EC8751	**OPTICAL COMMUNICATION**	**L**	**T**	**P**	**C**
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OBJECTIVES:

- To study about the various optical fiber modes, configuration and transmission characteristics of optical fibers
- To learn about the various optical sources, detectors and transmission techniques
- To explore various idea about optical fiber measurements and various coupling techniques
- To enrich the knowledge about optical communication systems and networks

UNIT I INTRODUCTION TO OPTICAL FIBERS 9

Introduction-general optical fiber communication system- basic optical laws and definitions-optical modes and configurations -mode analysis for optical propagation through fibers-modes in planar wave guide-modes in cylindrical optical fiber-transverse electric and transverse magnetic modes- fiber materials-fiber fabrication techniques-fiber optic cables-classification of optical fiber-single mode fiber-graded index fiber.

UNIT II TRANSMISSION CHARACTERISTIC OF OPTICAL FIBER 9

Attenuation-absorption --scattering losses-bending losses-core and cladding losses-signal dispersion –inter symbol interference and bandwidth-intra model dispersion-material dispersion- waveguide dispersion-polarization mode dispersion-intermodal dispersion-dispersion optimization of single mode fiber-characteristics of single mode fiber-R-I Profile-cutoff wave length-dispersion calculation-mode field diameter.

UNIT III OPTICAL SOURCES AND DETECTORS 9

Sources: Intrinsic and extrinsic material-direct and indirect band gaps-LED-LED structures-surface emitting LED-Edge emitting LED-quantum efficiency and LED power-light source materials-modulation of LED-LASER diodes-modes and threshold conditions-Rate equations-external quantum efficiency-resonant frequencies-structures and radiation patterns-single mode laser-external modulation-temperature effort.

Detectors: PIN photo detector-Avalanche photo diodes-Photo detector noise-noise sources-SNR-detector response time-Avalanche multiplication noise-temperature effects-comparisons of photo detectors

UNIT IV OPTICAL RECEIVER, MEASUREMENTS AND COUPLING 9

Fundamental receiver operation-preamplifiers-digital signal transmission-error sources-Front end amplifiers-digital receiver performance-probability of error-receiver sensitivity-quantum limit.

Optical power measurement-attenuation measurement-dispersion measurement- Fiber Numerical Aperture Measurements- Fiber cut- off Wave length Measurements- Fiber diameter measurements-Source to Fiber Power Launching-Lensing Schemes for Coupling Management-Fiber to Fiber Joints-LED Coupling to Single Mode Fibers-Fiber Splicing-Optical Fiber connectors

UNIT V OPTICAL COMMUNICATION SYSTEMS AND NETWORKS 9

System design consideration Point – to –Point link design –Link power budget –rise time budget, WDM –Passive DWDM Components-Elements of optical networks-SONET/SDH-Optical Interfaces-SONET/SDH Rings and Networks-High speed light wave Links-OADM configuration-Optical ETHERNET-Soliton

TOTAL:45 PERIODS

OPTICAL COMMUNICATION

Unit I. INTRODUCTION TO OPTICAL FIBERS.

Introduction:

A Fiber optic cable is a light pipe that is used to carry light beam from one place to another.

Communication medium is wire, free space or fiber optic cable.

Advantages of fiber:

* wide bandwidth
* low transmission loss
* light weight & small size
* Interference immunity & safety
* Electrical isolation.

Disadvantages:

* Small size & brittleness make more difficult to work with.

General Optical fiber communication System:

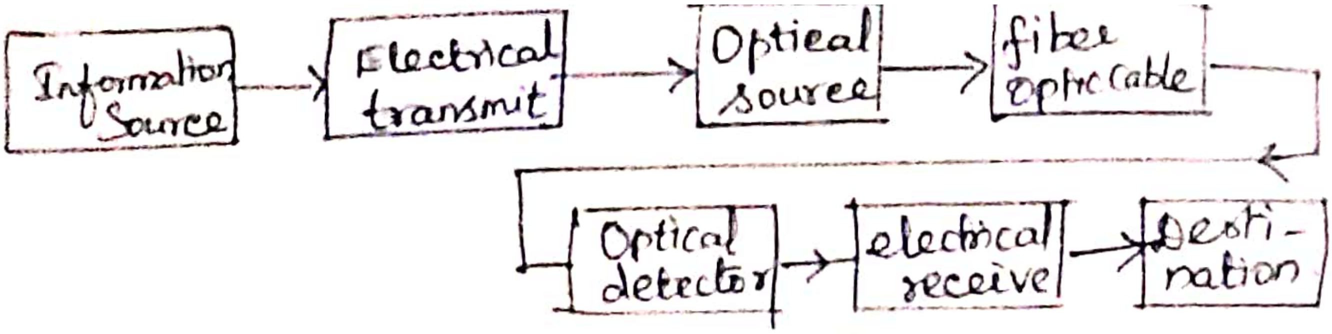
Information source provides electrical signal to transmitter which drives optical source to give modulation of optical carrier

Communication System - Transmitter, Source, transmission medium, receiver

Transmission medium - Optical fiber cable

Optical source - LED/LASER

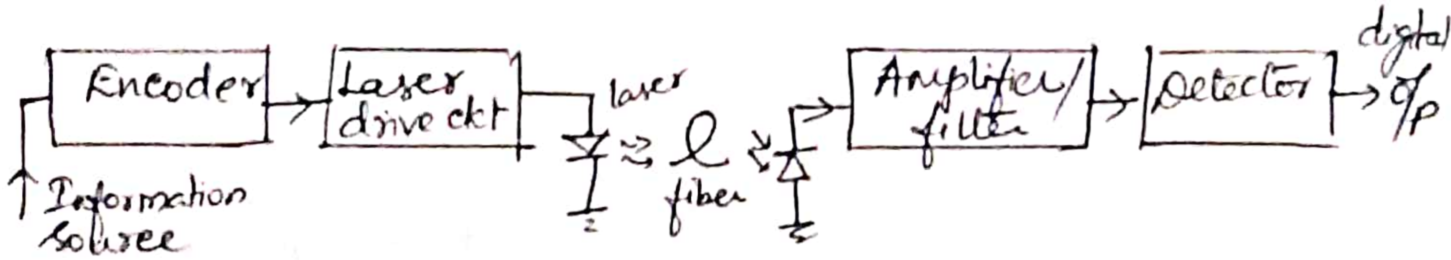
Optical detector - photo diode



Source provides electro-optical conversion. Detector performs optical-electrical conversion.

Digital Optical System:

Digital signal is encoded, laser drive circuit modulates intensity of laser. Digital signal is launched into fiber. APD followed by amplifier & filter provide gain, noise reduction. Finally, it is decoded to get original information.



Applications: * Telecommunication
* Instrumentation
* Cable TV N/w
* Data transmission.

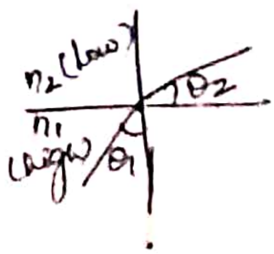
<u>Basic Optical laws and Definitions:</u>

* Refractive Index = $\frac{\text{Velocity of Light in Vaccum}}{\text{Velocity of light in medium}}$

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

ϕ_1, ϕ_2 - Angle of incidence & refraction.

n_1, n_2 - Refractive indices of core + cladding

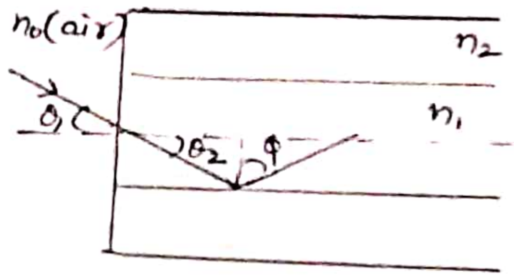


* Critical Angle ϕ_c → Min angle of incidence beyond which total internal reflection occurs.

$$\sin \phi_c = n_2/n_1$$

* Total internal reflection → Angle of incidence θ_1 in dense material becomes smaller, reflected angle θ_2 approaches zero. Beyond this, no refraction, rays become totally internally reflected
* Acceptance angle θ_a → Max. angle to the axis at which light ray enters the fiber to be propagated.
* Meridional ray → Light ray passed thro' axis of fiber
* Skew rays → follow helical path, not thro' axis.
* Numerical Aperture (NA) → Light collecting ability of fiber.

Relationship between θ_a, n_1, n_2:



By Snell's law,

$$n_0 \sin \theta_1 = n_1 \sin \theta_2$$
$$= n_1 \cos \phi$$
$$= n_1 (1 - \sin^2 \phi)^{1/2}$$

If θ_1 becomes θ_a, $\phi = \phi_c$, then

$$NA = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{1/2}$$

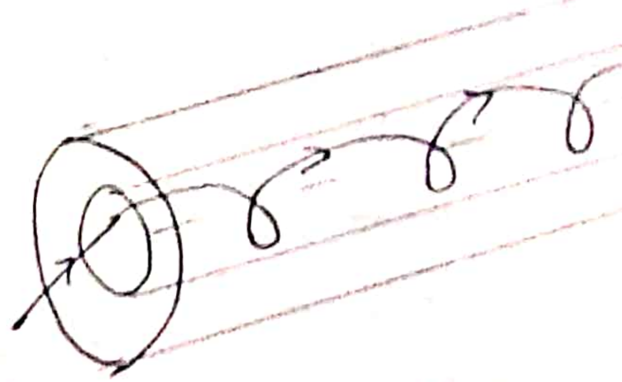
Refractive index difference between core + cladding.

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \approx \frac{n_1 - n_2}{n_1} \text{ for } \Delta << 1$$

$$\therefore NA = n_1 (2\Delta)^{1/2}$$

Skew rays:

- These rays are not transmitted thro' fiber axis.
- follow a helical path.
- difficult to travel as they travel along fiber.
- don't lie in single plane



If γ is angle of between projection of ray in two dimensions and radius of fiber core at point of reflection.

Acceptance conditions for skew rays are

$$n_0 \sin\theta_{as} \cos\gamma = (n_1^2 - n_2^2)^{1/2} = NA$$

If fiber in air ($n_0 = 1$), then $NA = \sin\theta_{as} \cos\gamma$

Acceptance angle $\theta_{as} = \sin^{-1}(NA/\cos\gamma)$

Optical modes and configurations:

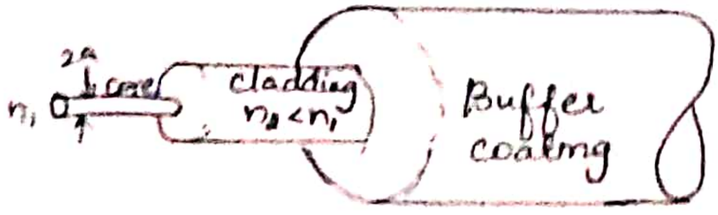
Optical fiber → dielectric waveguide that operates at optical frequencies.

→ It is in cylindrical.

→ It confines EM energy in the form of light.

The propagation of light is described in terms of set of guided EM waves called modes of waveguide. These guided modes are bound or trapped modes.

Structure:



core - Single solid dielectric cylinder of radius 'a' & index of refraction 'n_1'.

cladding - Core is surrounded by a solid dielectric. $n_2 < n_1$
- It adds mechanical strength to fiber.
- It protects the core from absorbing surface contaminants.

Mode analysis for Optical propagation through fibers:

Mode analysis is based on the nature of light and allows to apply maxwell equations to explain its propagation. In EM wave, electric and magnetic fields are orthogonal to eachother.

If electric field is along x-axis, magnetic field is along y-axis, then direction of propagation of light will be along z-direction.

Plane wave is linearly polarized with polarization vector e_x. Another electric field with e_y.

Polarisation refers to orientation of EM field with respect to some plane.

$$E_x(z,t) = Re(E) = e_x E_{ox} \cos(\omega t - \beta z)$$

$$E(z,t) = \exp[j(\omega t - \beta z)]$$

e_x - unit vector along x direction

ω - angular frequency

β - z component of propagation constant

E_{ox} - amplitude of electric vector along x-direction

Assume another polarized wave $E_y(z,t)$ is orthogonal and independent of $E_x(z,t)$.

$$\therefore E_y(z,t) = Re(E) = e_y E_{oy} \cos(\omega t - \beta z + \delta)$$

e_y - unit vector along y-direction

δ - phase difference between two orthogonal vectors.

E_{oy} - Amplitude of electric vector.

Resultant of two waves can be,

$$E(z,t) = E_x(z,t) + E_y(z,t).$$

When $\delta = 0$, two orthogonal waves are in phase and resultant wave is linearly polarized.

$$\therefore |\vec{E}| = \sqrt{E_{ox}^2 + E_{oy}^2}.$$

Polarisation vector makes an angle θ with x-axis,

$$\therefore \theta = \tan^{-1}\left(\frac{E_{ox}}{E_{oy}}\right).$$

General eqn of ellipse is, (elliptically polarized)

$$\left(\frac{E_x}{E_{ox}}\right)^2 + \left(\frac{E_y}{E_{oy}}\right)^2 - 2\left(\frac{E_x}{E_{ox}}\right)\left(\frac{E_y}{E_{oy}}\right)\cos\delta = \sin^2\delta$$

When $E_{ox} = E_{oy} = E_0$

$$\delta = 2\pi m \pm \frac{\pi}{2}$$

Circularly polarised wave eqn

$$E_x^2 + E_y^2 = E_0^2$$

Electromagnetic waves:

EM wave propagation is provided by Maxwell's equations. For free space,

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad ; \quad \nabla \times H = \frac{\partial D}{\partial t} \; ;$$

$$\nabla \cdot D = 0 \quad ; \quad \nabla \cdot B = 0$$

$$D = \epsilon E \quad ; \quad B = \mu H$$

$$\nabla \times (\nabla \times E) = -\mu\epsilon\, \partial^2 E / \partial t^2$$

$$\nabla \times (\nabla \times H) = -\mu\epsilon\, \partial^2 H / \partial t^2$$

But, $\nabla \times (\nabla \times E) = \nabla(\nabla \cdot E) - \nabla^2 E$

So, non dispersive wave equations

$$\nabla^2 E = \mu\epsilon \frac{\partial^2 E}{\partial t^2} \quad ; \quad \nabla^2 H = \mu\epsilon \frac{\partial^2 H}{\partial t^2}.$$

Transverse Electric & Transverse Magnetic modes:

Wave equations in cylindrical coordinates are

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_z}{\partial \phi^2} + q^2 E_z = 0$$

$$\frac{\partial^2 H_z}{\partial r^2} + \frac{1}{r}\frac{\partial H_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 H_z}{\partial \phi^2} + q^2 H_z = 0$$

When $E_z = 0$, modes are Transverse Electric (TE) modes

$H_z = 0$, modes are Transverse Magnetic (TM) modes

Hybrid modes exist, when E_z & H_z are non zero.

If both are zero, TEM modes exist.

Wave equations for step index fiber:

$$\frac{\partial^2 F_1}{\partial r^2} + \frac{1}{r}\frac{\partial F_1}{\partial r} + \left(q^2 - \frac{v^2}{r^2}\right) F_1 = 0.$$

where $U^2 = k_1^2 - \beta^2$, $k_1 = 2\pi n_1/\lambda$

Inside core, $E_z(r<a) = A J_v(ur) e^{jv\phi} e^{j(\omega t - \beta z)}$

$H_z(r<a) = B J_v(ur) e^{jv\phi} e^{j(\omega t - \beta z)}$

where A & B are constants.

Outside core, $E_z(r>a) = C K_v(ur) e^{jv\phi} e^{j(\omega t - \beta z)}$

$H_z(r>a) = D K_v(ur) e^{jv\phi} e^{j(\omega t - \beta z)}$

$E_{z1} - E_{z2} = A J_v(ua) - C K_v(wa) = 0 \qquad W^2 = \beta^2 - k_2^2$.

$E_{\phi 1} - E_{\phi 2} = \frac{-j}{u^2}\left[A \frac{jv\beta}{a} J_v(ua) - B \omega \mu_0 u J_v'(ua)\right]$

$- j/_{W^2}\left[C \frac{jv\beta}{a} K_v(ua) - D\omega\mu w K_v'(wa)\right] = 0.$

$H_{z1} - H_{z2} = B J_v(ua) - D K_v(wa) = 0$

$H_{\phi 1} - H_{\phi 2} = -\frac{j}{u^2}\left[B \frac{jv\beta}{a} J_v(ua) + A \omega \epsilon_1 u J_v'(ua)\right]$

$- j/_{W^2}\left[D \frac{jv\beta}{a} K_v(ua) + C w \epsilon_1 u K_v'(ua)\right]$

By evaluating these equations,

$(J_v + K_v)(k_1^2 J_v + k_2^2 K_v) = \frac{\beta v}{a}\left(\frac{1}{u^2} + \frac{1}{w^2}\right)$

For TE_{om} modes, $J_o + K_o = 0$.

$$\frac{J_1(ua)}{u J_o(ua)} + \frac{K_1(wa)}{W K_o(wa)} = 0.$$

For TM_{om} modes, $k_1^2 J_o + k_2^2 K_o = 0$

$$\frac{k_1^2 J_1(ua)}{u J_o(ua)} + \frac{k_2^2 K_1(Wa)}{W K_o(Wa)} = 0.$$

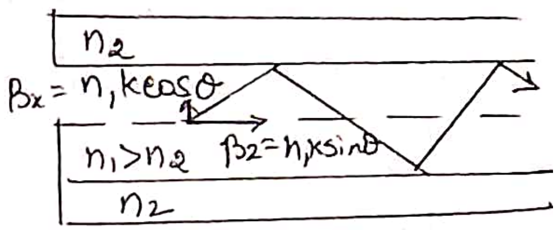
Modes in a Planar guide:

Planar waveguide consists of slab of dielectric with refractive index n_1 sandwiched between two region of lower refractive index n_2.

The component of phase propagation constant in

z direction $\beta_z = n_1 K \cos\theta$.

x direction $\beta_x = n_1 k \sin\theta$



Electric field distribution in x direction with only periodic z dependence is mode.

A specific mode is obtained when angle between propagation vectors & interface have a particular value

TE mode → H field is in the direction of propagation, $E_z = 0$

TM mode → E field is in the direction of propagation, $H_z = 0$

TEM mode → Total field lies in traverse plane, $E_z = H_z = 0$

Phase and Group velocity:

Wavefront → For plane waves, some constant points form a surface.

Phase velocity → $V_p = \omega/\beta$

Group velocity → $V_g = \delta\omega/\delta\beta$

Propagation constant → $\beta = n_1 \, 2\pi/\lambda = n_1 \frac{\omega}{c}$

$$V_p = \frac{\omega}{\beta} = \frac{c}{n_1}$$

$$V_g = \frac{d\omega}{d\beta} \times \frac{d\lambda}{d\lambda} = \frac{d\omega}{d\lambda} \times \frac{\delta\lambda}{d\beta} = \frac{d}{d\lambda}\left(n_1 \frac{2\pi}{\lambda}\right)^{-1}\left(\frac{-\omega}{\lambda}\right)$$

$$= \frac{-\omega}{2\pi\lambda}\left(\frac{1}{\lambda}\frac{dn_1}{d\lambda} - \frac{n_1}{\lambda^2}\right)^{-1}$$

$$= \frac{c}{n_1 - \lambda \frac{dn_1}{d\lambda}} = \frac{c}{N_g}$$ where N_g - group index of guide.

Modes in Cylindrical Optical fibers:

Planar guide TE & TM modes are obtained in dielectric cylinder. Cylindrical waveguide is bounded in two dimensions. They are TE_{lm} & TM_{lm}. Hybrid modes also occur, these designated as HE_{lm} & EH_{lm}.

Linearly polarized (LP) modes:

Optical fibers satisfy weakly guiding approximation where $\Delta \ll 1$. For weakly guiding fibers with dominant forward propagation, mode theory gives dominant transverse field component.

Degenerate modes:

As Δ in weakly guiding fibers is very small, then EH-HE mode pairs occur which have almost identical propagation constants. Such modes are said to be degenerate.

The relationship between the traditional HE, EH, TE and TM mode designations and the LP_{lm} mode designations is shown in table.

Linearly polarized	Exact
LP01	HE11
LP11	HE21, TE01, TM01
LP21	HE31, EH11
LP02	HE12
LP12	HE22, TE02, TM02
LP_{lm}	HE_{2m}, TE_{om}, TM_{om}
LP_{lm} ($l \neq 0$ or 1)	$HE_{l+1,m}$, $EH_{l-1,m}$

Wave eqn under cylindrical coordinates

$$\frac{d^2\varphi}{dr^2} + \frac{1}{r}\frac{d\varphi}{dr} + \frac{1}{r^2}\frac{d^2\varphi}{d\phi^2} + \left|n^2k^2 - \beta^2\right|\varphi = 0.$$

where φ is field (E or H).

n_1 - core refractive index.

k - propagation constant

r, ϕ - cylindrical coordinates.

The propagation constants of guided modes β lie in the range; $n_2k < \beta < n_1k$.

n_2 - refractive index of cladding.

U & W are eigen values of core & cladding

$$U = a(n_1^2k^2 - \beta^2)^{1/2}$$

$$V = a(\beta^2 - n_2^2k^2)^{1/2}$$

Normalized Frequency.

The sum of squares of U & W defines a useful quantity is the normalized frequency.

$$V = (U^2 + W^2)^{1/2} = ka(n_1^2 - n_2^2)^{1/2}.$$

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

V – dimensionless parameter – It is V no. (or) value of fiber.

No. of guided modes $m = \frac{V^2}{2}$.

Fiber Materials:

In selecting materials of fiber, no. of requirements must be satisfied.

* To make long, thin, flexible fiber from material.
* Material must be transparent to guide light effectively
* Materials have slightly different refractive indices for core & cadding.

Materials satisfy these requirements are glass + plastics.

Glass fiber → consists of silica
→ moderate loss fiber

Plastic fiber → less widely used due to high attenuation
→ Used for short distance applications.
→ provides greater mechanical strength.

1) Glass Fibers:

→ Made up of mixures of metal oxides, sulphides etc
→ random n/w of well defined structure.
→ donot have well defined melting point. So, temperature increases, it begins to soften, becomes viscous liquid. Melting is used in glass manufacture.

To produce two different indices for core & cladding, dopants added to Silica.

Addition of P_2O_5 & GeO_2 increases refractive index, Silica with fluorine or B_2O_5 decreases it.

ex:
1) $GeO_2 - SiO_2$ Core ; SiO_2 cladding
2) $P_2O_2 - SiO_2$ core ; SiO_2 cladding
3) SiO_2 Core ; $B_2O_3 - SiO_2$ cladding
4) $GeO_2 - B_2O_3 - SiO_2$ core ; $B_2O_3 - SiO_2$ cladding

2) Active glass fibers:

Include rare elements (57-71) into passive glass gives resultant new optical & magnetic properties. This allows material to perform amplification, attenuation etc.

Commonly used materials: erbium/neodymium.

3) Chalgenide Glass fibers:

These are discovered to make use of nonlinear properties of glass fibers. It contains S, Se, or Te. Mostly used glass is As_2-S_3. Insertion loss 1db/km

4) Plastic Optical Fibers:

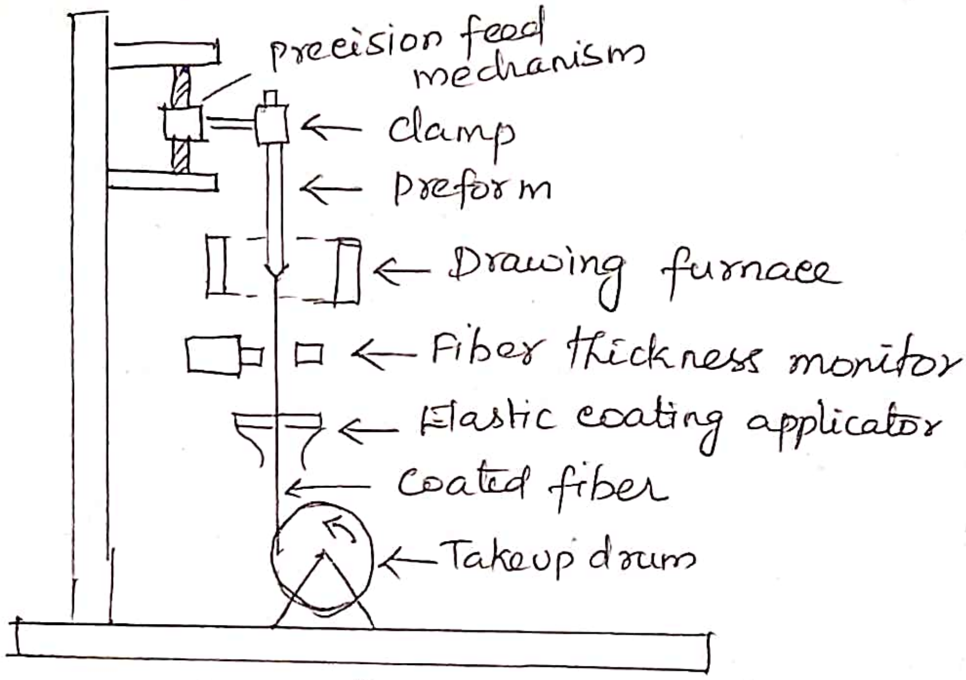
- made up of plastic. Core is made up of Polymethylmethacrylate (PMMA) or Perflourinated Polymer (PFP).
- Plastic have more attenuation
- Used for short distance.

5) Fluoride glass fibers:

Halide glass fiber contains fluorine, chlorine, bromine & iodine. Common halide glass fiber is 'metal fluoride glass'. It uses ZrF_4. Other constituents ZrF_4, BaF_2, LaF_3, NaF etc.

Insertion loss 0.01 to 0.001 db/km.

Fiber fabrication techniques:



Fiber drawing apparatus.

* Direct-melt method - Follows traditional glass making procedures in that optical fibers are made directly from molten state of purified component of Silica glass.

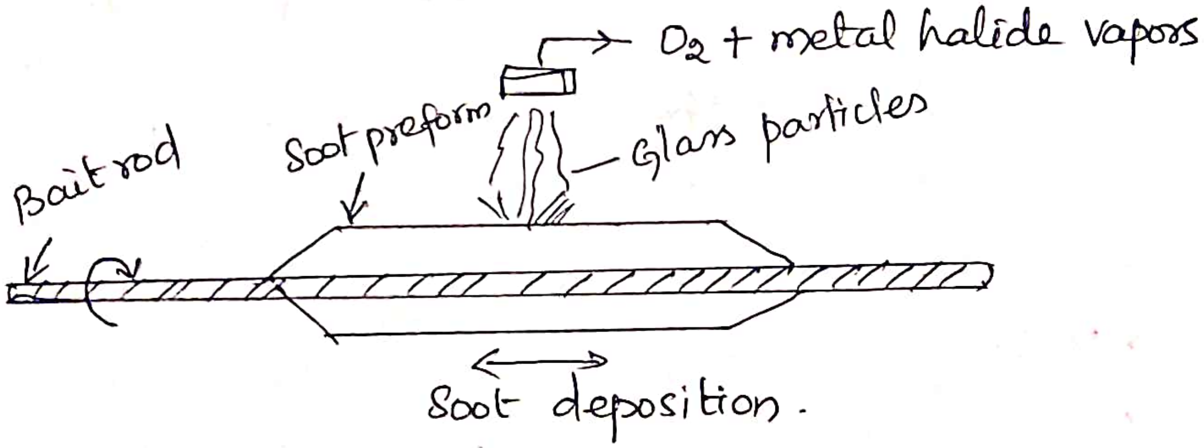
* Vapor-phase oxidation process - Pure vapors of metal halides react with O_2 to form SiO_2. They are sintered to form glass rod, (ie) preform. It is feed into circular heated called

drawing furnace. It canbe drawn into filament becomes optical fiber. Fiber thickness monitor is used for speed regulation. Elastic coating protects the fiber from contaminants.

Outside Vapor phase oxidation:

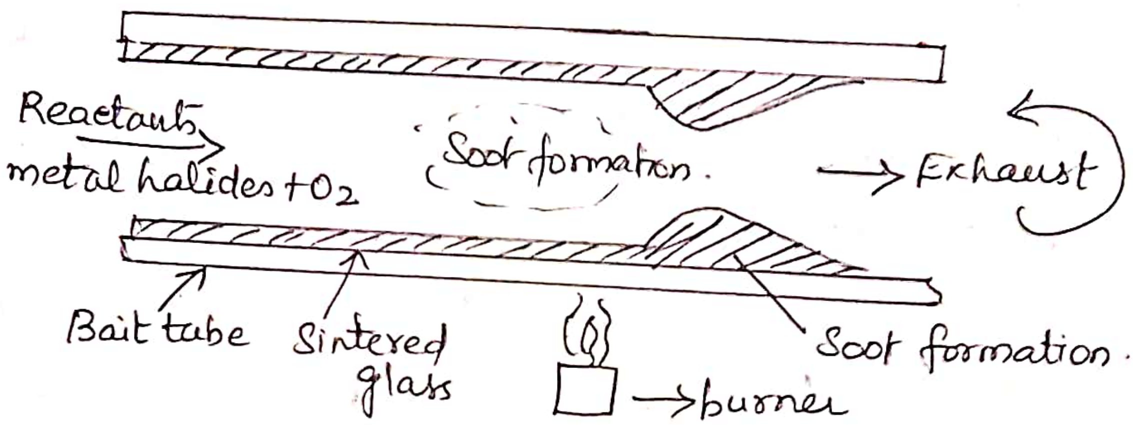
Layer of SiO_2 called soot is deposited from burner onto a rotating graphite. Glass soot adheres into bait rod, glass preform is built up.

When deposition process is completed, mandrel is removed and porous tube is vitrified to a clear glass preform. It is mounted in a fiber drawing tower is made into fibers. The central hole in the tube preform collapses during process.



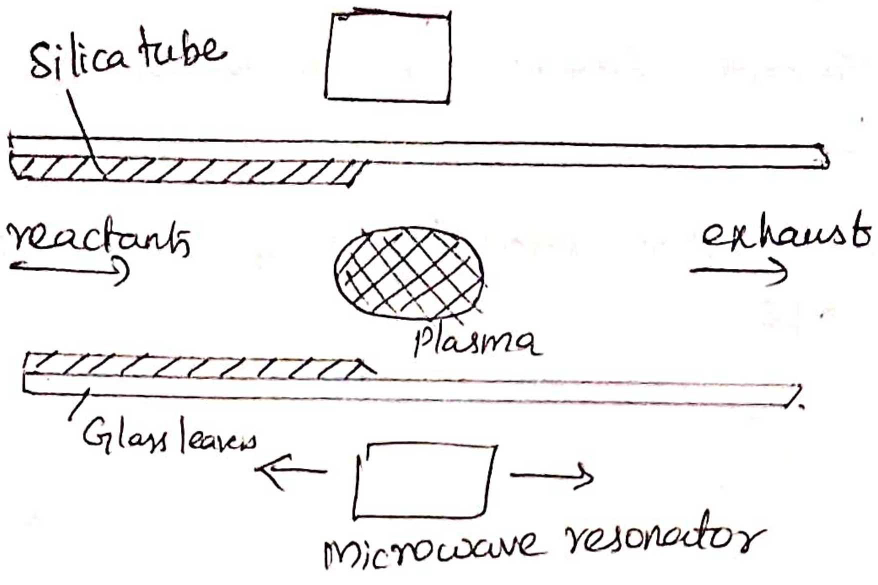
Modified Chemical Vapor Deposition (MCVD):

It is used to produce very low loss graded index fiber. Glass particles arise from metal halides flow thro' silica tube. As SiO_2 deposited, they are sintered into glass layer by an oxyhydrogen torch which travels back & forth along the tube. When glass is deposited, vapor flow is shut off & tube is heated to collapse into solid rod preform. Fiber is drawn from preform rod will have a core that consists of vapor deposited material and cladding that consists of original silica tube.



Plasma-Activated Chemical Vapor Deposition: (PCVD)

- Non isothermal microwave plasma operating at low pressure initiates chemical reaction. With silica tube held at 1000-1200°C to reduce mechanical stress in glass film, microwave resonator operates at 2.45 GHz generates plasma inside the tube to activate chemical reaction. This deposits glass material on tube wall. There is no soot formation. No sintering is required. When one has deposited the desired glass thickness, tube is collapsed into preform.



Schematic of PCVD.

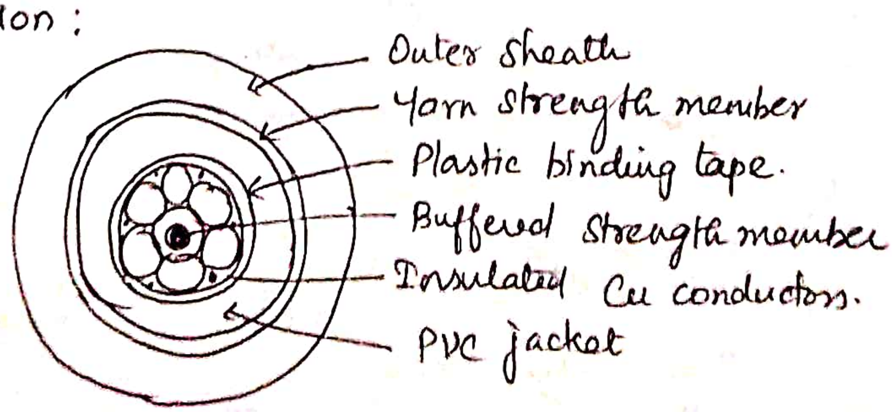
Fiber Optic Cables:

Cable structures: One of the mechanical property is max. allowable axial load on the cable, since it determines length of cable that is installed.

In copper cables, wires are principal load-bearing members of cable, elongation 20% is possible without fracture.

Steel wire has been used for reinforcing electric cables & used as strength member for fiber cable. Also, Plastic strength members & Synthetic yarns are used. ex: Tough yellow synthetic nylon - aramid

Configuration:



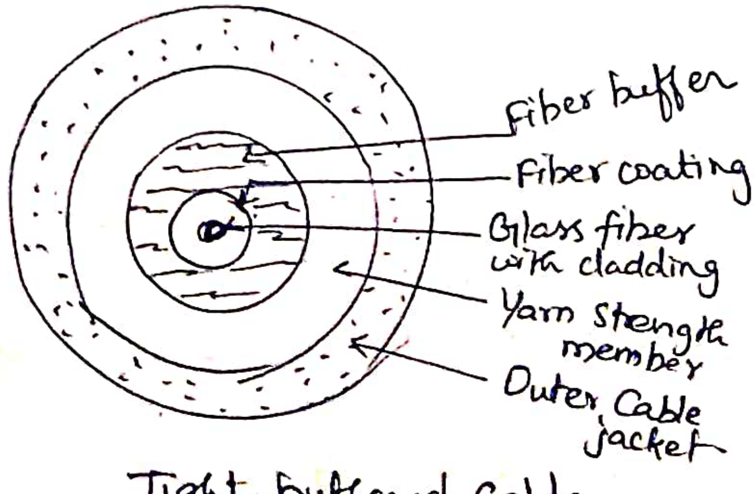
Individual fibers are wound around central buffered strength member. A cable wrapping tape encapsulate & bind these fiber groupings together. All components surrounded by polymer jacket that protects fiber.

Types: * Tight buffered cable - used in indoors
* Loose tube cable - used in outdoor.

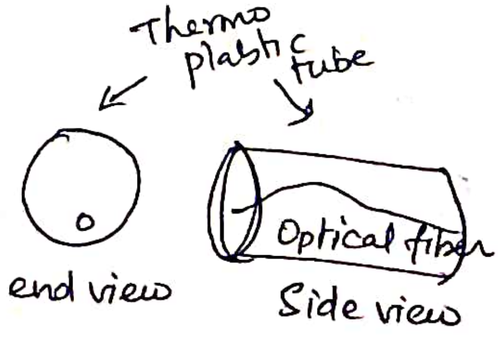
In tight buffered, each fiber is encapsulated by plastic fiber (900 μm). It is 4 times the diameter, 5 times thickness of coating material.

In loose tube, std coated fibers are enclosed in a thermoplastic tube. Fibers in the cable are longer than it. It isolates fiber from surrounding. The tube is filled with gel that acts as buffer.

Ribbon cable is extension of tight buffered cable. Here, fibers are encapsulated in a plastic buffer to form long continuous ribbon. No. of fibers in a ribbon from 4-12.



Tight-buffered cable



Loose-tube cable.

Indoor Cables:

- Used for interconnecting instruments, for distributing signals among users, for connections to printers, short patch cords in telecommunication equipment racks.

Types: 1) Interconnect Cable - It serves light-duty low fiber count indoor applications such as fiber to desk links, patch cords, point to point runs in trays. This is flexible, compact and light weight.

2) Breakout or fanout cable - It consists of 12 tight-buffered fibers around a central strength member. Such cables serve low to medium fiber count applications. This cable allows easy installation of connectors in the cable.

3) Distribution cable - It consists of individual tight buffered fibers around central strength member. This cable serves network applications for sending voice, video & data signals.

Outdoor Cables:

1) Aerial cable - mounted outside between building or on poles. Two popular designs are,

* Self supporting cable - Contains internal strength member sting between poles without additional support.
* Facility supporting cable - strength member is stung between poles & cable is clipped to this member.

2) Armored Cable - Used for direct-burial or underground duct applications, has one or more layers of steel wire below a layer of polyethylene jacket.

3) Underwater Cable - Submarine cable is used in rivers, lakes and ocean environments. Such cables are exposed to high water pressure. This can be used in rivers, lakes and ocean environments. Such cables ~~are~~ run under ocean.

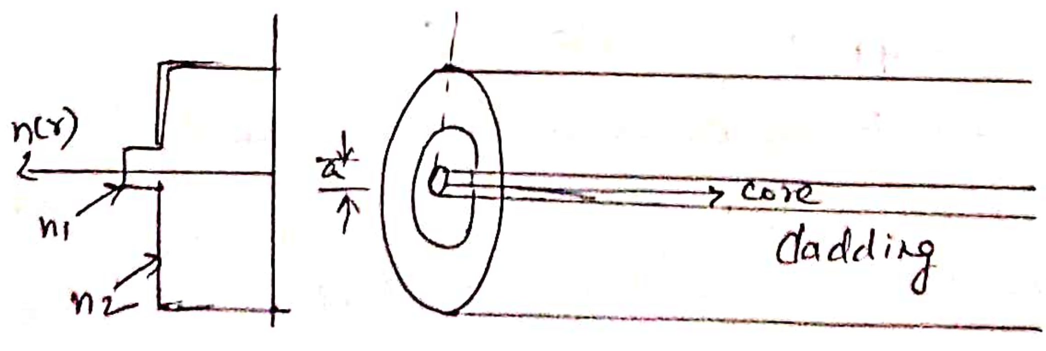
<u>classification of Optical fiber:</u>

Step index fiber: The refractive index of core is uniform throughout and undergoes an abrupt change at cladding boundary.

Graded-index fiber: The refractive index of core is made to vary as a function of radial distance from the centre of fiber.

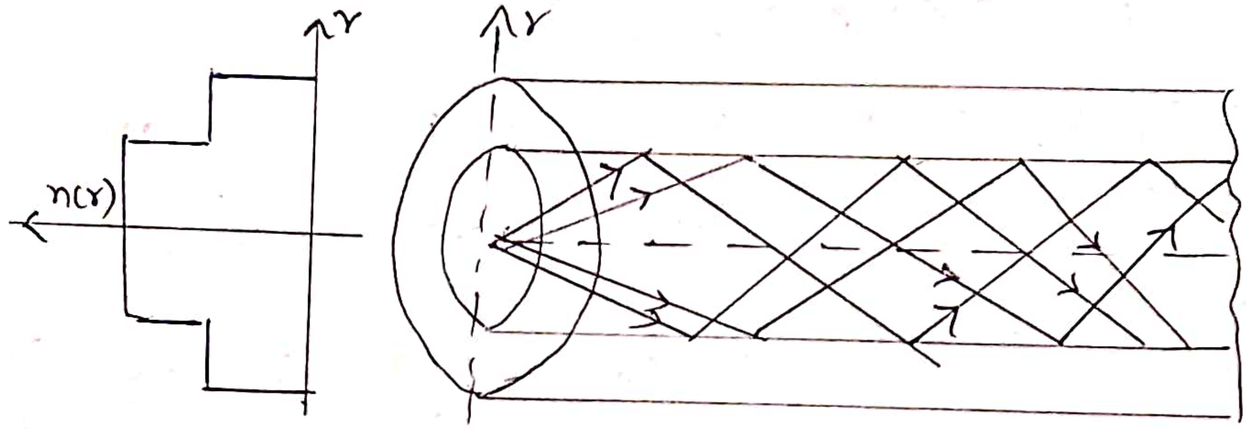
Single mode step index fiber:

- It allows propagation of only one transverse EM mode. Core diameter is small.



Multimode Step index fiber:

A multimode step index fiber with core diameter 50 μm, large enough to allow propagation of many modes within core. It allows finite no. of guided modes along the channel.



Advantages of multimode fibers:

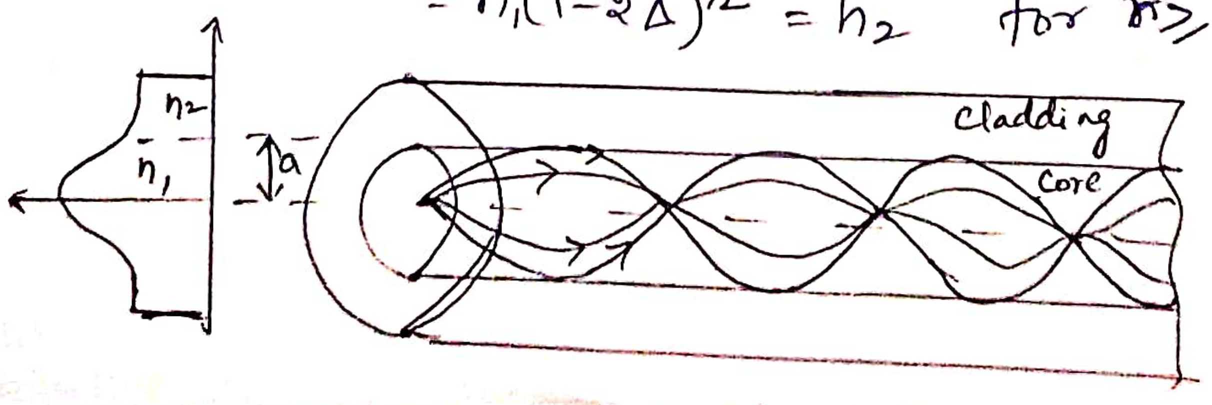
* Inherent optical sources can't efficiently coupled
* Large numerical aperture, facilitates easy coupling to optical sources.
* low tolerance requirements for connectors.

Graded index fiber:

Core refractive index is not uniform. Its variation maybe represented as,

$$n(r) = n_1(1 - 2\Delta(r/a)^{\alpha})^{1/2} \quad \text{for } r < a$$

$$= n_1(1-2\Delta)^{1/2} = n_2 \quad \text{for } r \geq a.$$



Single-mode fibers (SM fiber)

Advantage of single mode is signal dispersion caused by delay differences between modes is avoided.

→ Single mode propagation of LP_{01} in step index fiber is $0 \le V \le 2.405$

→ Cut off value of normalized frequency V_c in graded index is $V_c = 2.405 (1 + 2/\alpha)^{1/2}$.

→ Cut off wavelength $\lambda_c = \frac{2\pi a}{V_c} [n_1 (2\Delta)^{1/2}]$

$$\lambda_c / \lambda = V / V_c$$

Thus, for step index fiber, $V_c = 2.405$,

cut off wavelength $\lambda_c = V\lambda / 2.405$

Transverse electric and Magnetic Modes

The wave equations in cylindrical Coordinates are

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_z}{\partial \phi^2} + q^2 E_z = 0$$

$$\frac{\partial^2 H_z}{\partial r^2} + \frac{1}{r}\frac{\partial H_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 H_z}{\partial \phi^2} + q^2 H_z = 0$$

When $E_z = 0$, the modes are called transverse electric or TE Modes and when $H_z = 0$ they are called transverse magnetic or TM modes. Hybrid modes exist if both E_z and H_z are non zero. These are designated as EH and HE modes, depending on whether H_z or E_z, respectively

The solution for the wave equations are

$$E_r = \frac{-j}{q^2}\left(\beta \frac{\partial E_z}{\partial r} + \frac{\mu\omega}{r} \frac{\partial H_z}{\partial \phi}\right)$$

$$E_\phi = \frac{-j}{q^2}\left(\frac{\beta}{r} \frac{\partial E_z}{\partial \phi} - \mu\omega \frac{\partial H_z}{\partial r}\right)$$

$$H_r = \frac{-j}{q^2}\left(\beta \frac{\partial H_z}{\partial r} - \frac{\omega\varepsilon}{r} \frac{\partial E_z}{\partial \phi}\right)$$

$$H_\phi = \frac{-j}{q^2}\left(\frac{\beta}{r} \frac{\partial H_z}{\partial \phi} + \omega\varepsilon \frac{\partial E_z}{\partial r}\right)$$

UNIT - II

Transmission Characteristics of Optical Fibers.

2:1 ATTENUATION:

* Signal transmitting through the fiber is degraded by two mechanisms:

  i) Attenuation

  ii) Dispersion

* Power Loss in a fiber cable is the most important characteristics of the cable. This power loss is often called as attenuation.

* Attenuation of a light signal, as it propogates along a fiber is an important consideration in the design of an optical communication systems.

— It determines the maximum transmission distance between a transmitter and receiver.

* Attenuation is a measure of decay signal strength or loss of light power than occurs as light pulses propogate through length of the fiber.

* Attenuation has several adverse effects on the performance of the fiber including reducing the s/m bandwidth, information transmission rate, efficiency and overall s/m capacity.

* Signal attenuation within the optical fibers is expressed in logarithmic unit of the decibel.

— The decibel which is used for comparing two power levels, may be defined for a particular optical wavelength as, "the ratio of the input optical power (P_i) into a fiber to the output optical power (P_o) from the fiber."

* Total power loss in an optical fiber cable is

$$\alpha_{dB} = 10 \log_{10}\left(\frac{P_i}{P_o}\right) \qquad \text{——— (a)}$$

where

α_{dB} → Total reduction in power level in decibels.

P_o → Optical cable output power (Watts)

P_i → optical cable input power (watts)

* Relation between an input and output optical power is given by,

$$\frac{P_i}{P_o} = 10^{(dB/10)} \qquad \text{——— (b)}$$

* Basic attenuation mechanism in a fiber are,

i) Absorption

ii) Scattering losses

iii) Radiative losses of the optical energy.

* The attenuation consider the propogation distance, which is expressed in decibels per unit length (ie.. $dB\,km^{-1}$) as,

$$\alpha_{dB} L = 10 \log_{10} \frac{P_i}{P_o} \qquad \text{(c)}$$

where,

α_{dB} → Signal attenuation per unit length in decibels,

L → fiber length (km).

* Absorption is related to the fiber material and Scattering are due to fiber material and with structural imperfections in the optical waveguide.
* Radiative Loss occur whenever an optical fiber undergoes a bend of finite radius of curvature.

1:1:1 ATTENUATION UNITS:

* As light travels along a fiber, its power decreases exponentially with the distance.
  - The power at distance z is given by,

$$p(z) = P(0)\, e^{-\alpha z} \qquad \text{(d)}$$

where,

$P_i = P(0)$ = Optical power in a fiber at the origin ($z = 0$)

$P(z) = P_o$ = Optical power in a fiber at a distance z.

* α is the fiber attenuation constant (per km) and it is given by,

$$\alpha = \frac{1}{z} \ln \left[\frac{P(0)}{P(z)}\right] (km^{-1}) \quad \text{——— (e)}$$

* The attenuation coefficient (α) in the units of dB/km is expressed as,

$$\alpha\left(\frac{dB}{km}\right) = \frac{10}{z} \log\left[\frac{P(0)}{P(z)}\right] \quad \text{——— (f)}$$

$$\Rightarrow 4.343\, \alpha\, (km^{-1}) \quad \text{——— (g)}$$

* This parameter is known as fiber loss of fiber attenuation. An attenuation is also a function of wavelength.

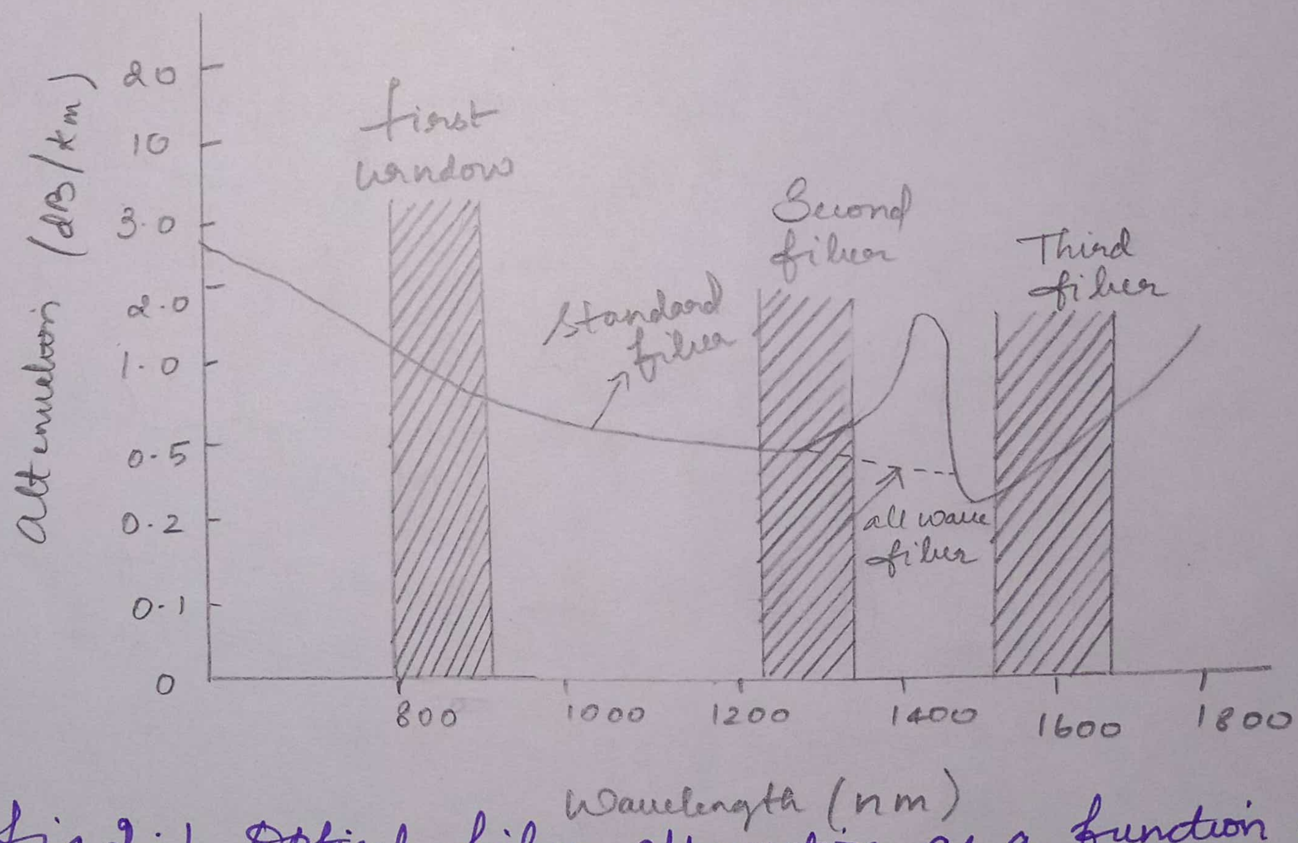


fig 2:1 Optical fiber attenuation as a function of wavelength (nm)

2:2 ABSORPTION LOSSES :

* Absorption loss is related to the material compositions and fabrication process of the fiber.
  - It is caused by three different mechanism

(i) absorption by atomic defects in the glass composition
(ii) Extrinsic absorption by impurity atoms in the glass material.
iii) Intrinsic absorption by the basic constituent atoms of the fiber material.

* Intrinsic absorption caused by the interaction with one or more of the major components of the glass.
  - Extrinsic absorption caused by the impurities within the glass.

2:2:1 ABSORPTION BY ATOMIC DEFECTS :

* Atomic defects are imperfections in the atomic structure of the fiber material such as missing molecules, high-density cluster of atom groups, or oxygen defects in the glass structure.
  - Radiation damages a material by changing its internal structure.
  - These damages depend on the energy of ionizing particles or rays, the radiation flux and the fluence.

* Total does of a material received is expre-ssed in rad (Si) which is a measure of radiation absorbed in bulk silicon. And the unit is defined as,

$$1 \, rad(Si) = 0.01 \, J/kg.$$

2:2:2 EXTRINSIC ABSORPTION

⟹ Extrinsic Absorption:

* Absorption is due to impurities in the fiber material,

  Transition metal impurities

  OH ions

(a) Transition Metal Impurities:

* In ultra low loss fibers due to Vapour Axial Deposition (VAD) method the impurity level ranges from 1 to 10 parts per billion (ppb).

  — The transition metal ions produce losses from 1 to 10 dB/km. This effect of metallic impurities can be reduced by glass refining techniques.

* Impurity absorption losses occur either because of electronic transitions between energy level associated with the incompletely filled inner subshell of these ions or because of charge transitions from one ion to another.

(b) OH (Water) Ion impurities:

* Caused by absorption due to water (OH) or (hydroxyl) dissolved in the glass.
* The hydroxyl group are bounded into the glass structure and have fundamental streching vibrations which occur at wave-length between 2.7 and 4.2 μm depending on group position in the glass n/w.
* Presence of OH ion impurities in fiber results from the oxyhydrogen flame used for the hydrolysis reaction of the $SiCl_4$, $GeCl_4$ & $POCl_3$.
* This type of absorption gets reduced by reducing the water content in the fiber around one ppb, as a result the single mode fibers have nominal attenuations of 0.5 dB/km in 1300 nm window and 0.3 dB/km in the 1550 nm window.

2:2:3 INTRINSIC ABSORPTION:

* Intrinsic absorption occurs when a material is in absolutely pure state with no density variations, impurities & material in homogen-eties.

* Intrinsic absorption results from electronic absorption bands in an ultra violet region and from atomic vibration bands in the near - infrared region.

→ Electronic Absorption :

2 24(a)

* Electronic absorption bands are associat-ed with the band gap 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.

* Ultra violet edge of absorption bands of both crystalline and amorphous materials follow the empirical relationship (Urbach's rule) as, ——— (a)

$$\alpha_{uv} = C e^{E/E_0}$$

where

C + E_0 are empirical constants and

E is the photon energy.

* UV absorption decays exponentially with an increasing wavelength (λ). The ultraviolet loss at any wavelength is expressed as,

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

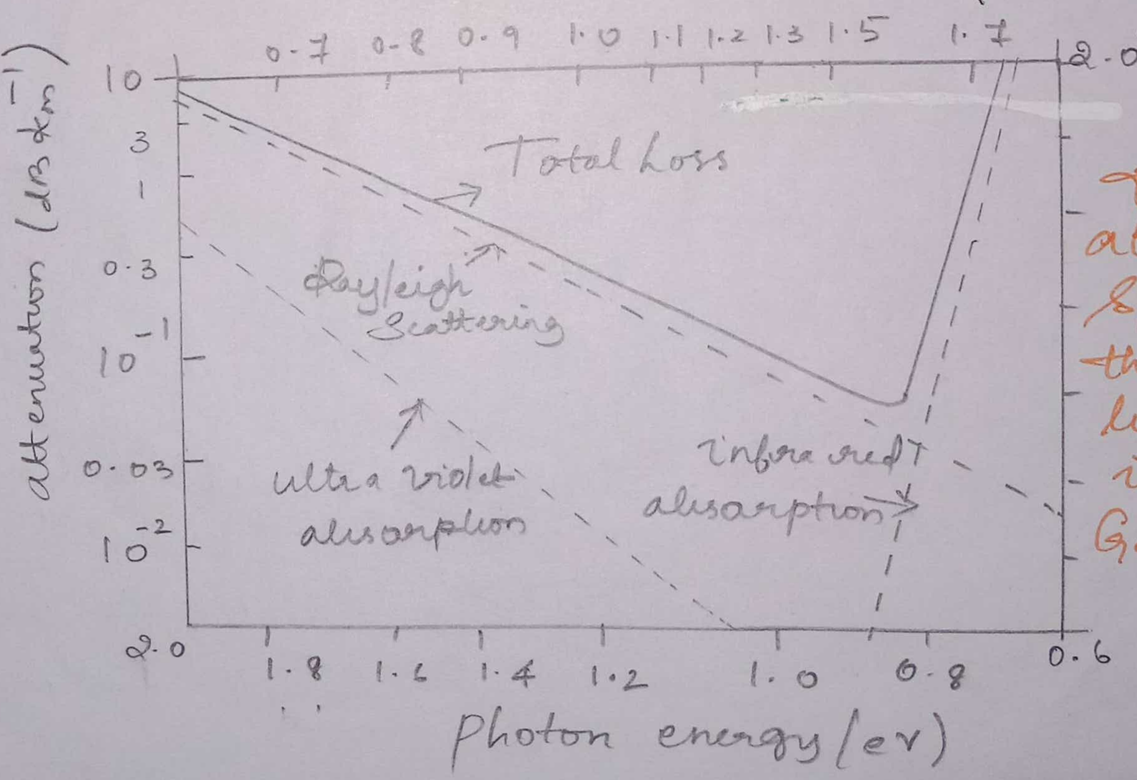
x → mole fraction of GeO_2

λ → operating wavelength
α_{uv} → dB/km

2:2:4(b) ATOMIC VARIATION:

* In the near IR (infra red) region above 1.2 μm, the optical waveguide loss is determined by the presence of OH ions and inherent IR absorption of the constituent material.
* Inherent infrared absorption (IR) is associated with the characteristic vibration frequency of the particular chemical bond between the atoms of which the fiber is composed.
* Loss in infrared (IR) region (above 1.2 μm) is given by an expression which is derived for $GeO_2 - SiO_2$ glass fiber as

$$\alpha_{IR} = 7.81 \times 10^{11} \times \exp\left(\frac{-48.48}{\lambda}\right) \quad \text{— (b)}$$



(b)

fig 2:2 attenuation spectra from the intrinsic loss mechanism in pure $GeO_2 - SiO_2$ glass.

2:3 SCATTERING LOSSES :-

* Scattering losses in glass arise due to the following factors.

→ Microscopic variations in material density
→ Compositional fluctuations
→ Structural inhomogeneities
→ Structural defects occuring during fiber fabrication.

* As glass is composed by randomly connected network of molecules and several oxides (eg,.. SiO_2, GeO_2 & P_2O_5) these are the major cause of compositional structure fluctuation.

* This will gives rise to the refractive-index variations within the glass over distance that are small compared with wavelength.

—These index variations cause a scattering of light which is named as Rayleigh Scattering

* Types Of Scattering Losses :-

Scattering Losses

Linear Scattering Loss
i) Rayleigh Scattering
ii) Mie Scattering

Non Linear Scattering Loss
i) Stimulated Brillouin Scattering
ii) Stimulated Raman Scattering.

2:3:1 LINEAR SCATTERING LOSSES :-

* In the linear scattering, some or all the optical power contained within one propogation mode to be transferred Linearly into a different mode.
  - These losses will occur in the Leaky mode or radiation mode.
* It will not continue to propogate within the core of fiber and is radiated out from the fiber, within cladding.
* Scattering loss will be more in multimode fibers due to higher dopant concentration and greater compositional fluctuations.
  - All liniar processes there is no change of frequency on scattering.

a) RAYLEIGH SCATTERING:

* Rayleigh Scattering is the dominant intrinsic loss mechanism in the Ultra Violet region. It extends upto infrared region.

*) Raleigh Scattering is a fundamental loss mechanism arising from local microscopic fluctuations in density.
  - Density fluctuations lead to random fluctuations of the refractive index on a scale

smaller than the optical wavelength λ.

– Light scattering in such a medium is known as Rayleigh scattering.

* Rayleigh scattering in the glass is the same phenomenon that scatters light from sun in the atmosphere which gives rise to a blue sky.

* This produces an attenuation proportional to $1/\lambda^4$.

– For single component glass, Rayleigh loss given by,

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4}(n^2-1)^2 k_B T_f \beta_T \quad \text{—— (a)}$$

where,

$n \rightarrow$ Refractive index of silica

$k_B \rightarrow$ Boltzmann's constant

$\beta_T \rightarrow$ Isothermal compressibility of the material at fictive temperature

$\alpha_{scat} \rightarrow$ Rayleigh scattering coefficient

$T_f \rightarrow$ fictive temperature

FICTIVE TEMPERATURE:

* Fictive temperature is defined as, the temperature at which the glass can reach a state of thermal equilibrium and is closely

related to the anneal temperature.

* Now eq(a) can be written in another form,

ie,

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 K_B T_f \beta_T \quad \text{——— (b)}$$

where, $p \rightarrow$ photo-elastic coefficient.

* The two equations are in neper units. To convert neper units to decibel, the equation can be multiplied by $10 \log e = 4.343$.

— For multi-component glasses the scattering is given by,

$$\alpha = \frac{8\pi^3}{3\lambda^4} (\delta n^2)^2 \delta V \quad \text{——— (c)}$$

where $(\delta n^2)^2 \longrightarrow$ mean-square refractive index fluctuation over a volume of δV, which is given as,

$$(\delta n^2)^2 = \left(\frac{\partial n}{\partial \rho}\right)^2 (\delta \rho)^2 + \sum_{i=1}^{m} \left(\frac{\partial n^2}{\partial c_i}\right)^2 (\delta c_i)^2 \quad \text{——— (d)}$$

where $\delta \rho \rightarrow$ density fluctuation

$\delta c_i \rightarrow$ concentration fluctuation of the i^{th} glass component.

* Magnitudes of the composition and density fluctuations are generally not known and must be determined from experimental

scattering data.

– They are known as, the scattering loss can be calculated.

* Rayleigh scattering is related to the transmission loss factor of the fiber length L following relation.

$$\phi = \exp(-\alpha_{scat} L) \quad \text{———— (e)}$$

where, L ⟶ length of the fiber.

(b) MIE SCATTERING :-

* Linear scattering may also occur at inhomogeneties which are comparable in size to the guided wavelength.

– These result from the non perfect cylindrical structure of the waveguide and may be caused by fiber imperfections such as irregularities in the core-cladding interface, core cladding refractive index differences along the fiber length, diameter fluctuations, strain and bubbles.

* The scattering created by such inhomogeneties in the forward direction is called as MIE Scattering.

– Depending upon fiber material, it can cause significant losses.

Inhomogeneities (Or) Mie Scattering can be reduced by,

i) Removing imperfections due to the glass manufacturing process.

ii) Carefully controlled extrusion + coating of the fiber

iii) Increasing the fiber guidance by increasing the relative refractive index difference.

2:3:2 Non - Linear Scattering Losses :-

* This non-linear scattering causes the optical power from one mode to be transferred in either forward or backward direction to the same or other modes at different frequency.

* It depends critically upon the optical power density within the fiber and hence become significant above threshold power levels.

* Most important types of non-linear Scattering within optical fibers are

(i) Stimulated Brillouin Scattering (SBS)

(ii) Stimulated Raman Scattering (SRS)

* Intensity of scattered light in both cases grow exponentially once the incident power

exceeds a threshold value.

* These scattering mechanism give rise to optical gain but with shift in frequency.

(Q:) STIMULATED BRILLOUIN SCATTERING (SBS):

* Stimulated brillouin Scattering (SBS) may occur, when the light is modulated through the thermal molecular Vibrations within the fiber.

* The Scattered 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 maximum in back-ward direction and reducing to Zero in the forward direction which is making SBS mainly as a backward process.

* SBS is significant above threshold power density, threshold power density (P_B) is given by,

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \, v \quad \text{Watts} \qquad \text{— (f)}$$

where,

$d \rightarrow$ filber core diameters in micrometres

$\lambda \rightarrow$ Operating wavelength in micrometer

$\alpha_{dB} \rightarrow$ Filber attenuation in decibel per kilometer

$v \rightarrow$ Source bandwidth in Gigahertz (GHz)

* This allows the determination of the threshold optical power which must be launched into single-mode optical fiber before SBS occurs.

(b) STIMULATED RAMAN SCATTERING (SRS):

* SRS is similar to SBS but except a high frequency optical photon rather than an acoustic photon which is generated in the scattering process.

* SRS can occur in both forward and backward direction in optical fiber.

_ Optical power threshold of SRS is higher than Brillouin threshold in a particular fiber.

* Optical power threshold (P_R) for SRS in long single - mode fiber is given by,

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} \text{ Watt} \quad (9)$$

2:4 BENDING LOSSES :-

* Optical fiber suffer radiation losses which causes the light energy to be radiated from the fiber, whenever an optical fiber undergoes a bend or curves on their path.

→ Types of bending losses:

i) Macroscopic bending loss
ii) Microscopic bending loss.

1) MACROSCOPIC BENDING LOSSES (OR) LARGE RADIUS LOSSES :

* These losses occur when the radius of curvature of a bend is greater than fiber diameter.
* As the radius of curvature of the bend decreases, the loss increases exponentially upto a certain critical radius then the curvature loss becomes observable.
* Bend radius is made smaller, otherwise it will reach the threshold point, then the losses become extremely large, suddenly.

* Fig 2:4 shows that the part of the mode which is on the cladding outside the dashed arrowed line may be required to travel faster than that on the inside.

– So that a wave front perpendicular to the direction of propogation is maintained

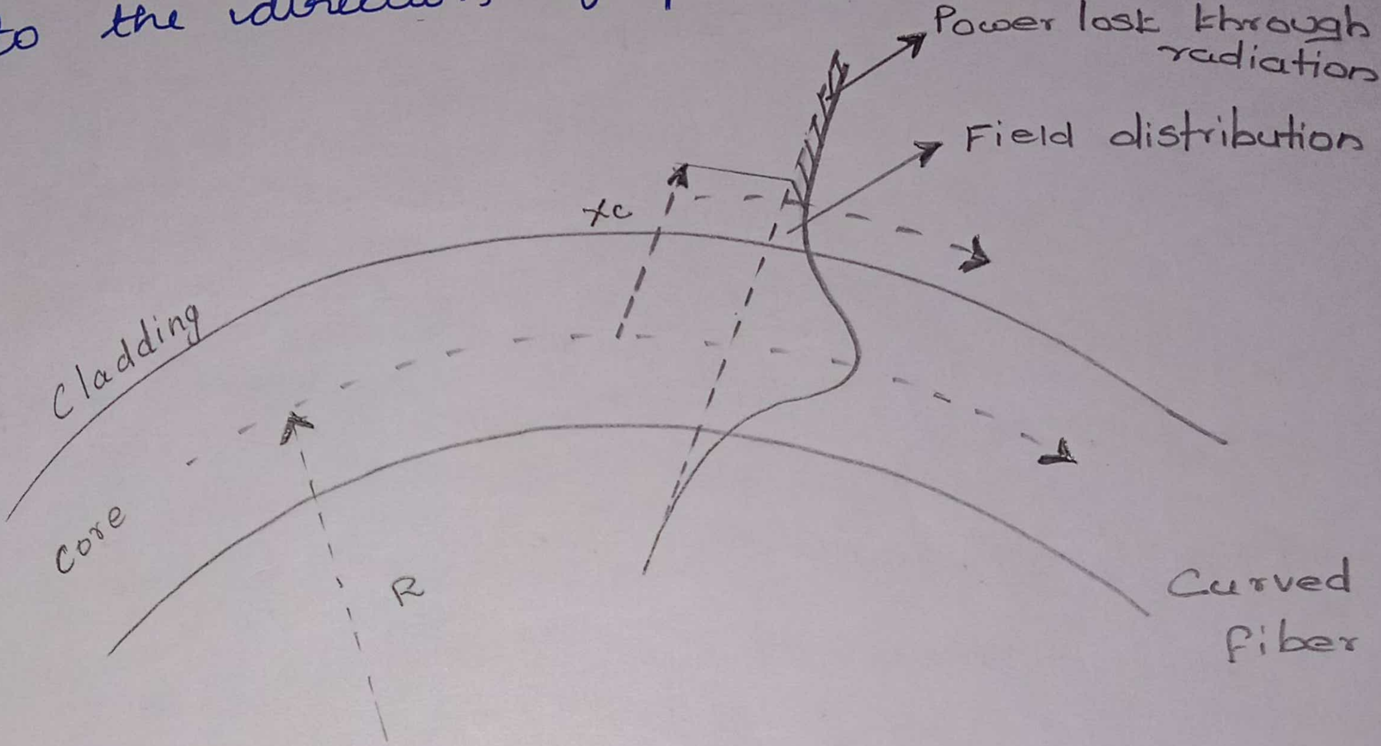


Fig. 2.4. An illustration of the radiation loss at fiber bend

* The amount of optical radiation from a bent fiber is depending on the field strength at "X_c" and on the radius of curvature R.
* The higher-order modes are bound less tightly to the fiber core than the lower order modes, these higher-order modes will radiate out of the fiber.

⟹ Radius Of Curvature:

* Large bending losses tend to occur in multimode fiber at a critical radius of curvature R_c is given by,

$$R_c \approx \frac{3 n_1^2 \lambda}{4\pi (n_1^2 - n_2^2)^{3/2}} \quad \text{———— (a)}$$

* Critical radius of curvature (R_{cs}) for a single-mode fiber can be estimated as,

$$R_{cs} \approx \frac{20 \lambda}{(n_1 - n_2)^{3/2}} \left(2.748 - 0.996 \frac{\lambda}{\lambda_c}\right)^{-3} \quad \text{———— (b)}$$

⟹ Total Number Of Modes:

* Total number of modes that can be supported by a curved fiber is less than in a straight fiber.

* The effective number of modes N_{eff} that are supported by a curved multimode fiber is given by,

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

where,

$\alpha \rightarrow$ Graded-index profile

$\Delta \rightarrow$ Core-cladding index difference

$n_2 \rightarrow$ Cladding refractive index,

$a \rightarrow$ core radius

$k = \frac{2\pi}{\lambda}$ → Wave propogation constant

N_α → Total number of modes in a straight fiber & given as,

$$N_\alpha = \frac{\alpha}{\alpha+2} (n_1 k a)^2 \Delta \qquad \text{(d)}$$

Macro bending losses can be reduced by,

i) Designing fibers with large relative refractive index differences

ii) Operating at the shortest wavelength is possible.

II) MICRO BENDING LOSSES (OR) MODE COUPLING LOSS:

* Micro bend are due to small scale fluctuations in the radius of curvature of the fiber axis.
  - This arises when the fibers are incorporated into cables.

* The fluctuation in the radius of curvature are caused either by non-uniformities in the manufacturing of fiber or by non-uniform lateral pressures created during cabling of the fiber.

* This type of bending introduces slight surfa

imperfections which can cause mode coupling between adjacent modes or coupling of energy between the guided modes and leaky modes in the fiber which inturn creates a radiative loss.

Minimizing Micro bending Losses:

* Micro bending losses can be minimized by introducing compressible jacket over the fiber.

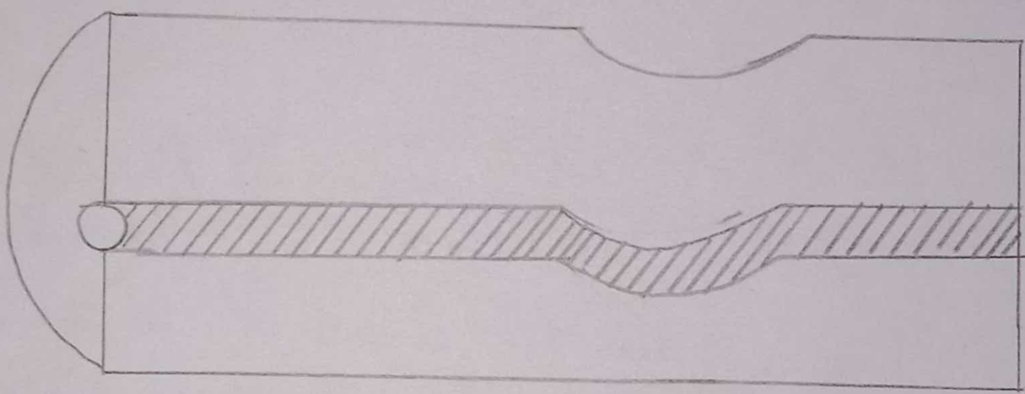


fig 2:6 A compressible jacket extruded over a fiber reduces microbending resulting from external forces.

* When an external forces are applied, the jacket will be deformed but the fiber will tend to stay relatively straight.

2:5 CORE AND CLADDING LOSSES :

* Core and cladding have different refractive indices because they are having different composition.

— Core and cladding have different attenuation coefficients, denoted as α_1 & α_2 respectively,

i) Step - Index Fiber :

* For step index fiber, the loss for a mode of order (v, m) is given by,

$$\alpha_{(v,m)} = \alpha_1 \frac{P_{core}}{P} + \alpha_2 \frac{P_{clad}}{P} \qquad \text{——— (a)}$$

where,

$P_{core} \rightarrow$ power in the core

$P_{cladding} \rightarrow$ Power in the cladding

$P \rightarrow$ Total power in the fiber

$\frac{P_{core}}{P}$ & $\frac{P_{clad}}{P} \longrightarrow$ fractional powers.

* For low-order modes, the power relation between core and cladding is given as,

$$\frac{P_{core}}{P} = 1 - \frac{P_{clad}}{P} \qquad \text{——— (b)}$$

by sub eq (b) in eq in (1), we get

$$\alpha_{(v,m)} = \alpha_1 \left(1 - \frac{P_{clad}}{P}\right) + \alpha_2 \frac{P_{clad}}{P} \qquad \text{——— (c)}$$

$$\alpha_{(v,m)} = \alpha_1 + (\alpha_2 + \alpha_1) \frac{P_{clad}}{P}$$

* Total loss of the waveguide can be found by summing over all modes weighted by the fractional power in that mode.

ii) Graded - index Fiber:-

* Attenuation coefficient and modal power are functions of radial coordinate.

— Loss at radial distance 'r' from core axis is expressed as,

$$\alpha(r) = \alpha_1 + (\alpha_2 - \alpha_1)\frac{n^2(0) - n^2(r)}{n^2(0) - n_2^2} \quad \text{——— (d)}$$

where, α_1 & α_2 → axial and cladding attenuation coefficient respectively.

$$n(r) = \begin{cases} n_1\left[1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]^{1/2} & \text{for } 0 \le r \le a \\ n_1(1-2\Delta)^{1/2} \simeq n_1(1-\Delta) = n_2 & \text{for } r \ge a \end{cases} \quad \text{——— (e)}$$

where α → defines shape of index profile

* The loss at a particular graded - index fiber mode is given by,

$$\alpha_{gi} = \frac{\int_0^{\infty} \alpha(r)\, P(r)\, r\, dr}{\int_0^{\infty} P(r)\, r\, dr} \quad \text{——— (f)}$$

$P(r)$ → power density of that mode at distance r.

— The loss increases with an increasing mode number.

4.6 SIGNAL DISTORTION IN OPTICAL WAVEGUIDES:

* Dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along the optical fibers.
* An optical signal gets distorted as it travels along a fiber.
  - This distortion is due to an intramodal dispersion and intermodal effects.

Dispersion:-

* The term dispersion refers to the spreading of light pulse as it propogates through the fiber.
* It results in the introduction of Inter Symbol interference (ISI).
  - It also limits the information carrying capacity of fiber.

TYPES OF DISPERSION:

* Dispersion effect can be explained on the basis of behaviour of group velocities of the guided modes in the optical fiber.

Dispersion → Intramodal dispersion, Intermodal dispersion

Intramodal dispersion:
i) Material (or) chromatic dispersion
ii) Waveguide dispersion
iii) Group Velocity dispersion (GVD)

Intermodal dispersion:
Modal dispersion

(a) INTRAMODAL DISPERSION:

⇒ INFORMATION CAPACITY DETERMINATION:

Inter Symbol Interference and Bandwidth

* Dispersion and attenuation of pulse travelling along the fiber is shown below, fig( )
* fig shows, after travelling some distance, pulse starts broadening and overlap with the neighbouring pulses.

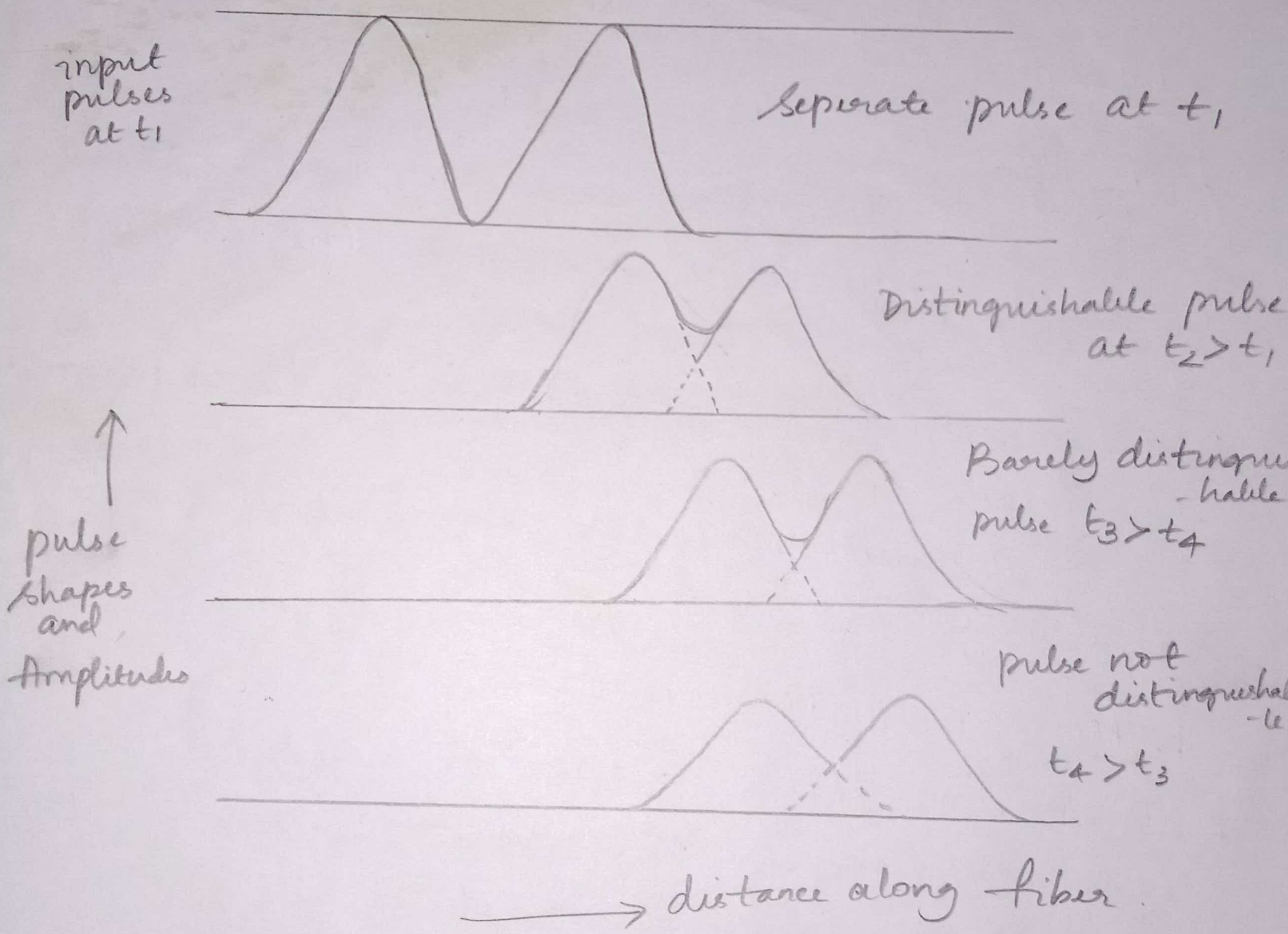


fig 2: Dispersion and attenuation in fiber

* 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 (MHz · km).

* For step index bandwidth distance product is 20 MHz . km and for gradient index it is; 2.5 MHz . km

* The bandwidth decreases with increases in optical cable length.

- The information carrying capacity can be computed by short light pulse propogating along the filer.

→ Group Delay:

* Consider a filer cable carrying optical signal equally with various modes and each mode contains all the Spectral components in the wavelength band.

* All the sepectral components travel independently and they observe different time delay and group delay in the direction of propogation.

* The velocity at which the energy in a pulse travels along the filer is known as group velocity.

Group velocity is given by,

$$V_g = \frac{\partial \omega}{\partial \beta} \quad \text{------------ (a)}$$

* Thus, different frequency components in a signal will travel at different group velocities and so will arrive at their destination at

different times, for digital modulation of Carrier, this results in dispersion of pulse which affect the maximum rate of modulation

- Let the difference in propogation times for two side band is $\delta\tau$

$$\delta\tau = \frac{d\tau}{d\lambda} \times \delta\lambda \quad \text{———} \quad (2)$$

where, $\delta\lambda \rightarrow$ wavelength difference between upper and lower sideband (Spectral width)

$\frac{d\tau}{d\lambda} \rightarrow$ Dispersion Coefficient D.

Then,

$$D = \frac{1}{L} \cdot \frac{d\tau}{d\lambda}$$

where $L \rightarrow$ Length of fiber.

$$D = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right)$$

As $\tau = \frac{1}{V_g}$ and considering unit length $L = 1$

Now,

$$\frac{1}{V_g} = \frac{d\beta}{d\omega}$$

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

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

$$D = \frac{d}{d\lambda}\left(\frac{-\lambda^2}{2\pi c} \cdot \frac{d\beta}{d\lambda}\right) \quad \text{———} \quad (3)$$

* Dispersion is measured in picoseconds per nanometer per kilometer.

(a) 2:6:1 Material Dispersion :-

* Material dispersion is also called as chromatic dispersion.
  - Material dispersion exists due to change in index of refraction for different wavelengths.
  - A light ray contains components of various wavelength centered at wavelength λ_0.
* The time delay is different for different wavelength components.
  - This results in time dispersion of pulse at the receiving end of fiber.

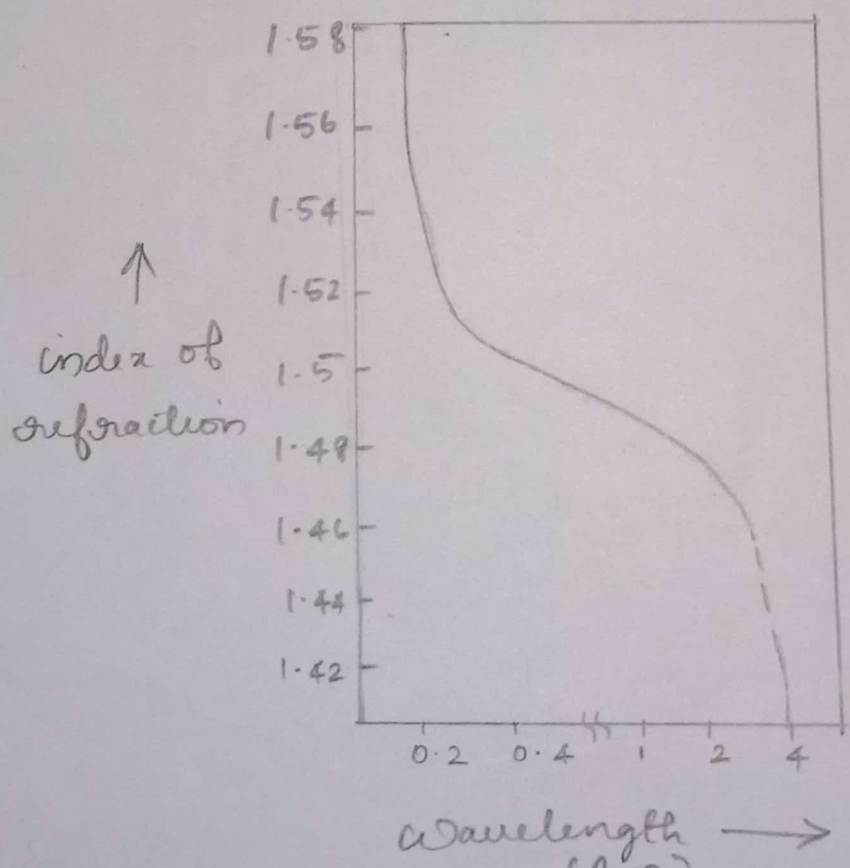


fig 2. Index of refraction as a function of wavelength.

* Material dispersion for unit length L=1 is given by,

$$D_{mat} = \frac{-\lambda}{c} \times \frac{d^2n}{d\lambda^2} \quad \text{——— (4)}$$

where, c → Light velocity

λ → Center wavelength

$\frac{d^2n}{d\lambda^2}$ → Second derivative of index of refraction with respect to wavelength

* Negative sign (−) shows that the upper sideband signal (lowest wavelength) arrives before the lower sideband (highest wavelength).

* Unit of dispersion is ps/nm·km. The amount of material dispersion depends upon the chemical composition of glass.

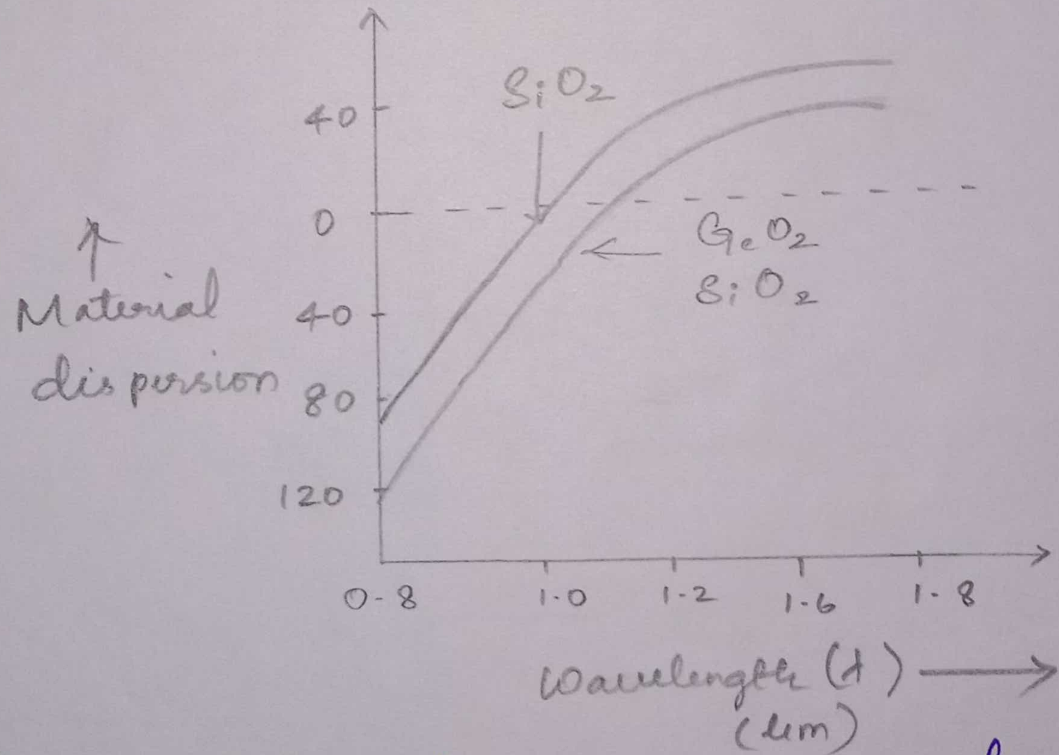


fig 2: Material dispersion as a function of λ.

2:6:2 WAVEGUIDE DISPERSION :.

* Waveguide dispersion is caused by the difference in the index of refraction between the core and cladding, resulting in a drag effect between the core and cladding portions of the power.

* Waveguide dispersion is significant only in fibers carrying fewer than 5–10 modes.
  – Since multimode optical fibers carry hundreds of mode, they will not have observable waveguide dispersion.

* Group delay τ_{wg} arises due to waveguide dispersion.

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d(kb)}{dk}\right] \qquad (5)$$

where,

$b \rightarrow$ Normalized propogation constant

$k \rightarrow 2\pi/\lambda$ (group velocity)

Normalized frequency V,

$$V = ka\left(n_1^2 - n_2^2\right)^{1/2}$$

$$V = kan_2\sqrt{2\Delta} \quad (\text{for small } \Delta)$$

$$\therefore \tau_{wg} = \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d(Vb)}{dV}\right] \qquad (6)$$

$\frac{d(Vb)}{dV} \longrightarrow$ waveguide dispersion and is mode dependent term.

(a) 2:6:3 CHROMATIC DISPERSION:

* Combination of material dispersion and waveguide dispersion is called chromatic dispersion.
  - These losses primarily concern the spectral width of transmitter and choice of correct wavelength.
* A graph of effective refractive index against wavelength illustrates the effects of material, chromatic and waveguide dispersion.

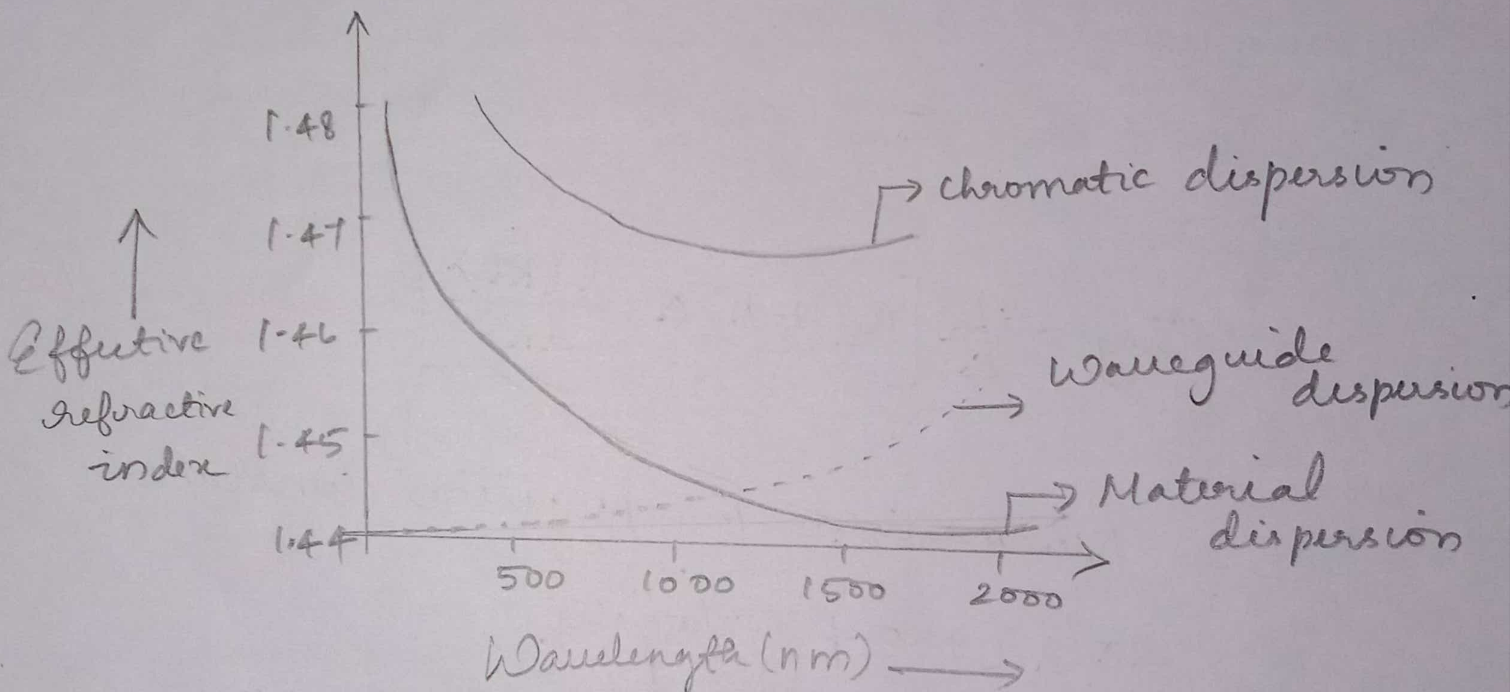


fig: 2: Graph of effective refractive index against wavelength showing effects of chromatic, waveguide and material dispersion.

* Material dispersion and waveguide dispersion effect vary in opposite senses as the wavelength increased, but at an optimum wavelength around

1300 nm, two effects almost cancel each other and chromatic dispersion is at minimum.

- Attenuation is therefore also at minimum and makes 1300 nm a highly attractive operating wavelength.

Q.6.4 (b) MODAL DISPERSION :-

* As only certain number of modes can propagate down the fiber, each of these modes carries the modulation signal and each one is incident on the boundary at a different angle, they will each have their own individual propogation times.

- The net effect is spreading of pulse, this form of dispersion is called modal dispersion.

* Modal dispersion takes place in multimode fiber.

- It moderately present in graded index fiber and almost eliminated in single mode step index fibers.

* Modal dispersion is given by,

$$\Delta t_{modal} = \frac{n_1 z}{c}\left(\frac{\Delta}{1-\Delta}\right)$$

where, $\Delta t_{modal} \rightarrow$ dispersion

$n_1 \rightarrow$ core refractive index

$Z \rightarrow$ Total fiber length

$c \rightarrow$ Velocity of light in air

$\Delta \rightarrow$ fractional refractive index $\left(\frac{n_1 - n_2}{n_1}\right)$

Sub, $\Delta = \frac{NA^2}{2n_1^2}$ in above eq,

$$\Delta t_{modal} = \frac{(NA^2)\, Z}{2 n_1 c}$$

* Modal dispersion Δt_{modal} describes the optical pulse spreading due to modal effects optical pulse width can be converted to electrical rise time through the relationship.

$$t_{r\,mod} = 0.44 \left(\Delta t_{modal}\right)$$

SIGNAL DISTORTION IN SINGLE MODE FIBERS:

* The pulse spreading σ_{wg} over range of wavelength can be obtained from derivative of group delay with respect to λ.

$$\sigma_{wg} = \left| \frac{d\tau_{wg}}{d\lambda} \right| \sigma_{\lambda}$$

$$\sigma_{wg} = L \left| D_{wg}(\lambda) \right| \sigma_{\lambda}$$

$$\sigma_{wg} = \frac{V}{\lambda} \left| \frac{d\tau_{wg}}{d\lambda} \right| \sigma_{\lambda}$$

$$\sigma_{wg} = \frac{n_2 L \Delta \sigma_{\lambda}}{c\lambda} \left[V \frac{d^2 (Vb)}{dV^2} \right] \quad \text{——— (7)}$$

where,

$$D_{wg}(\lambda) = \frac{-n_2 \Delta}{c\lambda}\left[V \frac{d^2(Vb)}{dV^2}\right] \quad \text{——— (8)}$$

equation for waveguide dispersion of unit length.

⇒ HIGHER ORDER DISPERSION:

* Higher order dispersive effective effects are governed by dispersion slope S.

$$S = \frac{dD}{d\lambda}$$

where, D → total dispersion.

Also,

$$S = \left(\frac{2\pi c}{\lambda^2}\right)^2 \beta_3 + \left(\frac{4\pi c}{\lambda^3}\right)\beta_2$$

where,

β_2 & β_3 → second & third order dispersion parameters.

⇒ DISPERSION INDUCED LIMITATIONS:

* Extent of pulse broadening depends on the width and the shape of input pulses.

The pulse broadening is studied with the help of wave equation;

BASIC PROPOGATION EQUATION:

* The basic propogation equation which governs pulse evolution in a single mode fiber is given by,

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2} \cdot \frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6} \frac{\partial^3 A}{\partial t^3} = 0$$

where,

β_1 & β_2 & $\beta_3 \rightarrow$ different dispersion parameters.

CHIRPED GAUSSIAN PULSES :-

* A pulse is said to be chirped if its carrier frequency changes with time.
* For a gaussian spectrum having spectral width σ_ω, the pulse broadening factor is given by,

$$\frac{\sigma^2}{\sigma_0^2} = \left(1 + \frac{C\beta_2 L}{2\sigma_0^2}\right)^2 + (1+V_\omega^2)\left(\frac{\beta_2 L}{2\sigma_0^2}\right)^2 + (1+C+V_\omega^2)^2 \left(\frac{\beta_3 L}{4\sqrt{2}\sigma_0^3}\right)^2$$

where, $V_m = 2\sigma_\omega \sigma_0$

LIMITATIONS OF BIT RATE :

* Limiting bit rate is given by,

$$4B\sigma \leq 1$$

* Condition relating bit rate-distance product (BL) and dispersion (D) is given by,

$$BL\,|D|\,\sigma_\lambda \leq \frac{1}{4}$$

$$BL\,|S|\,\sigma_\lambda^2 \leq \frac{1}{\sqrt{8}}$$

where $S \rightarrow$ dispersion slope.

2.7 POLARIZATION MODE DISPERSION:

* Different frequency component of a pulse acquires different polarization states (Linear polarization & circular polarization).
  - This results in pulse broadening is known as polarization mode dispersion. (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 of the fiber 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 fiber's ability to maintain polarization.
  - The beat length describes the length required for the polarization to rotate 360°.
  - For a given wavelength, it is inversely propotional to the fiber birefringence.

2:8 PULSE BROADENING IN GI FIBERS:-

IntraModel Dispersion & InterModel Dispersion

* Core refractive index varies radially in case of graded index fibers, hence it supports multimode propogation with low intermodal delay distortion and high data rate over long distance is possible.

- Higher order modes travelling in outer region of the core, will travel faster than the lower order modes travelling in high refractive index region.

* If the index profile is continued, then the transit times of the individual modes will be identical, so eliminating modal dispersion.

* R.M.S pulse broadening is given as,

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

where,

$\sigma_{intermodal}$ → RMS pulse width due to intermodal delay distortion.

$\sigma_{intramodal}$ → RMS pulse width resulting from pulse broadening within each mode.

* The intermodal delay and pulse broadening are related by expression given by personick:

$$\sigma_{intermodal} = \left(\langle \tau_g^2 \rangle - \langle \tau_g \rangle^2\right)^{1/2} \quad (2)$$

where, τ_g → group delay.

From this the expression for intermodal pulse broadening is given as,

$$\sigma_{intermodal} = \frac{LN_1\Delta}{2c} \cdot \frac{\alpha}{\alpha+1}\left(\frac{\alpha+2}{3\alpha+2}\right)^{1/2} \times \left[C_1^2 + \frac{4C_1C_2(\alpha+1)\Delta}{2\alpha+1} + \frac{16\Delta^2C_2^2(\alpha+1)^2}{(5\alpha+2)(3\alpha+2)}\right]^{1/2}$$ ——— (3)

where, $C_1 = \frac{\alpha-2-\epsilon}{\alpha+2}$ & $C_2 = \frac{3\alpha-2-2\epsilon}{2(\alpha+2)}$

* 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, $\sigma_\lambda \rightarrow$ Spectral width of optical source.

Solving the expression gives,

$$\sigma^2_{intramodal} = \frac{L}{c} \cdot \frac{\sigma_\lambda}{\lambda}\left[\left(-\lambda^2 \frac{d^2n_1}{d\lambda^2}\right)^2 - N_1C_1\Delta \left(2\lambda^2\frac{d^2n_1}{d\lambda^2}\frac{\alpha}{\alpha+1} - N_1C_1\Delta\frac{4\alpha^2}{(\alpha+2)(3\alpha+2)}\right)\right]^{1/2},$$

——— (5)

2.9 MODE COUPLING:

* After certain initial length, the pulse distortion increases less rapidly because of mode coupling.
  - The energy from one mode is coupled to other

modes because of :

→ Structural Imperfections
→ Fiber diameter Variations
→ Refractive index Variation
→ Microbends in cable.

* Due to the mode coupling, average propogation delay becomes less and intermodal distortion reduces.

* Suppose certain initial coupling length = L_c

mode coupling Length, Over $L_c = Z$.

– Additional loss associated with mode coupling is h (dB/km)

* Therefore the excess attenuation resulting from mode coupling = hZ

– Improvement in pulse spreading by mode coupling is given as :

$$hZ\left(\frac{\sigma_c}{\sigma_0}\right) = C \quad \text{——— (1)}$$

where, C → Constant independent of all dimensional quantities and refractive indices.

σ_c → pulse broadening under mode coupling

σ_0 → pulse broadening in absence of mode coupling.

* For long fiber length's the effect of mode coupling on pulse distortion is significant.

— For a graded index fiber, the effect of distance on pulse broadening for various coupling losses are shown below,

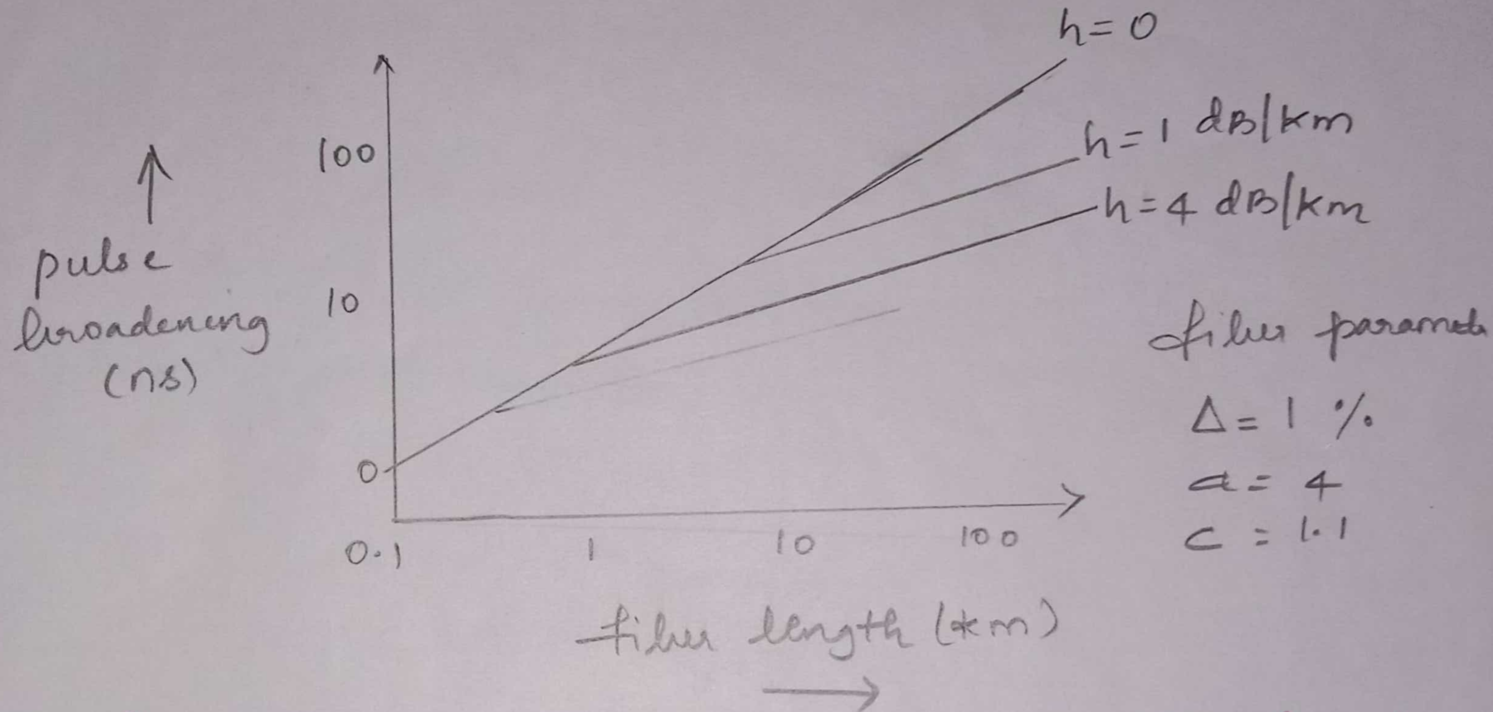


fig 2: Mode coupling effects on pulse broadening

* Significant mode coupling occurs of connectors, splices and with other passive components of an optical link.

2:10 DESIGN OPTIMIZATION OF SINGLE MODE FIBERS :-

* Features of single mode fibers are,

→ Longer Life

→ Low attenuation

→ Signal transfer quality is good
→ Modal noise is absent
→ Largest BW distance product.

* Basic design - optimization includes the following:
  → Cut-off wavelength
  → Dispersion
  → Mode field diameter
  → Bending loss
  → Refractive index profile.

2:10:1 REFRACTIVE INDEX PROFILE:

* Dispersion of single mode silica fiber is lowest at 1300 nm while its attenuation is minimum at 1500 nm.

- For acheiving maximum transmission distance the dispersion null should be at the wavelength of minimum attenuation.

- The waveguide dispersion is easier to control than the material dispersion.

∴ Therefore variety of core-cladding refractive index configuration fibers.

* Such as 1300nm - optimized fibers, dispersion shifted fibers, dispersion-flattened fibers and large effective core area fibers.

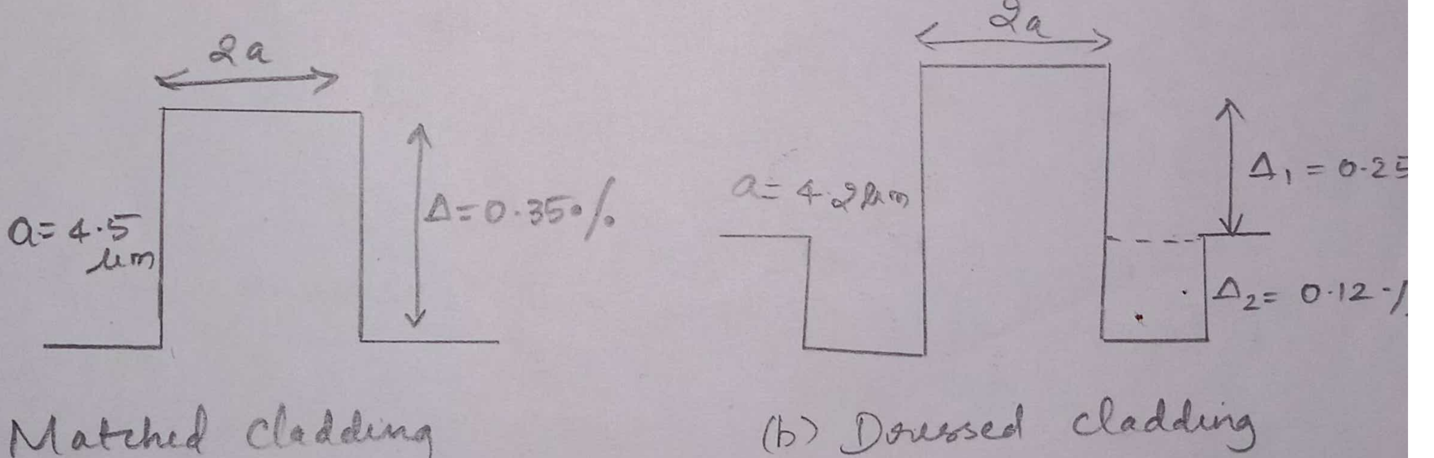
i) 1300 nm – Optimized Fibers:

* These are most popularly used fibers: The two configurations of 1300 nm – optimized single mode fibers are:

  *) Matched cladding fibers
  *) Depressed cladding fibers

* Matched cladding fibers have uniform refractive index throughout its cladding.
  Typical diameter is 9.0 µm and $\Delta = 0.35\%$

* Depressed cladding fibers have the inner most cladding portion has low refractive index than outer cladding region.
  Typical diameter is 8.4 µm and $\Delta_1 = 0.25\%$
  $\Delta_2 = 0.12\%$



(a) Matched Cladding (b) Dressed cladding

fig 2: 1300 nm – Optimized refractive index profile

ii) DISPERSION SHIFTED FIBERS:

* Addition of waveguide and material

dispersion can shift the zero dispersion point to longer wavelength.

– Two configuration of dispersion shifted fibers are:

a) Step Index dispersion shifted fiber

b) Triangular dispersion shifted fiber

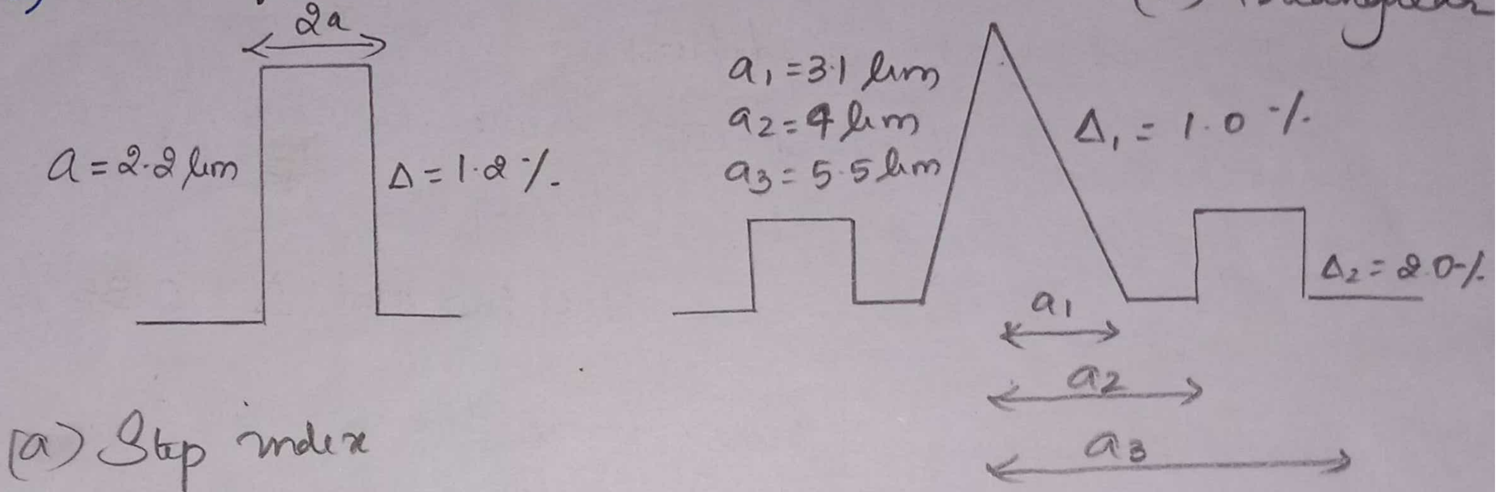


fig 2: Dispersion Shifted fiber

(III) DISPERSION FLATTENED:

* Dispersion flattened fibers are more complex to design.

– It offers much broader span of wavelength to suit desirable characteristics.

Two configurations are,

i) Double clad profile   ii) Quadruple clad profile

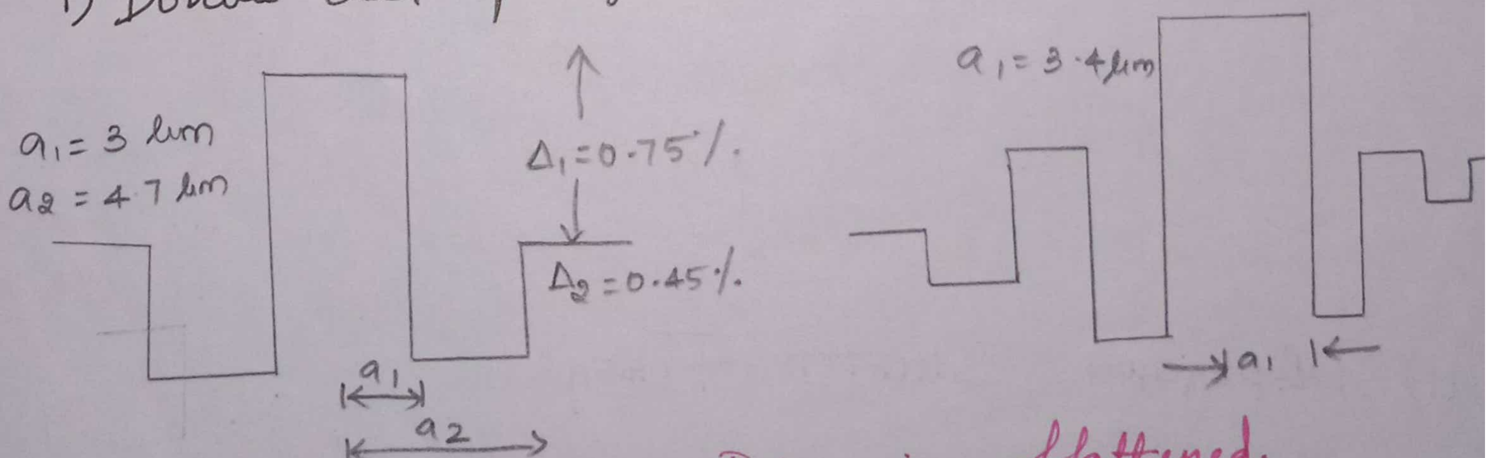


fig 2: Dispersion flattened.

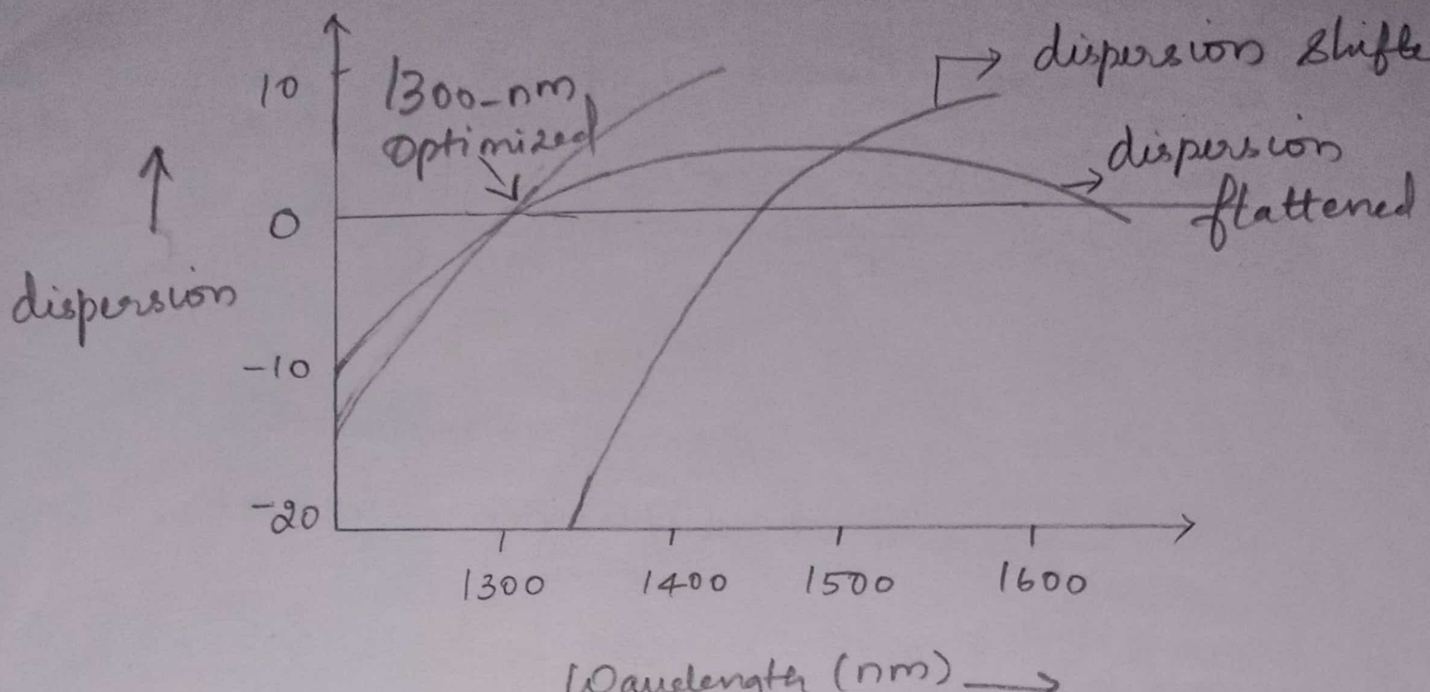


fig 2: Total resultant dispersion.

Dispersion Calculations:

* Total dispersion consists of material and waveguide dispersions. The resultant intermodal dispersion is given as,

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

where $\tau \rightarrow$ group delay per unit length of fiber

* The broadening σ of an optical pulse is given as

$$\sigma = D(\lambda) L \sigma_\lambda \quad \text{——— (1)}$$

where, $\sigma_\lambda \rightarrow$ half power spectral width of source.

* As the dispersion varies with wavelength and fiber type.

Different formula are used to calculate dispersion for variety of fiber at different wavelength.

* For Non-dispersion shifted fiber between 1270 nm to 1340 nm wavelength, dispersion is given as,

$$D(\lambda) = \frac{\lambda}{4} S_0 \left[1 - \left(\frac{\lambda_0}{\lambda}\right)^4\right] \quad (2)$$

where,

$\lambda_0 \rightarrow$ Zero dispersion wavelength

$S_0 \rightarrow$ Value at dispersion slope at λ_0.

* Maximum dispersion specified as 3.5 ps/(nm.km) marked in dotted line at the fig below,

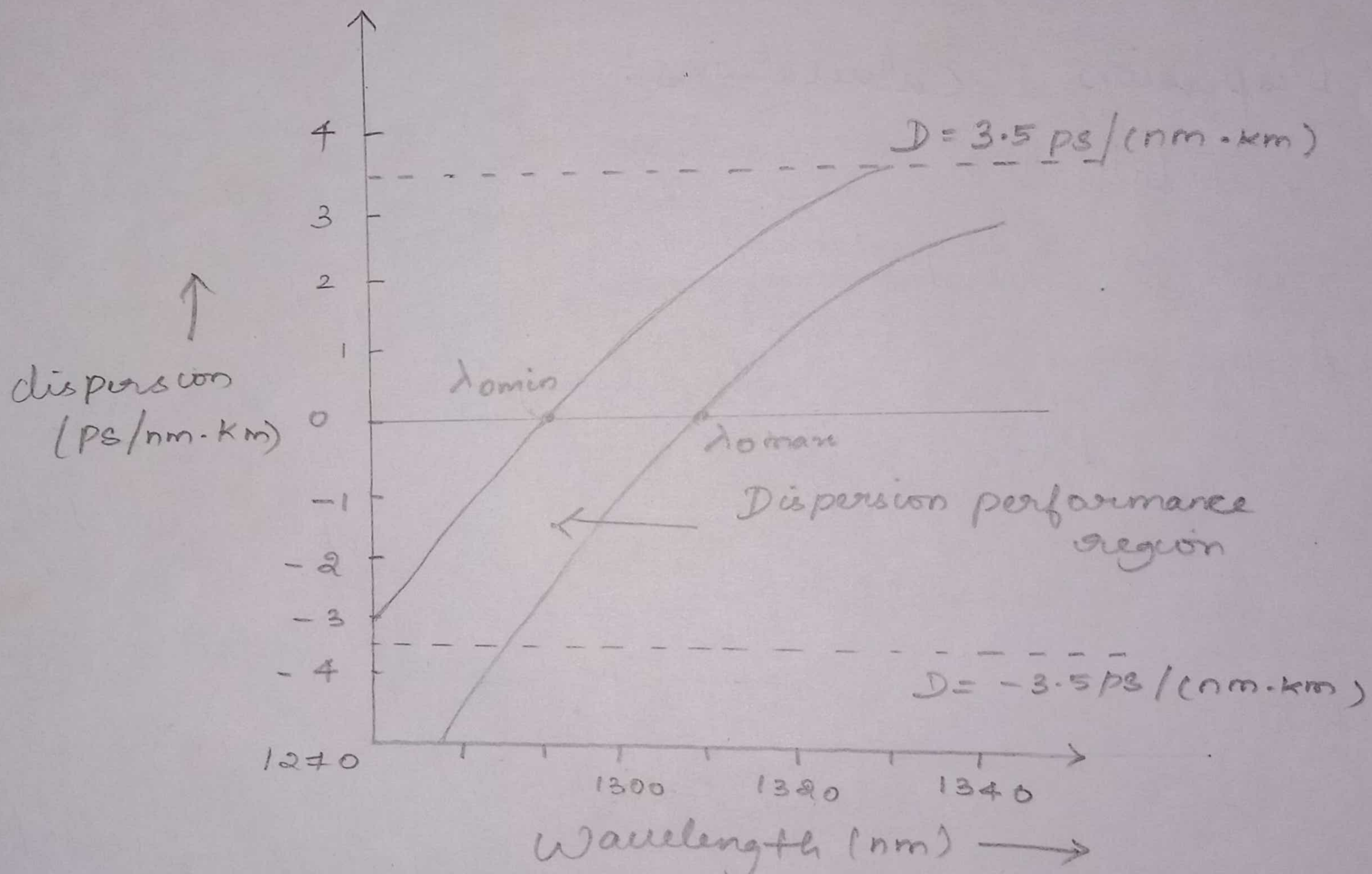


fig 2. Dispersion performance curve for non-dispersion shifted fibers in 1270-1340 nm region.

2:9:2 CUT-OFF WAVELENGTH OF AN OPTICAL FIBER:

* cut off frequency of an optical fiber is determined not only by the fiber itself but also by the amount of material dispersion caused by the spectral width of transmitter.

* Cut-off wavelength of a single mode operation is given as,

$$\lambda_c = \frac{2\pi a}{V_c}(n_1^2 - n_1^2)^{1/2} \quad \text{——— (a)}$$

(or)

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

where, $V_c \rightarrow$ cut off normalized frequency

$V_c = 2.405$ for step index fiber.

* Cut-off wavelength also decides the radius of curvature.

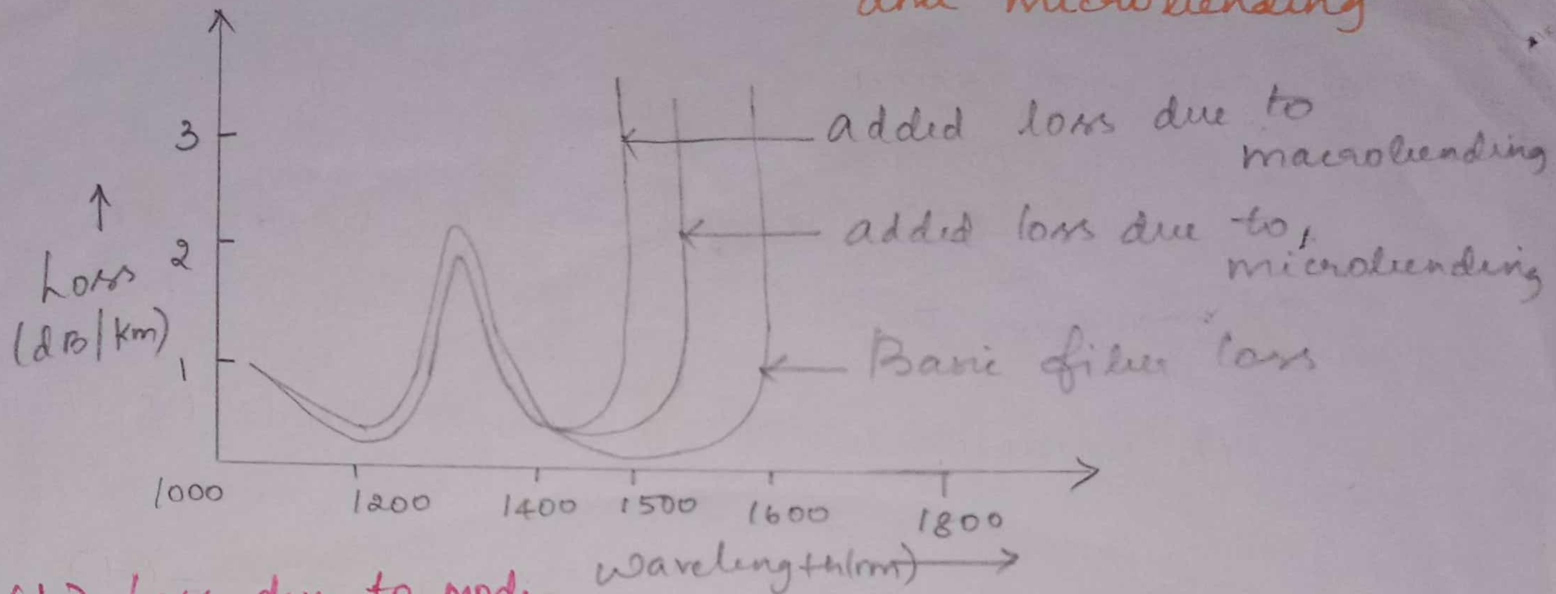
- For a single mode fiber the radius of curvature is given by expression:

$$R_{cs} = \frac{20\lambda}{(n_1 - n_2)^{3/2}}\left(2.748 - 0.996\frac{\lambda}{\lambda c}\right)^{-3} \quad \text{——— (b)}$$

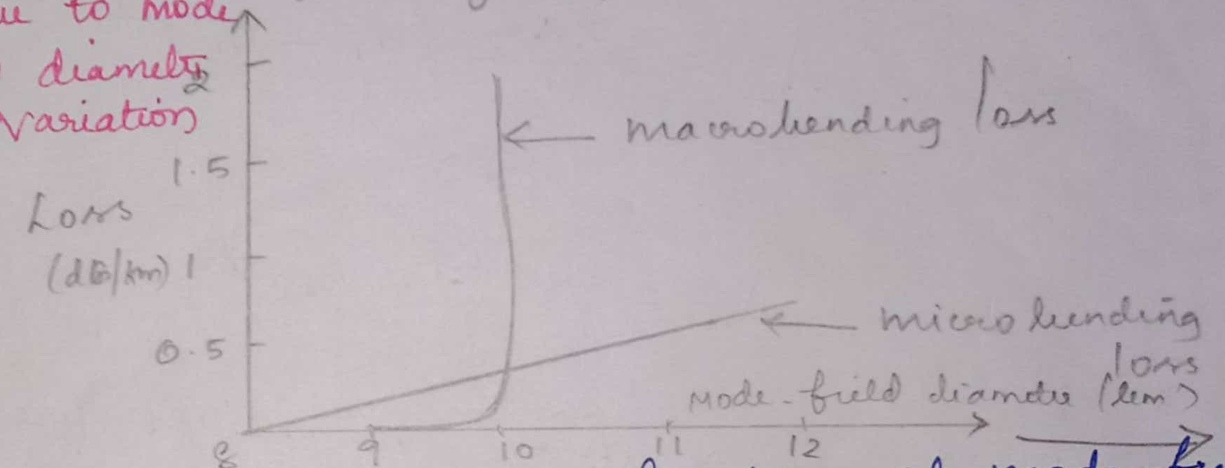
2:9.3 BENDING LOSS LIMITATIONS:

* Macrobending and microbending losses are significant in single mode fibers at 1550 nm region, the lower cut-off wavelength affects more.

(a) fiber attenuation due to macrobending and microbending



(b) Loss due to mode field diameter variation



* The bending losses are function of mode-field diameter, smaller the mode-field diameter, the smaller the bending loss fig above, shows loss due to mode-field diameter.

* The bending losses are also function of bend radius of curvature.
  - If the bend radius is less, the losses are more and when the radius is more, the bending losses are less.

Characteristics of Single Mode fiber

- Longer life
- Low Attenuation
- Signal transfer Quality is good.
- Modal Noise is absent
- Largest BW-distance product

Mode field Diameter

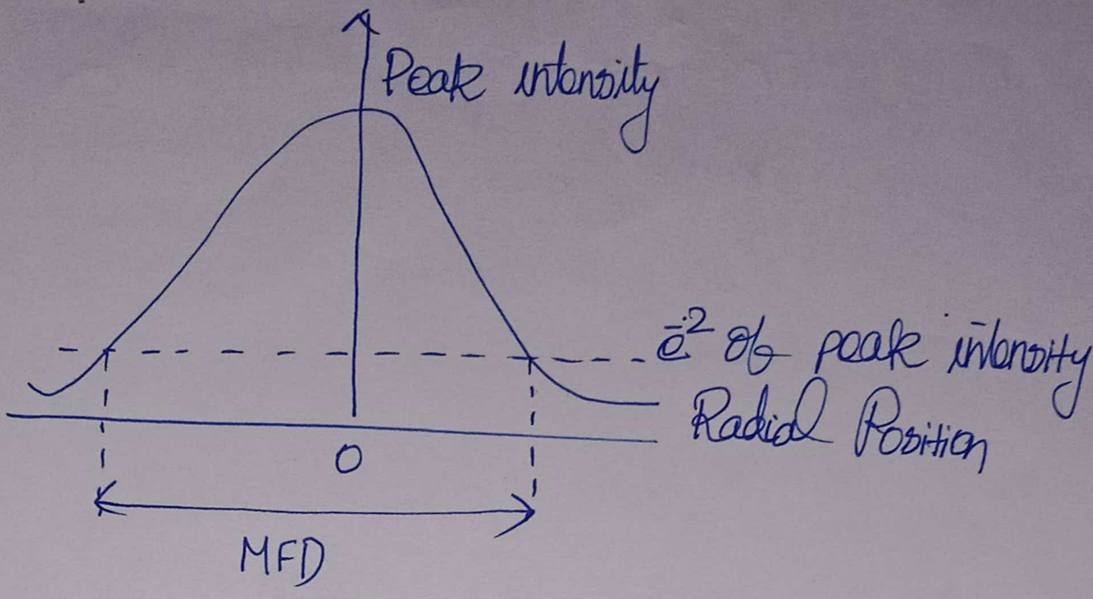
Mode field diameter (MFD) is determined by the Numerical Aperture (NA) and cut off wavelength of the fiber, and is related to the diameter of the fiber core.

MFD is typically defined as the radial position where intensity falls to e^{-2} of the peak intensity.

$$MFD = 2a\left(0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^{6}}\right]$$

V = V-value of fiber

a = Core radius



MFD is typically larger than the core diameter. In telecoms fiber operated above cut-off, the core diameter might be around 9 μm, and the MFD is around 10.4 μm. With very high NA fiber, up around 0.2 or 0.3, the core diameter is just a few microns while MFD might be around 5 μm.

UNIT III

Optical Sources And Detectors.

3:1 DIRECT AND INDIRECT BAND GAP MATERIALS:-

* When electron transitions to take place to or from the conduction band with the absorption or emission of a photon respectively, both energy and momentum must be conserved.
* Although a photon have considerable energy its momentum $\frac{h\nu}{c}$ is very small.
* Depending on the shape of the band gap as a function of the momentum k, the Semiconductor are classified as,

quantity of motion of a moving electron $k = m \times v$

i) Direct band gap material
ii) Indirect band gap material

3:1:1 DIRECT BAND GAP MATERIAL:-

* An electron from the conduction band can recombine with a hole in the valance band directly by emitting a light photon of energy $h\nu$.
  - Here, the electron and hole have the same momentum value. The direct recombination is possible
  - This is a direct band gap material.

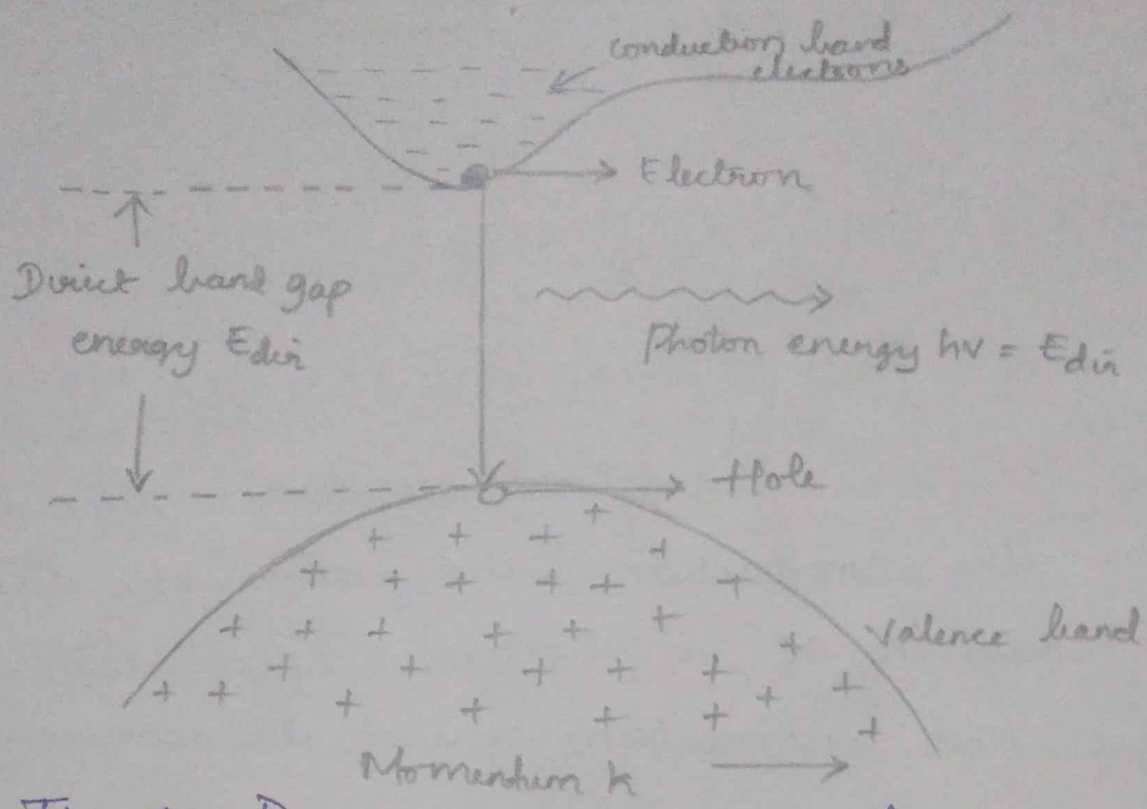


Fig 3:1 Direct - band gap material

* The life time of charge carriers is very less. They are used to fabricate LED and Laser diodes

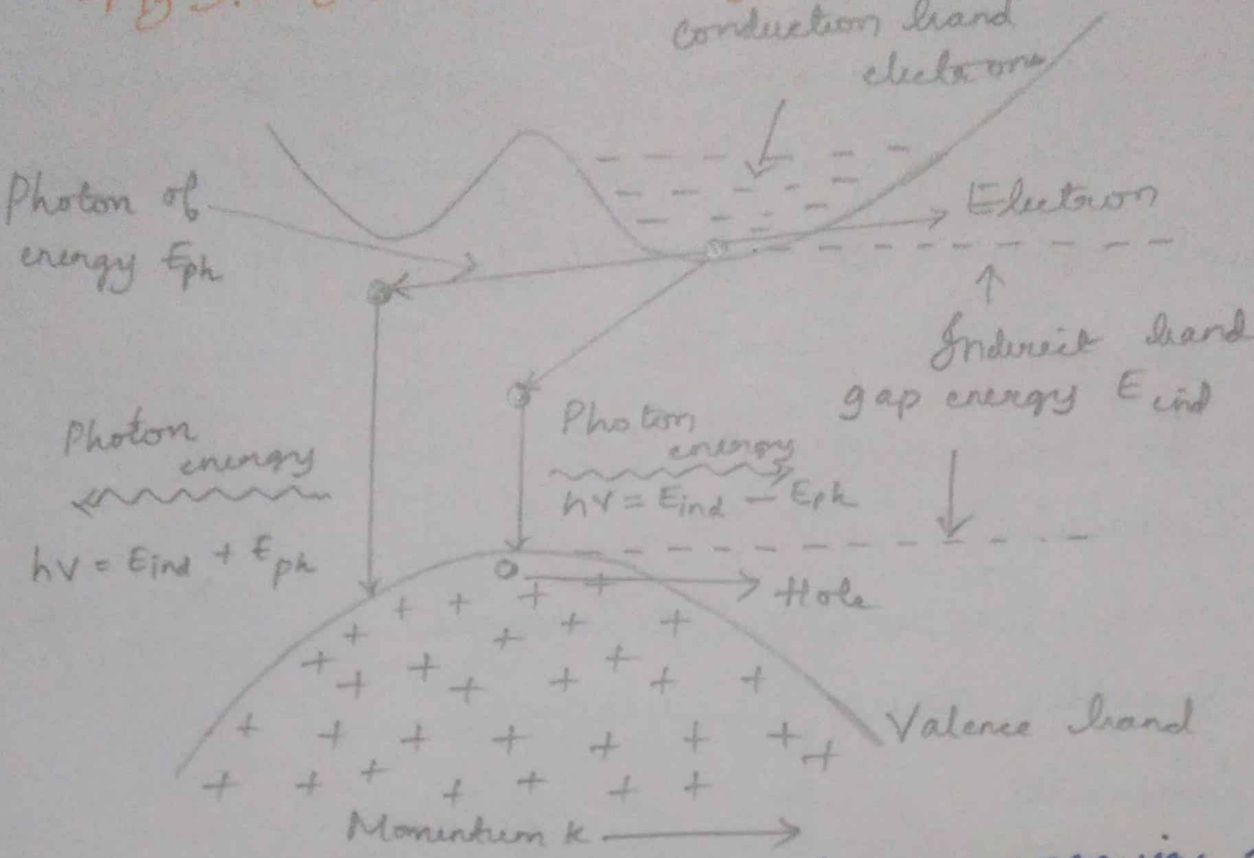
* Direct bandgap semiconductor devices in general have much higher internal quantum efficiency.

3:1:2 INDIRECT BAND GAP MATERIAL :-

* For indirect band gap material, the conduction band minimum and the valence band maximum energy levels occur at different values of momentum.

* To perform band to band recombination it must involve a third particle photons to conserve momentum, since the photon momentum is very small.

Fig 3:2 Indirect band - gap material



* Here, the life time of charge carriers is more. Due to its longer life time of charge carriers, these are used to fabricate the rectifier diodes and transistors which are used to make amplifiers, switches and intergrated circuits.

3:2 LIGHT EMITTING DIODE (LED's)

* Normally, an empty conduction band of the semiconductor is populated by electrons injected into it by the forward current through the junction and light is generated when these electron recombine with holes with valance band to emit photon.
  - This is the mechanism by which light is emitted from an LED.

ADVANTAGES :-

* LED has a number of distint Advantages which have given it a prominent place in optical fiber communications.

1) Simple fabrication
2) Cost : Reduction of cost
3) Reliability
4) Less temperature dependence
5) Simpler drive circuitry.
6) Linearity.

DRAWBACK COMPARING TO INJECTION LASERS :-

1) Lower optical power coupled into fiber
2) Lower modulation bandwidth
3) Harmonic disortion.

PRINCIPLE OF OPERATION :-

* LED can be used in fiber transmission applications. LED must have

i) High radiance output or brightness
ii) fast emission response time
iii) High quantum efficiency

* RADIANCE (BRIGHTNESS)

* It is a measure of optical power radia-ted

into a unit solid angle per unit area of the emitting surface.

— The unit for radiance or power is Watts.

* High radiance are required to couple sufficiently high optical power level into a fiber

* EMISSION RESPONSE TIME:-

* It is a time delay between the application of a current pulse and a respective optical emission.

* This time delay is the factor limiting the bandwidth with which the source can be modulated directly by varying the injected current.

* QUANTUM EFFICIENCY:

— It is related to the fraction of the electron hole pair that recombine radiatively.

3:2:1 LED STRUCTURE:-

* LED should provide a high radiance and high quantum efficiency.

— It must acheive a carrier and optical confinement.

* Carrier confinement is used to achieve high

level of radiative recombination in the active region of the device, which yields a high quantum efficiency.

* Optical confinement is used for preventing absorption of the emitted radiation by the material surrounding pn junction.

HETERO JUNCTION STRUCTURE :-

* Hetero junction structure are used to acheive carrier and optical confinement.

- It consists of two adjoining semiconducto materials with different band-gap energies.

- Hetero junction are also known as Double Hetero structure device (DH) because of two different alloy layers on each side of the active region.

* The band gap energy differences between the adjacent layers confine the charge carrier and refractive indices difference between the adjoining layers confine the optical field to the central active layer.

— So High efficiency and high radiance

is obtained due to this dual confinement.

- The electron - hole recombination occurs only in active layer.

* DH structure will confine both holes and electrons to a narrow active layer.

- Under forward bias, there will be a large number of carriers injected into an active region where they are efficiently confined.

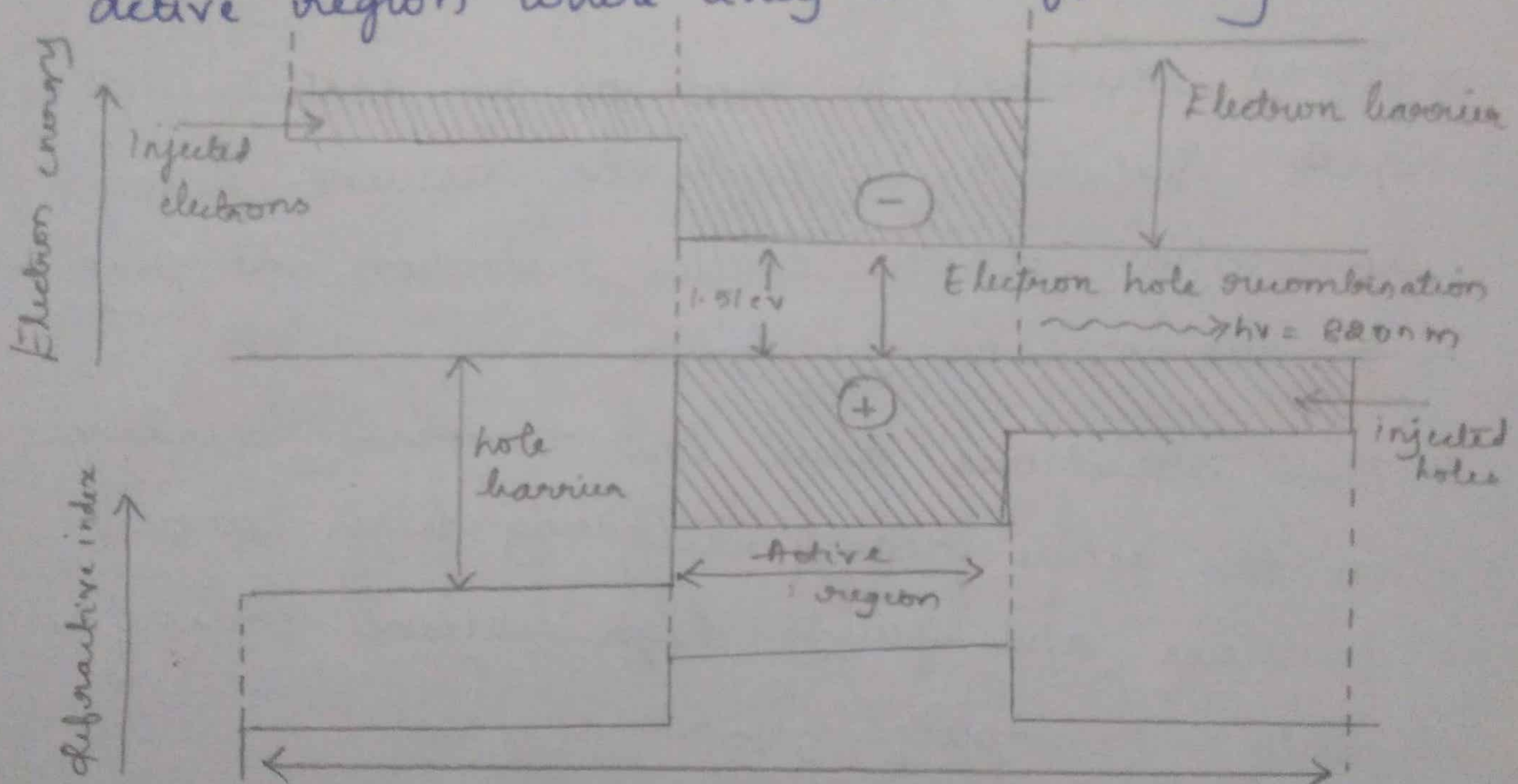


Fig 3:3 GaAlAs double hetero structure light emitting

3:3 LED CONFIGURATION :-

* Two basic LED configurations are used in optical fiber links are,

i) Surface emitters LED (Burrus or front emitters)

ii) Edge emitter LED.

1) Surface or Burrus Emitting LED's (SLED):

* These types of LED are needed where data rate excess of 100 Mbps are required.
* In surface emitting LED, the plane of active light-emitting region will be always perpendicular to the fiber axis.

HOMO (MONO) STRUCTURE :-

* Homo structure is used as an etched well in GaAs substrate in order to prevent heavy apsorption of the emitted radiation and physically to accommodate the fiber.
* These structures have low thermal impedance in the active region allowing high current densities and giving high radiance emission into the optical fiber.

DOUBLE HETERO JUNCTION (DH) STRUCTURE :-

* DH structures has increased efficiency from electrical and optical confinement as well as less absorption of the emitted radiation.
* The structure of a high radiance etched well DH surface emitter for 0.8 to 0.9 µm.

* The internal absorption is very low due to the larger band gap confining layers, and the reflection coefficient at the back crystal face is high giving good forward radiance

* A well etched in a substrate (GaAs) to avoid the heavy absorption of the emitted radiation and the fiber is then connected to accept the emitted light.

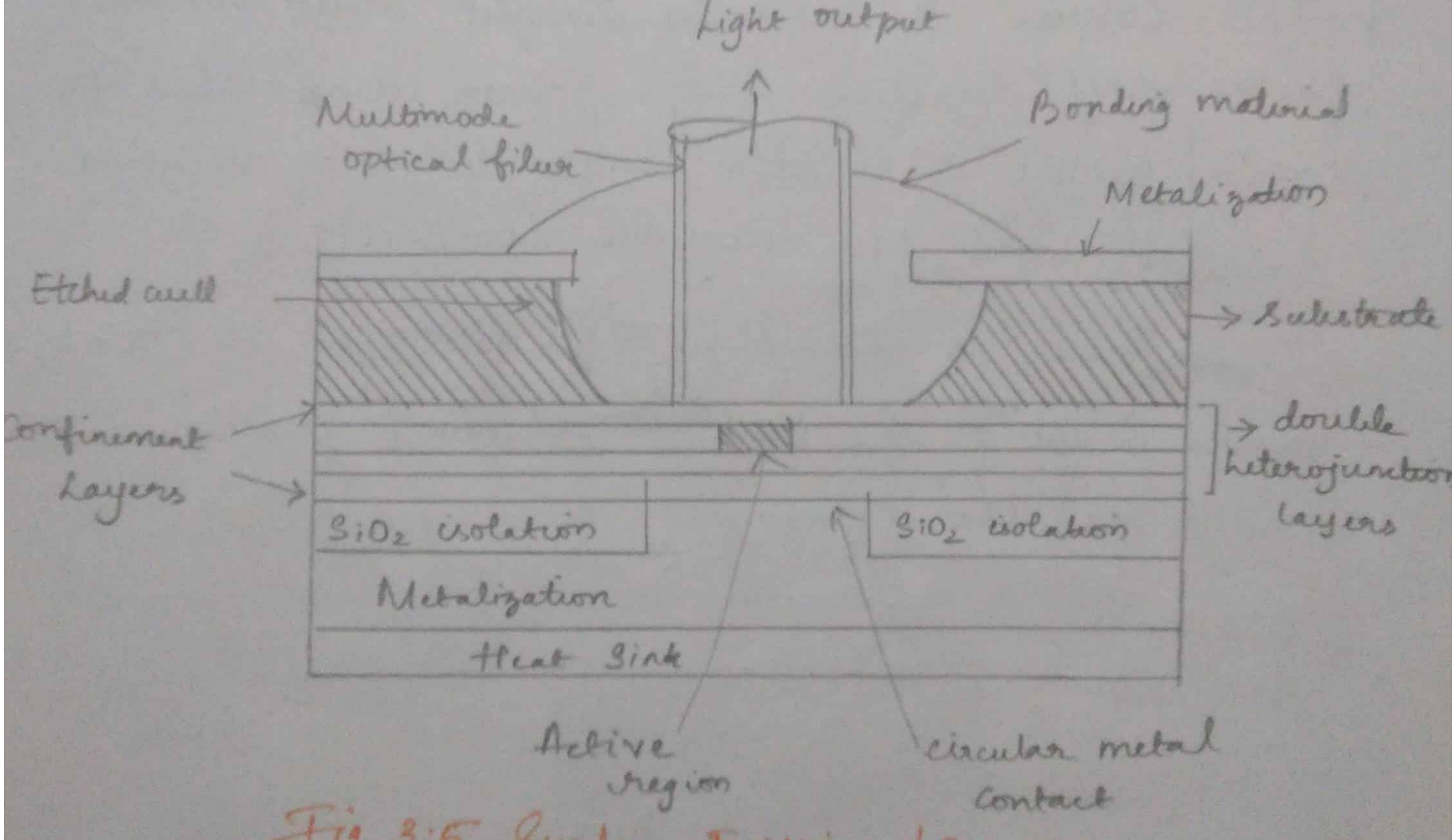


Fig 3:5 Surface Emitting LED

* The circular active area in practical surface emitters is nominally 50 µm in diameter and upto 2.5 µm thick.

– The emission pattern is isotropic with 120° half power beam width.

LAMBERTIAN PATTERN :-

* Isotropic pattern from a surface emitter is called lambertian pattern.

  - In this pattern, the source is equally bright when viewed from any direction.

  - This radiation pattern decides the coupling efficiency of LED.

* The source is equally bright when viewed from any direction but power diminishes as cos θ, where θ is the angle between viewing direction and the normal surface.

  - Power is exactly 50% down at its peak, when θ = 60°. So that total half power beam width is 120°.

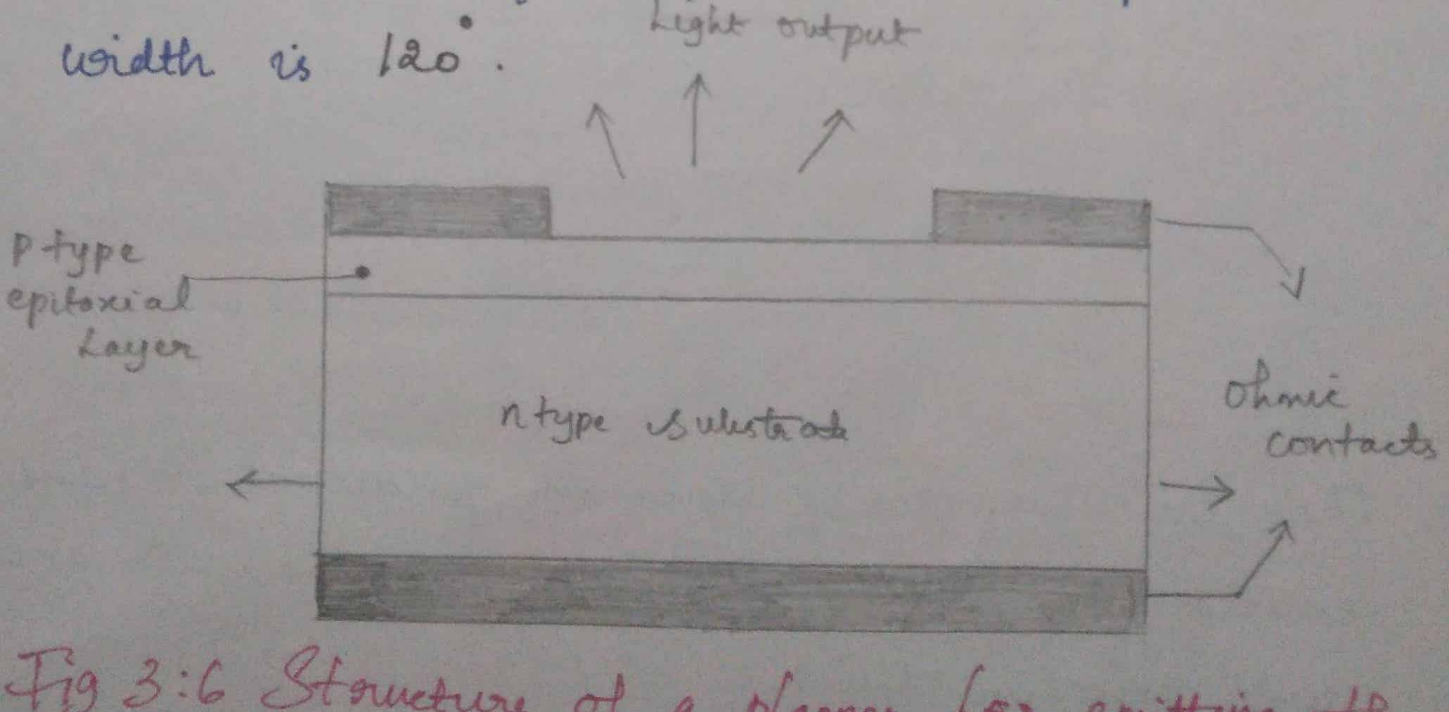


Fig 3:6 Structure of a planner LED emitting the Light from all surface

COUPLED POWER (P_c) :-

* The power coupled (P_c) from surface emitter LED into a multimode step index fiber is given as,

$$P_c = \pi(1-r) A R_D (NA)^2$$

where,

$r \rightarrow$ Fresnel reflection coefficient at fiber surface

$A \rightarrow$ Emission area of the source

$R_D \rightarrow$ Radiance of the source.

* This lambertian pattern allow more power to be coupled into the optical fiber, but they are also more difficult and expensive to manufacture.

* Lens coupling may give increased levels of optical power coupled into the fiber but it will also leads to additional complexity.

2) DH EDGE EMITTER LED (ELED's) :-

* Edge emitting LED emit more directional light pattern than the surface emitting LED.

* In order to reduce the losses caused by an absorption in the active layer and to make the beam more directional, the light is collected from the edge of LED.

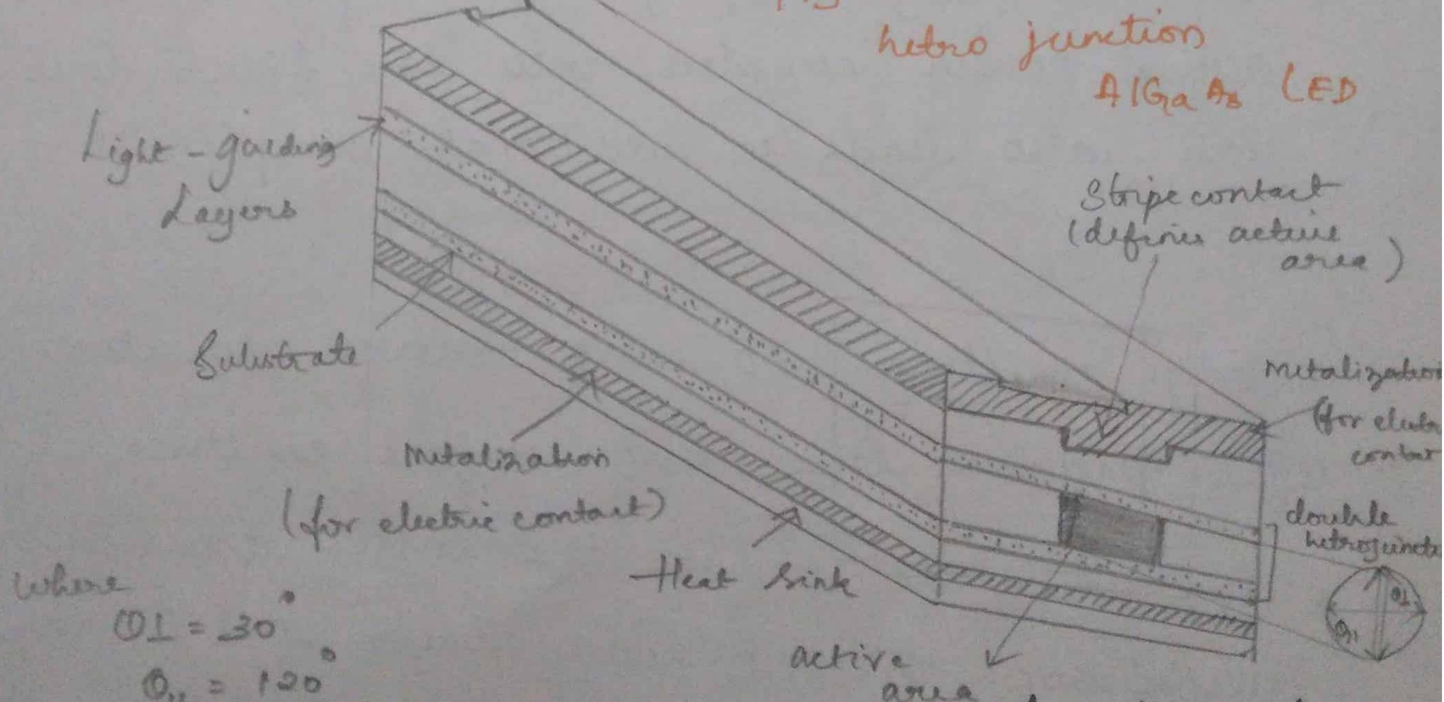
Such device is known as Edge emitting LED or ELED.

* The edge emitting LED has transparent guiding layers with very thin active layer of about 50 to 100 μm in order that the light produced in the active layer spreads into the transparent guiding layers, thereby reducing self absorption in the active layer.

* The guiding layer have refractive indices lower than the active region but higher than the outer surrounding material.

  — Surrounding guiding layers are like the core and cladding of the fiber.

Fig 3:7 Edge Emitting double hetro junction AlGaAs LED



* This structure forms a waveguide channel that directs the optical radiation towards the fiber core.

* To match the typical fiber-core diameter (50 – 100 µm) the contact stripes for the edge emitter are (50 – 70 µm) wide.
* In the plane parallel to the junction, where there is no waveguide effect, the emitted beam is lambertian with half power width of $\theta_{\parallel} = 120^\circ$ (Horizontal).
* In the plane highly directionally perpendicular to the junction, when the half power beam width $\theta_{\perp}$ is ranging from 25° to 35° by a proper choice of waveguide thickness.

ADVANTAGES :-

1) Edge emitters have a substantially better modulation bandwidth of the order of hundred megahertz, than comparable surface-emitting structures with the same drive level.
2) Coupling loses with surface emitters are greater and they have narrow bandwidth.
3) An edge emitter couples 7.5 times more power into the low NA fiber than a comparable surface emitter.

5.3 LIGHT SOURCE MATERIAL :-

* The semiconductor material that is used for the active layer of an optical source must have a direct band gap.

* In a direct band gap semiconductor, electrons and holes can recombine directly across the band gap without needing third particle to conserve momentum.

* In these material, the optical radiation is sufficiently high.

  - These materials are compound of a group $\overline{III}$ element (Al, Ga or In) and a group $\overline{V}$ element (P, As, Sb)

* Various ternary and quaternary combinations of binary compounds of $\overline{III}$ & $\overline{V}$ group elements are also direct gap materials and suitable for optical sources.

* For 800 – 900 nm spectrum, the ternary alloy $Ga_{1-x}Al_xAs$ is used.

  - The ratio x of aluminum arsenide to gallium arsenide determines the band gap of the alloy and correspondingly, the wavelength of the peak emitted radiation.

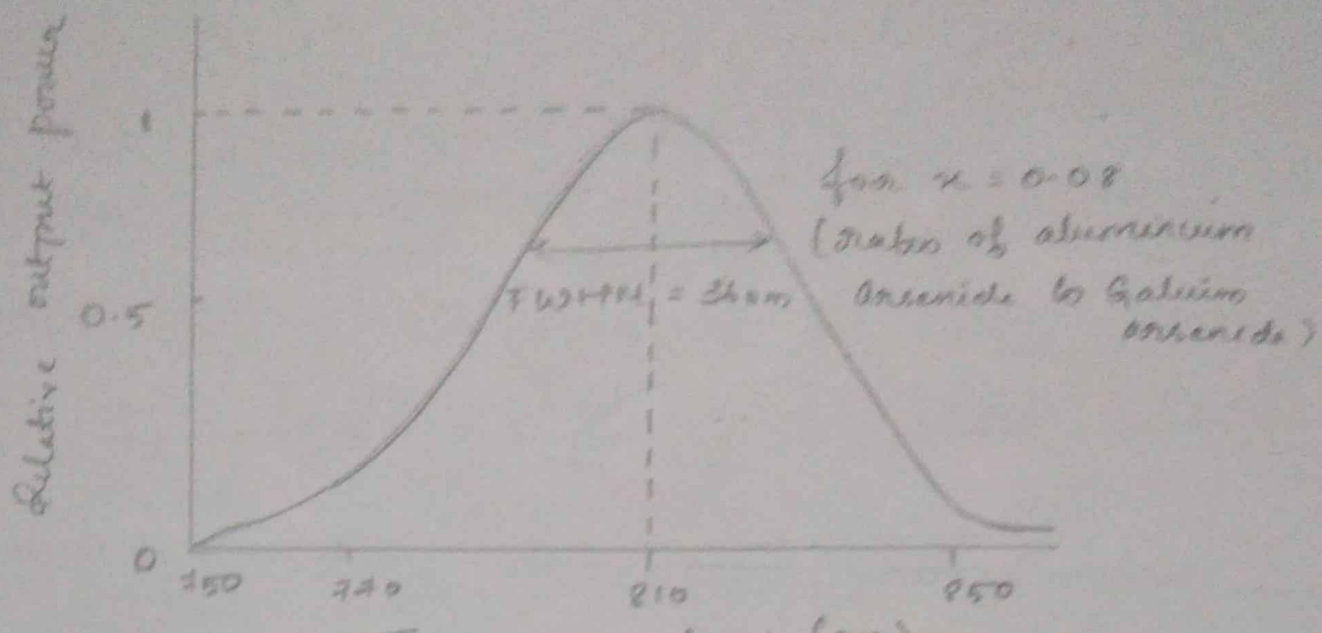


Fig 3:8 Spectral emission of $Ga_{1-x} Al_x As$ LED

* The value of x for the active area material is usually chosen to give an emission wavelength of about 800 – 850 nm.
* In the above fig $x = 0.08$. The width of the spectral pattern at its half power point is 36 nm and the peak output power is obtained at 810 nm.

FULL WIDTH HALF MAXIMUM (FWHM):

* The width of the spectral pattern at its half power point is known as full-width half maximum (FWHM) spectral width.
  - For the given LED FWHM is 36 nm.
* Using the fundamental quantum mechanical relationship between energy E and frequency ν.

The relation between E & V is expressed as,

$$E = h\nu \quad \text{——— (1)}$$

$$E = h\frac{c}{\lambda} \qquad \text{where } c = \nu\lambda$$

$$\nu = \frac{c}{\lambda}$$

$$\lambda = \frac{hc}{E} \quad \text{——— (2)}$$

where energy (E) is in joules and wavelength (λ) in meters.

* The peak emission wavelength λ (micrometer) can be expressed as a function of the band gap energy E_g in electron volts,

$$\lambda(\mu m) = \frac{1.240}{E_g(eV)} \quad \text{——— (3)}$$

* Different materials and alloy have different band gap energies.

— The band gap energy (E_g) can be controlled by two compositional parameters x & y within direct band gap region.

* Energy gap in electron volts for values of x between zero & 0.37 can be found from the empirical eq,

$$E_g = 1.424 + 1.266x + 0.266x^2 \quad \text{——— (4)}$$

* For the given value of E_g in electron volts, the peak emission wavelength in micrometers can be found from eq (5).

* The compositional parameters x & y follow the relationship $y \approx 2.20x$ with $0 \leq x \leq 0.47$.

* For $In_{1-x}Ga_xAs_yP_{1-y}$ compositions that are lattice matched to InP, the band gap in eV varies as,

$$E_g = 1.35 - 0.72y + 0.12y^2 \quad \text{(4)}$$

* Band-gap wavelength from 0.92 to 1.65 μm are covered by this material system.

3:4 QUANTUM EFFIENENCY AND LED POWER:

* An excess of electrons and holes in p & n type material, respectively are created in semiconductor light source by the injection of carrier at the device contacts.

* Excess carriers can recombine either radiatively or non-radiatively.

* When there is a constant current flow into LED, an equillibrium condition is established.
  — ie, excess density of electrons n and holes P are equal, then the recombination of injected

carriers is in accordance with the requirement of charge neutrality within the device.

* Total rate at which carriers are generated is the sum of the externally supplied and the thermally generated rates.

* Externally supplied rate is given by J/qd

where $J \rightarrow$ current density in A/cm^2

$q \rightarrow$ Electron charge

$d \rightarrow$ Thickness of the recombination region.

* Thermal generation rate is given by n/τ

where,

$\tau \rightarrow$ Carrier life time

$n \rightarrow$ Excess carrier density.

* Rate equation for carrier recombination in an LED is given as,

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau} \quad \text{——— (1)}$$

At equillibrium condition,

$$\frac{dn}{dt} = 0$$

$$n = \frac{J\tau}{qd} \quad \text{——— (2)}$$

* This relationship gives the steady state electron density in the active region when a constant current is flowing through it.

INTERNAL QUANTUM EFFICIENCY (η_{int}) :-

* Internal quantum efficiency in the active region is the fraction of the electron hole pairs that recombine radiatively.

* Internal quantum efficiency η_{int} is defined as the ratio of radiative recombination rate to the total recombination rate.

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}} \quad \text{--- (3)}$$

where, $R_r \rightarrow$ radiative recombination rate

$R_{nr} \rightarrow$ Non-radiative recombination rate

* Radiative recombination life time τ_r is expressed as,

$$\tau_r = \frac{n}{R_r} \quad \text{--- (4)}$$

* Non-radiative recombination life time τ_{nr} is expressed as,

$$\tau_{nr} = \frac{n}{R_{nr}} \quad \text{--- (5)}$$

eq ③ can rewrite as,

$$\eta_{int} = \frac{1}{1 + \frac{R_{nr}}{R_r}} \quad \text{——— ⑥}$$

* The bulk recombination life time τ is expressed as,

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} = \frac{\tau_{nr} + \tau_r}{\tau_{nr}\tau_r} \quad \text{——— ⑦}$$

from eq ⑦,

$$\tau = \frac{\tau_{nr}\tau_r}{\tau_{nr} + \tau_r} \Rightarrow \frac{\tau}{\tau_r} = \frac{1}{1 + \frac{\tau_r}{\tau_{nr}}} \quad \text{——— ⑧}$$

by sub eq ④ & ⑤ in eq ⑥ and using eq ⑧ we get,

$$\eta_{int} = \frac{1}{1 + \frac{n/\tau_{nr}}{n/\tau_r}}$$

$$\eta_{int} = \frac{1}{1 + \frac{\tau_r}{\tau_{nr}}} = \frac{\tau}{\tau_r} \quad \text{——— ⑨}$$

* If the current injected into the LED is I, then the total number of recombinations per second is,

$$R_r + R_{nr} = \frac{I}{q} \quad \text{——— ⑩}$$

by substituting eq ⑨ in eq ⑤, we get

(11)

$$\eta_{int} = \frac{R_r}{I/q} \quad \text{——— (11)}$$

$$R_r = \frac{\eta_{int} I}{q} \quad \text{——— (12)}$$

* 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 in LED is given as,

$$P_{int} = \eta_{int} \frac{I}{q} h\nu \quad \text{——— 13 a}$$

$$P_{int} = \eta_{int} \frac{hcI}{q\lambda} \qquad (\nu = c/\lambda) \text{ ——— 13 b}$$

* The internal quantum efficiency is about 50% for simple homo junction LED.

— However, LED having double-hetero junction structures can have quantum efficiencies of 60-80%.

EXTERNAL QUANTUM EFFIENCY (η_{EXT}) :-

* The external quantum efficiency is used to find the emitted power of the optical source.

* The external quantum efficiency η_{ext} is defined as ratio of photons emitted from LED to the

number of photons generated internally.

$$= \frac{\text{Total number of output photons}}{\text{Total number of internal photons}}$$

* The external quantum efficiency is given as,

$$\eta_{ext} = \frac{1}{4\pi} \int_0^{\phi_c} T(\phi)\,(2\pi \sin\phi)\, d\phi \quad \text{——— (14)}$$

where,

critical angle $\phi_c = \frac{\pi}{2} - \theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$ ——— (15)

$T(\phi) \rightarrow$ fresnel transmission coefficient or fresnel transmissivity.

* $T(\phi)$ depends on the incidence angle ϕ,

when $\phi = 0$, then

$$T(0) = \frac{4 n_1 n_2}{(n_1 + n_2)^2} \quad \text{——— (16)}$$

Let us consider $n_1 = n$ & $n_2 = 1$ (outside medium is air).

—Then $T(0)$ can be written as,

$$T(0) = \frac{4n}{(n+1)^2} \quad \text{——— (17)}$$

$$\eta_{ext} = \frac{1}{4\pi} \int_0^{\phi_c} T(\phi)\, 2\pi \sin\phi\, (d\phi)$$

$$= \frac{2\pi}{4\pi} \frac{4n}{(1+n)^2} \int_0^{\phi_c} \sin\phi\, (d\phi)$$

$$\eta_{ext} = \frac{2n}{(1+n)^2}(-\cos\phi_c + 1)$$

$$\eta_{ext} = \frac{2n}{(1+n)^2}(1 - \cos\phi_c) \quad \text{———} \quad (17)$$

By substituting eq (15) in eq (17), we get

$$\eta_{ext} = \frac{2n}{(1+n)^2}\left(1 - \cos\left(\frac{\pi}{2} - \theta_c\right)\right)$$

$$= \frac{2n}{(1+n)^2}(1 - \sin\theta_c)$$

$$= \frac{2n}{(1+n)^2}\left(1 - \sin\left(\sin^{-1}\frac{n_2}{n_1}\right)\right)$$

$$\because \phi_c = \frac{\pi}{2} - \theta_c$$

$$= \frac{2n}{(1+n)^2}\left(1 - \frac{n_2}{n_1}\right)$$

$$\theta_c = \frac{\pi}{2} - \phi_c$$

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

$$= \frac{2n}{(1+n)^2}\left(\frac{n_1 - n_2}{n_1}\right)$$

$$\eta_{ext} = \frac{2n}{(1+n)^2}\left(\frac{n_1 - n_2}{n_1}\right)\frac{n_2}{n_2} \quad \text{———} \quad (18)$$

Consider $n = n_1 n_2$ and $n_2 = 1.0$, so $n = n_1$

$$\eta_{ext} = \frac{2n(n_1 n_2 - n_2^2)}{(1+n)^2 n}$$

Consider, $n(n_1 n_2 - n_2^2) = \frac{1}{2}$

$$\eta_{ext} = \frac{1}{n(n+1)^2} \quad \text{——— (19)}$$

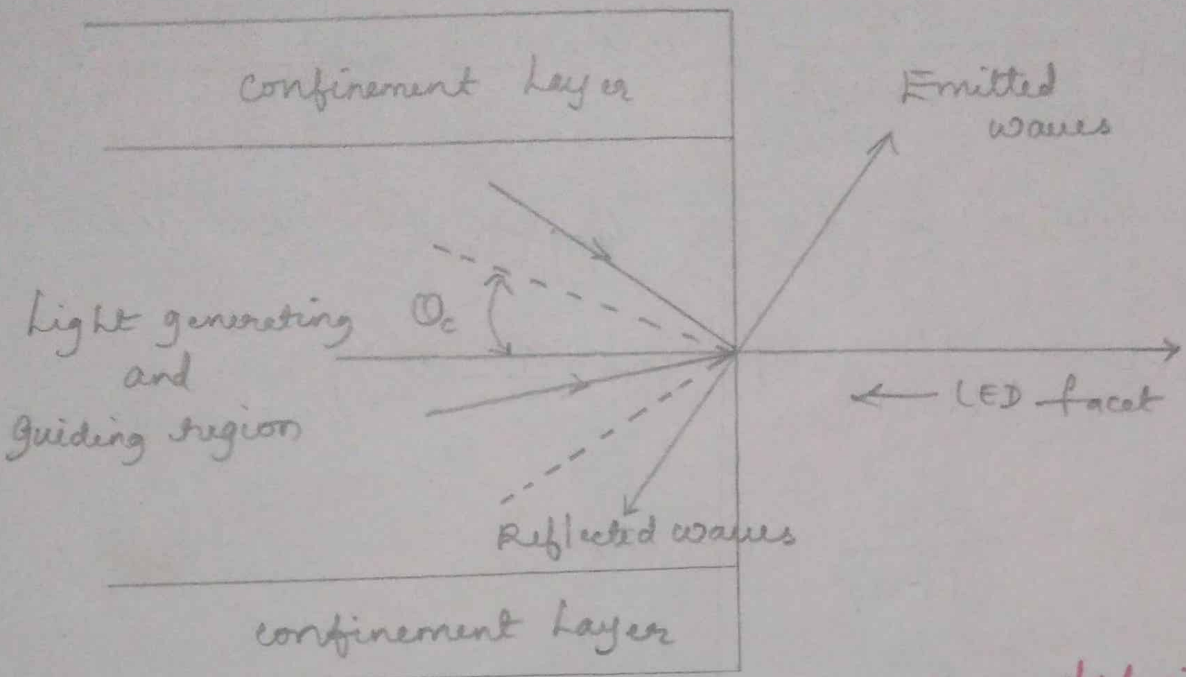


fig 3:9 Only light falling within a cone defined by the critical angle will be emitted from an optical source

LED POWER :-

* The optical power (p) emitted from LED is defined as,

$$P = \eta_{ext} \cdot P_{int} \quad \text{——— (20)}$$

by substituting eq (13 b) & (19) in eq (20) we get

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

$$P = \frac{\eta_{int}\, h c I}{q \lambda n(n+1)^2}$$

3.5 MODULATION OF LED :-

* Three factors are used to determine the frequency response of LED.

i) Doping level in the active region
ii) Injected carrier life time τ_i in the recombination region
iii) Parasitic capacitance of LED.

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

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

where, P_0 → Power emitted at zero modulation frequency.

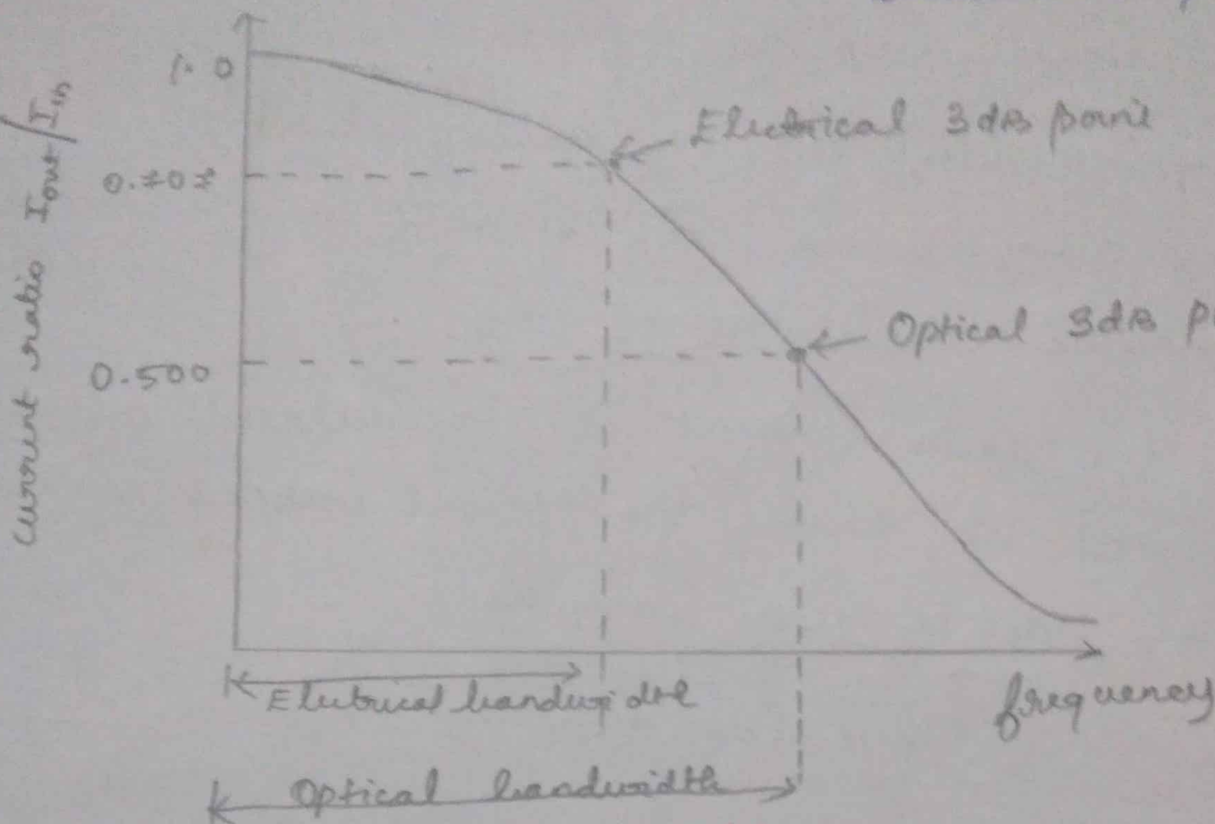
* Parasitic capacitance can cause a delay of the carrier injection into the active junction due to this optical output.

—This delay is negligible when a small constant forward bias is applied to the diode

—During this condition, eq ① becomes Valid and also the modulation response is limited only by the carrier recombination time.

COMPARISON BETWEEN OPTICAL & ELECTRICAL BANDWIDTH :-

Fig 3:10 Frequency response of an optical source showing the electrical and optical 3dB bandwidth point.



1) ELECTRICAL BANDWIDTH :-

* Modulation bandwidth of the LED is defined in electrical as, where the electrical signal power has dropped to half of its constant value resulting from the modulated portion of the optical signal.

—This gives the electrical 3-dB point.

* Electrical 3-dB point is nothing but, the frequency at which the output electrical power is reduced by 3dB with respect to the input electrical power.

(14)

* An electrical bandwidth (EB_{dB}) is defined as the ratio of the electrical output power to the electrical input power in decibels & it is given as,

$$EB_{dB} = 10 \log 10 \frac{\text{Electrical power out (at the detector)}}{\text{Electrical power in (at the source)}}$$

(Or)

$$EB_{dB} = 10 \log_{10} \frac{\text{output electrical power at frequency } (\omega)}{\text{Electrical power at Zero modulation}}$$

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

$$= 10 \log_{10} \frac{I^2(\omega)/R_{out}}{I^2(\omega)/R_{in}} \quad \text{——— (2)}$$

* consider that the input resistance and output resistance are equal, ie $R_{in} = R_{out} = R$

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

* Electrical 3 dB points occur when,

$$\left(\frac{I(\omega)}{I(0)}\right)^2 = \frac{1}{2}$$

$$\frac{I(\omega)}{I(0)} = \frac{1}{\sqrt{2}} = 0.707 \quad \text{——— (3)}$$

* Thus, the electrical bandwidth may be defined as the frequency when the output current has dropped to $1/\sqrt{2}$ or 0.707 of the input current to the system.

2) OPTICAL BANDWIDTH:-

* The optical bandwidth (OB_{dB}) is defined as, the ratio of the optical output power to the optical input power in decibels & given as,

$$OB_{dB} = 10 \log_{10} \frac{\text{Optical power output (received at detector)}}{\text{Optical power input (transmitted at source)}}$$

(Or)

$$OB_{dB} = 10 \log_{10} \frac{\text{Optical power at frequency } (\omega)}{\text{Unmodulated value of the optical power}}$$

$$OB_{dB} = 10 \log_{10} \frac{I(\omega)}{I(0)}$$

* Hence, the optical 3dB points occur when the ratio of currents is equal to 1/2

$$\frac{I(\omega)}{I(0)} = \frac{1}{2} = 0.5 \quad \text{——— (4)}$$

* Therefore the optical bandwidth is defined as the frequencies at which the output current has dropped to 1/2 or 0.5 of the input current to the system.

—This corresponds to an electrical power attenuation of 6 dB.

3:6 LASER DIODES:-

* LASER is an acronym for Light Amplification by stimulated Emission of Radiation.
* Ideal laser light has single-wavelength only.

—This is related to the molecular characteristics of the material being used in the laser.

—It is formed in parallel beams and in single phase. ie it is coherent.

PRINCIPLE OF OPERATION:-

* Three key processes are,

i) photon absorption

ii) Spontaneous emission

iii) stimulated emission.

* These processes are represented by the simple two energy level diagrams. where,

$E_1 \longrightarrow$ lower energy state level

$E_2 \longrightarrow$ higher energy state level

PHOTON ABSORPTION :-

* When photon with an energy $E_2 - E_1$ is incident on an atom.

— An atom is intially in the state E_1 get excited into the higher energy state E_2 through the absorption of photon.

— This process is sometimes referred to as stimulated absorption.

Incident photon energy $E = E_2 - E_1 \rightarrow h\nu$

where, $h = 6.626 \times 10^{-34}$ Js is plank's constant

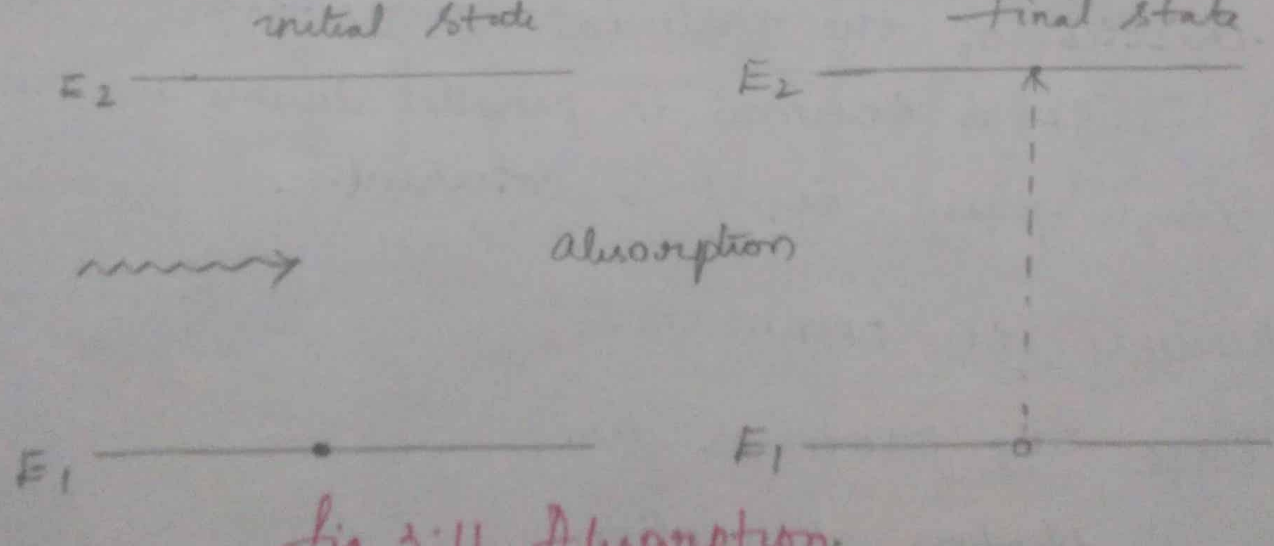


fig 3:11 Absorption.

* When an atom is at the higher energy state E_2 it can make a transition to lower energy state E_1 and thus the emission of photon takes place. This emission process can occur in 2 ways,

a) Spontaneous emission

b) Stimulated emission.

a) SPONTANEOUS EMISSION :-

* Spontaneous emission occur when an atom in higher energy state level (E_2) returns to the lower energy state in a random manner.

  - It gives an incoherent radiation.

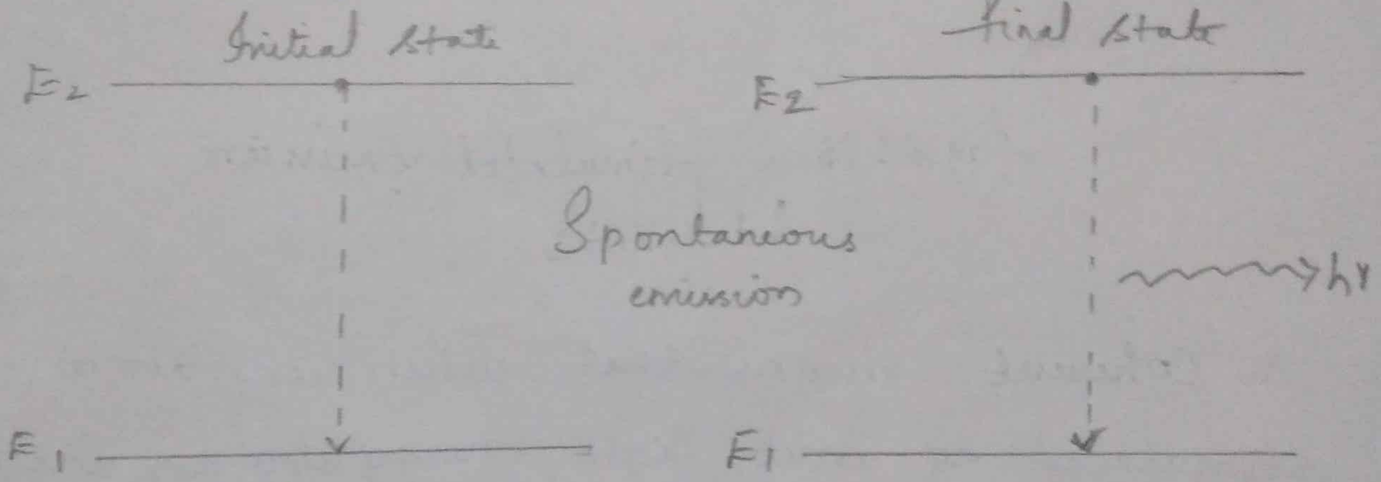


fig 3:12 Spontaneous Emission

b) STIMULATED EMISSION :-

* Stimulated emission is one which occurs, when a photon having an equal energy to the difference between the two states ($E_2 - E_1$) interacts with the atom causing it to the lower state with the creation of the second (emitted photon).

  - It gives the coherent radiation.

* The light associated with an emitted photon

of same frequency of the incident photon and in same phase with same polarization.

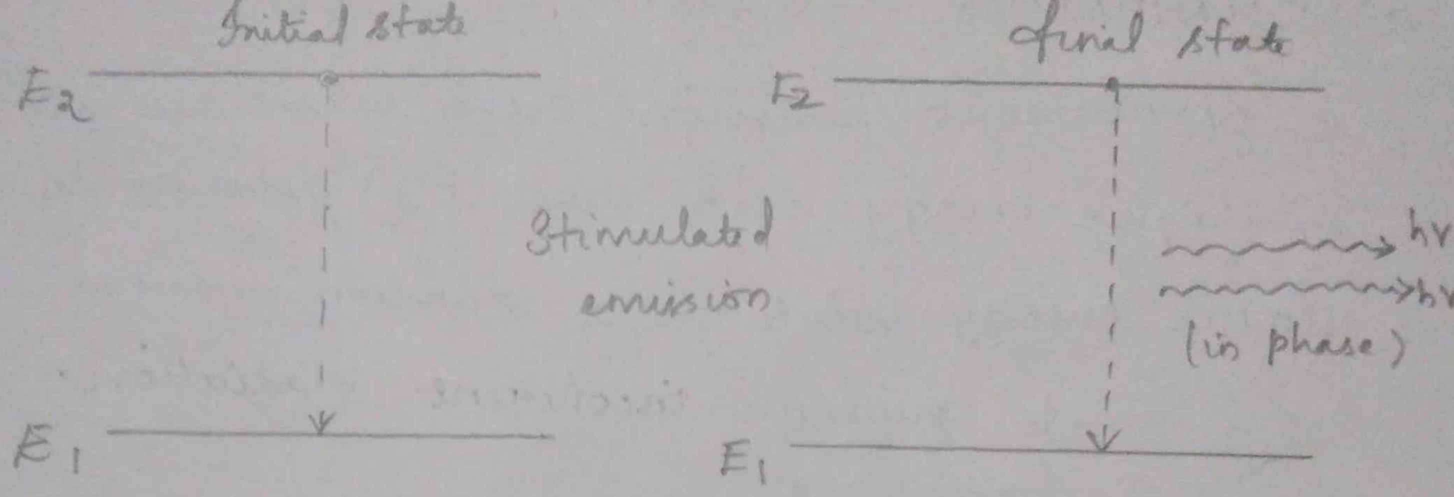


fig 3:13 Stimulated Emission

* Coherent means that, when an atom is stimulated to emit light energy by an incident wave, the liberated energy can be added to the wave in constructive manner and provides amplification.

POPULATION INVERSION :-

* At the thermal equilibrium the density of excited electrons is very small.

  - Most photons incident on the system will be absorbed, so the stimulated emission is essentially negligible.

(17)

— Stimulated emission will exceed absorption only if the population of the excited states is greater than that of the ground state.

— This condition is known as population inversion.

* At non-equilibrium condition, the population inversion can be acheived by various pumping techniques.

ADVANTAGES & DISADVANTAGES OF LASER :-

ADVANTAGES :-

1) Laser diode emit coherent light, whereas LED's emit incoherent light.

- Therefore, laser have a more direct radian pattern, which makes it easier to couple limit emitted by the laser diode into an optical fiber cable.

— This reduces the coupling losses and allows smaller fibers to be used.

ii) The radiant output power from laser is greater than that for an LED.

— A typical output power lasers to provide a higher drive power and to be used for systems that operate over longer distances.

iii) Lasers can be used at higher bit rates than LED.

iv) Lasers generate monochramatic light which reduces chromatic or wavelength dispersion.

v) Good spatial coherence which allows the output to be focused by a lens into a spot which has a greater intensity than dispered unfocused emission.

DISADVANTAGES :-

i) LASER's are typically 10-times more expensive than LED.

ii) Laser's operate at higher power, they typically have a much shorter lifetime than LED.

iii) Laser's are more temperature dependent than LED.

5:7 MODES AND THRESHOLD CONDITIONS :-

i) MODES OF THE CAVITY :

* The optical radiation within the resonance cavity of a laser diode sets up a pattern of both electric and magnetic field lines is called the modes of the cavity.
* Two modes are available in the optical cavity. They are,
  - i) Transverse Electric (TE) modes
  - ii) Transverse Magnetic (TM) modes.
* Each set of modes can be described in terms of longitudinal, lateral and transverse half sinusoi-dal variations of the electromagnetic fields along the major axes of the cavity and it is shown below, fig

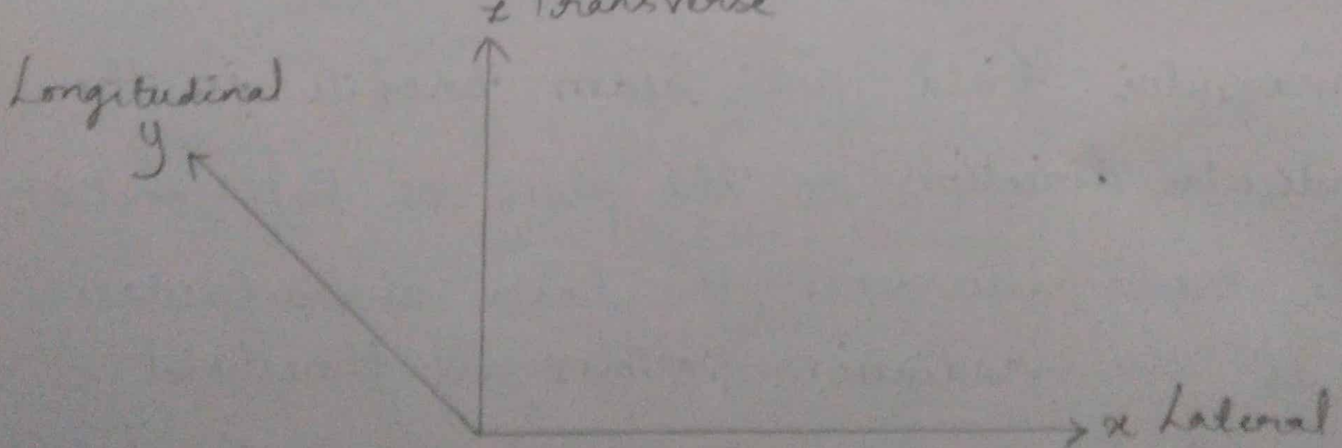


Fig 3:14

LONGITUDINAL MODES :-

* The longitudinal modes are related to the length L of the cavity and it determines 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 may longitudinal modes can exit.

LATERAL MODES :

* Lateral modes lie in the plane of p-n junction
  – These modes depend on the side wall preparation and width of the cavity and it determines the shape of lateral profile of the laser beam.

TRANSVERSE MODES :-

* Transverse modes are associated with the electromagnetic field and beam profile in the perpendicular direction to the plane of P-n junction
* These modes determines the laser characteristics such as the radiation pattern and threshold current density ie, the point at which the lasing starts.

2) THRESHOLD CONDITIONS :-

* To determine the lasing conditions and the resonant frequencies, the electromagnetic wave propogating in the longitudinal direction is expressed as,

$$E(z,t) = I(z)\,e^{j(\omega t - \beta z)} \quad \text{—— (1)}$$

where,

$I(z) \rightarrow$ Optical field intensity
$\omega \rightarrow$ Optical radian frequency
$\beta \rightarrow$ propogation constant

LASING :-

* Lasing is the condition at which light amplification becomes possible in the laser diode.
  - The condition for lasing is that a population inversion can be acheived.

* The stimulated emission rate for a particular mode is proportional to the intensity of the radiation in that mode.

* The radiation intensity at a photon energy $h\nu$ varies exponentially with the distance z, ie it transverse along the lasing cavity according to the relationship as,

$$I(z) = I(0)\exp\left\{(\Gamma g(h\nu) - \bar{\alpha}(h\nu)x)\right\} \quad \text{--- (2)}$$

where,

$\bar{\alpha}$ → Effective absorption coefficient of the material in the optical path

Γ → Optical field confinement factor or fraction of optical power in the active layer.

g → Gain coefficient

$h\nu$ → Photon energy

z → Distance travels along the lasing cavity.

* Lasing occurs when the gain of guided modes exceeds above an optical loss during one round trip through the cavity i.e, $z = 2L$

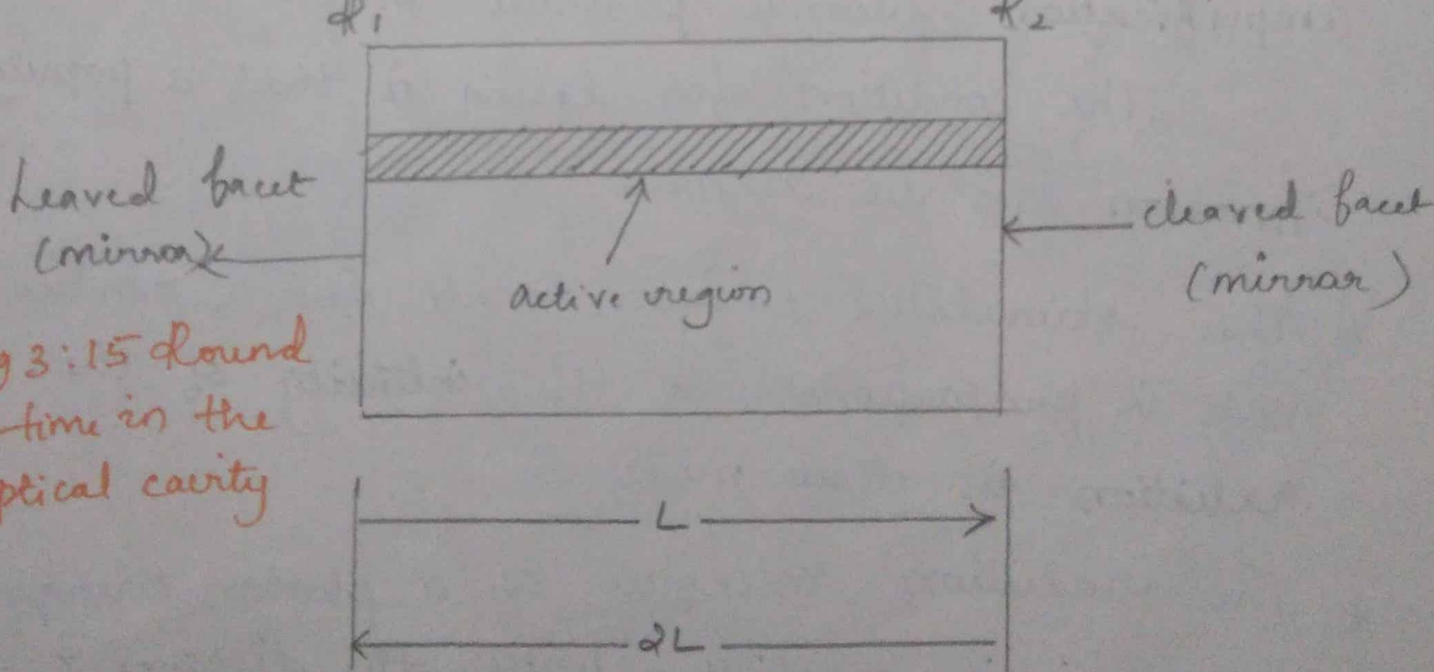


fig 3:15 Round trip-time in the optical cavity

* During this roundtrip, only the fractions R_1 and R_2 of the optical radiation are the reflected

from the two laser ends 1 and 2, respectively where R_1 + R_2 are the mirror reflectivities Or fresnel reflection coefficient, which are given as,

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \quad \text{—— (3)}$$

Now the expression (2) for lasing is modified as expressed in eq (4) as,

$$I(2L) = I(0)\, R_1 R_2 \exp\{2L(\Gamma g(h\nu) - \bar{a}(h\nu))\} \quad \text{—— (4)}$$

LASING CONDITON :-

* At the lasing threshold, a steady-state osillation take place, and the magnitude and phase of the returned wave must be equal to those of the original wave.

* The conditions of lasing threshold is then given as,

i) for amplitude : $I(2L) = I(0)$ —— 5a

ii) for phase : $e^{-j2\beta L} = I$ —— 5b

eq 5b gives information concerning the resonant frequencies of the fabry perot cavity.

* The condition to just reach the lasing threshold is the point at which the optical gain is equal to the total loss a_1 in the cavity

optical gain at threshold = Total loss in the cavity (a_1)

* from eq 5a, the above condition are expressed as,

$$\Gamma g_{th} = a_1 = \bar{a} + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right) \quad \text{—— 6a}$$

$$\Gamma g_{th} = \bar{a} + a_{end} \quad \text{—— 6b}$$

where, $a_{end} \rightarrow$ mirror loss in the lasing cavity

* An important condition for lasing to occur is that gain $g \geq g_{th}$ ie threshold gain

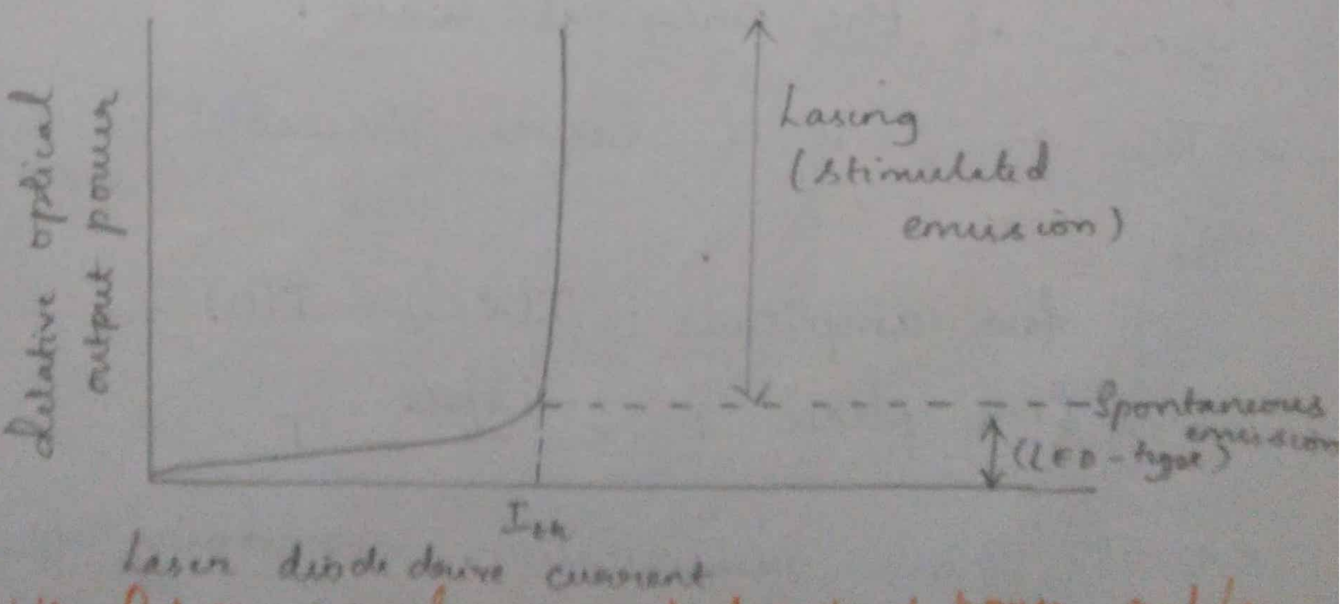


fig 3:16 Relationship between optical output power and Laser diode drive current

* From the above fig 3:16 it is clear that

below the threshold current (I_{th}) where (21)
only spontaneous emission occurs, and there is
a small increase in optical output power with
drive current.

* At this threshold when lasing conditions
are satisfied, the optical power increases
sharply after the lasing threshold because
of stimulated emission.

* The lasing threshold optical gain (g_{th}) is
related to the threshold current density (J_{th})
for stimulated emission and this expression is
given as,

$$g_{th} = \beta J_{th} \quad \text{——— (7)}$$

where, $\beta \rightarrow$ constant that depends on the
specific device constructions.

* The threshold current density (J_{th}) is given
by,

$$J_{th} = \frac{1}{\beta}\left[\bar{\alpha} + \frac{1}{2L} \ln \frac{1}{R_1 R_2}\right] \quad \text{——— (8)}$$

5.8 RATE EQUATIONS :-

* The relationship between an 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 pn junction with carrier confinement region of depth d, the rate equations are given as,

i) In terms of number of photons ϕ as,

$$\frac{d\phi}{dt} = Cn\phi + R_{sp} - \frac{\phi}{\tau_{ph}} \ m^{-3} s^{-1} \quad (1)$$

= Stimulated emission + Spontaneous emission + photons loss

ii) In terms of number of electrons (n) as

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\phi \ m^{-3} s^{-1}$$

= injection + Spontaneous recombination + Stimulated emission.

where,

$C \rightarrow$ coefficient describing the strength of the optical absorption and emission interactions.

$R_{sp} \rightarrow$ rate of spontaneous emission into the lasing diode

$\tau_{ph} \rightarrow$ photon lifetime

$\tau_s \rightarrow$ spontaneous recombination lifetime

$J \rightarrow$ injection current density.

* Solving eq (1) & (2), for steady state conditions that is $\frac{d\phi}{dt} = 0$ $\frac{dn}{dt} = 0$, where n & ϕ have non zero values.

* In eq (1), assume R_{sp} is negligible and $\frac{d\phi}{dt}$ must be positive when ϕ is small, then we have

$$Cn - \frac{1}{\tau_{ph}} \geq 0 \qquad (3)$$

* from eq (3) it is clear that n, must exceed threshold value n_{th} in order for ϕ to increase and the threshold value for the electron density n_{th} from eq (3) by substituting $n = n_{th}$ in the steady state and it can be expressed as,

$$n_{th} = \frac{1}{c\tau_{ph}} \quad (m^{-3}) \qquad \text{---} \quad (4)$$

* from eq (21), the above threshold value (n_{th}^{t}) can be expressed in terms of the threshold current J_{th}, when the number of photons, $\phi = 0$ as,

$$\frac{J_{th}}{qd} - \frac{n_{th}}{\tau_{sp}} = 0$$

$$\frac{n_{th}}{\tau_{sp}} = \frac{J_{th}}{qd} \quad m^{-3} s^{-1} \qquad \text{---} \quad (5)$$

* This eq (5) gives the current required to sustain an excess electron density in the laser when spontaneous emission is the only decay mechanisms.

* Consider the photon & electron rate equations in the steady-state condition at lasing threshold is given as,

$$C n_{th} \phi_s + R_{sp} - \frac{\phi_s}{\tau_{ph}} = 0 \qquad \text{---} \quad (6)$$

$$\frac{J}{qd} - \frac{n_{th}}{\tau_{sp}} - C n_{th} \phi_s = 0 \qquad \text{---} \quad (7)$$

where, $\phi_s \longrightarrow$ steady state photon density

STEADY STATE PHOTON DENSITY (ϕ_s) :-

* Adding eq ⑥ & ⑦,

$$C n_{th} \phi_s + R_{sp} - \frac{\phi_s}{\tau_{ph}} + \frac{J}{qd} - \frac{n_{th}}{\tau_{sp}} - C n_{th} \phi_s = 0 \quad \text{——— ⑧}$$

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

$$\phi_s = \frac{\tau_{ph}}{qd}(J - J_{th}) + \tau_{ph} R_{sp} \quad \text{——— ⑨}$$

$$\phi_s = \left\{ \begin{array}{c} \text{Number of photons} \\ \text{resulting from} \\ \text{Stimulated emission} \end{array} \right\} + \left\{ \begin{array}{c} \text{Spontaneously} \\ \text{Generated} \\ \text{photons} \end{array} \right\}$$

5:9 EXTERNAL QUANTUM EFFICIENCY (η_{ext}) :-

* The external differential quantum efficiency η_{ext} is defined as, the number of photons emitted per radiactive electron - hole pair recombination above the threshold level.

- The external quantum η_{ext} is given by,

$$\eta_{ext} = \frac{\eta_i (g_{th} - \overline{\alpha})}{g_{th}} \quad \text{——— ⑩}$$

where,

$\eta_i \rightarrow$ Internal quantum efficiency (0.6 – 0.7)

$g_{th} \rightarrow$ Threshold gain

$\overline{\alpha} \rightarrow$ Absorption coefficient.

* η_{ext} is calculated from the straight line portion of the curve for the emitted optical power P versus drive current I, which is given by,

$$\eta_{ext} = \frac{q}{E_g} \frac{dP}{dI} \quad \text{—— (2)}$$

$$= 0.8065 \lambda(\mu m) \frac{dP(mW)}{dI(mA)}$$

where,

$E_g \rightarrow$ Band gap energy in eV

$dP \rightarrow$ Incremental change in the emitted optical power (mW)

$dI \rightarrow$ Incremental change in the drive current (mA)

$\lambda \rightarrow$ Emission wavelength (micrometers)

* Typical value of η_{ext} for standard semi-conductor laser is ranging between 15-20%.
  - The high quality devices have differential quantum efficiencies of 30 – 40%.

3:10 RESONANT FREQUENCIES :-

* To check the resonant frequencies of the laser, use the lasing threshold equation as,

$$e^{-j2\beta l} = 1 \quad \text{—— (1)}$$

This condition holds when

$$2\beta L = 2\pi m \quad \text{—— (2)}$$

where, $m \rightarrow$ integer.

we know that,

powpogation constant,

$$\beta = \frac{2\pi n}{\lambda} \quad \text{——— (3)}$$

from eq (2)

$$m = \frac{\beta L}{\pi} \quad \text{——— (4)}$$

* By substituting eq (3) in eq (4)

$$m = \frac{L}{\lambda / 2n} \quad \text{——— (5)}$$

$$c = v\lambda \Rightarrow \lambda = \frac{c}{v} \quad \text{——— (6)}$$

By substituting eq (6) in eq (5) we get,

$$m = 2L \frac{nv}{c} \quad \text{——— (7)}$$

* The above eq states that, the cavity resonates when an integer number m of half-wavelength spans the region between the mirrors.

* The gain is a function of frequency or wavelength
 - Each of these frequencies corresponds to a mode of oscillation of the laser.
 - The relationship between gain and frequency can be assumed to have Gaussian form

$$g(\lambda) = g(0)\exp\left(-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}\right) \quad \text{——— (8)}$$

where,

$g(0) \rightarrow$ maximum gain which is proportional to the population inversion

$\sigma \rightarrow$ Spectral width of the gain

$\lambda_0 \rightarrow$ Wavelength at the center of the Spectrum.

* Consider the frequency or wavelength, Spacing between the modes of a multimode laser.
  - We consider only the longitudinal modes.

* For each longitudinal mode, there may be several transverse mode that arise from one or more reflections of the propogating wave at the sides of the resonator cavity.

* To find the frequency Spacing, consider two successive modes of frequencies V_{m-1} and V_m represented by the integers $m-1$ & m

from eq (7), we have

$$m-1 = \frac{2Ln}{c} V_{m-1} \quad \text{——— (9)}$$

$$m = \frac{2Ln}{c} V_m \quad \text{——— (10)}$$

By substracting eq (9) & (10) we will get,

$$m-(m-1) = \frac{2Ln}{c} V_m - \frac{2Ln}{c} V_{m-1}$$

$$1 = \frac{2Ln}{c} (V_m - V_{m-1})$$

$$1 = \frac{2Ln}{c} \Delta\nu$$

the frequency spacing

$$\Delta\nu = \frac{c'}{2Ln} \quad \text{——— (11)}$$

$$\frac{\Delta\nu}{\nu} = \frac{\Delta\lambda}{\lambda}$$

$$\Delta\lambda = \frac{\Delta\nu\,\lambda}{\nu} \quad \text{——— (12)}$$

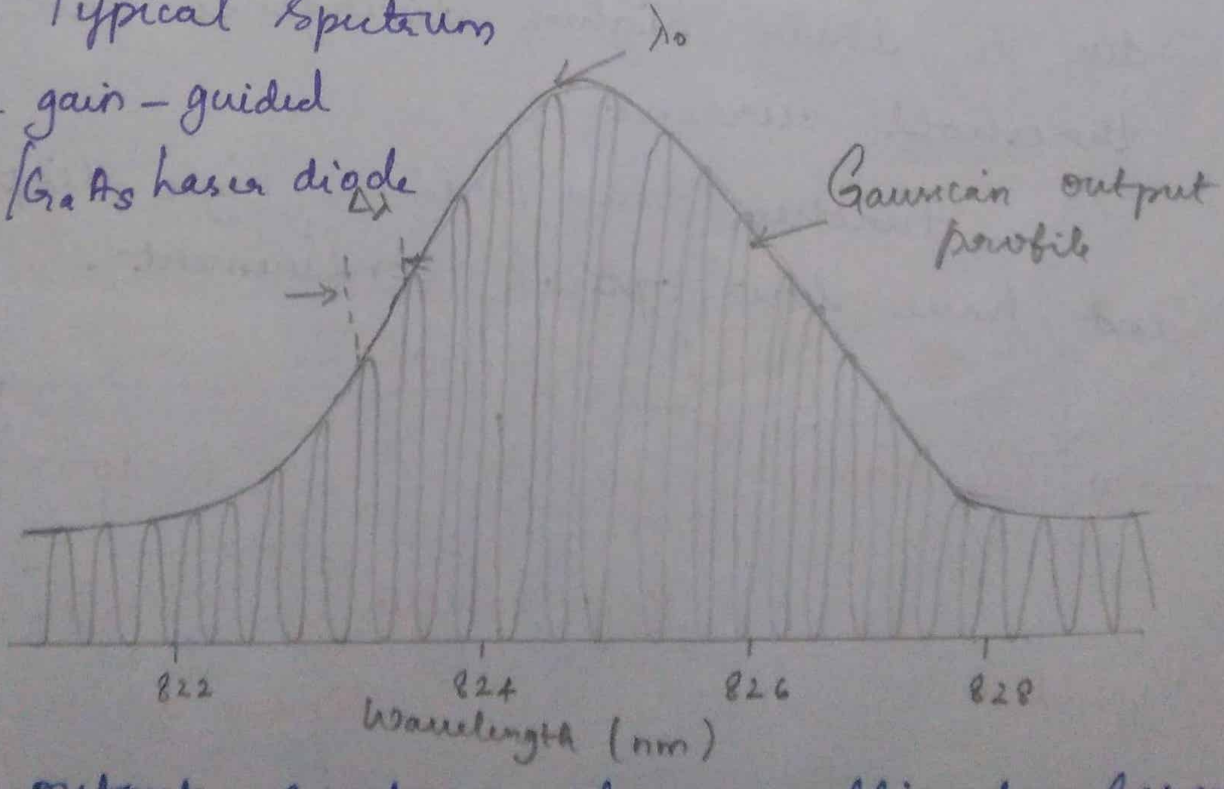
$$c = \lambda\nu \Rightarrow \nu = \frac{c}{\lambda}$$

By substituting eq (11) & (13) in eq (12), we obtain

$$\Delta\lambda = \frac{(c/2Ln)\,\lambda}{c/\lambda}$$

$$\Delta\lambda = \frac{\lambda^2}{2Ln} \quad \text{——— (14)}$$

fig 3:17 Typical Spectrum from a gain-guided GaAlAs/GaAs laser diode



* The output spectrum of a multimode laser

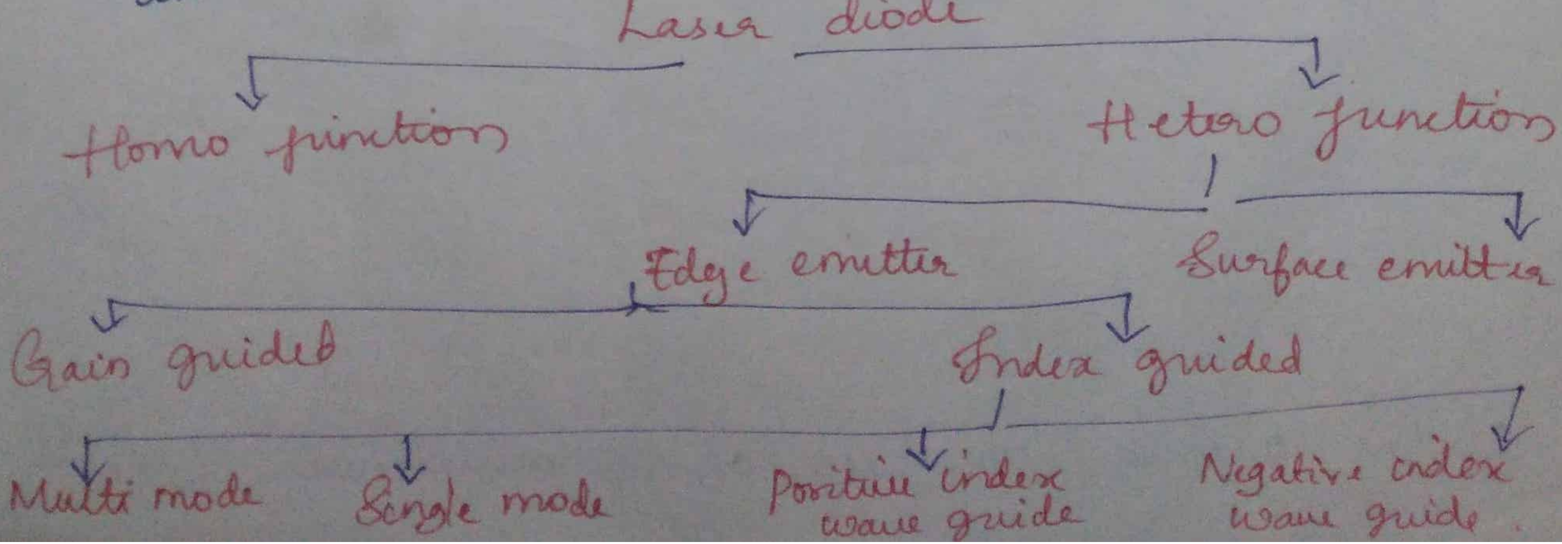
follows the typical gain-versus-frequency plot as given in fig 3: where the exact number of modes, their heights & their spacing depends on the laser construction.

3:11 LASER DIODE STRUCTURES :- AND RADIATION PATTERN

Various classification of laser diode is shown in fig 3:

HOMO-JUNCTION LASER DIODE :-

* If PN junction is formed by a single crystal semiconductor material, it is said to be homo-junction laser diode.
* Generally, the homo junction lasers are not used in the communication application due to their higher divergence and high threshold current.
  - Further they produce high dispersion and have low optical confinement.



HETERO JUNCTION DIODE :-

* Hetero junction is an interface between two adjoining single crystal semiconductors with different band gap energies.

* Hetero junction lasers are used in the communication applications. The two types are,
  i) Edge emitting lasers which gives the laser output through the mirror end or facet.
  ii) Surface emitting lasers which gives the laser output through the surface of the diode.

* The edge emitting lasers are divided into two types.
  i) Gain guided lasers
  ii) Index guided lasers.

* Here, optical confinement methods are used for bounding laser light in the lateral direction.

* DH laser structure provides optical confinement in the vertical direction through the surface refractive index step at the hetero junction interfaces but lasing takes place across the whole width of the device.

1) GAIN GUIDED LASERS:

* Fabrication of multimode injection lasers with a single or small number of lateral modes is achieved by the use of stripe geometry.
  - These devices are often called gain guided lasers.

* Narrow electrode stripe runs along the length of the diode.
  - Injection of electrons and holes into the device alters the refractive index of the active layer directly below the stripe.

* The profile of these injected carriers creates a weak, complex waveguide that confines the light laterally.

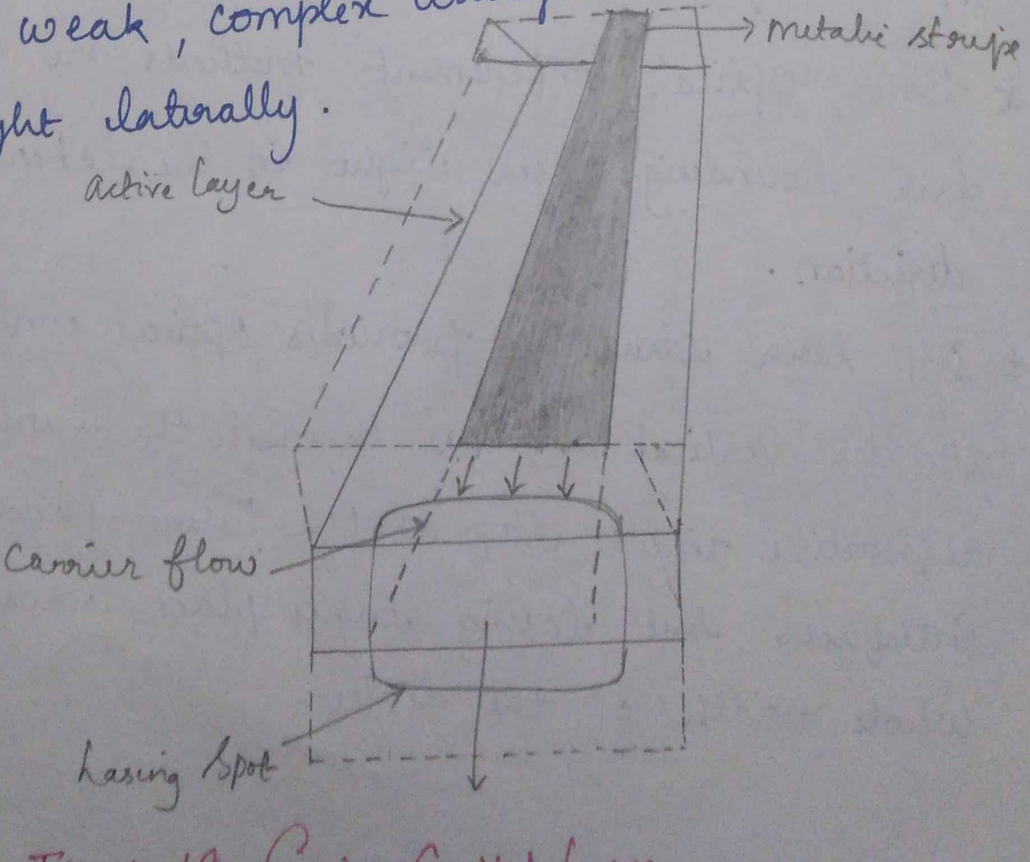


Fig 3:18 Gain-Guided laser

* These lasers can emit optical power exceeding 100 mW, they have strong instabilities and highly astigmatic.

INDEX GUIDED LASERS:-

* These devices have been fabricated to operate at various wavelength with a single lateral mode.
* The variation in the real refractive index of the various materials in these structures control the lateral mode in the laser.
  - These devices are called index guided Lasers.
* Index guided lasers can have either positive index or negative index wave confining Structure

POSITIVE INDEX WAVEGUIDE LASER:.

* Here, the central region of the active region has higher refractive index than the outer region.
  - All ~~of~~ the guided light is reflected at the dielectric boundary...

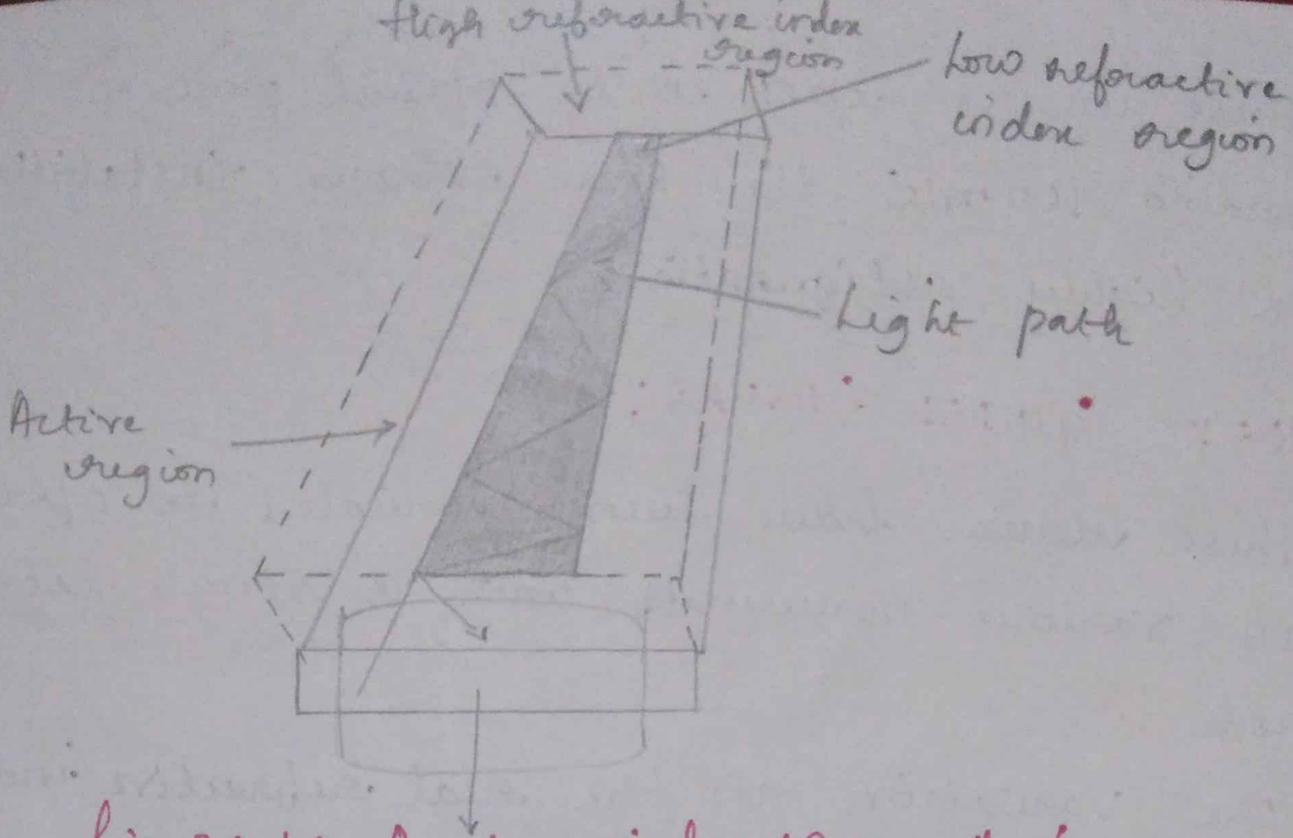


fig 3:11 Positive index waveguide laser

NEGATIVE INDEX WAVEGUIDE LASER:

* Here, the central region of the active layer has lower refractive index than the outer regions:
* At the dielectric boundaries, part of the light is reflected and the rest is refracted into the surrounding material
* This radiation loss appears in the far-field radiation pattern as narrow side lobes to the main beam as shown in the fig 3:

3.12 TEMPERATURE EFFECTS :-

* Threshold current $I_{th}(T)$ of laser diode is temperature dependent.
  - $I_{th}(T)$ increases with temperatures in all types of semiconductor laser because of various complex temperature - dependent factors.
* Empirical expression that shows the relationship between I_{th} and temperature (T) is given as,

$$I_{th}(T) = I_x e^{T/T_0} \quad (1)$$

where,

$T_0 \rightarrow$ measure of the relative temperature insensitivity

$I_x \rightarrow$ Constant

$T \rightarrow$ device absolute temperature.

* Experimental values of T_0 for 1300 nm InGaAsP lasers are typically 60 - 80K (333 - 353°c)
* Fig 3: shows the relation between threshold current and optical output power.
  - Thus threshold current increases by a factor of about 1.4 between 20 and 60°c.

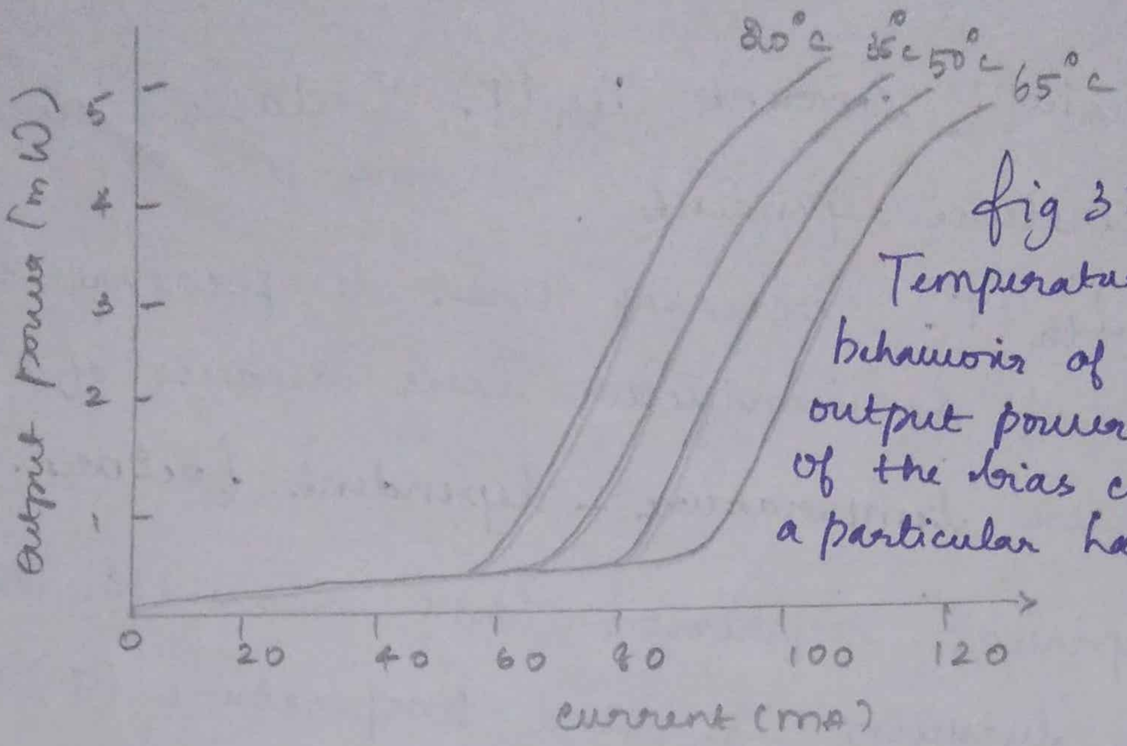


fig 3:20
Temperature dependent behaviour of the optical output power as a function of the bias current for a particular laser diode

* Lasing threshold can change as the laser ages.
  - If a constant output power level is to be maintained at the temperature of the laser changes or at the laser ages then the de-bias current level must be adjusted.

* Possible methods for acheiving this automatically are optical feedback and feed forward schemes, temperature matching transistors and predistortion techniques.

FEEDBACK – STABILIZING CIRCUIT :-

* The light emerging from the rear facet of the laser is monitored by pin photo diode.

_ With this circuit, the electric input signal pattern is compared with the optical output level of the laser diode.

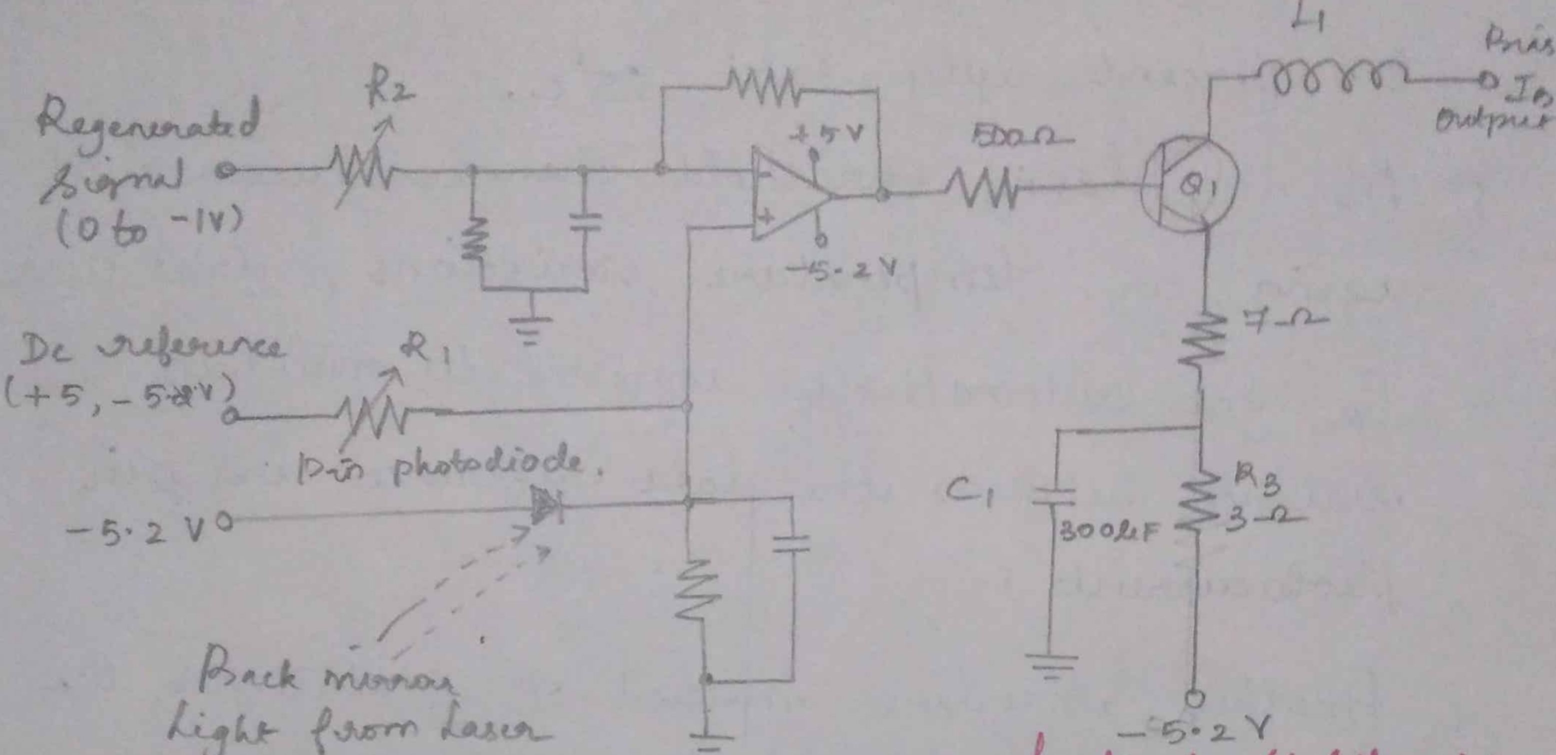


Fig 3:21 Bias circuit that provides feedback stabilization of laser output power

* This effectively prevents the feedback circuit from inaccurately raising the bias current level during long sequences of digital zero or during a period in which there is no input signal on the channel.

* In this circuit, the dc reference through resistor R_1 sets the bias current at the proper operating point during long sequence of zeros.

* When this bias current is added to the laser drive current, the desired peak output

power from the laser is obtained.

* Resistor R_2 balances the signal reference current against the pin photo current for 50 percent duty ratio 25°c.

* As the lasing threshold changes because of aging or temperature variations, bias current I_B gets automatically adjusted to maintain balance between the data reference and pin photocurrent.

* Another standard method of stabilizing the optical output of a laser diode is using a miniature thermoelectric cooler.

5:13 QUANTUM WELL LASERS:-

* DH Lasers are fabricated with very thin active layer thickness of around 10nm instead of the typical range for conventional DH structures of 0.1 to 0.3 µm in order to overcome the following limitations in DH.

i) Modulation speed
ii) Line width of the device
iii) Threshold current density

* The above limitations can be overcome by Quantum Well lasers.
  - The carrier motion normal to the active layer in these devices is restricted, resulting in quantization of the kinetic energy into discrete energy levels for the carrier moving in that direction.

i) SINGLE QUANTUM WELL LASER :- (SQW)

* Both single quantum-well (SQW) corresponding to single active region and Multi Quantum well (MQW) corresponding to a multiple active regions, lasers have been fabricated.

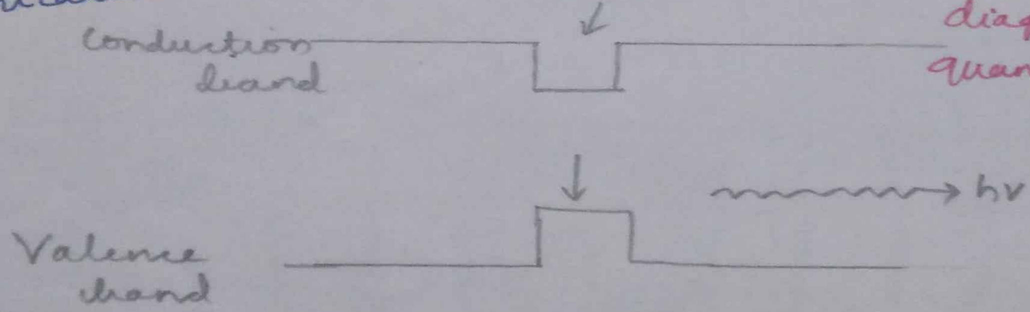


fig 3.22 Energy band diagram of single quantum-well Laser

ii) MULTIPLE QUANTUM - WELL LASER (MQW) :-

* In the ladder structure, the layers which seperate the active region are called barrier layers.

* The parameter ΔEij represents the allowed energy-level transitions which lead to photo emission.

* MQW laser have better optical-mode confinement, which results in a lower threshold current density for these devices.

– The wavelength of the output light can be changed by adjusting the layer thickness 'd'.

* Substantial amount of experimental work has been carried out by MQW lasers using AlGaAs / GaAs material system.

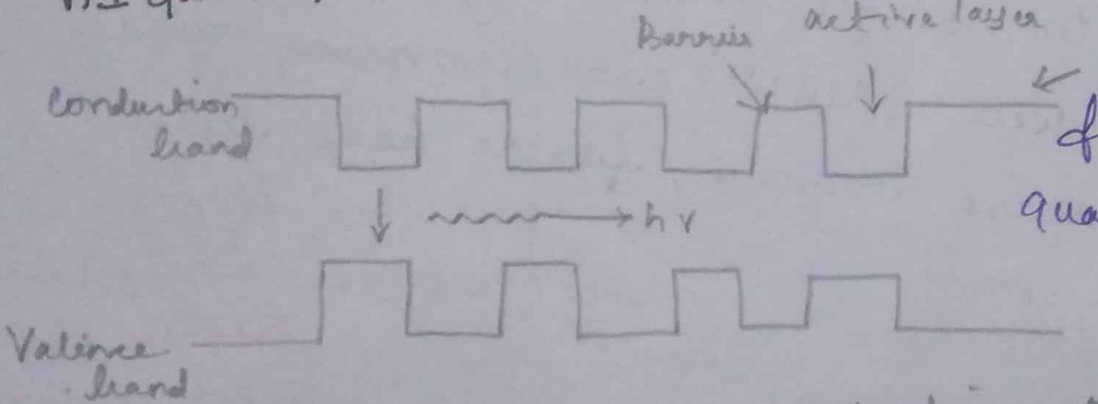


fig 3:23 (a) Multi quantum-well Laser

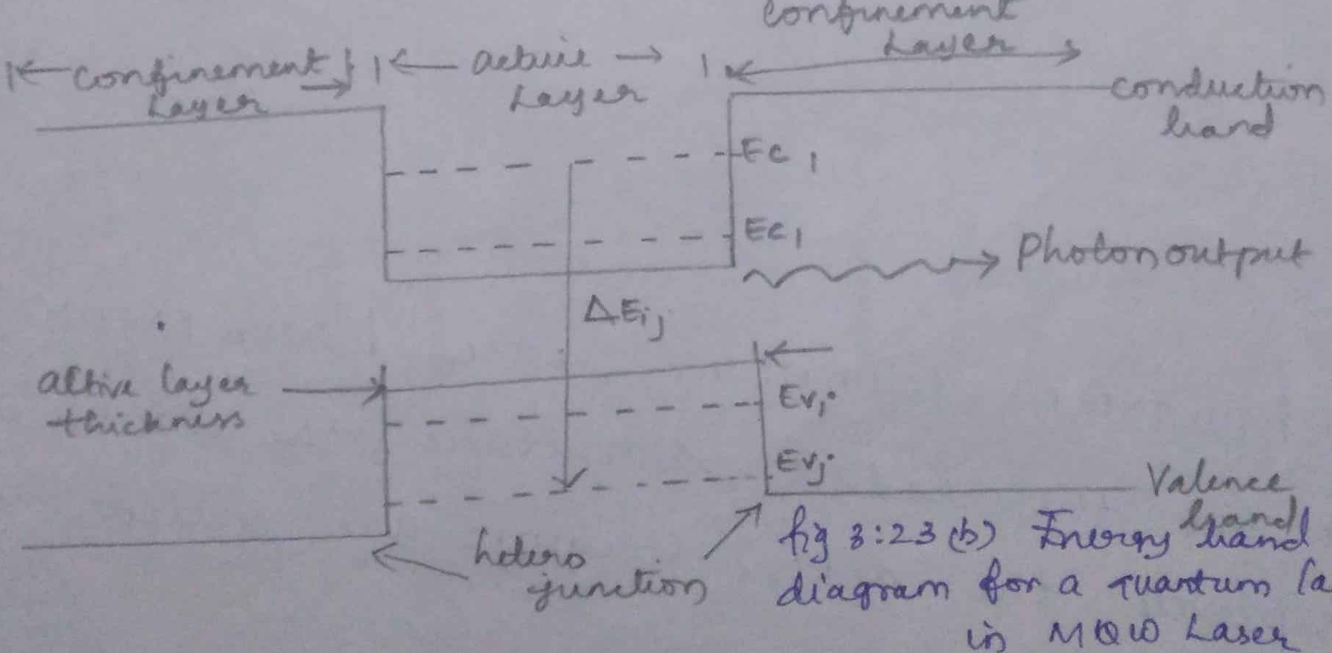


fig 3:23 (b) Energy band diagram for a quantum layer in MQW Laser

* for example, in InGaAs quantum well laser, the peak output wavelength moves from 1550 nm when d = 10 nm to 1500 nm when d = 8 nm.

(3) MODIFIED MULTI QUANTUM - WELL LASER :- (MMQW)

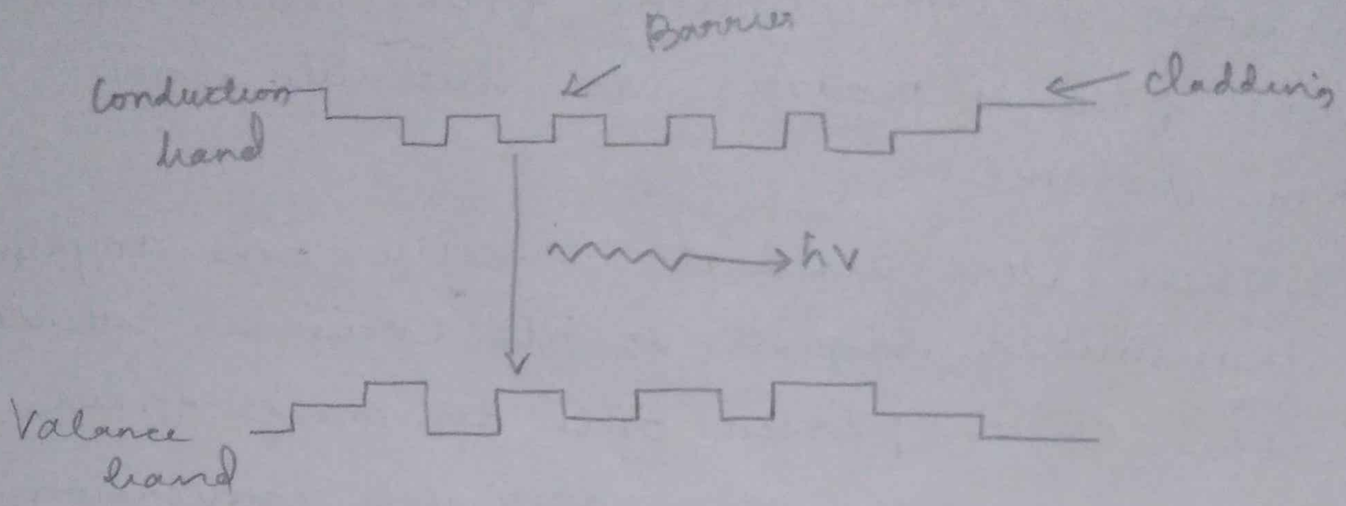


fig 3 : 24 Energy band diagram of MMQW Laser

* When the band gap energy of the barrier layer differ from the cladding type in a MQW devices it is usually referred to as Modified Multi Quantum well laser (MMQW).

ADVANTAGES :-

1) Allow high gain at low carrier density, thus providing the possibility of significantly lower threshold currents.
2) Narrow linewidth.
3) Higher modulation speed
4) Lower frequency chirp
5) Less temperature dependence.

Optical Sources: Intrinsic and Extrinsic Material

The Optical output from a Source is measured in radiance (B)

Radiance is defined as optical power radiated into solid angle per unit emitting Surface area.

Radiance is important in defining Source to fiber coupling efficiency.

Two types of light sources used in fiber optics are Light Emitting diodes and Laser diodes.

Characteristics of Light Source for Communication

* It must be possible for operate the device Continuously at a variety of temperature for many years.
* It must be possible to Modulate the

light output over a wide range of Modulating frequencies.

* To couple large amount of power into an optical power, the emitting area should be small.

* To reduce material dispersion in an optical fiber link, the output spectrum should be narrow.

* The power requirement for its operation must be low

External Modulation

External Modulation is when the Modulation is imposed onto the laser signal after the light is generated.

Modulation such as Electro-optic Modulation (EOM), Acousto Optic Modulation (AOM) can be used to manipulate the laser output with electric fields.

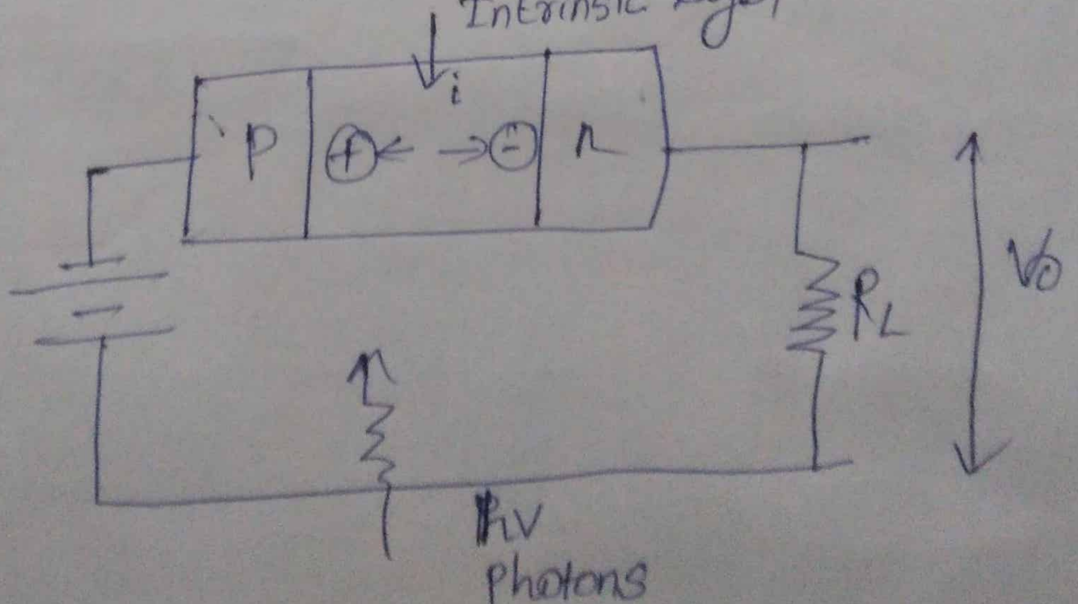
Optical detectors

Optical detectors are used to convert variation in optical power into corresponding variation in electric current.

PIN Photodiode

Construction

PIN diode consists of an intrinsic semiconductor sandwiched between two heavily doped p type & n type semiconductors



PIN Photodiode structure

Principle of Operation

Sufficient reverse Voltage is applied so as to keep intrinsic region free from carriers. So it resistance is high, Mode of diode Voltage appears across it, and the electrical forces are Strong within it.

The incident photons give up their energy and excite an electron from Valance to Conduction band.

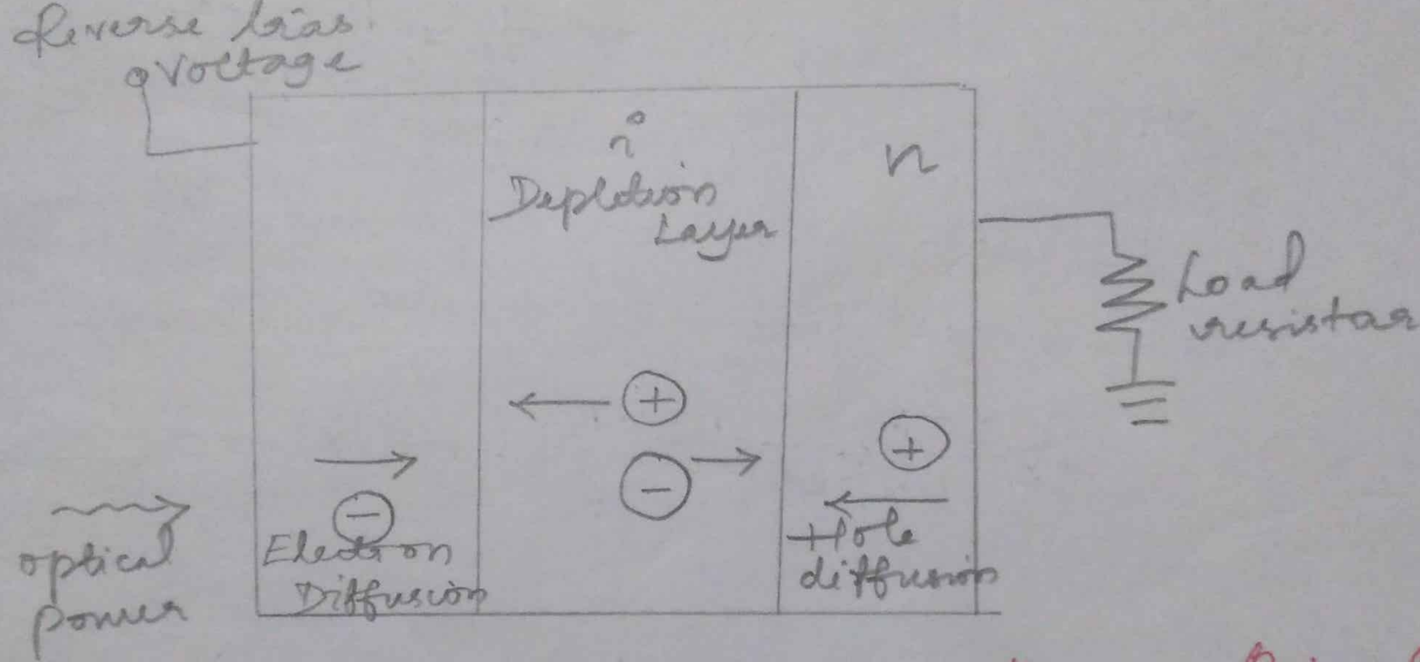
The free electron hole pair is generated these are called as photocarriers

These carriers are collected across the reverse bias junction resulting in rise in current in external circuit called Photocurrent.

DETECTOR RESPONSE TIME :-

3:20:1 DEPLETION LAYER PHOTO CURRENT :-

* The electron hole pairs generated due to absorption of an incident photons will be seperated by the reverse - bias - voltage induced by an electric field.



Schematic Representation Of A Reverse Biased Pin Photodiode

* The carriers get drifted across the depletion layer, then the current flows in the external circuit.
* Under steady state conditions, ~~total~~ current density through depletion layer is,

$$J_{tot} = J_{dr} + J_{diff} \quad \text{——— (1)}$$

where,

$J_{dr} \rightarrow$ drift current density due to carriers generated inside the depletion region.

$J_{diff} \rightarrow$ diffusion current density due to carriers generated outside depletion region.

* Drift current density is expressed as,

$$J_{dr} = \frac{I_p}{A} = q\phi_0 (1 - e^{-\alpha_s w}) \quad \text{——— (2)}$$

Where,

$A \rightarrow$ photodiode area

$\phi_0 \rightarrow$ Incident photon flux per unit area & it is given by $\phi_0 = \frac{P_0(1-R_f)}{A(h\nu)}$ ——— (3)

$R_f \rightarrow$ Surface reflectivity.

* Hole diffusion can be determined by the one-dimensional diffusion equation as,

$$D_p \frac{\partial^2 P_n}{\partial x^2} - \frac{P_n - P_{no}}{\tau_p} + G(x) = 0 \quad \text{——— (4)}$$

where,

$D_p \rightarrow$ hole diffusion co-efficient

$P_n \rightarrow$ hole concentration in n-type material.

$\tau_p \rightarrow$ Excess hole life time.

$P_{no} \rightarrow$ Equillibrium hole density

$G(x) \rightarrow$ Electron - hole generation rate and it is given by

$$G(x) = \phi_0 (a_s e^{-a_s x}) \quad \text{——— (5)}$$

from equation (4), the diffusion current density is expressed as,

1) QUANTUM / SHOT NOISE :-

* Noise arises from the statistical nature of the production and collection of photoelectrons, when an optical signal is incident on a photo detector.

* Quantum noise current has mean square value in bandwidth B which is proportional to the average value of the photocurrent I_p.

$$\langle I_Q^2 \rangle = \sigma_Q^2 = 2 q I_p B M^2 F(M) \qquad (6)$$

where,

$I_p \rightarrow$ Primary photo current

$B \rightarrow$ Bandwidth of photo detector

$M \rightarrow$ Avalanche multiplication factor $(M=1)$

$F(M) \rightarrow$ Noise figure associated with the random nature of the avalanche process.

$F(M) \approx M^x$, $x \, (0 \leq x \leq 1.0)$ depends on the material

2) DARK CURRENT NOISE :-

* The current that flows through the bias circuit when no light is incident on the diode is known as dark current.

- This is a combination of bulk and surface currents.

It is divided into two types of noises.

(i) Bulk dark current noise

(ii) Surface dark current noise / Surface leakage current noise.

(a) BULK DARK CURRENT :-

* Bulk dark current i_{DB} is due to thermally generated electrons and holes in the pn junction of the photodiode.

— Mean Square of the bulk current is given by,

$$\langle I_{DB}^2 \rangle = \sigma_{DB}^2 = 2q I_D M^2 F(M) B \quad \text{———} (7)$$

where

$I_D \rightarrow$ primary (unmultiplied) detector bulk dark current

(b) SURFACE LEAKAGE CURRENT :-

* The surface dark current is due to surface defects, cleanliness, bias voltage + surface area.

— Mean Square value of the surface dark current is given by

$$\langle i_{DS}^2 \rangle = \sigma_{DS}^2 = 2q I_L B \quad \text{--- (8)}$$

where, $I_L \rightarrow$ surface leakage current
$q \rightarrow$ charge on an electron.

* Dark current may be reduced by careful design and fabrication of the detector.

3) Total Photo Detector Noise Current:-

* Total mean square photo detector noise current $\langle i_N^2 \rangle$ can be written as,

$$\langle i_N^2 \rangle = \sigma_N^2 = \langle i_Q^2 \rangle + \langle i_{DB}^2 \rangle + \langle i_{DS}^2 \rangle \quad \text{--- (9)}$$

$$= \sigma_Q^2 + \sigma_{DB}^2 + \sigma_{DS}^2$$

$$\langle i_N^2 \rangle = 2q (I_P + I_D) M^2 F(M) B + 2q I_L B \quad \text{--- (10)}$$

4) Thermal Noise / Amplifier Noise:-

* Photo detector load resistor gives thermal noise and it is expressed as,

$$\langle i_T^2 \rangle = \sigma_T^2 = \frac{4 k_B T}{R_L} B$$

where, $k_B \rightarrow$ Boltzmann's constant

T ⟶ Absolute temperature

B ⟶ Post detection bandwidth of the S/m

5) SIGNAL TO NOISE RATIO (S/N) :-

* Signal to noise ratio at the input of the amplifier is given as,

$$\frac{S}{N} = \frac{\text{Input Signal}}{\text{Noise due to quantum, bulk dark, surface current + Johnson or thermal noise}} \quad (12)$$

By substituting eq (4) (10) (11) in eq (12) we get,

$$\frac{S}{N} = \frac{\langle i_P^2 \rangle M^2}{2q(I_P + I_D)M^2 F(M)B + 2qI_L B + 4k_B \frac{TB}{R_L}} \quad (13)$$

3.19 SIGNAL TO NOISE RATIO :-

* Noise is reffered as any spurious or undesired disturbances that mask the received signal in a communication system.

Types of optical Receiver Noise :-

- Optical Receiver Noise
  - Photodetector Noise
    - Quantum or Shot noise
    - Dark current noise
      - Bulk dark current noise
      - Surface dark current noise.
  - Amplifier Noise
    - Thermal Noise or Shonson noise

* Photo detector noise is from the statistical nature of Photon to electron conversion process and the thermal noise associated with the amplifier circuitary.

* Performance of the receiver is evaluated by the power signal to Noise (S/N) ratio at the output of an optical receiver.

$$\frac{S}{N} = \frac{\text{Signal power from photo current}}{\text{Photodetector noise power + Amplifier noise power}}$$

→ To get high Signal to Noise Ratio (SNR) :- ①

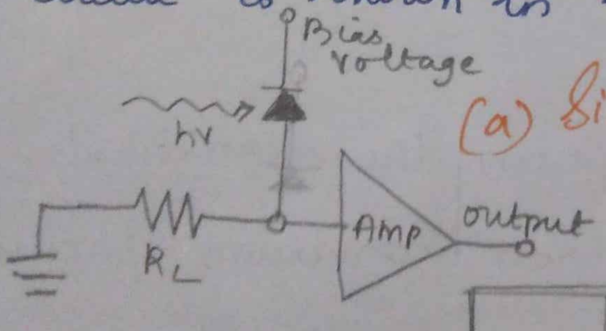
i) The photo detector must have high quantum efficiency to generate large signal power

ii) Photo detector and amplifier noises should be very low.

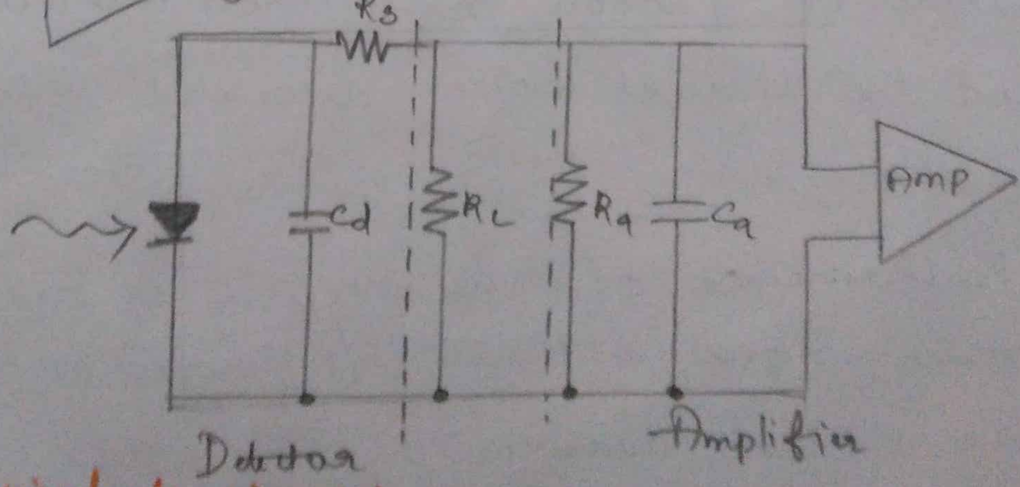
* To get high sensitivity of a photo detector (Sensitivity is inversely proportional to the minimum detectable optical power) S/N ratio should be more.

A) Noise Source :-

* Simple photo detector model and its equivalent circuit is shown in fig 3:



(a) Simple model of a photodetector receiver



(b) Equivalent circuit

fig 3:38

* The photodiode has a small series resistance R_s, total capacitance C_d consisting of function and packaging capacitances, and bias resistor R_L

* The amplifier has an input capacitance C_a and resistance R_a.
  - If $R_s << R_L$ then R_s can be neglected.

* The primary photocurrent $i_{ph}(t)$ is generated when the modulated signal of optical power $P(t)$ falls on the detector,

$$i_{ph}(t) = \frac{\eta q}{h\nu} P(t) \quad \text{------ (2)}$$

* Primary current consists of dc value of I_P, which is the average photocurrent due to signal power and signal component $i_p(t)$.

* For pin photodiodes, the mean square signal current $\langle i_s^2 \rangle$ is given by,

$$\langle i_s \rangle^2 = \sigma^2_{s,pin} = \langle i_p^2(t) \rangle \quad \text{------ (8)}$$

where, $\sigma \longrightarrow$ Variance

* For avalanche photodiode, the mean square signal current is given as,

$$\langle i_s^2 \rangle = \sigma^2_{s,APD} = \langle i_p^2(t) \rangle M^2 \quad \text{------ (4)}$$

where, M $\longrightarrow$ avalanche multiplication factor

$\langle\rangle \rightarrow$ ensemble average

* The signal component $\langle i_p^2\rangle$ for a sinusoidally varying input signal of modulation index 'm' and it is given as,

$$\langle i_p^2(t)\rangle = \sigma_p^2 = \frac{m^2}{2} I_p^2 \quad \text{—— (5)}$$

$m \rightarrow$ modulation index / modulation depth and it is defined as,

$$m = \frac{\Delta I}{I'_B}$$

where,

$I_B \longrightarrow$ current at bias point

$I_{th} \longrightarrow$ Threshold current

$I'_B \longrightarrow I_B - I_{th}$

$\Delta I \longrightarrow$ Variation in current about the bias point.

* Noise associated with photo detector that have no internal gain are

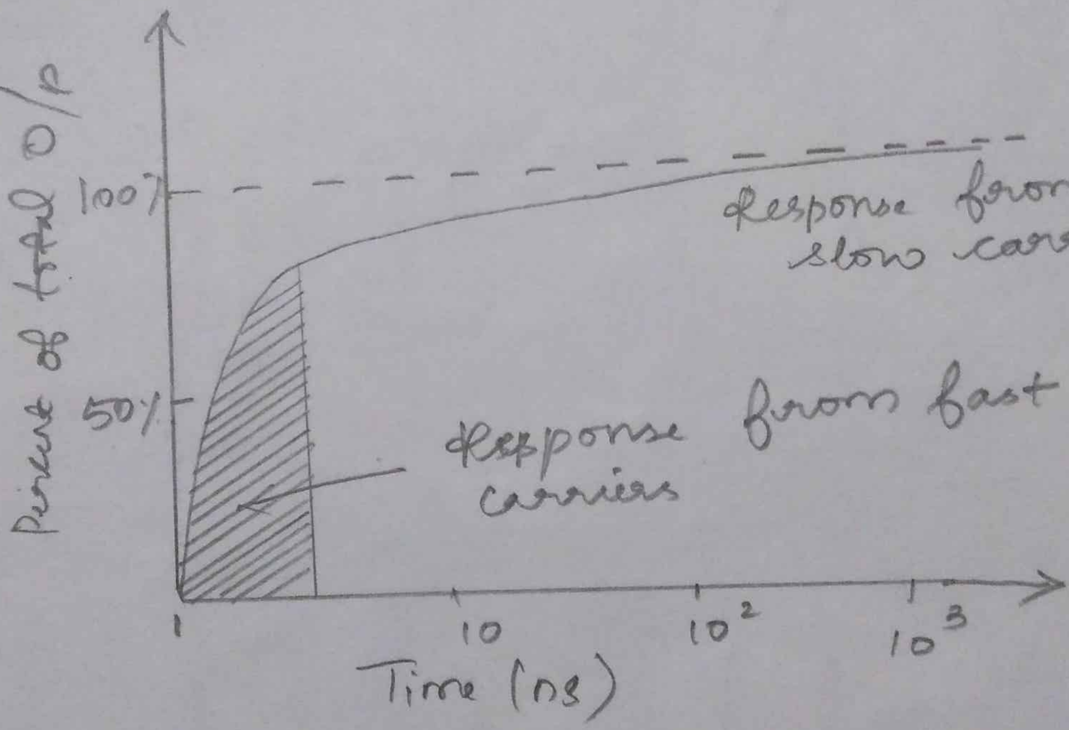
i) Quantum noise / Shot noise

ii) Dark current noise

a) TRANSIT TIME :-

* Response speed of a photodiode is limited by time taken by the photo generated carriers to travel across the depletion region.

* Transit time (t_d) of the photo carriers in depletion region is, the ratio between carrier drift velocity (V_d) and the depletion



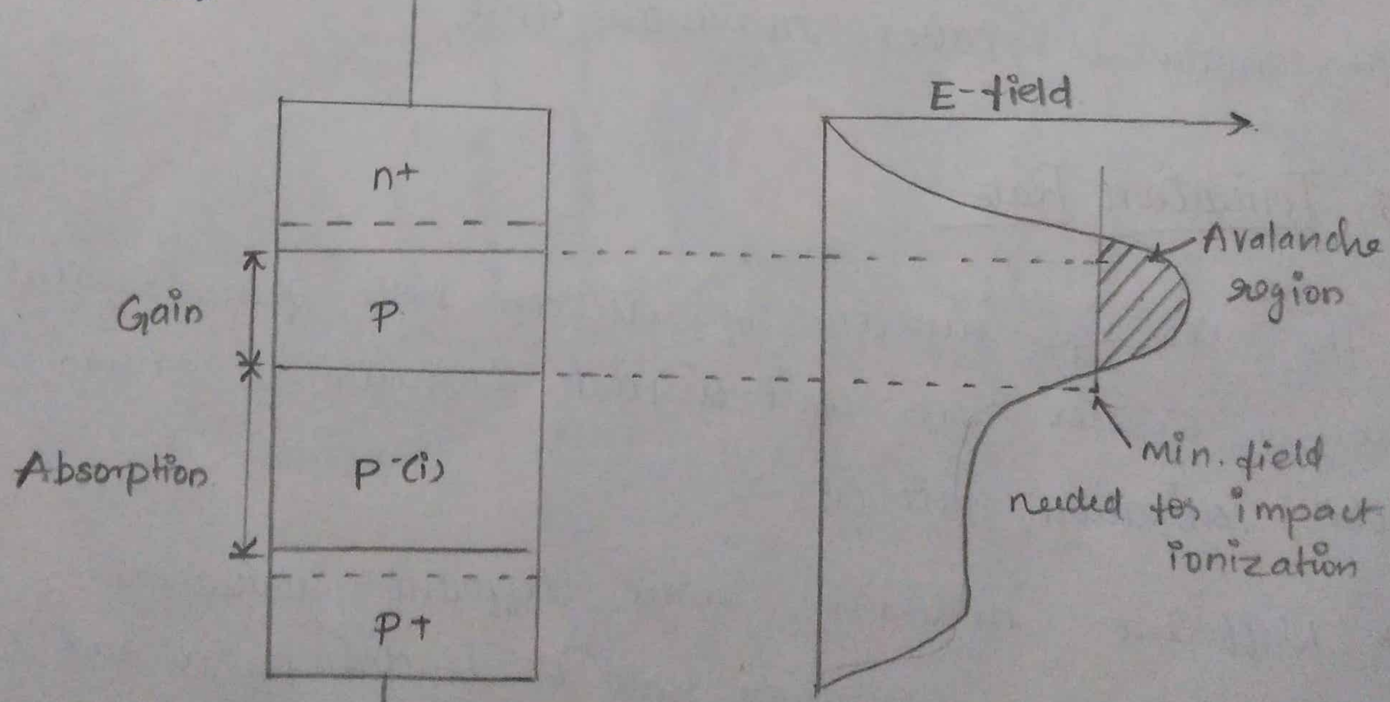
Typical response time of a photodiode that is not fully depleted.

Avalanche Photodiode (APD)

When a P-n junction diode is applied with high reverse bias breakdown can occur by two seperate mechanisms direct ionization of the lattice, zener breakdown and high velocity carriers causing impact ionization of the lattice atoms called avalanche breakdown.

*APD uses the avalanche breakdown phenomena for its operation. The APD has its internal gain which increases its responsitivity.

Fig: APD schematic & Variation of E-field across diode



* Under normal operating bias, the I-layer (the P⁻ region) is completely depleted. This is known as reach through condition, hence APD's are also known as

reach through APD or RAPDs.

Photo Detectors Noise

1. Impact Ionization

* The photo generated carrier traverse a region where a thick electric field is present. These carriers can gain enough energy under high electric field and excite new electron-hole pairs. This phenomena is called impact ionization.

2. Avalanche Effect

* During ionization new generated carriers also accelerated by high electric field and gain enough energy to cause further impact ionization. This phenomena is called avalanche effect.

3. Ionization Rate

* The average number of electron hole pairs created by a carrier per unit distance travelled is called the ionization rate (K).
* Different materials have different ionization rates. Electron ionization rate is denoted by α and hole ionization rate is denoted by B.
* A photodetector performance is measured by the

ratio of two ionization rates i.e. $K = \beta/\alpha$

* If the APD is biased close to breakdown, it will result in reverse leakage current. Thus APD's are usually biased just below breakdown, with the bias voltage being tightly controlled.

4. Avalanche Multiplication

The Multiplication for all carriers generated in PD is,

$$M = \frac{I_M}{I_p}$$

where, I_m = Average value of total multiplied o/p current

I_p = primary unmultiplied photocurrent.

Responsitivity of APD is given by,

$$R_{APD} = \frac{\eta q}{h\nu} M$$

$$R_{APD} = \frac{\eta q \lambda}{hc} M \qquad \because \nu = \frac{c}{\lambda}$$

$$R_{APD} = R_0 M$$

where, R_0 is unity gain responsitivity

Advantages:

1. Excellent linearity over optical power range from nanowatts to microwatts.
2. Better sensitivity (5 - 15 dB)
3. Wide range of gain variation

4. APD offers internal gain.
5. Better S/N ratio.

Disadvantages :

1. Due to complex structure, fabrication is difficult.
2. ADP and supporting circuitry is more supportive.
3. Random nature of gain mechanism contributes additional noise.
4. High voltage and temprature compensation is needed for stabilisation.
5. Internal gain of APD is temprature dependent.

Comparision of PIN and APD (Photodetectors)

S.no	Parameters	PIN	APD
1.	Sensitivity	- Less sensitive (0-12)dB.	- More sensitive (0-15 dB)
2.	Biasing	- Low reverse biased voltage (5-10V)	- High reverse biased voltage (20-400V)
3.	Wavelength region	- 300-1100 nm	- 400-100 nm
4.	Gain	- No internal gain	- Internal gain.
5	S/N ratio	- poor	- Better
6.	Detector circuit	- Simple	- More complex
7.	Conversion efficiency	- 0.5 to 10Amps/watt	- 0.5 to 100 Amps/watt

UNIT IV

Optical Receiver, Measurements and Coupling

4:1 FUNDAMENTAL RECEIVER OPERATION:

* The design of an optical receiver is much more complicated than that of an optical transmitter because the receiver must first detect weak signal, disorted signal and make decisions on what type of data was sent based on an amplified version of this disorted signal.

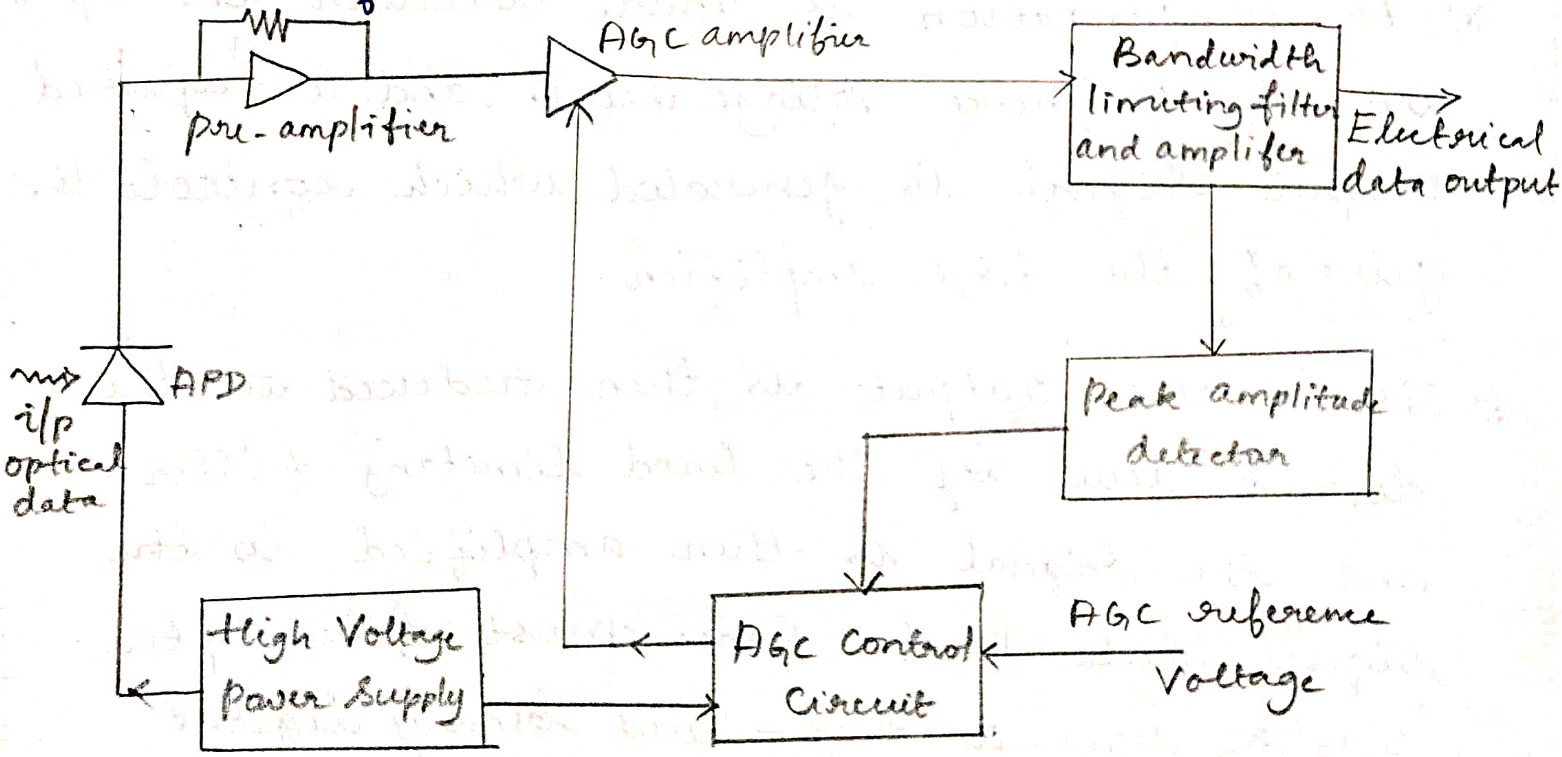


Fig 4:1 Fiber Optic Link Receiver:

* When an optical data are incident on the APD, higher current pulses get flow through the circuit as shown in fig 4:1

* The photocurrent is amplified by the pre-amplifier. This, it converts the voltage pulses to have an adequate voltage levels.

* The peak amplitude of the voltage pulses are maintained as constant by the AGC controlled amplifier.

* The signal from the output of AGC amplifier is fed back to the AGC amplifier via a peak amplitude detector.

* A compensation is made between the input and the reference voltage level and a required output signal is generated which controls the gain of the AGC amplifier.

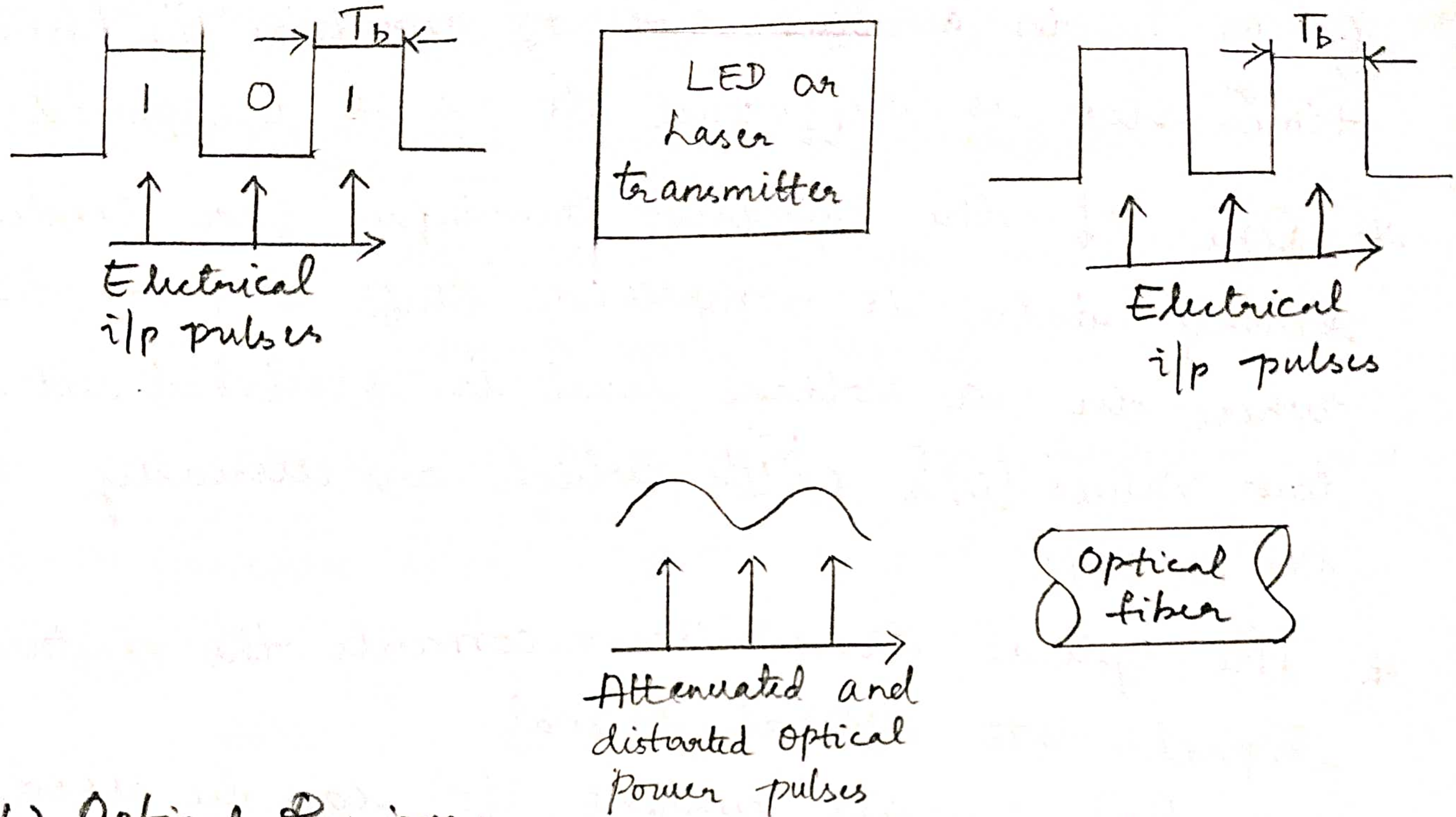
* The noise output is then reduced to the desired level by the band limiting filter and the signal is then amplified to the signal data level. Since most fiber optic system uses a two-level binary digital signal.

4:1:1 DIGITAL SIGNAL TRANSMISSION :-

(a) Optical Transmitter :- (fig 4:2)

(b) Optical Receiver :- (fig 4:3)

(a) Optical Transmitter:



(b) Optical Receiver:

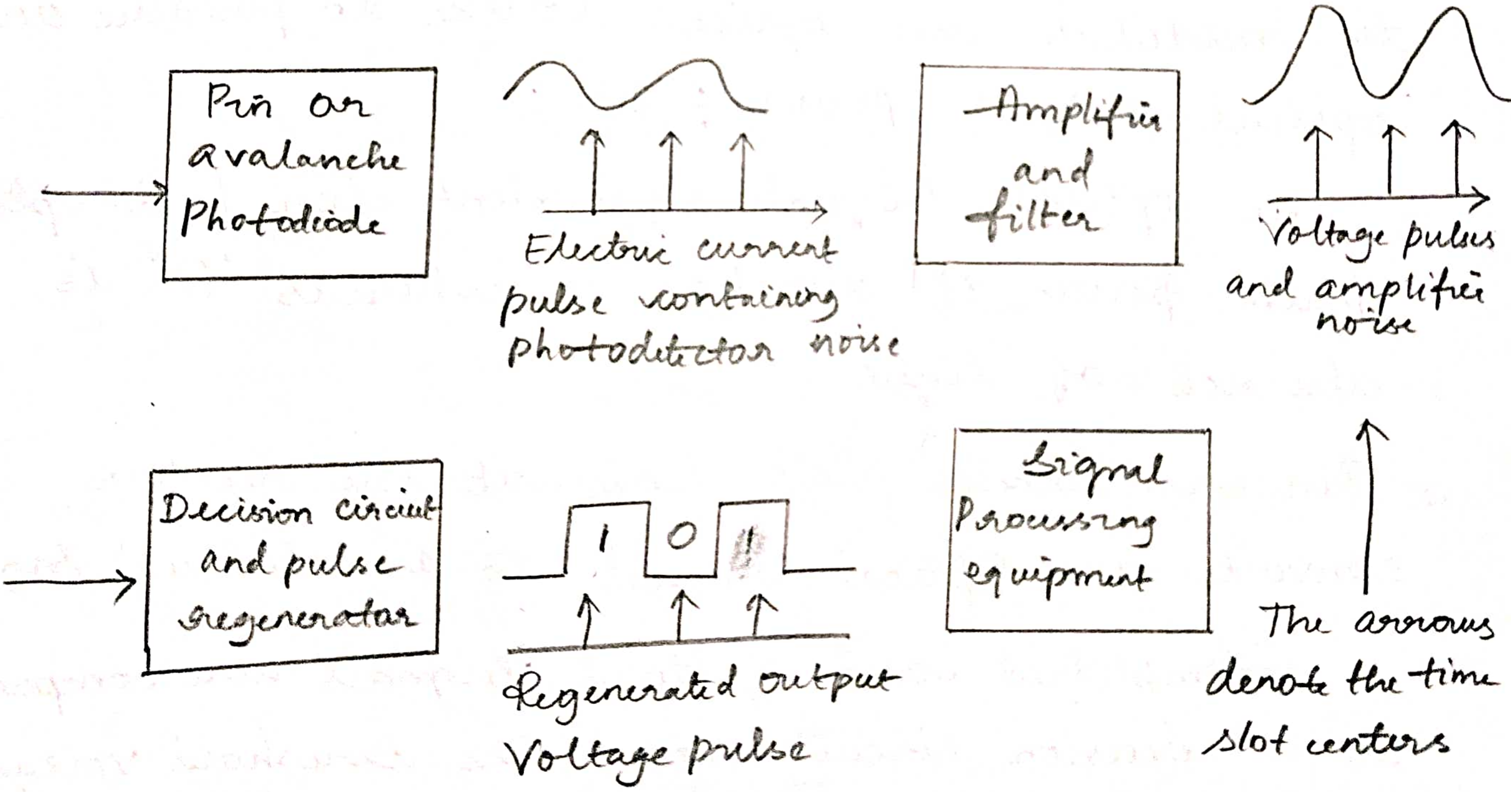


fig 4:2 Signal path through an optical data link.

⇒ Bit Period (T_b):

* The transmitted signal is a two-level

binary data stream consisting of either 0 or 1 in a time slot of duration T_b. This time slot is refferred to as a bit period.

* One of the simplest techniques for sending binary data is Amplitude Shift Keying (ASK), where in a voltage level is switched between two values (0)'s or (1)'s, which are usually ON or OFF.

* The optical transmitter converts the electrical signal into optical signal.

  — An electrical current i(t) can be used to modulate an optical source to produce an optical output power P(t).

* The optical signal equivalent for "1" is optical pulse power of duration T_b whereas "0" is absence of light.

* Pin or avalanche photo diode at the receiver converts an optical signal to an electrical signal

  — Amplified and filtered signals are compared in a decision circuit with the threshold voltage.

→ Threshold Level :

* A decision circuit compares the signal in each time slot with a certain reference voltage

known as the threshold level.

(i) Received Signal > Threshold = 1

(ii) Received Signal < Threshold = 0

* If the received signal is greater than threshold "1" is received else "0".

* An optical amplifier is placed ahead of the photodiode to boost the optical signal level before photo detection.

— An optical preamplifier provides a larger gain factor and broader bandwidth.

— This process also introduces additional noise to the optical signal.

4:1:2 Error Sources:

* Error in the detection mechanism can arise due to various noise and disturbances associated with the signal detection system.

4:1:2:1 ⟹ NOISE:

* The term noise is used to describe unwanted components of an electric signal that tend to disturb the transmission and processing of the signal in a physical s/m, and over which we have incomplete control.

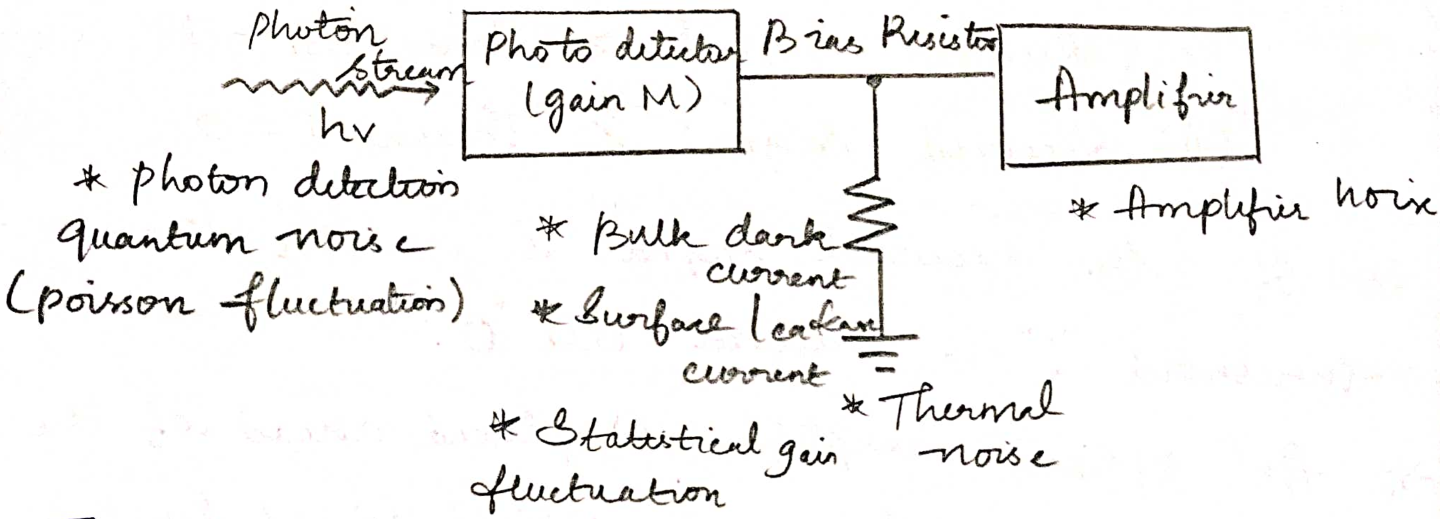
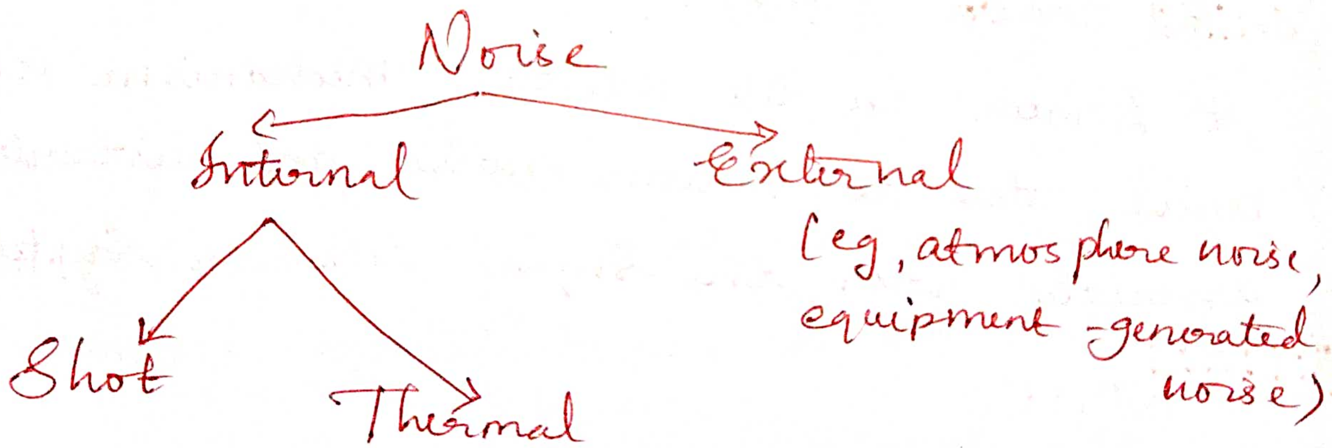


Fig 4:3 Noise Sources and disturbances in the optical pulse detection mechanism.

TYPES OF NOISE:

* The noise sources can be either external or internal to the system and it is classified as shown below :-



INTERNAL NOISE:

* Internal noise is caused by the spontaneous fluctuations of the current or voltage in electric circuits. Common internal noises are,

(a) Shot Noise

(b) Thermal Noise

* Shot noise arises in electronic devices bec-ause 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 produce a quantum / Shot noise at the photo detector. This noise depends on the Signal level.

* For an APD and p-i-n diodes additional shot noise arises from stastical nature of the multiplication process.

  - With increasing avalanche gain (M), the noise level increases.

* 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 expressed as,

$$\bar{N} = \frac{\eta}{h\nu}\int_0^{\tau} P(t)\,dt$$

$$\Rightarrow \frac{\eta E}{h\nu} \quad \text{------------ (a)}$$

where,

$\eta \rightarrow$ detector quantum efficiency,

$h\nu \rightarrow$ photon energy

$E \rightarrow$ Energy received in time interval τ

* The actual number of electron-hole pairs "n" that are generated fluctuates from the average according to the poisson distribution,

$$P_r(n) = \bar{N}^n \frac{e^{-\bar{N}}}{n!} \quad \text{------------ (b)}$$

where, $P_r(n) \rightarrow$ probability that "n" electrons are emitted in an interval τ.

* The random nature of the avalanche multi-plication process gives rise to a type of shot noise.

* A detector with a mean avalanche gain "M" and an ionization rate ratio k, then the excess noise factor $F(M)$ for an electron injections is expressed as,

$$F(M) = kM + \left(2 - \frac{1}{M}\right)(1-k) \quad \text{------------ (c)}$$

eq (c) is approximated by the empirical expression, ⑤

$$F(M) \approx M^x \quad (0 < x < 1.0) \qquad \text{(d)}$$

INTER - SYMBOL INTERFERENCE (ISI):

* when the pulses spreading in the optical fiber, the inter-symbol interference (ISI) will occur as shown below fig 4.5,

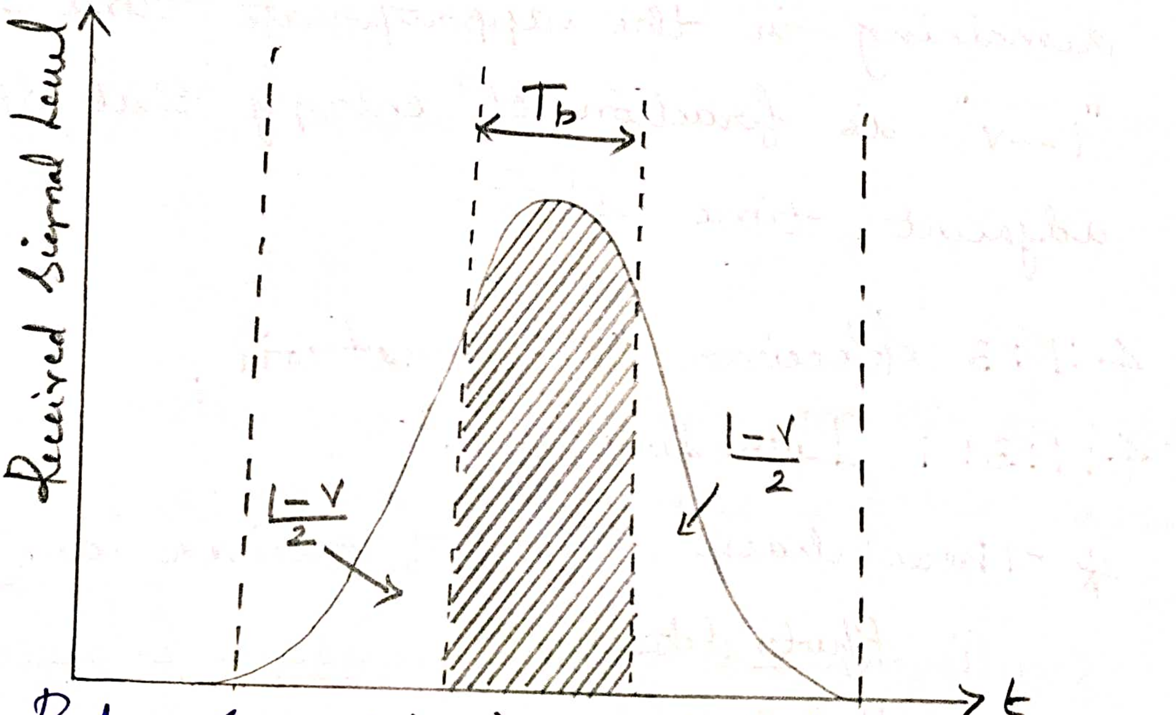


fig 4:4 Pulse spreading in an optical signal that leads to inter symbol interference

* When a pulse is transmitted in a given time slot, most of the pulse energy will arrive in the corresponding time slot at the receiver.

— However, because of pulse spreading induced by the receiver, some of the transmitted energy will progressively spread into neigh-bouring time slots as the pulse propogates along the fiber.

— The presence of this energy in adjacent time slots results in an interfering the signal. This is called as Inter-Symbol-Interference.

* From fig 4.5, if "γ" is the fraction of energy remaining in the appropriate time slot then "$1-\gamma$" is fraction of energy that spread into adjacent time slots.

4:1:3 Receiver Configuration.

4:1:3:1 Introduction:

* Three basic stages of receiver are,
  1) Photo detector
  2) An amplifier
  3) Equalizer

* Photo detector can be either an avalanche photodiode with a mean gain "M" or a pin photodiode for which $M = 1$,

— The photo diode has a quantum efficiency η and a capacitor C_d.

— The detector bias resistor has a resistance R_b

which generats a thermal noise current $i_b(t)$.

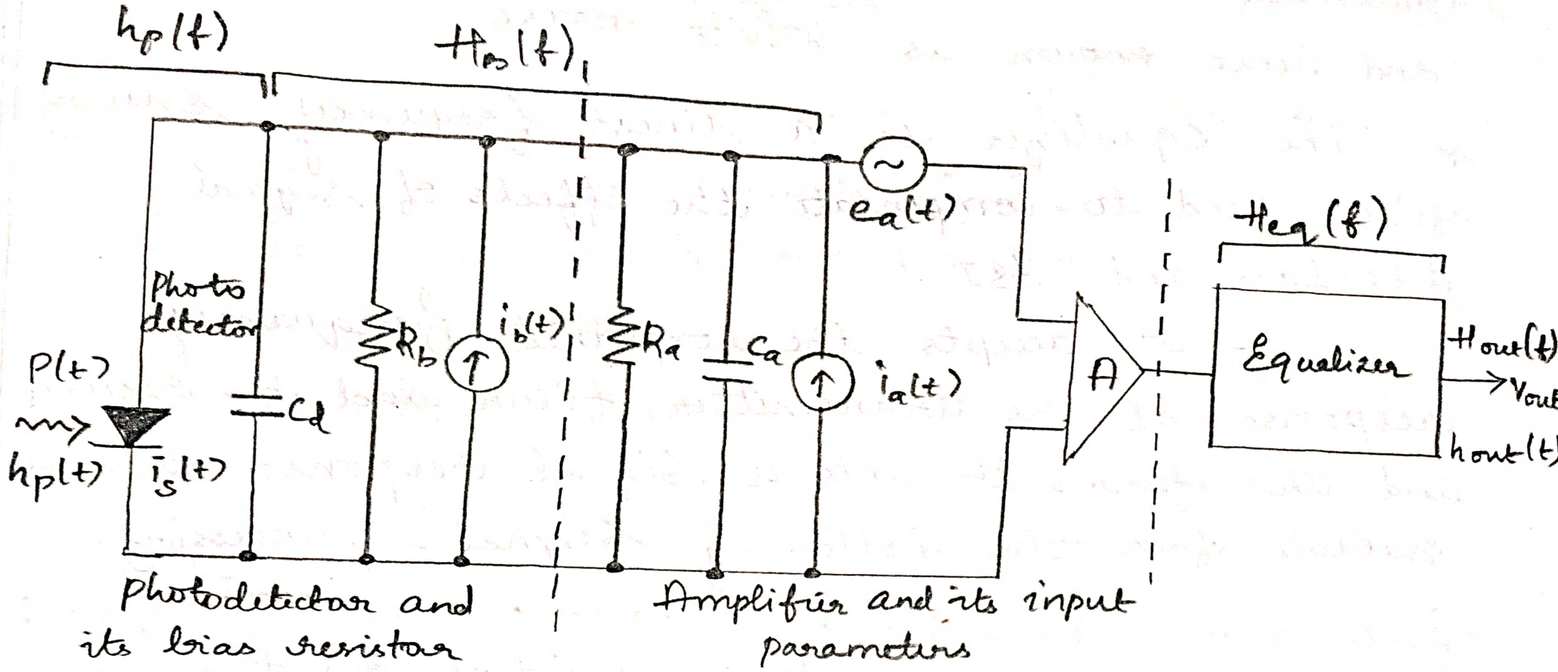


fig 4:5 Schematic diagram of a typical optical receiver.

* The amplifier input impedence is the parallel combination of a resistance R_a and a shunt capacitance C_a.
    - Voltages appearing across this impedence causes current to flow in the amplifier output.
* Amplifying function is represented by the voltage controlled current sources which is characterized by trans-conductance g_m.
* There are two amplifier noise sources.
    - One is thermal noise due to resistor R_a and noise voltage source $e_a(t)$ represents the thermal noise of amplifier channel.

* These noise sources are assumed to be Gaussian in statistics and have flat spectrum and hence known as white noise.

* The equalizer is a linear frequency-shaping filter used to compensate the effects of signal distortion and ISI.

  - It accepts the combined frequency response of the transmitter, fiber and the receiver and transforms it into a signal response that is suitable for the following signal-processing.

Expression for Mean Output from Photodiode:-

* The binary pulse train incident on the photo detector is given by,

$$p(t) = \sum_{n=-\alpha}^{\alpha} b_n h_p(t - nT_b) \quad \text{——— (a)}$$

where,

$p(t) \rightarrow$ received optical power

$b_n \rightarrow$ Amplitude of n^{th} message digit.

$T_b \rightarrow$ Bit period

$h_p(t) \rightarrow$ Received pulse shape, which is positive for all 't'.

* For binary data the parameter b_n can take on the two values, b_{on} & b_{off} corresponding to a binary 1 & 0 respectively.

- If $h_p(t)$ is the non negative photodiode i/p pulse, that is to be normalized to have unit area

– It is expressed as,

$$\int_{-\alpha}^{\alpha} h_p(t)\,dt = 1 \quad \text{——— (b)}$$

Then, $b_n \rightarrow$ the energy in n^{th} pulse.

* The mean output current from the photo-diode at time t due to pulse train is given as,

$$\langle i(t) \rangle = \frac{\eta q}{h\nu} M P(t) \quad \text{——— (c)}$$

by substituting eq (a) in eq (c), we get

$$\langle i(t) \rangle = R_o M \sum_{n=-\alpha}^{\alpha} b_n h_p(t - nT_b) \quad \text{——— (d)}$$

Where,

$\eta \rightarrow$ Quantum efficiency $\quad \because R_o = \frac{\eta q}{h\nu}$

$R_o \rightarrow$ Responsitivity of the detector.

* This current is then amplified and filtered to produce a mean voltage at the o/p of the equalizer.

4:2 PRE-AMPLIFIERS :-

* Receiver amplifiers are the front end Pre-amplifiers
  – The Sensitivity and bandwidth of a receiver are dominated by the noise sources at the pre-amplifier stage.

* Main goals are to maximize the receiver sensitivity while maintaining a suitable bandwidth.

* Pre-amplifiers are generally used in optical fiber communication receivers.

— Three basic pre-amplifier structures are:

(i) Low impedance pre-amplifiers
(ii) High impedance pre-amplifier
(iii) Trans-impedance pre amplifiers.

ADVANTAGES OF PREAMPLIFIERS:

* Pre-amplifier should satisfy the following requirements: Low noise level, high bandwidth, high dynamic range, high sensitivity & high gain.

4:2:1 LOW IMPEDANCE PRE AMPLIFIER:

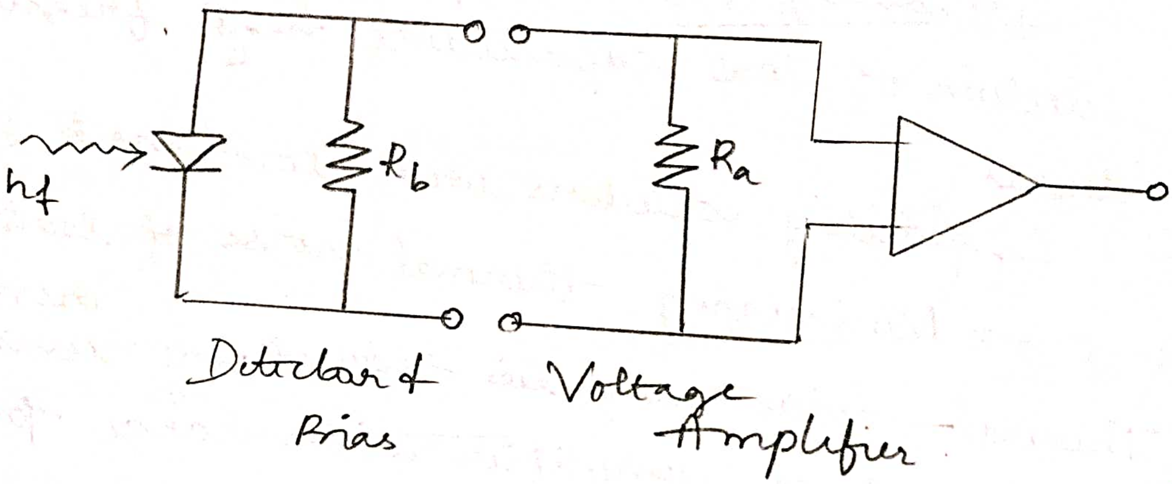
* A photo diode operates into a low-impedance amplifier and a bias or load resistor R_b is used to match the amplifier impedence along voltage amplifier with an effective input resistance R_a.

* R_b along with the input capacitance of amplifier decides the bandwidth of amplifier.

— Pre amplifiers bandwidth is equal to or greater than the signal bandwidth.

- The load resistance R_{TL} is given by,

$$R_{TL} = \frac{R_b R_a}{R_b + R_a}$$



4:6 Low impedance front end optical fiber receiver with voltage amplifier.

* Low impedance preamplifier can operate over a wide bandwidth but it has poor receiver sensitivity.
  - Used in special short-distance applica-tion where high sensitivity is not a major concern.

4:2:2 HIGH IMPEDANCE / INTEGRATING PRE AMPLIFIER :-

* Second configuration consists of a high input impedance amplifier together with a large detector bias resistor R_a in order to reduce the effect of thermal noise.

* In high-impedance preamplifier, the main

goal is to reduce all sources of noise to the absolute minimum. This can be achieved by,

→ Reducing input capacitance through the selection of low capacitance high frequency devices.

→ Selecting detectors with low dark current

→ Minimizing thermal noise of biasing resistors.

* Thermal noise can be reduced by using high impedance amplifier with large photo detector bias resistor R_b, as shown below,

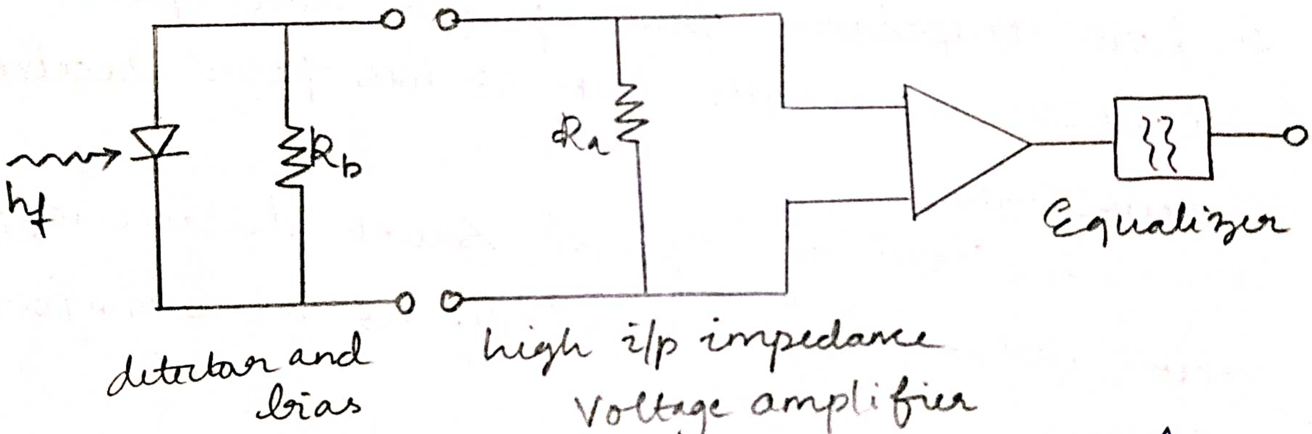


fig 4:7 High impedance integrating front end optical fiber receiver with equalized voltage amplifier.

* High impedance produces a large input RC time constant, the front end bandwidth is less than the signal bandwidth.

— Thus the input signal is integrated

and where the equalization techniques must be employed to compensate this.

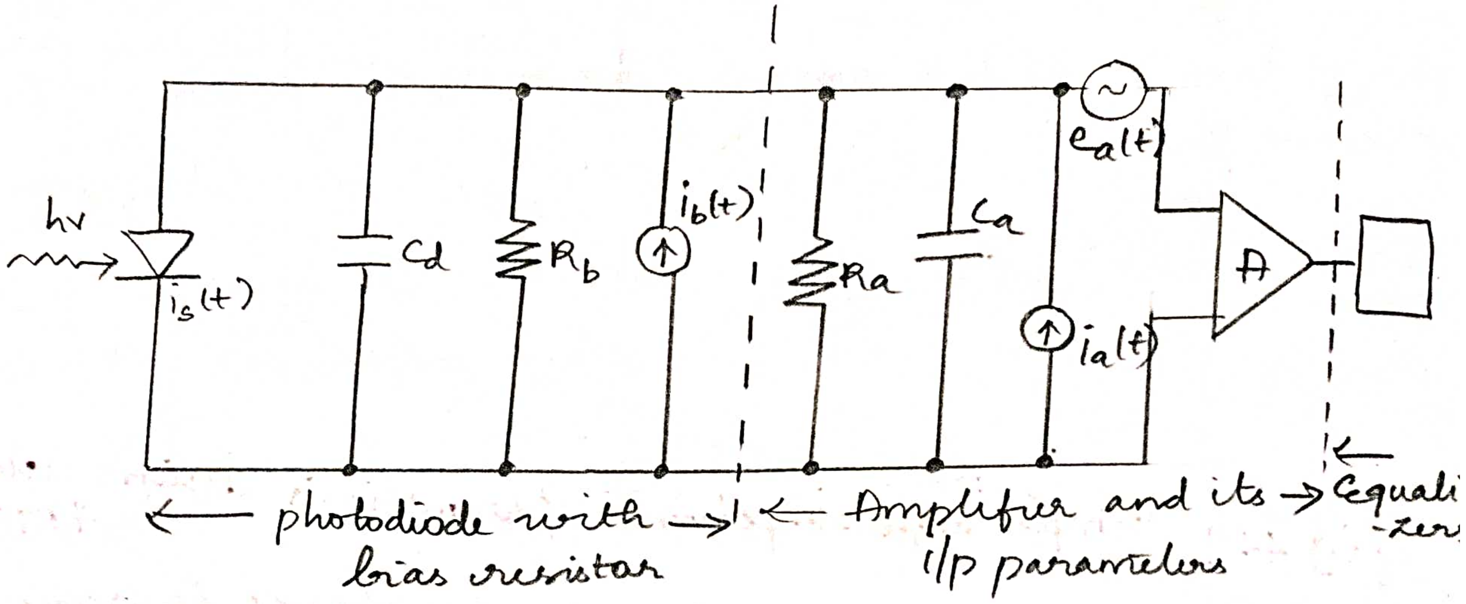


fig 4 : 8 An equivalent circuit of a high-impedance amplifier.

(a) High-Impedance FET Amplifiers :

* For gigabit-per second data rates, the lowest noise receivers are made using GaAs MESFET (MEtal Semiconductor Field-Effect Transistor) Preamplifiers.
* At lowest frequencies, Silicon MOSFET's (Metal Oxide Semiconductor Field-Effect Transistors) or JFET's (Junction field-effect Transistor) are generally used.

— Simple high-impedance preamplifier design using FET is shown below,

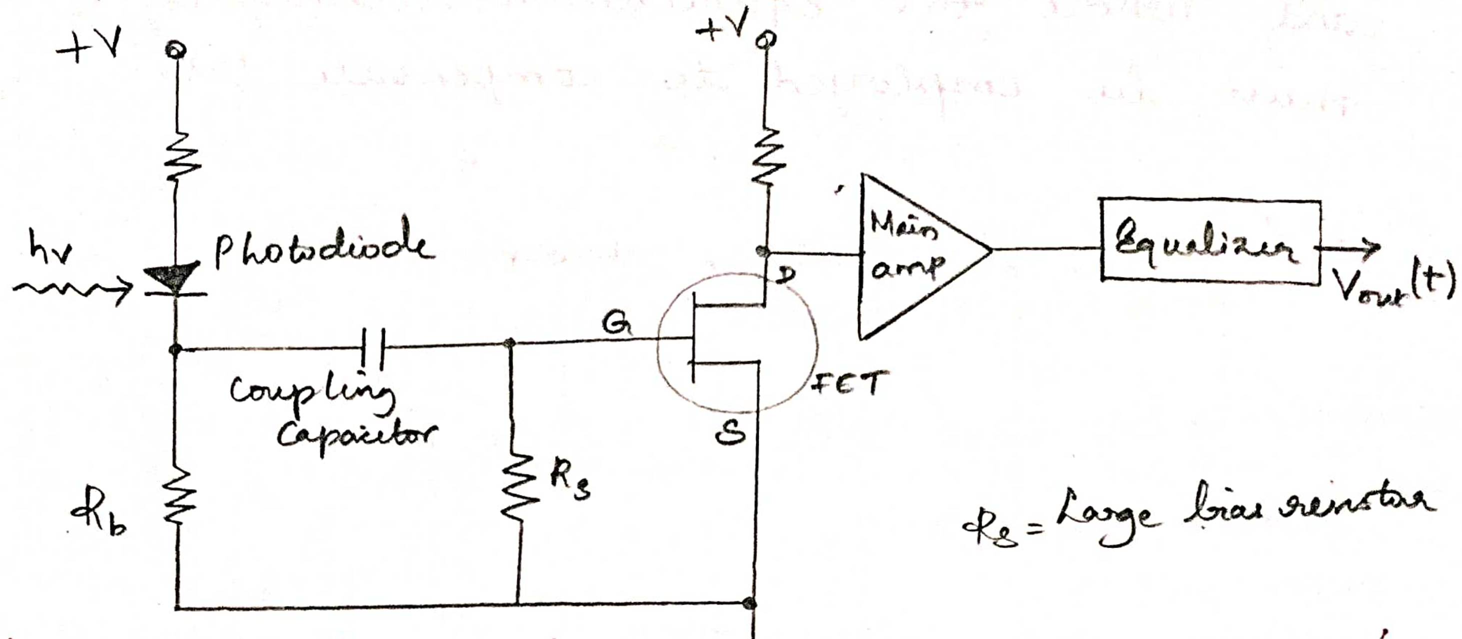


fig 4:9 Simple high-impedance preamplifier design using FET

* As the amplifier input resistance is very high; the input current noise spectral density S_I is,

$$S_{I,FET} = \frac{4k_BT}{R_a} + 2qI_{gate} \quad \text{——— (a)}$$

* FET has very large input resistance R_a usually greater than $10^6\,\Omega$ for practical purpose $R_a = \infty$, then eq (a) becomes,

$$S_{I,FET} = 2qI_{gate} \quad \text{——— (b)}$$

I_{gate} → gate leakage current of FET

* The voltage noise spectral density is expressed as,

$$S_E = \frac{4k_BT\Gamma}{g_m} \quad \text{——— (c)}$$

Γ → channel-noise factor

$g_m \rightarrow$ transconductance.

* To minimize the noise in a high impedance design, the bias resistor should be very large.

  - Effect is that the detector output signal is integrated by the amplifier input resistance.

* It is to be compensated by means of differentiators in the equalizing filter.

  - This integration - differentiation approach is known as the high - impedance amplifier design technique.

(b) HIGH IMPEDANCE BIPOLAR TRANSISTOR:

* The circuit below shows a simple bipolar grounded - emitter transistor amplifier.

  - Input resistance R_{in} of a bipolar transistor is given as,

$$R_{in} = \frac{k_B T}{q I_{BB}} \quad \text{——— (d)}$$

* Fig 4:10 shows the amplifier input resistance R_a is given by the parallel combination of the bias resistor R_1 and R_2 and the transistor input resistance R_{in}.

  - For low noise design ($R_a = R_{in}$).

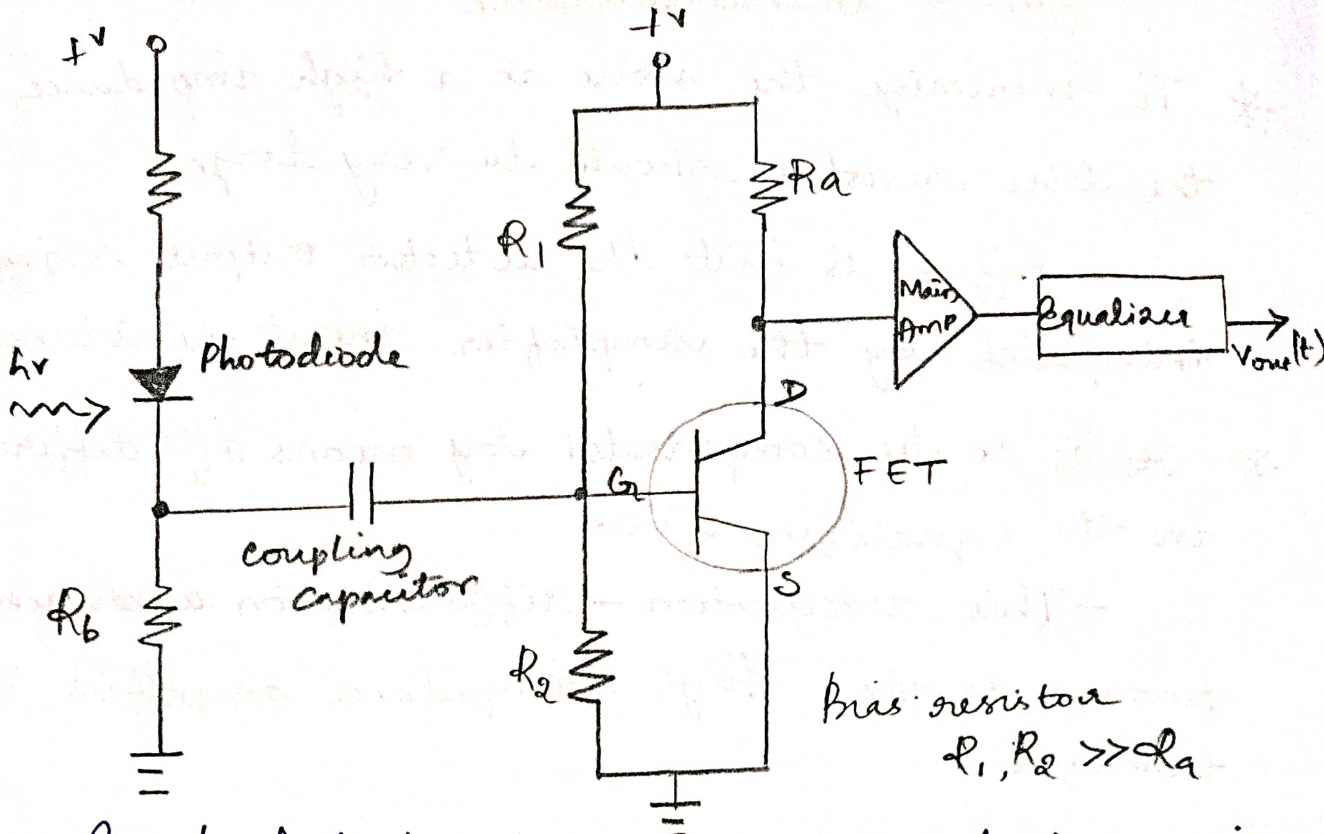


fig 4:10 Simple high-impedance preamplifier designs using a bipolar transistor

* Spectral density of the input noise current source due to shot noise of the base current is

$$S_1 = 2q\, I_{BB} \qquad \text{——— (e)}$$

from eq. (d)

$$q = \frac{K_B T}{R_{in} I_{BB}}$$ sub in eq (e) we get

$$S_1 = \frac{2 K_B T}{R_{in}} \qquad \text{——— (f)}$$

* Spectral height (V^2/Hz) of the noise voltage source is expressed as,

$$S_E = \frac{2 K_B T}{g_m} \qquad \text{——— (g)}$$

where $K_B \rightarrow$ Boltzmann constant

4:2:3 TRANSIMPEDANCE AMPLIFIER:

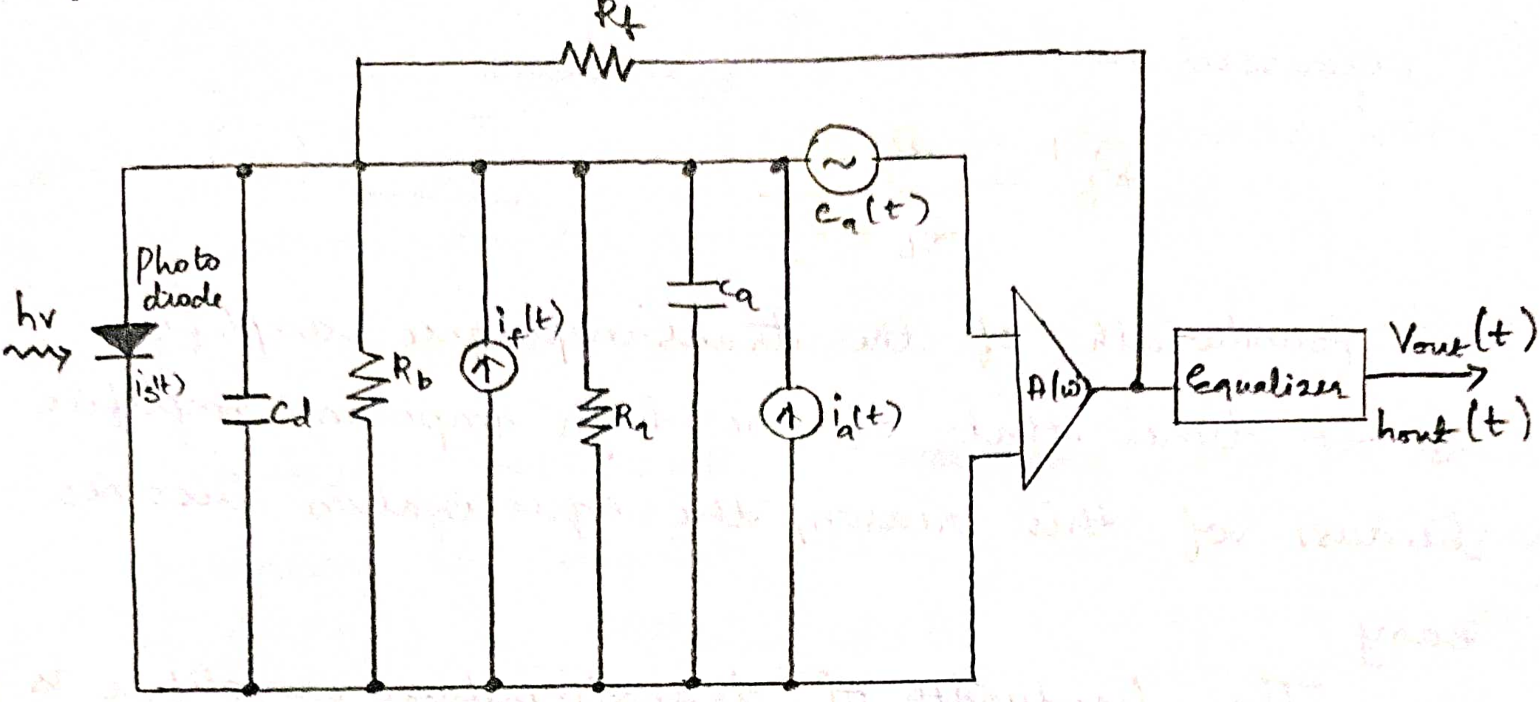


fig 4:11 An equivalent circuit of an transimpedance receiver design

* The transimpedance amplifier is nothing but the low noise high impedance amplifier with a negative feedback R_f resistor.
  - The device therefore operates as a current mode amplifier where the high input impedance is reduced by the negative feedback.
* Transimpedance amplifier design over comes the drawback of high impedance amplifier such as,
  (a) for broadband applications, equalization is required.
  (b) Limited dynamic range.

* The equalizer output resistance R_b' is expressed as,

$$R_b' = \frac{R_b R_f}{R_b + R_f} \quad \text{——— (h)}$$

– Bandwidth of the transimpedance amplifier is A times that of the high impedance amplifier because of this reason, the equalization becomes easy.

– The bandwidth of transimpedance amplifier is,

$$B_{TZ} = \frac{A}{4RC} \quad \text{——— (i)}$$

ADVANTAGES :

* Wide dynamic range
* Little or no equalization is required
* Less susceptible to pick up noise, cross talk etc
* Easy controllable & stable
* Less sensitivity.

4:3 RECEIVER CONFIGURATION:

* Digital receiver performance can be evaluated by measuring the probability of error and quantum limit.

4:3:1 PROBABILITY OF ERROR:

* Common approach to measure rate of error occurrence in digital data stream is Bit Error Rate (BER) or Error Rate.

⇒ **BIT ERROR RATE (B):**

* BER is defined as the ratio between number of errors (N_e) occurring over a certain time interval t to the number of pulses transmitted (N_t) during this interval.

$$BER = \frac{N_e}{N_t} \Rightarrow \frac{N_e}{Bt} \quad \text{——— (a)}$$

where, Bit rate, $B = \frac{1}{T_b}$ (ie pulse transmission rate).

* Error rate for optical fiber telecommunication system range from 10^{-9} to 10^{-12}.
  - Error rate depends on the S/N at the receiver.
* The probability distribution of signal at the equalizer output should be known to compute BER.

- Here, the decision is made as to whether 0 or 1 is sent.

$$P_1(V) = \int_{-\alpha}^{V} P(y/1)\,dy \quad \text{—— (b)}$$

$$P_0(V) = \int_{V}^{\alpha} P(y/0)\,dy \quad \text{—— (c)}$$

where,

$P_1(V) \rightarrow$ Probability that the equalizer o/p voltage is less than V when logical 1 is sent.

$P_0(V) \rightarrow$ Probability that the output Voltage exceeds V when logical 0 is transmitted.

* The probability distribution for received logic 0 and 1.

- functions $P(y/1)$ & $P(y/0)$ are the conditional probability distribution functions, ie $P(y/x)$ is the probability that the output voltage is y, given that an x is transmitted.

* If the threshold voltage is V_{th}, then the error probability P_e is defined as,

$$P_e = a P_1(V_{th}) + b P_0(V_{th}) \quad \text{—— (d)}$$

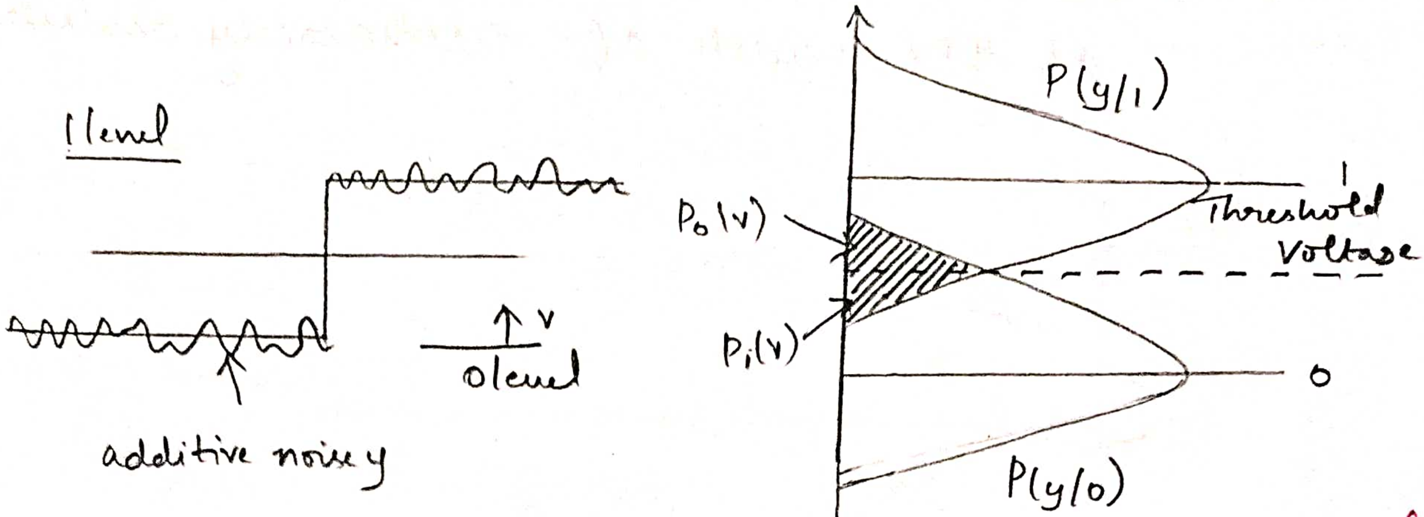


fig 4:12 Probability distribution for received logical 0 and 1 signal pulses

* Weighting factor a & b are determined by the prior distribution of the data.
 -ie, a & b are the probabilities that either 1 or 0 occurs respectively.

* To calculate P_e the mean and standard deviation of the output voltage $V_{out}(t)$ should be known.

* Let us assume that a signal "s" has gaussian probability distribution function with mean value m.

$$f(s)\,ds = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(s-m)^2}{2\sigma^2}}\,ds \qquad \text{(e)}$$

where,

$f(s) \longrightarrow$ Probability density function for signal S

$m \longrightarrow$ Mean

$\sigma^2 \rightarrow$ Noise Variance

$\sigma \rightarrow$ Standard deviation, which is a measure of the width of probability distribution.

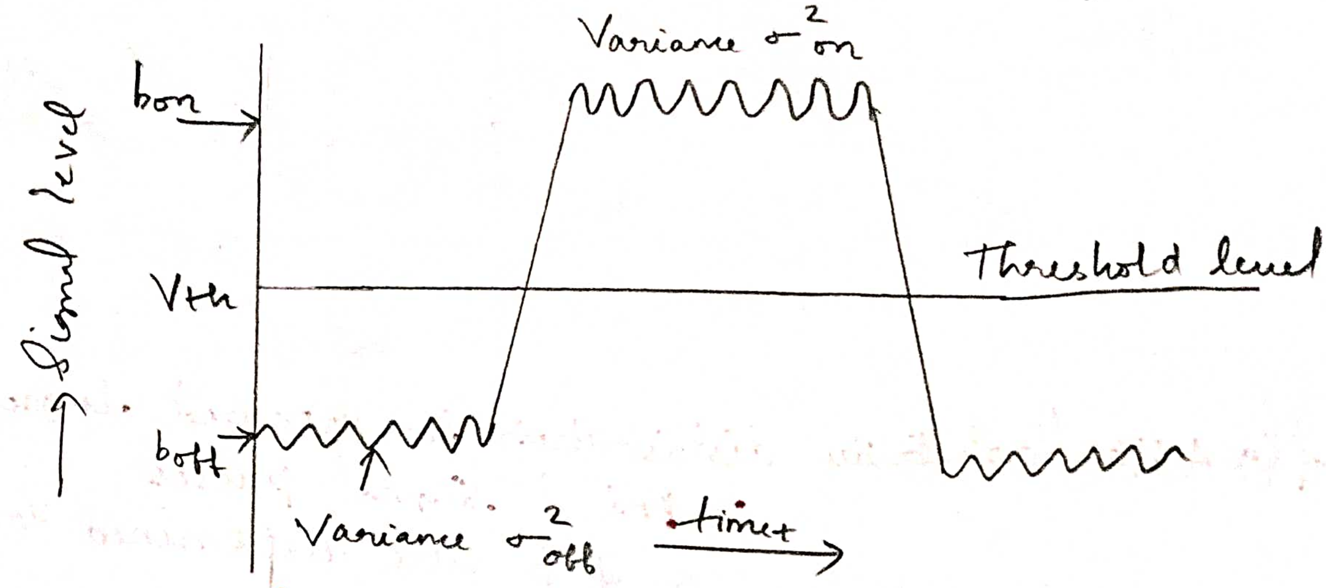


fig 4:13 Gaussian noise statistics of a binary signal showing variances about the On and Off signal levels.

* The probability density function is used to determine the probability of error for a data stream in which "1" pulses with amplitude (V).

*(Fig) shows that the mean & variance of gaussian o/p for "1" pulse are b_{on} & σ_{on}^2, where for "0" pulse b_{OFF} + σ_{OFF}^2 respectively.

→ PROBABILITY OF ERROR WHEN 0 PULSE SENT:

* Let us first consider the case of "0" pulse being sent, so that no pulse is present at the decoding time.

- Probability of error in this case is the probability that the noise will exceed then the threshold voltage V_{th} and be mistaken as "1" pulse.

- using eq (c) and (e), we get,

$$P_0(V_{th}) = \int_{V_{th}}^{\infty} p(y/0)\,dy = \int_{V_{th}}^{\infty} f_0(y)\,dy$$

$$P_0(V_{th}) = \frac{1}{\sqrt{2\pi}\sigma_{off}} \int_{V_{th}}^{\infty} \exp\left[-\frac{(v-b_{off})^2}{2\sigma_{off}^2}\right] dv \quad \text{(f)}$$

where, subscript 0 denotes the presence of 0 bit.

→ **PROBABILITY OF ERROR when 1 PULSE sent:**

* Transmitted pulse "1" is misinterpreted as 0 by decoder circuit following the equalizer,

$$P_1(V_{th}) = \int_{-\infty}^{V_{th}} p(y/1)\,dy$$

$$= \int_{-\infty}^{V_{th}} f_1(v)\,dv$$

$$P_1(V_{th}) = \frac{1}{\sqrt{2\pi}\sigma_{on}} \int_{-\infty}^{V_{th}} \exp\left[\frac{(b_{on}-v)^2}{2\sigma_{on}^2}\right] dv \quad \text{(g)}$$

Where, subscript "1" denotes the presence of 1 bit.

→ BIT ERROR RATE (BER) OR ERROR PROBABILITY (P_e):

* If probabilities of 0 & 1 pulses are equally likely then the Bit Error Rate (BER) or error probability P_e is given by,

$$BER = P_e(Q) = \frac{1}{\sqrt{\pi}} \int_{Q/\sqrt{2}}^{\infty} e^{-x^2} dx$$

$$= \frac{1}{2}\left[1 - \text{erf}\left(\frac{Q}{\sqrt{2}}\right)\right] \approx \frac{1}{\sqrt{2\pi}} \frac{e^{-\frac{Q^2}{2}}}{Q} \quad \text{—— (h)}$$

* Parameter Q is defined as,

$$Q = \frac{V_{th} - b_{off}}{\sigma_{off}} = \frac{b_{on} - V_{th}}{\sigma_{on}} \quad \text{—— (i)}$$

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy \quad \text{—— (j)}$$

* erf(x) is the error function. Since "Q" is related to the signal-to-noise ratio required to acheive a specific bit-error rate.

— when $\sigma_{off} = \sigma_{on} = \sigma$, $b_{off} = 0$, $b_{on} = V$, then $V_{th} = V/2$, $Q = V/2\sigma$

where, "σ" → Rms noise

$\frac{V}{\sigma}$ → Peak signal to Rms noise ratio.

eq (h) becomes,

$$P_e(\sigma_{on} = \sigma_{off}) = \frac{1}{2}\left[1 - \text{erf}\left(\frac{V}{2\sqrt{2}\sigma}\right)\right] \quad \text{—— (K)}.$$

4:3:2 QUANTUM LIMIT:

* For an ideal photo detector which has unity quantum efficiency and which produces no dark current, ie no electrons - hole pairs are generated in the absence of an optical pulse.
* It is possible to find the minimum received optical power required for a specific bit error rate performance in digital system.
  - This minimum received power level is known as the quantum limit.
* If an optical pulse of energy E falls on the photo detector in a time interval τ.
  - It can also be interpreted by the receiver as "0" pulse. If no electrons hole-pairs are generated.
* Probability that $n=0$ electrons are emitted in a time interval τ is,

$$P_r(0) = e^{-\bar{N}}$$

where, Average number of electron → hole pairs

$$\bar{N} = \frac{\eta E}{h\nu}$$

Optical Power Measurement

4:4 FIBER ATTENUATION MEASUREMENTS :-

* Fiber attenuation measurement techniques are used in order to determine the total fiber attenuation loss due to both absorption losses and scattering losses.

* Overall fiber attenuation is important to system designer, to determine attenuation in fiber three major techniques are used.

  i) Cutback technique
  ii) Insertion Loss method
  iii) Optical time domain Reflectometers (OTDR's) trace.

i) CUTBACK TECHNIQUE:

* Cutback technique is a destructive method requiring access to both ends of the fibers for measuring attenuation.

* To find the transmission loss, the optical power is measured first at the output of the fiber as shown in fig 4.

* Without disturbing the i/p condition, the fiber is cut off of few meter's from the source and the output power at this end is measured.

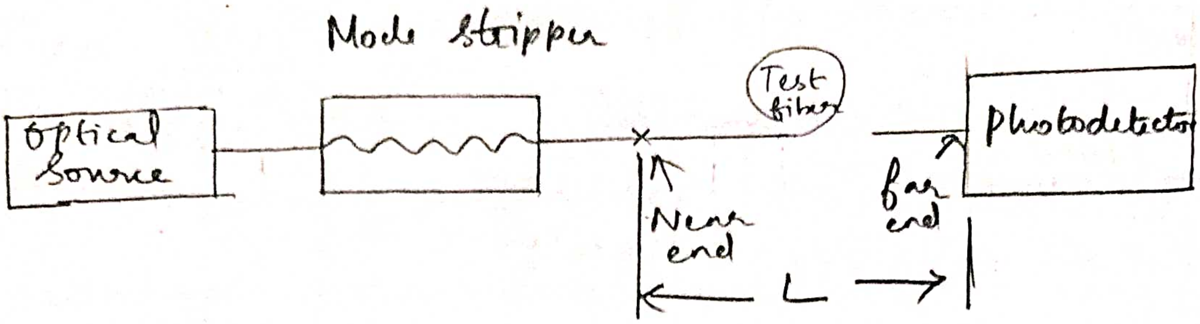


fig 4:14 Experimental Setup of cutback method

* Let P_F & P_N represent the output power at far and near end of the fiber respectively.

- Then the attenuation α in decibels per kilometer is expressed as,

$$\alpha = \frac{10}{L} \log \frac{P_N}{P_F}$$

where, L → Seperation distance of two measurement point (in km)

ii) INSERTION LOSS METHOD :

* Optical fiber cables with connectors, the cutback method for attenuation measurement is not suitable.
- In this case, insertion loss technique is used.

* When comparing to cut back method, this is a less accurate method but it gives the total attenuation of a cable in decibels.

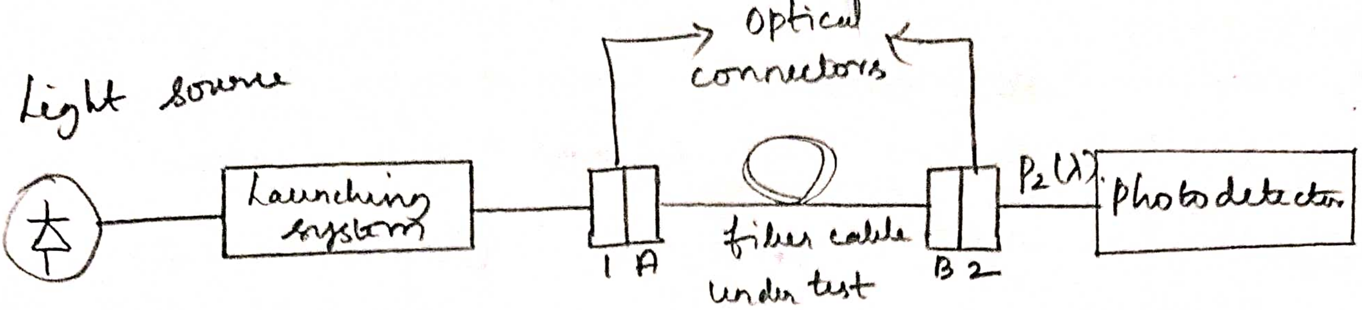


fig 4:15(b) Cable attenuation Measurement

* The launching system is used to launch the light signal into an optical fiber.
  - The launching system and detector are coupled, which is made through optical connectors.

* The wavelength - tunable light source is coupled to a short length of fiber that has the same characteristics as the fiber tested.

* For multimode fiber, a mode scrambler is used to ensure that the fiber core contains an equillibruim - mode distribution.

* In single-mode fiber, a cladding-mode stripper is employed so that the fundamental mode is allowed to propogate along the fiber.

* Wavelength - Selective device is an optical

fiber generally used to find out the atte-nuation as a function of wavelength.

* First, the connector of the short-length launching fiber is attached to the connector of the receiving system and the corresponding launching power level $P_1(\lambda)$ is recorded.

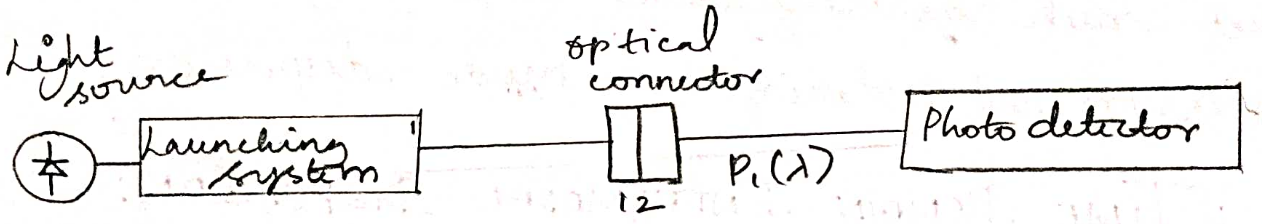


fig 4:15(a) Reference Measurement

* The cable to be tested is connected between the launching and receiving system and the received-power level $P_2(\lambda)$ is recorded.

— The attenuation of the cable in decibels is expressed as,

$$\alpha = 10 \log \frac{P_1(\lambda)}{P_2(\lambda)}$$

* This attenuation is the sum of the loss of the cabled fiber and the connector between the launch connector and the cable.

4:5 DISPERSION MEASUREMENTS:

* Three basic forms of dispersion produce pulse broadening of light wave signals in an optical fiber, thereby limiting the informating carrying capacity.
* There are many ways to measure the dispersion effect such as intermodal dispersion, chromatic dispersion and polarization mode dispersion.

4.5.1 : TIME DOMAIN INTERMODAL DISPERSION:

* The simplest approach for making pulse-dispersion measurement in the time domain is to inject a narrow pulse of an optical energy into one end of an optical fiber and detect the broadened output pulse at other end.

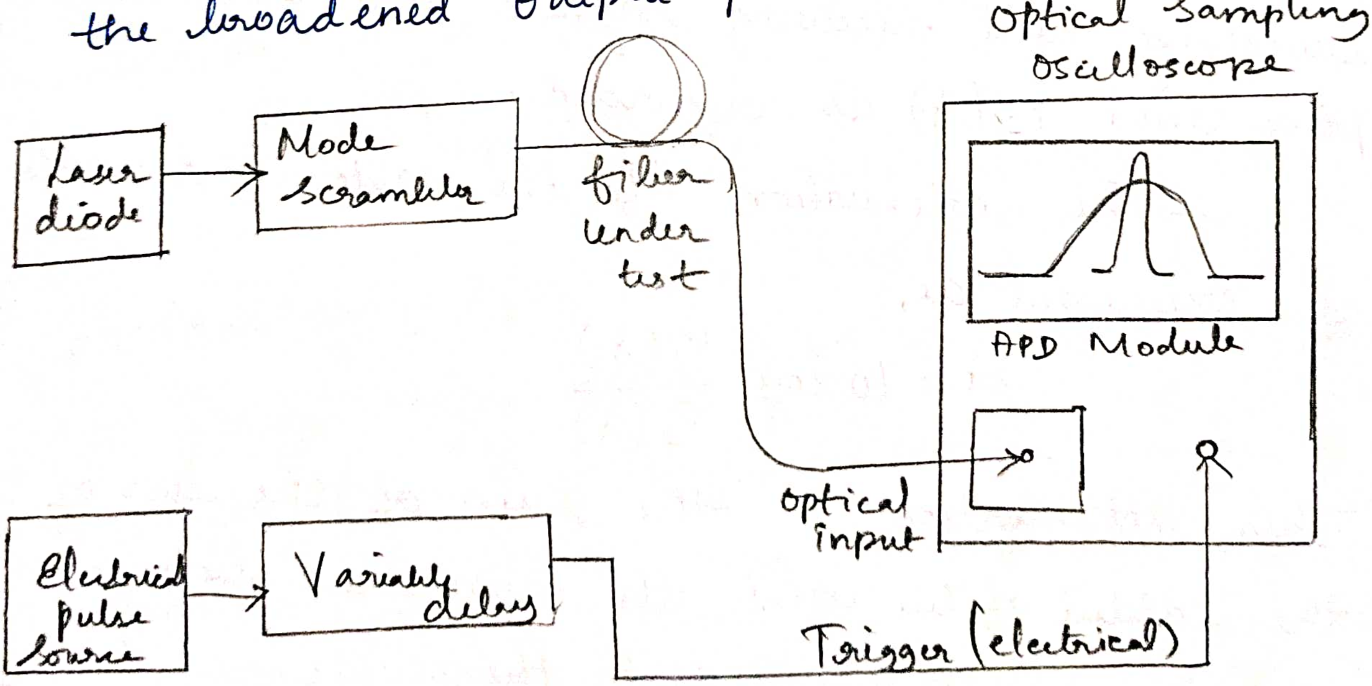


fig 4:16 Test setup for making pulse-dispersion measurements in the time-domain

* The output pulses from a laser source are coupled a mode scrambler into 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 (APD) 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 percent of the test fiber length.
* Assume that the output response of a fiber can be approximated by a gaussian and it is expressed as,

$$P_{out}(t) = \frac{1}{\sigma\sqrt{2\pi}} = \exp\left(-\frac{t^2}{2\sigma^2}\right) \quad \text{——— (1)}$$

where $\sigma \rightarrow$ rms pulse width

DETERMINATION OF RMS PULSE WIDTH (σ):

* Assume that the optical power emerging from the fiber has a gaussian temporal response given by,

$$g(t) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{t^2}{2\sigma^2}} \quad \text{——— (2)}$$

from eq (2), time ($t_{1/2}$) required for the pulse to reach its half maximum value, ie the time required to have,

$$g(t_{1/2}) = 0.5 g(0) \quad \text{——— (3)}$$

it is given by, $t_{1/2} = (2 \ln 2)^{1/2} \sigma$ ——— (4)

$$t_{FWHM} = 2t_{1/2} = 2\sigma(2 \ln 2)^{1/2} \quad \text{——— (5)}$$

where, t_{FWHM} → full width of the pulse at its half maximum value.

Relation between t_{FWHM} and 3 dB Optical Bandwidth:

* 3 dB optical bandwidth 3dB is defined as, the modulation frequency f_{3dB} at which the received optical power has fallen to 0.5 of the zero frequency value.

$$f_{3dB\ optical} = \frac{0.440}{t_{FWHM}} = \frac{0.187}{\sigma} \text{ Hz} \quad \text{——— (6)}$$

where, 3 dB optical → means 50% optical power reduction.

* Electrical bandwidth are related to Optical bandwidth by $1/\sqrt{2}$, so that

$$f_{3dB\ electrical} = \frac{1}{\sqrt{2}} f_{3dB\ optical} = \frac{0.311}{t_{FWHM}} = \frac{0.133}{\sigma} \text{ Hz}$$

——— (7)

4:6 FIBER REFRACTIVE INDEX PROFILE MEASUREMENTS:

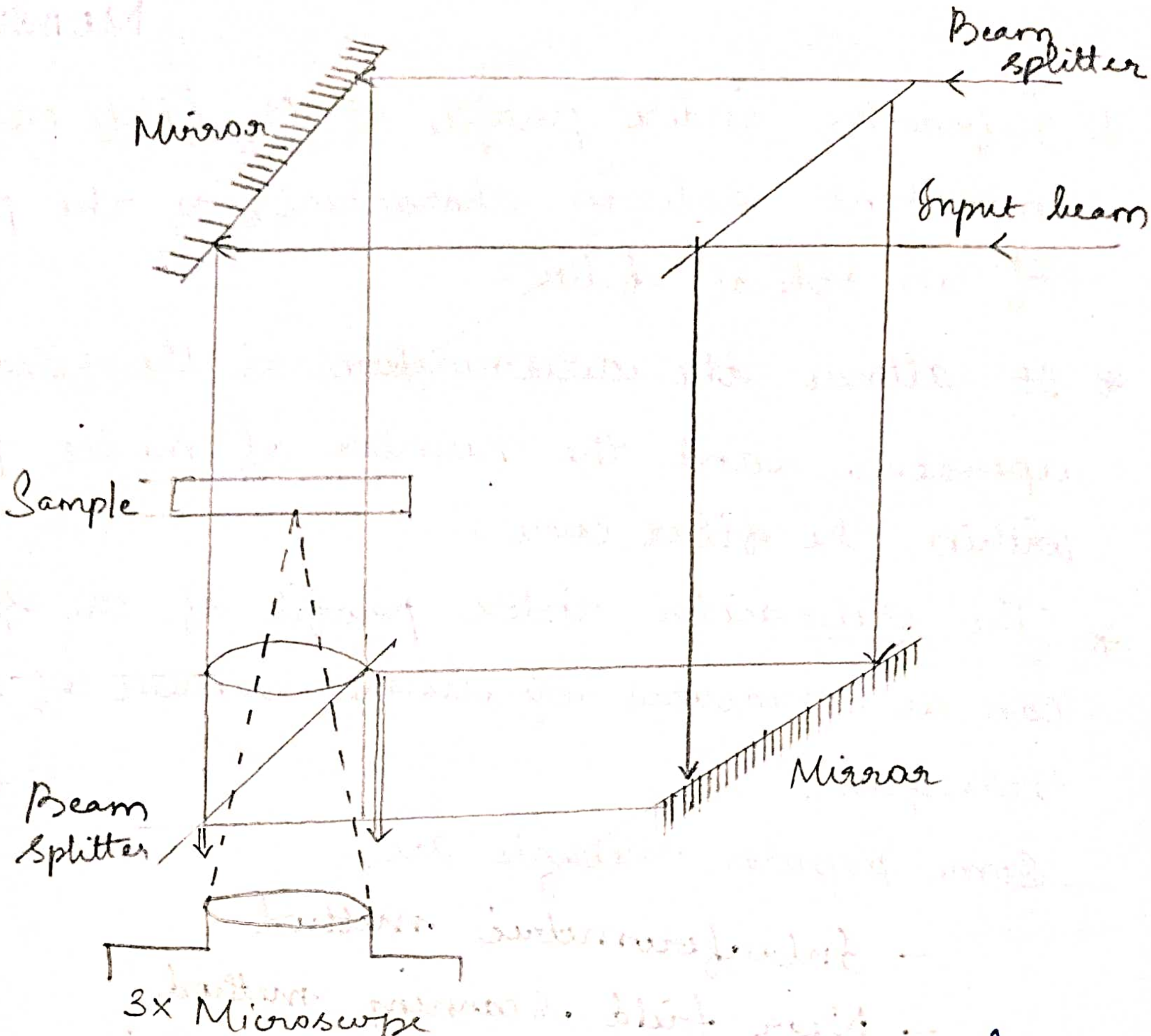
* Refractive index profile of the fiber core play an important role in characterizing the properties of an optical fiber.
* It allows the determination of the fiber's numerical aperature and the number of modes propogating within the fiber core.
* The refractive index profile of the fiber core can be measured by using number of different techniques.

- Some popular methods are,
    - Interferometric method
    - Near field scanning method
    - Refracted near field method

i) INTERFEROMERIC METHODS :-

* Interference microscopes (Mach - Zehnder) are widely used to determine the refractive index profile of optical fibers.
* A thin slice of fiber (slab) with both ends accurately polished to obtain optically flat surfaces.
* The slab is often immersed in an index matching fluid, and then an assembly is examined with an interface microscope.

Fig 4:17 Principle of the Mach-Zehnder Interferometer



* It is using either a transmitted light interferometer or a reflected light from the interferometre.
* In both cases, light from the microscope travels normal to the prepared fiber faces.
* When the phase of the incident light is compared with the phase of the emerging light a field of parallel interference fringes is observed.
* The fringe displacement for the points within the fiber core are then measured using a reference namely the parallel fringes outside the fiber core.

* Refractive index difference between a point in the fiber core and the cladding can be obtained from the fringe shift q, which corresponds to a number of fringe displacement.
* The difference in refractive index δn is given by,

$$\delta n = \frac{q\lambda}{x}$$

where, $x \rightarrow$ thickness of the fiber slab

$\lambda \rightarrow$ incident optical wavelength

2) NEAR FIELD SCANNING METHOD :

* Near field scanning or transmitted near field method utilizes the close resemblance that exists between the near field intensity distribution and the refractive index profile for a fiber with all the guided modes equally illuminated.
* Lambertain Source (LED) is focused on to the end of the fiber using a microscope objective lens
* Magnified image of the fiber output end is displayed in the plane of a small active area photodetector.

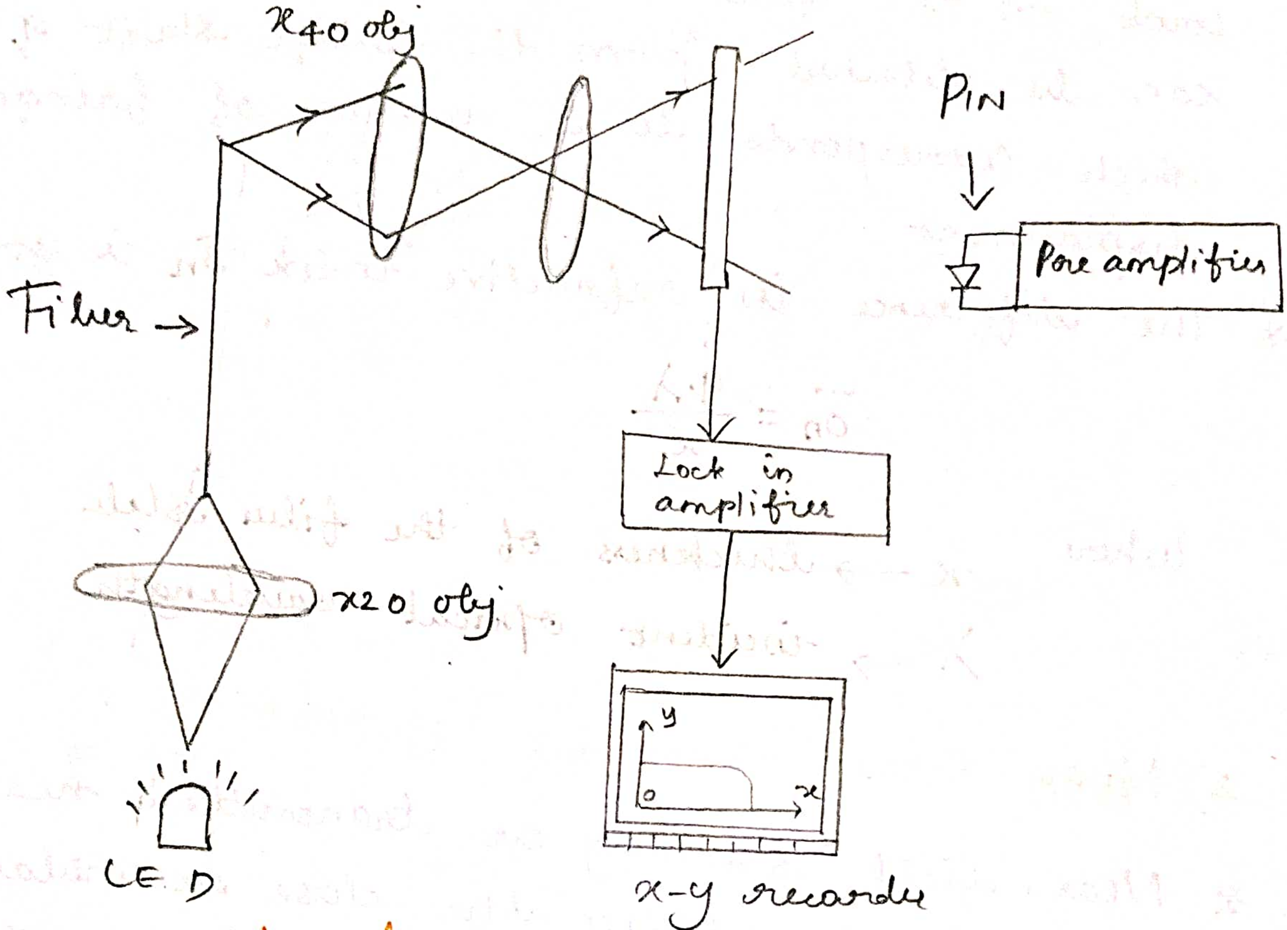


fig 4:18 Near field Scanning measurements of refractive index profile

* Photodetector which Scans the field transversely receives an amplification from the phase Sensitive combination of the optical chopper and lock-in amplifier.

* The refractive index profile may be plotted directly on an X-Y recorder.

3) REFRACTED NEAR FIELD METHOD :

* Short length of the fiber is immersed in the

a cell containing a fluid of slightly higher refractive index.

* Small spot of light typically emitted from 633 nm helium neon laser for best resolution is scanned across the cross sectional diameter of the fiber.

* Measurement technique utilizes that light which is not guided by the fiber but escapes from the core into the cladding.

* Light escaping from the fiber core partly results from the power leakage from the leaky modes which is an unknown quantity.

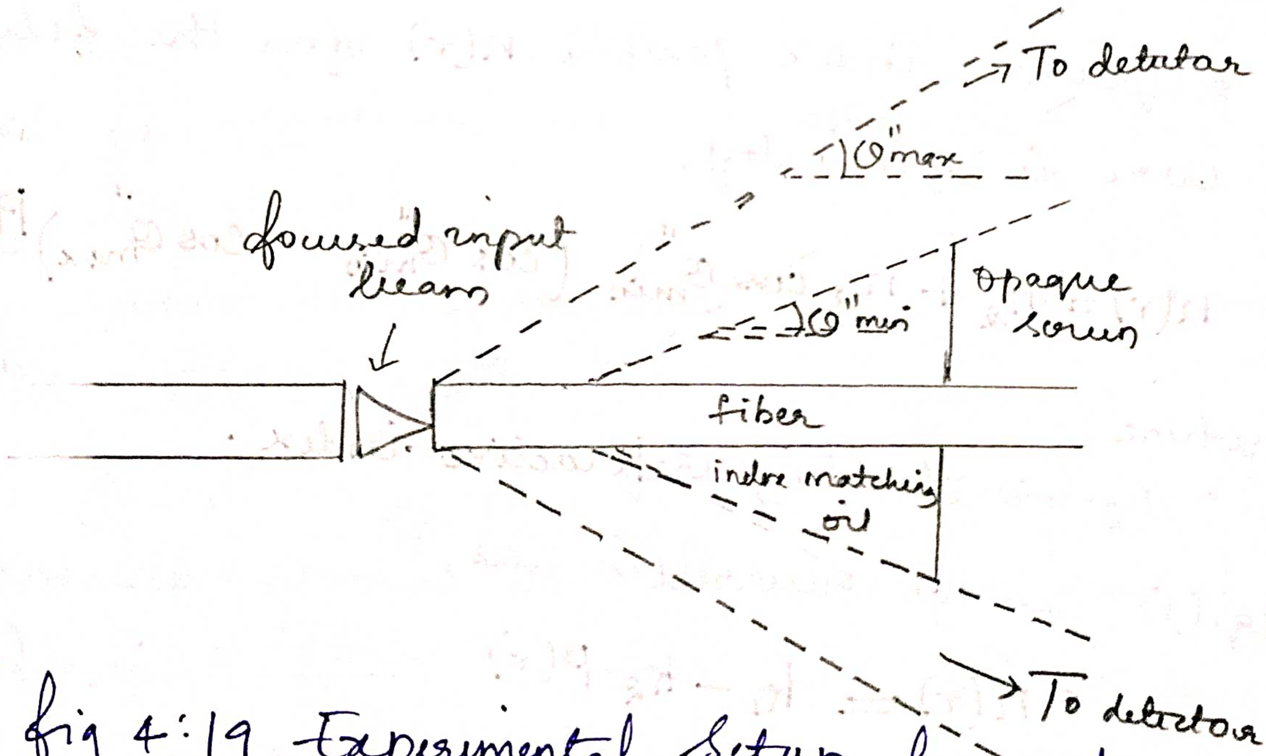


fig 4:19 Experimental Setup for refracted near field method

* Effect of this radiated power reaching the detector is undesirable and therefore it is blocked using an opaque circular screen.

* All the refracted light emitted from the fiber at angles over the range θ_{min} to θ_{max} may be detected.

* Detected optical power as a function of the radial position of the input beam $P(r)$ is measured and value $P(a)$ corresponding to the input beam being focused into the cladding is also obtained.

* Refractive index profile $n(r)$ for the fiber core is given by,

$$n(r) = n_2 + n_2 \cos\theta''_{min} \left(\cos\theta''_{min} - \cos\theta''_{max}\right) \frac{P(a) - P(r)}{P(a)} \quad \text{——— (a)}$$

where,

$n_2 \rightarrow$ cladding refractive index.

eq (1) can be rewritten as,

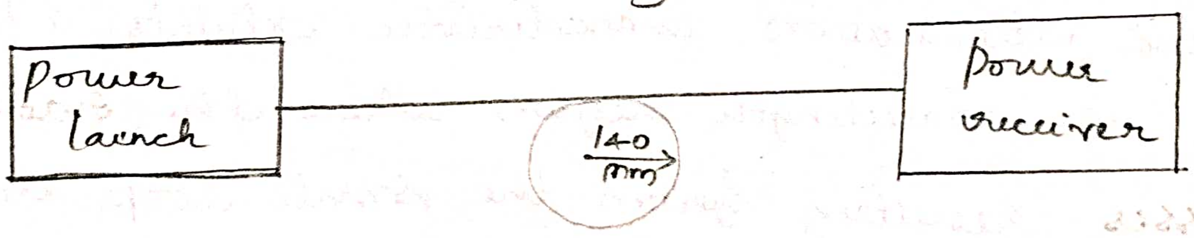
$$n(r) = k_1 - k_2 P(r) \quad \text{——— (b)}$$

$n(r)$ is proportional to $P(r)$ and hence the measurement system can be calibrated to obtain the constants k_1 and k_2.

4:7 FIBER CUTOFF WAVELENGTH MEASUREMENT

* Multimode fiber has many cut-off wavelength because the number of bound propogating modes is usually large.
* cut-off wavelength of Lim mode is the maximum wavelength for which the mode is guided by the fiber.
* cut off wavelength in LP_{11} (longest cutoff wavelength) that makes single moded fiber when the fiber diameter is reduced 8 – 9 µm.
* Configuration for the measurement of uncabled fiber cutoff wavelength for single turn and split mandrell is shown in fig 4:

(a) Single turn



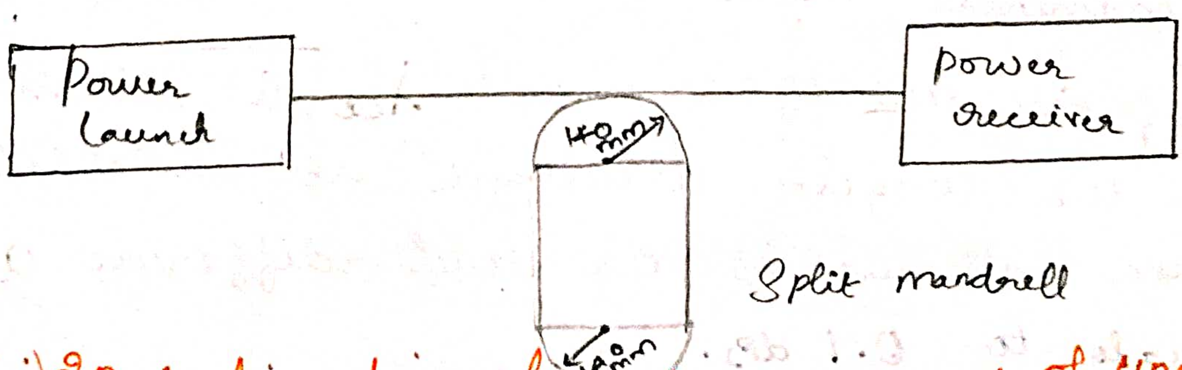


fig 4:20 Configurations for the measurement of uncabled fiber cutoff wavelength

* In the bending reference technique the power $P_s(\lambda)$ is transmitted through the fiber sample and it is measured as a function of wavelength
- The quantity of $P_s(\lambda)$ corresponds to the total power.
* Smaller transmitted power $P_b(\lambda)$ is measured which correspond to the fundamental mode power.
* Bend attenuation $a_b(\lambda)$ comprising the level difference between the total power and the fundamental power is calculated as,

$$a_b(\lambda) = 10 \log_{10} \frac{P_s(\lambda)}{P_b(\lambda)}$$

* Bend attenuation characteristic exhibits a peak in the wavelength region where the radiation losses resulting from the small loop are much higher for the LP_{11} mode than for the LP_{01} fundamental mode.
* Effective cut-off wavelength λ_{ce} is determined as the longest wavelength at which the bend attenuation or level difference $a_b(\lambda)$ equals to 0.1 dB.

4.8 FIBER NUMERICAL APERTURE MEASUREMENTS :

* Numerical aperture is an optical fiber parameter as it affects the characteristics such as light gathering efficiency and normalized frequency of the fiber (V).

* For step index fiber in air, Numerical aperture (NA) is expressed as,

$$NA = \sin \theta_a$$

$$NA = (n_1^2 - n_2^2)^{1/2} \qquad (1)$$

where,

$\theta_a \rightarrow$ maximum acceptance angle

$n_1 \rightarrow$ core refractive index

$n_2 \rightarrow$ cladding refractive index.

* In eq (1), that the light is incident of the fiber end face from air with a refractive index (n_0) of unity.

* In graded index fiber, local NA's are the refractive index changes radially from core axis.

* In general, a graded index fiber these local numerical aperture NA(r) at different radial distance r from the core axis expressed as,

$$NA(r) = \sin \theta_a(r) = (n_1^2(r) - n_2^2)^{1/2} \qquad (2)$$

* Commonly used techniques for determination of fiber NA are,

i) Measurement of the far field radiation pattern from fiber

ii) Trignometric fiber numerical aperture measurement.

1) MEASUREMENT OF THE FAR FIELD RADIATION PATTERN FROM FIBER :-

* The method involves direct measurement of far field angle from the fiber using a rotating stage.
* 2m length of graded index fiber with smooth faces and the fiber output end is then positioned on the rotating stage as shown below, fig 4:

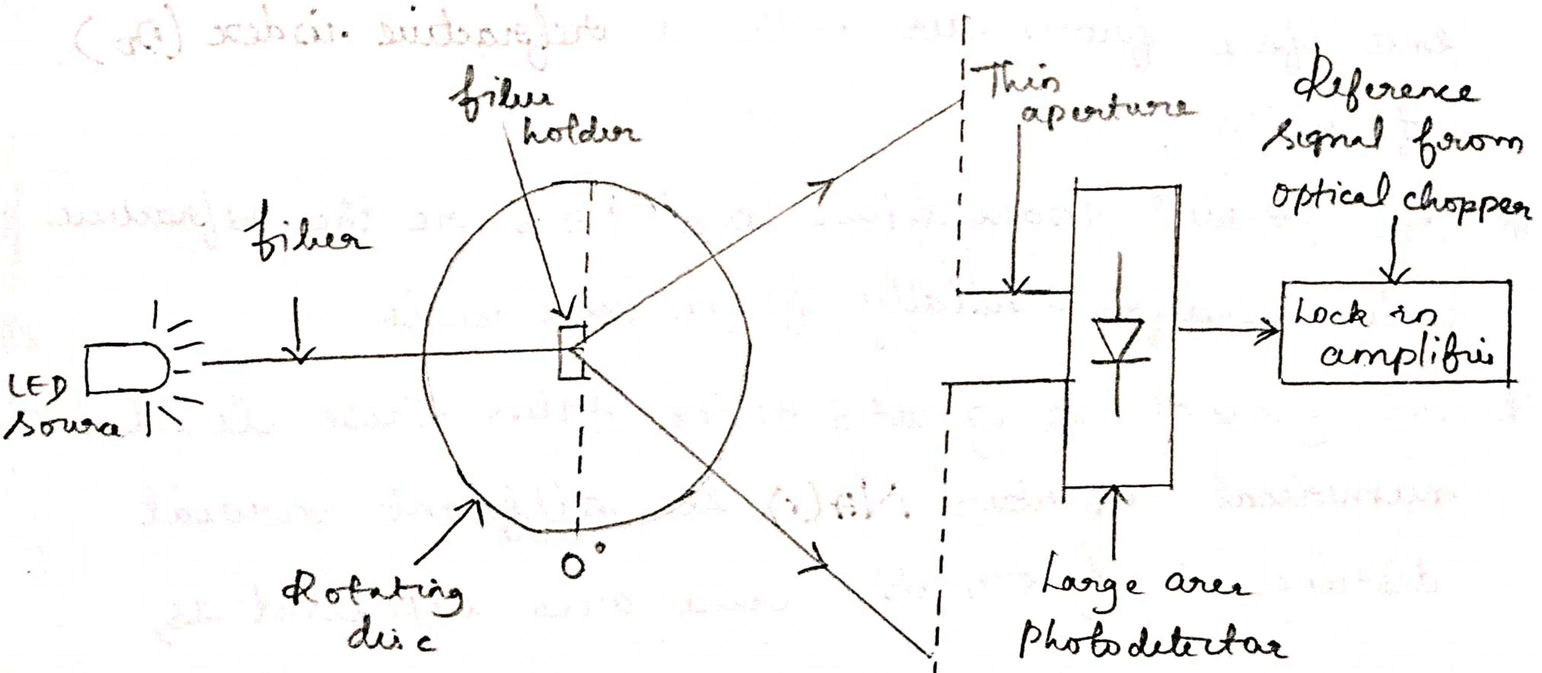


fig 4:21 Fiber numerical aperture measurements using rotating stage

* End face of fiber is parallel to the plane of the photodetector input and its output is perpendicular to the axis of rotation.
* Light at a wavelength of 0.85 μm is launched into the fiber at all possible angles.
* The photodetector, which may be either a small area device or an apertured large area device is placed 10 to 20 cm from the fiber and it is positioned in order to obtain a maximum signal with no rotation (0°).
* When rotating disc is turned, the far field pattern may be recorded.
  – The output power is monitored and it is plotted as a function of angle.
* The maximum acceptance angle is recorded, when the power drops to 5% of maximum intensity.

II) TRIGNOMETRIC FIBER NUMERICAL APERTURE MEASUREMENT:

* The end prepared fiber is located on an optical base plate or slab.
  – The light is launched into the fiber under test over the full range of its numerical aperture, and the far field from the fiber is

displayed on a screen which is positioned at a known distance D from the fiber output end face.

* The test fiber is then aligned, so that the optical intensity on the screen is maximized.
* Finally, the pattern size on the screen A is measured using a calibrated vernier caliper.
* Numerical aperture can be obtained from simple trignometrical relationships,

$$NA = \sin \theta_a$$

$$= \frac{A/2}{\left[(A/2)^2 + D^2\right]^{1/2}} \Rightarrow \frac{A}{(A^2+4D^2)^{1/2}}$$

Where, D → Distance of screen located from the fiber output end faces

A → Pattern size on the screen

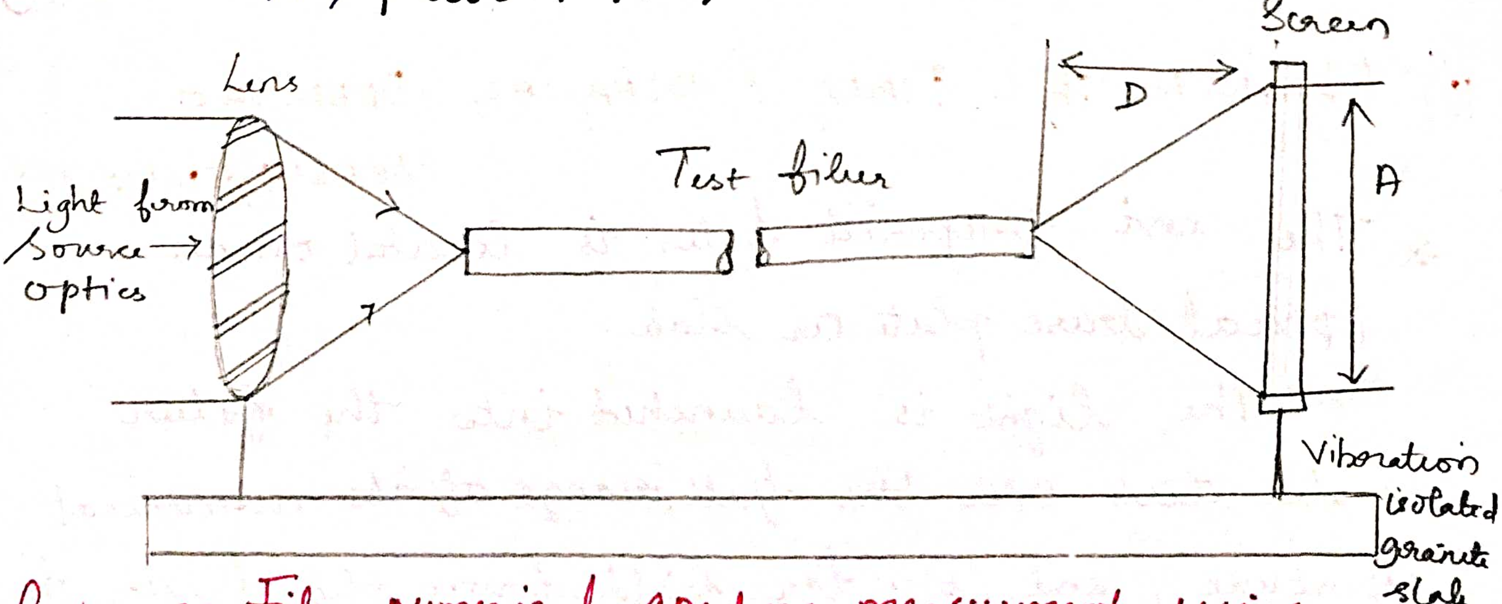


fig 4:22 Fiber numerical aperture measurements using rotating stage

4:9 FIBER DIAMETER MEASUREMENTS :

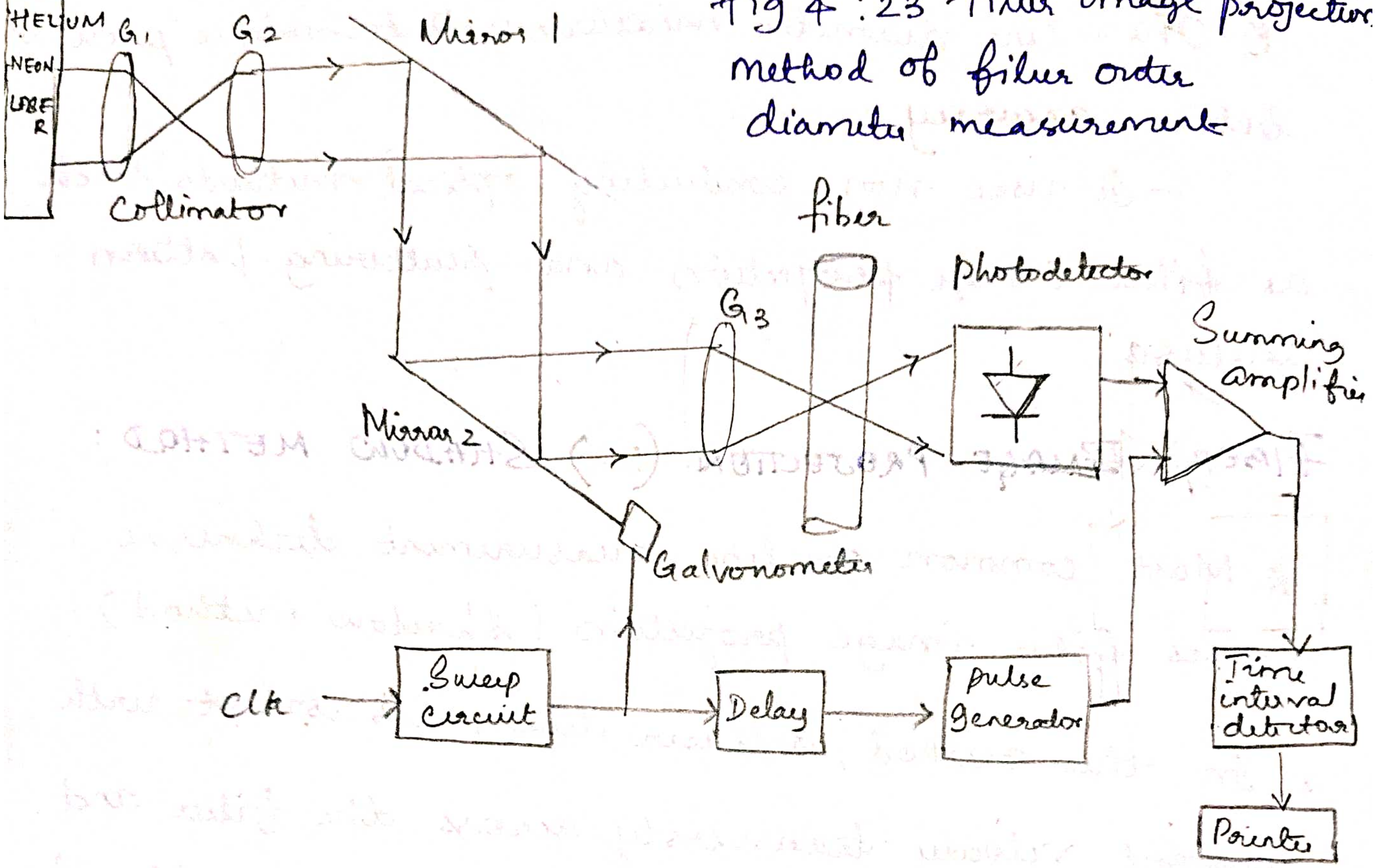
* One-line diameter measurement technique provide better accuracy
  - It uses non-conducting optical methods such as fiber image projection and scattering pattern analysis.

FIBER IMAGE PROJECTION (or) SHADOW METHOD :

* Most common on line measurement technique uses fiber image projection (Shadow method)
* In this method, a laser beam is swept with constant velocity transversely across the fiber and a measurement is done at definite time interval when fiber intercepts the beam and creates a shadow on the photo detector.
* A laser beam operating at 632 nm is collimated using two lenses G_1 and G_2.
  - The beam is then reflected by two mirror M_1 & M_2.
* Second mirror M_2 is driven by galvanometer which makes it rotate through a small angle at a constant angular velocity before returning

to its original starting position.

fig 4:23 fiber image projection method of fiber outer diameter measurement



* Laser beam which is focused in the plane of the fiber by lens G_3 and swept across the fiber by oscillating mirror.

* The beam incident on the photodetector unless it is blocked by the fiber.

* The velocity $\frac{ds}{dt}$ of the fiber shadow thus created at the photo-detector is directly proportional to the mirror velocity $d\phi/dt$

$$\frac{ds}{dt} = l \frac{d\phi}{dt} \quad \text{——— (1)}$$

$l \rightarrow$ distance between mirror and photo detector

* Shadow is registered by the photo-detector as an electrical pulse of width W_e which is related to the fiber outer diameter d_o and it is expressed as,

$$d_o = W_e \frac{ds}{dt} \qquad (2)$$

Thus, the fiber outer diameter may be determined & recorded on the pointer.

(44)

$$P_{s,out} \le \min\left\{P_{s,in}\exp(\rho\sigma_e L),\ P_{s,in} + \frac{\lambda_p}{\lambda_s}P_{p,in}\right\}.$$

(4)

* In the below fig 3:30 as the fiber length increases for low pumping power, the gain starts decreasing after certain length because the pump become week and not able to create a complete population inversion in the downward portion of the amplifier.

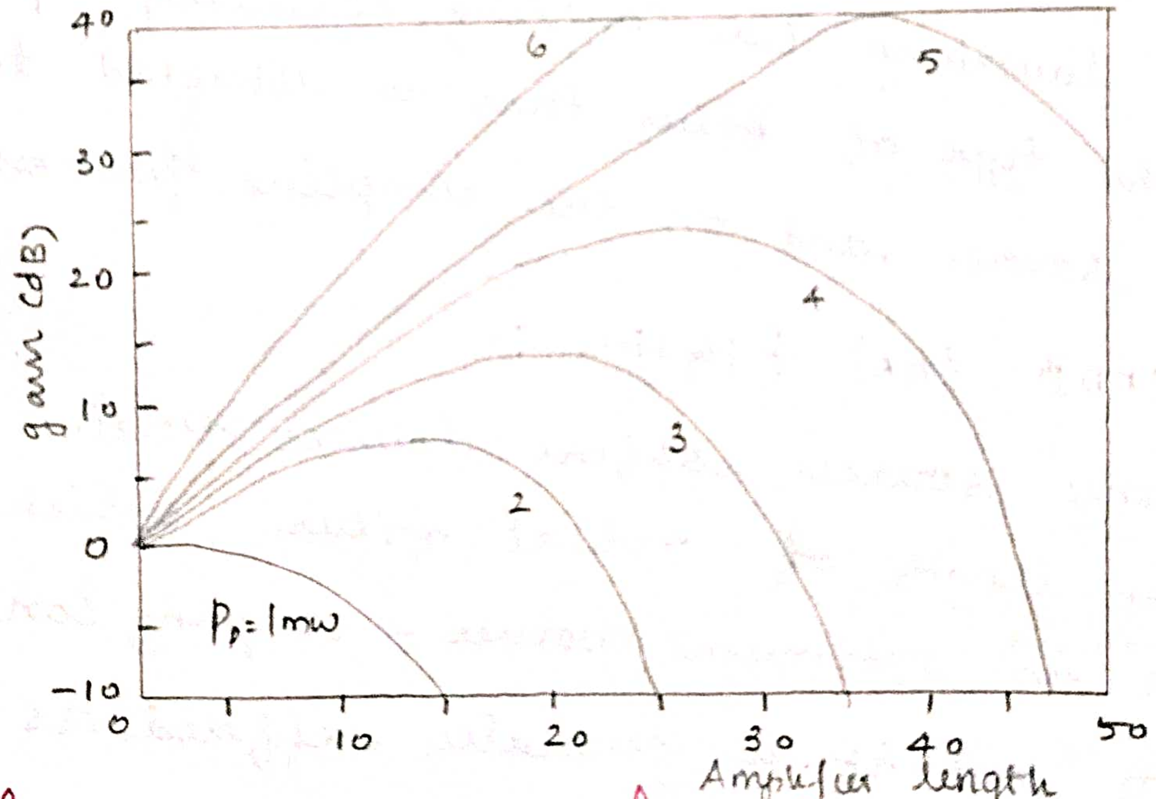


fig 3:30 EDFA gain on fiber length and pump power for 1480 nm pump and 1550 nm signal.

3:15 POWER LAUNCHING AND COUPLING :-

⇒ COUPLING EFFIENCY (η_F) :-

* It is defined as "measure of the amount of optical power emitted from a source that can be coupled into fiber". It is expressed as,

$$\eta_F = \frac{P_F}{P_S} \quad \text{——— (1)}$$

where,

P_F → power coupled into the fiber

P_S → power emitted from the light source.

* The launching or coupling efficiency depends on the type of fiber that is attached to the source and on the coupling process.

⇒ FLYLEAD (OR) PIGTAIL :-

* Many sources offers devices with short length of optical fiber, which is used in optimum power - coupling configuration and it is generally reffered as flylead or pigtail.

* This flylead sources reduces many

power - launching problems and make the coupling easier.

* SOURCE TO FIBER POWER LAUNCHING :-

- Launching of optical power from the source into fiber depends on,

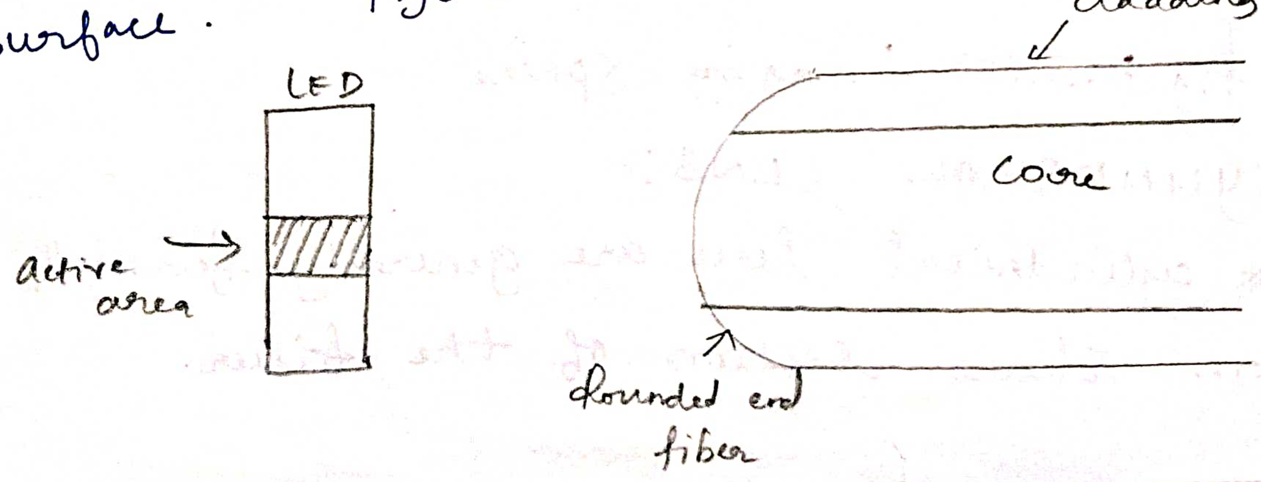
i) Numerical aperture (NA)
ii) Core size
iii) Refractive index profile
iv) core cladding index difference of the fiber
v) Radiance
vi) Alignment between source & fiber
vii) Wavelength

3:16 LENSING SCHEMES :-

i) ROUNDED - END FIBER :

* The fiber itself rounded known as rounded end fiber.
- Here whole radiation from LED emitting area is incident fully on the fiber end surface.

fig 3:31(a) Rounded end fiber



2) NON IMAGINE MICROSPHERE :-

* Small glass sphere gets contact with both the fiber and the source, to couple the maximum power.

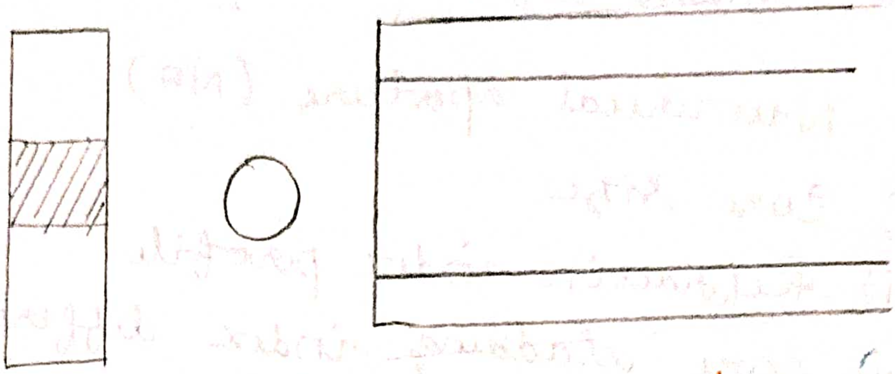


fig 3:31(b) Non imaging microsphere

3) IMAGING SPHERE :-

* A large spherical lens is used to image the source on the core area of the source.

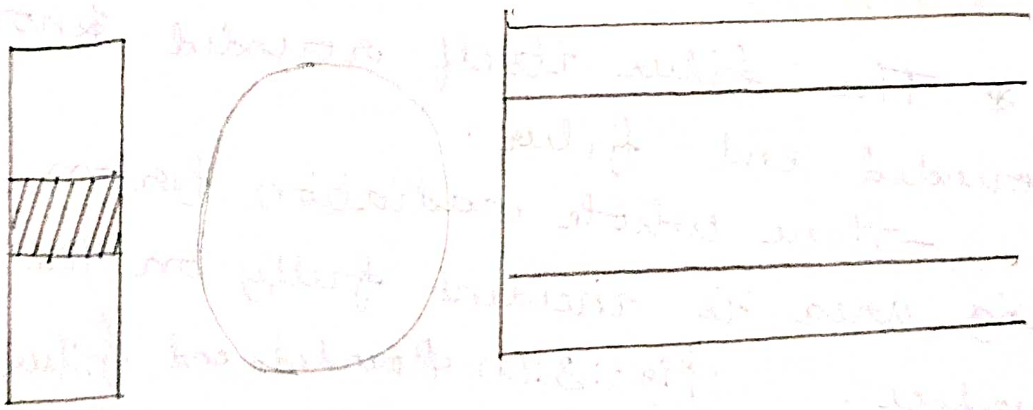


fig 3:31(c) Imaging Sphere

4) CYLINDRICAL LENS :-

* cylindrical lens are generally formed from short section of the fiber.

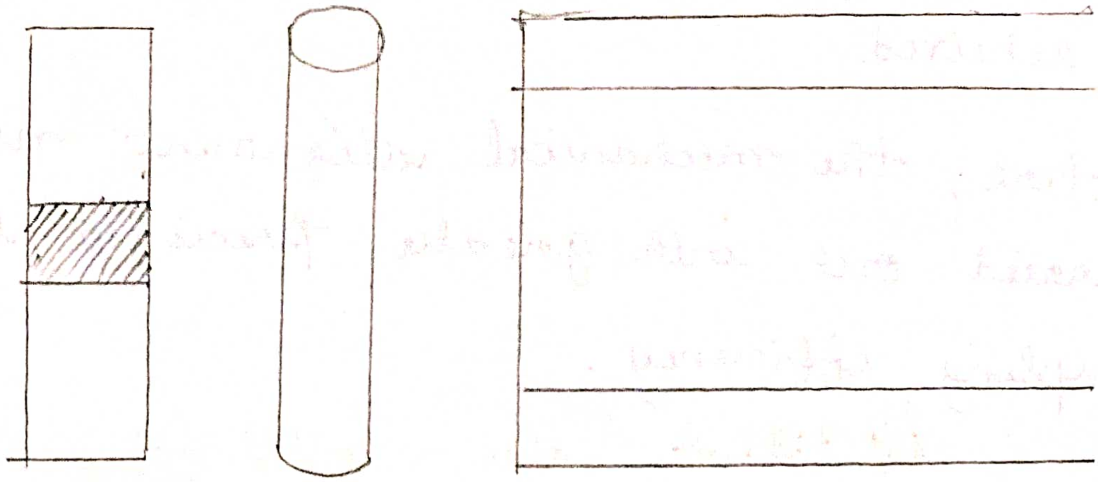


fig 3:31 d) Cylindrical Lens

5) SPHERICAL - SURFACE LED AND SPHERICAL ENDED FIBER :-

* Here, both the LED and fiber ends are Spherically shaped to couple the maximum power.

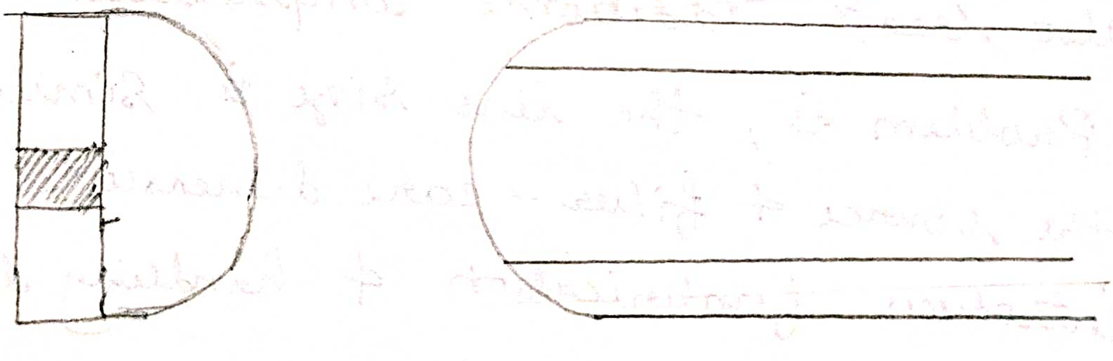


fig 3.31 e) Spherical Surfaced LED & Spherical ended fiber

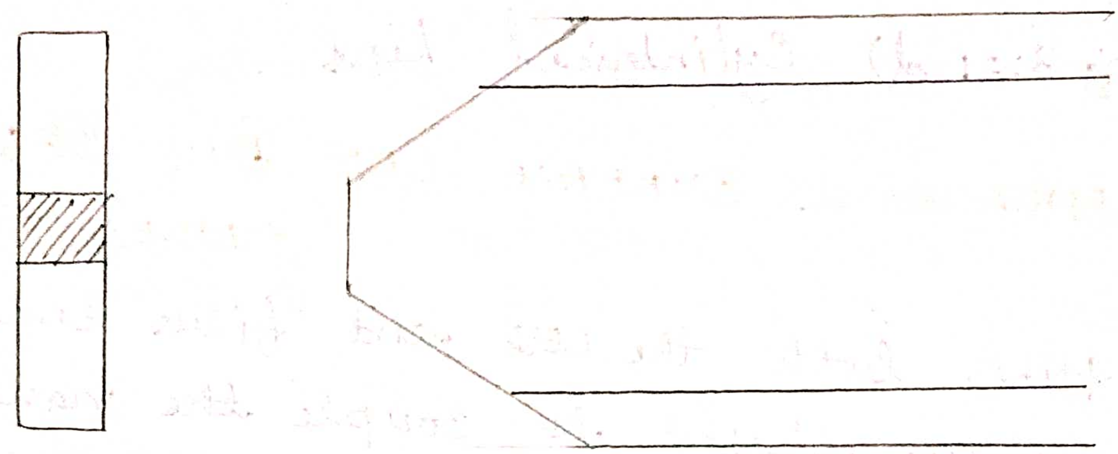
6) TAPER - ENDED FIBER :-

* If the width of taper ended fiber is equal to the width of the emitting surface

of the LED, the maximum coupling efficiency is acheived.

* Here, the mechanical alignment must be carried out with greater precision to acheive coupling efficiency.

fig 3:31 f Taper - ended fiber



* All the above techniques improves the source - to - fiber coupling efficiency they also create additional complexities.

* Problem is, the lens size is similar to the source & fiber - core dimensions which introduces fabrication & handling difficulties.

3:17 FIBER TO FIBER JOINTS :-

* Optical fiber link is used for both joining and termination of the transmission medium.

— Number of intermediate fiber connections or joints is dependent upon the link length.

* Interconnections normally occur at,
  - → optical source
  - → Photo detector
  - → intermediate points within cable where two fibers are jointed
  - → points where two cables are connected.

⇒ TWO MAJOR CATEGORIES OF FIBER JOINT :-

(a) FIBER SPLICES :-

* These are semi permanent or permanent joints which find major use is most optical fiber telecommunication systems.

(b) DEMOUNTABLE FIBER CONNECTORS (OR) SIMPLE CONNECTORS :-

* These are removable joints which allow easy, fast, manual coupling and uncoupling fibers.

⇒ OPTICAL POWER LOSSES AT THE JOINTS DEPENDS ON THE PARAMETERS :-

- Input power distribution at the joints
- Length of the fiber between the optical source and the joint

- Geometrical and waveguide characteristics of two fiber ends and,
- Fiber end - face qualities.

* For graded - index fiber with core radius "a" a cladding index n_2 with propogation constant $k = \frac{2\pi}{\lambda}$, then the ~~total~~ number of modes is expressed as,

$$M = M = k^2 \int_0^a [n^2(r) - n_2^2] r \, dr \quad \text{—— (1)}$$

where, $n(r) \rightarrow$ variations in the refractive index profile of the core

eq (1), can be written as,

$$M = k^2 \int_0^a NA^2(r) r \, dr \quad \text{—— (2a)}$$

$$M = k^2 NA^2(0) \int_0^a \left[1 - \left(\frac{r}{a}\right)^a\right] r \, dr \quad \text{—— (2b)}$$

where,

$NA(0) \rightarrow$ Axial numerical aperture

$a \rightarrow$ Index profile of the core.

→ FIBER TO FIBER COUPLING EFFICIENCY (η_F) :- 48

* The fraction of energy coupled from one fiber to other fiber is proportional to the common mode volume M_{comm}.

* The fiber to fiber coupling efficiency (η_F) is given by,

$$\eta_F = \frac{M_{comm}}{M_E} \quad \text{———} \quad (3)$$

where, M_E → number of modes in the emitting fibers.

⇒ FIBER TO FIBER COUPLING LOSS :-

* The fiber to fiber coupling loss L_F is given by,

$$L_F = -10 \log \eta_F \quad \text{———} \quad (4)$$

3:17:1 MECHANICAL MISALIGNMENT :-

* Potentially greater source of loss at a fiber to fiber connection is caused by misalignment of two jointed fibers.

* Radiation losses result from mechanical misalignment because the radiation care of

the emitting fiber does not match the acceptance core of the receiving fiber.

* The magnitude of radiation loss depends upon,

i) Degree of misalignment

ii) fiber type

iii) core diameter

iv) Distribution of the optical power between the propogation modes.

A) TYPES OF MECHANICAL MISALIGNMENT :-

* The three types of mechanical misalignment which may occur when joining compatible optical fibers.

i) Longitudinal misalignment.

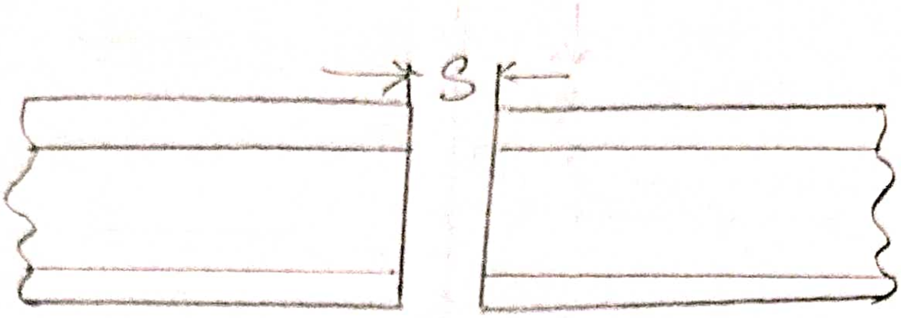
ii) Lateral misalignment

iii) Angular misalignment.

1) LONGITUDINAL MISALIGNMENT :-

* Longitudinal misalignment occurs when the fibers have the same axis but have a gap between their end faces.

fig 3:32 (a) Longitudinal misalignment



2) LATERAL MISALIGNMENT :-

* Lateral or axial misalignment occurs when the axes of two fibers are seperated by distance "d".
* Lateral misalignment gives significant greater losses per unit displacement than the longitudinal misalignment.

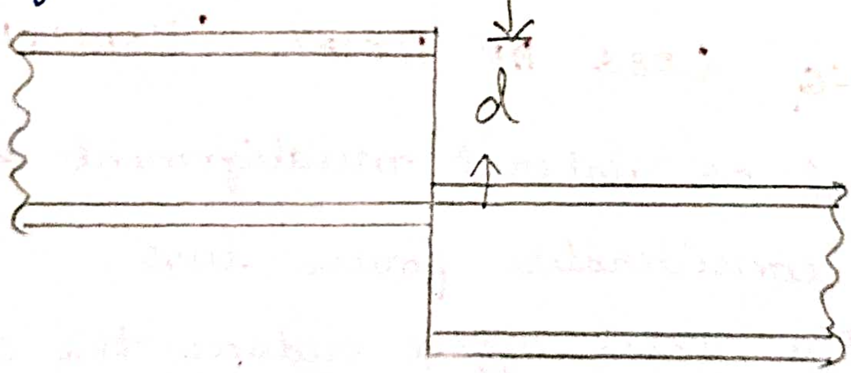


fig 3:32(b) Lateral Misalignment.

* Lateral displacement of 10 lim gives about 1 dB insertion loss whereas a similar longitudinal displacement gives insertion loss around 0.1 dB.

3) ANGULAR MISALIGNMENT :.

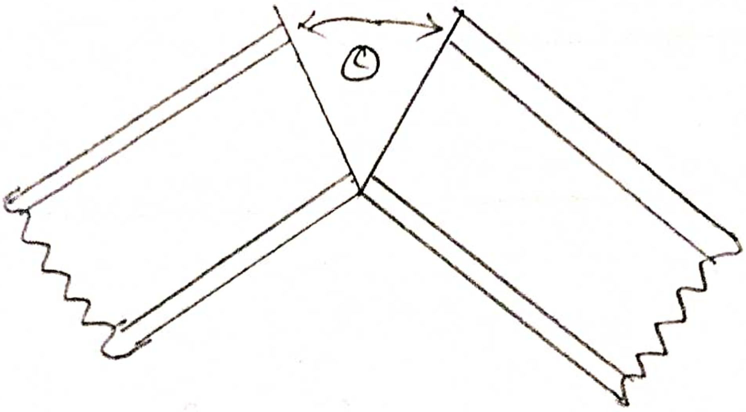


Fig 3:32 c) Angular Misalignment

* Angular misalignment occurs when two fiber axes forms an angle θ between fiber and faces which is no longer parallel

* An index matching fluid in the fiber gap causes increased losses with angular misalignment.

B) COUPLING LOSS OF AXIAL MISALIGNMENT :.

* The axial or lateral misalignment is most common considerable power loss.
  - The axial offset reduces the common area of two fiber and faces.

* Optical power coupled from one fiber to another is proportional to common area A_{comm} of two fiber cores and it is expressed as,

(50)

$$A_{comm} = 2a^2 \arccos \frac{d}{2a} - d\left(a^2 - \frac{d^2}{4}\right)^{1/2} \quad \text{--- (5)}$$

where,

a → core radius of fiber

d → Separation of core fiber

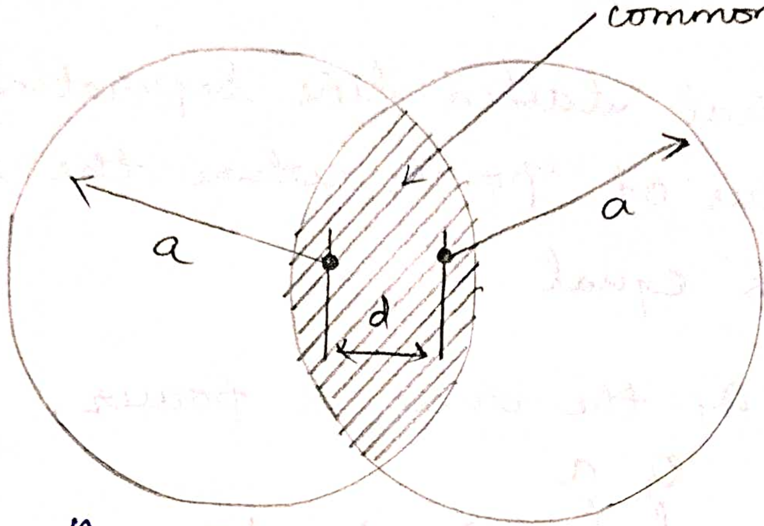


Fig 3:33 Axial offset reduces the common core area of the two fiber end faces.

* For step index fiber, the coupling efficiency is simply the "ratio of the common core area to the core end-face area" and is expressed as,

$$\eta_{F,step} = \frac{A_{comm}}{\pi a^2} \quad \text{--- (6)}$$

$$\eta_{F,step} = \frac{2}{\pi} \arccos \frac{d}{2a} - \frac{d}{\pi a}\left[1 - \left(\frac{d}{2a}\right)^2\right]^{1/2} \quad \text{--- (7)}$$

* Fig 3: Shows the butt joint of the two parabolic graded index fibers with axial offset d.

– The overlap region must be considered separately for the areas A_1 + A_2.

→ POWER AT AREA A_1 :-

* In area A_1 the numerical aperture is limited by that of the emitting fiber, whereas in area A_2 the numerical aperture of the receiving fiber is smaller than that of the emitting fiber.

* The vertical dashed line seperating two areas is the locus of points where the numerical aperture is equal.

– In area A_1 the received power,

$$P_1 = 2\int_0^{\theta_1}\int_{r_1}^{a} p(r)\, r\, dr\, d\theta$$

$$= 2p(0)\int_0^{\theta_1}\int_{r_1}^{a}\left[1-\left(\frac{r}{a}\right)^2\right] r\, dr\, d\theta \qquad (8)$$

where

$p(r)$ → Optical power density at point r on the fiber end

$p(0)$ → power density at the core axis (or) axis power density.

* Limits of integration can be estimated from the above fig 3:

$$r_1 = \frac{d}{2\cos\theta} \qquad (9a) \qquad\qquad \theta_1 = \arccos\frac{d}{2a} \qquad (9b)$$

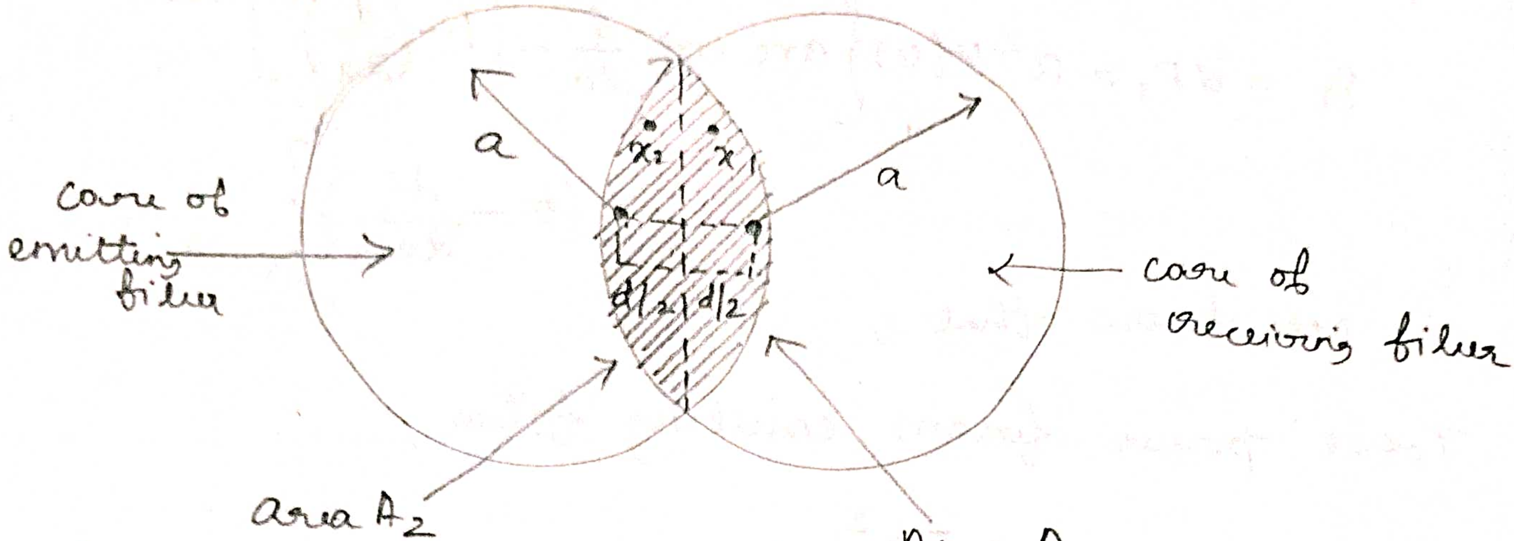


Fig 3:34 Core overlap region for two identical parabolic graded-index fiber with an axial seperation.

* By substituting eq (9a) & (9b) in eq (8) and carrying out the integration then it becomes,

$$P_1 = \frac{a^2}{2} P(0) \left\{ \arccos \frac{d}{2a} - \left[1 - \left(\frac{d}{2a} \right)^2 \right]^{1/2} \frac{d}{6a} \left(5 - \frac{d^2}{2a^2} \right) \right\} \quad (10)$$

⇒ POWER AT AREA A_2 :-

* In area A_2, the emitting fiber has a larger numerical aperture than the receiving fiber.

* The optical power accepted by the receiving fiber at any point x_2 in area A_2 is equal to that emitted from the symmetrical point x_1 in area A_1.

— Because of equal numerical aperture,

the total power P_T accepted by the fiber is given as,

$$P_T = 2P_1 = a^2 P(0)\left\{\arccos\frac{d}{2a} - \left[1-\left(\frac{d}{2a}\right)^2\right]^{1/2} \frac{d}{6a}\left(5-\frac{d^2}{2a^2}\right)\right\} \quad \text{— (11)}$$

as we know that,

Total power from emitting fiber,

$$P = \frac{\pi a^2}{2} P(0)$$

$$P(0) = \frac{2P}{\pi a^2} \quad \text{— (12)}$$

– By substituting eq (12) in (11), we get

$$P_T = \frac{2}{\pi} P\left\{\arccos\frac{d}{2a} - \left[1-\left(\frac{d}{2a}\right)^2\right]^{1/2} \frac{d}{6a}\left(5-\frac{d^2}{2a^2}\right)\right\} \quad \text{— (13)}$$

* When the axial misalignment d is small compared with the core radius a, $(d < a)$.

$$P_T \approx P\left(1 - \frac{8d}{3\pi a}\right) \quad \text{— (14)}$$

COUPLING LOSS :-

* The coupling loss for the offset given by eq (13) & (14) is,

$$L_F = -10 \log \eta_F = -10 \log \frac{P_T}{P} \quad \text{— (15)}$$

C) COUPLING LOSS DUE TO LONGITUDINAL MISALIGNMENT :-

* Fig 3 : illustrates the loss effect when the fiber ends are seperated longitudinally by a gap S.

For step-index fiber the coupling loss due to longitudinal misalignment is expressed as,

$$L_F = -10 \log \left(\frac{a}{a + S \tan \theta_c} \right)^2 \quad \text{—— (16)}$$

where $\theta_c \rightarrow$ critical acceptance angle of the fiber.

D) COUPLING LOSS DUE TO ANGULAR MISALIGNMENT :-

* for two step-index fiber that have an angular misalignment θ, then the optical power loss at the joint is expressed as,

$$L_F = -10 \log \left[\cos\theta \left\{ \frac{1}{2} - \frac{1}{\pi} p \left(1-p^2\right)^{1/2} - \frac{1}{\pi} \arcsin p - q \left[\frac{1}{\pi} y \left(1-y^2\right)^{1/2} + \frac{1}{\pi} \arcsin y + \frac{1}{2} \right] \right\} \right] \quad \text{—— (17)}$$

where,

$$p = \frac{\cos\theta_c (1 - \cos\theta)}{\sin\theta_c \sin\theta}$$

Power launching / coupling
Lensing / F-F joint

$$q = \frac{\cos^3\theta}{(\cos^2\theta_c - \sin^2\theta)^{3/2}}$$

$$y = \frac{\cos^2\theta_c(1 - \cos\theta) - \sin^2\theta}{\sin\theta_c \cos\theta_c \sin\theta}$$

5:18 FIBER SPLICING :-

* Fiber splicing is a permanent or semi permanent joint between the two fibers. /
  And the process of joining these two fibers is called as splicing.
* The splicing are used to create long optical links or in situations where a frequent connections and disconnections are not required.
* Splices offer lower attenuation and lower back reflection than connectors and are less expensive
* factors to be considered in splicing are,
  - Geometrical difference between two fibers
  - Fiber misalignments at the joint
  - Mechanical strength of the splice.

i) SPLICING TECHNIQUES :-

* Splices may be divided into three categories depending upon the splicing technique utilized.

i) Fusion splicing (or) welding
ii) Mechanical splicing
iii) Elastic tube splices.

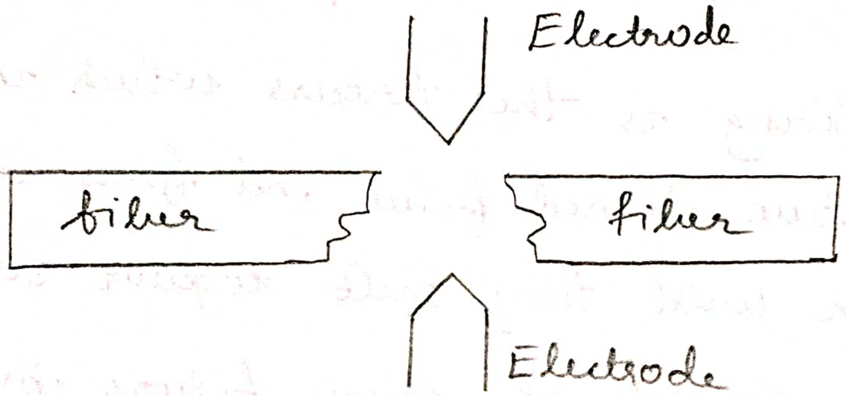
1) FUSION SPLICING (or) WELDING :-

* Fusion splicing is the process which involves butting of two cleaned fiber end faces and heating them until they melt together or fuse.
* The fusion splicing of single fibers involves the heating of the two prepared fiber ends to their fusing point with the application of sufficient axial pressure between the two optical fibers.

* Butt joint is then heated with an electric are or a laser pulse so that the ends are momentarily melted and bonded together.

— This technique can produce very low splice losses.

a) INITIAL SETTING :-

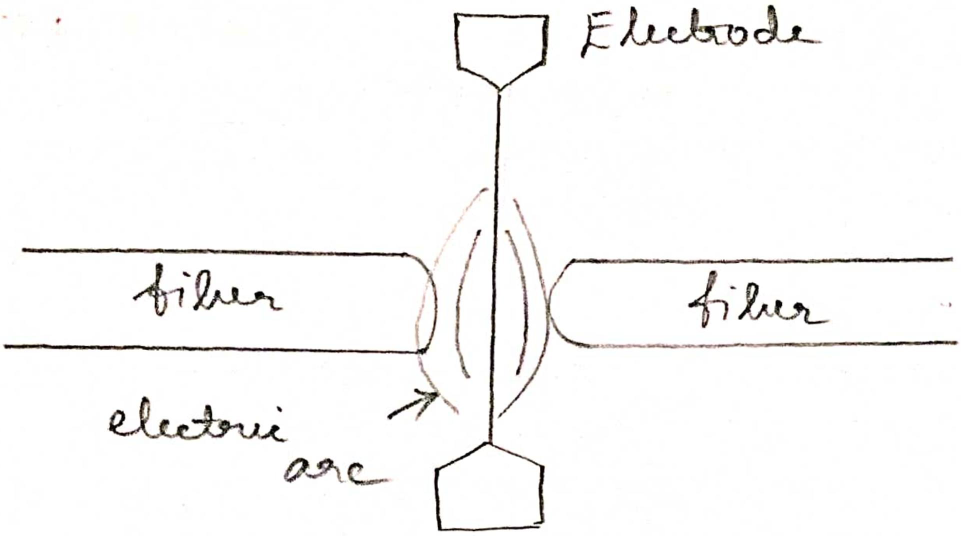


b) ARRANGEMENT OF SMOOTH SURFACE BY PREFUSION

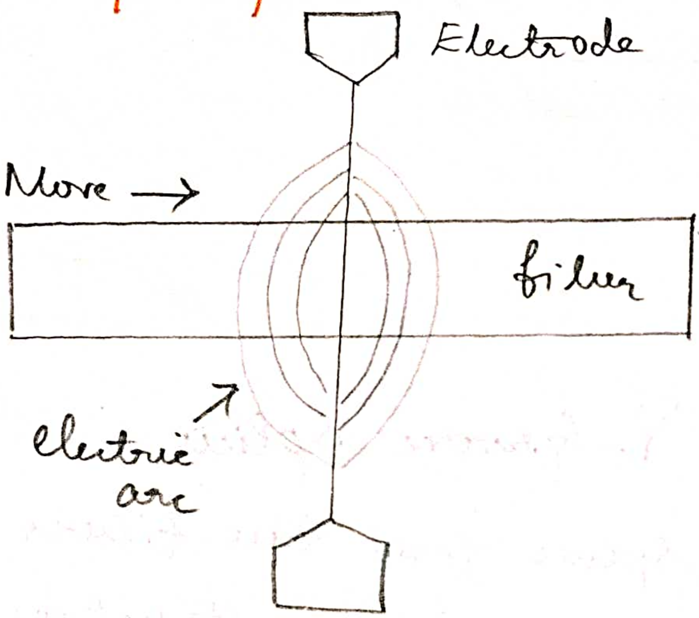
* Basic arc fusion process which involves the rounding of the fiber ends with low energy discharge before pressing the fibers together and fusing with a stronger arc.

— This technique is known as prefusion.

* It helps for fiber and preparation which has a distinct advantages in the field environment.



c) PRESSED TOGETHER :-



d) ACCOMPLISHMENT - OF SPLICE :-

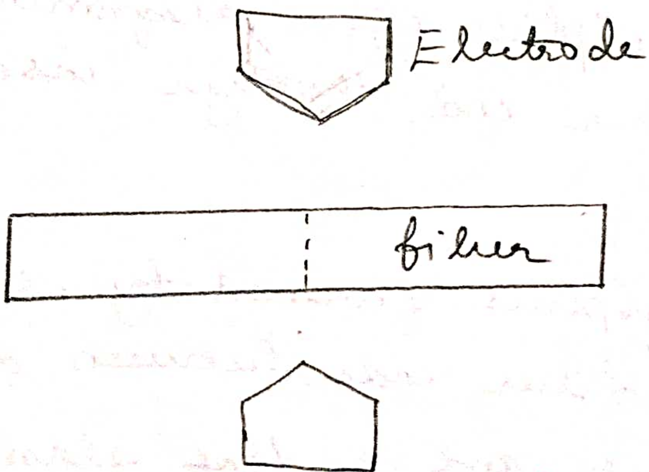


fig 3:35 Electric arc fusion Splicing

2) MECHANICAL SPLICING / V-GROOVE SPLICE TECHNIQUE :-

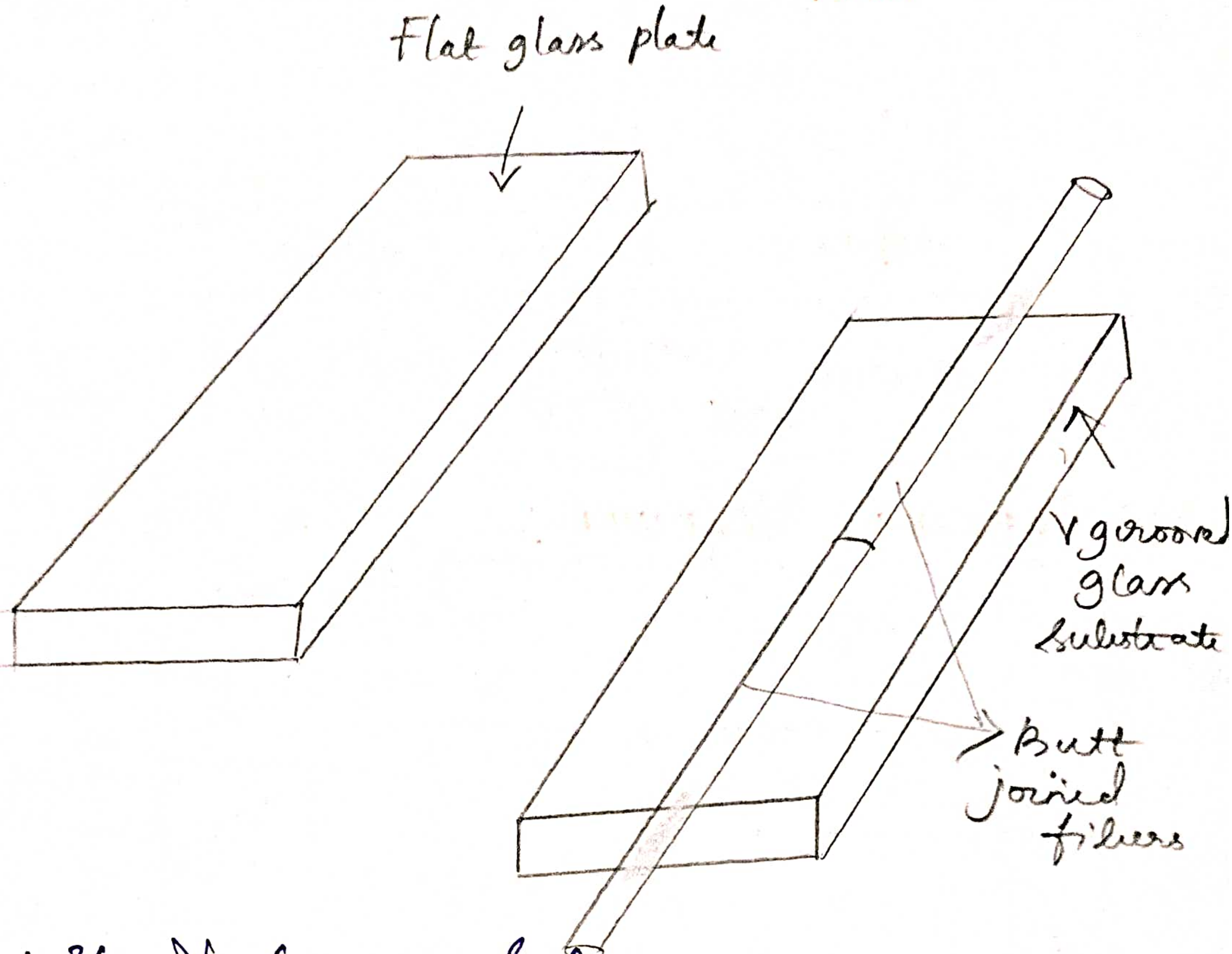


fig 3 : 36 V-Groove Splices

* Mechanical splices join two fibers together by clamping them with a structure or by epoxying the fibers together.
* V-groove splices gives alignment of the prepared fiber end through insertion in the groove.
* V-groove splices formed by sandwiching the butted fiber ends between a V groove glass substrate and a flat glass retainer plate.

* The prepared fiber ends are first butted together in V shaped groove.
  - They are then bonded together with an adhesive or they are held in place by means of a cover plate.
* V shapped channel can be either a grooved silicon, plastic, ceramic or metal substrate.
  - The splice loss depends strongly on the fiber size and eccentricity.
* Mechanical Splices may have a slightly higher loss and back reflection.
  - These can be reduced by inserting index matching gel.

3) ELASTIC - TUBE SPLICE :-

* Elastic - Tube is a unique device that automatically performs lateral, longitudinal and angular alignment.
* It Splices multimode fibers to give losses in the same range as commercial fusion splices, but much less equipment and skills are needed.

* The device is made up of an elastic material.

- The central hole diameter is slightly smaller than that of the fiber to be spliced and is tapered on each end for easy fiber insertions.

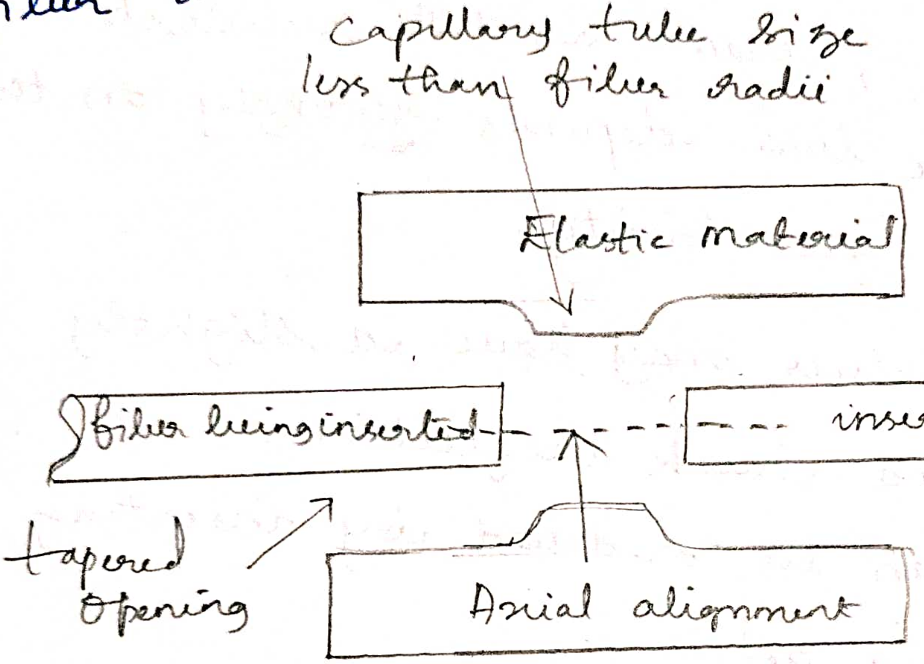


fig 3:37 Schematic of an elastic-tube Splice

* The fiber expands the hole diameter when it is inserted so that the elastic material exerts a symmetrical force on the fiber.

- This allows accurate and automatic allignment of axes of the two fibers to be joined.

* The fibers to be spliced do not have to be equal in diameter.

(57)

$$J_{diff} = q\phi_0 \frac{a_s L_p}{1+a_s L_p} e^{-a_s W} + q P_{no} \frac{D_p}{L_p} \quad \text{—— (6)}$$

3:20:2 TOTAL CURRENT DENSITY :-

* By substituting eq (20) & (6) in (1), we get total current density through reverse biased depletion layer as,

$$J_{tot} = J_{dr} + J_{diff}$$

$$= q\phi_0 (1 - e^{-a_s W}) + q\phi_0 \frac{a_s L_p e^{-a_s W}}{1+a_s L_p} + q P_{no} \frac{D_p}{L_p}$$

$$= q\phi_0 \left(1 - e^{-a_s W} + \frac{a_s L_p e^{-a_s W}}{1+a_s L_p}\right) + q P_{no} \frac{D_p}{L_p}$$

$$= q\phi_0 \left(\frac{1 - e^{-a_s W}(1+a_s W) + a_s L_p e^{-a_s W}}{1+a_s L_p}\right) + q P_{no} \frac{D_p}{L_p}$$

$$= q\phi_0 \left(\frac{1 + a_s L_p - e^{-a_s W} - a_s L_p e^{-a_s W} + a_s L_p e^{-a_s W}}{(1+a_s L_p)}\right) + q P_{no} \frac{D_p}{L_p}$$

$$\therefore J_{tot} = q\phi_0 \left(1 - \frac{e^{-\alpha_s W}}{1+\alpha_s L_p}\right) + q\, P_{no} \frac{D_p}{L_p}$$ (7)

* P_{no} is very small, total current density is proportional to the photon flux Φ_0.

3:20:3 RESPONSE TIME:-

* Response time of a photo diode depends on,

i) Transit time of photo carriers within the depletion region.

ii) Diffusion time of photo carriers outside the depletion region

iii) RC time constant of the photo diode and its associated circuit.

* These factors depend upon the photodiode parameters such as absorption coefficient 'α_s', the depletion region width W, the photodiode junction and package capacitances, the amplifier capacitance, the detector load resistance, amplifier input resistance and the photodiode series resistance.

Receiver sensitivity.

To calculate optical receiver sensitivity, total noise in the receiver is calculated.

$$B_{bae} = \frac{I_2}{T_b} = I_2 B$$

&

$$B_e = I_2 B + (2\pi RC)^2 I_3 B^3$$

Substituting these values and gives.

$$\langle V_N^2 \rangle = R^2 A^2 \left[2q \langle i_0 \rangle M^2 + \frac{4 K_B T}{R_b} + S_I + \frac{S_E}{R^2} \right] I_2 B + (2\pi RC)^2 A^2 S_E I_3 B^3$$

Front end Amplifier

The front end consists of two parts. the driving amplifier and the RC filter. The amplifier conditions the input signal - as well as acting as a low impedance buffer between the signal source and the ADC input. The RC filter limits the amount of out of band noise arriving at the ADC input and helps to attenuate the kick from the switched capacitors in the ADC's input.

LED Coupling to Single Mode fibers

The edge emitting LED have laser like Output hence can launch sufficient optical power for the data rates upto 560 Mb/s over several Kilometers. Also LEDs are cost effective and reliable.

LED to step index fiber coupling efficiency is given by

$$\eta = \frac{P_{in}}{P_S}$$

$$\eta = T_x T_y$$

P_S is total source output power.

T_x is directional coupling efficiency in parallel direction.

T_y is directional coupling efficiency in perpendicular direction.

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.

Various fiber optic connectors from different manufactures are available SMA 906, ST, Biconic.

These different types of connectors are used for connecting fiber optic cables. These are

1) Subscriber channel (SC) Connector
2) Straight tip (ST) Connector.
3) MT-RJ Connector.

SC connector are general purpose connectors. It has push-pull type locking system.

ST Connectors are more suited for networking devices. It is more reliable than SC Connector. ST Connector has bayonet type locking System.

UNIT V

Optical Communication Systems & Networks.

5:1 SONET / SDH ::

* SONET - Synchronous Optical Network is an optical transmission interface originally proposed by bellcore and standardized by ANSI
* SONET standard address the following specific issues:

i) Establishes a standard multiplexing format using any number of 51.84 Mbps signals as building blocks.

ii) Establishes an optical signal standard for interconnecting equipment from different suppliers.

iii) Establishes extensive operations, administration and maintenance capabilitils as part of the standard.

iv) Defines a synchronous multiplexing format for carrying lower level digital signals.

SONET / SDH BENEFITS :

* Advantages are given below,

– Reduced cost :

a) Operation cost is low

b) Same interface for all vendors.

- Integrated network elements:
  a) It allows multivendor internetworking
  b) It has enhanced network element management.
- Offers network survivability features.
- It is compatible with legacy and future networks
- Remote operation capabilities.
  → Remotely provisioned, tested, inventoried, customized and reconfigured.

Why Use SONET/SDH?

* Why glass fiber is better than copper wire?

Following are the benefits glass fiber:

→ fiber yields thinner cable than copper.

→ Fiber can transmit without repeaters at longer distances as compared with copper.

→ Higher bandwidth per fiber.

→ Lower bit error rate.

→ Higher transmission reliability.

*) Glass fiber is not as susceptible to radio frequency or EMI as copper wire unless it is shielded and well grounded.

5:1:1 SONET/SDH NETWORK: [Elements of Network]

* SONET/SDH network consists of nodes or network elements (NE) that are interconnected

with fiber over which user and network information is transmitted.

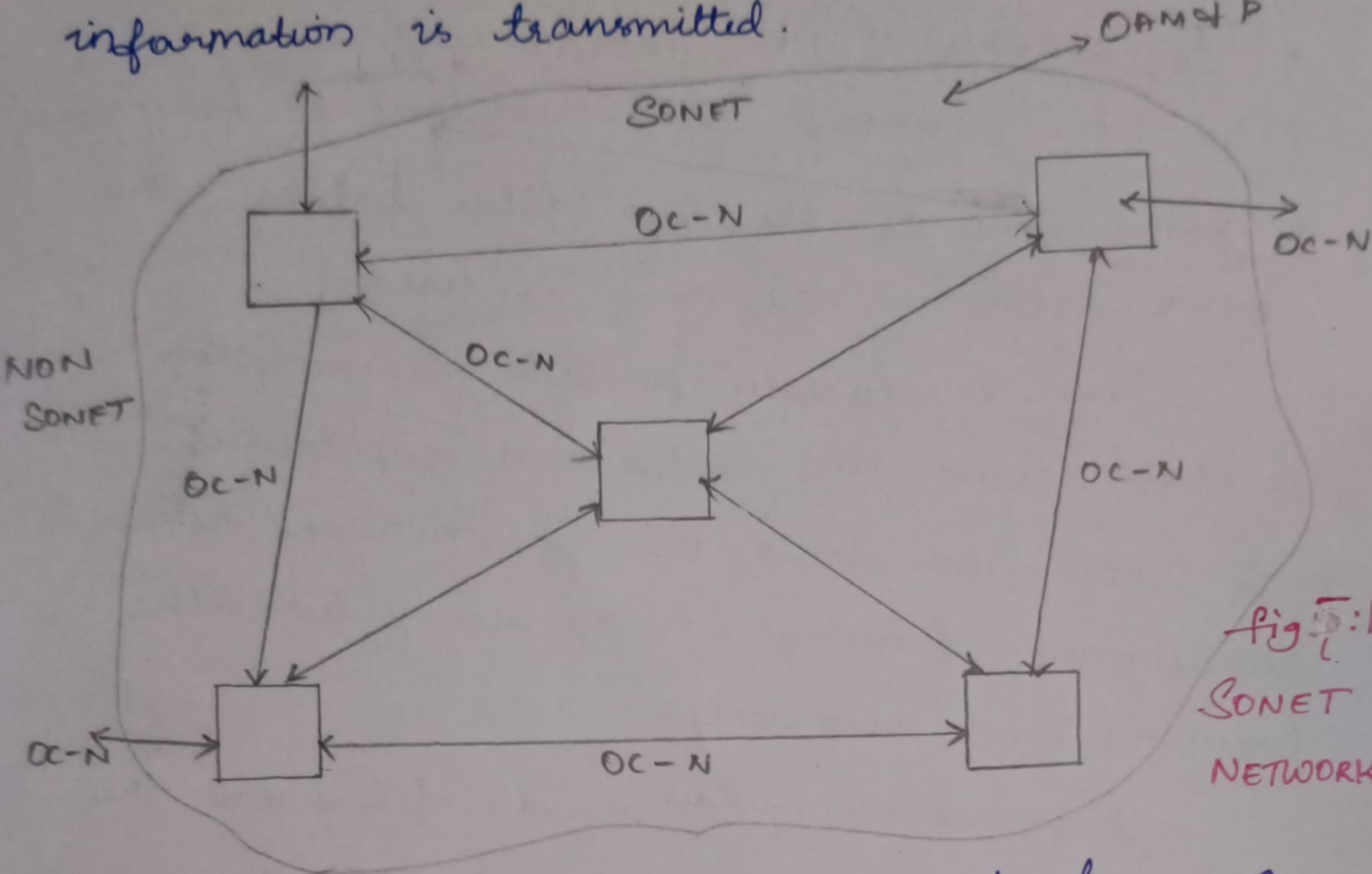


fig 5:1 SONET NETWORK

* SONET NE's may receive signals from a variety of facilities such as DSI, DS3, ATM, internet and LAN/MAN/WAN.
  - They also may receive signals from a variety of network topology.

* SONET NE's must have a proper interface to convert the incoming data format into the SONET format.

5:1:2 NETWORK TOPOLOGIES :

* Network falls into three topologies:

a) Ring b) Mesh c) Tree

a) RING TOPOLOGY :

* It consists of NEs interconnected with a dual fiber, the primary and secondary to form Ring
* When one of the two fiber breaks, the other fiber in the ring is used.
  - This mechanism provides transmission protection and ring restoration capabilities.
* If both fiber break, then the network is reconfigured, forming a ring using both the primary and secondary.
  - Information flows in all fibers but the broken ones.
* Ring topology offers fast path protection and is widely used in LAN.

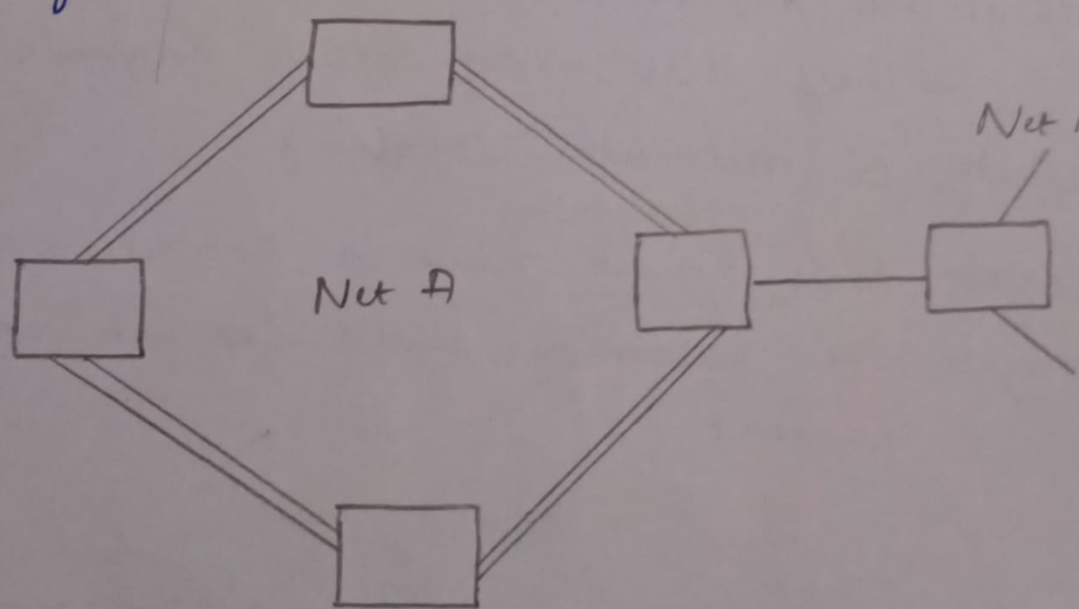


Fig 5:2 RING Topology.

b) MESH TOPOLOGY :

* It consists of NE's fully interconnected.
* when an interconnecting link break, the adjacent NE detects the breakage and routes the traffic to another NE.
  - This mechanism provides transmission protection and network restoration capabilities.
* Mesh topology is better applicable in densely populated area.

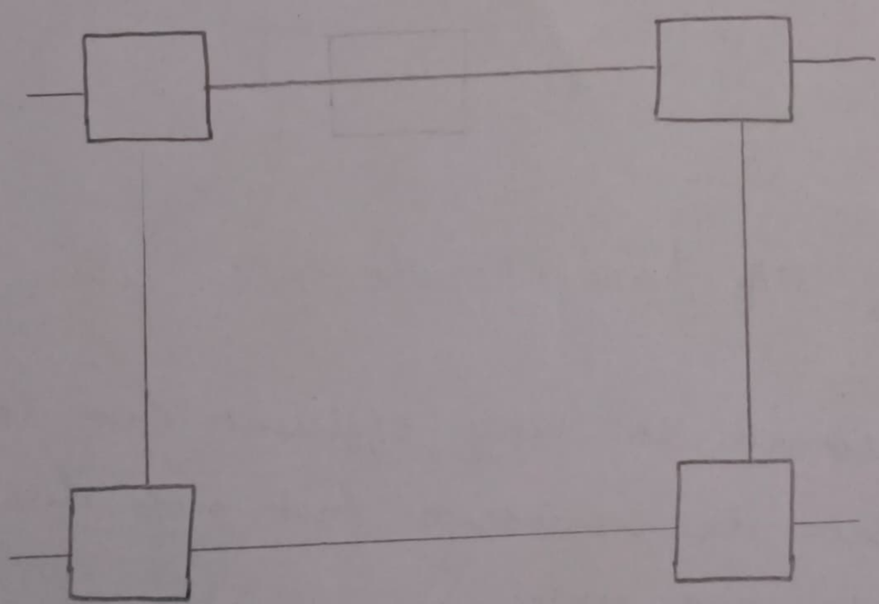


fig 5 :3 MESH topology

c) TREE TOPOLOGY :

* It is hierarchial distribution of NE's and is mostly used in LAN's such as Ethernet.
* A source is connected to a distribution function known as a hub, that routes the

packet to its destination node.

- A connection between the source and a destination is established for the duration of the packet through hub.

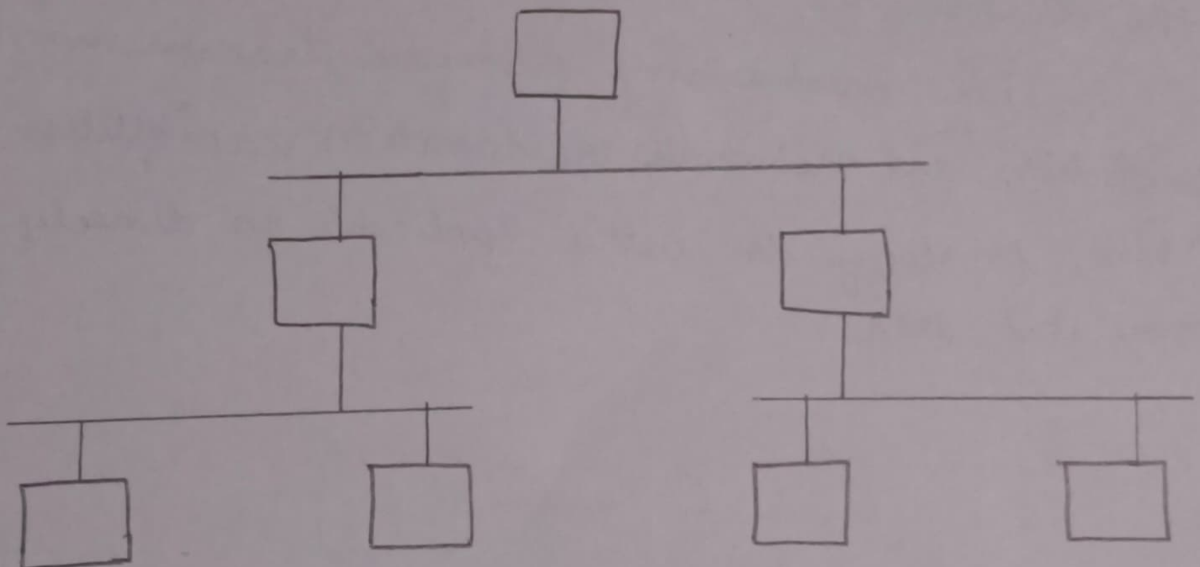


fig 5:4 Tree Topology.

* This network is very efficient for asynchro-nous data transmission but not for real time data and voice.

5:1:3 SONET MULTIPLEXING:

* SONET Specification defines a hierarchy of standardized digital data rates.

- The basic transmission rate defined in SDH is 155.52 Mbps and is known as a synchronous transport module level 1 signal (STM1

- Higher rates of STM4 (622 Mbps) and STM-16 (2.4 Gbps) are also defined. (4)

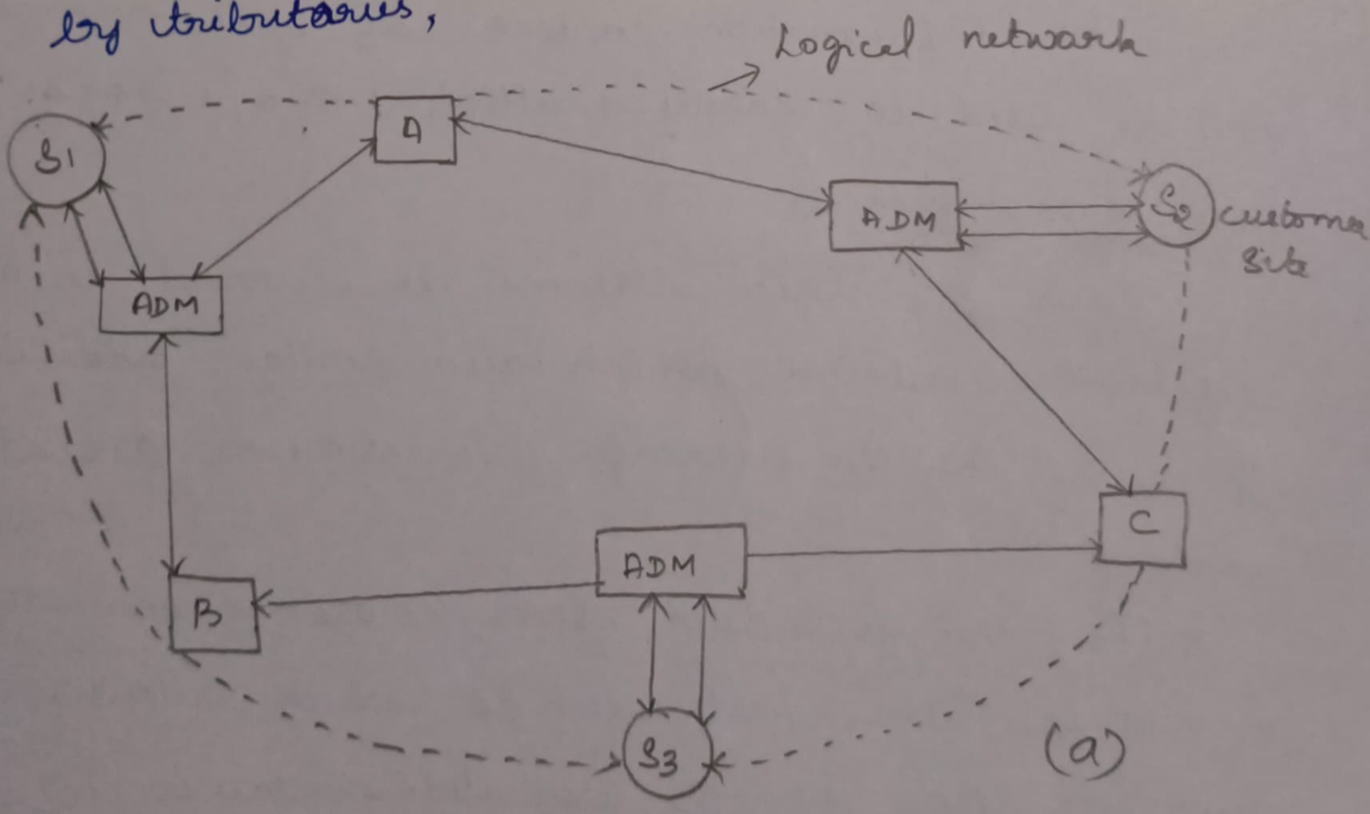
* In the SONET hierarchy the term synchronous transport signal (STS) or Optical signal (OS) is used to define the equivalent of an STM signal.
  - An STM-1 signal is produced by multiplexing three such signals together and hence is equivalent to an STS-3/OC-3 signal.
  - As with the plesiochronous digital hierarchy (PDH), the STM-1 signal is comprised of a repetitive set of frames which repeat with a period of 125 microseconds.
  - The information content of each frame can be used to carry multiple 1.5/2/6/34/45 or 140 Mbps stream.
  - Each of these streams is carried in a different container which also contain additional stuffing bits to allow for variations in actual rate.
  - To this is added some control information known as the path overhead which allow such thing as BER of the associated container to be

monitored on an end-to end basis of network management.

* To provide the necessary flexibility for each higher order signal in addition to the overhead at the head of each lower level STM frame, a pointer is used to indicate the lower level STM frame's position within the higher order frame.

— Multiplexing and Demultiplexing operation is performed by a device known as a drop and insert or add drop multiplexer ADM

* ADM is the combination of SONET equipment allow distant switching nodes to be connected by tributaries,



(a)

(b)

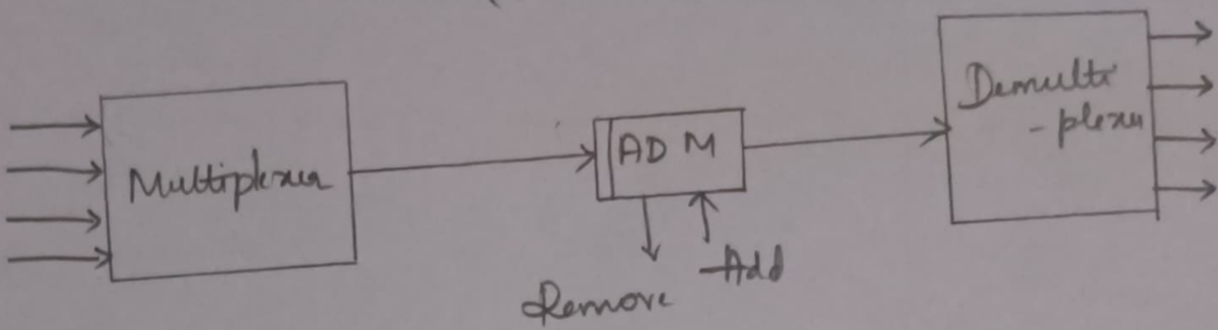


fig 5.5 ADM Multiplexing

5:1:4 SONET SYSTEM HIERARCHY :

* SONET system hierarchy has four layers as mentioned below:

a) Photonic Layer:

* This specifies the types of optical fibers, the minimum required laser power, sensitivity of the receivers and dispersion characteristics of lasers.

b) Section Layer:

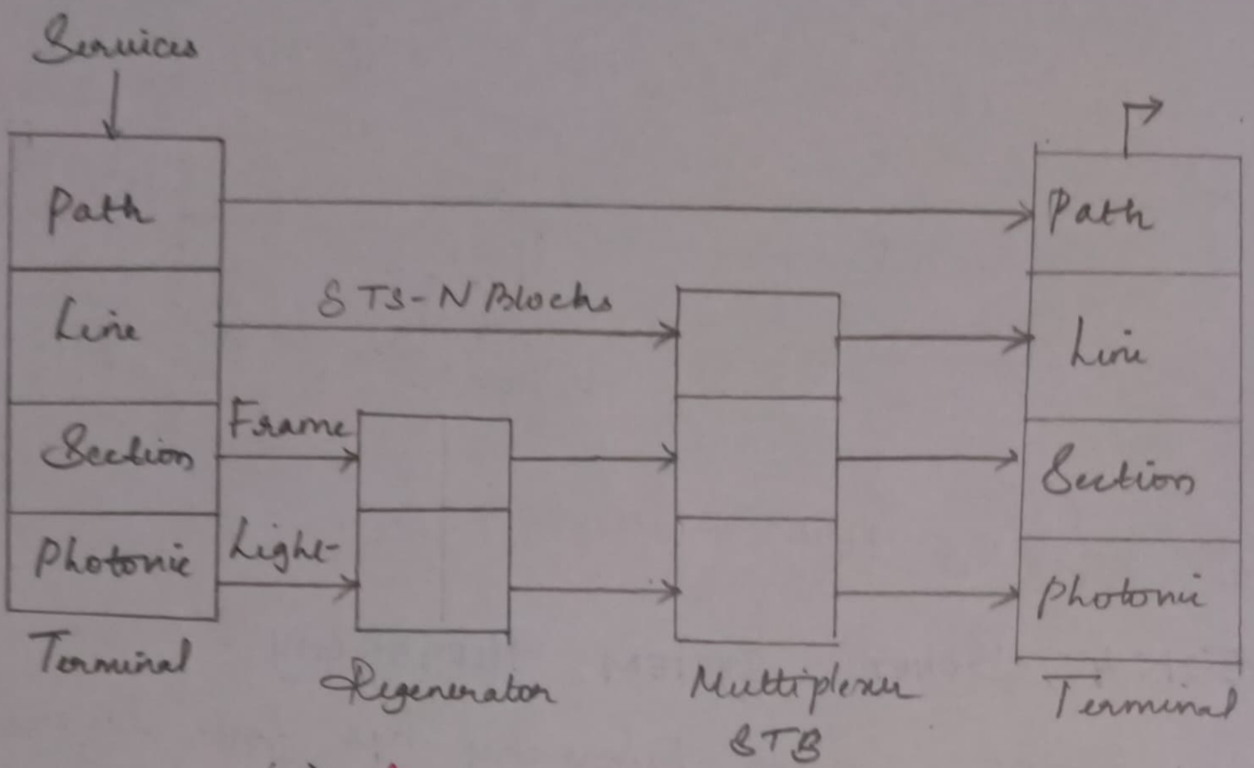
* This Layer generates SONET frames and convert the electronic signals to photonic signals

c) Line Layer:

* This Layer synchronizes and multiplexes the data into SONET frame.

d) Path Layer:

* This Layer performs end to end transport of data at the proper rate.



(a) fig 5:6 Logical hierarchy

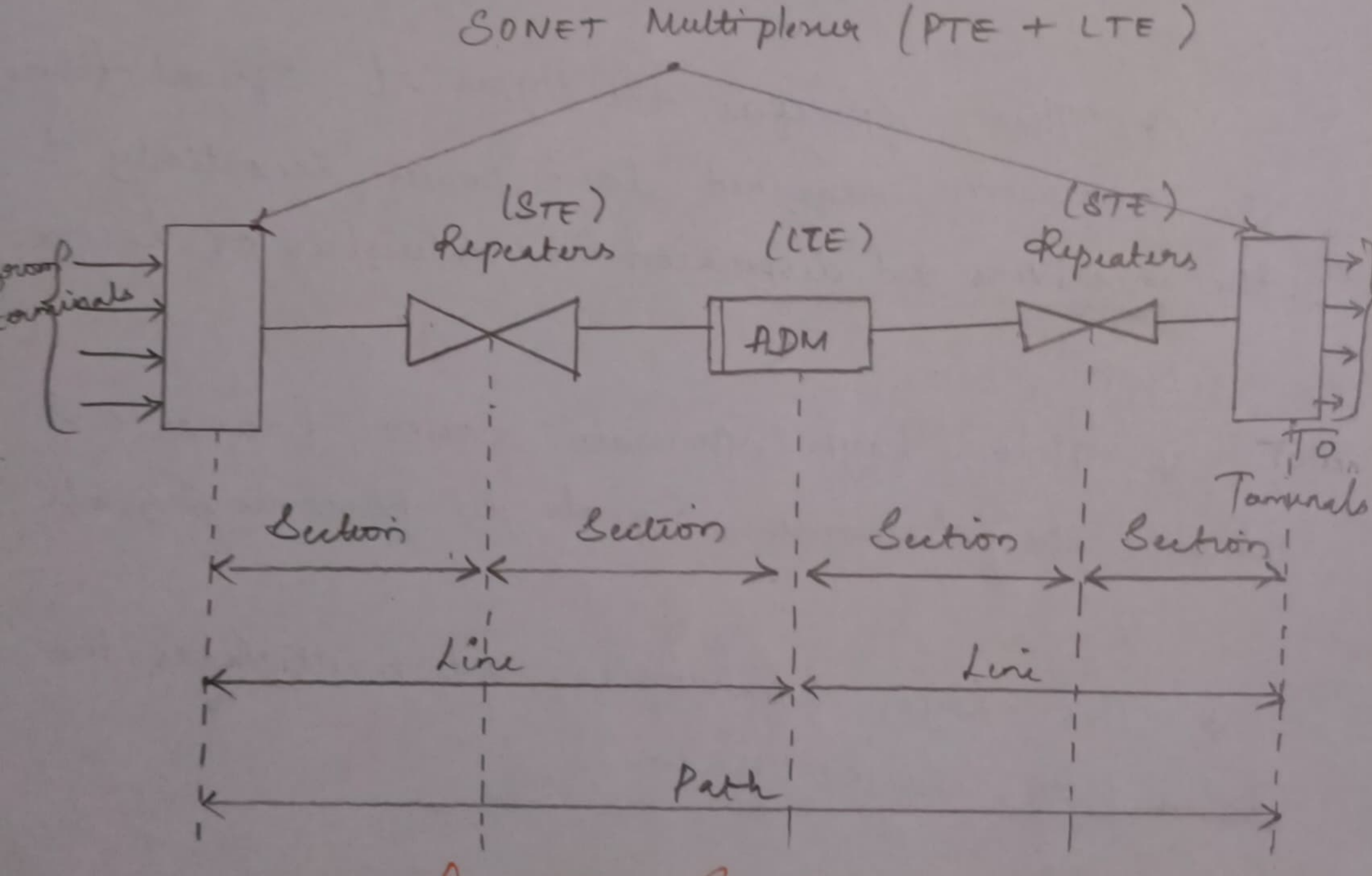


fig 5:7 System hierarchy

* A Section is the basic physical building block and represents a single run of Optical

fiber transmitter or receivers.

– For shorter run the cable may run directly between two end points.

– For longer distances, repeaters are used. Repeater amplify the signals.

* A line is a sequence of one or more sections such that the internal signal or channel structure of the signal remain constant.

– End points and intermediate switches or multiplexers that may add or drop channels terminate a line.

* A path connects to end terminals, it correspond to an end to end circuit.

– Data are assembled at the beginning of a path and are not accessed.

APPLICATIONS:

1) High speed backbone networks
2) Basic architecture for B-ISDN
3) Basic architecture for ATM
4) High speed optical network for data communication

5:2 BROADCAST AND SELECT WDM NETWORKS:

* All optical WDM networks have full potential of optical fiber transmission capability and versatility of communication network beyond SONET Architectures.

* These network can be classified as,
  i) Broadcast and select techniques
  ii) Wavelength - routing network.

* Broadcast and select techniques employing passive optical stars, buses and wavelength routers are used for local network applications.

* Broadcast and select network can be classified as,
  i) Single-hop networks
  ii) Multi-hop network

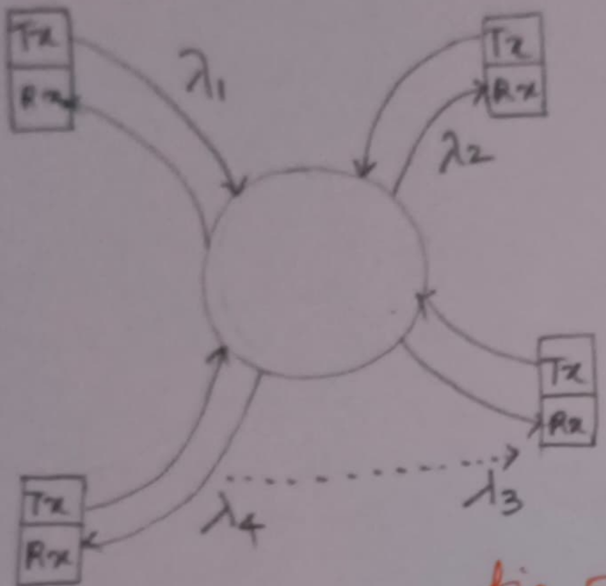
* Single-hop refers to network where information transmitted in the form of light reaches its destination without being converted to an electrical form at any intermediate point.

* In Multi-hop network, intermediate electro-optical conversion can occured.

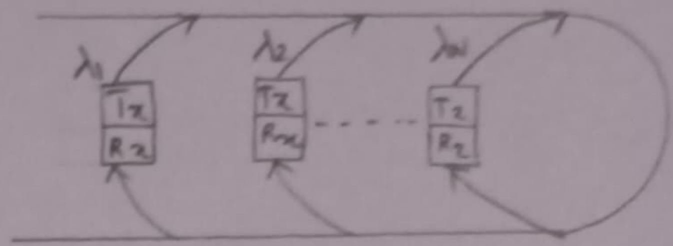
5:2:1 BROADCAST AND SELECT SINGLE HOP NETWORK:

* Two alternate physical architectures for a

WDM - based local network have N sets (7)
of transmitters and receivers are attached
to either a star coupler or a passive bus.



(a) Star



(b) Bus

fig 5: physical architecture of WDM based local network

* Each transmitters send its information at a different fixed wavelength.
* All the transmissions from the various nodes are combined in a passive star - coupler or coupled onto a bus and sent out to all receivers.
* WDM setup is protocol transparent.
* Protocol transparent means that, different set of communicating nodes can use different information - exchange rules without affecting other nodes in the network.

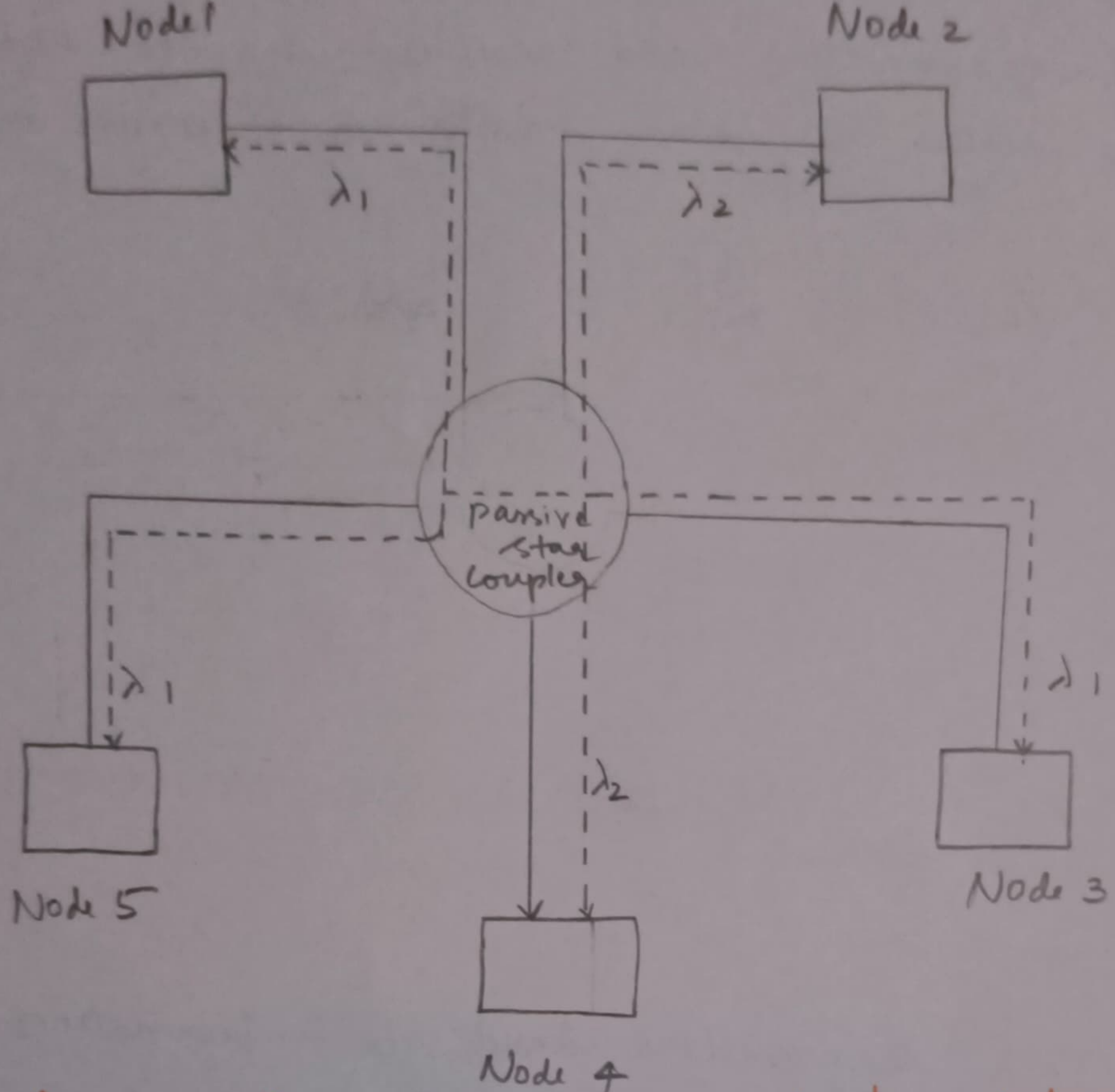


fig 5: 9 Architecture of single hop network.

* The architecture of single hop broadcast and select network are fairly simple, there needs to be careful dynamic coordination between the nodes.
* Transmitter sends its information at a unique fixed wavelength, then the desired receiver need to be informed when a message being sent to it
* It can tune its selective filter to that wavelength.

* Two sending stations need to coordinate their transmissions, so that collisions of information stream at the wavelength do not occur. (8)

5:2:2 BROADCAST AND SELECT MULTIHOP NETWORK:

* Drawback of single hop network is the need for rapidly tunable lasers or receiver optical fiber.
* This is overcomed by Multi-Hop Network.
* Multihop network do not have direct path between each node pair.
* Each node has a small number of fixed tuned optical transmitters and receivers.
* An example, four node broadcast and select multihop network where each node transmits one one set of two fixed wavelength and receives on another set of fixed wavelength.
* Information destined for other nodes will have to be routed through intermediate stations.
* Considering the operation, a simplified transmission scheme in which message are sent as packets with a data field and an address header containing source and

destination identifiers with control bits.

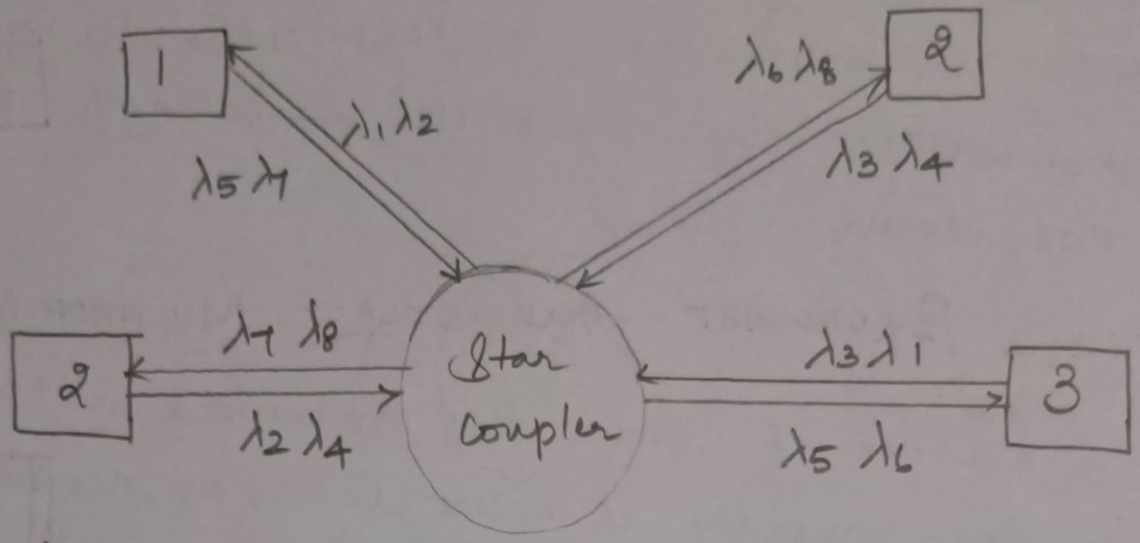


fig 5:10 Broadcast and Select Multihop networks.

* At each intermediate node, the optical signal is converted to an electrical format.
* The address header is decoded to examine the routing information field, which will indicate where the packet should go.
* Routing information is used to send the electronic packets from the optical transmitter to the next node in logical path toward its final destination.

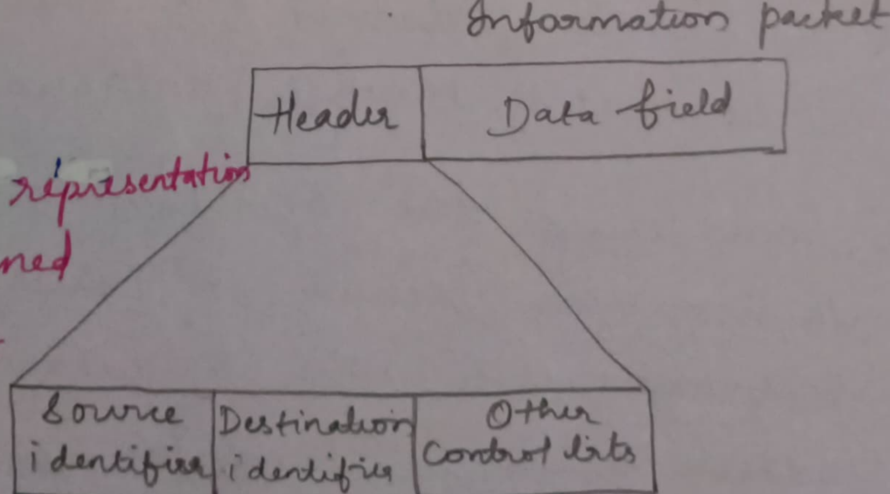


fig 5:11 simple representation of fields contained in data packet

ADVANTAGE:

* There are no destination conflicts or packet collisions in the network.
- For H hops between nodes, there is a network throughput penalty of atleast 1/H

SHUFFLE NET MULTIHOP NETWORK.

* Scheme called Perfect Shuffle is widely used to form processor - interconnect patterns in multiprocessor.
* For optical networks, the extension of this to the logical configuration consists of a cylindrical arrangement k columns each having p^k nodes, where $P \rightarrow$ number of fixed transceiver pairs per nodes.
* Total number of nodes N is given as,

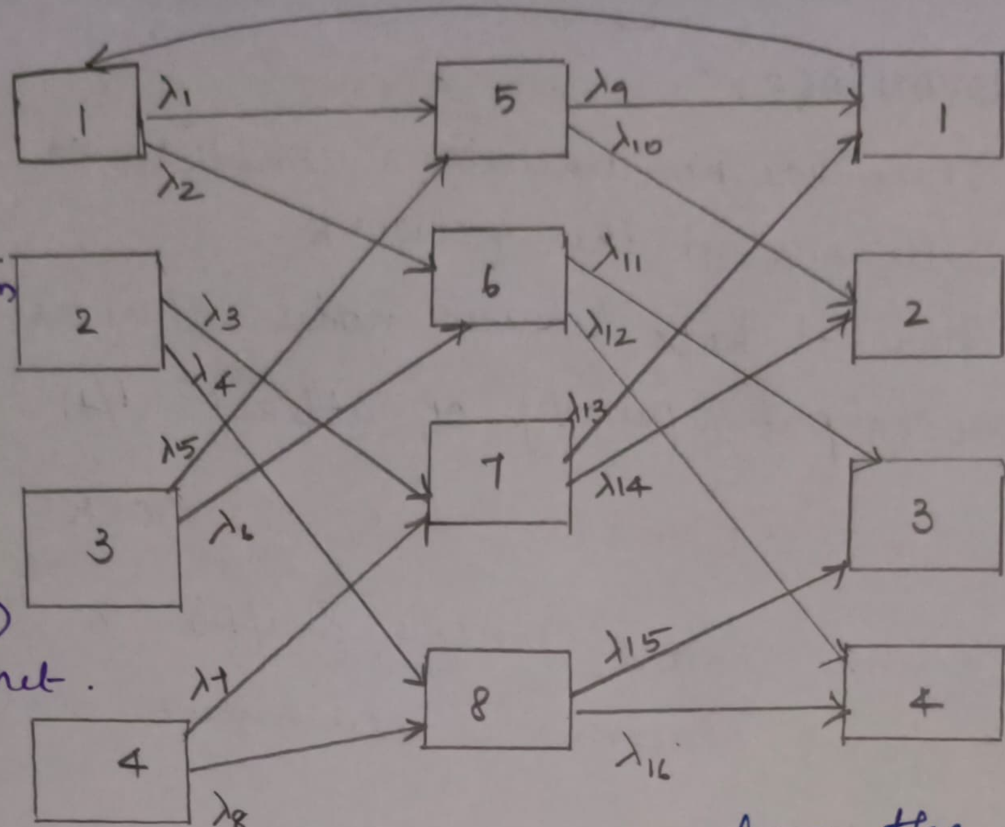
$$N = k\, p^k \qquad \text{--- (1)}$$

with $k = 1, 2, 3 \ldots$ $\quad p = 1, 2, 3 \ldots$

* Each node requires P wavelength to transmit information, then the total number of wave-length N_λ needed in the network is,

$$N_\lambda = P_N = k p^{k+1} \qquad \text{--- (2)}$$

fig: 5: Logical Interconnection pattern and wavelength assignment of a(P, k) = (2, 2) Shuffle net.



* a(P, k) = (2, 2) ShuffleNet, where the (k+1)th column represents the completion of a trip around the cylinder back to the first column, as indicated by the return arrow.
  - In this example, there are eight nodes and sixteen wavelengths.
* The maximum number of hops is calculated as,

$$H_{Max} = 2k - 1 \quad \text{--- (3)}$$

* Consider the connections between nodes 1 & 5 between nodes 1 & 7.
  - In the first case, hop number is 1.
  - In the second case, three hops are needed with the routes being either 1 – 6 – 4 – 7

(or) 1-5-2-7. (10)

* Average number of hops $\overline{H}$ of a shufflenet is,

$$\overline{H} = \frac{1}{N-1}\left\{\sum_{j=1}^{k-1} jP^{j} + \sum_{j=0}^{k-1}(k+j)(P^{k}-P^{j})\right\}$$

$$\overline{H} = \frac{kP^{k}(P-1)(3k-1) - 2k(P^{k}-1)}{2(P-1)(kP^{k}-1)} \quad \text{—— (4)}$$

* If the system has $NP = kP^{k+1}$ links, the total network capacity C is,

$$C = \frac{kP^{k+1}}{\overline{H}} \quad \text{—— (5)}$$

Per-user throughput S is,

$$S = \frac{C}{N} = \frac{P}{H} \quad \text{—— (6)}$$

* Different (P, k) combination results in different throughputs, so one can make the variable to get a better tradeoff's among network performance.

5.3 Wavelength Routed Networks :-

When the broadcast and select networks are extended into wide area network (WAN), 2 main issues can occur,

i) More wavelength are needed as the number of nodes in the network grows.

ii) Can use large number of optical booster amplifier over wide area that cannot readily be interconnected with a broadcast & select network.

Wavelength routed networks overcome these limitations through wavelength reuse, wavelength conversion & optical switching.

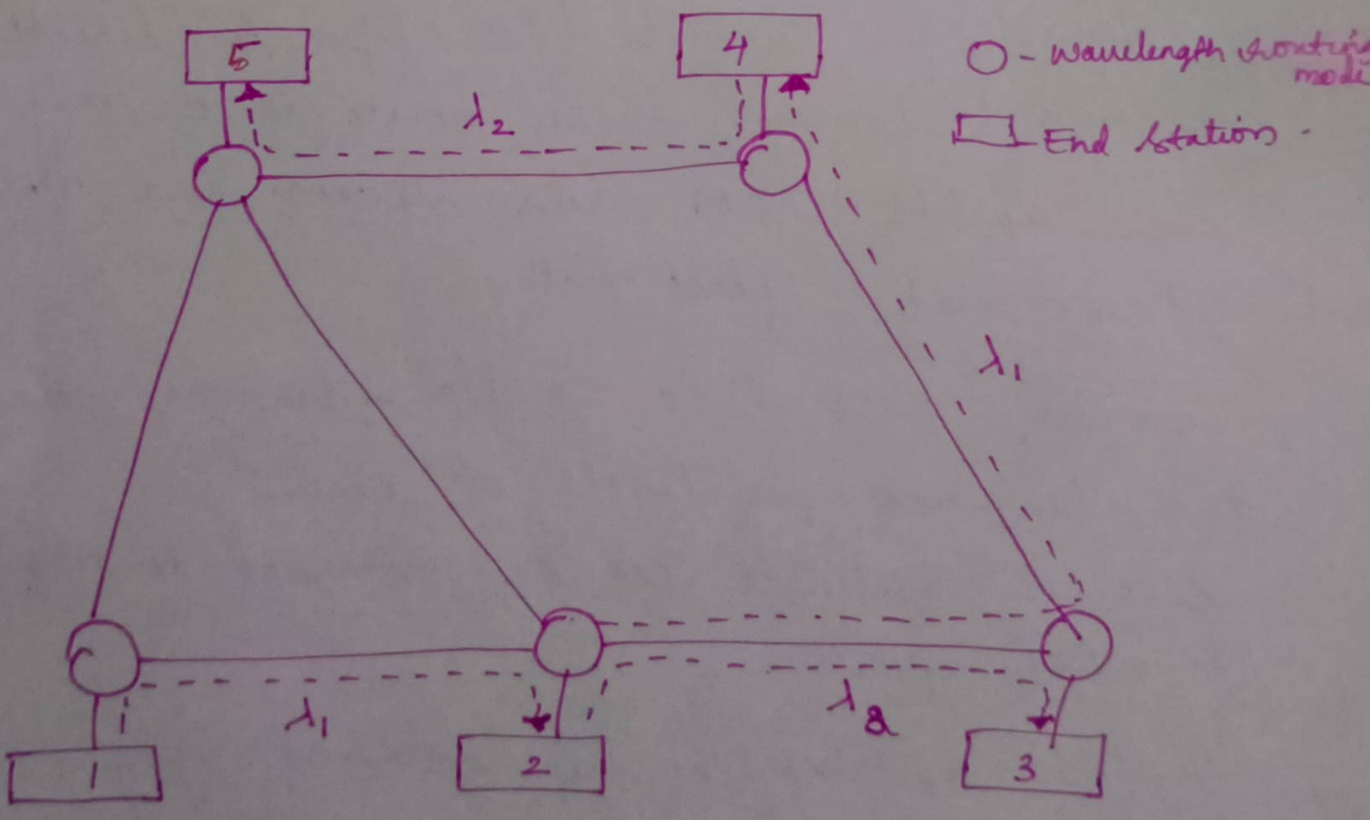


fig: Wavelength Reuse on a mesh network

- fig shows physical topology of a wavelength routed network consists of optical wavelength routers interconnected by pairs of point-point fiber links in an arbitary mesh configuration.

- Connection from node 1 to node 2 and from node 2 to node 4 can be on λ_1, where the connection between node 2 & node 3 and from 4 & 5 requires different wavelength λ_2.

- Every link can carry a certain number of wavelengths which can be directed independently to the different o/p path at a node.

Optical cross Connects :-

- Optical cross connects (OXC) operate directly in the optical domain & can route at a very high capacity WDM data streams over n/w of interconnected optical path.

- Consider 4×4 OXC, 2 i/p fibers are carrying two different wavelength of each.
- Either wavelength can be switched to any of the four o/p ports.

- Optical switches can be constructed using a cascade of electronically controlled optical directional coupler

- Fig shows the wavelength utilization as a function of number of wavelength for 10^{-3} blocking probability in a n/w using wavelength conversion.

- Let the probability is P_b that the connection request from A to B is blocked if each wavelength is used on atleast one of H links,

$$P_b = \left[1 - (1-p)^{H}\right]^{F} \quad \text{——— (3)}$$

- P - acheivable utilization for a given blocking probability is a n/w without wavelength conversion,

$$P = 1 - \left(1 - P_b^{1/F}\right)^{1/H} \approx -\frac{1}{H} \ln\left(1 - P_b^{1/F}\right) \quad \text{——— (4)}$$

- To measure the benefit of wavelength conversion the gain (G) is defined as,

$$G = q/P \quad \text{——— (5)}$$

- Consider $P_b' = P_b$ in eq (1) & (3). Sub eq (2) + (4) in (5) we get,

$$G = \frac{\left[1 - (1-P_b)^{1/H}\right]^{1/F}}{1 - \left(1 - P_b^{1/F}\right)^{1/H}}$$

$$= \frac{\left(P_b/H\right)^{1/F}}{-1/H \ln\left(1 - P_b^{1/F}\right)}$$

$$\frac{\left(\frac{1}{H}\right)^{1/F}}{\left(\frac{1}{H}\right)} = \frac{H^{-1/F}}{H^{-1}} \Rightarrow H^{1-\frac{1}{F}}$$

$$G \approx H^{1-1/F} \times \frac{P_b^{1/F}}{-\ln\left(1-P_b^{1/F}\right)} \quad \text{——— (6)}$$

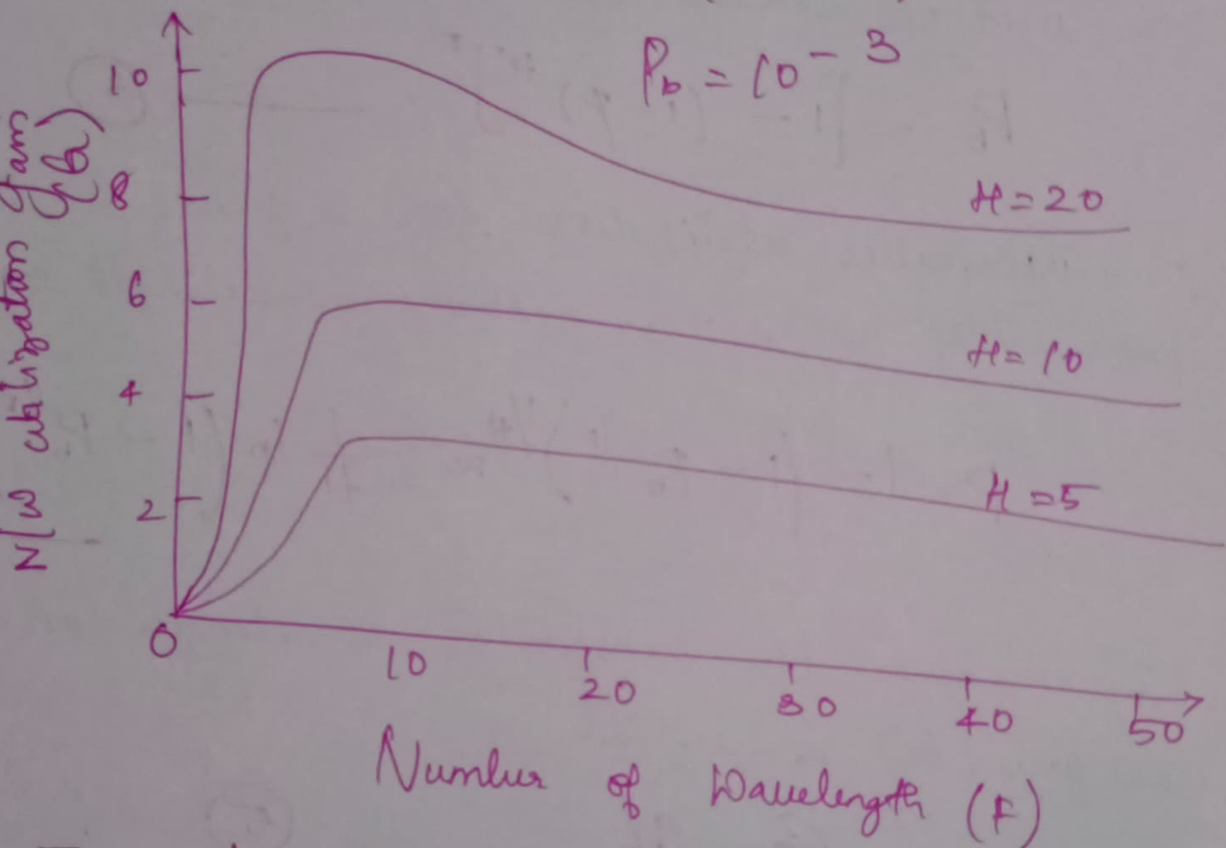


Fig: N/w utilization gain (G) as a function of the number of wavelength for 10^{-3} blocking probability when wavelength conversion used.

node A & B. The number of available λ per fiber link to be F.

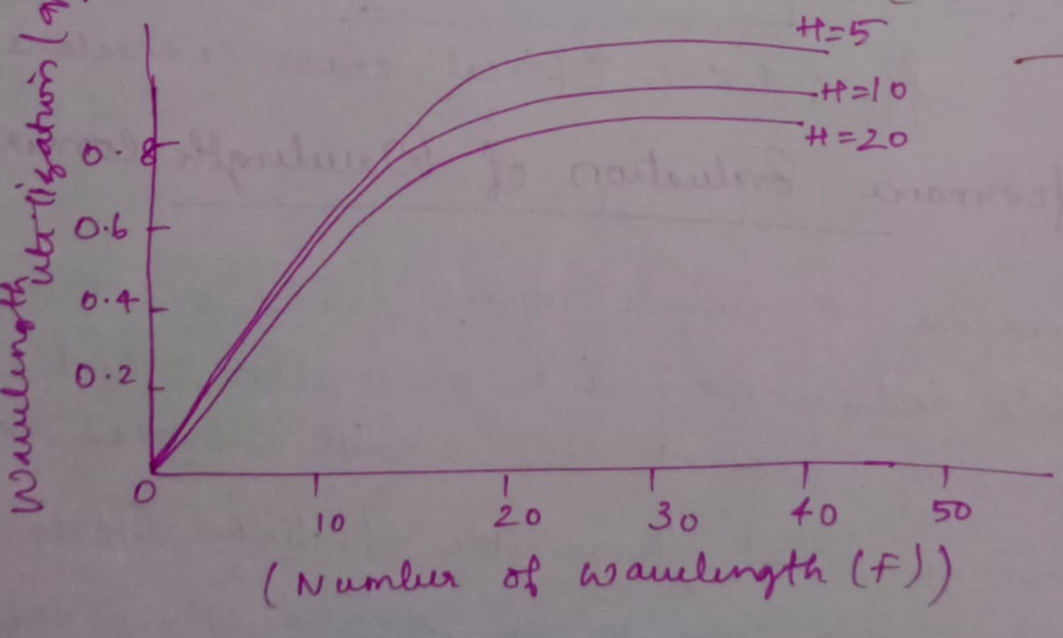
- p be the probability that a wavelength is used on any fiber link, then p^F is expected number of busy wavelength on any link.

- P_b are the blocking probability that the connection request from A to B is blocked, when in fiber link all F wavelength in use and H number of fiber link & it is expressed as,

$$P_b' = 1 - (1 - p^F)^H \quad \text{——— (1)}$$

- If q is the acheivable utilization for a given blocking probability in a network with wavelength conversion, then

$$q = \left[1 - (1 - P_b')^{1/H}\right]^{1/F} \approx \left(\frac{P_b'}{H}\right)^{1/F} \quad \text{——— (2)}$$



elements or semiconductor optical amplifier switching gates.

- OXC consists of three 2×2 switch elements.
- Suppose λ_2 on i/p fiber 1 need to be switched to o/p fiber 2 & that λ_1 on o/p fiber 2 needs to be switched to o/p fiber 1.
- This is acheived by having the first two switch elements set in the bar state & the third element set in the cross state.

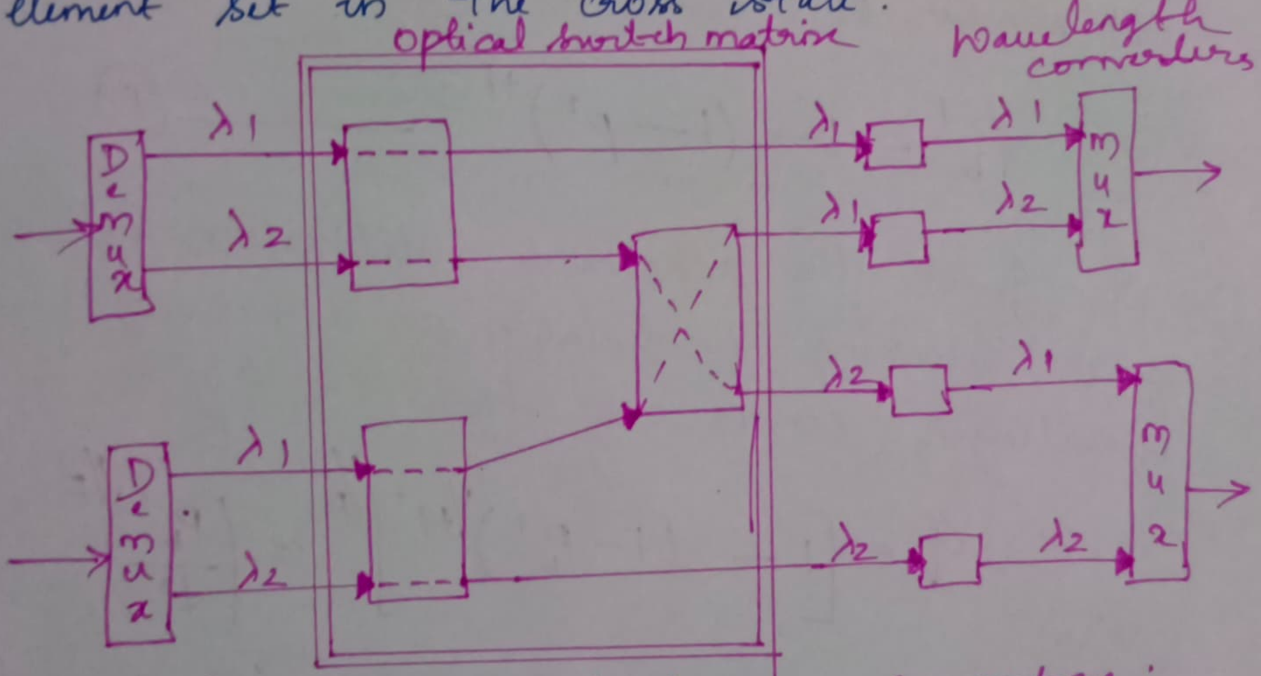


fig: 4×4 Optical cross connectors:-

Performance Evaluation of Wavelength Conversion:-

- Consider a simple model based on standard series independent - link assumptions which is commonly used in the circuit switched networks.
- Assume that there are H-links between 2 nodes that need to be connected, which are called

(2)

* Connection request between nodes A & B is blocked if one of the H intervening fiber is full.

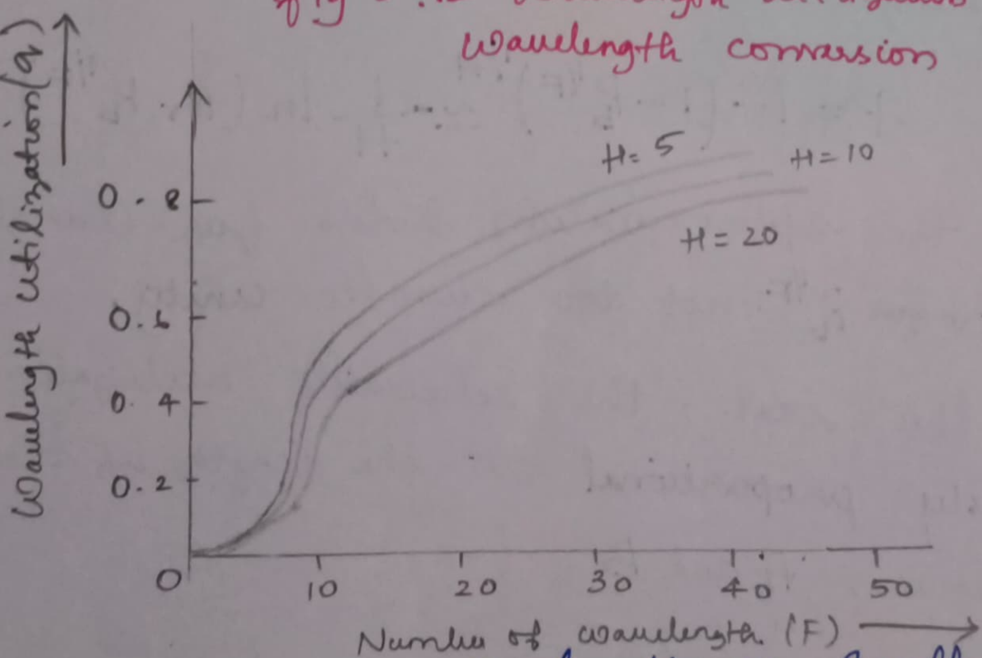
* The probability P_b' that gives connection request from A to B is blocked the probility and fiber link with all wavelengths F.

* If q is the acheivable utilization for a given blocking probability in a network with wavelength conversion. —— (1)

$$P_b' = 1 - (1 - p^F)^H$$

$$q = \left[1 - (1 - P_b')^{1/H}\right]^{1/F} \simeq \left(\frac{P_b'}{H}\right)^{1/F} \quad \text{—— (2)}$$

fig 5:12 Wavelength utilization using wavelength conversion



* The effect of path length is small and q rapidly approaches 1 as F becomes large.

Network without Wavelength conversion:

* Connection request between A and B can be honored only if there is a free wavelength.

* The probability P_b that connects request from A to B is blocked, the probability of each wavelength is used on atleast one of the H links

$$P_b = \left[1-(1-p)^H\right]^F \quad \text{——— (3)}$$

* Letting p be the acheivable utilization for a given blocking probability in a network without wavelength conversion.

$$P = 1-\left(1-P_b^{1/F}\right)^{1/H} \simeq -\frac{1}{H} \ln\left(1-P_b^{1/F}\right) \quad \text{——— (4)}$$

where the approximation holds for large values of H ~~&~~ for $P_b^{1/F}$ not too close to unity.

* In this case, the acheivable utilization is inversely proportional to the length of the path H between A and B.

* Here the effect of path length (i.e. the number of links) is dramatic.

5.5 Link - power budget & Rise-time budget :-

- Optical power received at the photodetector depends on
  - amount of light coupled into the fiber
  - The losses occurring in the fiber
  - At the connectors & splices.

- Let,

  l_c - denotes the losses occur at connector

  l_{sp} - loss at splices

  α_f - loss in fiber.

- Link loss budget is derived from sequential loss contribution of each element of the link.

$$Loss = 10 \log \frac{P_{out}}{P_{in}} \quad \text{--- (1)}$$

P_{in} — Optical power enter into the loss element

P_{out} — Optical power o/p from loss element.

- Link power margin considers the losses due to component aging, temperature fluctuations & losses arising from the components.

- The total power loss (P_T) in the link is,

total power loss = {Optical power at light source} − {optical power at receiver (or) Receiver sensitivity}

$$P_T = P_S - P_R \quad \text{--- (2)}$$

Total optical power loss (P_T) =

{connector loss} + {Splicing loss & fiber attenuation} + {System margin}

$$P_T = 2 l_c + \alpha_F L + P_m \quad \text{——— (3)}$$

where P_S —— o/p power emerging from end of the fiber flylead attached to the light source

P_R — Receiver Sensitivity

l_c — Connector loss

α_F — fiber attenuation in dB/km

L → Transmission distance

Rise Time budget :-

— Rise time budget analysis determine dispersion limitation of an optical fiber link.

— Total rise time t_{sys} is root sum square of the rise time from each contributor t_i to the pulse rise time degradation.

$$t_{sys} = \sqrt{t_1^2 + t_2^2 + t_3^2 + \cdots} \quad \text{——— (4)}$$

$$t_{sys} = \left(\sum_{i=1}^{N} t_i^2 \right)^{1/2} \quad \text{——— (5)}$$

— System speed is limited by, transmitter rise time t_{tx}, Model dispersion rise time (t_{mode}) of the fiber, Group velocity dispersion (GVD) rise time t_{GVD}. & receiver rise time t_{rx}.

- total rise time t_{sys} becomes

$$t_{sys} = \left(t_{tx}^2 + t_{mod}^2 + t_{GVD}^2 + t_{rx}^2\right)^{1/2} \quad \text{--- (6)}$$

A) Transmitter Rise-time (t_{tx}):-

- Transmitter rise time is due to the light source & its drive circuitry.

B) Receiver Rise - Time (t_{rx}):

- Receiver rise time results from photo detector responses & 3 dB electrical bandwidth of the receiver front end modeled by first order low pass filter having a step response.

$$g(t) = \left[1 - \exp(-2\pi B_{rx}\, t)\right] u(t) \quad \text{--- (7)}$$

$u(t) \rightarrow$ unit step i/p function $\begin{cases} 1 & \text{for } t \geq 0 \\ 0 & \text{for } t < 0 \end{cases}$

$B_{rx} \rightarrow$ 3 dB electrical bandwidth of the receiver.

- Receiver rise time t_{rx} is defined as the time interval between $g(t) = 0.1$ & $g(t) = 0.9$. This is known as 10 - 90 percent rise-time.

- Receiver front end rise-time in nanoseconds is,

$$t_{rx} = \frac{350}{B_{rx}} \quad \text{--- (8)}$$

B_{rx} is in MHz.

c) Group velocity Dispersion Rise-Time (t_{GVD}):

- Group velocity dispersion rise time over a length L is given as,

$$t_{GVD} \approx |D| L \sigma_\lambda \quad \text{—— (9)}$$

σ_λ – half spectral width of the source

D – Dispersion.

- To find the model dispersion rise time, Bandwidth B_m in a link of length L can be expressed as,

$$B_M(L) = \frac{B_0}{L^q} \quad \text{—— (10)}$$

q – parameter ranges between 0.5 & 1

B_0 – is the bandwidth of 1km length of cable.

Based on curve fitting of experimental data the bandwidth B_m is,

$$\frac{1}{B_m} = \left[\sum_{n=1}^{N} \left(\frac{1}{B_n} \right)^{1/q} \right]^q \quad \text{—— (11)}$$

B_n – bandwidth of n_{th} Section.

$$t_m(N) = \left[\sum_{n=1}^{N} (t_n)^{1/q} \right]^1 \quad \text{—— (12)}$$

$t_m(N)$ – Pulse broadening over N cable sections

t_n – individual pulse broadening

Relation between fiber rise time & 3dB bandwidth (FWHM)

- Optical power emerging from the fiber has a gaussian temporal response & is given by

$$g(t) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{\frac{-t^2}{2\sigma^2}} \quad \text{—— (13)}$$

σ, rms pulse width.

fourier transform of $g(t)$ is given by,

$$G(\omega) = \frac{1}{\sqrt{2\pi}} e^{-\frac{\omega^2\sigma^2}{2}} \quad \text{—— (14)}$$

from eq (13), time ($t_{1/2}$) required for the pulse to reach its half maximum is,

$$g(t_{1/2}) = 0.5\, g(0) \quad \text{—— (15)}$$

$$t_{1/2} = (2\ln 2)^{1/2}\sigma \quad \text{—— (16)}$$

$$t_{FWHM} = 2t_{1/2} = 2\sigma(2\ln 2)^{1/2} \quad \text{—— (17)}$$

t_{FWHM} — full width of the pulse at its half maximum value.

Relation between t_{FWHM} & 3-dB bandwidth :-

- 3dB optical bandwidth is defined as modulated frequency f_{3dB} at which the received optical power has fallen to 0.5 of the zero frequency.

$$f_{3dB} = B_{3dB} = \frac{0.44}{t_{FWHM}} \quad \text{—— (18)}$$

- If t_{FWHM} is the rise time resulting from model dispersion & it is given by

$$t_{mod} = \frac{0.44}{B_m} = \frac{0.44 L^q}{B_0} \quad \text{—— (19)}$$

- If t_{mod} & B_m are in nanoseconds & MHz, then eq (19) can be rewritten as,

$$t_{mod} = \frac{440}{B_m} = \frac{440 L^q}{B_0} \quad \text{—— (20)}$$

Total Rise Time :-

- Total s/m rise time t_{sys} is

$$t_{sys} = \left(t_{tx}^2 + t_{mod}^2 + t_{GVD}^2 + t_{rx}^2\right)^{1/2} \quad \text{—— (21)}$$

By sub eq (8), (9), (20) in (21), we get

$$t_{sys} = \left[t_{tx}^2 + \left(\frac{440 L q}{B_0}\right)^2 + D^2 \sigma_\lambda^2 L^2 + \left(\frac{350}{B_{rx}}\right)^2\right]^{1/2} \quad (22)$$

- Material dispersion for a dispersion shifted fiber & it is given by,

$$t_{GVD}^2 \approx t_{mat}^2 = D_{mat}^2 \sigma_\lambda^2 L^2 \quad \text{—— (23)}$$

5:7 NOISE EFFECTS ON SYSTEM PERFORMANCE:

* The various interactions between the Spectral imperfections in the propogating optical power and the dispersive waveguide give rise to Variation in the optical power level falling on the photo detector.

* Main penalties are due to model noise, Wavelength chirp, Spectral broadening induced by optical reflections back into the laser and mode-partition noise.

* Model Noise is not present in single mode links, however, mode partition noise, chriping and reflection noise are critical in these systems.

5:7:1 MODEL NOISE (OR) SPECKLE NOISE:

* Model noise arises when the light from a coherent laser is coupled into a multimode fiber.
  - It is a random Variation in optic power occuring in multimode fiber.

* There is no problem for the links operating below 100 Mb/s but it considers around 400Mb/s & higher.

* Modal noise may be prevented on an optical fiber link through suitable choice of the system components.

1) Factors Producing Model Noise :

(a) Differential Mode Delay :

* Mechanical disturbances along the fiber such as vibrations, discontinuities, connectors, splices, source/detector coupling may cause fluctuations in the speckle pattern and hence modal noise.

* It is generated when the correlation between two or more modes give the original interference which is differentially delayed by these disturbances.

b) Fluctuations in the frequency :

* Fluctuations in the frequency of an optical source can give rise to intermodal delay.

* The speckle patterns are formed by the interference of the modes from a coherent source when the coherence time of the source is greater than the intermodal dispersion time (δT) within the fiber

* If the source has a frequency width (δv), then its coherance time is $1/\delta v$.

— The modal noise occur when the speckle pattern fluctuates : ie when the source coherence time becomes much lesser than the intermodal dispersion time.

* The modal disartion resulting from the interference

between a single pair of modes will appear as a sinusoidal ripple frequency.

$$V = \delta T \frac{d\nu_{source}}{dt}$$

where, $\frac{d\nu_{source}}{dt}$ → rate of change of optical frequency

* This modal noise degrades the Bit Error Rate (BER) performance of a digital link

II) Ways to Avoid Modal Noise:

* The model - noise can be avoided by the following ways.

i) Use broad spectrum source in order to eliminate the modal interference effects.

- This may be achieved by either increasing the width of the single longitudinal mode, which results in decreasing its coherence time or by increasing the number of longitudinal modes.

ii) use LED's (incoherent source). This totally avoids modal noise

iii) use a Laser which has a large number of longitudinal modes (10 or more)

iv) Use a fiber with a large numerical aperture, since it supports the transmission of a large number of modes, it gives a greater number of speckles, and hence reduce the modal noise generating effect of individual speckles.

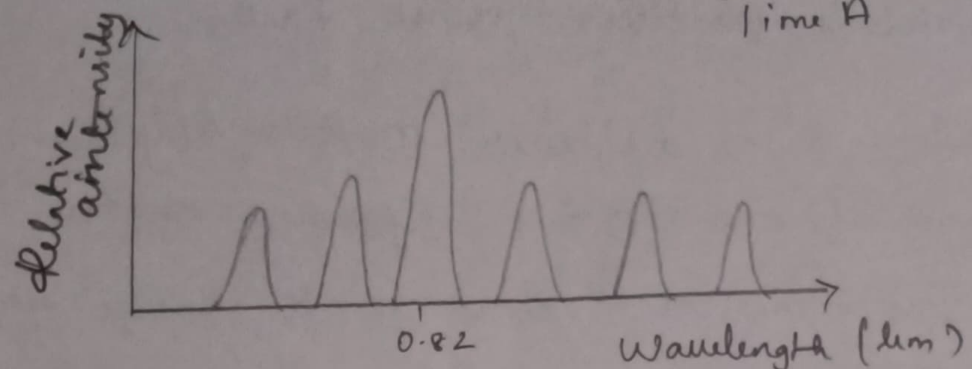
V) Use a single-mode fiber, because it supports only one mode and thus has no modal interfer-ence.

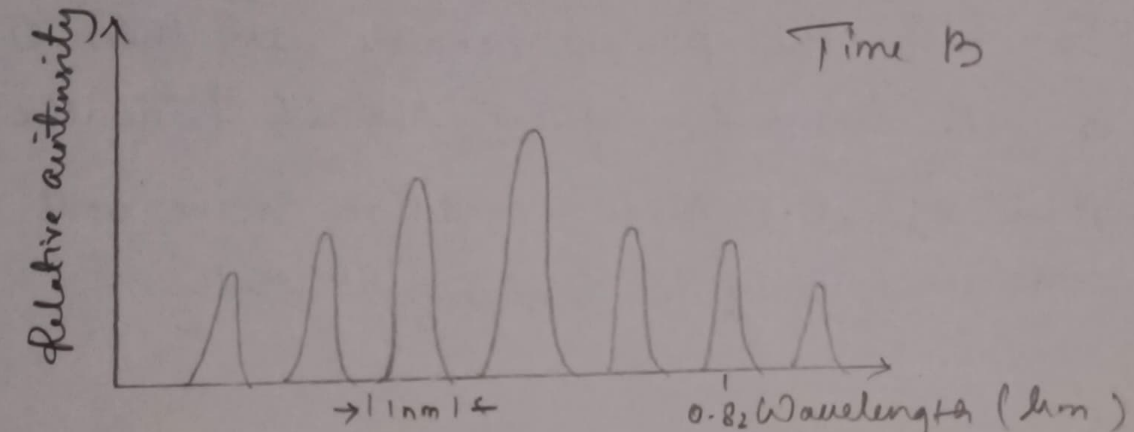
5:1:2 MODE - PARTITION NOISE :

* Mode partition noise is a phenomenon which occurs in multimode semiconductor laser when the modes are not well stabilized.
* This noise is associated with intensity fluctuation in the longitudual modes of a laser diode.
* Even when the total output power from a laser is maintained nearly constant, temperature changes can cause the relative intensities of the various longitudinal modes in the laser's output spectrum to vary considerably from one pulse to the next.

* Fig 5: shows the effect of partition noise in a multimode injection laser at different time.
  — It is displayed as a variation in the distribution of the various longitudinal modes emitted from the device.

fig 5:20 Effect of Partition noise in a multimode injection laser (15)





* Mode partition noise can also occur in single-mode devices as a result of the residual side modes in the laser output spectrum.

* The power penalty in decibels caused by laser mode-partition noise and it can approximated by,

$$P_{mpn} = -5\frac{X+2}{X+1}\log\left[1-\frac{K^2Q^2}{2}(\pi BLD\sigma_\lambda)^4\right]$$

where, $x \rightarrow$ Excess noise factor of an APD

$Q \rightarrow$ Signal to noise factor

$B \rightarrow$ Bit rate in Gb/s

$L \rightarrow$ fiber length in km

$D \rightarrow$ fiber chromatic dispersion in ps/(nm.km)

σ_λ → Rms spectral width of the source in nm

k → Mode partition noise factor.

* Parameter 'k' is difficult to quantify since it can vary from 0 to 1 depending on the laser.
  - Experimental values of k range from 0.6 to 0.8

* To keep the power penalty less than 0.5 dB, a well designed system should have the quantity $BL D \sigma_\lambda < 0.1$ Mode-partition noise will be considered only in higher bit rates.

1) REDUCTION :

* The error due to mode-partition noise can be reduced or eliminated by setting the bias point of the laser above the threshold value.

*) The effect is reduced by using a laser diode with few longitudinal modes as possible.
  - A single-longitudinal mode laser diode is generally preferred.

* The curves represent the total system performance for error probabilities of 10^{-9} & 10^{-12}.

* As an example, to maintain a total system BER of 10^{-9} and also have a receiver error

probability of 10^{-12}, the required error rate for mode partitioning is less than 10^{-12}, as shown by point A.

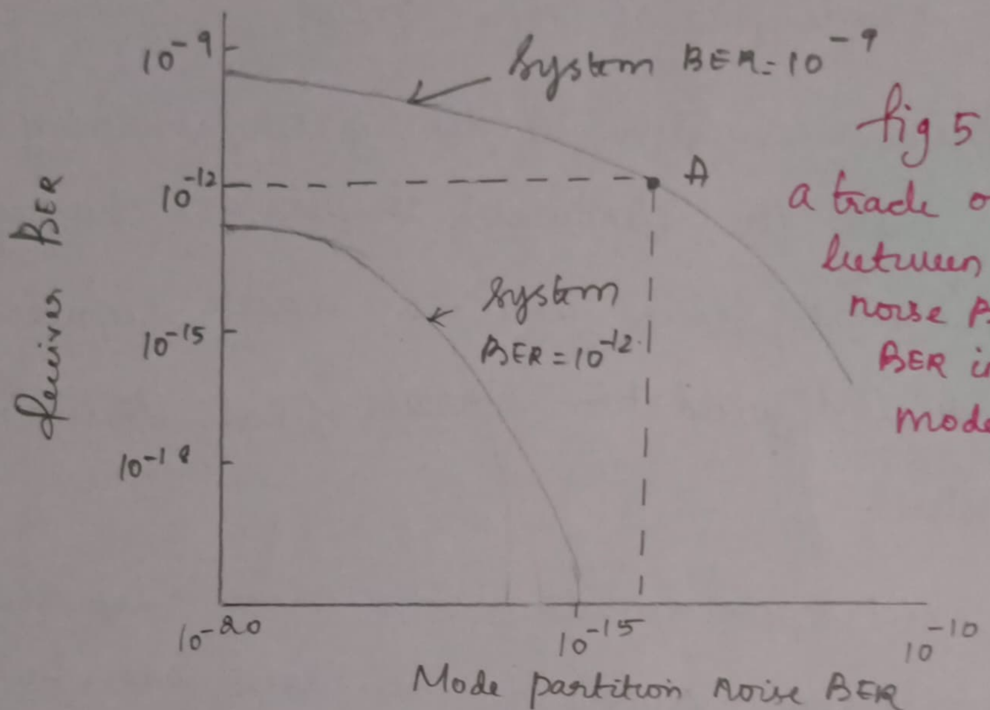


fig 5:21 Example of a trade off analysis between the mode partition noise BER and the s/m BER in the absence of mode partition s/m

5:1:3 FREQUENCY CHIRPING (OR) CHIRPING:

FREQUENCY CHIRPING:

* The direct current modulation of a single longitudinal mode semiconductor laser can cause dynamic shift of the peak wavelength from the device.

— This phenomenon, which results in dynamic linewidth broadening under the direction of modulation of the injection current and it is referred to as frequency chirping.

* Laser chirping leads to significant - dispersion effects for intensity modulated pulses when the laser emission wavelength is shifted from the zero dispersion wavelength of the fiber.

* The laser linewidth broadening or chirping combined with the chromatic dispersion characteristic of single - mode fiber and can cause significant performance degradation within high transmission rate system.

* To a good approximation, the time - dependent frequency change $\Delta\nu(t)$ of the laser can be given in terms of the output optical power $P(t)$ as,

$$\Delta\nu(t) = \frac{-a}{4\pi}\left[\frac{d}{dt}\ln P(t) + kP(t)\right]$$

where, a → Line width enhancement factor

k → frequency independent factor that depends on the laser structure.

* The factor a ranges from −3.5 to −5.5 for AlGaAs lasers. For InGaAsP laser "a" ranges from −6 to −8.

* When the effect of laser chrip is small, Δ can be approximated by,

$$\Delta = \left(\frac{4}{3}\pi^2 - 8\right) t_{chrip} \, DLB^2 \delta\lambda \left[1 + \frac{2}{3}(DL\delta\lambda - t_{chrip}\right]$$

where,

t_{chrip} → chrip duration

B → fiber chromatic dispersion

L → fiber length

$\delta\lambda$ → chrip – induced wavelength excursion.

II) Reduction of chirping :-

* Frequency chriping can be reduced by the following ways :

I) One approach is to bias the laser sufficiently above the threshold so that the modulation current does not drive the device below the threshold where the rate of change of optical output power varies rapidly with time.

II) The best approach is to choose the laser emission wavelength close to the zero – dispersion wavelength of the fiber.

III) Use dispersion shifted fibers having total zero dispersion.

5:7:4 REFLECTION NOISE :

*) When light travels through a fiber link, some optical power get reflected at refractive index discontinuities such as splices, couplers, filters & air glass interfaces in connectors.

*) The reflected signals can degrade both transmitter and receiver performance,

– In high speed systems, this reflected power causes optical feedback which can induce laser instabilities.

* These instabilities show up as either intensity noise, jitter or phase noise in the laser.

* They can change its wavelength, linewidth & threshold current of the laser.

– As a result of this, the signal-noise ratio is reduced.

POWER PENALTIES DUE TO REFLECTION NOISE :

* The reflection noise effects create two types of power penalties in receiver sensitivities.

1) Multiple reflections between two connectors
11) Inter Symbol Interferences (ISI)

I) MULTIPLE REFLECTIONS:

* Multiple reflection point set up an inter-ferometric cavity that feeds power back into the laser cavity, thereby converting phase-noise into intensity noise.

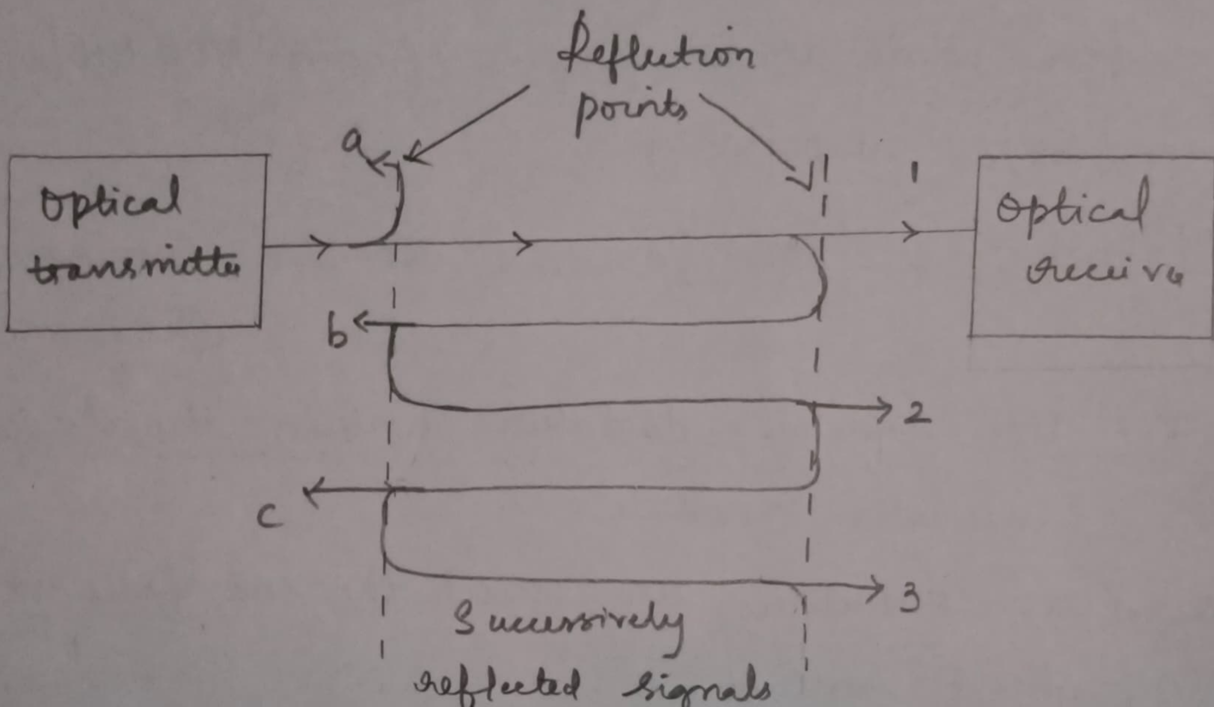


fig 5:22 Two refractive index discontinuities can set up multiple reflections in fiber link

II) INTER SYMBOL INTERFERENCE (ISI):

* A second effect created by multiple optical signal path is the appearance of spurious signal arriving at the receiver with variable delays, thereby causing inter symbol interference.

*) Each roundtrip between reflection points of the back-transmitted portion of a light

pulse creates another attenuated and delayed pulse, which can cause ISI.

*) The power penalties can be reduced to a few tenth of a decibel by keeping the return losses below value ranging from −15 to −32 dB for data rates varying from 500 Mb/s to 4 Gb/s respectively.

TECHNIQUES FOR REDUCING OPTICAL FEEDBACK (REFLECTION):

*) Use optical isolator within the laser transmitter module.

* Use connectors in which the end faces make physical contact.
  - Return losses of 25 − 40 dB have been measured with these connectors.

*) Use index-matching oil or gel air glass interference

*) Prepare fiber end faces with curved surface or an angle relative to the laser emitting facet.
  — This directs reflected light away from the fiber axis, so it does not re-enter into the wave guide.

5:8 : OPERATIONAL PRINCIPLES OF WDM PERFORMANCE OF WDM + EDFA SYSTEM:-

LINE BANDWIDTH :-

* If N transmitters in WDM links, operate at bit rates of B_1 through B_N, then the total bandwidth is

$$B = \sum_{i=1}^{N} B_i \qquad (1)$$

* When all the bit rates are equal, then the system capacity is enhanced by a factor N as compared with a single-channel link.
  - for example, if the bandwidth of each channel is given as 5 Gb/s, then the total bandwidth of the WDM link, for eight channels is 40 Gb/s and for 40 channels it is 200 Gb/s.
* The total capacity of a WDM link depends on the bandwidth of the optical amplifier and on how closely the channels can be spaced in the available transmission window.
* Through the use of closer channel spacings and an extended EDFA range, vendors are making commercially available dense WDM links with 128 wavelength.

OPTICAL POWER REQUIREMENTS FOR A SPECIFIC BER:

* At the outputs of the demultiplexer, system parameters that need to be considered include the signal level, noise level and crosstalk.
* Bit Error Rate (BER) of a WDM channel is determined by the optical Signal - Noise Ratio (SNR) delivered to the photo detector.
* In an ideal link, the acceptable low BER is approximately 14 dB measured in 0.01nm optical bandwidth.
* In an optically amplified link, the main noise factor for a digital 1 arises from the signal mixing with the Amplified Spontaneous Emission (ASE) noise from the EDFA, whereas for a digital 0 signal the probability of error is determined by ASE noise alone.
* For a given channel, transmitted over a optical link that contains several optical amplifiers and the SNR starts out at a high level.

— It then decreases at each amplifier as ASE noise accumulates through the length of the link as shown in fig 5:

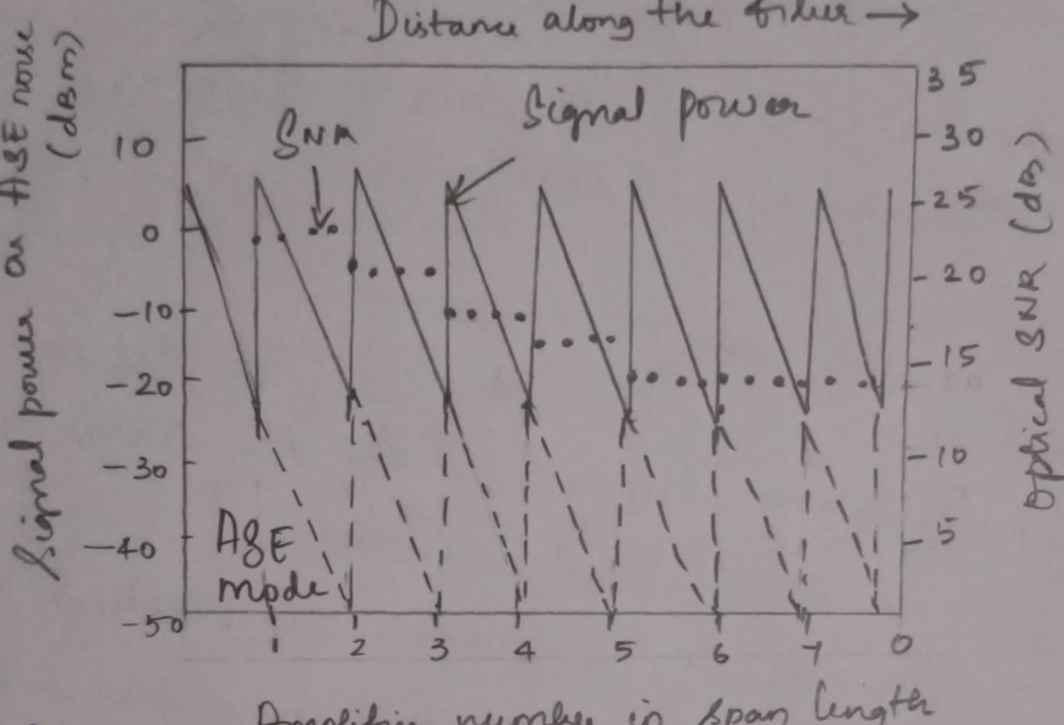


fig 5:23 SNR Vs number of amplifiers

* When the number of Erbium doped fiber amplifier (EDFA) increases, the SNR will gets decreases.

CROSS TALK :

* Crosstalk is defined as the feedthrough of one channel's signal into another channel.
* Crosstalk can be introduced by almost any component in a WDM system, including optical filters, wavelength multiplexers & demultiplexers

optical switches ; optical amplifiers & filter itself.

* The two types of crosstalk that can occur in WDM systems are,

i) Intrachannel Crosstalk
ii) Interchannel Crosstalk

i) INTRACHANNEL CROSSTALK :

* In Intrachannel Crosstalk is defined as the interfering signal is at the same wave-length as the desired signal.

- This effect is more severe than inter-channel crosstalk, since the interference falls completly within the receiver bandwidth.

* In the fig, 5 : , two independent signals each at a wavelength λ_1 enter an optical switch.

- This switch routes the signal entering port 1 to output port 4 and routes the signal entering port 2 to output port 3.

* Within the switch, a spurious fraction of the optical power entering port 1 gets coupled to port 3, where it interfers with the signal from port 2.

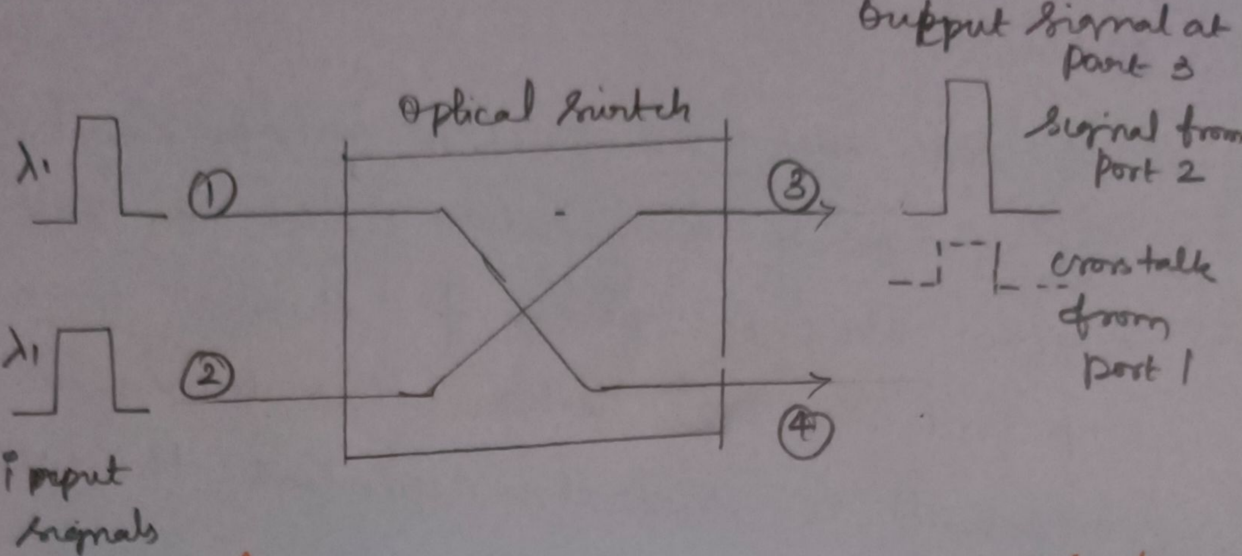


fig 5:24 Intrachannel crosstalk in WDM systems

II) INTERCHANNEL CROSSTALK:

* Interchannel crosstalk arises when an interfering signal comes from a neighbouring channel that operates at a different wavelength.

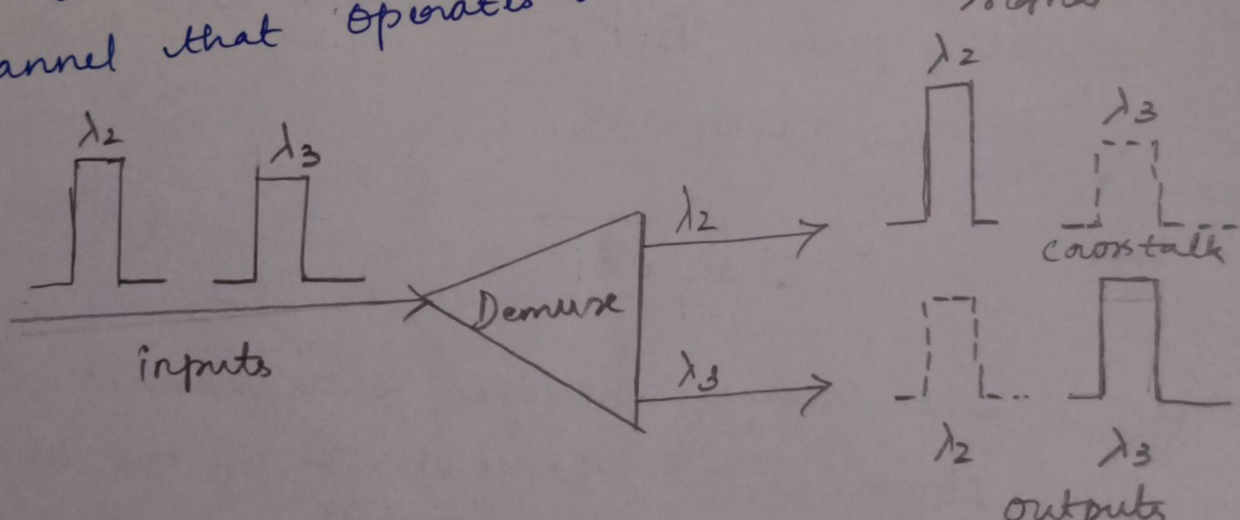


fig 5:25 Interchannel crosstalk in WDM systems

* This normally occur when a wavelength-selecting device imperfectly rejects or isolates

the signal from other nearby wavelength channels.

* If the average received intrachannel cross-talk power is a fraction ε of the average received signal power P then it in an amplified system, where the dominant noise component is signal-dependent, the intra channel power penalty.

$$\text{Penalty}_{\text{intra}} = -5 \log (1 - 2\sqrt{\varepsilon}) \quad \text{——} \quad (2)$$

* If there are N interfering channels in a WDM system, each contributing an average crosstalk power $\varepsilon_i P$, then the factor ε in eq (2) is given by,

$$\sqrt{\varepsilon} = \sum_{i=1}^{N} \sqrt{\varepsilon_i} \quad \text{——} \quad (3)$$

* If the average received interchannel cross-talk power is a fraction ε of the average received signal power P, then consider an amplified system the interchannel power penalty is

$$\text{Penalty}_{\text{intra}} = -5 \log (1 - \varepsilon) \quad \text{——} \quad (4)$$

* If there are N interfering channels in a WDM system, each contributing an average crosstalk power $\varepsilon_i P$, then the factor ε in eq (4) is given by,

$$\varepsilon = \sum_{i=1}^{N} \varepsilon_i \quad \text{——} \quad (5)$$

5:9 SOLITONS :-

Group Velocity Dispersion (GVD) causes most pulse to broaden in time as they propogate through an optical fiber.

i) SOLITONS :

* A solitons are pulse that travel along the fiber without change in shape or amplitude or velocity.

* The term soliton refers to a special kind of waves that can propogate undistorted over long distances and remain unaffected even after collisions with each other.

* Solitons take advantage of nonlinear effects in silica, particularly self pulse modulations (SPM)

resulting from the Kerr nonlinearity to overcome the pulse-broadening effects of GVD.

* Attenuation in the fiber will eventually decreases the soliton energy.

* The family of pulses that do not change in shape are called fundamental solitons.

* the family of pulse that undergo periodic shape change are called higher order solitons

ii) SOLITON PULSES :-

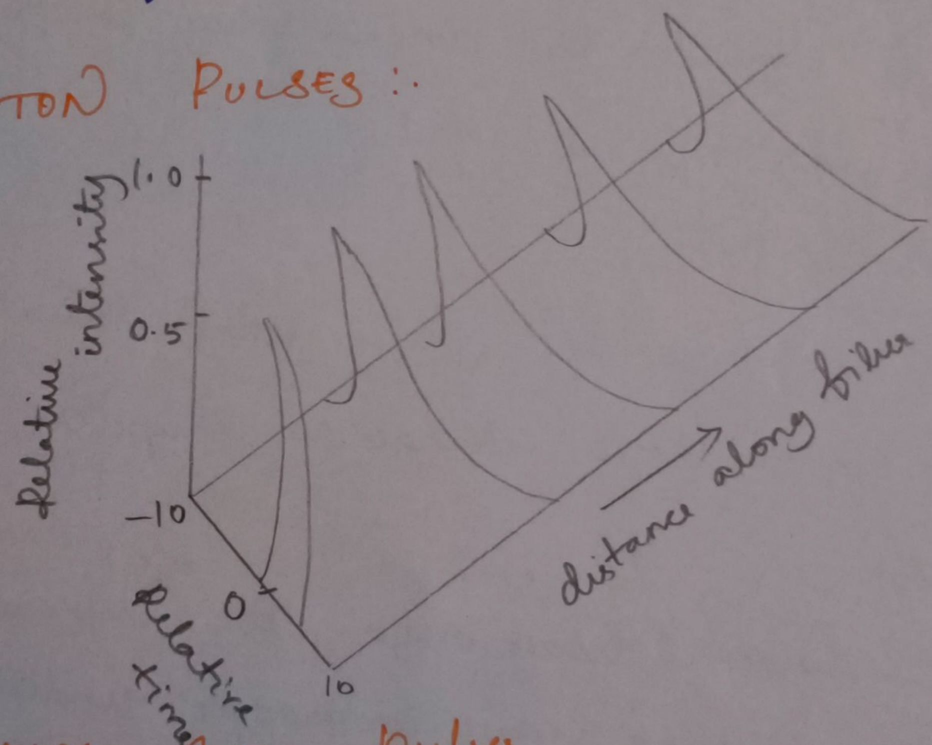


fig 5:26 Soliton pulses

* To derive the evolution of the pulse shape required for soliton transmission, we consider the Nonlinear Schrodinger (NLS) equation as,

$$-j\frac{\partial u}{\partial z} = \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + N^2|u|^2 u - j\left(\frac{\alpha}{2}\right)u \quad (1)$$

where,

$u(z,t) \rightarrow$ pulse envelope function

$z \rightarrow$ Propogation distance along the fiber

$N \rightarrow$ An integer designating the order of the soliton

$a \rightarrow$ Coefficient of energy gain per unit length with negative values of a representing energy loss.

* For the three right hand terms in eq (1),

— The first term represents GVD effects of the fiber.

- Dispersion tends to broaden pulses in time.

— The second nonlinear term denotes the fact that the refractive index of the fiber depends on the light intensity

— Third term represents the effect of energy loss or gain.

* The solution to eq (1) for the fundamental soliton is given by,

$$u(z,t) = \operatorname{sech}(t) \exp\left(\frac{jz}{2}\right) \quad \text{——— (2)}$$

where, $\operatorname{sech}(t) \longrightarrow$ hyperbolic secant function.

This is a bell shaped pulse.

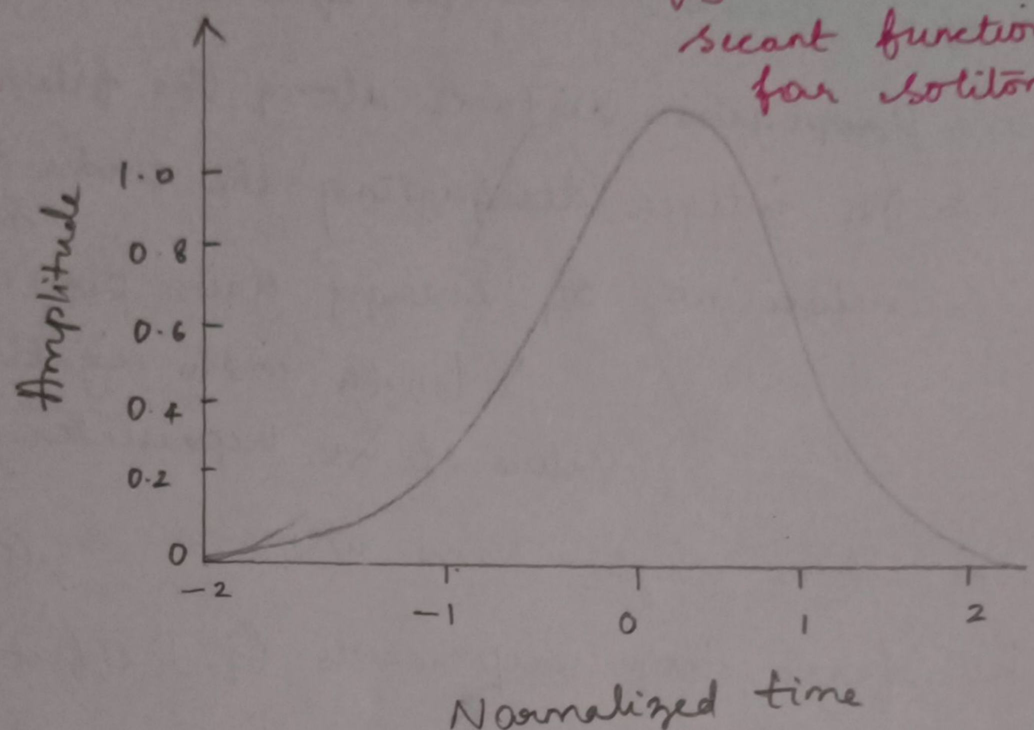


fig 5:27 Hyperbolic secant function used for soliton pulses

* The phase term $\exp\left(\frac{jz}{2}\right)$ in eq (I) has no influence on the shape of the pulse, the soliton is independent of z and hence it is non dispersive in the time domain.

iii) SOLITON PARAMETERS :-

a) FULL WIDTH HALF MAXIMUM (FWHM)

* Full width half maximum (FWHM) of a pulse is defined as the full width of the pulse at its half maximum power level.
* FWHM T_s of the fundamental soliton pulse in normalized time T_0 is found

from the relationship

$$Sech^2(\tau) = \frac{T_s}{2T_0}$$

where $T_0 \rightarrow$ basic normalized time unit

$$T_0 = \frac{T_s}{2\cosh^{-1}\sqrt{2}} = \frac{T_s}{1.7627} \approx 0.567\, T_s \quad (3)$$

where $T_s \rightarrow$ FWHM pulse width.

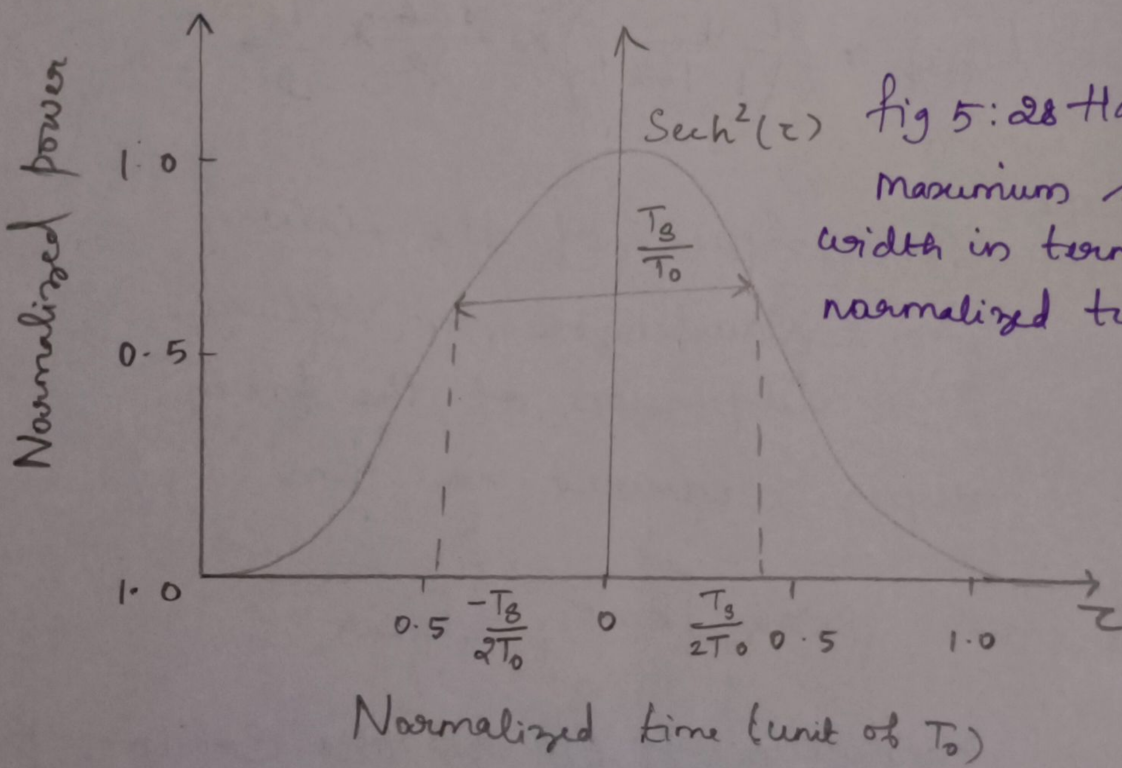


fig 5:28 Half maximum Soliton width in terms of normalized time units

(6) DISPERSION LENGTH (L_{disp}):

* The normalized distance parameter L_{disp} is a characteristic length for the effects of the dispersion term.

* L_{disp} is a measure of the period of soliton. This is given by.

$$L_{disp} = \frac{2\pi c}{\lambda^2} \frac{T_0^2}{D} \quad \text{--- (4)}$$

By substituting eq (3) in (4) we get,

$$L_{disp} = \frac{1}{(2\cosh^{-1}\sqrt{2})^2} \frac{2\pi c T_s^2}{\lambda^2 D}$$

$$L_{disp} \approx 0.322 \times \frac{2\pi c}{\lambda^2} \times \frac{T_s^2}{D} \quad \text{--- (5a)}$$

$$L_{disp} \approx \left(\frac{1}{1.7627}\right)^2 \times \frac{2\pi c}{\lambda^2} * \frac{T_s^2}{D} \quad \text{--- (5b)}$$

where,
- $c \rightarrow$ Speed of the light
- $\lambda \rightarrow$ Wavelength in Vaccum
- $D \rightarrow$ dispersion of the fiber
- $L_{disp} \rightarrow$ measured in km

(c) SOLITON PEAK POWER (P_{peak}):

* The parameter P_{peak} is the soliton peak power and it is given by,

$$P_{peak} = \frac{A_{eff}}{2\pi n_2} \frac{\lambda}{L_{disp}} \quad \text{--- (6)}$$

by substituting eq 5(a) in eq (6),

$$P_{peak} = \frac{A_{eff}}{2\pi n_2} \frac{\lambda}{\frac{1}{(1.7627)^2} \frac{2\pi c}{\lambda^2} \frac{T_s^2}{D}}$$

$$P_{peak} = \left(\frac{1.7627}{2\pi}\right)^2 \frac{A_{eff}\,\lambda^3}{n_2\, c} \frac{D}{T_s^2} \quad \text{--- (7)}$$

where

$A_{eff} \rightarrow$ effective area of the fiber core

$n_2 \longrightarrow$ non linearity intensity dependent refractive index coefficient.

d) SOLITON WIDTH AND SPACING :-

* If T_B is the width of the bit slot, then we can relate the bit rate (B) to the soliton half maximum width T_s by,

$$B = \frac{1}{T_B} = \frac{1}{2S_0 T_0} = \frac{1.7627}{2S_0 T_0} \quad \text{--- (8)}$$

where the factor $2S_0 = \frac{T_B}{T_0}$ is the normalized seperation between neighboring solitons.

* For solitons that are initially in phase and seperated by $2S_0 >> 1$, the soliton seperation is periodic with an oscillation period.

$$\Omega = \frac{\pi}{2} \exp(8_0) \quad \text{--- (9)}$$

* Mutual interactive force between the in-phase solitons results in periodic attraction, collapse and repulsion.

The interaction distance is then given as,

$$L_1 = \Omega L_{disp} = L_{period} \exp(8_0) \quad \text{--- (10)}$$

* This interaction distance particularly the ratio L_1 / L_{disp}, determines the maximum bit rate allowable in solitons systems,

$$\Omega L_{disp} >> L_T \quad \text{--- (11)}$$

where $L_T \rightarrow$ total transmission distance

* The system design, in which soliton interaction can be ignored

$$(\text{dispersion})\, D = \frac{1}{L} \frac{d\tau_g}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta^2 \quad \text{--- (12)}$$

Using eq 5b for L_{disp}, eq (8) for T_0 and D from eq (12), design condition $\Omega L_{disp} >> L_T$ becomes,

$$P_{peak} = \frac{A_{eff}}{2\pi n_2} \frac{\lambda}{\frac{1}{(1.7627)^2} \frac{2\pi c}{\lambda^2} \frac{T_s^2}{D}}$$

$$P_{peak} = \left(\frac{1.7627}{2\pi}\right)^2 \frac{A_{eff} \lambda^3}{n_2 c} \frac{D}{T_s^2} \quad \text{--- (7)}$$

Where

A_{eff} → effective area of the fiber core

n_2 → non linearity intensity dependent refractive index coefficient.

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Where the factor $2S_0 = \frac{T_B}{T_0}$ is the normalized seperation between neighboring solitons.

* For solitons that are initially in phase and seperated by $2S_0 >> 1$, the soliton seperation is periodic with an oscillation period.

$$B^2 L_T << \left(\frac{2\pi}{S_0 \lambda}\right)^2 \frac{c}{16D} \exp(S_0) = \frac{\pi}{8 S_0^2 |\beta_2|} \exp(S_0)$$ (13)

This eq (13) shows, the effect of the Bandwidth, B or the total transmission distance L_T for the selected values of S_0.

5:10 OPTICAL CDMA :-

* Optical code division Multiple Access (CDMA) scheme can provide multiple access to a network without using wavelength sensitive components as in WDM, and without employing very high-speed electronic data processing devices as are needed in TDM networks.

* Multiple access is nothing but two or more users simultaneously communicate with each other using the same propagation channel.

WHY SPREAD SPECTRUM ?

* In digital communication systems an efficient use of bandwidth and power are the main two factors.

* In some situations like, providing security for military communication it is necessary to sacrifice this efficiency.

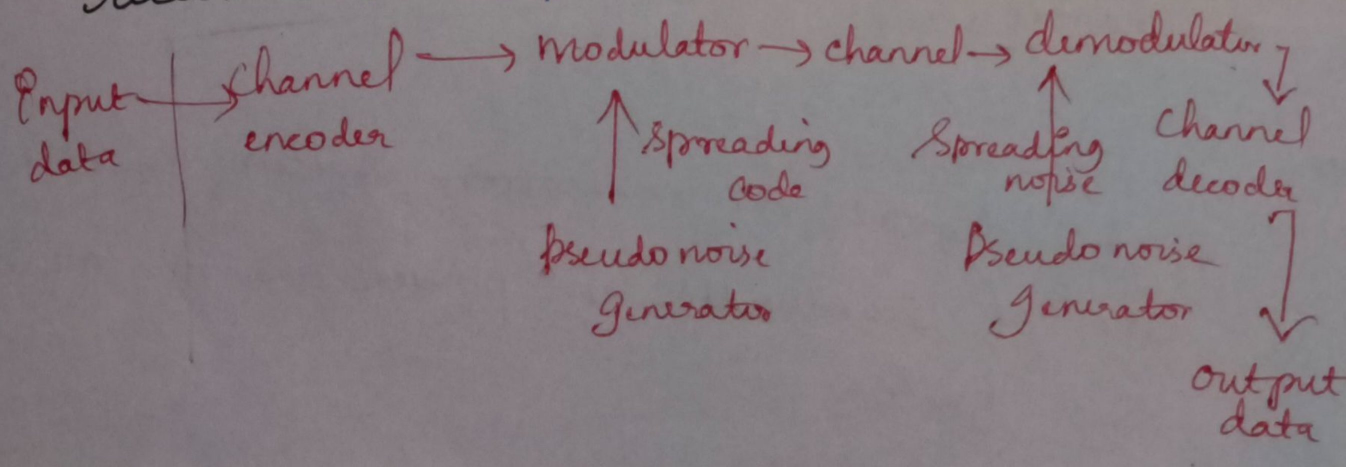
— This requirement is obtained by a class of signally techniques known as spread spectrum modulation.

5:10:1 PRINCIPLE OF SPREAD SPECTRUMS:

* Spread spectrum modulation is a technique whereby a modulated signal is modulated a second time in such a way so as to generate an expanded bandwidth signal, that does not significantly interfere with other signal.

* Spreading is achieved by a code which is independent of the data sequence.

— The same code is used at the receiver to despread the received signal.



UNIT-5

Optical Communication Systems and Networks

System Design Considerations

In optical system design major Consideration involves

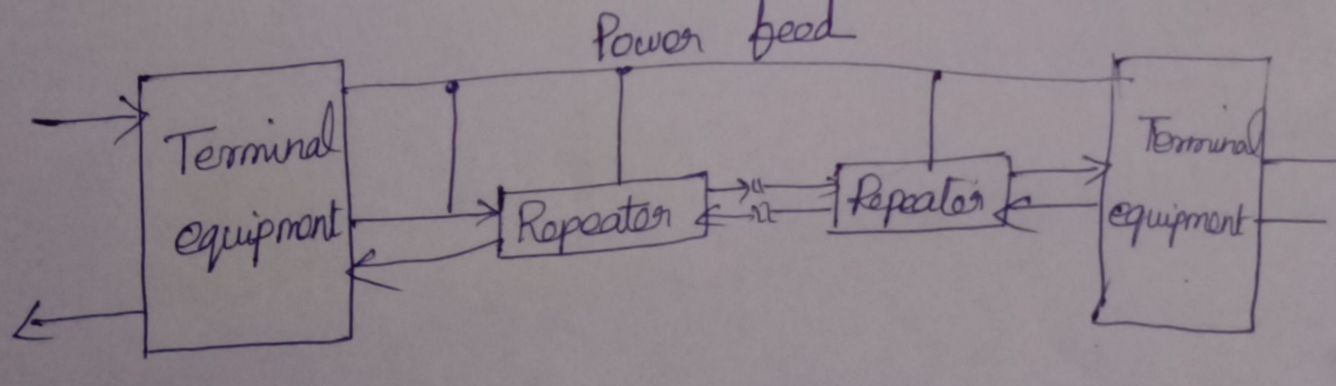
1) Transmission characteristics of fiber (Attenuation and dispersion.

(2) Information transfer capability of fiber

(3) Terminal equipment and technology.

(4) Distance of transmission

- In long-haul communication applications repeaters are inserted at regular intervals



Repeater generates the original data before it is transmitted as a digital optical signal. The cost of system increases because of installation of repeaters.

An optical communication system should have following basic required specifications.

a) Transmission type
b) Required transmission Bandwidth.
c) Cost of system
d) Cost of maintenance
e) Reliability.

High Speed Light Wave Links.

High speed light waveguide is designed for high Band width, low power dissipation and for long distance power transmission.

(1) Propagation loss < 0.04 dB/cm @ 850 nm

(2) Data rate $\cong$ 20 Gbps / channel

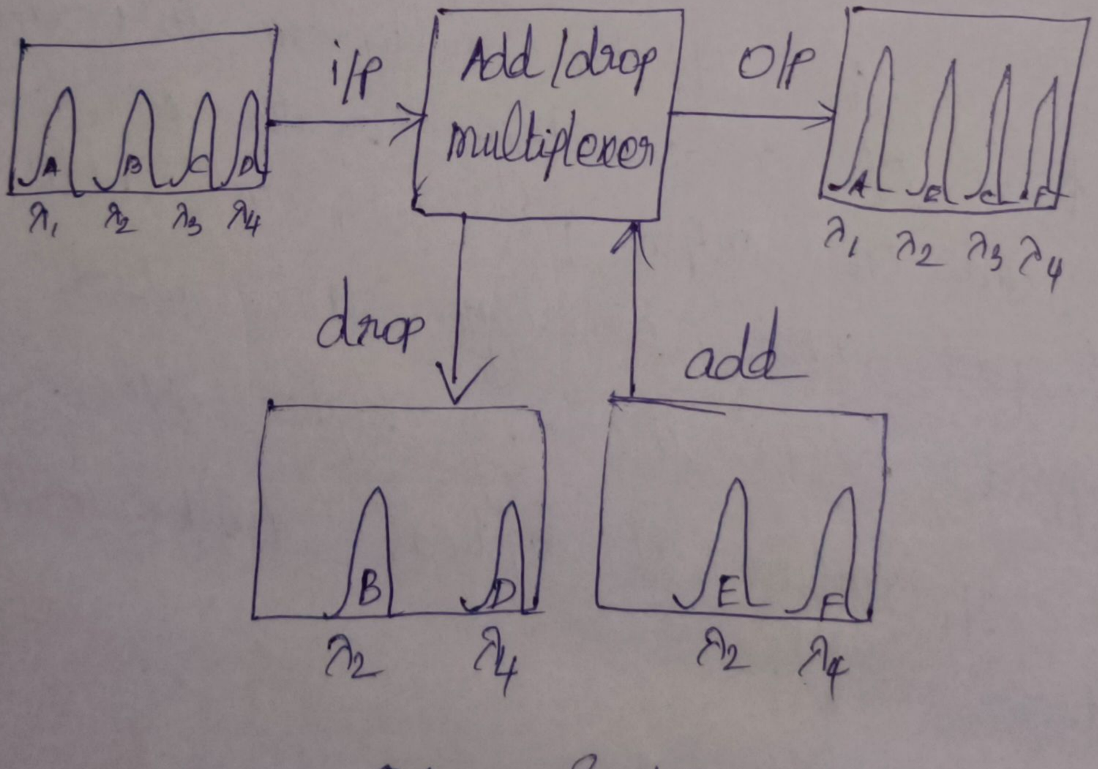
(3) Cross talk < -20 dB @ 62.5 μm pitch.

Optical Add / Drop Multiplexer. (OADM)

An add / drop multiplexer is essentially a form of a wavelength router with one input port and one output port with an additional local part where wavelengths are added to / dropped from incoming light signal. It is an application of optical filter in optical Networks.

OADM Technology.

The introduction of optical add drop multiplexers into optical networks allows traffic to be inserted, removed and most importantly bypassed. Moreover OADM can support functions such as protection, drop/continue, loop-back and wavelength reuse of the optical channels.



OADM System.

Drop and Continue refer that the channel is removed at the node but allowed to pass through to the next OADM.

Wavelength reuse means the dropped channel does not pass through to the next OADM, instead, a new channel of the same wavelength can be added.

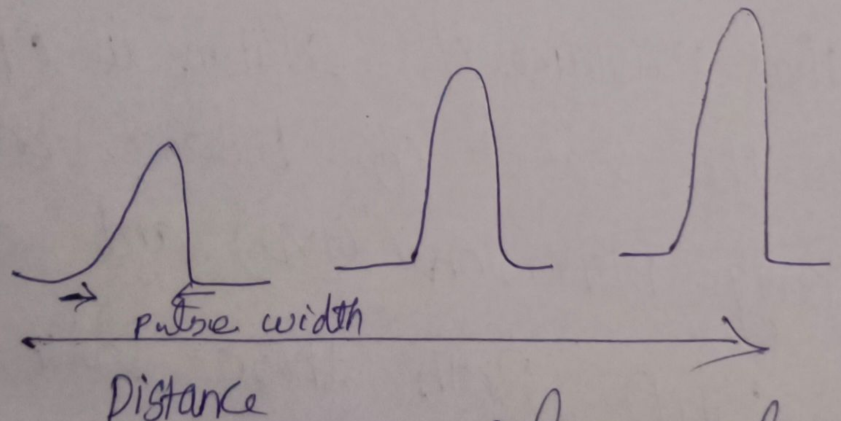
Optical Ethernet - Solitons.

The existance of solitons in optical fibers is the result of balance between the Group velocity Dispersion (GVD) and self phase Modulation (SPM). Both these limit the performance of fiber Communication system.

Soliton pulse

A soliton pulse is a pulse of light of sufficient intensity and correct wavelength, travelling down a special non-linear optical fiber (dispersion shifted fiber) is called as soliton pulse.

The soliton pulse exhibits a unique characteristics of getting shorter with distant travelled.



soliton pulse.

Fundamental Soliton equation

$$U(z,t) = \text{sech}(t)\, e^{(jz/2)}$$

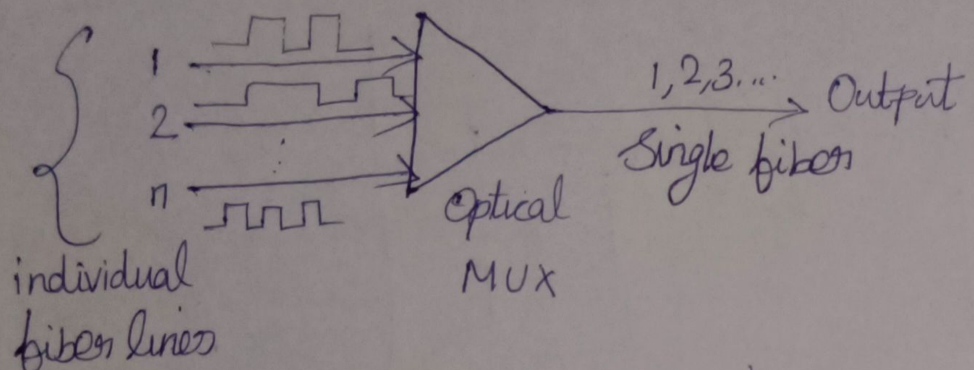
Where sech(t) hyperbolic secant function.

Soliton Parameters

1) Full Width Half Maximum.
2) Dispersion Length
3) Soliton Peak Power.

Wavelength Division Multiplexing (WDM)

Many different wavelengths between 1300 to 1600 nm can be sent over a fiber simultaneously.



The technique of combining multiple wavelengths is called wavelength Division Multiplexing (WDM).

WDM Scheme

Optical signals of different wavelength (1300-1600 nm) can propagate without interfacing with each other. The scheme of combining a number of wavelengths over a single fiber is called wavelength Division Multiplexing (WDM).

Each input is generated by a separate 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 separate the different carriers before photodetection of individual signals

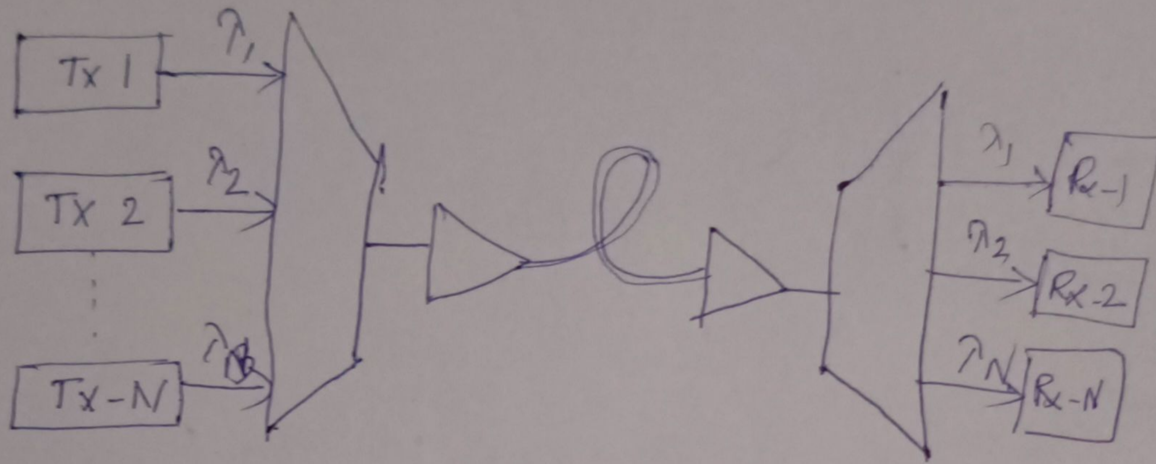


Fig:- WDM scheme

To prevent spurious signals to enter into receiving channel, the demultiplexer must have narrow spectral operation with sharp wavelength cut offs

Features of WDM

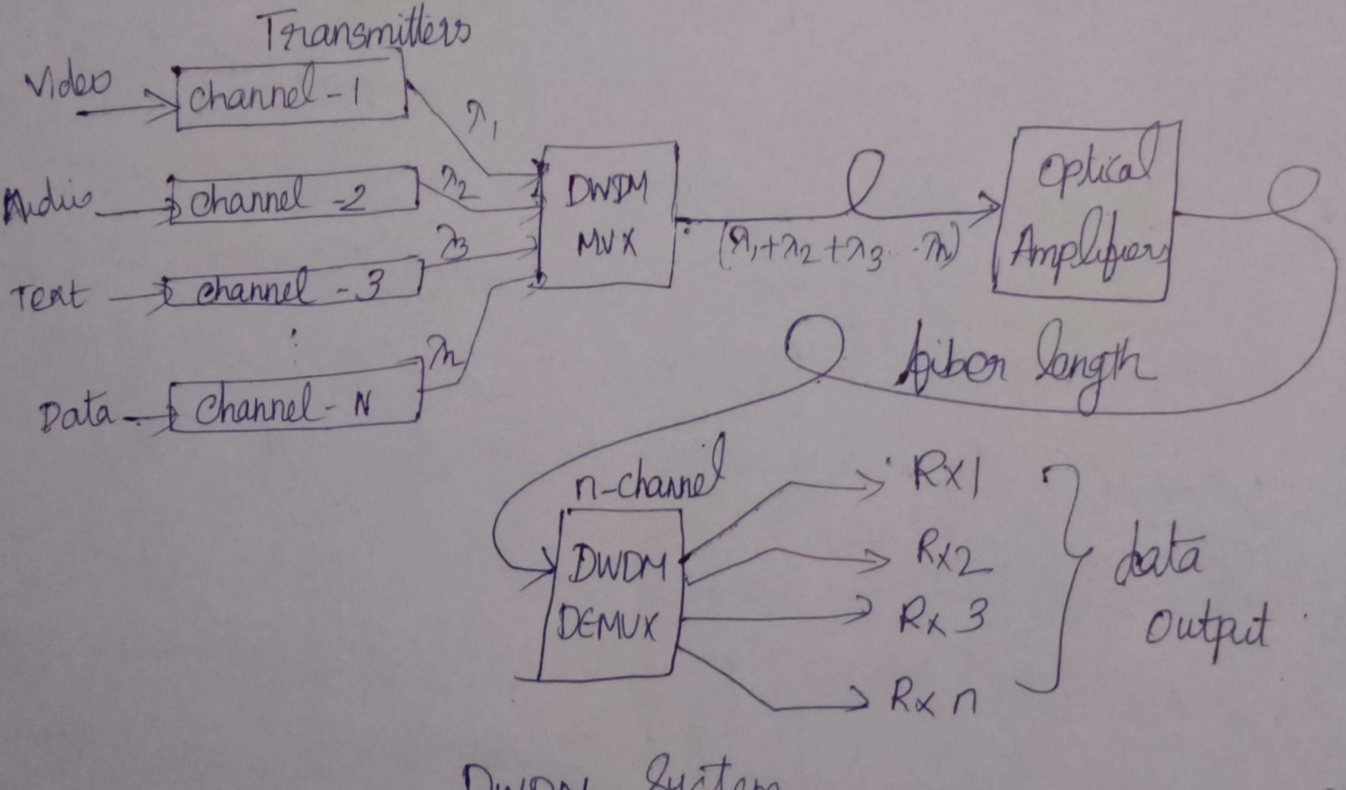
1) Capacity upgrade
2) Transparency
3) wavelength routing
4) wavelength switching

Dence Wavelength Division Multiplexing (DWDM)

1) DWDM is a data transmission technology having very large capacity and efficiency.

2) Optical data channels of optical signals are assigned different wavelengths, and are multiplexed onto one fiber.

3) DWDM System consists of transmitters, multiplexer, optical amplifier and demultiplexer.



DWDM System

4) DWDM uses Single mode fiber to carry multiple light waves of different frequencies

5) DWDM system uses Erbium-Doped fiber Amplifiers (EDFA) for its long haul applications and to overcome the effects of dispersion and attenuation channel spacing of 100 GHz is used.

Point to Point link design.

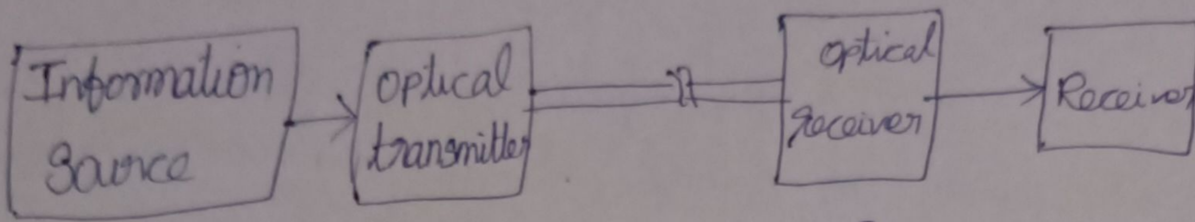
A point to point link comprises of one transmitter and a receiver system. This is the simplest form of optical communication link and it sets the basis for examining complex optical communication links

for analyzing the performance of any link following important aspects are to be considered.

(a) Distance of transmission b) channel data rate

(c) Bit error rate

All the above parameters of transmission link are associated with the characteristics of various devices employed in the link



When the link length extends between 20 to 100km, losses associated with fiber cable increases. In order to compensate the losses optical amplifier and regenerators are used over the span of fiber cable.

A regenerator is a receiver and transmitter pair which detects incoming optical signal, recovers the bit stream electrically and again convert back into optical form by modulating an optical source.

An optical amplifier amplify the optical bit stream without converting it into electrical form.

The spacing between two repeater or optical amplifier is called as repeater spacing (L).

Two important analysis for deciding performance of any fiber link are

i) Link power budget / power budget

(ii) Rise time budget / Bandwidth Budget.

Optical interfaces

In a fiber optic Communications link, a point at which an optical signal is passed from one equipment or medium to another without conversion to an electrical signal is known as optical interface.

An ONT (Optical Network terminal) is used to terminate the fiber optic line, demultiplex the signal into its component parts and provide power to customer telephones.

A parallel optical interface is a form of optical fiber technology used in communications and Networking over relatively short distances and at high Bandwidth.

Different Methods exist for splitting the data over this high Bandwidth link. In the simplest form, the parallel optical link is a replacement for many serial data communication links.

SONET/SDH Networks AND RINGS

SONET networks can be divided into three categories

1) Linear Networks

2) Ring Network

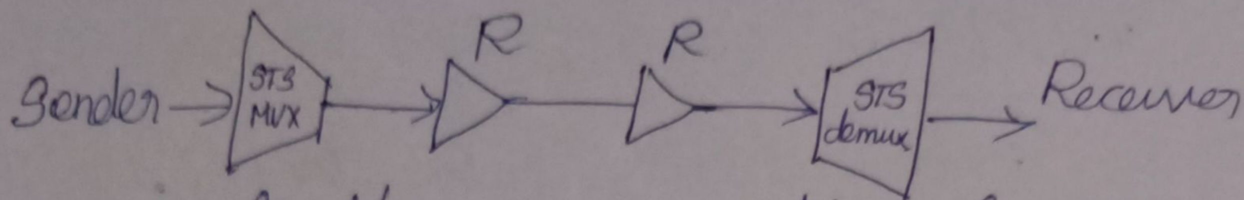
3) Mesh Networks.

SONET Networks

- Linear Networks
  1) Point to point
  2) Multipoint
- Ring Networks
  1) UPSR
  2) BLSR.
- Mesh Networks

Point to point SONET

A point to point network is normally made of an STS multiplexer, an STS demultiplexer, and zero or more regenerators with no add/drop multiplexers.

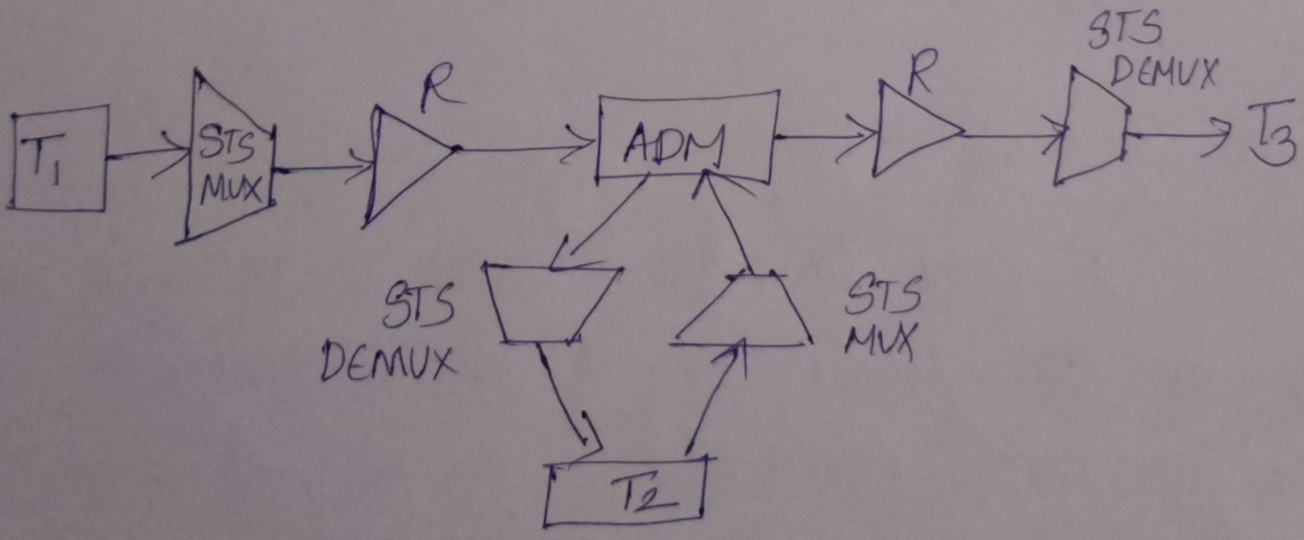


The signal flow can be unidirectional or bidirectional.

Multipoint SONET

A multipoint network uses ADMs to allow the Communications between several terminal. An ADM removes the signal belonging to the Terminal Connected to it and adds the signal transmitted from another terminal.

Each terminal can send data to one or more downstream terminals.

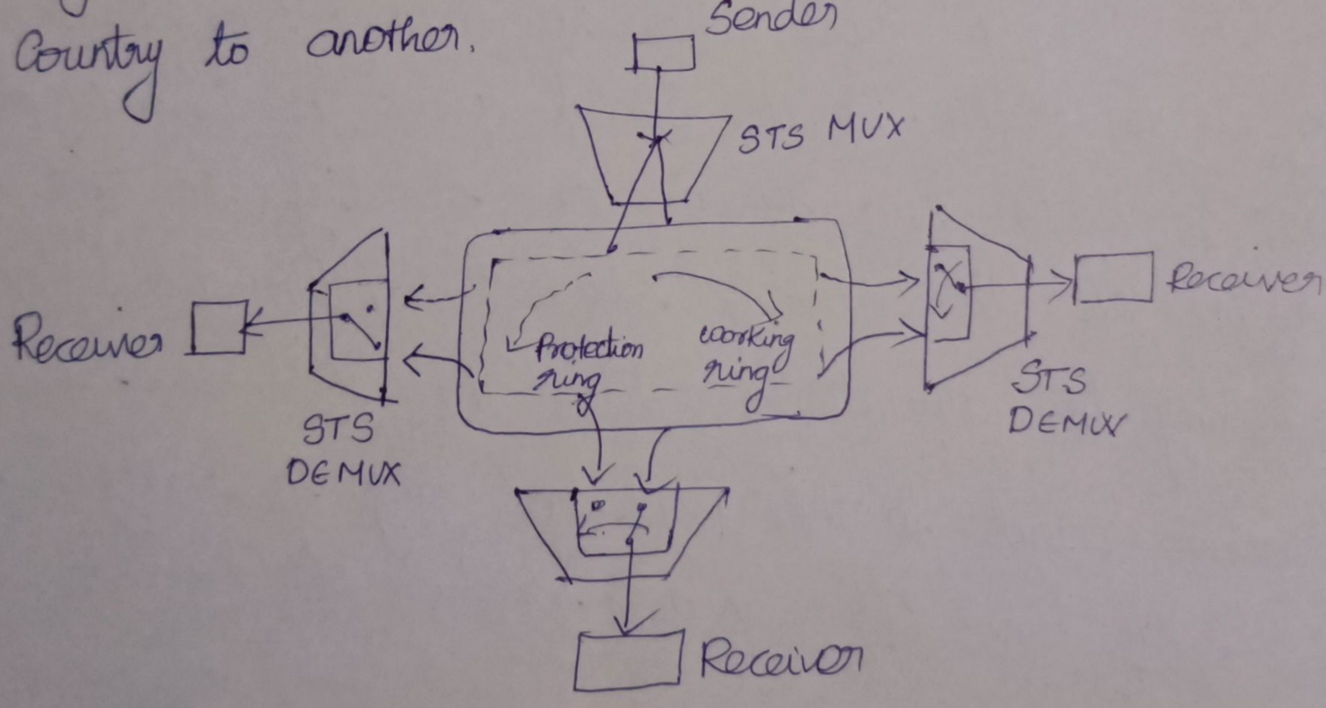


Multipoint Sonet Network.

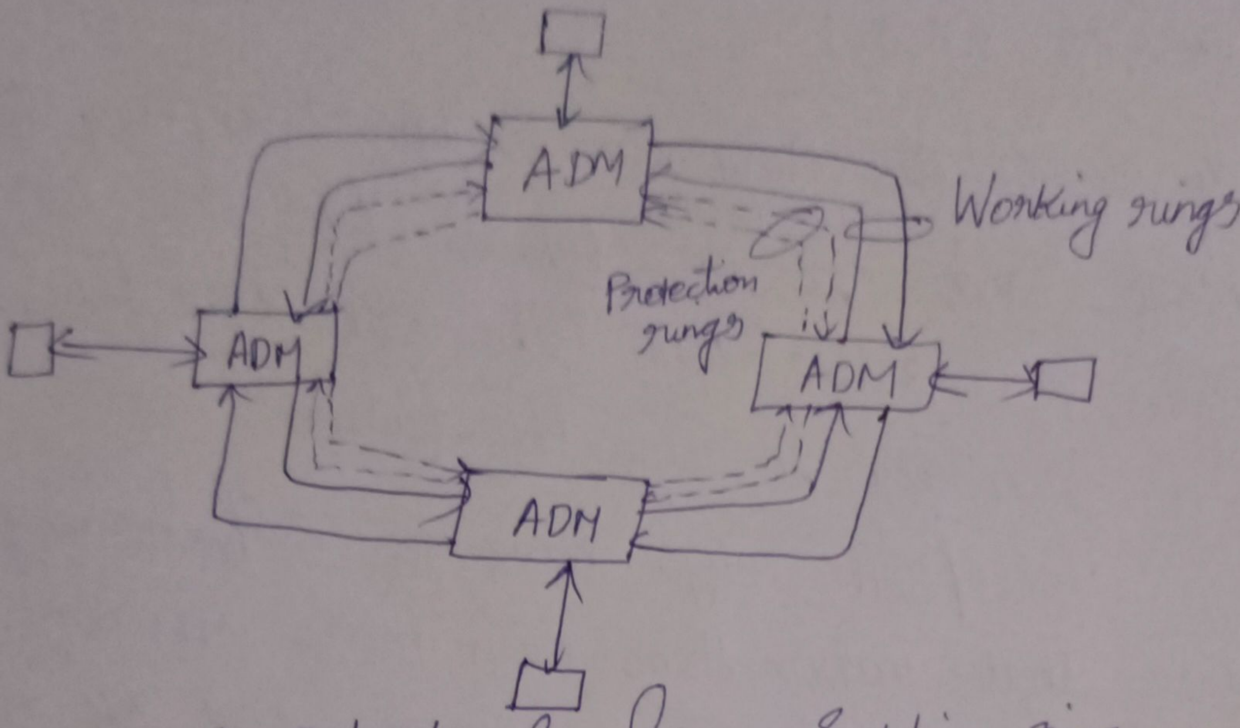
SONET RINGS

A SONET/SDH ring can contain two pairs of transmit and receive fibers. One pair can be designed as active with the other one functioning as a secondary in case of failure.

SONET/SDH rings have a self healing feature that makes them even more appealing for long distance connections from one end of the country to another.



A unidirectional path switching ring



A Bidirectional line Switching ring.

One piece of fiber called the working ring, handles all data traffic, but a second piece of fiber called the protection ring remains on standby. In case of failure of the working ring, SONET/SDH includes the capability to automatically detect the failure and transfer control to the protection ring in a very short period of time, often in a fraction of second