy "metal Fluoride glass". It uses ZrF_4 as major component. This fluoride glass is known by the name ZBLAN. Since it is constituents are ZrF_4, BaF_2, LaF_3 AlF_3 and NaF.

The percentage of elements to from ZBLAN fluoride glass is shown below.

Materials	Molecular percentage
ZrF_4	54%
BaF_2	20%
LaF_3	4.5%
AlF_3	3.5%
NaF	18%

These materials add up to make the core of a glass fiber. replacing ZrF_4 by HaF_4. The lower refractive index glass is obtained. The intrinsic losses of these glasses is 0.01 to 0.001 dB/km.

ii). Active Glass Fibers:

Active glass fibers are formed by adding erbium and neodymium to the glass fibers. These materials perform amplification, attenuation and phase retardation on the light passing through it. Doping can be carried out for silica, tellurite and halide glasses.

iii) Chalgenide glass fiber:

chalgenide glass fiber are discovered inorder to make use of the non linear properties of glass fibers. It contains either S, Se or Te because they are highly non linear and it also contains one element from Cl, Br, Cd, Ba, or Si. The mostly used chalgenide glass is As_2-S_3, $As_{40}S_{58}Se_2$ is used to make the core and As_2-S_3 is used to make the cladding material of the glass fiber. The ~~rotation~~ insertion loss is around 1dB/m.

Plastic optical Fibers:

→ The growing demand for delivering high speed services directly to the work station has led fiber developers to create high bandwidth graded index polymer (plastic) optical fibers (POF).

→ The core of these fibers is either polymethyl methacrylate (PMMA) or a perfluorinated polymer (PF). These fibers are referred to as PMMA POF and PF POF respectively.

→ They exhibit considerably greater optical signal attenuations than glass fibers, they are tough and durable due to the presence of plastic material.

→ compared with silica fibers, the core diameters of plastic fibers are 10-20 times larger, which reduces the connector losses without sacrificing optical coupling efficiencies.

(P) Graded index fiber has parabolic Refractive index profile with core diameter 50μm & NA=0.2. Find the number of modes guided at wavelength 1μm.

sol: Given core diameter = 50μm ⟹ $a = \frac{50\mu m}{2} = 25\mu m$

$NA = 0.2$, $\lambda = 1\mu m$ parabolic profile ⟹ $\alpha = 2$

$$V = \frac{2\pi a}{\lambda}(NA) = \frac{2 \times \pi \times 25 \times 10^{-6}}{1 \times 10^{-6}}(0.2) = 31.4$$

$$M = \frac{V^2}{4} = \frac{(31.4)^2}{4} = 246.49 \simeq 247$$

(P) Estimate cutoff wavelength for stepindex fiber in single mode operation. The core refractive index is 1.46 and core radius is 4.5μm. The relative index difference is 0.25%.

Sol: Given $n_1 = 1.46$ $\quad a = 4.5\mu m = 4.5\times10^{-6} m$

$\Delta = 0.25\% = 0.0025$

cutoff wavelength is given by

$$\lambda_c = \frac{2\pi a n_1 (2\Delta)^{1/2}}{V_c}$$

For cutoff wavelength $V_c = 2.405$

$$\lambda_c = \frac{2\pi \times 4.5\times10^{-6} \times 1.46\ (0.005)^{1/2}}{2.405}$$

$$\underline{\underline{\lambda_c = 1.214\ \mu m}}$$

(P) A Graded index fiber with a parabolic Refractive index profile core has a Refractive ~~factor~~ index at the core axis of $n_1 = 1.5$ & relative index difference $\Delta = 1\%$. Estimate possible core diameter which allows single mode operation at a wavelength of 1.3 μm.

Given $n_1 = 1.5$ $\quad \Delta = 1\% = 0.01$ $\quad \lambda = 1.3\mu m$

$$V = 2.405\left(1+\frac{2}{\alpha}\right)^{1/2}$$

$$= 2.405\left(1+\frac{2}{2}\right)^{1/2} \qquad \alpha = 2$$

$$V = 2.405\sqrt{2}$$

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

$$a = \frac{V\lambda}{2\pi n_1 \sqrt{2\Delta}}$$

$$= \frac{2.405\sqrt{2} \times 1.3\times10^{-6}}{2\pi \times 1.5 \times \sqrt{2\times0.01}}$$

$$\underline{a = 3.3\mu m}$$

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UNIT-II Signal Distortion in Optical Fibers

Introduction: Two transmission characteristics ~~are~~ of optical fibers are signal attenuation and signal distortion.

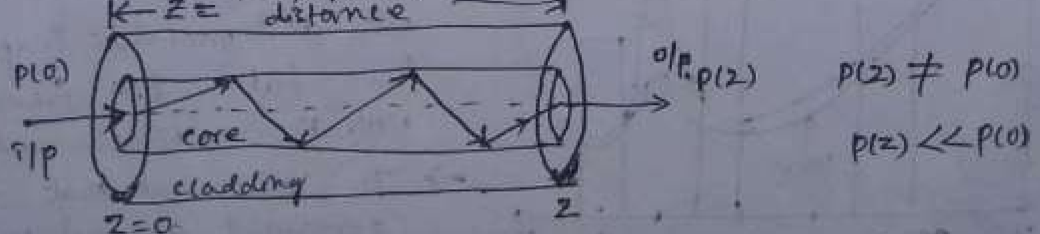
→ Signal attenuation is also known as fiber loss or signal loss. The signal attenuation of fiber determines the maximum distance between transmitter and receiver. It also determines the number of repeaters required.

→ Signal distortion cause that optical signal pulse travels along the fiber length it becomes broader. After sufficient length the broad pulses starts overlapping with adjacent pulses. This creates error in the receiver output, resulting in the limitation of information carrying capacity of a fiber.

Attenuation (Fiber loss): Attenuation is a measure of decay of signal strength or loss of light power that occurs as light pulses propagate through the length of the fiber. The attenuation is mainly caused by two physical ~~parameters~~ factors absorption and scattering losses. Absorption is because of fiber material and scattering due to structural imperfection with in the fiber. The rate at which light is absorbed is dependent on the wavelength of the light and the characteristics of particular glass. The Ray leight scattering is wavelength dependent and reduces rapidly as the wavelength of the incident radiation increases. The attenuation of fiber is governed by the materials from which it is fabricated, the manufacturing process and the refractive index profile chosen. Attenuation loss is measured in dB/km.

Sources of Attenuation: 1. Material absorption 2. Scattering losses 3. Bending loss 4. core & cladding loss 5. Dispersion 6. Mode coupling 7. Leaky modes 8. Pulse broadening.

Attenuation Units:



As attenuation leads to a loss of power along the fiber, the output power is significantly less than the coupled power.

Let the coupled power is $P(0)$ i.e at origin $(z=0)$. Then the power at distance 'z' is given by

$$P(z) = P(0)\, e^{-\alpha_p \cdot z}$$ where α_p - fiber attenuation constant (per km)

$$e^{\alpha_p \cdot z} = \frac{P(0)}{P(z)}$$

$$\ln e^{\alpha_p \cdot z} = \ln\left[\frac{P(0)}{P(z)}\right] \Rightarrow \alpha_p \cdot z \ln e = \ln\left[\frac{P(0)}{P(z)}\right] \qquad \because \ln e = 1$$

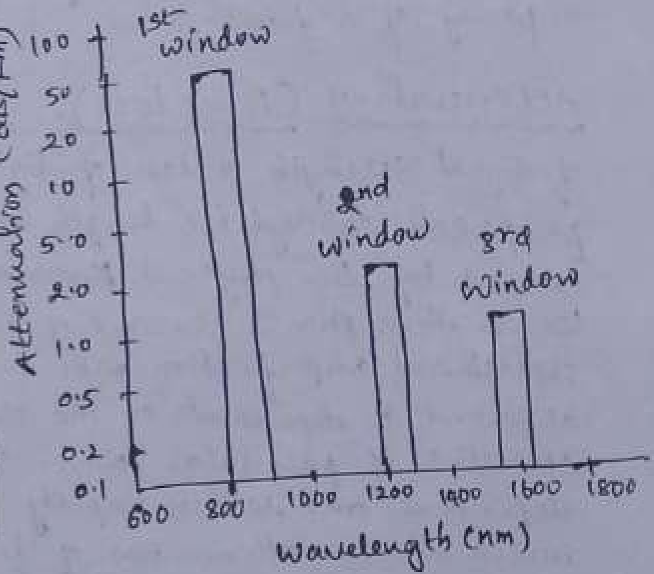
$$\alpha_p \cdot z = \ln\left[\frac{P(0)}{P(z)}\right] \Rightarrow \alpha_p = \frac{1}{z}\ln\left[\frac{P(0)}{P(z)}\right]$$

$$\boxed{\alpha_p\,(dB/km) = \frac{1}{z}\log_{10}\left[\frac{P(0)}{P(z)}\right]} \qquad \alpha_{dB/km} = 4.343\,\alpha_p \text{ per km}$$

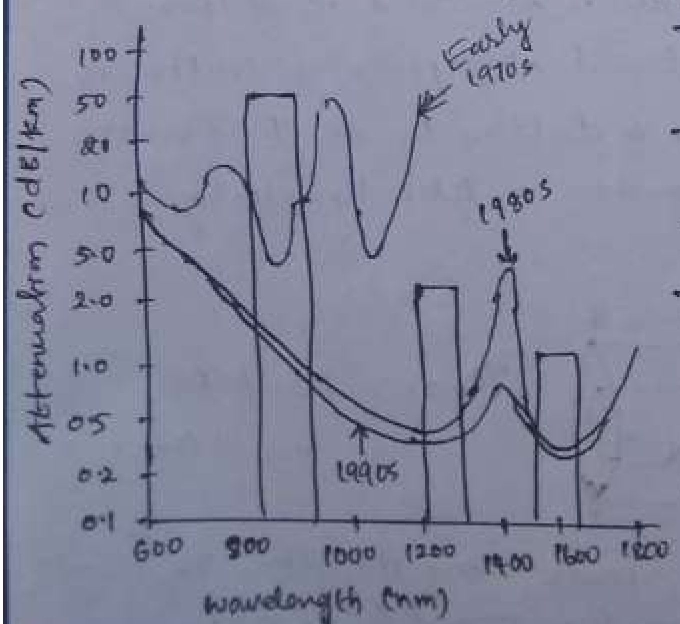
This parameter is known as fiber loss or fiber attenuation.

Fiber optic window :

	Window Range	Operating Wavelength
First window	800nm - 900nm	850nm
Second window	1260nm - 1360nm	1310nm
Third window	1500nm - 1600nm	1550nm



Attenuation in early 1970s & 1980s & 1990s.



→ Early applications in the 1970s made use of 770 to 910nm wavelength there was low loss window

→ GaAlAs optical sources and silicon photo detectors operating at these wavelength.

→ Early fibers has minimum losses around 850nm

→ By reducing the concentration of hydroxyl ions and metallic impurities, manufactures have fabricated fibers with low attenuation with 1300nm window and 1550nm window.

→ It is observed that absorption spike remained around 1400nm.

→ Light sources was made up of InGaAsP

→ photo detector was made up of InGaAs

(P) A low loss fiber has ~~arrange~~ average loss of 3dB/Km at 900nm. compute the length over which a) power decreases by 50% b) power decreases by 75%

Sol: $\alpha = 3 dB/Km$

a) power decreases by 50%

$$\frac{P(0)}{P(z)} = 50\% = 0.5$$

$$\alpha = 10 \cdot \frac{1}{z} \log \left[\frac{P(0)}{P(z)}\right]$$

$$3 = 10 \cdot \frac{1}{z} \log [0.5] \Rightarrow z = 1Km$$

b) $\frac{P(0)}{P(z)} = 25\% \Rightarrow \frac{P(0)}{P(z)} = 0.25$

$\therefore$ power decreases by 75%.

$$3 = 10 \times \frac{1}{z} \log (0.25)$$

$$z = 2Km$$

(P) When mean optical power launched into an 8 km length of fiber is 12 µW. the mean optical power at the fiber output is 3 µW. Determine (1) overall signal attenuation in dB. (2) The overall signal attenuation for a 10km optical link using the same fiber with splices at 1km intervals, each giving an attenuation of 1dB.

Sol: Given $z = 8 Km$ $P(0) = 120 \mu W$ $P(z) = 3 \mu W$

(1) overall attenuation is given by $\alpha = 10 \cdot \log \left[\frac{P(0)}{P(z)}\right]$

$$\alpha = 10 \log \left[\frac{12.0}{3}\right] = 16.02 dB.$$

(2) overall attenuation for 10Km.

Attenuation per km $\alpha_{dB} = \frac{16.02}{z} = \frac{16.02}{8} = 2.00 dB/Km$

Attenuation in 10km link $= 2.00 \times 10 = 20dB$

In 10km link these will be a splices at 1km interval. Each splice introducing attenuation of 1 dB.

Total attenuation = 20dB + 9 dB = 29 dB

(P) A continuous 12 km long optical fiber link has a loss of 1.5 dB/km i) what is the minimum optical power level that must be launched in to the fiber to maintain as optical power level of 0.3 μW at the receiving end?
ii) what is the required input power if the fiber has a loss of 2.5 dB/km?

Sol: Given data $z = 12\,km$ $\alpha = 1.5\,dB/km$ $P(0) = 0.3\,\mu W$

i) Attenuation in optical fiber is given by

$$\alpha = 10 \times \frac{1}{z} \log\left[\frac{P(0)}{P(z)}\right] \Rightarrow 1.5 = 10 \times \frac{1}{12} \log\left[\frac{0.3\,\mu W}{P(z)}\right]$$

$$\log\left(\frac{0.3\,\mu W}{P(z)}\right) = \frac{1.5}{0.833}$$

$$= 1.80$$

$$\frac{0.3\,\mu w}{P(z)} = 10^{1.8} \Rightarrow P(z) = \frac{0.3\,\mu w}{10^{1.8}} = \frac{0.3}{63}$$

optical power o/p $P(z) = 4.76 \times 10^{-9}\,W$

ii) Input power $P(0) = ?$

when $\alpha = 2.5\,dB/km$ $\alpha = 10 \times \frac{1}{z} \log\left[\frac{P(0)}{P(z)}\right]$

$$2.5 = 10 \times \frac{1}{12} \log\left(\frac{P(0)}{4.76 \times 10^{-9}}\right)$$

$$\log\left[\frac{P(0)}{4.76 \times 10^{-9}}\right] = \frac{2.5}{0.833} = 3$$

$$\frac{P(0)}{4.76 \times 10^{-9}} = 10^{3} = 1000 \Rightarrow \therefore P(0) = 4.76\,\mu W$$

Input power = 4.76 μW

<u>ABSORPTION</u>: Absorption loss is related to the material composition and fabrication process of fibers. Absorption loss results in dissipation of some optical power as heat in the fiber cable. Although glass fibers are extremely pure, some impurities still remain as residue after purification. The amount of absorption by these impurities depends on their concentration and light wavelength.

Absorption is caused by three different mechanisms.

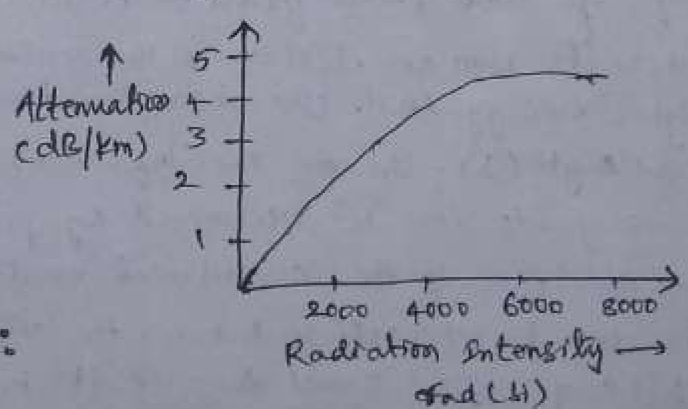
1) Absorption by atomic defects in glass composition
2) Extrinsic absorption by impurity atoms in glass matts.
3) Intrinsic absorption by basic constituent atom of fiber.

<u>Absorption by atomic defects</u>: Atomic defects are imperfections in the atomic structure of the fiber materials such as missing molecules, high density clusters of atom groups. These absorption losses are negligible compared with intrinsic and extrinsic losses. The absorption effect is most significant, when fiber is exposed to ionizing radiation in nuclear reactor, medical therapies, space missions. Thus radiation damages are proportional to the intensity of ionizing particles. This results in increasing attenuation due to atomic defects and absorbing optical energy.

$$1 \text{ rad (Si)} = 0.01 \text{ J.kg}$$

The higher the radiation intensity more the attenuation as shown in fig

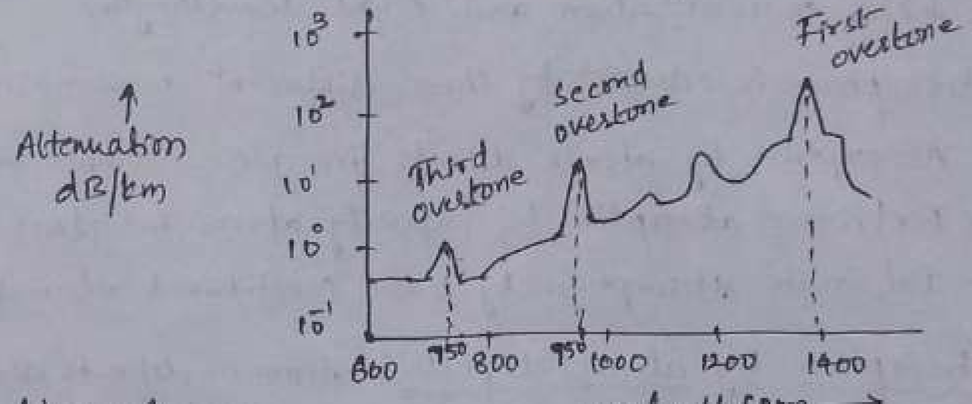
fig. ionizing radiation intensity vs fiber attenuation.



<u>Extrinsic Absorption</u>:

Extrinsic absorption occurs due to electronic transitions between the energy level and because of charge transitions from one ion to another. A major source of attenuation is from transition of metal impurity ions such as iron, chromium, cobalt and copper. These losses can be up to 1 to 10 dB/Km.

Another major extrinsic loss is caused by absorption due to OH (Hydroxil) ions impurities disolved in glass. Vibrations occurs at wavelengths between 2.7 and 4.2 μm. The absorption peaks occurs at 1400, 950 and 750 nm. These are first, second and third overtones respectively. Fig. shows absorption spectrum for OH group in silica.



Intrinsic Absorption:

Intrinsic absorption occurs when material is in absolutely pure state, no density variation and inhomogenities. Thus intrinsic absorption sets the fundamental lower limit on absorption for any particular material. Intrinsic absorption results from electronic absorption bands in UV region and from atomic vibration bands in the near infrared region.

The electronic absorption bands are associated with the band gaps of amorphous glass materials. Absorption occurs when a photon interacts with an electron in the valence band and excites it to a higher energy level. UV absorption decays exponentially with increasing wavelength (λ). In the IR (infrared) region above 1.2 μm the optical wave guide loss is determined by presence of the OH ions and inherent IR absorption of the constituent materials. The inherent IR absorption is due to interaction between the vibrating band and the electromagnetic field of optical signal this results in transfer of energy from field to the band, there by giving rise to absorption, this absorption is strong because of many bands present in the fiber.

Attenuation spectra for the intrinsic loss mechanism in pure Ge is shown in fig.

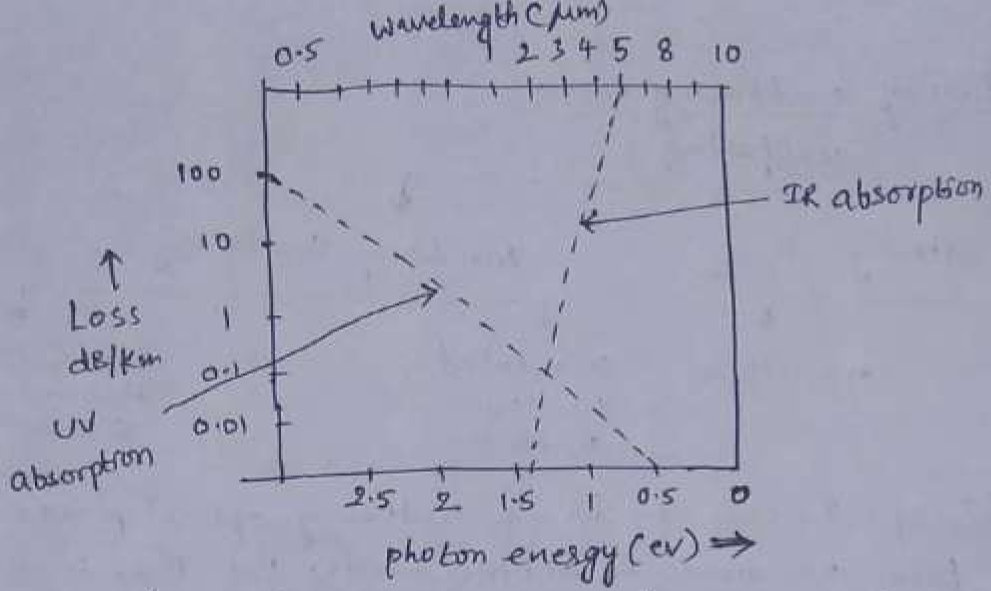


fig Attenuation spectra for intrinsic loss

The ultraviolet loss at any wavelength is expressed as

$$\alpha_{uv} = \frac{154.2}{46.6x+60} \times 10^{-2} \times e^{\left(\frac{4.63}{\lambda}\right)}$$

where x – mole fraction of GeO_2, λ – operating wavelength

α_{uv} – in dB/Km

The loss in infrared (IR) region (above 1.2μm) is expressed as

$$\alpha_{IR} = 7.81 \times 10^{11} \times e^{\left(\frac{-48.48}{\lambda}\right)}$$

The expression is derived for GeO_2-SiO_2 glass fiber.

Scattering losses: scattering losses are caused by the interaction of light with density fluctuations with in a fiber. Density changes are produced when optical fibers are manufactured. During manufacturing regions of higher and lower molecular density areas, relative to the average density of the fiber are created. Light travelling through the fiber interacts with the density areas as shown in light is then partially scattered in all directions.

Scattering losses in fiber exists due to various factors

1. Microscopic variations in density of fiber materials.
2. compositional fluctuations.
3. structural inhomogenities.
4. structural defects in fiber.

Classification of scattering loss:

scattering
- linear scattering
  - Rayleigh scattering
  - Mie scattering
- Non linear scattering
  - Stimulated Brillouin scattering
  - Stimulated Raman scattering

Linear scattering: In case of linear scattering optical power transferred from one mode to another mode. But there is no change in frequency on the scattering.

Rayleigh scattering losses: Rayleigh scattering of light is due to small localized changes in the refractive index of the core and cladding material. There are two causes during the manufacturing of fiber. The first is due to slight fluctuations in mixing of ingradients. The random changes because of this are impossible to eliminate completely. The second is slight change in density as the silica cools and solidifies. When light ray strikes such zones it gets scattered in all directions. The amount of scatter depends on the size of the discontinuity compared with the wavelength of the light so the shortest wavelength suffers most scattering.

fig. The relationship between wavelength and Rayleigh scattering loss

scattering loss for single-component glass is given by

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4}(n^2-1)^2 K_B T_f \beta_c \text{ nepers}$$

where n – refractive index, K_B – Boltzman's constant

β_c – Isothermal compressibility of material

T_f – Temperature at which density fluctuations are frozen in to a glass as it solidifies.

Another form of equation is

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 k_B T_f \beta_c \text{ nepers}$$

where p – photoelastic coefficient

scattering loss for multicomponent glasses is given by

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} (\delta_n^2)^2 \delta v$$

where δ_n^2 – mean-square refractive index fluctuation.

δv – Volume of fiber.

Mie scattering loss: The scattering caused by homogenetic which are comparable in size with guided wavelength are called as Mie scattering. This is a linear scattering which is always in forward direction.

Factors responsible for Mie scattering are as follows

- cylindrical structure of cable is not perfect
- Imperfection of core and cladding interface
- core and cladding refractive index is not uniform through out of fiber.
- There are fluctuations in core diameter
- Due to bubble or strain in fiber

Mie scattering results significant attenuation depending upon fiber material, size, design and manufacturing process. It can be reduce by following steps

- Removing imperfections during glass manufacturing process.
- controlling the coating of fiber
- Increase refractive index difference between core and cladding.

Non linear Scattering: when the optical power is transferred from one mode to other mode or same mode with different frequency, Non linear scattering happens. This scattering takes place either in forward or backward direction. It produces optical gain but there is a shift in frequency. This shift in frequency results loss of signal and creates attenuation.

There are two types of Non linear scattering.

- stimulated Brillouin Scattering
- stimulated Raman Scattering.

Stimulated Brillioun Scattering (SBS): SBS may be regarded as the modulation of light through thermal molecular vibrations with in the fiber. The scattering light appears as upper and lower sidebands which are seperated from the incident light by the modulation frequency. The incident photon in this scattering process produces a photon of acoustic frequency as well as a scattered photon. This produces an optical frequency shift which varies with the scattering angle because the frequency of the sound wave varies with acoustic wavelength. The frequency shift is a maximum in the backward direction reducing to zero in the forward direction making SBS a mainly backward process.

Threshold optical power $P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu$ watts

where d - core diameter (μm) λ - operating wavelength (μm)

α_{dB} - fiber attenuation (dB/km) ν - source bandwidth (GHz)

Stimulated Raman Scattering (SRS): This scattering is similar to stimulated Brillioun scattering except that a high frequency optical phonon rather than an acoustic phonon is generated in the scattering process. SRC can occurs in both forward and backward direction in an optical fiber, and may have an optical power threshold of up to three orders of magnitude higher than the Brillowin threshold in particular fiber. $P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB}$ watts

Raman scattering basically represents inelastic scattering of photons. When a laser light is travelling through optical cable, the spontaneous scattering takes place. In this process, some of the photons are transferred to the near frequencies. when the scattered photons lose their energy then it is called as stokes shift and when the scattered photons gain energy then it is called as anti-stokes shift. But if the photons of other frequencies are already present then the scattering of such photons takes place and in this case the two photons are generated. It is called as stimulated Raman Scattering.

(P) A long single mode optical fiber has an attenuation of 0.5 dB/km when operating of a wavelength of 1.3 μm. The fiber core diameter is 6 μm and the laser source bandwidth is 600 MHz. Compare the threshold optical power for stimulated Brillouin and Raman scattering with in the fiber at the wavelength specified.

$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu$

$= 4.4 \times 10^{-3} \times 6^2 \times 1.3^2 \times 0.5 \times 0.6$

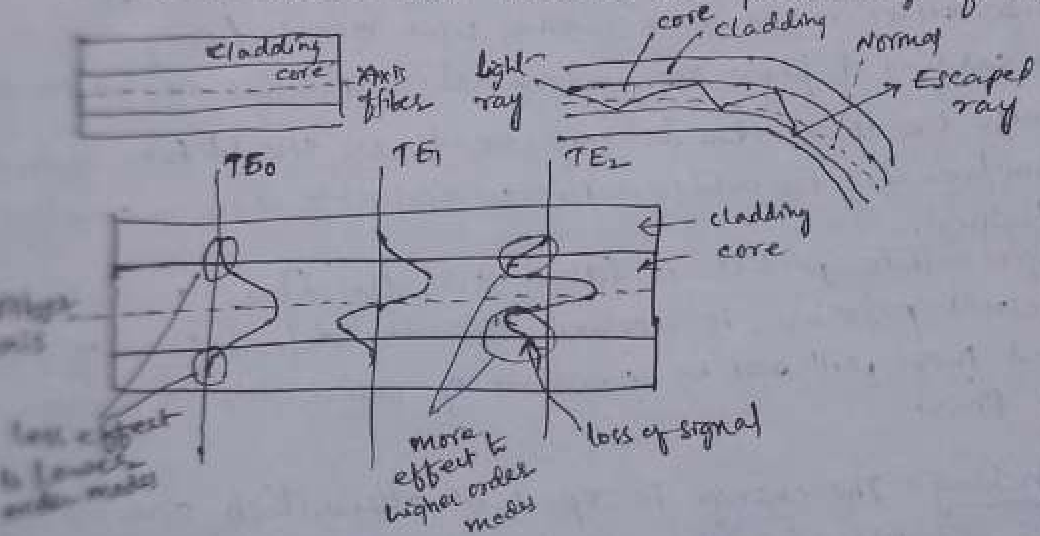
$= \underline{80.3\,mW}$

$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB}$

$= 5.9 \times 10^{-2} \times 6^2 \times 1.3 \times 0.5$

$= \underline{1.38\,W}$

Fiber Bending losses: Losses due to curvature and losses caused by an abrupt change in radius of curvature are referred to as bending losses. The sharp bend of a fiber causes significant radiative losses and there is also possibility of mechanical failure.



As the core bends the normal will follow it and the ray will now find itself on the wrong side of critical angle and will escape. The sharp bends are therefore avoided. The radiation loss from a bent fiber depends on i) Field strength of certain critical distance X_c from fiber axis where power is lost through radiation. ii) The radius of curvature R.

The higher order modes are less tightly bound to the fiber core, the higher order modes radiate out of fiber first. For multimode fiber, the effective number of modes that can be guided by curved fiber is given by.

$$N_{eff} = N_\infty \left\{ 1 - \frac{\alpha+2}{2\alpha\Delta} \left[\frac{2a}{R} + \left(\frac{3}{2 n_2 k R} \right)^{2/3} \right] \right\}$$

where α – graded index profile

Δ – core-cladding index difference n_2 – refractive index of cladding

k – wave propagation constant $(2\pi/\lambda)$

N_∞ – Total number of modes in straight fiber $N_\infty = \frac{\alpha}{\alpha+2} (n_1 k a)^2 \Delta$

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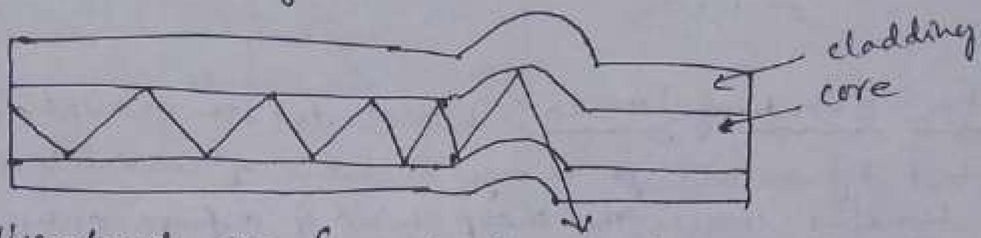
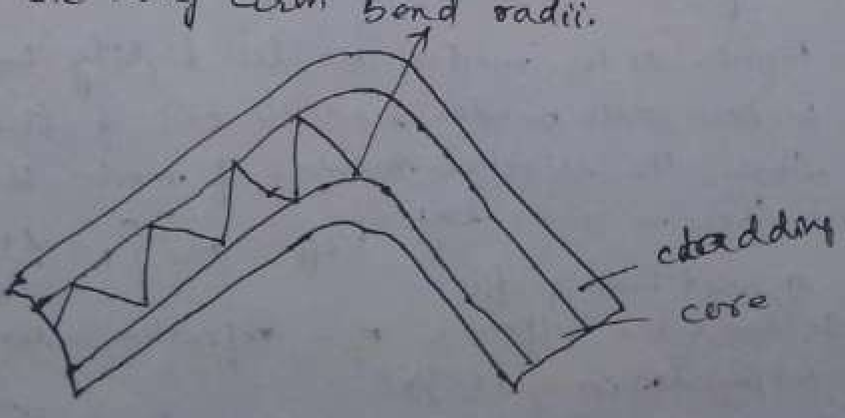
Microbending: These are the losses due to small bending or small distortion. This small microbending is not visible. The losses due to this are temperature related, tensile related or crush related. The effects of microbending on multimode fibes can result in increasing attenuation to a series of periodic peaks and troughs on the spectral attenuation curve. These effects can be minimized during installation and testing.



→ The Microbends are formed due to two main reasons:
- Non uniformities in the core radius, while manufacturing the cable.
- During the cabling of fibers, nonuniform lateral pressure can be created.

→ To minimize the losses due to microbends we should takes following steps
- While manufacturing the cable, a precise control of core diameter is maintained.
- A compressible jacket is fitted over the fiber, so that when the external pressure is applied then the deformation of jacket place and there will not be creation of microbends in the core layer of fiber.

Macrobending: The change in spectral attenuation caused by macrobending is different to microbending. Usually there are no peaks and troughs because in a macrobending no light is coupled back in to the core from the cladding as can happen in the case of microbends. The macrobending losses are cause by large scale bending of fiber. The losses are eliminated when the bends are straightened. The losses can be minimized by not exceeding the long term bend radii.



Scanned with CamScanner

core and cladding losses:

Since the core and cladding have different indices of refraction hence they have different attenuation coefficients α_1 and α_2 respectively.

For step index fiber, the loss for a mode order (ν, m) is given by:

$$\alpha_{\nu m} = \alpha_1 \frac{P_{core}}{P} + \alpha_2 \frac{P_{cladding}}{P}$$

For low-order modes, the expression reduced to

$$\alpha_{\nu m} = \alpha_1 + (\alpha_2 - \alpha_1) \frac{P_{cladding}}{P}$$

where $\frac{P_{core}}{P}$ and $\frac{P_{cladding}}{P}$ are fractional powers.

For graded index fiber, loss at radial distance r is expressed as

$$\alpha(r) = \alpha_1 + (\alpha_2 - \alpha_1) \frac{n^2(0) - n^2(r)}{n^2(0) - n_2^2}.$$

The loss for a given mode is expressed by

$$\alpha_{Graded\ Index} = \frac{\int_0^{\infty} \alpha(r) P(r)\, r\, dr}{\int_0^{\infty} P(r)\, r\, dr}$$

where, $P(r)$ is power density of that mode at radial distance r

(P) For a 30 Km long fiber attenuation 0.8 dB/Km at 1300 nm. If a 200 μ watt power is launched in to the fiber, find the output power.

Sol: Given data $z = 30\,km$ $\alpha = 0.8\,dB/km$ $P(0) = 200\mu W$

Attenuation in optical fiber is given by

$$\alpha = \frac{10}{z} \log\left[\frac{P(0)}{P(z)}\right]$$

$$0.8 = \frac{10}{30} \log\left[\frac{200\mu W}{P(z)}\right]$$

$$\frac{0.8 \times 30}{10} = \log\left[\frac{200\mu W}{P(z)}\right] \Rightarrow 2.4 = \log\left[\frac{200\mu W}{P(z)}\right]$$

$$\frac{200\mu W}{P(z)} = 10^{2.4} \Rightarrow P(z) = \frac{200\mu W}{251.1886} = 0.7962\,\mu W$$

$$\therefore \quad P(z) = 0.7962$$

(P) Optical power launched in to the fiber at transmitter end is 150 μW. The power at the end of 10 km length of the link working in first window is −38.2 dBm. Another system of same length working in second window is 47.5 μW. Same length system working in third window has 50% of launched power. Calculate fiber attenuation for each case and mention wavelength of operation.

Sol: Given data $P(0) = 150\,\mu W$ $\quad z = 10\,km$

$P(z) = -38.2\ dBm \Rightarrow \begin{cases} -38.2 = 10\log \frac{P(z)}{1\,mW} \\ P(z) = 0.151\,\mu W \end{cases}$

$$\alpha = \frac{10}{z}\log\left[\frac{P(0)}{P(z)}\right]$$

Attenuation in 1st window:

$$\alpha_1 = \frac{10}{10}\log\left[\frac{150}{0.151}\right] = 2.99\ dB/Km$$

Attenuation in 2nd window:

$$\alpha_2 = \frac{10}{10}\log\left[\frac{150}{47.5}\right] = 0.49\ dB/Km$$

Attenuation in 3rd window:

$$\alpha_3 = \frac{10}{10}\log\left[\frac{150}{75}\right] = 0.30\ dB/Km$$

∴ Wavelength in 1st window is 850 nm

wavelength in 2nd window is 1300 nm

wavelength in 3rd window is 1550 nm.

(P) The input power to an optical fiber is 2 mW, while the power measured at the output end is 2 μW. If the fiber attenuation is 0.5 dB/Km, calculate the length of the fiber.

Sol. Given $P(0) = 2\,mW = 2\times10^{-3}\,W$

$P(z) = 2\,\mu W = 2\times10^{-6}\,W$

$\alpha = 0.5\ dB/Km$

$$\alpha = \frac{10}{z}\log\left[\frac{P(0)}{P(z)}\right] \Rightarrow 0.5 = \frac{10}{z}\log\left[\frac{2\times10^{-3}}{2\times10^{-6}}\right]$$

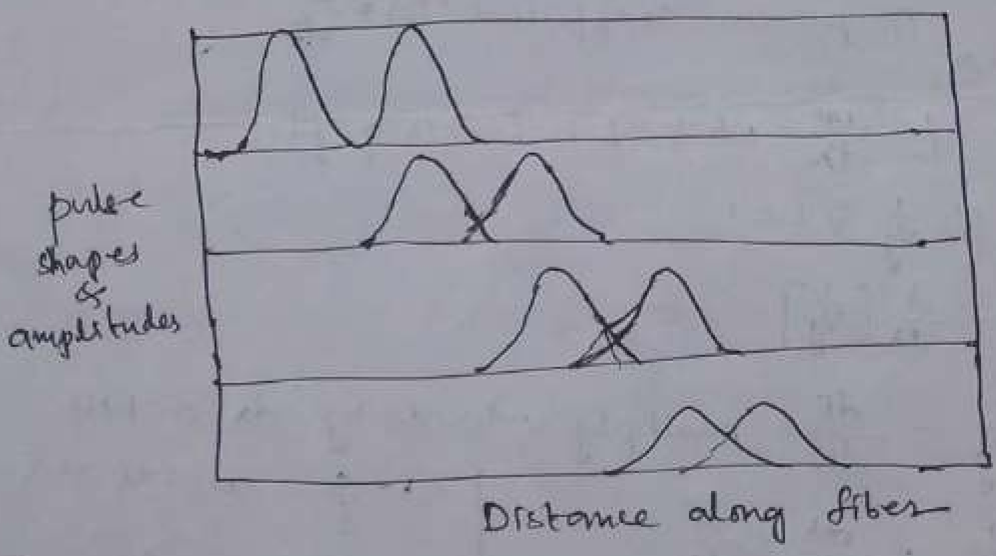
$$0.05 = \frac{1}{z}\times 3$$

$$\therefore\ \underline{z = 60\ km}$$

Information capacity Determination

The pulse gets distorted as it travels along the fiber lengths. Pulse spreading in fiber is referred as dispersion. Dispersion is caused by difference in the propagation times of light rays that takes different paths during the propagation. The light pulses travelling down the fiber encounter dispersion effect because of this the pulse spreads out in time domain. Dispersion limits the information bandwidth. The distortion effects can be analyzed by studying the group velocities in guides modes.

Dispersion of attenuation of pulse travelling along the fiber is shown in fig.



After travelling some distance, pulse starts broadening and overlap with the neighbouring pulses. At certain distance the pulses are not even distinguishable and error will occur at receiver. Therefore the information capacity is specified by bandwidth-distance product. For multi mode step index bandwidth distance products is 20 MHz. km, ~~and~~ for graded index it is 2.5 GHz. km & For single mode fibers are higher than 10 GHz. Km.

Group Delay : consider a fiber cable carrying optical signal equally with various modes and each mode contains all the spectral components in the wavelength band. All the spectral components travel independently and they observe different time delay and group delay in the direction of propagation. The velocity at which the energy in a pulse travels along the fiber is known as group velocity and is given by.

$$V_g = \frac{\partial W}{\partial \beta}$$

Thus different frequency components in a signal will travell at different group velocities and so will arrive at their destination at different times, which results in dispersion of pulse. Let the difference in propagation for two sidebands is δT.

Dissipation Dispersion coefficient (D) $= \frac{d\tau}{d\lambda}$

$D = \frac{1}{L} \cdot \frac{d\tau}{d\lambda}$ where L is Length of fiber

As $\tau = \frac{1}{V_g}$ & $L = 1$

$$D = \frac{d}{d\lambda}\left[\frac{1}{V_g}\right]$$

Now $\frac{1}{V_g} = \frac{d\beta}{dW}$ multiply & divide by '$d\lambda$' on RHS

$$\frac{1}{V_g} = \frac{d\lambda}{dW} \times \frac{d\beta}{d\lambda}$$

$\lambda = \frac{c}{f}$ $\cdot\ \omega = 2\pi f \Rightarrow f = \frac{\omega}{2\pi}$

$\lambda = \frac{2\pi c}{\omega} \Rightarrow \frac{d\lambda}{d\omega} = \frac{-2\pi c}{\omega^2}$

$= \frac{-2\pi c}{(2\pi)^2 f^2} = \frac{-c}{2\pi \frac{c^2}{\lambda^2}}$

$= \frac{-\lambda^2}{2\pi c}$

$$\frac{1}{V_g} = -\frac{\lambda^2}{2\pi c} \times \frac{d\beta}{d\lambda}$$

$$D = \frac{d}{d\lambda}\left[\frac{-\lambda^2}{2\pi c} \cdot \frac{d\beta}{d\lambda}\right]$$

Dispersion is measured in picoseconds per nanometer per kilometer.

There are two types of Dispersion
1. Intramodal Dispersion : Dispersion in single mode fibers
2. Intermodal Dispersion : Dispersion in multimode fibers

- Dispersion
  - Intramodal (Chromatic) Dispersion
    - Material dispersion
    - Waveguide dispersion
  - Intermodal Dispersion

<u>Intramodal dispersion</u>: This dispersion is due to finite bandwidth of the signal. This dispersion is pulse spreading that takes place with in a single mode. This spreading arises from the finite spectra emission width of an optical source. The phenomenon also known as group velocity dispersion, since the dispersion is a result of the group velocity being a function of the wavelength.

The two main causes of intramodal dispersion are

1. <u>Material dispersion (Chromatic dispersion)</u>: This is due to intrinsic properties of the material, glass. Material dispersion exists due to change in index of refraction for different wavelengths. A light ray contains components of various wavelengths centered at wavelength "λ". The time delay is different for different wavelength components. This results in time dispersion of pulse at the receiving end of fiber. The pulse spread due to material dispersion obtained by considering the group delay τ_g in the optical fiber which is the reciprocal of the group velocity v_g defined by eqns. $v_g = \frac{\delta\omega}{\delta\beta} \rightarrow (1)$ and

$$v_g = \frac{c}{\left(n_1 - \lambda \frac{dn_1}{d\lambda}\right)} = \frac{c}{N_g} \rightarrow (2) \quad (N_g - \text{group index of the guide})$$

Hence the group delay is given by

$$\tau_g = \frac{d\beta}{d\omega} = \frac{1}{c}\left(n_1 - \lambda \frac{dn_1}{d\lambda}\right) \rightarrow (3)$$ n_1 - refractive index of the core.

The pulse delay τ_m due to material dispersion in a fiber of length L

$$\therefore \quad \tau_m = \frac{L}{c}\left(n_1 - \lambda \frac{dn_1}{d\lambda}\right) \rightarrow (4)$$

For a source with rms spectral width σ_λ and a mean wavelength λ, the rms pulse broadening due to material dispersion σ_m obtained from the expansion of eqn - (4) in a Taylor series about λ where;

$$\sigma_m = \sigma_\lambda \frac{d\tau_m}{d\lambda} + \sigma_\lambda \frac{\lambda\, d^2\tau_m}{d\lambda^2} + \cdots \longrightarrow (5)$$

As the first term in Eqn (5) usually dominates, especially for sources operating over the 0.8 to 0.9 μm wavelength range, then

$$\sigma_m \simeq \sigma_\lambda \frac{d\tau_m}{d\lambda} \longrightarrow (6)$$

Hence the pulse spread may be evaluated by considering the dependence of τ_m on λ, where from Eqn (4)

$$\frac{d\tau_m}{d\lambda} = \frac{L\lambda}{c}\left[\frac{dn_1}{d\lambda} - \frac{d^2n_1}{d\lambda^2} - \frac{dn_1}{d\lambda}\right]$$

$$= \frac{-L\lambda}{c}\frac{d^2n_1}{d\lambda^2} \longrightarrow (7)$$

∴ Substituting the eqn (7) in to Eqn (6), the rms pulse broadening due to material dispersion is given by

$$\sigma_m \simeq \frac{\sigma_\lambda L}{c}\left|\lambda \frac{d^2n_1}{d\lambda^2}\right| \longrightarrow (8)$$

The material dispersion for optical fibers is sometimes quoted as a value for $\left|\lambda^2 \frac{d^2n_1}{d\lambda^2}\right|$ or simply $\left|\frac{d^2n_1}{d\lambda^2}\right|$

However, it may be given in terms of a material dispersion parameter M which is defined as

$$M = \frac{1}{L}\frac{d\tau_m}{d\lambda} = \frac{\lambda}{c}\left|\frac{d^2n_1}{d\lambda^2}\right| \longrightarrow (9) \quad \text{units} - \text{ps nm}^{-1}\text{km}^{-1}$$

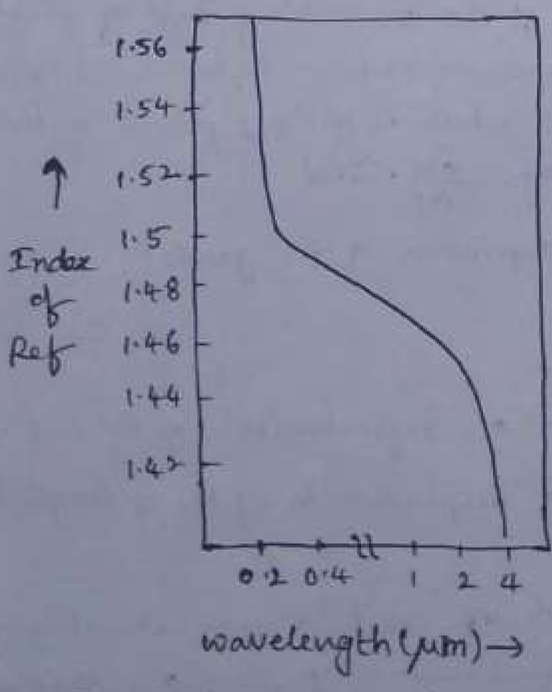
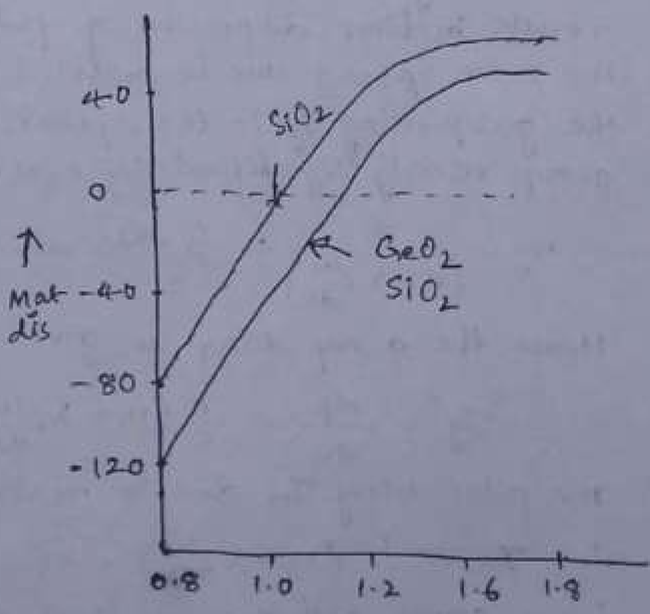


Fig. Index of refraction as a function of wavelength



Waveguide dispersion: waveguide dispersion causes pulse spreading because only part of the optical power propagation along a fiber is confined to the core. Dispersion arises because the fraction of light power propagating in the cladding travels faster than the light confined to the core, since the index is lower in the cladding. When the speed of wave in a wave guide depends on its frequency then waveguide dispersion takes place. Wave guide dispersion usually can be ignored in multimode fibers, but it effect is significant in single mode fibers.

Waveguide dispersion is significant only in fibers carrying fewer than 5-10 modes. Since multimode optical fibers carry hundreds of modes, they will not have observable wave guide dispersion.

The group delay (τ_{wg}) arising due to waveguide dispersion

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d(kb)}{dk}\right]$$

$\tau_{wg} = \frac{L}{c}[n_2 + n_2 \Delta$ where b – Normalized propagation constant

$K - 2\pi/\lambda$ (group velocity)

Normalized frequency V

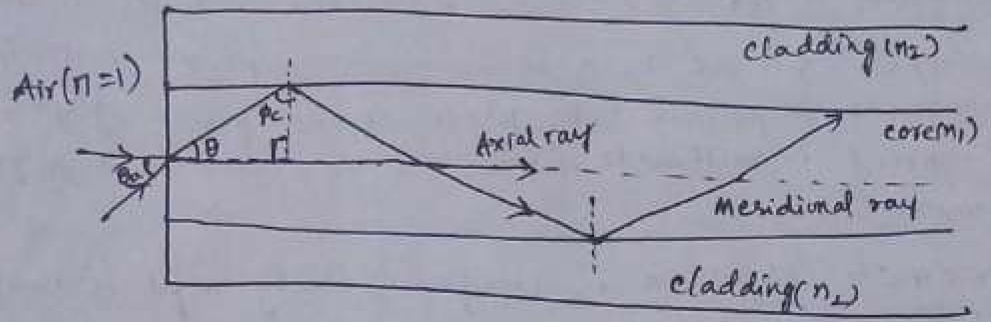
$$V = Ka(n_1^2 - n_2^2)^{1/2} = Kan_2\sqrt{2\Delta} \quad \text{(For small } \Delta\text{)}$$

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d(V_b)}{V}\right]$$

$\frac{dV_b}{dV}$ – waveguide dispersion term & mode dependent term.

Intermodal dispersion :– It is also known as modal or mode dispersion. Pulse broadening due to intermodal dispersion results from the propagation delay differences between modes within a multimode fiber. The different modes in a multimode fiber travel along the channel at different group velocities. Multimode stepindex fibers exhibit a large amount of intermodal dispersion which gives the greatest pulse broadening. The overall pulse broadening in multimode graded index fibers is far less than that multimode step index fibers. Graded index fibers used with a multimode source gives a tremendous bandwidth advantage over multimode stepindex fibers.

Multimode step index fiber: Using the ray theory model, the fastest and slowest modes propagating in the step index fiber may be represented by the axial ray and the meridional ray respectively and the paths taken by these rays as shown in the fig.



The delay difference between these two rays when travelling in the fiber core allows estimation of the pulse broadening resulting from intermodal dispersion with in the fiber. As both rays are travelling at the same velocity within the constant refractive index fiber core, then the delay difference is directly related to their respective path lengths within the fiber. Hence the time taken for the axial ray to travel along the a fiber of length L gives the minimum delay time T_{min}

$$T_{min} = \frac{\text{distance}}{\text{Velocity}} = \frac{L}{(c/n_1)} = \frac{Ln_1}{c} \longrightarrow ①$$

where n_1 - core refractive index c - Velocity of light in a Vacuum

The meridional ray exhibits the maximum delay time T_{max}

$$T_{max} = \frac{L/\cos\theta}{c/n_1} = \frac{Ln_1}{c\cos\theta} \longrightarrow ②$$

using snell's law

$$\sin\phi_c = \frac{n_2}{n_1} = \cos\theta \longrightarrow ③$$

substitute $\cos\theta$ in to eqn ②

$$T_{max} = \frac{Ln_1^2}{cn_2} \longrightarrow ④$$

The delay difference δT_s between meridional ray and axial ray is

$$\delta T_s = T_{max} - T_{min} = \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c} = \frac{Ln_1^2}{cn_2}\left[\frac{n_1 - n_2}{n_1}\right] \longrightarrow ⑤$$

$$\simeq \frac{Ln_1^2\Delta}{cn_2} \longrightarrow ⑥ \quad \text{when } \Delta \ll 1$$

where Δ - Relative refractive index difference

The relative refractive index difference may also be given approximately

$$\Delta \simeq \frac{n_1 - n_2}{n_2} \quad \text{when } \Delta \ll 1 \longrightarrow (7)$$

Hence rearranging eqn (5)

$$\delta T_s = \frac{L n_1}{c}\left(\frac{n_1 - n_2}{n_2}\right) \simeq \frac{L n_1 \Delta}{c} \longrightarrow (8)$$

Also subtracting for $\Delta = \frac{(NA)^2}{2n_1^2}$

$$NA = n_1\sqrt{2\Delta}$$

$$NA^2 = n_1^2 2\Delta$$

$$\Delta = \frac{(NA)^2}{2n_1^2}$$

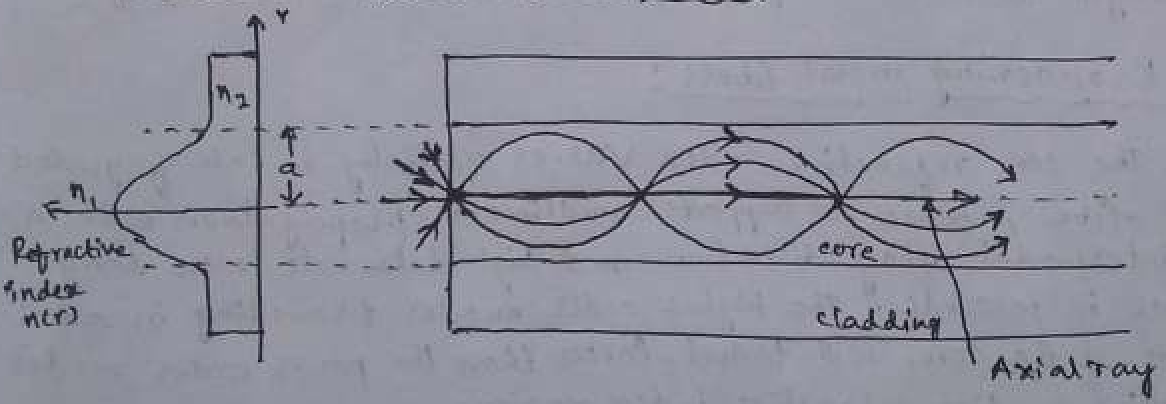
$$\delta T_s = \frac{L n_1}{c}\frac{(NA)^2}{2n_1^2}$$

$$\delta T_s = \frac{L (NA)^2}{2 n_1 c}$$

Intermodal dispersion may be reduced in nonperfect multimode fibers by with the mode coupling mechanism. In perfect step index fiber, the rms pulse broadening at the fiber output due to intermodal dispersion is given by

$$\sigma_s \simeq \frac{L n_1 \Delta}{2\sqrt{3}\, c} \simeq \frac{L (NA)^2}{4\sqrt{3}\, n_1 c}$$

Multimode graded index fiber



Intermodal dispersion in multimode fibers is minimized with the use of graded index fibers. The improvement in multimode fiber bandwidth achieved with a parabolic refractive index profile as shown in fig. Using a ray theory approach the delay difference is given by

$$\delta T_g \simeq \frac{L n_1 \Delta^2}{2c} \simeq \frac{L (NA)^4}{8 n_1^3 c}$$

The best minimum theoretical intermodal rms pulse broadening for a graded index fiber is given by

$$\sigma_g = \frac{L n_1 \Delta^2}{20\sqrt{3}\, c}.$$

Polarization Mode Dispession (PMD):

Different frequency components of a pulse acquires different polarization states (such as linear polarization and circular polarization). This results in pulse broadening is known as polarization mode dispession (PMD). PMD is the limiting factor for optical communication system at high data rates. The effects of PMD must be compensated.

Fiber birefringence:

The algebraic difference of the index of refraction of the fiber for plane polarized light vibrating parallel to the longitudinal axis of the fiber and the index of refraction for light vibrating perpendicular to the long axis is called fiber birefringence

Fiber beat length:

It is a characteristic of optical fiber used to calculate the fibers ability to maintain polarization. The beat length describes the length required for the polarization to rotate 360°, For a given wavelength it is inversely proportional to the fiber birefrigence.

Pulse Broadening in GI fibers:

The core refractive index varies radially in case of graded index fibers, hence it supports multimode propagation with a low intermodal delay distortion and high data rate over long distance is possible. The higher order modes travelling in outer regions of the core, will travel faster than the lower order modes travelling in high refractive index region.

The rms pulse broadening is given as

$$\sigma = (\sigma^2_{intermodal} + \sigma^2_{intramodal})^{1/2}$$

where $\sigma_{intermodal}$ – rms pulse width due to intermodal delay distortion

$\sigma_{intramodal}$ – r.m.s pulse width resulting from pulse broadening within each mode

The intermodal delay and pulse broadening are related by expression given by Personick

$$\sigma_{intermodal} = \left[\langle \tau_g^2 \rangle - \langle \tau_g \rangle^2 \right]^{1/2}$$

where τ_g is group delay.

From this the expression for intermodal pulse broadening is given as

$$\alpha_{intermodal} = \frac{LN_1\Delta}{2c} \cdot \frac{\alpha}{\alpha+1} \left(\frac{\alpha+2}{3\alpha+2} \right)^{1/2} \left[c_1^2 + \frac{4c_1c_2(\alpha+1)}{2\alpha+1} + \frac{16\Delta^2 c_2^2 (\alpha+1)^2}{(5\alpha+2)(3\alpha+2)} \right]^{1/2}$$

where $c_1 = \frac{\alpha-2-\epsilon}{\alpha+2}$ and $c_2 = \frac{3\alpha-2-2\epsilon}{2(\alpha+2)}$

The intramodal pulse broadening is given as:

$$\sigma^2_{intramodal} = \left(\frac{\sigma_\lambda}{\lambda} \right)^2 \left\langle \left[\lambda \frac{d\tau_g}{d\lambda} \right]^2 \right\rangle$$

where σ_λ is spectral width of optical source

Solving the expression gives

$$\sigma^2_{intramodal} = \frac{L}{c} \cdot \frac{\sigma_\lambda}{\lambda} \left[\left(-\lambda^2 \frac{d^2 n_1}{d\lambda^2} \right)^2 - N_1 c_1 \Delta \left(2\lambda^2 \frac{d^2 n_1}{d\lambda^2} \cdot \frac{\alpha}{\alpha+1} - N_1 c_1 \Delta \frac{4\alpha^2}{(\alpha+2)(3\alpha+2)} \right) \right]^{1/2}$$

Optical Fiber Connectors:

Connectors are mechanisms or techniques used to join an optical fiber to another fiber or to a fiber optic component. Different connectors with different characteristics, advantages and disadvantages and performance parameters are available. Suitable connector is chosen as per the requirement and cost. The principal requirements of a good connector design are as follows:

1. Low coupling losses: The connector assembly must maintain stringent alignment tolerance to low mating losses. These low losses must not change significantly during operation or after connects and disconnects.

2. Interchangeability: connectors of the same type must be compatible from one manufacturer to another.

3. Ease of assembly: A service technician should be able to install the connector in a field environment ie in a location other than the connector factory.

4. Low environmental sensitivity: conditions such as temperature, dust, and moisture should have a small effect on connector-loss variations.

5. Low-cost and reliable construction: The connector must have a precision suitable to the application, but its cost must not be a major factor in the fiber system.

6. Ease of connection: One should be able to mate and demate the connector, simply by hand.

Connector Types: The most commonly used connectors are the twist-on and snap-on design. These include both single channel and multichannel assemblies for cable-to-cable and for cable-to-circuit card connections. The basic coupling mechanisms used in these connectors belong to either the butt-joint or the expanded beam classes.

Butt-joint connectors employ a metal, ceramic or molded plastic ferrule for each fiber and a precision sleeve in to the ferrule fit. The fiber is epoxied in to a precision hole which has been drilled in to the ferrule. Butt joints are used for single mode as well as for multimode fiber systems. Two commonly used butt-joint alignment designs are 1. straight sleeve 2. Tapered-sleeve or Biconical.

1. straight-sleeve:

In the straight sleeve connector, the length of the sleeve and a guide ring on the ferrules determine the end of seperation of the fiber.

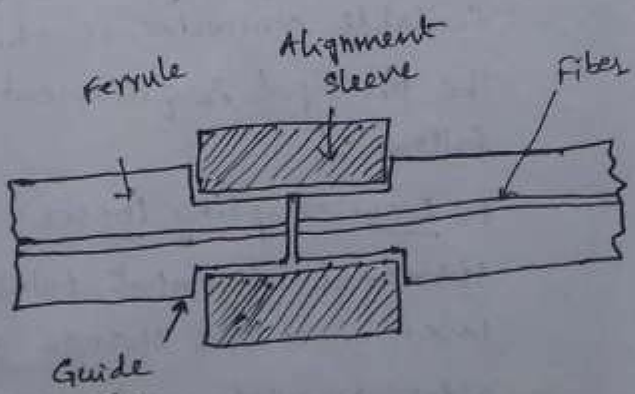


fig. Straight-sleeve Connector.

2. tapesed-sleeve (biconical) connector:

The tapesed-Sleeve connector uses a tapesed sleeve to accept and guide tapesed ferrules. Again, the sleeve length and guide rings maintain a given fiber end separation.

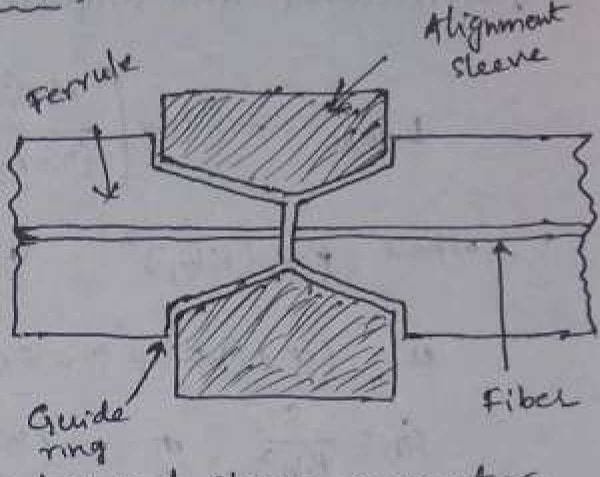


fig. tapesed sleeve connector.

An expanded beam connector employs lenses on the ends of the fibers. These lenses either collimate the light emerging from the transmitting fiber, or focus the expanded beam on to the core of the receiving fiber. The fiber to lens distance is equal to the focal length of the lens. The beam is collimated, seperation of the fiber ends may take place within the connector. Thus the connector is less dependent on lateral alignment. In addition optical processing elements, such as beam splitters and switches can easily be inserted on to the expanded beam between the fiber ends.

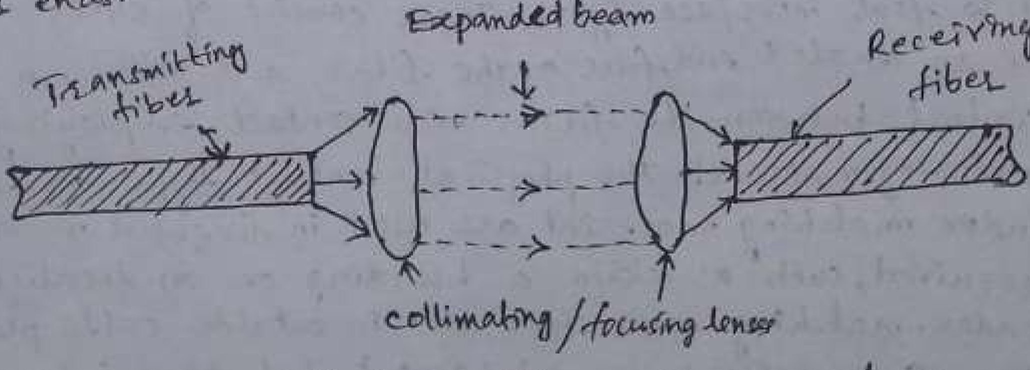


fig. expanded-beam fiber optic connector.

Single Mode Fiber Connectors: Because of the wide use of single mode fiber optic links and because of the greater aligoment precision required for these systems are single mode connector coupling losses. Based on the gaussian beam model of single mode fiber fields, the following equation gives the coupling loss between single mode fibers that have unequal modefield diameters and lateral, Longitudinal and angular offsets pulse reflections:

$$L_{SMff} = -10 \log\left[\frac{16 n_1^2 n_3^2}{(n_1+n_3)^4} \frac{4\sigma}{q} \exp\left(-\frac{\rho u}{q}\right)\right]$$

where $\rho = (KW_1)^2$, $q = G^2 + (\sigma+1)^2$, $F = \frac{d}{KW_1^2}$

$$u = (\sigma+1)F^2 + 2\sigma F G \sin\theta + \sigma(G^2+\sigma+1)\sin^2\theta$$

$$G = \frac{S}{KW_1^2}, \quad \sigma = (W_2/W_1)^2 \quad K = 2\pi n_3/\lambda$$

n_1 - core refractive index of fibers, d - lateral offset
n_3 - refractive index of medium between fibers
λ - wavelength of source, S - longitudinal offset
θ - angular misalignment
W_1 - $1/e$ mode field radius of transmitting fiber
W_2 - $1/e$ mode field radius of receiving fiber.

Connector Return Loss:

A connection point in an optical link can be categorized into four interface types. These consist of either a perpendicular or an angled end face on the fiber, and either a direct physical contact between the fibers or a contact employing an index-matching material. The physical contact type connectors without index matching material are used in frequent reconnections are required, such as within a building or on localized premises. Index-matching connectors are in outside cable plants where the reconnections are infrequent but need to have a low loss.

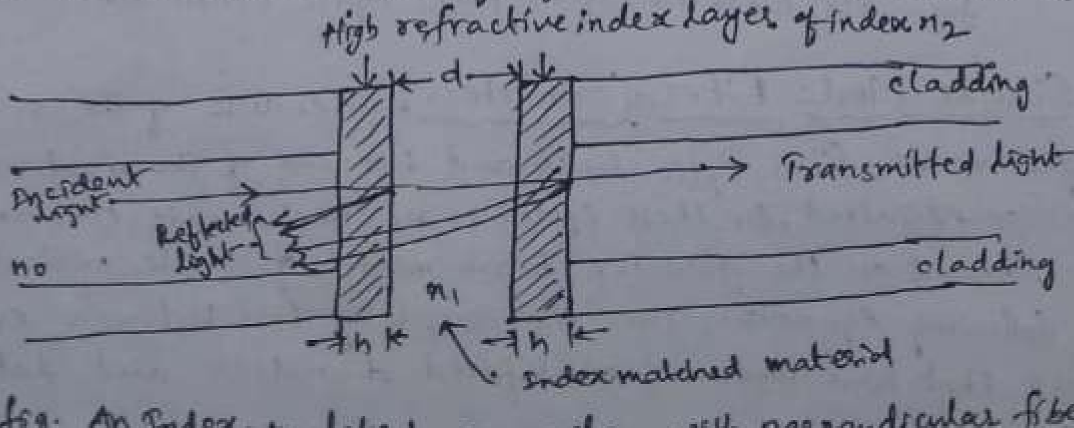


fig. An Index-matched connection with perpendicular fiber end faces.

Fig shows that the fiber end faces have a thin surface layer of thickness 'h' having a high refractive index n_2 relative to the core index, which is a result of fiber polishing. The fiber core has an index n_0, and the gap width d between the end faces is filled with index matching material having a refractive index n_1. The Return loss RL_{IM} in decibels for the index matched gap region is given by

$$RL_{IM} = -10 \log \left\{ 2R_1 \left[1 - \cos\left(\frac{4\pi n_1 d}{\lambda} \right) \right] \right\}$$

where $R_1 = \dfrac{r_1^2 + r_2^2 + 2 r_1 r_2 \cos\delta}{1 + r_1^2 r_2^2 + 2 r_1 r_2 \cos\delta}$

$r_1 = \dfrac{n_0 - n_2}{n_0 + n_2}$ and $r_2 = \dfrac{n_2 - n_1}{n_2 + n_1}$

$n_2 \rightarrow 1.46$ to 1.60

$h \rightarrow 0$ to $0.15\mu m$

$\delta = \dfrac{4\pi}{\lambda} n_2 h$

The perpendicular end faces are in direct physical contact, the return loss RL_{PC} in decibels is given by

$$RL_{PC} = -10 \log \left\{ 2R_2 \left[1 - \cos\left(\frac{4\pi n_2}{\lambda} 2h \right) \right] \right\}$$

where $R_2 = \left(\dfrac{n_0 - n_2}{n_0 + n_2} \right)^2$

Here R_2 - the refractivity at the discontinuity between the refractive indices of the fiber core and the high index surface layer.

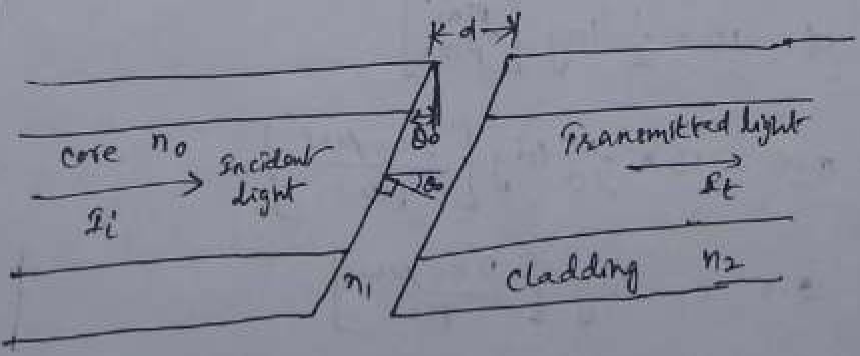


fig. Connection with angled end faces having a small gap of width 'd' seperating the fiber ends.

Fig shows that the connection with a small gap of width d seperating the fiber ends. The fiber core has an index n_0 and the material in the gap has a refractive index n_1. The end faces are polished at an angle θ_0 with respect to the plane perpendicular to the fiber axis. This angle is typically $8°$. If I_i and I_t are the incident and throughput optical power intensities, respectively. then the transmitted efficiency T through the connector is

$$T = \frac{I_t}{I_i} = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(\beta/2)}$$

where $\frac{\sin\theta_0}{\sin\theta} = \frac{n}{n_0}$, $\beta = \frac{4\pi n_1 d\cos\theta}{\lambda}$ and $R = \left(\frac{n_0-n_1}{n_0+n_1}\right)^2$

Note that when an index matching material is used $n_0 = n_1$, then $R=0$ and $T=1$. When $n_0 \neq n_1$, the transmitted efficiency has an oscillatory behavior as a function of the wavelength and end face angle.

(P) For a 30km long fiber attenuation 0.8 dB/km at 1300nm. If a 200 μwatt power is launched in to the fiber, find the output power.

Sol:

$Z = 30\,km$, $\alpha = 0.8\,dB/km$

$P(0) = 200\mu W$

Attenuation in optical fiber is given by

$$\alpha = 10 \times \frac{1}{Z}\log\left[\frac{P(0)}{P(Z)}\right]$$

$$0.8 = 10 \times \frac{1}{30}\log\left[\frac{200\mu W}{P(Z)}\right]$$

$$2.4 = \log\left[\frac{200\mu W}{P(Z)}\right]$$

$$\frac{200\mu W}{P(Z)} = 10^{2.4} \Rightarrow P(Z) = \frac{200\mu W}{251.1886}$$

$$\therefore P(Z) = 0.7962\,\mu W$$

(P) An LED operating at 850nm has a spectral width of 45nm. What is the pulse spreading in ns/km due to material dispersion.

Sol: Given $\lambda = 850nm$ $\sigma = 45nm$, $L=1$ (assume)

RMS pulse broadening due to material Dispersion

$\sigma_m = \sigma L M$

Material dispersion constant $D_{mat} = -\frac{\lambda}{c} \cdot \frac{d^2 n}{d\lambda^2}$

For LED source operating at 850nm $\left| \lambda^2 \frac{d^2 n}{d\lambda^2} \right| = 0.025$

$\therefore M = \frac{1}{c\lambda} \left| \lambda^2 \frac{d^2 n}{d\lambda^2} \right| = \frac{1}{3\times10^8 (850)} (0.25)$

$M = 9.8$ ps/nm/km

$\therefore \sigma_m = 45 \times 1 \times 9.8 = 441$ ps/km

$\sigma_m = 0.441$ ns/km.

(P) What is the pulse spreading having wavelength 2nm, when a laser diode having a 2 nm spectral width is used. Find the material dispersion induced pulse spreading at 1550nm for an LED with a 75nm spectral width

Sol: Given $\lambda = 2nm$, $\sigma = 2nm$

$D_{mat} = \frac{1}{c\lambda} \left| \lambda^2 \frac{d^2 n}{d\lambda^2} \right| = \frac{1}{(3\times10^8) \times 2} \times 0.03$

$= 50$ ps/nm/km

$\therefore \sigma_m = \sigma L M = 2 \times 1 \times 50 = 100$ns/km

For LED, $\lambda = 1550nm$, $\sigma = 75$

$D_{mat} = \frac{0.025}{(3\times10^8)\times1550} = 53.76$ ps/nm/km

$\sigma_m = 75 \times 1 \times 53.76 = 4.03$ns/km

(P) For a single mode fiber $n_2 = 1.48$ and $\Delta = 0.2\%$ operating at $\lambda = 1320nm$, compute the waveguide dispersion if $V \cdot \frac{d^2(Vb)}{dV^2} = 0.26$.

Sol. Given $n_2 = 1.48$, $\Delta = 0.2$, $\lambda = 1320nm$

The wave guide dispersion is given by $D_{wg}(\lambda) = \frac{-n_2 \Delta}{c\lambda} \left[V \frac{d^2(Vb)}{dV^2} \right]$

$D_{wg}(\lambda) = \frac{-1.48 \times 0.2}{3\times10^8 \times 1320} \times [0.20] = -1.943$ ps/ns/km

(P) A 6km optical link constant of multimode step index fiber with a core refractive index of 1.5 and a relative refractive index difference of 1%. Estimate:

a) The delay difference between the slowest and fastest modes at the fiber output.

b) The rms value pulse broadening due to intermodal dispersion on the link.

c) The maximum bit rate that may be obtained with out substantial errors on the link assuming only intermodal dispersion

d) The bandwidth length product corresponding to (c)

Sol: a) The delay difference is given by

$$\delta T_s = \frac{L n_1 \Delta}{c} = \frac{6\times10^3 \times 1.5 \times 0.01}{3\times10^8}$$

$$\delta T_s = 300\text{ns}$$

b) The rms pulse broadening due to intermodal dispersion is obtained from

$$\sigma_s = \frac{L n_1 \Delta}{2\sqrt{3}c} = \frac{1}{2\sqrt{3}} \frac{6\times10^3 \times 1.5 \times 0.01}{3\times10^8}$$

$$\sigma_s = 86.7\text{ns}$$

c) The maximum bit rate may be estimated in two ways

i) $B_T(\text{max}) = \frac{1}{2\delta T_s} = \frac{1}{600\times10^{-9}} = 1.7\text{ M bits/sec}$

ii) $B_T(\text{max}) = \frac{0.2}{\sigma_s} = \frac{0.2}{86.7\times10^{-9}} = 2.\text{M bits/sec}$

d) Using the most accurate maximum bit rate, the BW length product is.

$$B_{opt}\times L = 2.3\text{ MHz} \times 6\text{ Km}$$

$$= 13.8\text{ MHz Km}$$

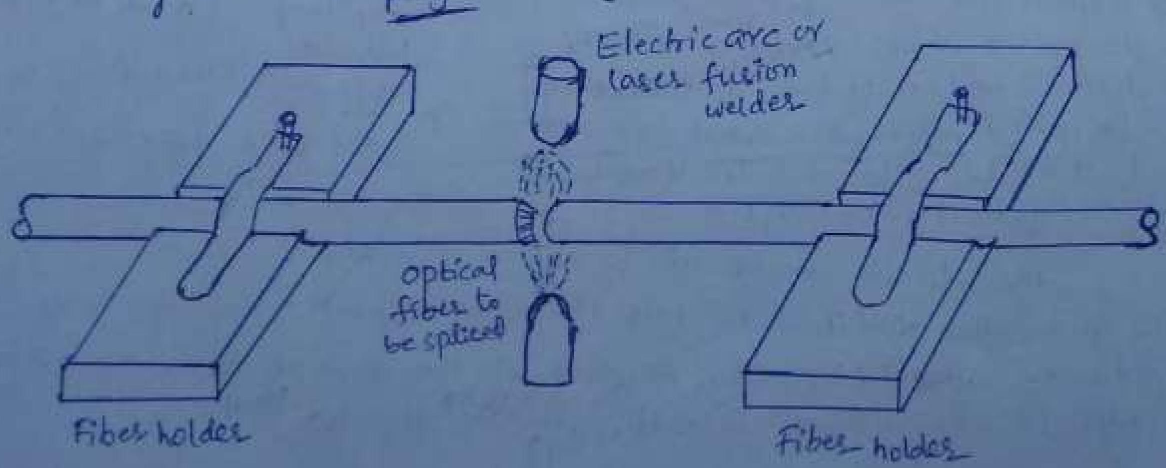
UNIT-III Fiber Splicing

Fiber Splicing: A permanent or semipermanent connection between two individual optical fibers is known as fiber splice, and the process of joining two fibers is called as splicing. A splice is used outside the buildings and connectors are used to join the cables within the buildings. splices offer lower attenuation and lower back reflection than connectors and are less expensive.

Optical fiber splicing Techniques
- Fusion Splicing
- Mechanical splicing
  - Spring groove splicing
  - precision pin splicing
  - V-grooved splicing
  - loose tube splicing
  - Elastic tube splicing
  - precision tube splicing

Fusion Splicing: splicing any fiber by making use of the fusion technique provides a permanent (long-lasting) contact between the two fibers. In the fusion splicing, the two fibers are thermally joined together. In this technique, an electrical instrument is necessarily used, that acts as an electric arc so as to form a thermal connection between the two. First, the two fibers are aligned and butted in the way of their connection, this alignment is done in a fiber holder.

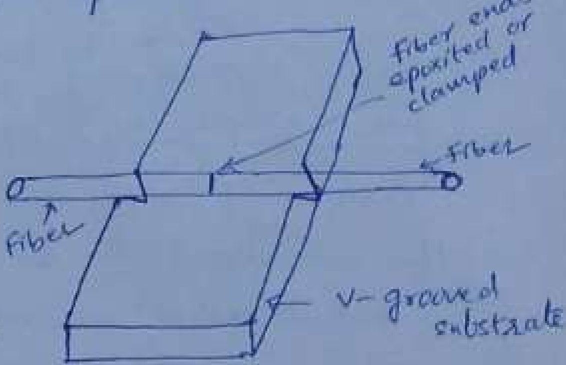
After this, the electric arc comes in to action as when it gets switched on then it produces some energy, that heats the butt joint. the heating effect melts the ends of the fiber and then the two gets bonded together. After the two forms a bond then their junction is covered with either polythelene jacket or plastic coating so as to project the joint.



This technique can produce very low splice losses. The loss range lies between 0·05 to 0·10 dB, both in case of single mode as well as multimode optical fibers. However, when fusion splicing is done, then the supply of heat that is to be provided must be in adequate amount. This is so because some times excess heat can generate fragile (delicate) joint.

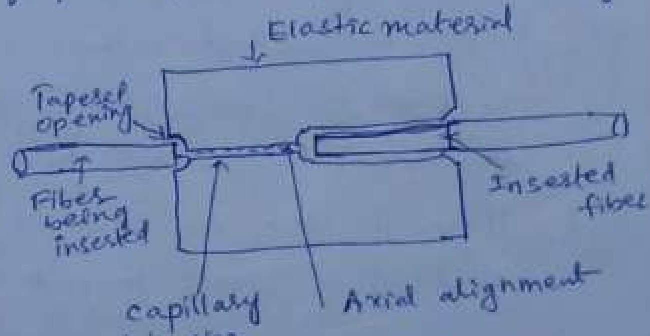
Mechanical (or ~~[illegible]~~) splicing: The fibers are aligned and then they are locked in position using various positioning devices. The different types of mechanical splicing are 1. Precision tube splice 2. loose tube splice 3. V-groove splice 4. Elastometric splice 5. Pricision pin splice 6. Spring groove splice.

V-groove splice:



It is also known as surface groove splice. Here V shaped groove is made at the center of metal plate. The dimensions of groove is such that fibes can be easily placed in the groove. Then adhesive epoxy material is placed in the V-groove. Then fiber optic ends are placed in one of the V-groove. Then they are butted together. This adhesive provides proper grip to the connection. The V substrate can be either composed of plastic, silicon, ceramic or any metal.

Elastometric Splice:



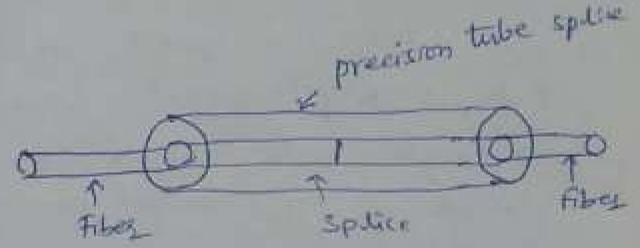
Elastic-tube Splicing

It is a technique of splicing the fiber with the help of the elastic tube and majorly finds its application in case of the multi mode optical fiber. The fiber loss is almost similar to that of the fusion technique. However, the need for equipment and skill is some what less than the fusion splicing technique.

The elastic material is rubber, inside a small hole is present. The diameter of hole is less than the diameter of the fiber to be spliced. Also, tapering is done at the ends of both the fibers in order to allow easy insertion inside the tube.

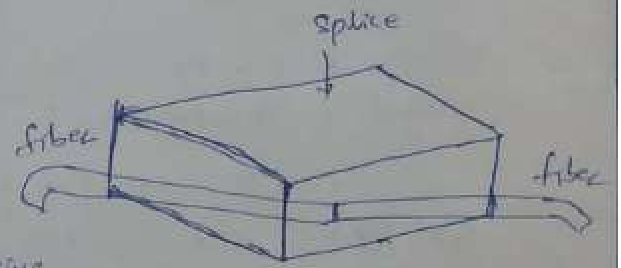
When the fiber with a slightly larger diameter than the hole is inserted inside the hole then, it eventually gets expanded as a symmetrical force is exerted by the material on the fiber. Due to this symmetricity, proper alignment between the two fibers is achieved. In this method, different diameters of fiber can be spliced as here the fibes moves according to the axis of the tube.

Precision tube splice:



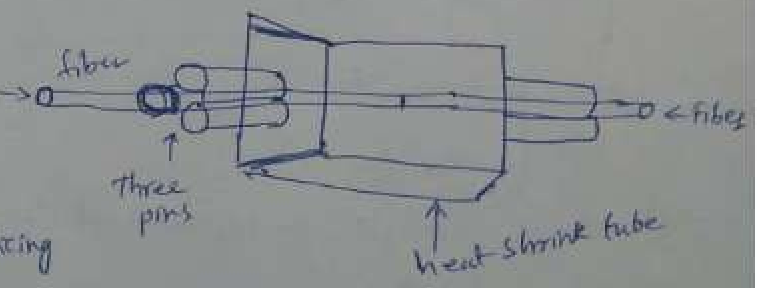
In this case precision tube is used to splice two fiber. Initially ends of fiber is cleaned and polished. splice compound has same refractive index as of fiber. Two fibers inserted in to splice and outer jacket is crimped.

Loose tube splice:



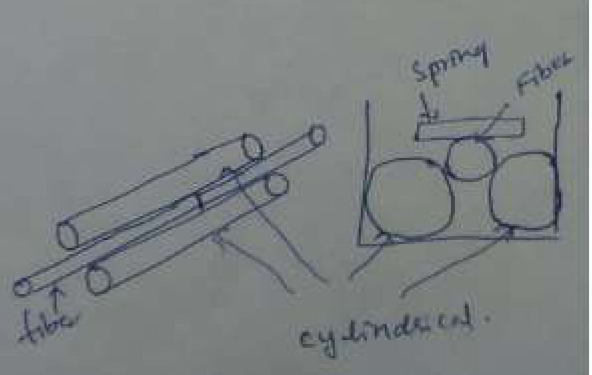
Here rectangular tube is for splicing. An adhesive material is added in tube to join two fibers. After cleaning and polishing fiber two ends are inserted in to splice. Because of adhesive material two ends of fiber will get joined. Adhesive material has same refractive index as of fiber

Precersion pin splice:



The heat shrink tube is used to held three steel pins together. The fiber tubes are inserted in openning between three pins. Using index matching epoxy. Splicing is done.

Spring groove splice:



Two cylindrical pins are used as alignment guide for fiber cables. Using spring. the fiber is pressed in the groove. Epoxy resin is used for splicing

Splicing Single-Mode Fibers

As is the case in multimode fibers, in single mode fibers the lateral (axial) offset misalignment presents the most serious loss. This loss depends on the shape of the propagating mode. For gaussian-shaped beam the loss between identical fibers is

$$L_{sm;lat} = -10\log\left\{\exp\left[-\left(\frac{d}{W}\right)^2\right]\right\}$$

where the spot size W is the mode field radius and d is the lateral displacement. Since the spot size is only a few micrometers in single mode fibers, low loss coupling requires a very high degree of mechanical precision in the axial dimension.

For angular misalignment in single mode fibers, the loss at a wavelength λ is

$$L_{sm;ang} = -10\log\left\{\exp\left[-\left(\frac{\pi n_2 W\theta}{\lambda}\right)\right]^2\right\}$$

where n_2 is the refractive index of the cladding, θ is the angular misalignment in radians and W is the mode field radius.

For a gap s with a material of index n_3 and letting $G = s/kW^2$, the gap loss for identical single-mode fiber splices is

$$L_{sm;gap} = -10\log\frac{64 n_1^2 n_3^2}{(n_1+n_3)^4(G^2+4)}$$

$$\boxed{L_{sm} = -10\log\left[\frac{16 n_1^2 n_3^2}{(n_1+n_3)^4}\frac{4\sigma}{q}\exp\left(-\frac{\rho u}{q}\right)\right]}$$

where $\rho = (kW_1)^2$

$q = G^2+(\sigma+1)^2$

$u = (\sigma+1)F^2+2\sigma FG\sin\theta+\sigma(G^2+\sigma+1)\sin^2\theta$

$F = \frac{d}{kW_1^2}$

$G = \frac{s}{kW_1^2}$

$\sigma = \left(\frac{W_2}{W_1}\right)^2$

$k = \frac{2\pi n_3}{\lambda}$

n_1 – core refractive index of fiber

n_3 – refractive index of medium between fibers

λ – wavelength of source

d – lateral offset

s – longitudinal offset

θ – angular misalignment

W_1 – 1/e mode field radius of transmitting fiber

W_2 – 1/e mode field radius of receiving fiber

(P1) A single mode fiber has a normalized frequency $V = 2.40$, a core refractive index $n_1 = 1.47$, a cladding refractive index $n_2 = 1.465$ and a core diameter $2a = 9\,\mu m$. Let us find the ~~inter~~ insertion losses of a fiber joint having a lateral offset of $1\,\mu m$.

The mode field diameter $W = a(0.65 + 1.619\, V^{-3/2} + 2.879\, V^{-6})$

$$W = 4.5\left[0.65 + 1.619(2.40)^{-3/2} + 2.879(2.40)^{-6}\right]$$

$$= 4.95\,\mu m$$

$$L_{SM\,lat} = -10\log\left\{\exp\left(-\left(\frac{d}{W}\right)^2\right)\right\}$$

$$= -10\log\left\{\exp\left[-\left(1/4.95\right)^2\right]\right\}$$

$$= 0.18\,dB$$

(P2) Consider the single mode fiber described in (P1). Let us find the loss at a joint having an angular misalignment of 1° at a 1300 nm wavelength.

$$L_{SM\,ang} = -10\log\left\{\exp\left[-\left(\frac{\pi n_2 W\theta}{\lambda}\right)^2\right]\right\}$$

$$= -10\log\left\{\exp\left[-\left(\frac{\pi(1.465)(4.95)(0.0175)}{1.3}\right)\right]\right\}$$

$$= 0.41\,dB$$

Advantages of fiber splicing

1. It allows long distance optical signal transmission
2. Less reflection at the time of signal transmission.
3. Splicing provides almost permanent connection of the two fibers.

Disadvantages of fiber splicing

1. Some times the fiber losses are very much higher than the acceptable limits.
2. Splicing increases, the overall cost of the optical fiber communication system

Fiber alignment and joint loss

A major consideration with all types of fiber to fiber connection is the optical loss encountered at the interface. Even when the two joined fiber ends are smooth and the two fiber axes are perfectly aligned, a small portion of the light-ray may be reflected back in to the transmitting fiber causing attenuation at the joint. This phenomenon known as Fresnel reflection, is associated with the step changes in refractive index at the jointed interface. The magnitude of this partial reflection of the light transmitted through the interface is given by

$$r = \left(\frac{n_1 - n}{n_1 + n}\right)^2$$

where r – the fraction of the light reflected at a single interface

n_1 – the refractive index of the fiber core

n – the refractive index of the medium between the two jointed fibers

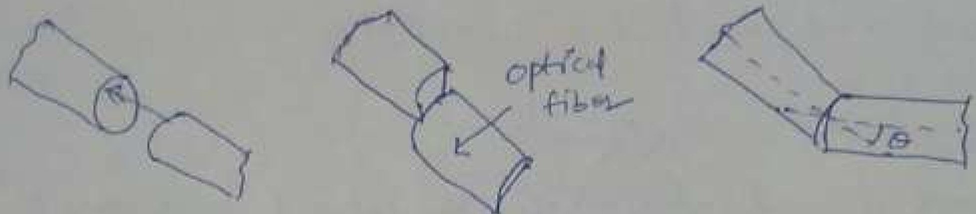
The loss in decibels due to due to Fresnel reflection at a single interface is given by

$$Loss_{Fres} = -10\log_{10}(1-r)$$

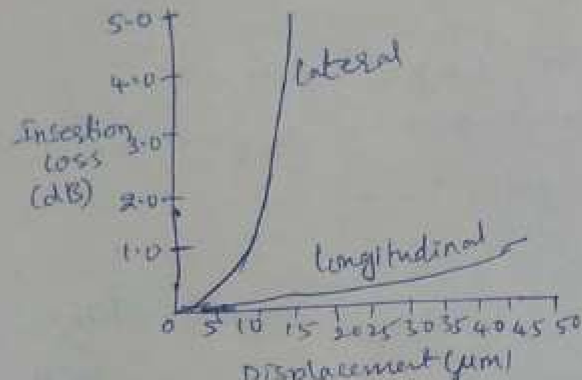
The effect of Fresnel reflection at a fiber to fiber connection can be reduced to a very low level through the use of an index matching fluid in the gap between the jointed fibers. A potentially greater source of loss at a fiber to fiber connection is caused by misalignment of the two jointed fibers. Any deviations in the geometrical and optical parameters of the two optical fibers which are jointed will affect the optical attenuation through the connection. There are inherent connection problems when jointing fibers with for instance.

a) different core and cladding diameters
b) different NA and relative refractive index difference (Δ)
c) different refractive index profiles
d) fiber faults.

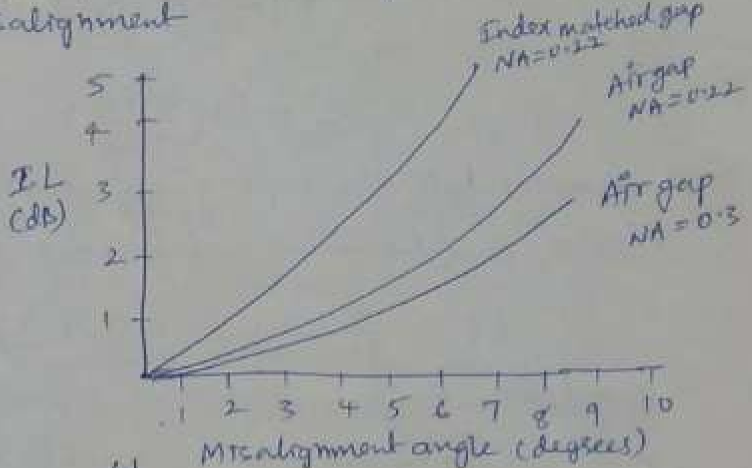
The losses caused by the above factors togther with those of Fresnel reflection are usually referred to as intrinsic joint losses. The misalignment may occur in three dimensions, the seperation between the fibers (longitudinal misalignment), the offset perpendicular to the fiber core axes (lateral/radial/axial misalignment) and the angle between the core axes (angular misalignment). Optical losses resulting from these three types of misalignment depend upon the fiber type, core diameter and the distribution of the optical power between the propagating modes.



a) Longitudinal misalignment b) Lateral misalignment c) angular misalignment



a)



b)

In Fig (a), the lateral misalignment gives significantly greater losses per unit displacement than the longitudinal misalignment.

In Fig (b), The attenuation characteristic for the angular misalignment of two multimode stepindex fibers with Numerical Aperture of 0.22 & 0.3. The effect of an index matching fluid in the fiber gap causes increased losses with angular misalignment. Therefore it clear that relatively small levels of lateral and/or angular misalignment can cause significant attenuation at a fiber joint.

Multimode Fiber Joints

In optical fiber connections, the losses are encountered with the various misalignments of different fiber types. Lateral misalignment reduces the overlap region between the two fiber cores. Assuming uniform excitation of all the optical modes in a multimode step index fiber the overlapped area between both fiber cores approximately gives the lateral coupling efficiency η_{lat}. The lateral coupling efficiency for two similar step index fibers may be written as

$$\eta_{lat} \simeq \frac{16(n_1/n)^2}{(1+(n_1/n))^4}\frac{1}{\pi}\left\{2\cos^{-1}\left(\frac{y}{2a}\right)-\left(\frac{y}{a}\right)\left[1-\left(\frac{y}{2a}\right)^2\right]^{\frac{1}{2}}\right\}$$

where n_1 – core refractive index, n – The refractive index of the medium b/t the fibers

y – The lateral offset of the fiber core axes, a – the fiber core radius.

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The lateral misalignment loss in decibels is

$$LOSS_{lat} = -10 \log_{10} \eta_{lat} \text{ dB}$$

In multimode graded index fibers, the lateral misalignment loss was dependent on the refractive index gradient α for small lateral offset given as

$$L_t = \frac{2}{\pi}\left(\frac{y}{a}\right)\left(\frac{\alpha+2}{\alpha+1}\right) \quad \text{for } 0 \leq y \leq 0.2a$$

where the lateral coupling efficiency was given by $\eta_{lat} = 1 - L_t$

With a parabolic refractive index profile $\alpha = 2$

$$L_t = \frac{8}{3\pi}\left(\frac{y}{a}\right) = 0.85\left(\frac{y}{a}\right)$$

Angular misalignment losses at joints in multimode stepindex fibers may be predicted with reasonable accuracy using an expression for the angular coupling efficiency η_{ang} is given by

$$\eta_{ang} = \frac{16(n_1/n)^2}{(1+(n_1/n))^4}\left[1 - \frac{n\theta}{\pi n_1 (2\Delta)^{1/2}}\right]$$

where θ - angular displacement in radians

Δ - relative refractive index difference for the fiber

The insertion loss due to angular misalignment may be obtained from the angular coupling efficiency

$$LOSS_{ang} = -10\log_{10}\eta_{ang}$$

The smaller the values of Δ imply small numerical aperture fibers, The larger the insertion loss due to angular misalignment is reduced by using fibers with large numerical apertures.

Factors causing fiber-fiber intrinsic losses were comprising a mismatch in the fiber core diameter, a mismatch in the fiber numerical apertures and differing fiber refractive index profiles as shown in fig.

a) core diameter mismatch
b) numerical aperture mismatch
c) refractive index profile difference

fig some intrinsic coupling losses at fiber joints.

Assuming all the modes are equally excited in a multimode step or graded index fiber, and that the numerical apertures and index profiles are the same, then the loss resulting from a mismatch of core diameters is given by

$$\mathrm{LOSS}_{CD}\begin{cases} = -10\log_{10}\left(\frac{a_2}{a_1}\right)^2 \ (\mathrm{dB}) & a_2 < a_1 \\ = 0 \ (\mathrm{dB}) & a_2 \geq a_1 \end{cases}$$

where a_1 and a_2 are the core radii of the transmitting & receiving fibers respectively.

Again assuming a uniform modal power distribution and fibers with equivalent refractive index profiles and core diameters, then the loss caused by a mismatch of numerical apertures

$$\mathrm{LOSS}_{NA}\begin{cases} = -10\log_{10}\left(\frac{NA_2}{NA_1}\right)^2 \ (\mathrm{dB}) & NA_2 < NA_1 \\ = 0 \ (\mathrm{dB}) & NA_2 \geq NA_1 \end{cases}$$

where NA_1 & NA_2 are the NA for the transmitting & receiving fibers respectively.

Finally, a mismatch in refractive index profile results in a loss is given by

$$\mathrm{LOSS}_{RI}\begin{cases} = -10\log_{10}\frac{\alpha_2(\alpha_1+2)}{\alpha_1(\alpha_2+2)} \ (\mathrm{dB}) & \alpha_2 < \alpha_1 \\ = 0 \ (\mathrm{dB}) & \alpha_2 \geq \alpha_1 \end{cases}$$

where α_1 and α_2 are the profile parameters for the transmitting and receiving fibers respectively.

The intrinsic losses obtained at multimode fiber-fiber joints is given by

$$\mathrm{LOSS}_{int}\begin{cases} = -10\log_{10}\frac{(a_2 NA_2)^2(\alpha_1+2)\alpha_2}{(a_1 NA_1)^2(\alpha_2+2)\alpha_1} \ (\mathrm{dB}) & a_2 > a_1, NA_2 > NA_1, \alpha_2 > \alpha_1 \\ = 0 \ (\mathrm{dB}) & a_2 \leq a_1, NA_2 \leq NA_1, \alpha_2 \leq \alpha_1 \end{cases}$$

where a_1, NA_1 and α_1 are the core radii, Numerical aperture and profile parameters for transmitting fibers, a_2, NA_2 and α_2 are the core radii, numerical aperture and profile parameter for receiving fibers.

Single mode fiber joints

In single mode fibers the misalignment losses at connections, in the absence of angular misalignment the loss T_l due to lateral offset y was given by

$$T_l = 2.17\left(\frac{y}{\omega}\right)^2 \text{ dB} \longrightarrow ①$$

where ω – the normalized spot size of the fundamental mode

The normalized spot size for the LP_{01} mode may be obtained as

$$\omega = a\,\frac{(0.65 + 1.62\,V^{-\frac{3}{2}} + 2.88\,V^{-6})}{2^{\frac{1}{2}}} \longrightarrow ②$$

where ω – spot size in μm, a – fiber core radius and

V – normalized frequency for the fiber.

The insertion loss T_a caused by an angular misalignment 'θ' at a joint in a single mode fiber may be given by

$$T_a = 2.17\left(\frac{\theta\,\omega\,n_1 V}{a\,NA}\right)^2 \text{ dB} \longrightarrow ③$$

where n_1 – core refractive index and NA – numerical aperture of the fiber

The eqns ② & ③ assume that the spot sizes of the modes in the two coupled fibers are the same.

Optical Sources

Introduction: The optical source is often considered to be the active component in an optical fiber communication system. Its fundamental function is to convert electrical energy in the form of a current into optical energy (light) in an efficient manner which allows the light output to be effectively launched or coupled into the optical fiber.

Mainly three types of optical light sources are available. These are

a) wide band 'continuous spectra' sources (incandescent lamps)

b) monochromatic incoherent sources (light emitting diodes, LEDs)

c) monochromatic coherent sources (lasers)

The most popular optical sources used in optical communication systems are Light-Emitting Diode (LED) and LASER Diode (LD). LEDs are suitable for short haul and low bit rate applications. They are associated with multimode fibers. LASER's are coherent devices and they are most suitable for long haul and high bit rate applications. They are usually associated with single mode fibers. These devices exhibit most of the characteristics than an optical source should posses. The characteristics are given in Table.

S.No.	Property	Characteristic
1	Wavelength	Selected operating wavelength must give Low-loss and low dispersion in fibers
2	Reliability	Long life, Good stability of operation
3	output power	It should be adequate to meet wide range of applications.
4	power efficiency	It should operate with a power supply required a low power and low voltage
5	spectral width	spectral width should be such that to realize maximum bandwidth
6	Focussing Effect	It must be possible to focus the output on to the fiber and to obtain high coupling efficiency.
7	Modulation	Direct modulation should be possible
8	Size	Size must be small and compatible with those of optical fibers.
9	weight	It should be light in weight
10	cost	It must be low

Light Emitting Diodes (LEDs)

For optical communication systems requiring bit rates less than approximately 100-200 Mb/s together with multimode fiber coupled optical power in the tens of microwatts, semiconductor light emitting diodes (LEDs) are usually the best light source choice. These LEDs require less complex drive circuitry than laser diodes since no thermal or optical stabilization circuits are needed and they can be fabricated less expensively with higher yields.

The generation of light is caused by the transition of an electron ~~from~~ from an energetically higher energy state (E_c) to a lower energy state (E_v). The energy difference ($E_c - E_v$) due to the transition of ~~one~~ the electron leads to a radiative or a non radiative process. The non-radiative processes typically lead to the creating of heat. The energy is simply dissipated by heat. In the case of radiative process photons are emitted. The emission of light, can take place either spontaneously or it can by stimulated by the presence of another photon of the right energy ($E = h\nu$).

The light emitting region of both LEDs and lasers diodes consists of a pn junction constructed of direct band gap semiconductor materials. When this junction is forward biased, electrons and holes are injected in to the p and n regions respectively. These injected minority carriers can recombine either radiatively or non-radiatively. This pn junction is thus known as the active or re-combination region.

LED structures

Homojunctions:

P type and N-type from same material and these materials have equal band gaps but typically have different doping carriers are not confined. Light is not confined. The carrier confinement problem can be resolved by sandwiching a thin layer ($\simeq 0.1 \mu m$) between p type and n type ~~material~~ layers. The middle layer may or may not be doped. The carrier confinement occurs due to bandgap discontinuity of the junction. Such a junction is called heterojunction and the device is called double heterostructure.

Heterojunctions:

A heterojunction is an interface between two adjoining single crystal semiconductors with different bandgaps. Heterojunctions are two types ① Isotype (n-n or p-p) or Anisotype (p-n).

Double Heterojunctions:

Inorder to achive efficient confinement of emitted radiation double heterojunctions are used in LED structures. A heterojunction is a junction formed by dissimilar semiconductors. Double heterojunction (DH) is formed by ~~two~~ two different semiconductors on each side of active region.

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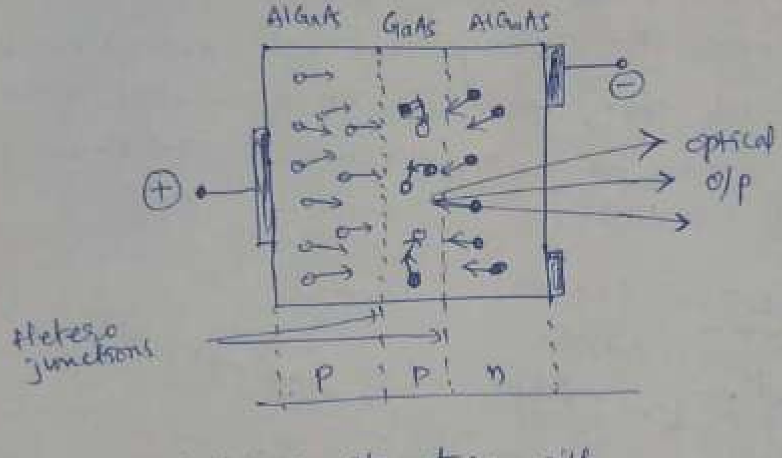
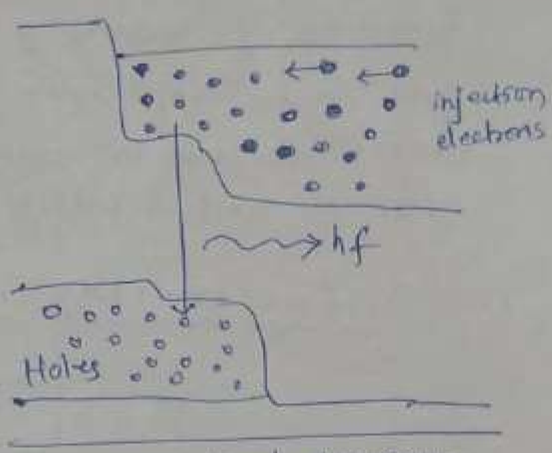
The principle of operation of the DH LED is shown in fig



a) Layer structure with forward bias



b) energy band diagram

The device consists of a p-type GaAs layer sandwiched between a p-type AlGaAs and an n-type AlGaAs layer. When a forward bias is applied electrons from the n-type layer through the p-n junction in to the p-type GaAs layer where they become minority carriers. These minority carriers diffuse away from the junction, recombining with majority carriers (holes) as they do so. photons are therefore produced with energy corresponding to the bandgap energy of the p type GaAs layer. The injected electrons are inhibited from diffusing in to the p type AlGaAs layer because of the potential barrier presented by the p-p heterojunction. Hence electro luminescence only occurs in the GaAs junction layer, providing both good internal quantum efficiency and high radiation emission. Furthermore, light is emitted from the device with out reabsorption because the bandgap energy in AlGaAs layer is large in comparision with that in GaAs. The DH structure is therefore used to provide the most efficient incoherent sources for application within optical fibres communications.

There are 5 major types of LED structures

1. Planar LED 2. Dome LED 3. Surface emitter LED

4. Edge Emitter LED 5. superluminescent LED

The surface emitter and edge emitter have found extensive in optical fiber communications and the superluminescent LED becoming of increasing interest. The planar LED and dome LED find more applications as cheap plastic encapsulated visible devices for use in such areas as intruder alarms, TV channel changes and industrial counting.

1. Surface Emitting LEDs (SLEDs):

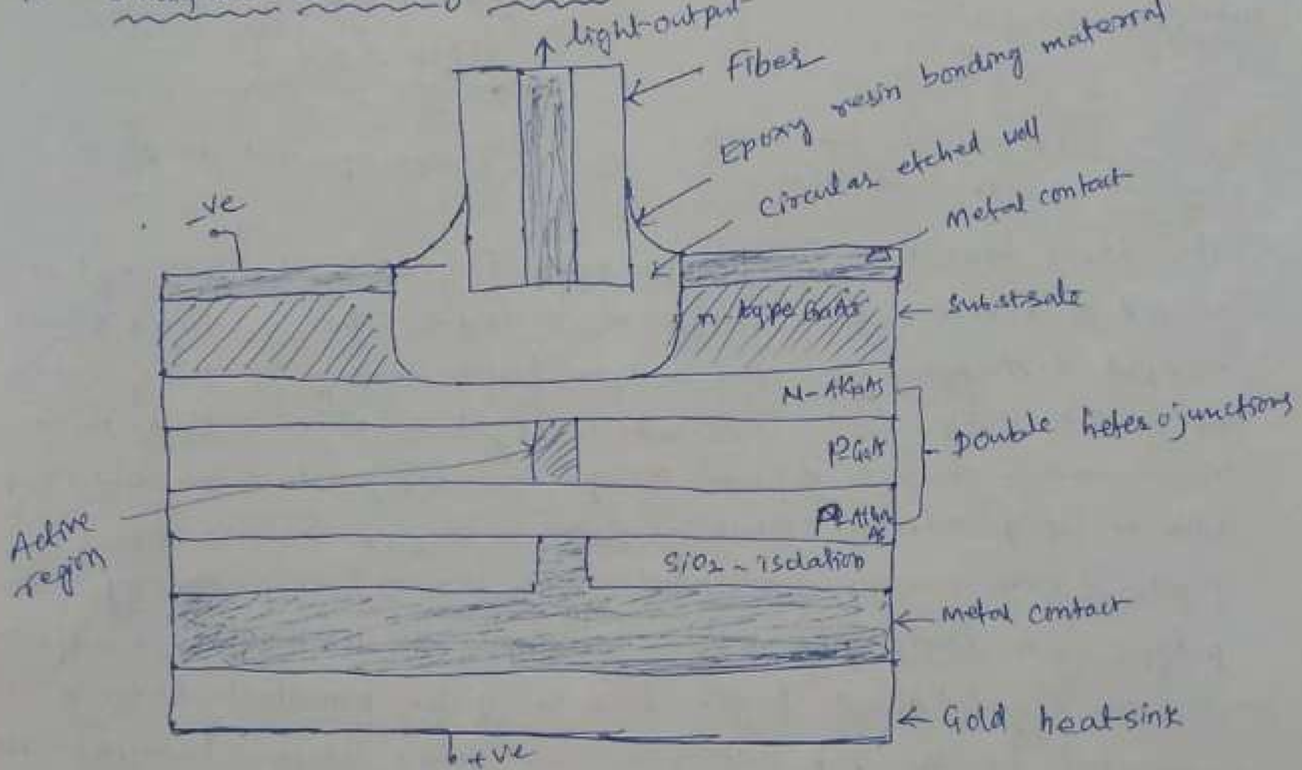


fig Structure of surface Emitting LED.

It is also called as Burrus or front emitters. In surface emitting LEDs the plane of active light emitting region is oriented perpendicularly to the axis of the fiber. A DH diode is grown on N-type substrate at the top of the diode. A circular well is etched through the substrate of the device. A fiber is then connected to accept the emitted light. At the back of the device is a gold heat sink. The current flows through the p-type material and form the small circular active region resulting in the intense beam of light. The circular active area in practical surface emitting is nominals 50 μm is diameter and up to 2.5 μm thick. The emission pattern is isotropic with of 120° half power beam width.

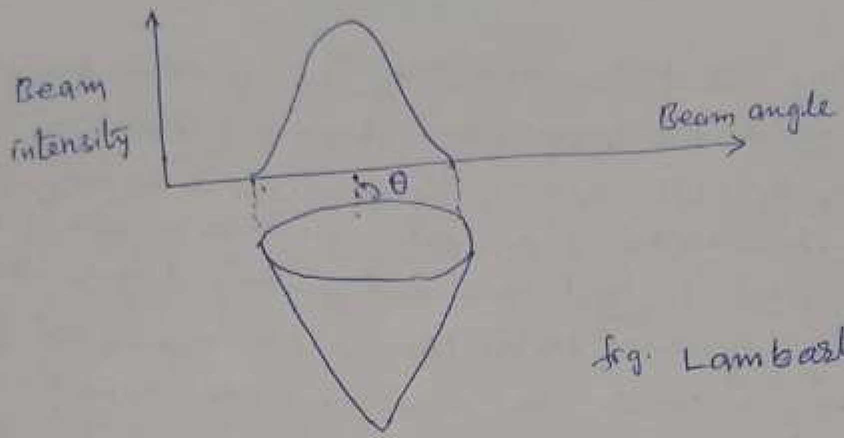


fig. Lambartian radiation

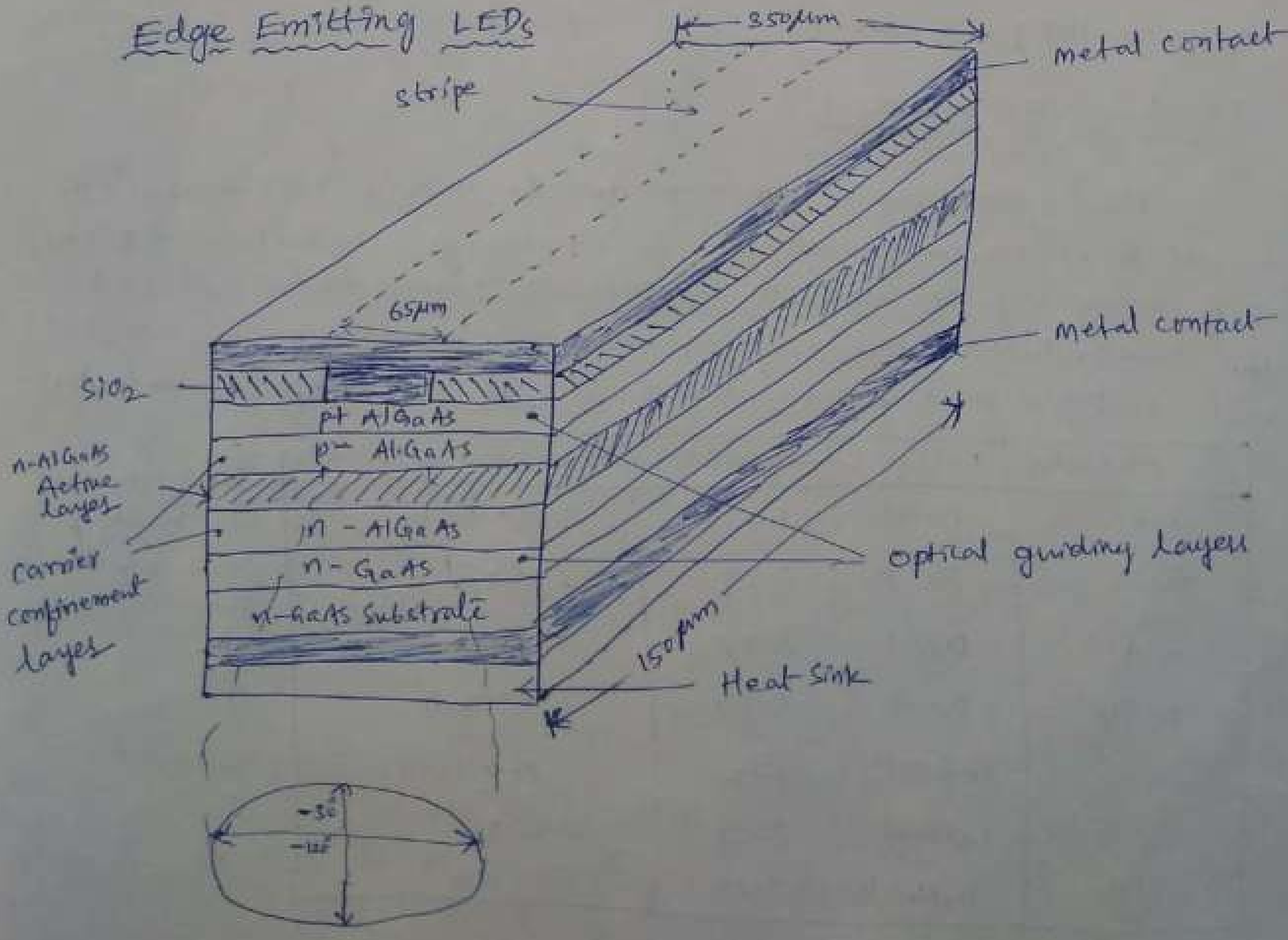
The isotropic emission pattern from surface emitting LED is called Lambartian pattern. In this pattern, the emitting surface is uniformly bright, but its projected area diminishes as $\cos\theta$, where θ is the angle between the viewing direction and the normal to the surface.

properties of surface Emitting LED:

- High radiance is obtained ($H = \frac{4 P_0}{\pi \theta^2 d^2}$)
- Low terminal impedance is obtained.
- Due to multiple p-type layers (Double Heterojunction) the coupling efficiency increased
- Emission pattern is isotropic with 120° Half power Beam width.

Disadvantages: - Low life time , - Low modulation bandwidth.

Edge Emitting LEDs



In order to reduce the losses caused by absorption in the active layer and to make the beam more directional, the light is collected from the edge of the LED. Such a device is known as edge emitting LED or ELED. It consists of an active junction region which is the source of incoherent light and two guiding layers. The refractive index of guiding layers is lower than active region but higher than outer surrounding material. Thus a waveguide channel is formed and optical radiation is directed in to the fiber.

Edge emitter's emission pattern is more directional providing improved coupling efficiency. In the plane parallel to the junction, where there is no beam confinement and the radiation waveguide effect. The emitted beam is Lambartian with a half power beam width 120°. In the plane perpendicular to the junction, The half power beam has been made as small as 25°-35° by a proper choice of the waveguide thickness. ELEDs are less temperature sensitive. ELEDs have better coupling efficiency than surface emitter LEDs.

LED type	Max modulation freq (MHz)	o/p power (mW)	Fiber coupled power (mW)
surface emitting	60	<4	<0.2
Edge emitting	200	<7	<1.0

Light source Material

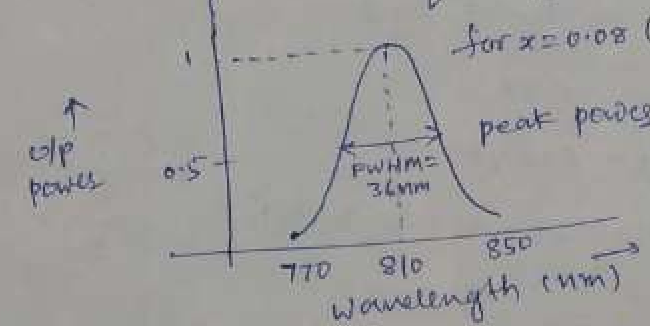
The spontaneous emission due to carrier recombination is called electro luminescence. To encourage electroluminescence it is necessary to select an appropriate semiconductor material. The semiconductors depending on energy bandgap can be classified in to 1. Direct bandgap semiconductors 2. Indirect bandgap semiconductors.

Semiconductor	Energy bandgap (eV)	Recombination B_r (cm^3/sec)
GaAs	Direct : 1.43	7.21×10^{-10}
GaSb	Direct : 0.73	2.39×10^{-10}
InAs	Direct : 0.35	8.5×10^{-11}
InSb	Direct : 0.18	4.58×10^{-11}
Si	Indirect : 1.12	1.79×10^{-15}
Ge	Indirect : 0.67	5.25×10^{-14}
GaP	Indirect : 2.26	5.37×10^{-14}

Some commonly used bandgap semiconductors are shown in Table.

Indirect bandgap semiconductors the electrons and holes on either side bandgap have same value of crystal momentum. Hence direct recombination is possible. The recombination occurs with in 10^{-8} to 10^{-10} sec.
In Indirect bandgap semiconductors, the maximum and minimum energies occur at different values of crystal momentum. The recombination in these semiconductors is quite slow i.e 10^{-2} to 10^{-3} sec
The active layer semiconductor material must have a different bandgap. Indirect bandgap semiconductor, electrons and holes can recombine directly without need of third particle to conserve momentum. In these materials the optical radiation is sufficiently high. These materials are compounds of group III elements (Al, Ga, In) and group V elements (P, As, Sb).

The emission spectrum of $Ga_{1-x}Al_x As$ LED is shown in fig.



The peak output power is obtained at 810 nm. The width of emission spectrum at half power (0.5) is referred as full width half maximum (FWHM) spectra width. For the given LED FWHM is 36nm.
The fundamental quantum mechanical relationship between gap energy E and frequency v is given as

$$E = hv = h\frac{c}{\lambda} \Rightarrow \lambda = \frac{hc}{E}$$

where energy (E) is in jouls and wavelength (λ) is in meters. Expressing the gap energy (E_g) in electron volts and wavelength (λ) in μm for this application.

$$\boxed{\lambda(\mu m) = \frac{1.24}{E_g(eV)}}$$

The bandgap energy (E_g) can be controlled by two compositional parameters x and y, within direct bandgap region. The quarternary alloy $In_{1-x}Ga_x As_y P_{1-y}$ is the principal material used in such LEDs. Two expressions relating E_g and x, y are

$$E_g = 1.424 + 1.266x + 0.266x^2 \quad E_g = 1.35 - 0.72y + 0.12y^2$$

(P) Compute the emitted wavelength from an optical source having $x = 0.07$.

Sol. $E_g = 1.424 + 1.266x + 0.266x^2$

$= 1.424 + (1.266 \times 0.07) + 0.266(0.07)^2$

$E_g = 1.513$ eV

$\lambda = \frac{1.24}{E_g} = \frac{1.24}{1.513} = 0.819 \mu m$

$\lambda = 0.82 \mu m$

(P) For an alloy $In_{0.74} Ga_{0.26} As_{0.57} P_{0.43}$ to be used in LED. Find the wavelength emitted by this source.

Sol. Comparing the alloy with quaternary alloy composition $In_{1-x} Ga_x As_y P_{1-y}$ it is found that

$x = 0.26$ and $y = 0.57$

$E_g = 1.35 - 0.72y + 0.12y^2$

$= 1.35 - (0.72 \times 0.57) + 0.12 \times 0.57^2$

$E_g = 0.978$ eV

$\lambda = \frac{1.24}{E_g} = \frac{1.24}{0.978} = 1.2671 \mu m$

$\lambda = 1.27 \mu m$

Quantum Efficiency and LED power

The internal quantum efficiency in the active region is the fraction of the electron-hole pairs that recombine radiatively. If the radiative recombination rate is R_r and the non radiative recombination rate is R_{nr} then the internal quantum efficiency η_{int} is the ratio of the radiative recombination rate to the total recombination rate

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}} \longrightarrow (1)$$

For exponential decay of excess carriers, the radiative recombination life time is $\tau_r = n/R_r$ and the nonradiative recombination life time is $\tau_{nr} = n/R_{nr}$.

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Thus, the internal quantum efficiency can be expressed as

$$\eta_{int} = \frac{1}{1+\frac{\tau_r}{\tau_{nr}}} = \frac{\tau}{\tau_r} \rightarrow (2)$$

where the bulk recombination life time τ is $\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \rightarrow (3)$

If the current injected into the LED is I, then the total number of recombinations per second is $R_r + R_{nr} = \frac{I}{q} \rightarrow (4)$

Substituting Eqn (4) in Eqn (1) then yields $R_r = \eta_{int} \cdot \frac{I}{q} \rightarrow (5)$

R_r is the total number of photons generated per second and that each photon has an energy $h\nu$, then the optical power generated internally to the LED is

$$P_{int} = \eta_{int} \frac{I}{q} h\nu = \eta_{int} \frac{hcI}{q\lambda} \rightarrow (6)$$

Not all internally generated photons will exit the device. To find the emitted power, one needs to consider the external quantum efficiency η_{eff}. External quantum efficiency is defined as the ratio of photons emitted from the LED to the number of internally generated photons and approximately is given by

$$\eta_{ext} = \frac{1}{n(n+1)^2} \longrightarrow (7)$$

From this the optical power emitted from the LED is

$$P = \eta_{ext} P_{int} = \frac{P_{int}}{n(n+1)^2} \longrightarrow (8)$$

(P) A double heterojunction InGaAsP LED emitting at a peak wavelength of 1310nm has radiative and nonradiative recombination times of 30 and 100ns respectively. The drive current is 40mA. Calculate 1) Bulk recombination life time 2) Internal quantum efficiency 3) Internal power level.

The bulk recombination life time is $\tau = \frac{\tau_r \tau_{nr}}{\tau_r + \tau_{nr}} = \frac{30 \times 100}{30+100}$ ns

$\tau = 23.1$ ns

The internal quantum efficiency is $\eta_{int} = \frac{\tau}{\tau_r} = \frac{23.1}{30} = 0.77$

Internal power $P_{int} = \eta_{int} \frac{hcI}{q\lambda} \Rightarrow$

$$P_{int} = 0.77 \frac{(6.6256 \times 10^{-34} \text{ J-s})(3 \times 10^8 \text{ m/s})(0.040\text{A})}{(1.602 \times 10^{-19} \text{ C})(1.31 \times 10^{-6} \text{ m})}$$

$$= 29.2 \text{ mW}$$

Modulation of an LED:

The response time or frequency response of an optical source dictates how fast an electrical input-drive signal can vary the light output level. Three factors determine the response time ① The doping level in the active region ② The injected carrier lifetime τ_i in the recombination region and ③ The parasitic capacitance of the LED.

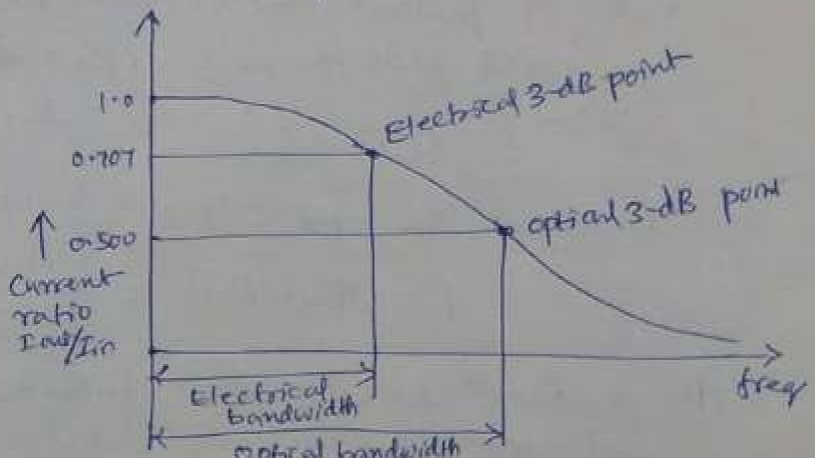
If the drive current is modulated at a frequency ω, the optical output power of the device will vary as

$$P(\omega) = P_0[1+(\omega\tau_i)^2]^{-1/2}$$

where P_0 – the power emitted at zero modulation frequency.

The modulation bandwidth of an LED can be defined in either electrical or optical terms. Normally electrical terms are used since the bandwidth is actually determined via the associated electrical circuitry. Thus the modulation bandwidth is defined as the point where the electrical signal power $P(\omega)$, has droped to half its constant value of optical signal. This is the electrical 3-dB point; i.e the frequency at which the output electrical power is reduced by 3 dB with respect to the input electrical power.

Since, $P(\omega) = \frac{I^2(\omega)}{R}$, the ratio of the o/p electrical power at the frequency ω to the power at zero modulation is given



$$\text{Ratio}_{elec} = 10\log\left[\frac{P(\omega)}{P(0)}\right]$$

$$= 10\log\left[\frac{I^2(\omega)}{I^2(0)}\right]$$

where $I(\omega)$ – the electrical current in the detection circuitry. The electrical 3-dB point occurs at that frequency point where the detected electrical power $P(\omega) = \frac{P(0)}{2}$ This happens when $\frac{I^2(\omega)}{I^2(0)} = \frac{1}{2}$ or $\frac{I(\omega)}{I(0)} = \frac{1}{\sqrt{2}} = 0.707$

The modulation bandwidth of an LED in terms of 3-dB bandwidth of the modulated optical power $P(\omega)$, i.e it is specified at the frequency where $P(\omega) = \frac{P_0}{2}$. The 3-dB bandwidth is determined from the ratio of the optical power at frequency ω to the unmodulated value of the optical power. Since the detected current is directly proportional to the optical power, this ratio is

$$Ratio_{optical} = 10\log_{10}\left[\frac{P(\omega)}{P(0)}\right] = 10\log\left[\frac{I(\omega)}{I(0)}\right]$$

The optical 3-dB point occurs at that frequency where the ratio of the currents is equal to $1/2$. As shown in fig. this gives an inflated value of the modulation bandwidth, which corresponds to an electrical power attenuation of 6dB.

Advantages of LED:
1. Simple design 2. Ease of manufacture 3. Simple system integration
4. low cost 5. High reliability 6. It needs less voltage for operate

Disadvantages of LED:
1. Refraction of light at semiconductor/air interface
2. The average lifetime of a radiative recombination is only a few nano seconds, therefore modulation BW is limited to only few hundred megahertz.
3. Low coupling efficiency
4. Large chromatic dispersion.

(5) The radiative and non radiative recombination life times of the minority carriers in the active region of double heterojunction LED are 50ns and 110ns respectively. Determine the carrier recombination life time and the power internally generated with in the device when the peak emission wavelength is 0.87 μm at a device current of 40mA.

So: $\tau_r = 50ns$ $\tau_{nr} = 110ns$

$$\tau = \frac{\tau_r \times \tau_{nr}}{\tau_r + \tau_{nr}} = \frac{50\times110}{50+110} = 34.37\,n\,sec$$

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{34.37}{50} = 0.6874 = 68.74\%$$

$\lambda = 0.87\,\mu m$ $I = 40mA$

$$P_{int} = \eta_{int}\left(\frac{hcI}{q\lambda}\right)$$

$$= \frac{0.6874 \times 6.625\times10^{-34} \times 3\times10^{8} \times 40\times10^{-3}}{1.6\times10^{-19} \times 0.87\times10^{-6}}$$

$$P_{int} = 392\times10^{-4}\,W = 39.2\,mW$$

(P) An optical transmitter uses DH structure InGaAsP LED operating at a wavelength of 1550 nm and $\tau_r = 25$ ns, $\tau_{nr} = 90$ ns. If the LED is given with a current of 35 mA.

i) Find internal quantum efficiency and power generated internally

ii) If n = 3.5, then power emitted by device is ?

Sol: $\lambda = 1550$ nm $\tau_r = 25$ ns $\tau_{nr} = 90$ ns $I = 35$ mA

$$\tau = \frac{\tau_r \times \tau_{nr}}{\tau_r + \tau_{nr}} = \frac{25 \times 90}{25 + 90} = 19.56 \text{ nsec}$$

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{19.56}{25} = 0.7824 = 78.24\%$$

$$P_{int} = \eta_{int}\left(\frac{hcI}{q\lambda}\right)$$

$$= 0.7824\left(\frac{6.625 \times 10^{-34} \times 3 \times 10^{8} \times 35 \times 10^{-3}}{1.6 \times 10^{-19} \times 1550 \times 10^{-9}}\right)$$

$$P_{int} = 0.2194 \times 10^{-1} = 21.94 \text{ mW}$$

$$\eta_{ext} = \frac{1}{n(n+1)^2} = \frac{1}{3.5(4.5)^2} = 0.0141$$

$$= 1.41\%$$

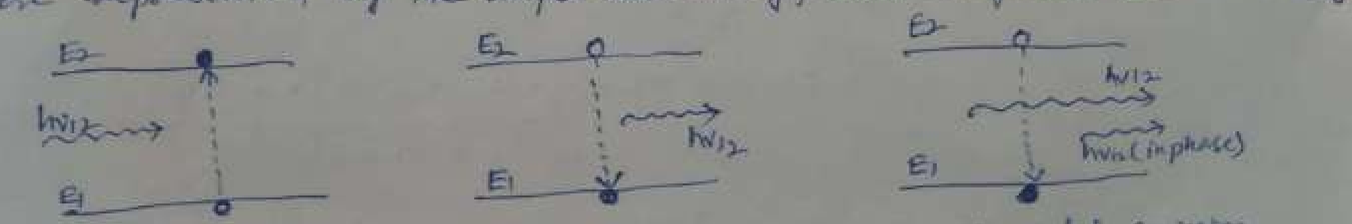
$$P_{end} = \eta_{ext} P_{int}$$

$$= 0.0141 \times 21.94 \times 10^{-3}$$

$$= \underline{0.309 \text{ mW}}$$

Laser Diodes or Injection Laser Diode (ILD)

For optical fiber systems the laser sources used almost exclusively are semiconductor laser diodes. It is also called as Injection laser diode. Laser stands for light amplification by stimulated emission of radiation. Laser action is the result of three key processors 1. Absorption 2. Spontaneous emission 3. Stimulated emission. These three processes are represented by the simple two-energy level diagrams as shown in fig



1. Absorption   2. Spontaneous emission   3. Stimulated emission

where E_1 is the ground state energy and E_2 is the excited state energy. Quantum theory states that any atom exists only in certain discrete energy state, absorption or emission of light causes them to make a transition from one state to another state. The frequency of the absorbed or emitted radiation f is related to the difference in energy E between the two states. $E = (E_2 - E_1) = h\nu_{12}$ where $h = 6.626 \times 10^{-34}$ J/s (plank's constant). ① Normally the system is in the ground state. when the photon with energy $(E_2 - E_1)$ is incident on the atom it will be excited into the higher energy state E_2 through the absorption of the photon. ② when the atom is in higher energy state E_2, since this is an unstable state, the electron will shortly return to the ground state, there by emitting a photon of energy $h\nu_{12}$. This occurs without any external stimulation and is called spontaneous emission. These emissions are isotropic and of random phase. ③ The electron can also be induced to make a downward transition from the excited level to the ground state by an external stimulation. If a photon of energy $h\nu_{12}$ impact on the system while the electron is still in its excited state, the electron is immediately stimulated to drop to the ground state and give off a photon of energy $h\nu_{12}$. This emitted photon is in phase with the incident photon and the resultant emission is known as stimulated emission.

population inversion:

under the conditions of thermal equilibrium, the lower energy level E_1 of the two level atomic system contains more atoms than the upper energy level E_2. This situation is normal for structures at room temperature. To achieve optical amplification it is necessary to create a non equilibrium distribution of atom such that the population of the upper energy level is greater than that of lower energy level ($N_2 > N_1$). This condition is known as population inversion, this process is achieved ~~by~~ using an external energy source and is referred to as pumping.

Laser Diode Configurations:

For optical fiber communication systems requiring bandwidths greater than approximately 200MHz, the semiconductor injection laser diode is preferred over the LED. Laser diodes have response times less than 1 ns, can have spectral widths of 2nm or less and are capable of coupling several tens of milliwatts. Stimulated emission in semiconductor lasers arises from optical transitions between distributions of energy states in the valance and conduction bands.

Two types of laser configurations.

1. Fabry - Perot resonator cavity:

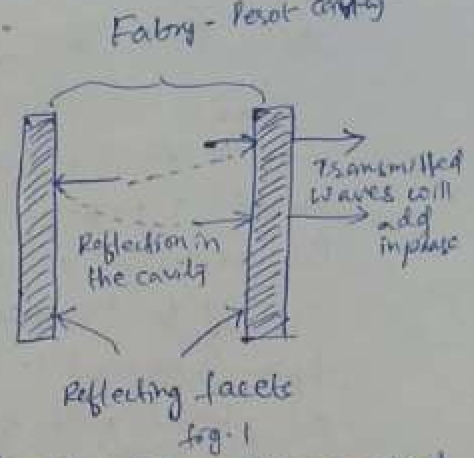
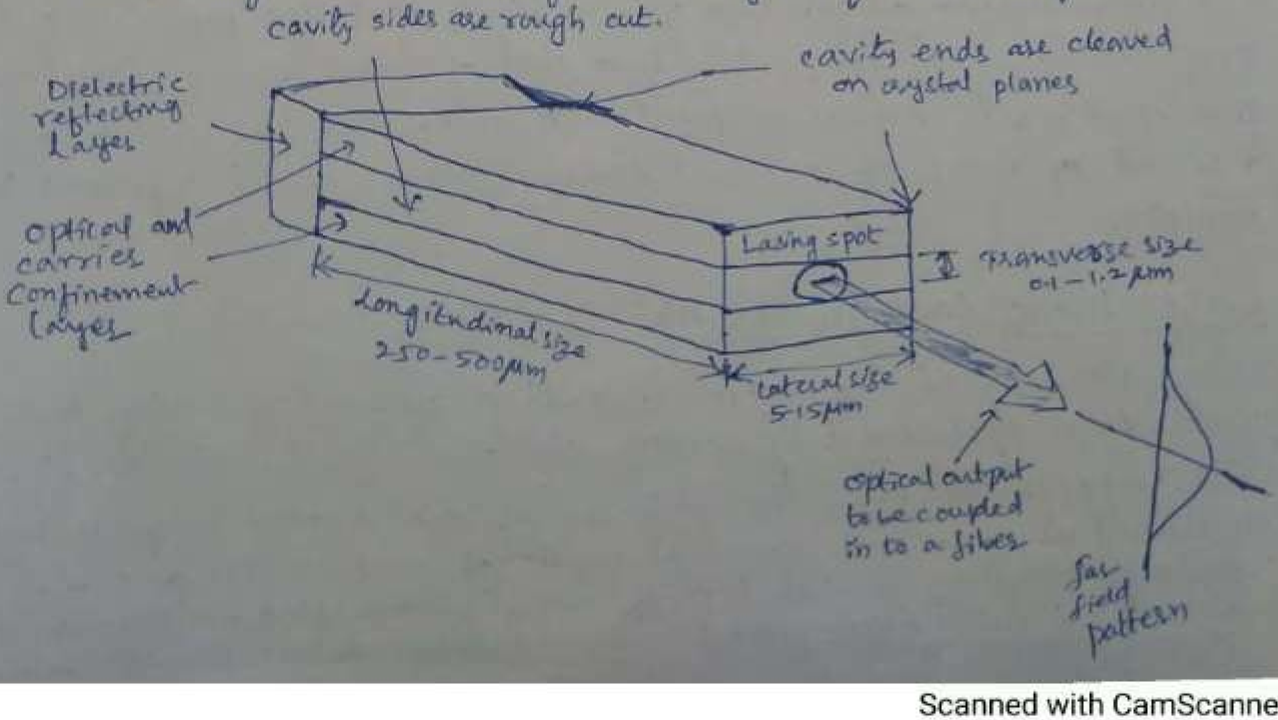


fig. 1

As shown in fig 1, two flat, partially reflecting mirrors are directed toward each other to enclose the Fabry-Perot resonator cavity. The mirror facets are constructed by making two parallel clefts along natural cleavage planes of the semi-conductor crystal. The purpose of the mirrors is to establish a strong optical feedback in the longitudinal direction. This feedback mechanism converts the device in to an oscillator with a gain mechanism that compensates for optical losses in the cavity at certain resonant optical frequencies. The sides of the cavity are simply formed by roughing the edges of the device to reduce unwanted emissions in the lateral directions.

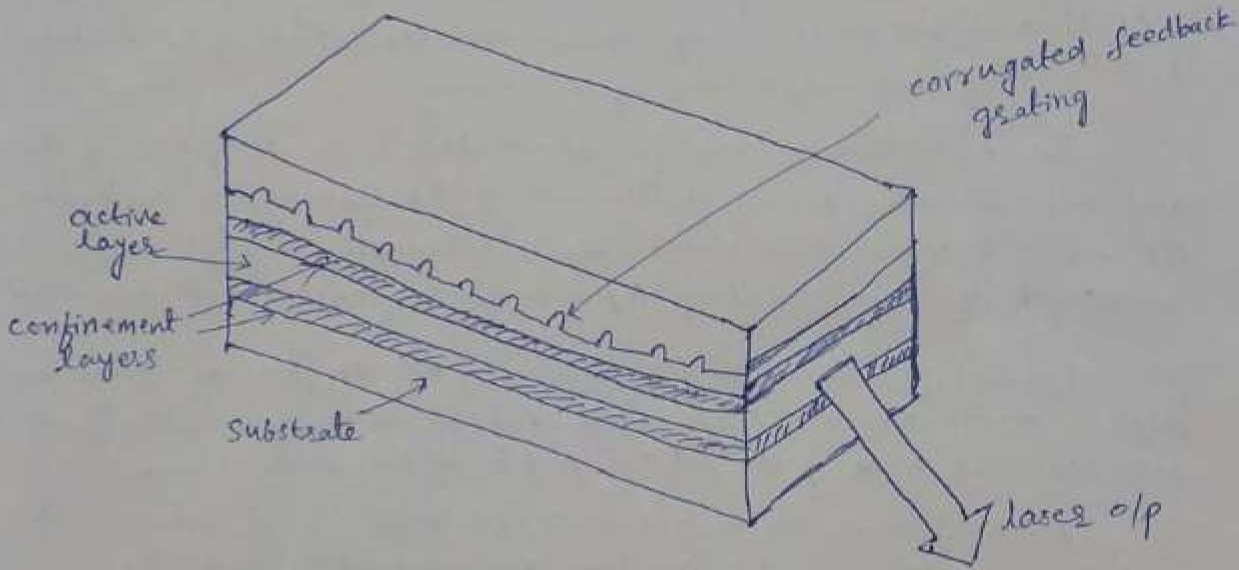
As the light reflects back and forth within the Fabry-Perot cavity, the electric fields of the light interfere on successive round trips. Those wavelengths that are integer multiples of the cavity length interfere constructively so that their amplitudes add when they exit the device through the right hand facet. All other wavelengths interfere destructively and thus cancel themselves out. The optical frequencies at which constructive interference occures are the resonant frequencies of the cavity.

Consequently, spontaneously emitted photons that have wavelengths at these resonant frequencies reinforce themselves after multiple trips through the cavity so that their optical field becomes very strong. The resonant wavelengths are called the longitudinal modes of the cavity since they resonate along the length of the cavity.



The cavity is much smaller being approximately 250-500 μm long, 5-15 μm wide and 0.1-0.2 μm thick. These dimensions commonly are referred to as the longitudinal, lateral and transverse dimensions of the cavity respectively.

2. Distributed feedback laser (DFB):



A distributed feedback laser (DFB) is an another type of laser diode, where the active region of the device contains a periodically structured element or diffraction gravity (Bragg reflectors). The structure builds a one-dimentional interference gravity and the grating provides optical feedback of the laser. The longitudinal diffraction gravity has periodic changes in refractive index that cause reflection back in to the cavity.

DFB lasers tend to be much more stable than Fabry-Perot lasers and are used frequently when clean single mode operation is needed, especially high speed fiber optic telecommunications.

Laser diode modes:

The optical radiation within the resonance cavity of a laser diode sets up a pattern of electric and magnetic field lines called the modes of the cavity. These can be separated in to two independent sets of transverse electric (TE) and transverse magnetic (TM) modes. Each set of modes can be described in terms of the longitudinal, lateral and transverse half sinusoidal variations of the electromagnetic fields along the major axes of the cavity.

The longitudinal modes are related to the length L of the cavity and determine the principal structure of the frequency spectrum of the emitted optical radiation. Since L is much larger than the lasing wavelength of approximately 1 μm, many longitudinal modes can exist.

Lateral modes lie in the plane of the pn junction. These modes depend on the side wall preparation and the width of the cavity and determine the shape of the lateral profile of the laser beam.

Transverse modes are associated with the electromagnetic field and beam profile in the direction perpendicular to the plane of the pn junction. These modes are of great importance, since they largely determine such laser characteristics as the radiation pattern and the threshold current density.

Threshold (lasing) conditions:

To determine the lasing conditions and resonant frequencies, we express the electromagnetic wave propagating in the longitudinal direction interms of the electric field phasor

$$E(z,t) = I(z)\, e^{j(\omega t - \beta z)}$$

where $I(z)$ - optical field intensity, ω - optical radian frequency

β - propagation constant.

Lasing is the condition at which light amplification becomes possible in the laser diode. The requirement for lasing is that a population inversion be achieved. This condition can be understood by considering the fundamental relationship between the optical field intensity I, the absorption coefficient α_λ and the gain coefficient g in the Fabry- Perot cavity.

The radiation intensity at a photon energy $h\nu$ varies exponentially with the distance z that it travelse along the lasing cavity according to the relationship

$$I(z) = I(0) \exp\{[\Gamma g(h\nu) - \bar{\alpha}(h\nu)] z\} \longrightarrow ①$$

where $\bar{\alpha}$ - the effective absorption coefficient of the material in the optical path. and Γ - optical field confinement factor (i.e the fraction of optical power in the active layes).

Lasing occurs when the gain of one or more guided modes is sufficient to exceed the optical loss during one roundtrip through the cavity ie $z = 2L$. During this roundtrip, only the fractions R_1 and R_2 of the optical radiation are reflected from the two laser ends 1 and 2 respectively, where R_1 and R_2 are the mirror reflectivities of Fresenel reflection coefficients, which are given by

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \longrightarrow ②$$

for the reflection of light at an interface between two materials having refractive indices n_1 and n_2. From this lasing condition eqn ① becomes

$$I(2L) = I(0) R_1 R_2 \exp\{2L[\Gamma g(h\nu) - \bar{\alpha}(h\nu)]\} \longrightarrow ③$$

At the lasing threshold, a steady state oscillation takes place and the magnitude and phase of the returned wave must be equal to these of the original waves. This gives the condition

$$I(2L) = I(0) \longrightarrow ④ \text{ for the amplitude}$$

$$e^{-j2\beta L} = 1 \longrightarrow ⑤ \text{ for the phase.}$$

The condition to just reach the lasing threshold is the point at which the optical gain is equal to the total loss α_t in the cavity. From eqn-④, this condition is

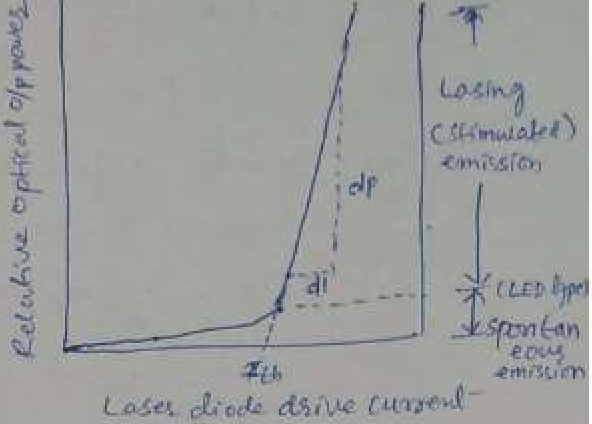
$$\Gamma g_{th} = \alpha_t = \bar{\alpha} + \frac{1}{2L} \ln\left[\frac{1}{R_1 R_2}\right] = \bar{\alpha} + \alpha_{end}$$

where α_{end} - mirror loss in the lasing cavity.

Thus, for lasing to occur, we must have the gain $g \geq g_{th}$. This means that the pumping source that maintains the population inversion must be sufficiently strong to support or exceed all the energy consuming mechanisms within the lasing cavity.

The relationship between optical output power and diode drive current is presented in fig.

A low diode currents, only spontaneous radiation is emitted. Both the spectral range and the lateral beam width of this emission are broad like that of an LED. A dramatic and sharply defined increase in the power output occurs at the lasing threshold. As this transition point is approached, the spectral range and the beam width both narrow with increasing drive current.



The threshold current I_{th} is defined by extrapolation of the lasing region of the power Vs current curve as shown in fig. At high power outputs, the slope of the curve decreases because of junction heating.

For laser structures that have strong carrier confinement, the threshold current density for stimulated emission J_{th} can to a good approximation be related to the lasing threshold optical gain by

$$g_{th} = \beta J_{th}$$

where β - constant that depends on the specific device construction.

Laser Diode Rate Equations:

The relationship between optical output power and the diode drive current can be determined by examining the rate equations that govern the interaction of photons and electrons in the active region. The total carrier population is determined by carrier injection spontaneous recombination and stimulated emission. For a pn junction with a carrier configuration region of depth d, the rate equations are given by

no. of photons 'ϕ' $$\frac{d\phi}{dt} = Cn\phi + R_{sp} - \frac{\phi}{\tau_{ph}} \longrightarrow (1)$$

= stimulated emission + spontaneous emission + photon loss

and $$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\phi \longrightarrow (2)$$

no. of electrons 'n'

= injection + spontaneous recombination + stimulated emission

C - coefficient describing the strength of the optical absorption and emission interactions. R_{sp} - rate of spontaneous emission

τ_{ph} - photon life time, τ_s - spontaneous recombination life time

J - injection current density.

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Solving these two equations for a steady state condition will yield an expression for the output power. The steady state is characterized by the left hand sides of eqns ① & ② being equal to zero. First from eqn ①, assuming R_{sp} is negligible and $\frac{d\phi}{dt}$ must be positive when ϕ is small, we have

$$Cn - \frac{1}{\tau_{ph}} \geq 0 \longrightarrow ③$$

using eqn ②, this threshold value can be expressed in terms of the threshold current J_{th} needed to maintain an inversion level $n = n_{th}$ in the state state when the number of photons $\phi = 0$.

$$\frac{n_{th}}{\tau_{sp}} = \frac{J_{th}}{qd} \longrightarrow ④$$

Next, consider the photon and electron rate equations in the steady state condition at the lasing threshold eqns ① & ② become

$$0 = Cn_{th}\phi_s + R_{sp} - \frac{\phi_s}{\tau_{ph}} \longrightarrow ⑤$$

$$0 = \frac{J}{qd} - \frac{n_{th}}{\tau_{sp}} - Cn_{th}\phi_s \longrightarrow ⑥$$

where ϕ_s - steady state photon density.

Adding eqns ⑤ & ⑥, using eqn ④ for the term $\frac{n_{th}}{\tau_{sp}}$ and solving for ϕ_s yields the number of photons per unit volume

$$\phi_s = \frac{\tau_{ph}}{qd}(J - J_{th}) + \tau_{ph} R_{sp} \longrightarrow ⑦$$

External Quantum Efficiency:

The external quantum efficiency η_{ext} is defined as the number of photons emitted per radiative electron-hole pair recombination above threshold. Under the assumption that above threshold the gain coefficient remains fixed at g_{th}, η_{ext} is given by

$$\eta_{ext} = \frac{\eta_i (g_{th} - \bar{\alpha})}{g_{th}}$$

η_i - internal quantum efficiency $\simeq 0.6 - 0.7$

η_{ext} is calculated from the straight line portion of the curve for the emitted optical power P versus drive current I, which gives

$$\eta_{ext} = \frac{q}{E_g}\frac{dP}{dI} = 0.8065\lambda(\mu m)\frac{dP(mW)}{dI(mA)}$$

E_g - bandgap energy in eV

λ - the emission wavelength in μm

dP - incremental change in the emitted optical power in mW

dI - incremental change in the drive current in mA

Resonant Frequencies

The Fabry-Perot structure forms a resonant cavity, when sufficient population inversion exists in the amplifying medium. the radiation builds up and becomes established as standing waves between the mirrors. These standing waves exist only at frequencies for which the distance between the mirrors is an integral number of half wavelengths, Thus when the optical spacing between the mirrors is L the resonance condition along the axis of the cavity is given by

$$L = \frac{\lambda m}{2n} \Rightarrow m = \frac{L \cdot 2n}{\lambda} = \frac{2Ln}{c} \cdot \nu \longrightarrow ①$$

where $c = \nu\lambda$, λ - emission wavelength, m - an integer
n - refractive index of amplifying medium.

To find the frequency spacing, consider two successive modes of frequencies ν_{m-1} and ν_m represented by the integers $m-1$ and m from eqn ①

$$m-1 = \frac{2Ln}{c}\nu_{m-1} \longrightarrow ② \quad \text{and}$$

$$m = \frac{2Ln}{c}\nu_m \longrightarrow ③$$

subtracting these two equations yields

$$1 = \frac{2Ln}{c}(\nu_m - \nu_{m-1}) = \frac{2Ln}{c} \cdot \Delta\nu \longrightarrow ④$$

From which we have the frequency spacing

$$\Delta\nu = \frac{c}{2Ln} \longrightarrow ⑤$$

This can be related to the wavelength spacing $\Delta\lambda$ through the relationship $\frac{\Delta\nu}{\nu} = \frac{\Delta\lambda}{\lambda}$, yielding

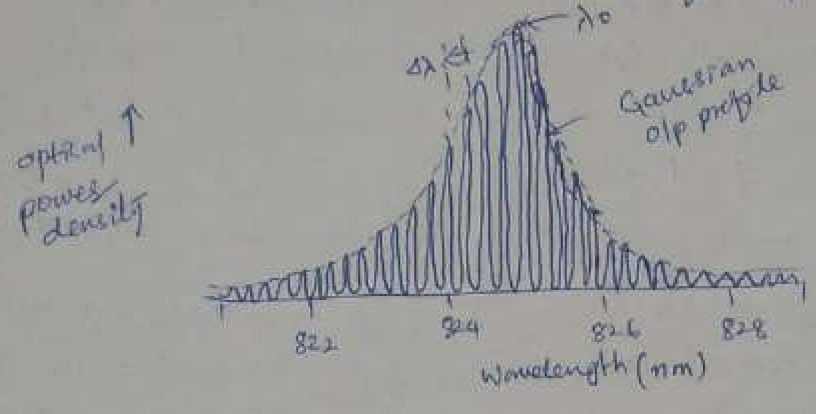
$$\Delta\lambda = \frac{\lambda^2}{2Ln} \qquad (\because c = \nu\lambda)$$

The relationship between gain and frequency can be assumed to have the gaussian form

$$g(\lambda) = g(0)\exp\left[-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}\right]$$

where λ_0 - wavelength at the center of the spectrum
σ - spectral width of gain, $g(0)$ - maximum gain.

The output spectrum of a multimode laser follows the typical gain versus frequency plot given in fig, where the exact number of modes, their heights and their spacings depend on the laser construction



Reliability of LED & ILD:

The operating lifetimes of light emitting diodes and laser diodes are affected by both operating conditions and fabrication techniques. There are relationships between ① light source operation characteristics ② degradation mechanisms and ③ system reliability requirements.

① light source operation characteristics: life time tests of optical sources are carried out either at room temperatures or at elevated temperature is 70°c. The two most popular techniques for determining the lifetime of an optical source either maintain a constant light output by increasing the bias current automatically or keep the current constant and monitor the optical output level.

In the first case, the end of life of the device is assumed to be reached when the source can no longer put-out a specified power at the maximum current value for CW operation.

In the second case, the life time is determined by the time taken for the optical output power to decrease by 3dB.

② degradation mechanisms: degradation of light sources can be divided in to three basic categories ⓐ internal damages ⓑ ohmic contact degradation for both LEDs & lasers ⓒ damage to the facets of laser diodes.

a) internal damage: The limiting factor on LED and laser diode life-time is internal degradation. This effect arises from the migration of crystal defects into the active region of the light source. These defects decrease the internal quantum efficiency and increase the optical absorption.

Fabrication steps that can be taken to minimize internal degradation include the use of substrates with low surface dislocation densities, Keeping work-damaged edges out of the diode current path, and minimizing stresses in the active region. For high-quality sources having lifetimes which follow a slow internal-degradation mode, the optical power P decreases with time according to the exponential relationship. $P = P_0 e^{-t/\tau_m}$

Here P_0 – initial optical power at $t=0$. τ_m – time constant.

b) ohmic contact degradation: In LEDs and laser diodes the thermal resistance of the contact between the light source chip and the device heat sink increases with time. This effect is a function of the solder used to bond the chip to the heat sink, the current density through the contact and the contact temperature. An increase in the thermal resistance results in a rise in the junction temperature for a fixed operating current. This leads to a decrease in the optical output power. However, careful designs and implementation of high quality bonding procedures have minimized effects resulting from contact degradation.

c) damage to the facets: Facet damage is a degradation problem that exists for laser diodes. This degradation reduces the laser mirror reflectivity and increases the non radiative carrier recombination at the laser facets. The two types of facet damage that can occur are generally referred to as catastrophic facet degradation and facet erosion. catastrophic facet degradation is mechanical damage of the facets that may arise after short operating times of laser diodes at high optical power densities. This damage tends to reduce greatly the facet reflectivity, there by increasing the threshold current and decreasing the external quantum efficiency. The catastrophic facet degradation has been observed to be a function of the optical power density and the pulse length.

Facet erosion is a gradual degradation occuring over a longer period of time than catastrophic facet damage. The decrease in mirror reflectivity and the increase in nonradiative recombination at the facets owing to facet erosion lower the internal quantum efficiency of the laser and increase the threshold current.

Facet erosion is minimized by deposing a half-wavelength-thick Al_2O_3 film on the facet. This type of coating acts as a mistuse barrier and does not affect the mirror reflectivity or the lasing threshold current.

Comparision of LED and Laser Diode:

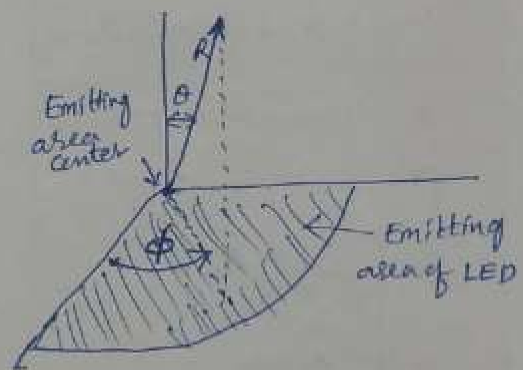
Sr. No	Parameter	LED	Laser Diode
1	principle of operation	spontaneous emission (random)	stimulated emission (In-phase)
2	output beam	Incoherent	coherent
3	output power	Linearly proportional to drive current (Low)	proportional to current above threshold (High)
4	Directivity	Low	High
5	speed of operation	slow	Faster
6	Numerical Aperture	Higher	Lower
7	Complexity	simple	complex
8	life time	longer (10^5 hours)	Shorter (10^4 hours)
9	cost	cheaper (Low)	Expensive (High)
10	population Inversion (P-I)	No Population Inversion	P-I is present
11	Type of spectral emission	Broad Spectrum (20nm - 100nm) 	Narrow band spectrum (1 to 5nm) 
12	Transmission distance	Smaller	Greater
13	Temperature Sensitivity	Less	More
14	coupling efficiency	Very low	High
15	compatible fibers	Multimode SI & Multimode GRIN	Single mode SI & Single mode GRIN
16	Wavelength available	0.66 to 1.65 μm	0.78 to 1.65 μm
17	current required	Drive current 50 to 100 mA	Threshold current 5 to 40 mA
18	Applications	Moderate distance low data rate	Long distance high data rate

Source to Fiber Power Launching:

Launching optical power from a source in to a fiber entails considerations such as the numerical aperture, core size, refractive index profile, core-cladding index difference of the fiber, pulse the size, radiance and angular power distribution of the optical source. A measure of the optical output of a luminescent source is its radiance (brightness) B at a given diode drive current. Radiance is the optical power radiated in to a unit solid angle per unit emitting surface area and is generally specified interms of watts per square centimeter per steradian. Since the optical power that can be coupled in to a fiber depends on the radiance, it is the important parameter when considering source-to-fiber coupling efficiencies.

Source output pattern:

To determine the optical power accepting capability of a fiber, the spatial radiation pattern of the source as shown in fig. A spherical coordinate system characterized by R, θ and ϕ, with the normal to the emitting surface being the polar axis. The radiance may be a function of both θ and ϕ and can also vary from point to point on the emitting surface. Assuming the emission to be uniform across the source area for simple analysis.



Surface-emitting LEDs are characterized by their lambertian output pattern, which means the source is equally bright when viewed from any direction. The power delivered at an angle θ, measured relative to a normal to the emitting surface, varies as $\cos\theta$ because the projected area of the emitting surface varies as $\cos\theta$ which viewing direction. The emission pattern for a lambertian source thus follows the relationship $B(\theta,\phi) = B_0\cos\theta$
where B_0 - the radiance along the normal to the radiating surface.

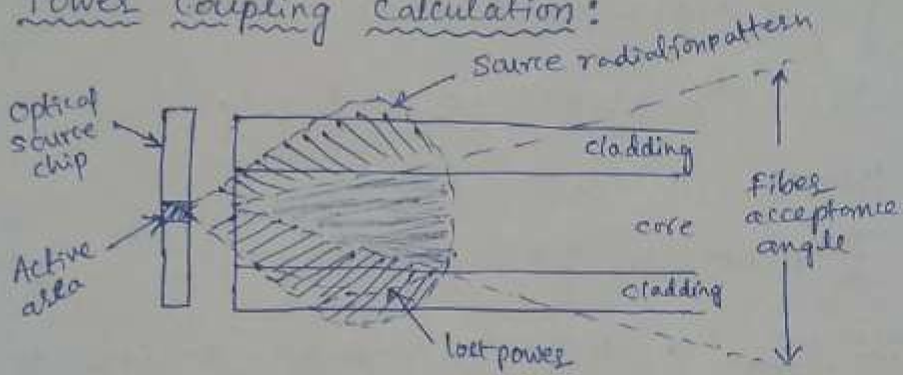
Edge-emitting LEDs and laser diodes have a more complex emission pattern. These devices have different radiances $B(\theta, 0^\circ)$ and $B(\theta, 90^\circ)$ in the planes parallel and normal respectively, to the emitting junction plane of the device.

The radiance can be approximated by the general form

$$\frac{1}{B(\theta,\phi)} = \frac{\sin^2\phi}{B_0 \cos^T\theta} + \frac{\cos^2\phi}{B_0 \cos^L\theta}$$

The integers T and L are the transverse and lateral power distribution coefficients respectively. In general, for edge emitters $L=1$ and T is significantly larger. For laser diodes, L can take on values over 100.

Power Coupling calculation:



To calculate the maximum optical power coupled in to a fiber, consider the fig shown, for a symmetric source of brightness $B(A_s, \Omega_s)$, where A_s and Ω_s are the area and solid emission angle of the source respectively. Here the fiber end face is centered over the emitting surface of the source and is positioned as close to it as possible.

The coupled power can be $\quad P = \int_{A_f} dA_s \int_{\Omega_f} d\Omega_s \; B(A_s, \Omega_s)$

$$P = \int_0^{r_m} \int_0^{2\pi} \left[\int_0^{2\pi} \int_0^{\theta_{0,max}} B(\theta,\phi) \sin\theta \, d\theta \, d\phi \right] d\theta_s \, r \, dr$$

where the area A_f and solid acceptance angle Ω_f of the fiber define the limits of the integrals.

The radiance $B(\theta,\phi)$ from an individual radiating point source on the emitting surface is integrated over the solid acceptance angle of the fiber. The total coupled power is then determined by summing up the contributions from each individual emitting point source of incremental area $d\theta_s r\,dr$ i.e integrating over the emitting area. Assume a surface emitting LED of radius r_s less than the fiber core radius a. Since this is a lambertian emitter

$$P = \int_0^{r_s} \int_0^{2\pi} \left(2\pi B_0 \int_0^{\theta_{0,max}} \cos\theta \sin\theta \, d\theta \right) d\theta_s \, r \, dr$$

$$= \pi B_0 \int_0^{r_s} \int_0^{2\pi} \sin^2\theta_{0,max} \, d\theta_s \, r\,dr = \pi B_0 \int_0^{r_s} \int_0^{2\pi} NA^2 \, d\theta_s \, r\,dr$$

For Stepindex Fibers: For stepindex fibers the numerical aperture is independent of the positions θ_s and r on the fiber end face, so

$$P_{LED,step} = \pi^2 r_s^2 B_0 (NA)^2 \simeq 2\pi^2 r_s^2 B_0 n_1^2 \Delta \quad \text{for } (r_s < a)$$

Consider now the total optical power P_s that is emitted from the source of area A_s in to a hemisphere (2π sr). This is given by

$$P_s = A_s \int_0^{2\pi} \int_0^{\pi/2} B(\theta, \phi) \sin\theta \, d\theta \, d\phi$$

$$= \pi r_s^2 2\pi B_0 \int_0^{\pi/2} \cos\theta \sin\theta \, d\theta = \pi^2 r_s^2 B_0$$

$$\therefore P_{LED,step} = P_s (NA)^2 \quad \text{for } r_s \leq a$$

$$P_{LED,step} = \left(\frac{a}{r_s}\right)^2 P_s (NA)^2 \quad \text{for } r_s > a$$

For Gradedindex Fiber: In the case of a graded index fiber, the numerical aperture depends on the distance r from the fiber axis through the relationship, the power coupled from a surface emitting LED in to a graded index fiber becomes

$$P_{LED,graded} = 2\pi^2 B_0 \int_0^{r_s} [n^2(r) - n_2^2] \, r \, dr$$

$$= 2\pi^2 r_s^2 B_0 n_1^2 \Delta \left[1 - \frac{2}{\alpha+2} \left(\frac{r_s}{a}\right)^\alpha\right]$$

$$= 2 P_s n_1^2 \Delta \left[1 - \frac{2}{\alpha+2} \left(\frac{r_s}{a}\right)^\alpha\right]$$

These analyses assumed perfect coupling conditions between the source and the fiber. This can be achieved only if the refractive index of the medium seperating the source and the fiber end matches the index n_1 of the fiber core. If the refractive index n of this medium is different from n_1, then for a perpendicular fiber end faces, the power coupled in to the fiber reduces by the factor

$$R = \left(\frac{n_1 - n}{n_1 + n}\right)^2$$ where R - Fresnel reflection or the reflectivity at the fiber core end face.

Power Launching: The optical power launched in to a fiber does not depend on the wavelength of the source but only on its brightness i.e its radiance. The number of modes that can propagate in a multimode graded-index fiber of core size a and index profile α is

$$M = \frac{\alpha}{\alpha+2} \left[\frac{2\pi a n_1}{\lambda}\right]^2 \Delta$$

The radiated power per mode, P_s/M from a source at a particular wavelength is given by the radiance multiplied by the square of the nominal source wavelength

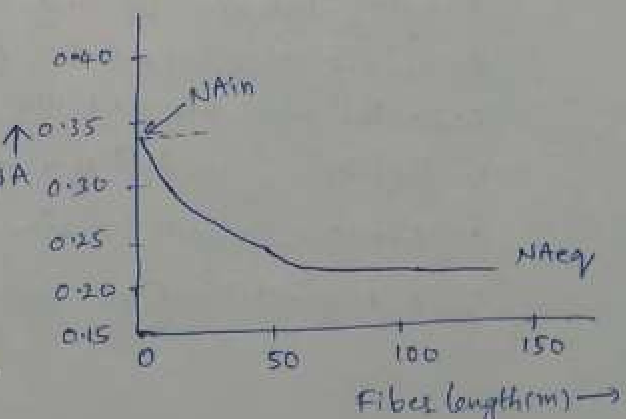
$$\frac{P_s}{M} = B_0 \lambda^2$$

Hence two identically sized sources operating at different wavelengths but having identical radiances will launch equal amounts of optical power in to the same fiber.

Equilibrium Numerical Aperture:

The light source has a short fiber flylead attached to it to facilitate coupling the source to a system fiber. For low coupling loss, this flylead should be connected to system fibers with identical Numerical aperture and core diameter. At this junction certain amount of optical power approximately 0.1 to 1 dB is lost, the exact loss depends on method of connecting. Also excess power loss occurs due to non propagating modes scattering out of fiber. The excess power loss is to be analyzed carefully in designing optical fiber system. This excess power loss is shown in terms of fiber numerical aperture (NA).

Numerical aperture at input light acceptance side is denoted by NA_{in}. When light emitting area of LED is less than fiber core cross-sectional area then power coupled to the fiber is $NA = NA_{in}$.



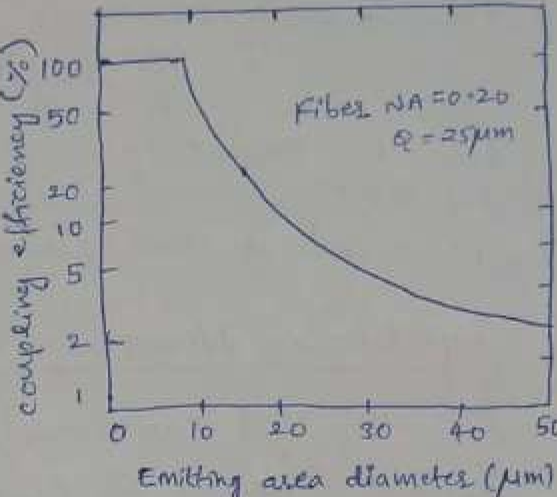
If the optical power is measured in long fiber lengths under equilibrium of modes, the effect of equilibrium numerical aperture NA_{eq} is significant. Optical power at this point is given by

$$P_{eq} = P_{50}\left[\frac{NA_{eq}}{NA_{in}}\right]$$

where P_{50} is optical power in fiber at 50m distance from launch NA.

The degree of mode coupling is mainly decided by core-cladding index difference. Most optical fibers attain 80-90% at their equilibrium NA after 50 m. Hence NA_{eq} is important while calculating launched optical power in telecomm. systems.

Laser Diode to Fiber Coupling:



The edge-emitting laser diodes have an emission pattern that has a full width at half-maximum (FWHM) of 30-50° in the plane perpendicular to the active-area junction and an FWHM of 5-10° in the plane parallel to the junction. The angular output distribution of the laser is greater than the fiber acceptance angle and the laser emitting area is much smaller than the fiber core, spherical or cylindrical lenses can be used to improve the coupling efficiency.

The use of homogeneous glass microsphere lenses has been tested in a series of several hundred laser diode assemblies. Spherical glass lenses with a refractive index of 1.9 and diameters ranging between 50 and 60 μm were epoxied to the ends of 50 μm core diameter graded index fibers having numerical aperture of 0.2. The measure FWHM values of the laser output beams as follows

1. Between 3 and 9 μm for the near field parallel to the junction.
2. Between 30 and 60 for the field perpendicular to the junction.
3. Between 15 and 55° for the field parallel to the junction.

UNIT-IV Optical Detectors

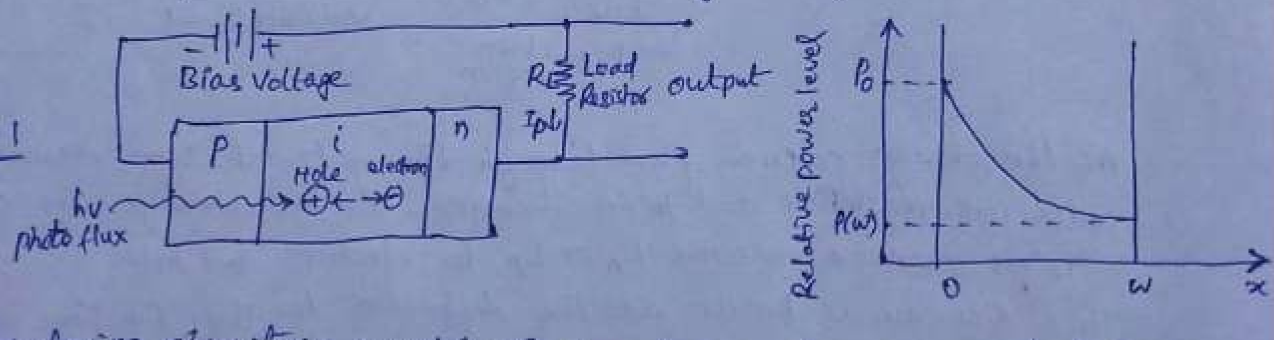
Introduction: At the output end of an optical transmission line, there must be a receiving device which interprets the information contained in the optical signal. The first element of this receiver is a photodetector. The photodetector senses the luminescent power falling up on it and converts the variation of this optical power in to a correspondingly varying electric current.

Several different types of photodetectors are in existence. Among these are photomultipliers, pyroelectric detectors, and semiconductor-based photoconductors, phototransistors and photodiodes. Of the semiconductor based photodetectors, the photodiode is used almost exclusively for fiber optic systems because of its small size, suitable material, high sensitivity and fast response time. The two types of photodiodes used are the pin photodetector and the avalanche photodiode (APD).

Physical Principles of Photodiodes

1. **The pin Photodetector:** The most common semiconductor photodetector is the pin photodiode shown schematically in fig. 1.

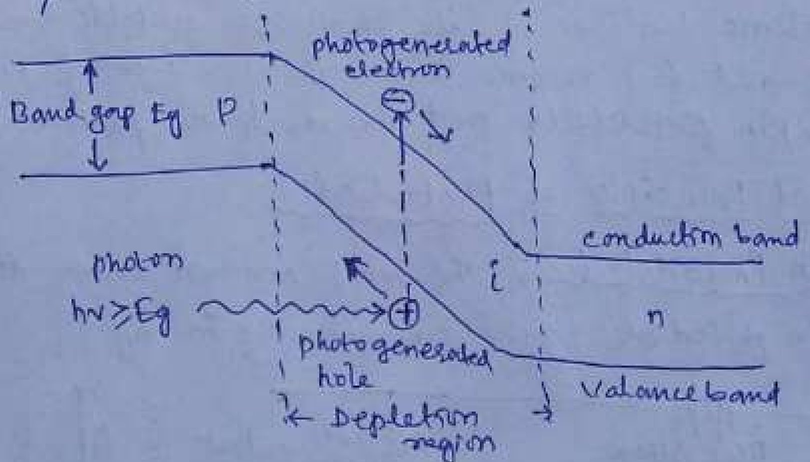
fig. 1



The device structure consists of p and n regions seperated by a very lightly n-doped intrinsic (i) region. In normal operation a sufficiently large reverse-bias voltage is applied across the device so that the intrinsic region is fully depleted of carriers i.e the intrinsic n and p carrier concentrations are negligibly small in comparison with the impurity concentration in this region. When an incident photon has an energy greater than or equal to the bandgap energy of the semiconductor material, the photon can give up its energy and excite an electron from the valance band to the conduction band.

This process generates mobile electron-hole pairs as shown in fig 2. These electrons and holes are known as photocarriers, since they are photon generated charge carriers that are available to produce a current flow when a bias voltage is applied across the device. The photodetector is normally designed so that these carriers are generated mainly in the depletion region (intrinsic region) where most of the incident light is absorbed. The high electric field present in the depletion region causes the carriers to seperate and be collected across the reverse-biased junction. This gives rise to a current flow in an external circuit, with one electron flowing for every carrier pair generated. This current flow is known as the photocurrent.

fig. 2



As the charge carriers flow through the material, some electron-hole pairs will recombine and hence disappear. On the average, the charge carriers move a distance L_n or L_p for electrons and holes respectively. This distance is known as the diffusion length. The time it takes for an electron or hole to recombine is known as the carrier life time and is represented by τ_n and τ_p respectively. The life times and the diffusion lengths are related by the expressions

$$L_n = (D_n \tau_n)^{1/2} \quad \text{and} \quad L_p = (D_p \tau_p)^{1/2}$$

where D_n and D_p are the electron and hole diffusion coefficients respectively which are expressed in units of cm^2/s. If P_{in} is the optical power falling on the photodetector at $x=0$ and $P(x)$ is the power level at a distance x into the material then the incremental change be given as $\boxed{dP(x) = -\alpha_s(\lambda)\, P(x)\, dx}$ where $\alpha_s(\lambda)$ - photon absorption coefficient at a wavelength λ. So that $\boxed{P(x) = P_{in} \exp(-\alpha_s x)}$

→ optical power absorbed $P(x)$ in the depletion region can be written in terms of incident optical power, P_{in}: $\boxed{P(x) = P_{in}(1 - e^{-\alpha_s(\lambda) x})}$

Cut-off wavelength (λ_c) : Any particular semiconductor can absorb photon over a limited wavelength range. The upper wavelength cutoff λ_c is determined by the bandgap energy E_g of the material. If E_g is expressed in units of electron volts (eV), then λ_c is given in units of micrometer (μm) by

$$\lambda_c(\mu m) = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)}$$

Typical value of λ_c for silicon is $1.06 \mu m$ and for Germanium is $1.6 \mu m$.

Quantum Efficiency (η): The quantum efficiency is defined as the number of electron-hole carrier pair generated per incident photon of energy $h\nu$ and is given as

$$\eta = \frac{\text{No of electron hole pairs generated}}{\text{No of incident photons}}$$

$$\eta = \frac{I_p/q}{P_{in}/h\nu}$$

Here, I_p - the photocurrent generated by a steady-state optical power P_{in} incident on the photodetector.

Responsivity: The performance of a photodiode is often characterized by the responsivity (R). The responsivity of a photodetector is the ratio of the current output in amperes to the incident optical power in watts.

$$R = \frac{I_p}{P_{in}}$$

But $\eta = \dfrac{I_p/q}{P_{in}/h\nu} = \dfrac{I_p}{q} \cdot \dfrac{h\nu}{P_{in}}$

$$\therefore \frac{I_p}{P_{in}} = \frac{\eta q}{h\nu}$$

$$\therefore \boxed{R = \frac{\eta q}{h\nu} = \frac{\eta q \lambda}{hc}} \qquad \because \nu = \frac{c}{\lambda}$$

Responsivity gives transfer characteristics of detector i.e. photocurrent per unit incident optical power.

(P) compute the cutoff wavelength for silicon and germanium PIN diodes. Their bandgap energies are 1.1eV and 0.67 eV respectively.

Sol. $\lambda_c = \frac{1.24}{E_g}$ for Silicon $\lambda_c = \frac{1.24}{1.1}$ $\lambda_c = 1.12\mu m$

for germanium $\lambda_c = \frac{1.24}{0.67}$ $\lambda_c = 1.85\mu m$

(P) A PIN photodiode is fabricated by GaAs which has a bandgap energy of 1.43eV at 300°K. Find its upper cutoff wavelength

Sol: $E_g = 1.43eV$

$$\lambda_c = \frac{1.24}{E_g} = \frac{1.24}{1.43}$$

$$\lambda_c = 0.867\mu m = 867\,nm$$

(P) On an InGaAs photodetector a pulse of 85ns emits 6×10^6 photons at 1300 nm wavelength. Average electron-hole pairs generated are 5.4×10^6. Calculate quantum efficiency of detector.

Sol: No of photons emitted $= 6\times10^6$

Average e-h pair generated $= 5.4\times10^6$

Quantum efficiency $(\eta) = \frac{\text{No of e-h pair generated}}{\text{No of incident photons.}}$

$$\eta = \frac{5.4\times10^6}{6\times10^6} = 0.9 = 90\%$$

(P) photons having energy 1.53×10^{-19} Joules are incident on a photodiode having responsivity of 0.65 A/W. If ~~output~~ optical power is 10μW. Find the generated photocurrent.

Sol: $R = 0.65\,A/W$ $P_{in} = 10\mu W$

$$R = \frac{I_p}{P_{in}} \Rightarrow I_p = R\times P_{in} = 0.65\times10\mu = 6.5\mu A$$

(P) The quantum efficiency for InGaAs is around 90%. Find the responsivity at 1300 and 1600nm wavelength. If the bandgap energy of the diode is 0.8eV. Find the cutoff wavelength.

Sol. Given Quantum efficiency $(\eta) = 90\% = 0.9$ $E_g = 0.8eV = 0.8\times1.6\times10^{-19}J$

$$R = \frac{\eta q\lambda}{hc} = \frac{0.9\times1.6\times10^{-19}\lambda}{6.625\times10^{-34}\times3\times10^{8}} = 7.25\times10^5\lambda$$

cutoff wavelength $\lambda_c = \frac{hc}{E_g} = \frac{6.625\times10^{-34}\times3\times10^{8}}{0.8\times1.6\times10^{-19}}$

$$\boxed{\lambda_c = 1.55\mu m}$$

at $\lambda = 1300nm$

$R_{800nm} = 7.25\times10^5\times1300\times10^{-9}$

$= 0.94\,A/W$

$R_{1500} = 7.25\times10^5\times1500\times10^{-9}$

$= 1.164\,A/W$

Avalanche Photodiodes (APD):

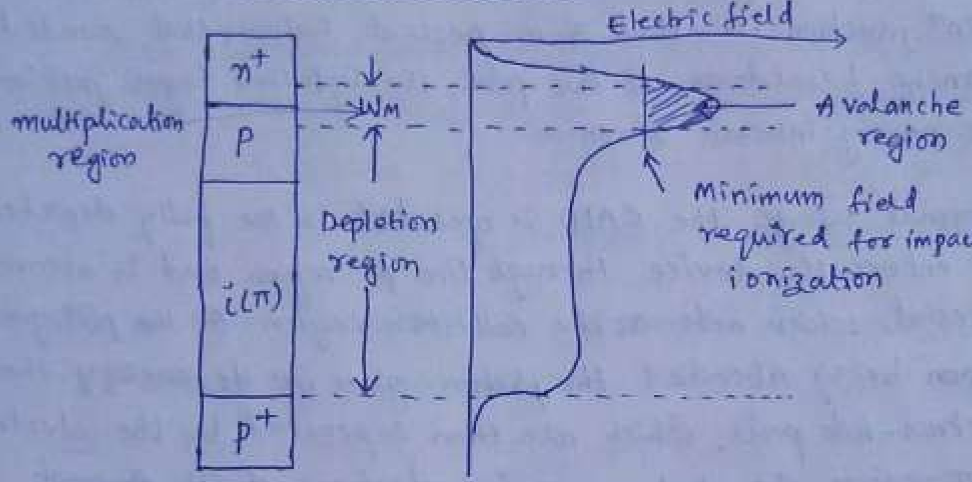


fig-3 Reach through avalanche photodiode structure

Avalanche photodiode (APDs) internally multiply the primary signal photocurrent before it enters the input circuitry of the following amplifier. In order for carrier multiplication to take place, the photogenerated carriers must ~~traverse~~ traverse a region where a very high electric field is present. In this high field region, a photogenerated electron or hole can gain enough energy so that it ionizes bound electrons in the valance band upon colliding with them. This carrier multiplication mechanism is known as impact ionization. The newly created carriers are also accelerated by the high electric field, thus gaining enough energy to cause further impact ionization. This phenomenon is the avalenche effect.

A commonly used structure for achieving carrier multiplication with very little excess noise reach through construction as shown in fig 3. The reach through avalanche photodiode (RAPD) is composed of a high-resistivity p-type material deposited as an epitaxial layer on a p^+ (heavily doped p-type) substrate. A P type diffusion or ion implant is then made in the high resistivity material, followed by the construction of an n^+ (heavily doped n-type) layer. This configuration is referred to as $p^+\pi p n^+$ reach-through structure. The π layer is basically an intrinsic material but has some P doping because of imperfect purification.

The term reach-through arises from the photodiode operation. When a low reverse-bias voltage is applied, most of the potential drop is across the pn^+ junction. The depletion layer widens with increasing bias until a certain voltage is reached at which the peak electric field at the pn^+ junction is about 5-10 percent below that needed to cause avalanche breakdown. At this point, the depletion layer just "reaches through" to the nearly intrinsic π region.

In normal usage, the RAPD is operated in the fully depleted mode. Light enters the device through the p^+ region and is absorbed in the π material, which acts as the collection region for the photogenerated carriers. Upon being absorbed, the photon gives up its energy, thereby creating electron-hole pair, which are then seperated by the electric field in the π region. The photogenerated electrons drift through π region in the pn^+ junction, where a high electric field exists. It is in this high field region that carrier multiplication takes place.

The multiplication M for all carriers generated in the photodiode is defined by

$$M = \frac{I_M}{I_p}$$

where I_M – average value of the total multiplied output current

I_p – primary unmultiplied photocurrent.

The performance of an APD is characterized by its responsivity R_{APD} which is given by

$$R_{APD} = \frac{\eta q}{h\nu} M = RM$$

where R is the unity gain responsivity.

Detector Response Time

1. Depletion Layer Photocurrent: Consider a reverse biased PIN photodiode as shown in fig 4

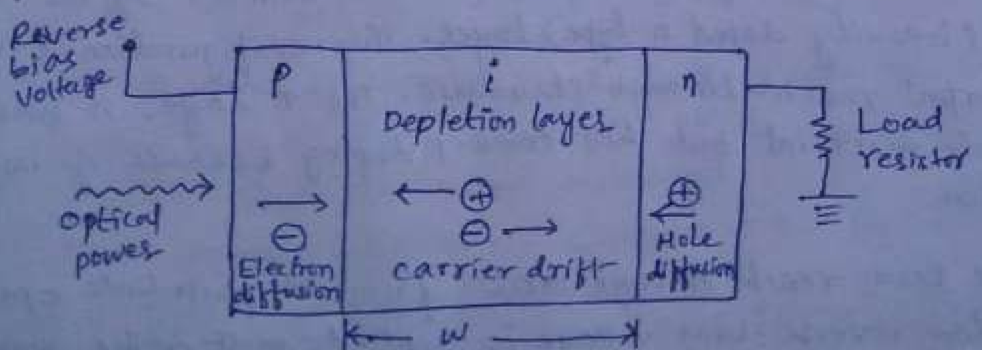


fig 4 Schematic representation of a reverse biased pin photodiode

Light enters the device through the p layer and produces electron hole pairs as it is absorbed in the semiconductor material. Those electron-hole pairs that are generated in the depletion region or within a diffusion length of it will be seperated by the reverse bias voltage induced electric field, there by leading to a current flow in the external circuit as the carriers drift across the depletion layer.

Under steady-state conditions, the total current density J_{tot} flowing through the reverse-biased depletion layer is

$$J_{tot} = J_{dr} + J_{diff} \longrightarrow (1)$$

Here J_{dr} - drift current density due to carriers generated inside the depletion region

J_{diff} - diffusion current density due to carriers generated outside of the depletion region.

The drift current density can be expressed as

$$J_{dr} = \frac{I_p}{A} = q\Phi_0(1-e^{-\alpha_s W}) \longrightarrow (2)$$

where A - photodiode area and Φ_0 - incident photon flux per unit area

$$\Phi_0 = \frac{P_{in}(1-R_f)}{Ah\nu}$$

The diffusion current density can be expressed as

$$J_{diff} = q\Phi_0 \frac{\alpha_s L_p}{1+\alpha_s L_p} e^{-\alpha_s W} + q p_{n0} \frac{D_p}{L_p} \longrightarrow (3)$$

where D_p - hole diffusion coefficient

p_n - hole concentration in n-type material

p_{n0} - equilibrium hole density

The total current density through the reverse biased depletion layer is

$$J_{tot} = q\Phi_0\left(1 - \frac{e^{-\alpha_s W}}{1+\alpha_s L_p}\right) + q p_{n0}\frac{D_p}{L_p} \longrightarrow (4)$$

The term involving p_{n0} is normally small, so that the total photogenerated current is proportional to the photon flux Φ_0.

2. <u>Response Time</u>: The response time of a photodiode depends mainly on the following three factors.

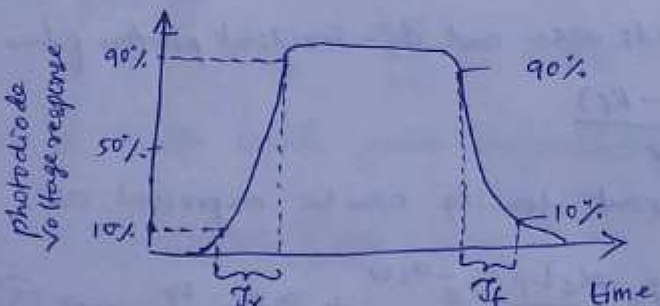
1. The transit time of the photocarriers in the depletion region.
2. The diffusion time of the photo carriers generated outside the depletion region
3. The RC time constant of the photodiode and external circuit.

The response speed of a photodiode is fundamentally limited by the time it takes photogenerated carriers to travel across the depletion region. This transit time t_d depends on the carrier drift velocity v_d and the depletion layer width w, is given by

$$t_d = \frac{w}{v_d}$$

The diffusion processes are slow compared with the drift of carriers in the high field region. Therefore to have a high speed photodiode, the photocarriers should be generated in the depletion region or so close to it that the diffusion times are less than or equal to the carrier drift times. The effect of long diffusion times can be seen by considering the photodiode response time. This response time is described by the rise time and fall time of the detector output when the detector is illuminated by a step input of optical radiation.

fig 5



The rise time τ_r is typically measured from the 10 to the 90 percent points of the leading edge of the output pulse as shown in fig 5. For fully depleted photodiodes the rise time τ_r and the fall time τ_f are generally same. A typical response time of a partially depleted photodiode is shown in fig 6.

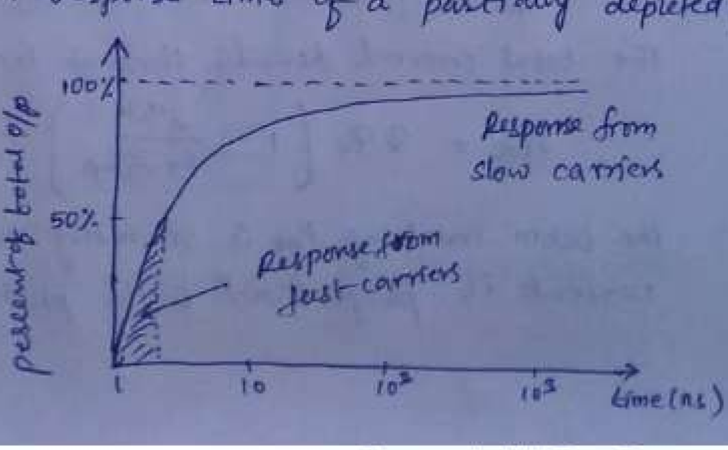


fig. 6. Typical response time of a photodiode that is not fully depleted.

The fast carriers allow the device output to rise to 50% of its maximum value in approximately 1 ns, but the slow carriers cause a relatively long delay before the output reaches its maximum value.

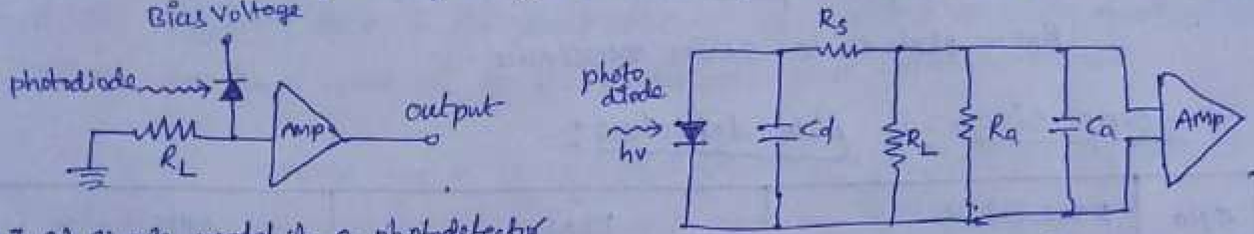


fig.7 a) simple model of a photodetector receiver b) its equivalent circuit.

If the photodiode capacitance is larger, the response time becomes limited by the RC ~~circuit~~ time constant of the load resistor R_L. If R_T is the combination of the load amplifier input response and C_T is the sum of the photodiodes and amplifier capacitance as shown in fig 7.

The detector behaves approximately like a simple RC low-pass filter with a passband given by

$$B_c = \frac{1}{2\pi R_T C_T}$$

Temperature Effect on Avalanche Gain:

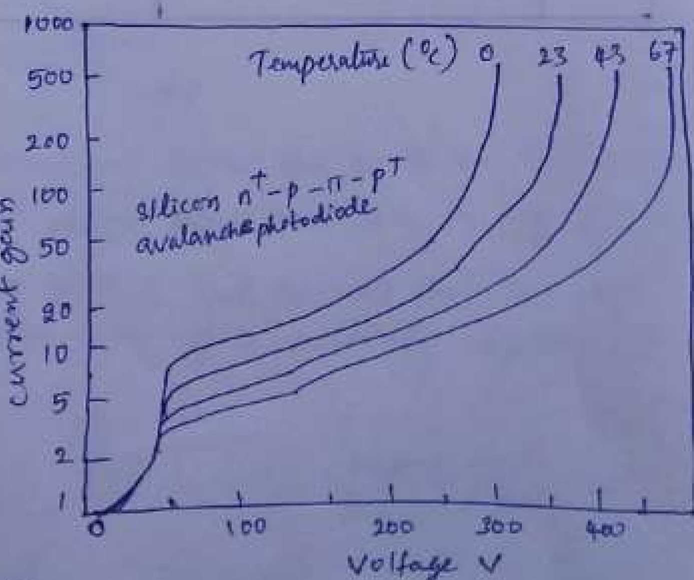
The gain mechanism of an avalanche photodiode is very temperature sensitive because of the temperature dependence of the electron and hole ionization rates. This temperature dependence is particularly critical at high bias voltages, where small changes in temperature can cause large variations in gain. An example is shown in fig. 8.

To maintain a constant gain as the temperature changes, the electric field in the multiplying region of the pn junction must also be changed. A simple temperature-dependent expression for the gain can be obtained from the relationship.

$$M = \frac{1}{1-(V/V_B)^n}$$

where V_B - breakdown voltage at which M goes to infinity.

n - Varies between 2.5 and 7 depending on the material.



$V = V_a - I_M R_M$

V_a - being the reverse bias voltage applied to the detector

I_M - multiplied photo current

R_M - photodiode series resistance

comparison of photodetectors:

S.No	parameters	PIN	APD
1	Sensitivity	Less sensitive (0-12dB)	More Sensitive (5 to 15 dB)
2	Biasing	Low reverse biased voltage (5 to 10V)	High reverse biased voltage (20 - 400 volts)
3	wavelength region	300 - 1100nm	400-100nm
4	Gain	No internal gain	Internal gain
5	S/N ratio	poor	Better
6	Detector circuit	simple	complex
7	conversion efficiency	0.5 to 1.0 Amps/watt.	0.5 to 100 Amps/watt.
8	cost	cheaper	More expensive
9	support circuitry required	None	High voltage & temperature compensator

(P) A Pn Photodiode has a quantum efficiency of 50% at wavelength of 0.9 μm calculate i) its responsivity ii) The received optical power if the photo current is 10^{-6}A.

Sol: $\eta = 50\% = 0.5$

$\lambda = 0.9\mu m$

$I_p = 10^{-6}A$

$$R = \frac{\eta q \lambda}{hc} = \frac{0.5 \times 1.6 \times 10^{-19} \times 0.9 \times 10^{-6}}{6.625 \times 10^{-34} \times 3 \times 10^{8}} = 0.3622 \times 10^{1} = 0.3622 \text{ A/W}$$

$\boxed{R = 0.3622 \text{ A/W}}$

$$R = \frac{I_p}{P_{opt}} \Rightarrow P_{opt} = \frac{I_p}{R} = \frac{10^{-6}}{0.3622} = 2.76\mu W$$

$\boxed{P_{opt} = 2.76\mu W}$

(P) A photodiode has a quantum efficiency of 65% when photons of energy 1.5×10^{-19} Joules are incident on it. i) At what wavelength is the photodiode operating ii) calculate the incident optical power required to obtain a photocurrent of $2.5\mu A$, when the photo diode is operating as above.

Sol: $\eta = 65\% = 0.65$ $\quad E = 1.5 \times 10^{-19} J$ $\quad I_p = 2.5 \mu A$

$$E = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E} = \frac{6.625 \times 10^{-34} \times 3 \times 10^{8}}{1.5 \times 10^{-19}} = 13.25 \times 10^{-7} = 1.325 \times 10^{-6}$$

$$\boxed{\lambda = 1.325 \mu m}$$

$$R = \frac{\eta q \lambda}{hc} = \frac{0.65 \times 1.6 \times 10^{-19} \times 1.325 \times 10^{-6}}{6.625 \times 10^{-34} \times 3 \times 10^{8}} = 0.06933 \times 10^{1} = 0.6933 \, A/W$$

$$\boxed{R = 0.6933 \, A/W}$$

$$R = \frac{I_p}{P_{opt}} \Rightarrow P_{opt} = \frac{I_p}{R} = \frac{2.5 \times 10^{-6}}{0.6933} = 3.6 \times 10^{-6} = 3.6 \mu W$$

$$\boxed{P_{opt} = 3.6 \mu W}$$

(P) compute the bandwidth of a photodetector having parameters as photodiode capacitance = 3pf, Amplifier capacitance = 4pf. Load resistance = 50Ω and Amplifier input resistance = 1MΩ.

Sol: Sum of photodide and amplifier capacitance

$$C_T = 3 + 4 = 7pf$$

$$R_T = 50\Omega // 1M\Omega = \frac{50\Omega \times 1M\Omega}{50\Omega + 1M\Omega} \approx 50\Omega$$

Bandwidth of photodetector $B = \frac{1}{2\pi R_T C_T} = \frac{1}{2\pi \, 50 \times 7 \times 10^{-12}} = 454.95 MHz$

$$\boxed{B = 454.95 MHz}$$

(P) A given APD has a quantum efficiency of 65% at wavelength of 900nm. If 0.5 μW of optical power produces a multiplied photocurrent of 10μA. Find the multiplication factor M.

Sol: Given.

Quantum efficiency $\eta = 65\% = 0.65$

wavelength $\lambda = 900nm = 900 \times 10^{-9} m$

Incident optical power $P_{in} = 0.5\mu W = 0.5\times10^{-6} W$

Multiplied output current $I_M = 10\mu A = 10\times10^{-6} A$

Responsivity $R = \frac{\eta q \lambda}{hc} = \frac{0.65\times1.6\times10^{-19}\times900\times10^{-9}}{6.63\times10^{-34}\times3\times10^{8}}$

$$\boxed{R = 0.4705\ A/W}$$

photocurrent $I_p = P_{in}\times R$

$= 0.5\times10^{-6}\times0.4705$

$= 2.3529\times10^{-7} A$

$$\boxed{I_p = 0.2352\mu A}$$

Multiplication factor $M = \frac{I_M}{I_p} = \frac{10\times10^{-6}}{2.3529\times10^{-7}} = 4.25$

$$\boxed{M = 4.25}$$

(4) A pin photodiode on average generates one electron hole pair per three incident photons at a wavelength of $0.8\mu m$. Assuming all the electrons are collected, calculate i) The quantum efficiency of the device ii) It maximum possible bandgap energy iii) The mean output photocurrent when the received optical power is $10^{-7}W$.

Sol: Given that

For a pin photodiode one electron hole pair generated for every three incident photons, Operating wavelength $\lambda = 0.8\mu m$

i) Quantum efficiency of the device(η).

$$\eta = \frac{\text{Number of electron hole pair generated}}{\text{Number of incident photons}}\times100 = \frac{n}{3n}\times100$$

$\eta = \frac{1}{3}\times100 = 0.3333\times100 = 33.33\% \Rightarrow \boxed{\eta = 33.33\%}$

ii) The maximum possible bandgap energy is given by

$E_g = \frac{hf}{e}$ $\qquad \because hf = \frac{hc}{\lambda} = \frac{6.63\times10^{-34}\times3\times10^{8}}{0.8\times10^{-6}} = 2.486\times10^{-19}$

$E_g = \frac{2.486\times10^{-19}}{1.602\times10^{-19}} = 1.552 eV \Rightarrow \boxed{E_g = 1.552 eV}$

iii) The mean output photocurrent is given by

$I_p = \frac{\eta P_o}{E_g} = \frac{0.3333\times10^{-7}}{1.552 eV} = 21.46 nA \Rightarrow \boxed{I_p = 21.46 nA}$

Optical Receiver Operation

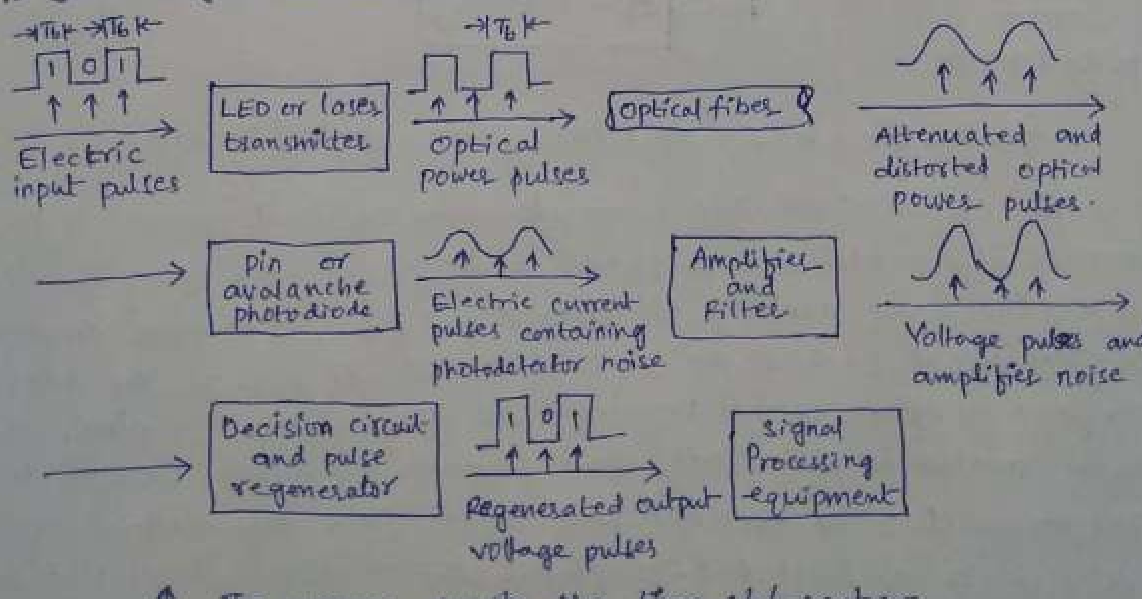
Introduction: An optical receiver consists of a photodetector, an amplifier and signal processing circuitry. The receiver has the task of first converting the optical energy emerging from the end of a fiber into an electrical signal, and then amplifying this signal to a large enough level so that it can be processed by the electronics following the receiver amplifier.

In these processes, various noises and distortions will be unavoidably introduced, which can lead to errors in the interpretation of the received signal. In designing a receiver, it is desirable to predict its performance based on mathematical models of the various receiver stages.

Fundamental Receiver Operation

The design of an optical receiver is much more complicated than that of an optical transmitter because the receiver must be able to detect weak, distorted signals and make decisions on what type of data was sent based on an amplified and reshaped version of this distorted signal. Since traditionally fiber optic communication links are intensity modulated direct detection (IM-DD) systems that use a binary on-off keyed (OOK) digital signal.

Digital Signal Transmission:



↑ The arrows denote the time slot centers

fig.1. signal path through an optical data link.

Fig. 1 shows the shape of a digital signal at different points along an optical link. The transmitted signal is a two level binary data stream consisting of either a 0 or a 1 in a time slot of duration T_b. This time is referred to as a bit period. One of the simplest techniques for sending binary data is amplitude shift keying (ASK) or on-off keying (OOK), where in a voltage level is switched between two values, which are usually on or off. The resultant signal wave thus consists of a voltage pulse of amplitude V when a binary '1' occurs and a zero-voltage level space when a binary '0' occurs. For simplicity, here we assume that when '1' is sent, a voltage pulse of duration T_b occurs, where for '0' the voltage remains at its zero level.

The function of the optical transmitter is to convert the electric signal to an optical signal. One way of doing this is by directly modulating the light source drive current with the information stream to produce a varying optical output power P(t). The optical signal coming from the LED or laser transmitter, 1 is represented by a pulse of optical power of duration T_b, where as '0' is the absence of any light.

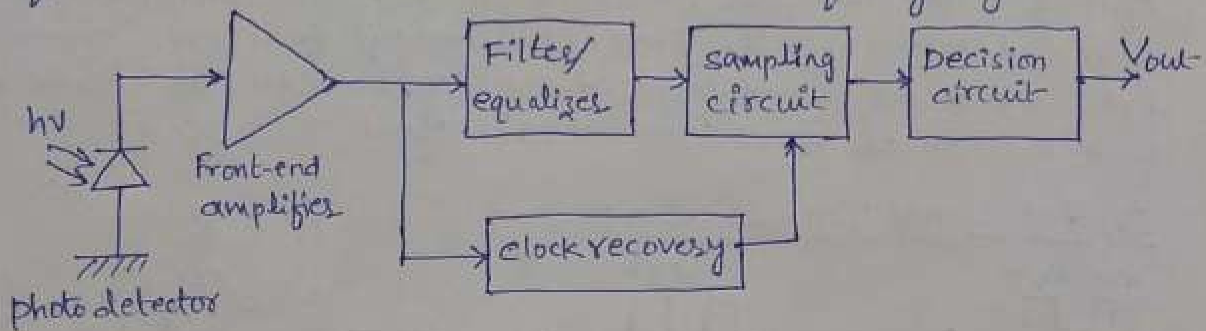


fig. 2 The basic sections of an optical receiver.

The optical signal that is coupled from the light source to the fiber becomes attenuated and distorted as it propagates along the fiber waveguide. Upon arriving at the end of a fiber, a receiver converts the original signal back to an electrical format. Fig. 2 shows the basic components of an optical receiver. The first element is either a pin or an avalanche photodiode, which produces an electric current that is proportional to the received power level. Since this electric current is very weak, a front-end amplifier boosts it to a level that can be used by the following electronics.

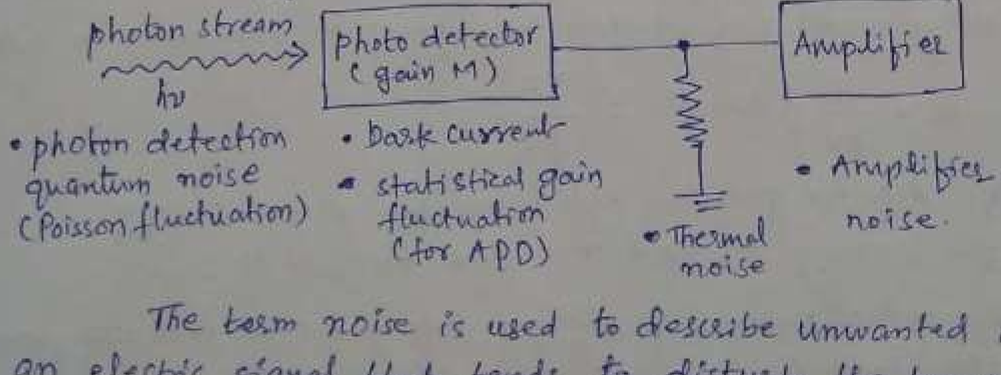
After the electric signal produced by the photodiode is amplified, it passes through a low-pass filter to reduce the noise that is outside of the signal bandwidth. This filter defines the receive bandwidth. To minimize the effects of intersymbol interference (ISI) the filter can reshape the pulses that have become distorted as they travelled through the fiber. This function is called equalization since it equalizes or cancels pulse-spreading effects.

The decision circuit samples the signal level at the midpoint of each time slot and compares it with a certain reference voltage known as the threshold level. If the received signal level is greater than the threshold level, 1 is said to have been received. If the voltage is below the threshold level, 0 is assumed to have been received. To accomplish the bit interpretation, the receiver must know where the bit boundaries are. This is done with the assistance of a periodic waveform called a clock, which has a periodicity equal to the bit interval. This function is called clock recovery or timing recovery.

In some cases, an optical preamplifier is placed ahead of the photodiode to boost the optical signal level before photodetection takes place. So that the signal to noise ratio degradation caused by thermal noise in the receiver can be suppressed, an optical preamplifier provides a larger gain factor and a broader bandwidth.

Error Sources:

Errors in the detection mechanism can arise from various noises and disturbances associated with the signal detection system as shown in fig.



The term noise is used to describe unwanted components of an electric signal that tends to disturb the transmission and processing of the signal in a physical system and over which we have incomplete control.

The noise sources can be either external to the system (ex electric power lines, motors, radio transmitters, lighting) or internal to the system (ex switch and power supply transients). The internal noise is caused by the spontaneous fluctuations of current or voltage in electric circuits. The two most common examples of these spontaneous fluctuations are shot noise and thermal noise. Shot noise arises in electronic devices because of the discrete nature of current flow in the device. Thermal noise arises from the random motion of electrons in a conductor.

The random arrival rate of signal photons produces a quantum (shot) noise at the photodetector. Since this depends on the signal level, it is important for pin receivers that have large optical input levels and for avalanche photodiode receivers. When using an avalanche photodiode, an additional shot noise arises from the statistical nature of the multiplication process. This noise level increases with larger avalanche gain M. Additional photodetector noises come from the dark current and leakage current. These are independent of the photodiode illumination and can be made very small in relation to other noise currents.

Thermal noises arising from the detector load resistor and from the amplifier electronics tend to dominate in applications with low signal-to-noise ratio when a pin photo diode is used. When an avalanche photodiode is used in low-optical-signal level applications, the optimum avalanche gain is determined by a design tradeoff between the thermal noise and the gain dependent quantum noise.

The primary photocurrent generated by the photodiode is a time-varying Poisson process resulting from the random arrival of photons at the detector. If the detector is illuminated by an optical signal $P(t)$, then the average number of electron-hole pairs $\bar{N}$ generated in a time τ is

$$\bar{N} = \frac{\eta}{h\nu}\int_0^{\tau} P(t)\,dt = \frac{\eta E}{h\nu}$$

where η - detector quantum efficiency, $h\nu$ - photon energy

E - energy received in a time interval τ.

The actual number of electron-hole pairs n that are generated fluctuates from the average according to the Poisson distribution

$$P_r(n) = \bar{N}^n \frac{e^{-\bar{N}}}{n!}$$

where $P_r(n)$ — the probability that n electrons are emitted in an interval τ.

It is not possible to predict exactly how many electron-hole pairs are generated by a known optical power incident on the detector is the origin of the type of shot noise called quantum noise. For a detector with a mean avalanche gain M and an ionization rate ratio k, the excess noise factor F(M) for electron injection is

$$F(M) = kM + \left(2 - \frac{1}{M}\right)(1-k)$$

This equation is expressed empirical as $F(M) \simeq M^x$

where factor x ranges between 0 and 1 depending on the photodiode material.

The other error source is intersymbol interference (ISI), which results from pulse spreading in the optical fiber. When a pulse is spreading transmitted in a given time slot, most of the pulse energy will arrive in the corresponding time slot at the receiver as shown in fig.

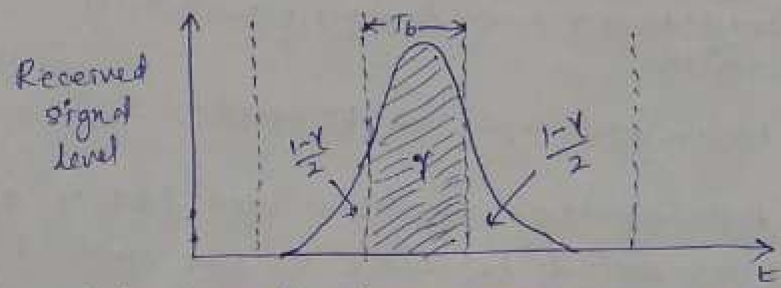


fig. pulse spreading in an optical signal that leads to ISI

Because of pulse spreading induced by the fiber, some of the transmitted energy will progressively spread in to neighboring time slots as the pulse propagates along the fiber. The presence of this energy in adjacent time slots results in an interfering signal called intersymbol interference.

γ - fraction of energy remaing in the time slot T_b

$1-\gamma$ - fraction of energy that has spread in to adjacent time slots.

Receiver configuration:

The bandwidth, noise and sensitivity of optical receiver are determined by preamplifier / Front end amplifier stage. Front-end amplifiers used in optical fiber communication systems can be classified in to two broad categories.

1. High-impedance preamplifier
2. Transimpedance preamplifier.

1. High-impedance preamplifier:

In high-impedance preamplifier the objective is to minimize the noise from all sources. This can be achieved by

- Reducing input capacitance by selecting proper devices.
- Selecting detectors with low dark currents
- Minimizing thermal noise of baising resistors
- Using high impedance amplifier with large R_b.

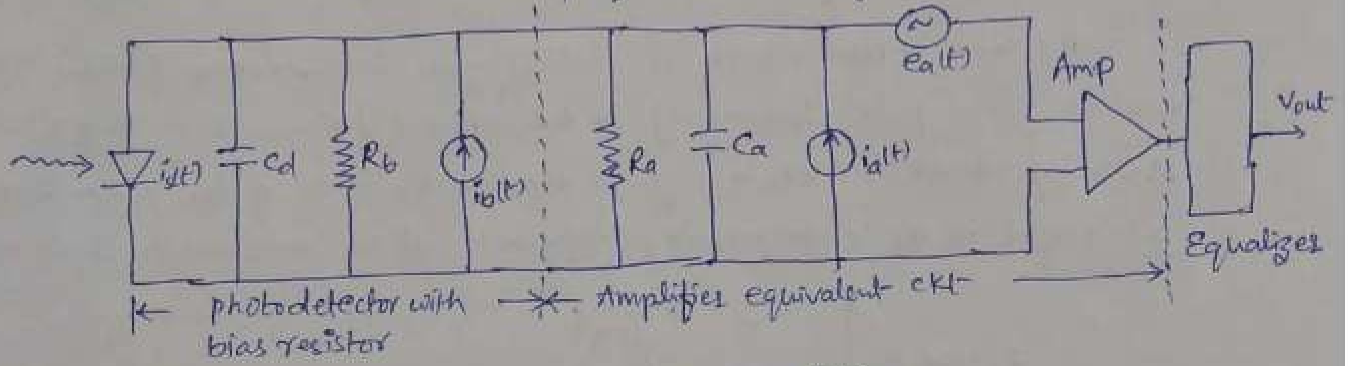


fig. High-input impedance preamplifier

The high impedance amplifier uses FET or a BJT. As the high impedance circuit has large RC time constant, the bandwidth is reduced. High-input impedance preamplifier are most sensitive and finds applications in long-wavelength, long haul routes. The high sensitivity is due to the use of a high input resistance($>1M\Omega$) which results in exceptionally low thermal noise. The combination of high resistance and receiver input capacitance, results in very low BW, typically $< 30MHz$ and this causes integration of the received signal. A differentiating, equalizing or compensating network at the receiver output corrects for this integration.

Transimpedance Preamplifier:

The drawbacks of high input impedance are eliminated. in transimpedance-preamplifier. A negative feedback is introduced by a feedback resistor R_f to increase the bandwidth of open loop preamplifier with an equivalent thermal noise current $i_f(t)$ shunting the input. An equivalent circuit of transimpedance preamplifier is shown in fig.

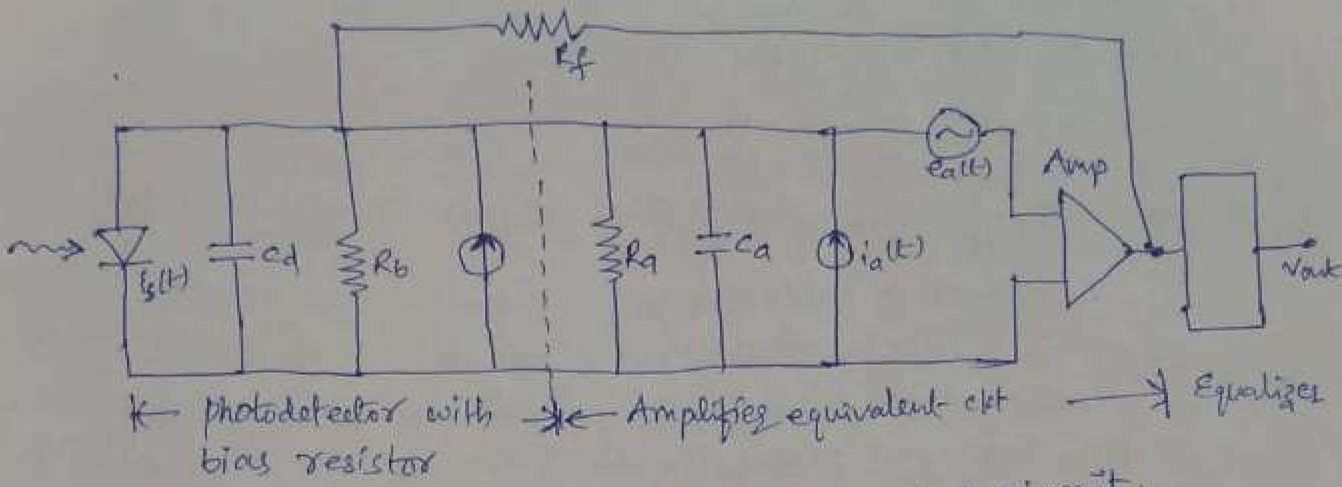


fig. Transimpedance preamplifier equivalent circuit.

$e_a(t)$ = Equivalent series voltage noise source

$i_a(t)$ = Equivalent shunt current noise

$R_{in} = R_a // C_a$

R_f = feedback resistor

$i_f(t)$ = Equivalent thermal noise current.

Although the resulting receiver is often not as sensitive as the integrating front end design, this type of preamplifier does not exhibit a high dynamic range and is usually cheaper to produce.

Digital Receiver Performance :

Ideally, in a digital receiver the decision circuit output signal voltage $V_{out}(t)$ would always exceed the threshold voltage when a '1' is present and would be less than the threshold when no pulse, '0' was sent. In actual systems, deviations from the average value of $V_{out}(t)$ are caused by various noises, interference from adjacent pulses, and conditions where in the light source is not completely extinguished during a zero pulse.

Probability of Error

There are several ways of measuring the rate of error occurrence in a digital data stream. A simple approach is to divide the number N_e of errors occuring over a certain time interval 't' by the number N_t of pulses (ones and zeros) transmitted during this interval. This is called either the error rate or the bit-error rate, which is commonly abbreviated BER.

$$BER = \frac{Ne}{Nt} = \frac{Ne}{Bt}$$

where $B = \frac{1}{T_b}$ is the bit rate (i.e the pulse transmission rate)

Typical error rates for optical fiber telecommunication systems range from 10^{-9} to 10^{-12}. This error rate depends on the signal-to-noise ratio at the receiver. To compute the bit error rate at the receiver, the signal probability distribution decision is made as to whether a '0' or a '1' is sent. The shapes of two signal probability distributions are shown in fig.

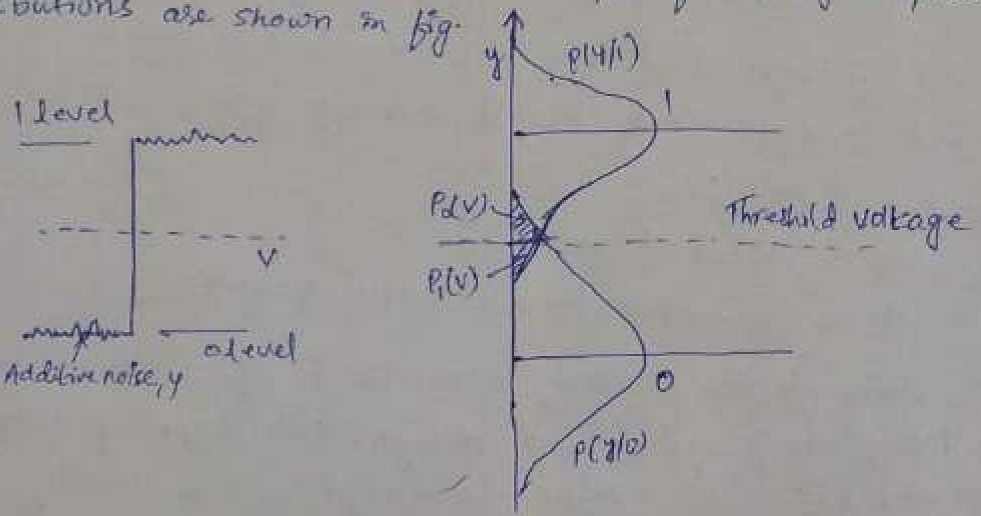


fig.

These are

$$P_1(v) = \int_{-\infty}^{v} p(y|1)\, dy$$

which is the probability that the equalizer output voltage is less than v when a logic 1 pulse is sent, and

$$P_0(v) = \int_{v}^{\infty} p(y|0)\, dy$$

which is the probability that the output voltage exceeds v when a logical 0 is transmitted. The functions $p(y|1)$ and $p(y|0)$ are the conditional probability distribution functions i.e $p(y|x)$ is the probability that the output voltage is y, given that an x was transmitted. If the threshold voltage is V_{th} then the error probability P_e is defined as

$$P_e = a \cdot P_1(V_{th}) + b \cdot P_0(V_{th})$$

The weighting factors a and b are determined by the probabilities that either a '1' or a '0' occurs respectively

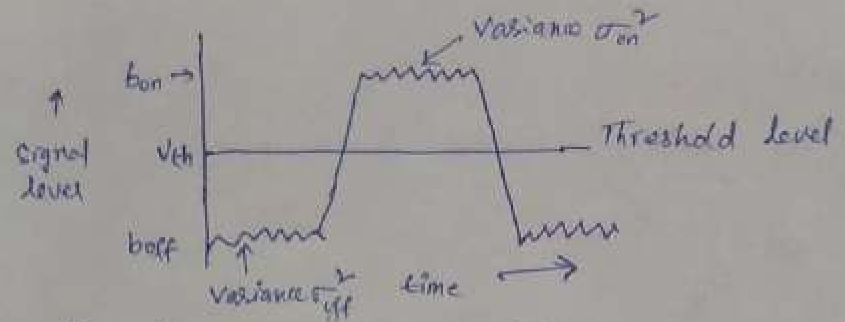


fig. Gaussian noise statistics of a binary signal showing variances around the on and off signal levels.

As shown in fig, the mean and variance of the gaussian output for a '1' pulse are b_{on} and σ_{on}^2, respectively, whereas for a '0' pulse they are b_{off} and σ_{off}^2 respectively. Let us first consider the case of a '0' pulse being sent, so that no pulse is present at the decoding time. The probability of error in this case is the probability that the noise will exceed the threshold voltage V_{th} and be mistaken for a '1' pulse. This probability of error $P_0(v)$ is the chance that the equalizer output voltage $v(t)$ will fall somewhere between V_{th} and ∞.

$$P_0(V_{th}) = \int_{V_{th}}^{\infty} p(y|0)\,dy = \int_{V_{th}}^{\infty} f_0(y)\,dy$$

From the probability density function

$$f(s)\,ds = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(s-m)^2/2\sigma^2}\,ds$$

$s \rightarrow$ signal, m - mean value σ - standard deviation.

$$P_0(V_{th}) = \int_{V_{th}}^{\infty} f_0(y)\,dy = \frac{1}{\sqrt{2\pi}\,\sigma_{off}} \int_{V_{th}}^{\infty} \exp\left[\frac{-(v-b_{off})^2}{2\sigma_{off}^2}\right] dv$$

Similarly, we can find the probability of error that a transmitted '1' is misinterpreted as a '0' by the decoder electronics following the equalizer. This probability of error that the sampled signal pulse-noise pulse falls below V_{th}, is given by

$$P_1(V_{th}) = \int_{-\infty}^{V_{th}} p(y|1)\,dy = \int_{-\infty}^{V_{th}} f_1(v)\,dv$$

$$= \frac{1}{\sqrt{2\pi}\,\sigma_{on}} \int_{-\infty}^{V_{th}} \exp\left[-\frac{(b_{on}-v)^2}{2\sigma_{on}^2}\right] dv$$

If the probabilities of '0' and '1' pulse are equally (i.e $a = b = 0.5$).

$$P_0(V_{th}) = P_1(V_{th}) = \frac{1}{2} P_e$$

The bit error rate or the error probability P_e becomes

$$BER = P_e(Q) = \frac{1}{\sqrt{\pi}} \int_{Q/\sqrt{2}}^{\infty} e^{-x^2} dx$$

$$= \frac{1}{2}\left[1 - \operatorname{erf}\left(\frac{Q}{\sqrt{2}}\right)\right] \approx \frac{1}{\sqrt{2\pi}} \frac{e^{-Q^2/2}}{Q}$$

where $Q = \frac{V_{th} - b_{off}}{\sigma_{off}} = \frac{b_{on} - V_{th}}{\sigma_{on}} = \frac{b_{on} - b_{off}}{\sigma_{on} + \sigma_{off}}$

and error funclim $\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy$

The Quantum Limit

The ideal photodetector which has unity quantum efficiency and which produces no dark current, i.e no electron-hole pairs are generated in the absence of an optical pulse. In this condition, it is possible to find the minimum received optical power required for a specific bit error rate performance in a digital system. This minimum received power level is known an the quantum limit.

Assume that an optical pulse of energy E falls on the photodetector in a time interval τ. This can only be interpreted by the receiver as a '0' pulse if no electron-hole pairs are generated with the pulse present. The probability that $n=0$ electrons are emitted in a time interval t is given from the equation.

$$P_r(n) = \bar{N}^n \frac{e^{-\bar{N}}}{n!}$$

$$P_r(0) = e^{-\bar{N}}$$

where the average number of electron-hole pairs

$$\bar{N} = \frac{\eta E}{h\nu}$$

So for a given error probability $P_r(0)$, we can find the minimum energy E required at a specific wavelength λ.

Analog Receivers:

For an analog receiver, the performance fidelity is measured in terms of a signal to noise ratio. This is defined as the ratio of the mean square signal current to the mean square noise current. The simplest analog technique is to use amplitude modulation of the source. In this, a time varying electric signal s(t) is used to modulate an optical source directly about some bias point defined by the bias current I_B as shown in fig.

The transmitted optical power $P(t)$ is the form

$$P(t) = P_t[1+ms(t)]$$

where

P_t - average transmitted power

$s(t)$ - analog modulation signal

m - modulation index

$$m = \frac{\Delta I}{I_B}$$

ΔI - Variation in current about bias point.

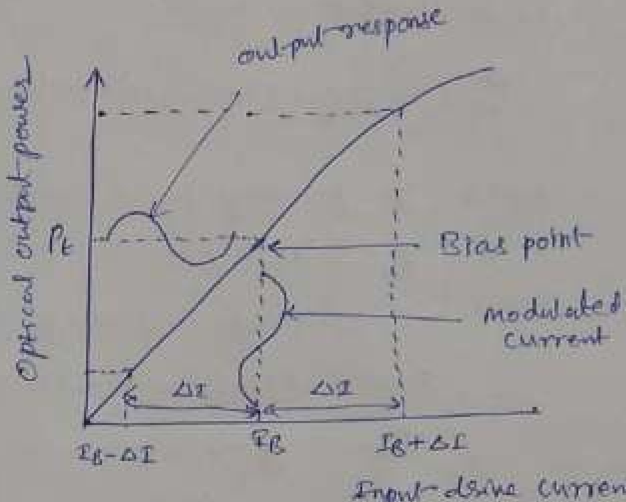


fig. analog modulation of an LED source.

In order not to introduce distortion into the optical signal, the modulation must be confined to the linear region of the light source output curve. Also, if $\Delta I > I_B$, the lower portion of the signal gets cut off and severe distortion results.

At the receiver end, the photocurrent generated by the analog optical signal is

$$i_s(t) = RMP_r[1+ms(t)]$$
$$= I_p M[1+ms(t)]$$

where R - detector responsivity

P_r - average received optical power

$I_p = RP_r$ - primary photo current

M - photodetector gain

If s(t) is a sinusoidally modulated signal, then the mean square signal current at the photodetector output is

$$\langle i_s^2 \rangle = \frac{1}{2}(RMmP_r)^2 = \frac{1}{2}(MmI_p)^2$$

The mean square noise current for a photodiode receiver is the sum of the mean square quantum noise current, the equivalent resistance thermal noise current, the dark noise current and the surface leakage noise current

$$\langle i_N^2 \rangle = 2q(I_p+I_D)M^2F(M)B_e + 2qI_LB_e + \frac{4K_BTB_e}{R_{eq}}F_t$$

where I_p - primary photocurrent = RP_r

I_D - dark current

I_L - surface leakage current

$F(M)$ - excess photodiode noise factor $\simeq M^x \; (0 < x \leq 1)$

B_e - effective receiver noise bandwidth

R_{eq} - equivalent resistance of photodetector load and amplifier.

F_t - noise figure of the baseband amplifier.

By a suitable choice of the photodetector, the leakage current can be negligible. The signal to noise ratio S/N is

$$\frac{S}{N} = \frac{\langle i_s^2 \rangle}{\langle i_N^2 \rangle} = \frac{\frac{1}{2}(RMmP_r)^2}{2q(RP_r + I_D)M^2F(M)B_e + \left(\frac{4K_BTB_e}{R_{eq}}\right)F_t}$$

$$= \frac{\frac{1}{2}(I_pMm)^2}{2q(I_p + I_D)M^2F(M)B_e + \left(\frac{4K_BTB_e}{R_{eq}}\right)F_t}$$

For a PIN photodiode $M=1$, when the optical power incident on the photodiode is small, the thermal noise term dominates the noise current.

$$\frac{S}{N} = \frac{\frac{1}{2}m^2I_p^2}{\left(\frac{4K_BTB_e}{R_{eq}}\right)F_t} = \frac{\frac{1}{2}m^2R^2P_r^2}{\left(\frac{4K_BTB_e}{R_{eq}}\right)F_t}$$

The signal to noise ratio is directly proportional to the square of the photodiode output current and inversely proportional to the thermal noise. For large optical signals incident on a pin photodiode, the quantum noise associated with the signal detection process.

$$\therefore \frac{S}{N} = \frac{m^2 I_p}{4qB_e} = \frac{m^2 R P_r}{4qB_e}$$

In this case, the signal to noise ratio is independent of the circuit noise, it represents the quantum limit for analog receiver sensitivity.

(P) An InGaAs PIN photodiode has the following parameters at a wavelength of 1300 nm, $I_D = 4\ nA$, $\eta = 0.9$, $R_L = 1000\ \Omega$ and the surface leakage current is negligible. The incident optical power is 300nW (−35dBm) and the receiver bandwidth is 20MHz. Find the various noise terms of the receiver.

Sol. Given $\lambda = 1300nm$ $I_D = 4\ nA$ $\eta = 0.9$ $R_L = 1000\ \Omega$

$P_{incident} = 300nW$ $B = 20MHz$.

Mean square quantum noise current.

$$I_q^2 = \sqrt{\frac{q \cdot P_{incident}\ \eta}{h\nu}} = \sqrt{\frac{q \cdot P_{incident}\ \eta \cdot \lambda}{hc}}$$

$$= \sqrt{\frac{(1.69\times10^{-19})(300\times10^{-9})(0.9)(1300\times10^{-9})}{(6.626\times10^{-34})(3\times10^{8})}}$$

$$I_q^2 = 2.23\times10^{11}\ Amp$$

Mean spark dark current

$$I_d^2 = 2eBI_D = 2(1.6\times10^{-19})(20\times10^{6})(4\times10^{-9})$$

$$I_d^2 = 0.256\times10^{-19}\ Amp$$

Mean square thermal noise current $I_t^2 = \frac{4KTB}{R_L}$

$$I_t^2 = \frac{4\times(1.38\times10^{-23})\times(298)(20\times10^{6})}{1000}$$

$$= \underline{3.28\times10^{-16}\ Amp}$$

$B = 1.38\times10^{-23}\ J/k$
$T = 25° + 273°$
$= 298K$

(P) A digital fiber link operating at 850 nm requires a maximum BER of 10^{-9}. Calculate i) the quantum limit in terms of the quantum efficiency and the energy of the incident photon. ii) minimum incident optical power P_i.

Sol. i) $\lambda = 850\text{nm} = 850\times10^{-9}\text{m}$ BER $= 10^{-9}$

Probability of error $P_r(0) = e^{-\bar{N}} = 10^{-9}$

$\bar{N} = 9\ln 10 = 20.7 \implies \bar{N} \simeq 21$

Hence, an average of 21 photons per pulse is required for this BER. No of electron-hole pairs generated ($\bar{N}$), quantum efficiency (η), photon energy ($h\nu$) and energy received (E) are related by

$$\bar{N} = \frac{\eta E}{h\nu} \implies E = \bar{N}\cdot\frac{h\nu}{\eta}$$

$$E = 20.7\frac{h\nu}{\eta}$$

ii) The minimum incident optical power P_i that must fall on the photodetector to achieve a 10^{-9} BER at a data rate of 10Mb/s for a simple binary-level signaling scheme. If the detector quantum efficiency $\eta = 1$ then

$$E = P_i\tau = 20.7\frac{hc}{\lambda}$$

where $1/\tau$ is one-half the data rate B, that is $1/\tau = B/2$

Assuming equal numbers of 0 and 1 pulses

$$P_i \simeq 20.7\frac{hcB}{2\lambda}$$

$$= \frac{20.7(6.626\times10^{-34})(3\times10^{8})(10\times10^{6})}{2(0.85\times10^{-6})}$$

$P_i = 24.2$ pW or when the reference power level is 1mW

$$\underline{P_i = -76.2\text{ dBm}}$$

UNIT-V Optical System Design

System Design Factors: To achieve high quality transmission, careful decisions based on operating parameters apply for each component of a fiber optic transmission system. The main questions data rates and bit error rates in digital systems, bandwidth, linearity and signal to noise ratios in analog systems, transmission distances. These questions of how far, how good, and how fast define the basic application constraints. Once these are decided, it is time to evaluate the other factors involved.

Table: Factors for Evaluating Fiber optic System Design.

System Factor	Consideration choices
Type of Fiber	Single mode or multimode
Dispersion	Regenerators or Dispersion compensation
Fiber Non linearities	Fiber characteristics, wavelengths and transmitter power
Operating wavelength	780, 850, 1310, 1550 nm and 1625 nm typical
Transmitter power	Typically expressed in dBm
Source Type	LED or Laser.
Receiver sensitivity / over-load characteristics	Typically expressed in dBm.
Detector type	PIN Diode, APD or IDP
Modulation code	AM, FM, PCM or Digital
Bit Error Rate (BER) Digital systems only	10^{-9}, 10^{-12} Typical
Signal to Noise Ratio	Specified in decibels (dB)
Number of connectors	Loss increases with the number of connectors
Number of splices	Loss increases with the number of splices
Environmental Requirements	Humidity, Temperature, Exposure to sunlight
Mechanical Requirements	Flammability, Indoor / outdoor Application

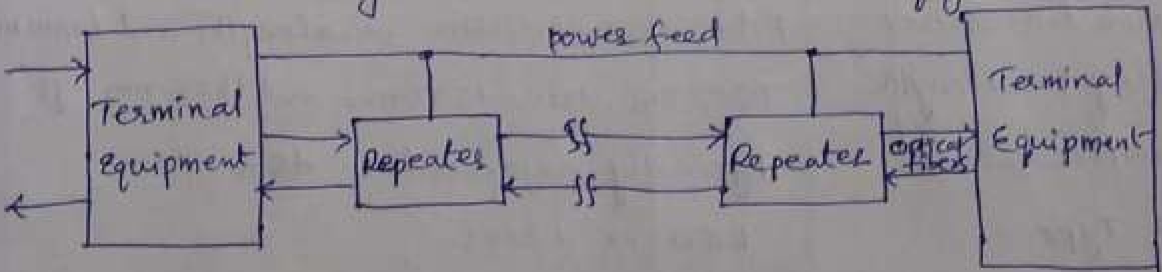
Many of these considerations are directly related to other considerations. For example, the detector choice will impact the receiver sensitivity which will affect the necessary transmitter output power. Output power impacts the transmitter light emitter type which will affect the usable fiber type and connector type. A logical way to proceed with designing a fiber link involves analysing the fiber optic link power budget or optical link loss budget.

System Design Considerations

→ In optical system design major consideration involves

1. Transmission characteristics of fiber (attenuation & dispersion)
2. Information transfer capability of fiber.
3. Technical equipment & technology
4. Distance of transmission.

→ In long-haul communication applications repeaters are inserted at regular intervals as shown in fig.



→ Repeater regenerates the original data before it is retransmitted as a digital optical signal. The cost of system and complexity increases because of installation of repeaters.

→ An optical communication system should have following basic required specifications.

a) Transmission type (Analog / digital)
b) System fidelity (SNR / BER)
c) Required Transmission Bandwidth
d) Acceptable repeater spacing
e) Cost of system
f) Reliability
g) Cost of maintenance

Multiplexing:

Multiplexing of several signals on a single fiber increases information transfer rate of communication link. In time division multiplexing (TDM) pulses from multiple channels are interleaved and transmitted sequentially, it enhance the bandwidth utilization of a single fiber link. In frequency division multiplexing (FDM) the optical channel bandwidth is various nonoverlapping frequency bands and each signal is assigned one of these bands of frequencies. By suitable filtering the combined FDM signal can be retrieved.

When number of optical sources operating at different wavelengths are to be sent on single fiber link wavelength division multiplexing (WDM) is used. At receiver end, the seperation or extraction of optical signal is performed by optical filters. Another technique called space division multiplexing (SDM) uses seperate fiber within fiber bundle for each signal channel. SDM provides better optical isolation which eliminates cross-coupling between channels. But this technique requires huge number of optical components (fiber, connector, sources, detectors etc) therefore not widely used.

Point-to-Point Links:

A point-to-point link comprises of a ~~one~~ transmitter on one end a receiver on the other end as shown in fig. This is the simplest form of optical communication link and it sets the basis for examining complex optical communication links.

For analyzing the performance of any link following important aspects are to be considered.

a) Distance of transmission b) channel data rate or bandwidth
c) Bit error rate (BER)

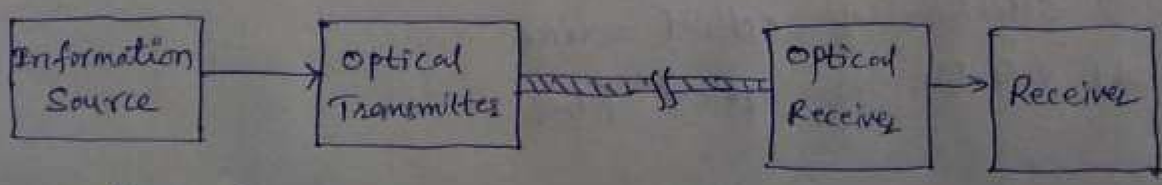


fig. Simplex point-to-point link

Components choice:

To fulfill the requirements the designer has a choice of the following components and their associated characteristics.

Components	Characteristics
1. Optical fiber (multimode/single mode)	a) core size b) core refractive index c) Bandwidth (B) d) Attenuation e) Numerical aperture (NA) f) dispersion
2. Optical Source (LED/LASER)	a) Emission wavelength b) output power c) Emission pattern d) Effective radiating area e) Number of emitting modes f) spectral line width g) stability and life time
3. optical detector (PIN/APD)	a) Responsivity b) operating wavelength c) speed d) sensitivity e) efficiency f) Noise figure

System considerations:-

- The overall system consideration includes following steps
  1) selection of operating wavelength
  2) selection of photodetector
  3) selection of optical source
  4) selection of optical fiber

1. Selection of operating wavelength:

Before selecting suitable components, the operating wavelength for the system is decided. The operating wavelength selection depends on the distance and attenuation. For shorter distance, the 800-900 nm region is preferred but for longer distance 1300 or 1550 nm region is preferred due to lower attenuations and dispersion.

2. Selection of photodetector:

While selecting a photodetector following factors are considered

i) Minimum optical power that must fall on photodetector to satisfy BER at specified data rate.
ii) Complexity of circuit.
iii) Cost of design
iv) Bias requirements.

3. Selection of optical source:

Next step in system consideration is choosing a proper optical source, important factors to consider are

i) Signal dispersion ii) data rate
iii) Transmission distance iv) cost
v) Optical power coupling vi) Circuit complexity

4. Selection of optical fiber:

The last factor in system consideration is to selection of optical fiber between single mode and multimode fiber with step or graded index fiber. Fiber selection depends on type of optical source and tolerable dispersion. Some important factors for selection of fiber are

i) Numerical aperture (NA), as NA increases, the fiber coupled power increases, the fiber coupled power increases also the dispersion
ii) Attenuation characteristics
iii) Environmental induced losses e.g due to temperature variation, moisture and dust etc.

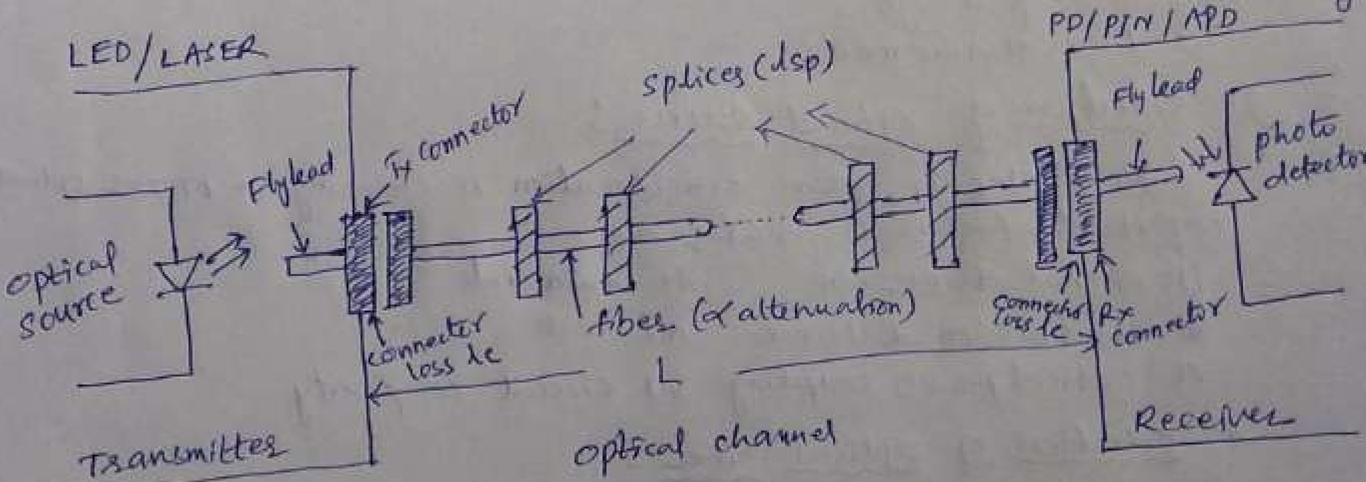
Link Power Budget :

Two important analysis for deciding performance of any link are

i) Link power Budget / power Budget

ii) Rise time Budget / Bandwidth budget.

In the link power budget analysis are first determines the power margin between the optical transmitter output and the minimum receiver sensitivity needed to establish a specified BER. This margin can be allocated to connector, splice and fiber losses plus any additional margins required for other components, possible component degradation transmission line impairments or temperature effects. An optical power loss model for a point to point link is shown in fig.



The optical power received at the photodetector depends on the amount of light coupled in to the fiber and the losses occuring in the fiber and at the connectors and splices. The link loss budget is derived from the sequential loss contribution of each element in the link. Each of these loss element is expressed in decibels (dB) as

$$loss = 10 \log \frac{P_{out}}{P_{in}}$$

where P_{in} and P_{out} are the optical power entering and leaving the loss element respectively.

The link loss budget simply consider the total optical power loss P_T That is allowed between the light source and the photodetector and allocates this loss to cable attenuation, connector loss, splice loss and system margin.

If P_s is the optical power emerging from the end of a fiber flylead attached to the light source and if P_R is the receiver sensitivity Then

$$P_T = P_s - P_R$$

$$= 2\,l_c + \alpha L + n\,l_{sp} + \text{system margin}$$

where l_c - connector loss

α - fiber attenuation (dB/km)

L - Transmission distance / length of fiber

l_{sp} - loss due to single splice.

(no. of splices $n = \frac{L}{\lambda} - 1$)

Assume $L = 10\,km$ splices are connector 2 km

$\therefore$ no of splices $n = \left(\frac{L}{\lambda} - 1\right) = \left(\frac{10}{2} - 1\right) = 4$

Here, the system margin is normally taken as 6 dB

<u>Example of link power Budget</u>

components chosen for a digital fiber link of overall length 10km and operating at 20 Mbps are as follows.

i) LED capable of launching an average power 0.1mw at 0.85μm
ii) Fiber attenuation 2.5 dB/km
iii) Requires splicing every 2km with a loss of 0.3dB per splice connector loss is of 1.5dB
iv) The receiver power needed of −46 dBm in order to get 10^{-10} BER
v) predicted safety margin 6dB.

Find link power budget

Sol: Given $L = 10\,km$, data rate - 20mbps

$P_s = 0.1\,mw = 0.1\times10^{-3}\,w = 10^{-4}\,w \Rightarrow P_s = 10\log 10^{-4} = -40\,dB$

$\lambda = 0.85\,\mu m$, $\alpha = 2.5\,dB/km$, $\lambda = 2\,km$ $\lambda_{sp} = 0.3\,dB$ $l_c = 1.5\,dB$

$P_R = -46\,dB = -46 - 30 = -76\,dB$

Total Loss (Allowed) $P_T = P_s - P_R = -40 - (76) = 36\,dB$

Total loss $= \alpha L + 2l_c + n\,l_{sp} +$ saftey margin

$$\text{Total loss} = 2.5\times10 + 2\times1.5 + \left(\frac{10}{2}-1\right)0.3 + 6$$

$$= 25+3+1.2+6 = 35.2\ \text{dB}$$

Total loss 35.2 dB is less than allowed loss (36 dB). so signal can be received with out problem

Rise Time Budget:

Rise time gives important information for initial system design. Rise time budget analysis determines the dispersion limitation of an optical link. Total rise time of a fiber link is the root sum-square of rise time of each contributor to the pulse rise time degradation

$$t_{sys} = \sqrt{t_{r_1}^2 + t_{r_2}^2 + t_{r_3}^2 + \cdots} = \sqrt{\sum_{i=1}^{N} t_{r_i}^2}$$

Connectors, couples and splices do not affect system speed, They need not be accounted in rise time budget but they appear in the link power budget.

Four basic elements that contributes to the rise time are

1) Transmitter rise time (t_{Tx})
2) Group velocity dispersion (GVD) rise time (t_{GVD}) or (t_{mat})
3) Modal dispersion rise time (t_{mod})
4) Receiver rise time (t_{Rx})

$$t_{sys} = \left[t_{Tx}^2 + t_{mod}^2 + t_{GVD}^2 + t_{Rx}^2\right]^{1/2}$$

1. Transmitter rise time (t_{Tx}) (LED/ LASER)

This type of rise time is contributed by the light source and the driving circuitry. This value is generally known to designer.

2. Group velocity dispersion rise time (t_{mat})

- optical cable has group delay dispersion
- For length L of optical cable, it is given by

$t_{mat} = DL\sigma_\lambda$ where L - length of fiber

D - Dispersion of optical link ($ns/nm\cdot km$)

σ_λ - Half power spectral width of source.

3. Model dispersion rise time (t_{mod})

$$t_{mod} = \frac{440}{B_m} = \frac{440 L q}{B_0}$$

Here B_m - Bandwidth

L - length of fiber (km)

q - parameter ranging between 0.5 & 1

B_0 - Bandwidth of 1 km length fiber

4. Receiver rise time (t_{Rx}) - (PD/PIN/APD)

It is photodetector response with 3-dB electrical bandwidth B_{rx}

$$t_{Rx} = \frac{350}{B_{rx}}$$

∴ Total rise time of system is given by

$$t_{sys} = \sqrt{t_{Tx}^2 + t_{mod}^2 + t_{mat}^2 + t_{Rx}^2}$$

$$= \sqrt{t_{Tx}^2 + \left(\frac{440 L q}{B_0}\right)^2 + D^2 L^2 \sigma_\lambda^2 + \left(\frac{350}{B_{rx}}\right)^2}$$

All times are in nanoseconds

For RZ (Return to zero) total maximum system bandwidth (Mbps)

$$BW = \frac{0.35}{t_{sys}}$$

For NRZ (Non Return to zero), total maximum system bandwidth

$$BW = \frac{0.70}{t_{sys}}$$

∴ $BW\,(\text{mbps}) \propto \frac{1}{t_{sys}}$ (more dispersion less the bandwidth.

(P) For a multimode fiber link following parameters are recorded
i) LED with drive circuit has rise time of 15ns ii) LED spectral width = 40nm
iii) Material dispersion related risetime degradation = 21ns over 6km link
iv) Receiver bandwidth = 25MHz v) Model dispersion rise time = 3.9 sec
Calculate system rise time.

Sol: $t_{Tx} = 15\text{ns}$, $t_{mat} = 21\text{ns}$, $t_{mod} = 3.9\text{ns}$ $t_{Rx} = \frac{350}{B_{rx}} = \frac{350}{25} = 14\text{ns}$

$$t_{sys} = \left[\sum_{i=1}^{N} t_{ri}^2\right]^{1/2} = \left[15^2 + 21^2 + 3.9^2 + 14^2\right]^{1/2}$$

$t_{sys} = 29.61\text{ns}$

(P) An optical fiber system is to be designed to operate an 8km length without repeaters. The rise times of the chosen components are

Source (LED) = 8ns , Fiber cable : 5ns/km

detector (PIN) = 6ns , Intramodal : 1ns/km

Estimate maximum bit rate using NRZ and RZ format.

Sol: $L = 8km$, $t_{TX} = 8ns$, $t_{mat} = 5ns \times 8 = 40\,nsec$, $t_{mod} = 1ns \times 8 = 8ns$

$t_{RX} = 6\,ns$

$$t_{sys} = \sqrt{t_{TX}^2 + t_{mat}^2 + t_{mod}^2 + t_{RX}^2}$$

$$= \sqrt{8^2 + 40^2 + 8^2 + 6^2} = 42\,ns$$

Max. bit rate for RZ $\quad BW = \frac{0.35}{t_{sys}} = \frac{0.35}{42 \times 10^{-9}} = 8.333$ Mbps

Max. bit rate for NRZ $\quad BW = \frac{0.70}{t_{sys}} = \frac{0.70}{42 \times 10^{-9}} = 16.666$ Mbps.

(P) A transmitter has an output power of 0.1mW. It is used with a fiber having NA = 0.25, attenuation of 6 dB/km and length 0.5km. The link contains two connectors of 2dB average loss. The receiver has a minimum acceptable power (sensitivity) of −35 dBm. The designer has allowed a 4 dB margin. Calculate the link power budget.

Sol: Source power $P_s = 0.1\,mW = -10\,dBm$, $NA = 0.25$

coupling loss $= -10\log(NA^2) = -10\log(0.25^2) = 12\,dB$.

Fiber loss $(\alpha_f) = \alpha_f \times L = (6\,dB/km)(0.5\,km) = 3\,dB$

Connector loss $(l_c) = 2(2\,dB) = 4\,dB$

Design margin $= 4\,dB$

∴ Actual output power P_{out} = Source power − (Σ losses)

$$P_{out} = -10\,dBm - [12\,dB + 3 + 4 + 4] = -33\,dBm$$

Since receiver sensitivity given is $= -35\,dBm$

$P_{min} = -35\,dBm$

As $P_{out} > P_{min}$, the system will perform adequately over the system operating life.

Line coding in optical links:

Line coding or channel coding is a process of arranging the signal symbols in a specific pattern. Line coding introduces reducing in to the data stream for minimizing errors.

In optical fibes communication, three types of line codes are used.

1. Non-return-to-zero (NRZ)
2. Return-to-zero (RZ)
3. phase-encoded (PE)

Describe properties of Line codes:

1. The line code should contain timing information
2. The line code must be immune to channel noise and interference.
3. The line code should allow error detection and correction.

NRZ codes:

Different types of NRZ codes are introduced to suit the variety of transmission requirements. The simplest form NRZ code is NRZ-level. It is unipolar code ie the waveform is simple on-off type. Since this process turns the light signal on and off. It is known as amplitude shift keying (ASK) or on-off keying (OOK). When symbol '1' is to be transmitted, the signal occupies high level for full bit period. When a symbol '0' is to be transmitted. The signal has zero volts for full bit period. Fig shows example of NRZ-L data pattern.

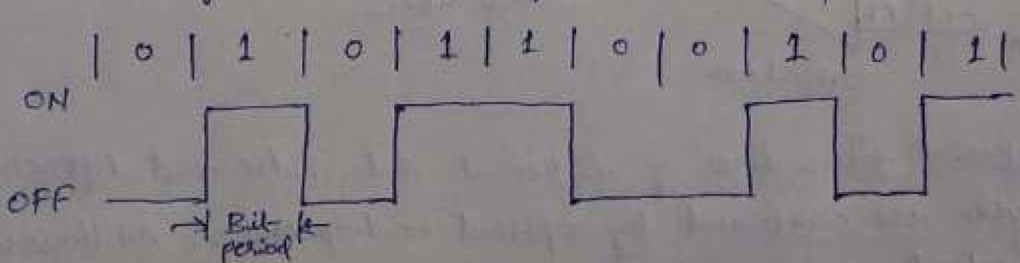


Fig. NRZ-level data pattern

Features of NRZ codes:

1. Simple to generate and decode
2. No timing information
3. Non error-monitoring or correcting capabilities
4. NRZ coding needs minimum BW.

RZ codes :

In unipolar RZ data pattern a 1-bit is represented by a half period in either first or second half of the bit period. A 0 bit is represented by zero volts during the bit period. Fig shows RZ data pattern.

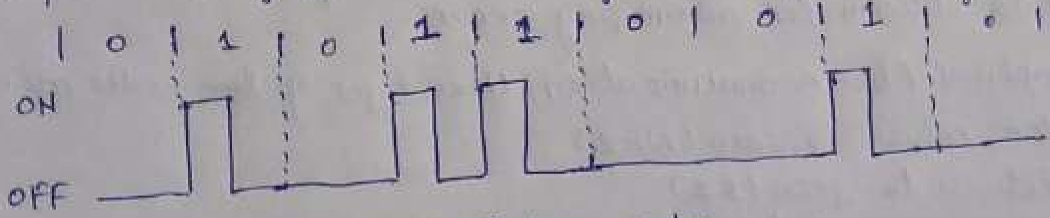


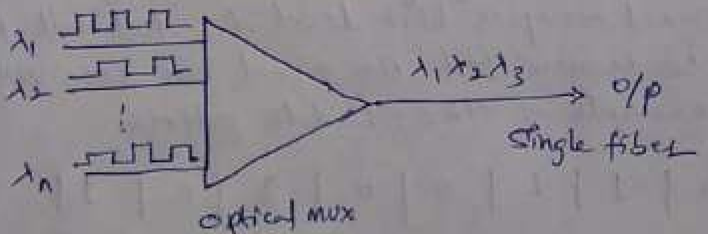
fig RZ unipolar codes.

Features of RZ codes:

1. The signal transition during high-bit period provides the timing information
2. Long strings of 0 bits can cause loss of timing synchronization.

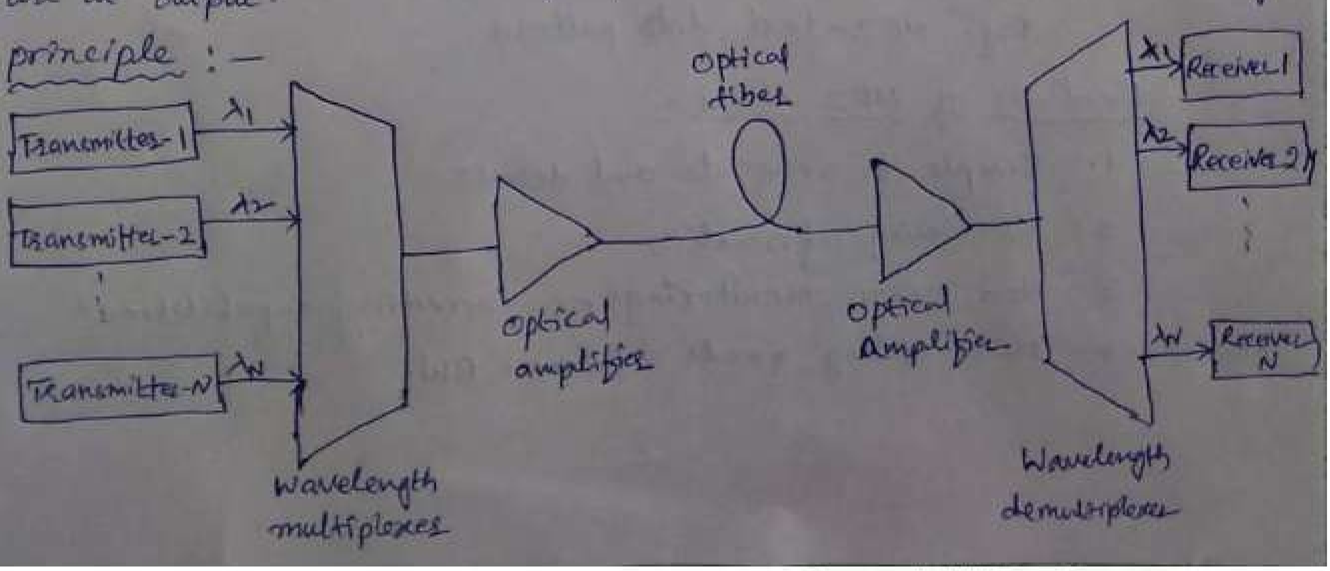
Wavelength Division Multiplexing (WDM) :—

Wavelength Division multiplexing is a technique of multiplexing multiple optical carrier signals through a single optical fiber channel by varying the wavelengths of laser lights. WDM allows communication in both the directions in the fiber cable.



Different fiber lines of different data rates and different wavelengths are combined by optical multiplexer. All these wavelengths are at output.

principle :—



Optical signals of different wavelengths (1300 – 1600nm) can propagate with out interfering with each other. The scheme of combining a number of wavelengths over a single fiber is called wavelength division multiplexing. Each input is generated by a seperate optical source with a unique wavelength. An optical multiplexer couples light from individual sources to the transmitting fiber. At the receiving station, an optical demultiplexer is required to seperate the different carriers before photodetection of individual signals. As shown in fig.

To prevent spurious signals to enter in to receiving channel, the demultiplexer must have narrow spectral operation with sharp wavelength cut-offs. The acceptable limit of cross talk is – 30dB.

Features of WDM :

Important advantages or features of WDM are as mentioned below.

1) Capacity upgrade : Since each wavelength supports independent data rate in Gbps.
2) Transparency : WDM can carry fast asynchronous, slow synchronous, synchronous analog and digital data.
3) Wavelength routing : Link capacity and flexibility can be increased by using multiple wavelength.
4) Wavelength switching : WDM can add or drop multiplexers, cross connects and wavelength converters.

Applications :

Applications of WDM technique are found in all levels of communication links including long haul distance terrestrial and under sea transmission systems, metro networks and fiber to the premises (FTTP) networks.

Types of WDM :

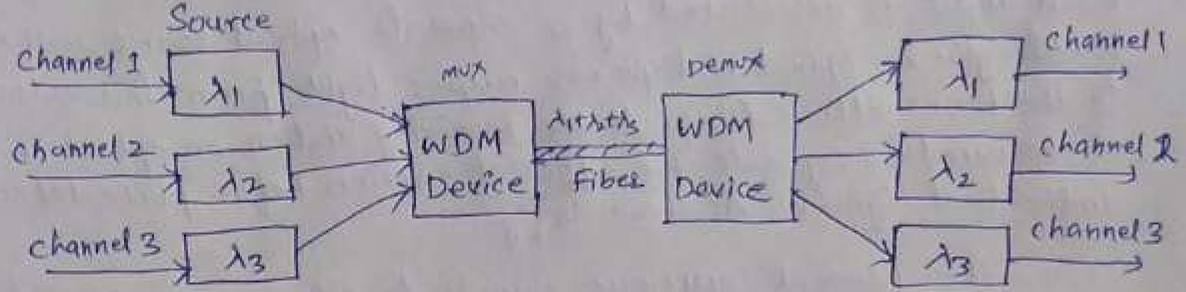
The WDM implementation can be done in two types

i) Unidirectional WDM ii) Bidirectional WDM

i) Unidirectional WDM :

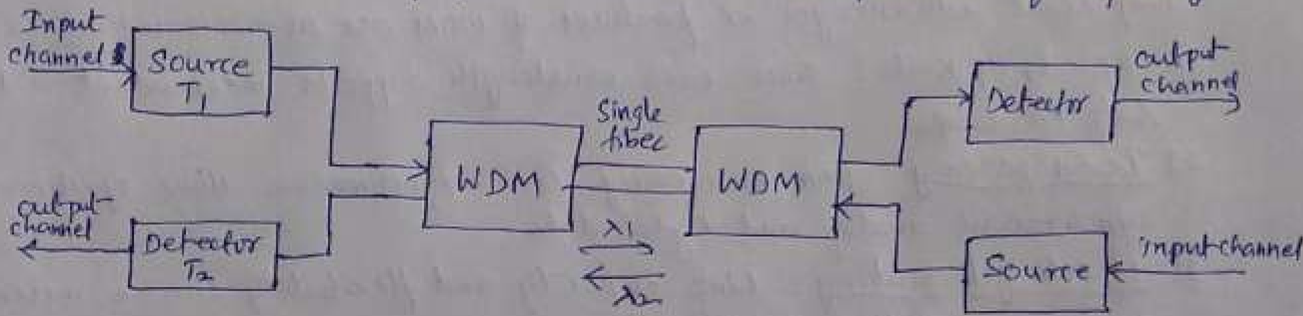
In unidirectional WDM system, single carrier wavelengths are fed in to single fibers at one end and then seperate them in to their corresponding detectors at other end.

The insertion loss, channel width and cross talk are the three basic parameters which are used to decide the performance of a WDM system.



Bidirectional WDM:

The bidirectional WDM technique enables bidirectional communications over one strand of fiber, as well as multiplication of capacity.



Categories of WDM:-

Based on the wavelength patterns, WDM can be divided in to two categories

① coarse WDM (CWDM) ② Dense WDM (DWDM)

① Coarse WDM (CWDM):-

Coarse WDM provides up to 16 channels across multiple transmission windows of silica fibers. No effective BW utilization as space between wavelengths are more. To provide 16 channels on a single fiber, CWDM uses the entire frequency band spanning the second and third transmission windows (1310 & 1550 nm respectively). Transceiver design is cheaper.

Amplification is difficult.

CWDM is being used in cable Television networks, where different wavelengths are used for the down stream and upstream signals.

Dense WDM (DWDM):

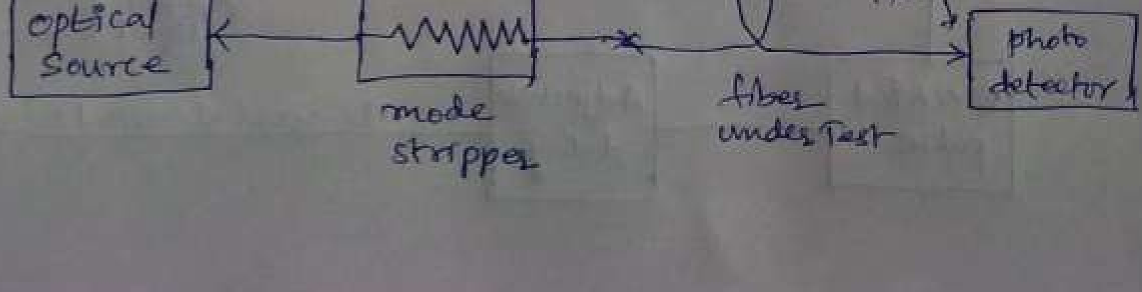
- DWDM uses the C-band (1530nm - 1565nm) transmission window but with denser channel spacing.
- In DWDM, the number of multiplexed channels much larger than CWDM.
- It is either 40 at 100GHz spacing or 80 with 50GHz spacing due to this they can transmit the huge quantity of data through a single fiber link.
- DWDM is generally applied in core networks of telecommunications and cable networks. It is also used in cloud data centers.

Measurement of Attenuation:

- Signal attenuation is one of the most important properties of an optical fiber because it mainly determines the maximum repeater-less seperation between transmitter and receiver.
- As the repeaters are expensive to fabricate, install and maintain, therefore the fiber attenuation has large influence on system cost and equally important in signal distortion.
- The distortion mechanism in a fiber cause optical signal pulses to boarder as they travel along a fiber. When these pulses travel sufficiently far, they evantually overlap with neighbouring pulses creating errors in receiver output. This signal distortion mechanisms limits the information carrying capacity of fiber.
- For determining attenuation in fibers three major techniques are used
  1. Cutback technique 2. Insertion loss method 3. OTDR trace

Cutback technique:

Cutback technique is a destructive method of measuring attenuation. It requires access to both ends of fiber as shown in fig.



Firstly, the optical power is measured at the output (farend) of fiber. Then without disturbing the input condition, the fiber is cut-off few meters from the source and output power at nearend is measured.

Let P_F and P_N are the output powers at far end and near ends of fiber respectively. Then attenuation in dB/km is given by

$$\alpha = \frac{10}{L} \log \frac{P_N}{P_F}$$

L - Seperation length of two measurement points (in km)

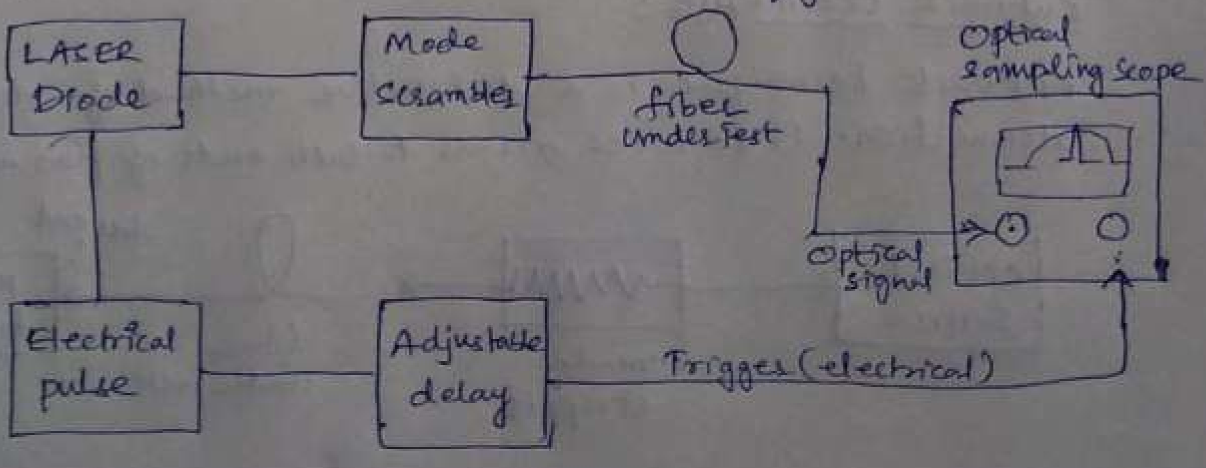
Dispersion measurement:

An optical signal gets distorted as it travels down the fiber due to three basic forms of dispersion, that limits the information carrying capacity.

There are different methods to measure the dispersion effects. such as ① intermodal dispersion in time domain ② intermodal dispersion in frequency domain ③ chromatic dispersion and ④ polarization mode dispersion.

① Time domain intermodal dispersion measurements:

Time domain intermodal dispersion measurement involves injecting a narrow pulse of optical energy in to one end of an optical fiber and detect the broadened output pulse at the other end. Test setup for this measurement is shown in fig.



Here output pulses from a laser source are coupled through a mode in to a test fiber. The output of the fiber is measured with a sampling oscilloscope that has a built in optical receiver, or the signal can be detected with an external photodetector, and then measured with a regular sampling oscilloscope. Next, the shape of the input pulse is measured the same way by replacing the test fiber with a short reference fiber that has a length less than 1% of the test fiber length. This reference fiber can be a short length cut from the test fiber or it can be a fiber segment. The variable delay is the trigger line is used to offset. The difference in delay between the test fiber and the shorter reference fiber.

Eye Pattern/ Eye diagram:

Eye pattern method is a measuring technique for assessing the data handling ability of digital transmission system. The eye pattern measurements are made in time domain and allow the effects of waveform distortion to observe on oscilloscope. Fig1 shows a typical display pattern, which is known as an eye pattern or eye diagram. The basic upper and lower bands are determined by logic one and zero levels shown by b_{on} and b_{off} respectively.

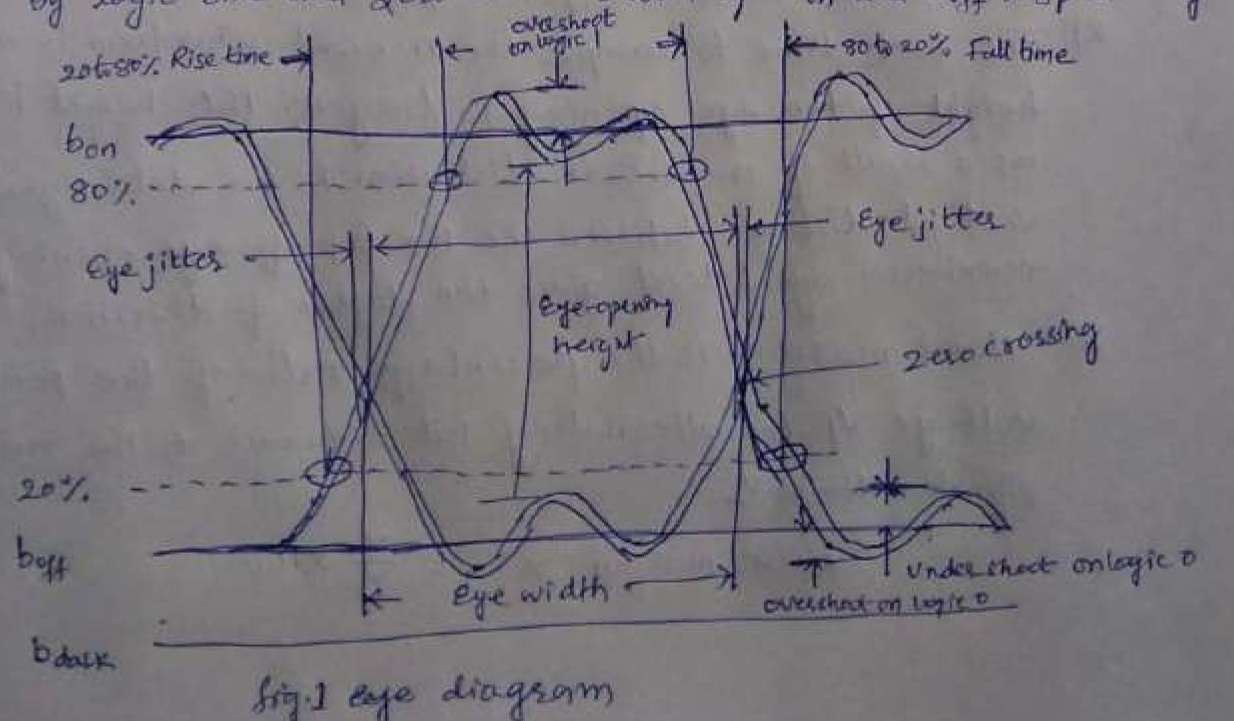


fig.1 eye diagram

To measure the performance of system various word pattens must be provided. consider fig 1 and simplified drawing shown in fig 2.

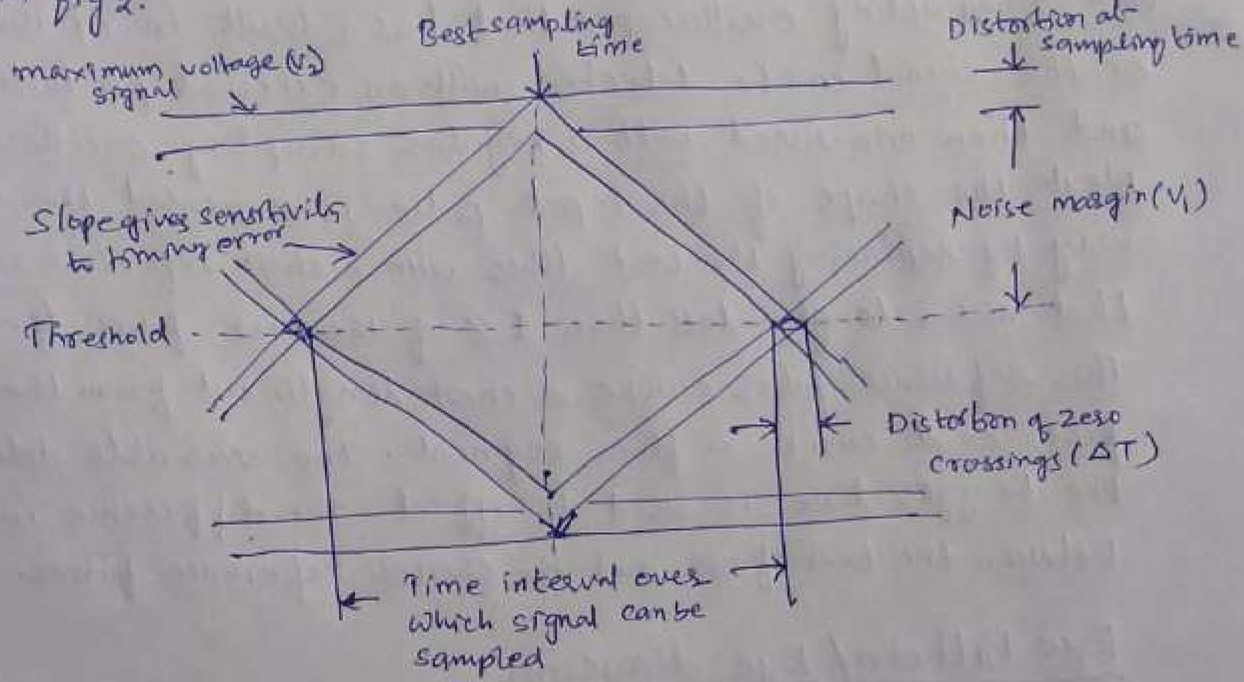


fig. simplified eye diagram

The following information regarding the signal amplitude distortion, timing jitter and system rise time can be derived.

1) The width of the eye opening defines the time interval over which the received signal can be sampled with out error due to interference from adjacent pulses.
2) The best time to sample the received waveform is when the height of the eye opening is largest. This height is reduced as a result of amplitude distortion in the data signal. The vertical distance between the the top of eye opening and the maximum signal level gives the degree of distortion.
3) Noise margin is the percentage ratio of the peak signal voltage V_1 for alternating bit sequence to the maximum signal voltage V_2

$$\text{Noise margin} (\%) = \frac{V_1}{V_2} \times 100$$

4) Timing jitter in optical fiber system arises from noise in the receiver and pulse distortion in the optical fiber. If the signal is sampled in the middle of time interval. Then the amount of distortion ΔT at the threshold level indicates the amount of jitter. and is given by

$$\text{Timing Jitter} = \frac{\Delta T}{T_b} \times 100$$

T_b - one bit interval

5) Rise time is defined as the time interval between the points where the rising edge of signal reaches 10% to 90% of its final amplitude, but when measuring amplitude optical signal 20% & 80% threshold points are normally used.

To convert from 20 to 80% rise time to a 10 to 90% rise time, the approximate relationship is

$$T_{10-90} = 1.25 \times T_{20-80}$$

A similar approach is used to determine the fall time.

6) Any nonlinear effects in the channel transfer characteristics will created an assymmetry in the eye pattern. If a purely random data stream is passed through a purely linear system, all the eye openings will be identical and symmetrical.