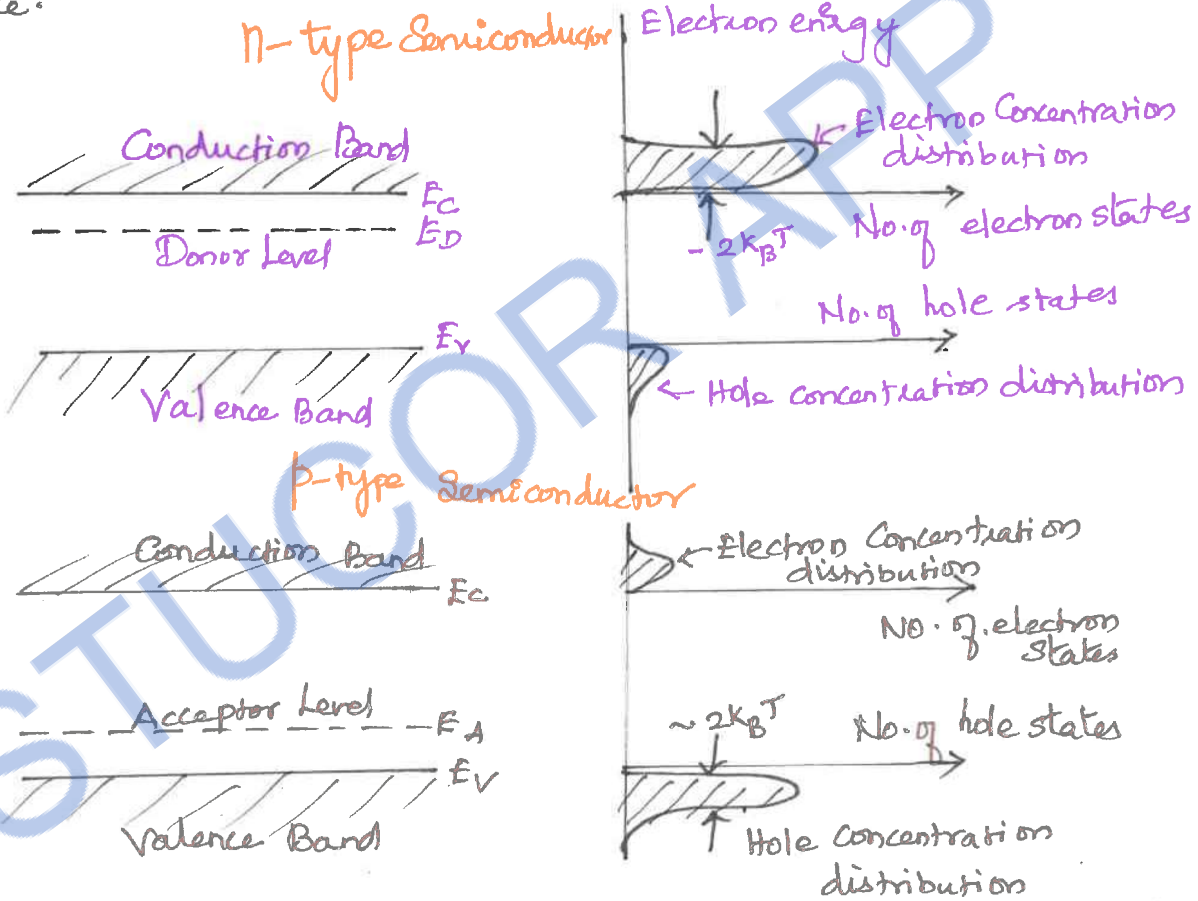
UNIT-3

OPTICAL SOURCES AND DETECTORS

A Semiconductor material is classified into two types on the basis of its energy band diagram in the energy momentum space.



Intrinsic & Extrinsic Materials:

Intrinsic material: A perfect material with no impurities.

$$n = p = n_i \propto \exp\left(-\frac{E_g}{2k_BT}\right)$$

n – Electron Concentration

p – Hole concentration

n_i – Intrinsic concentration ion

E_g – Gap energy

T – Temperature

Extrinsic material :- Donor or Acceptor type semiconductors

$$pn = n_i^2$$

majority carries → Electrons in n-type ; Holes in p-type

minority Carries → Holes in n-type ; Electrons in p-type

The operation of semiconductor devices is essentially based on the injection & extraction of minority carriers.

Direct and Indirect Band Gaps.

* The band gap represents the minimum energy difference between the top of the valence band and the bottom of the conduction band.

* However, the top of the valence band and the bottom of the Conduction band are not generally at the same value of electron momentum.

* In a direct band gap semiconductor, the top of the valence band and the bottom of the Conduction band occur at the same value of momentum

* In a indirect band gap semiconductor, the maximum energy of the valence band occurs at a different value of momentum to the minimum in the conduction band energy

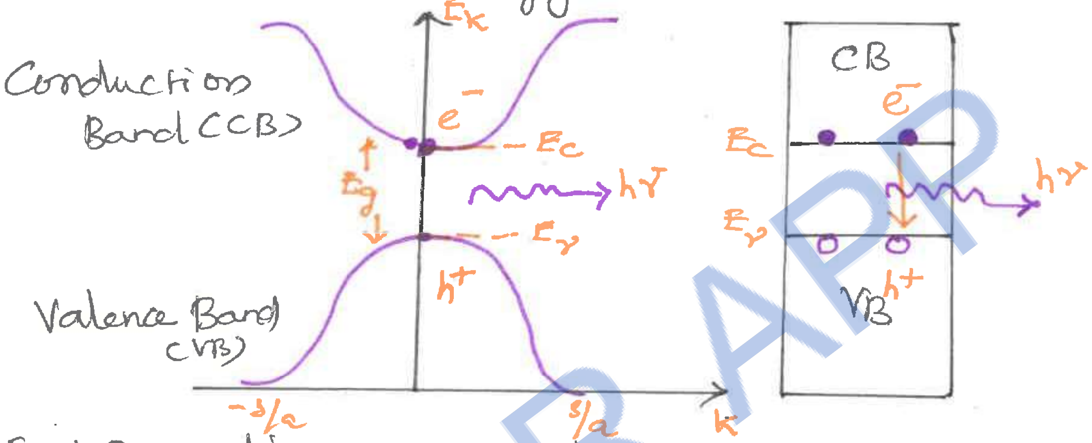
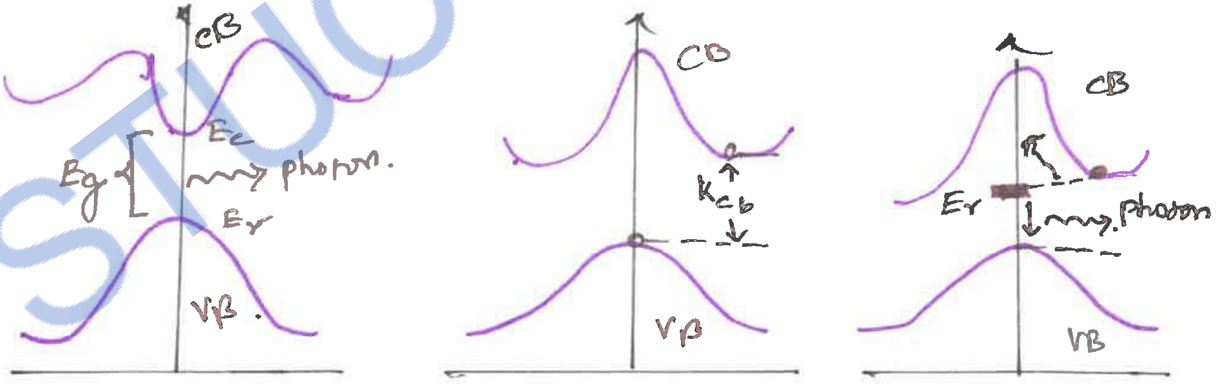


Fig: E-K diagram of a direect bandgap Semiconductor such as GaAs



GaAs Si Si with recombination centre

Fig: Indirect Band Gap for Various Semiconductor materials.

Light Emitting Diodes (LED)

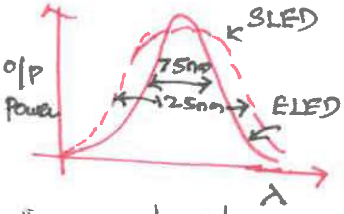
For photonic communications requiring data rate 100-200 Mb/s with multimode fiber with tens of microwatts.

LED is a semiconductor device that emits incoherent light, through spontaneous emission, when a current is passed through it. Typically LEDs for the 850 nm region are fabricated using GaAs and AlGaAs. LEDs for the 1300 nm and 1550 nm region are fabricated using InGaAsP and InP. The basic LED types used for fiber optic communication systems are

(i) Surface-Emitting LED (SLED)

(ii) Edge-Emitting LED (ELED)

(iii) Super Luminescent Diode (SLD)



LED performance differences help link designers decide which device is appropriate for the intended application. For short distance (0 to 3 km), low data rate fiber optic systems, SLEDs and ELEDs are the preferred optical source. Typically SLEDs operate efficiently for bit rate up to 250 Mbps, because SLEDs emit light over a wide area (wide far-field angle), they are almost exclusively used in multimode systems.

For medium distance, medium data rates ELEDs are preferred.

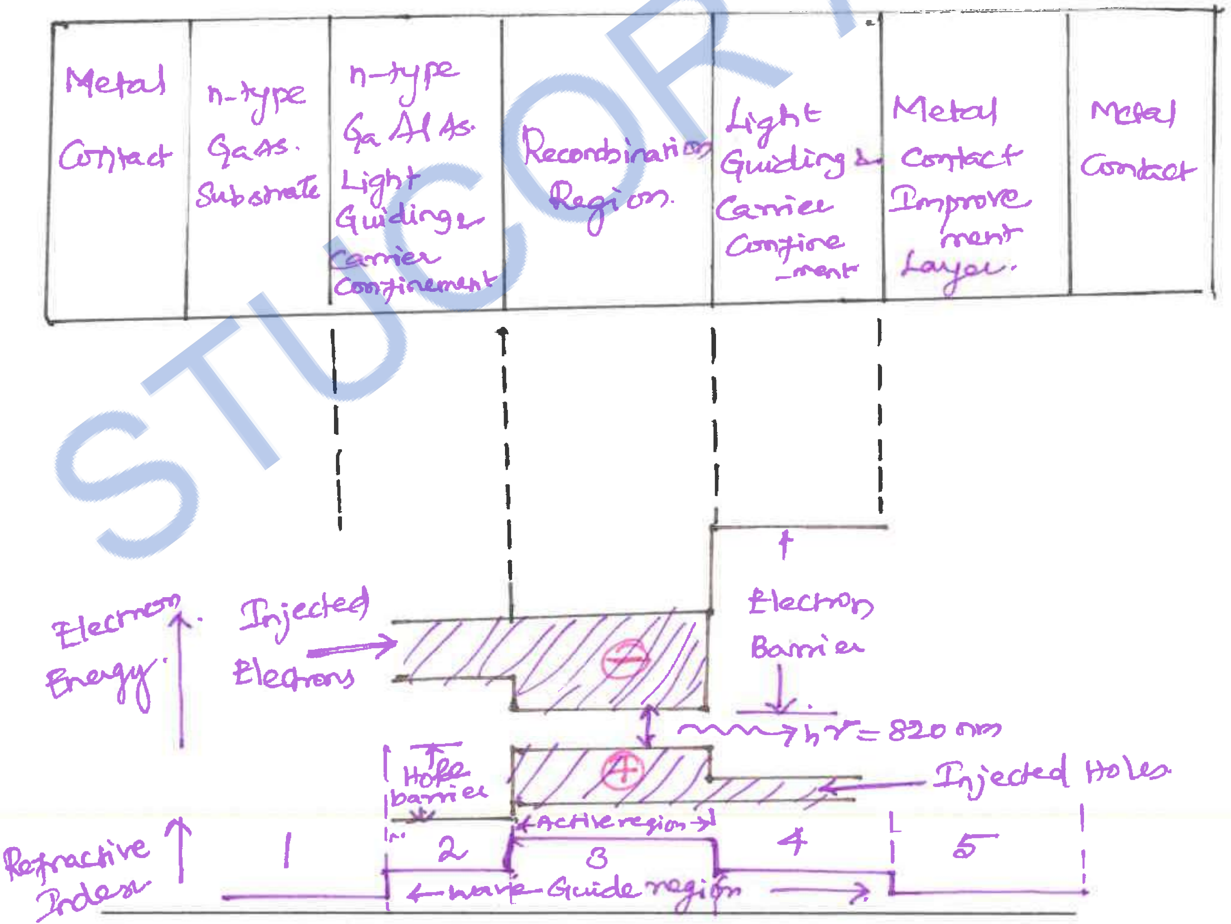
ELEDs may be modulated at rates upto 400 Mbps.

ELEDs may be used for both single mode and multi mode fiber systems.

Both SLEDs and ELEDs are used in long distance, high-data rate systems.

SLDs are ELED based diodes designed to operate in the super luminescence mode. SLDs may be modulated at bit rates of over 400 mbps.

LED band gap structure:

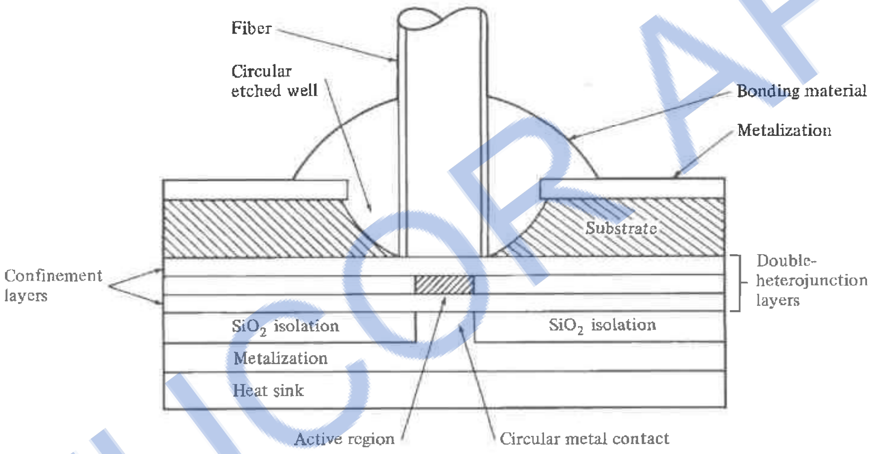


Surface Emitting LEDs:

The surface-emitting LED is also known as the Burrus LED in honors of C.A. Burrus, it's developer.

In SLEDs, the size of primary active region is limited to a small circular area of 20μm to 50μm in diameter.

Surface-Emitting LED



Schematic of high-radiance surface-emitting LED. The active region is limitted to a circular cross section that has an area compatible with the fiber-core end face.

Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

The active region is the portion of the LED where photons are emitted. The primary active region is below the surface of the semiconductor substrate perpendicular to the axis of the fiber.

A "well" is etched in to the substrate to allow "direct coupling" of the emitted light to the optical fiber.

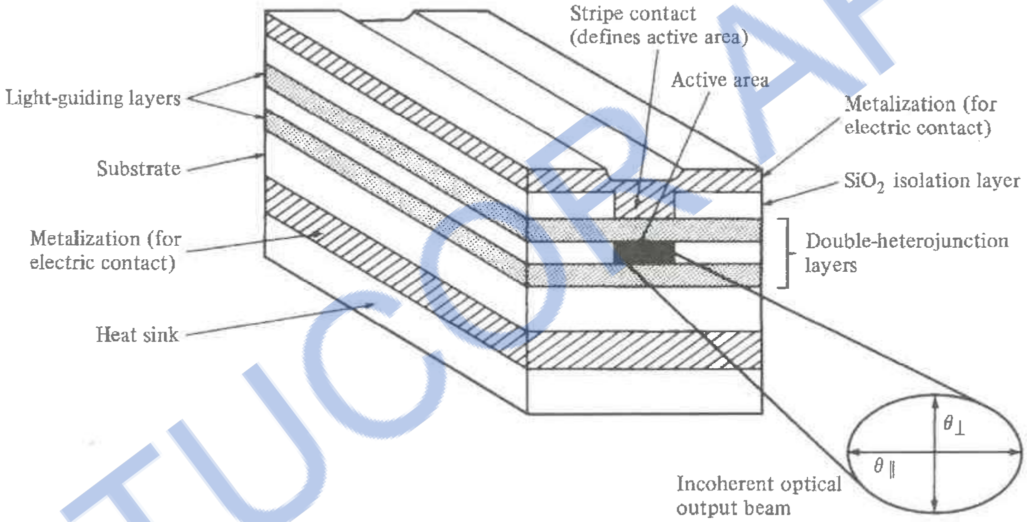
The etched well allows the optical fiber to come in to close contact with the emitting surface. In addition, the epoxy resin that binds the optical fiber to the SLED reduces the refractive index mismatch, increasing coupling efficiency.

Edge-Emitting LED (ELED):

The demand for optical sources for long distance, higher bandwidth systems operating at longer wavelengths led to the development of edge emitting LEDs. The Figure shows the typical ELED structure. It shows the different layers of semiconductor material used in the ELED. The primary active region of the ELED is a narrow stripe, which lies below the surface of the semiconductor substrate. The semiconductor substrate is cut or polished so that the stripe runs between the front and back of the device. The polished or cut surfaces at each end of the stripe are called facets.

In an ELED the rear facet is highly reflective and the front facet is antireflection coated. The rear-facet reflects the light propagating toward the, front facet. By coating the front facet with antireflection material, the front facet reduces optical feed back and allows light emission. ELEDs emit light only through the front facet.

Edge-Emitting LED



Schematic of an edge-emitting double heterojunction LED. The output beam is lambertian in the plane of junction and highly directional perpendicular to pn junction. They have high quantum efficiency & fast response.

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ELEDs emit light in a narrow emission angle allowing for better source to fiber coupling. They couple more power in to small NA fibers than SLEDs. ELEDs can couple enough power in to singlemode fibers for some applications.

ELEDs Emit power over narrow spectral range and more sensitive to temperature fluctuations.

Quantum Efficiency and LED power:

Rate equations :

When there is no external carrier injection, the excess density decays exponentially due to electron-hole recombination.

$$n(t) = n_0 e^{-t/\tau}$$

n – Excess Carrier density.

n_0 - Initial injected excess electron density

τ - Carrier life time

Bulk recombination rate (R) :

$$R = \frac{-dn}{dt} = \frac{n}{\tau}$$

Bulk recombination rate (R) = Radiative Recombination Rate + Non radiative Recombination Rate.

$$R = R_r + R_{nr}$$

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

With an external supplied current density of J the rate equation for the electron-hole recombination is

$$\frac{dn(t)}{dt} = \frac{J}{qd} - \frac{n}{\tau}$$

q – charge of electron d – thickness of recombination region

In equilibrium condition : $\frac{dn}{dt}=0$

$$n = \frac{J\tau}{qd}$$

Quantum Efficiency:

Internal quantum efficiency η_{int} = $\frac{\text{No. of Photons generated}}{\text{Total no. of electron hole pair recombination}}$

External quantum efficiency η_{ext} = $\frac{\text{No. of photons guided to the fiber}}{\text{Total no. of photons generated}}$

Internal quantum efficiency depends on the intrinsic nature of the material and manufacturing process of material

$$\eta_{int} = \frac{R_r}{R_r+R_{nr}} = \frac{\tau_{nr}}{\tau_r+\tau_{nr}} = \frac{\tau}{\tau_r}$$

Optical power generated internally in the active region in the LED is.

$$P_{int} = \eta_{int}\frac{I}{q}h\nu = \eta_{int}\frac{hcI}{q\lambda}$$

I – Injected current to active region.

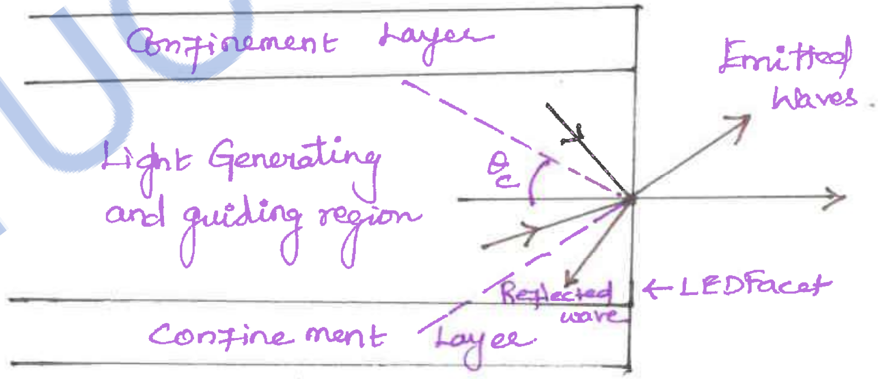
External Quantum Efficiency :

Inorder to calculate the external quantum efficiency we need to conside the reflection effects at the surface of the LED. If we consider the LED structure as a simple 2D slab waveguide, only light falling within a cone defined by critical angle will be emitted from an LED.

$$\eta_{ext} = \frac{1}{4\pi}\int_{0}^{\phi_c} T(\phi)\,(2\pi \sin\phi)\,d\phi$$

$T(\phi)$ – Fresnel Transmission coefficient. $\phi_c = \frac{\pi}{2} - \theta_c$

$$T(0) = \frac{4n_1n_2}{(n_1+n_2)^2}.$$



If $n_2 = 1 \Rightarrow \eta_{ext} = \frac{1}{n_1(n_1+1)^2}$.

The Emitted optical power $P = \eta_{ext}\cdot P_{int} = \frac{P_{int}}{n(n+1)^2}$

Modulation of LED:

The frequency response of an LED depends on

- Doping level of active region
- Injected carrier lifetime in the recombination region τ_i
- Parasitic capacitance of the LED.

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

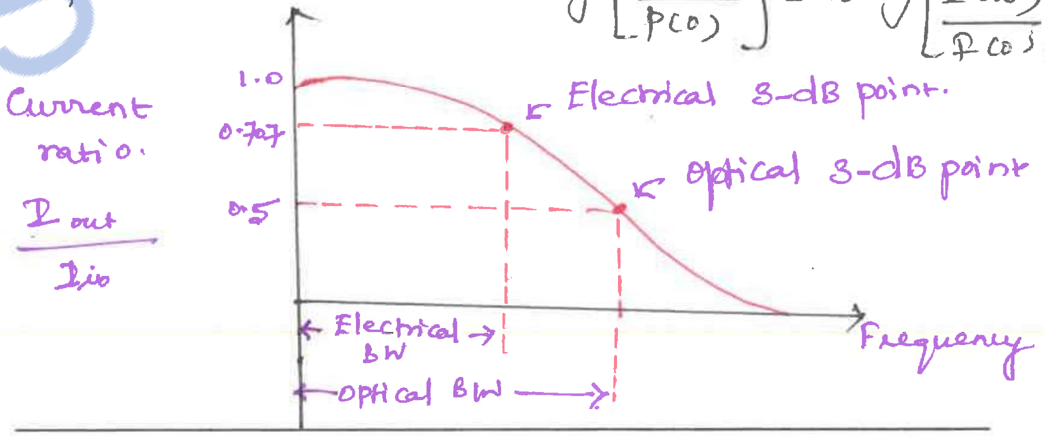
$$P(\omega) = \frac{P_0}{\sqrt{1+(\omega\tau_i)^2}}$$

Electrical current is directly proportional to the optical power.

$$\text{Electrical Bandwidth} = 10\log\left[\frac{P(\omega)}{P(0)}\right] = 20\log\left[\frac{I(\omega)}{I(0)}\right]$$

P – Electrical power I – Electrical current

$$\text{Optical Bandwidth} = 10\log\left[\frac{P(\omega)}{P(0)}\right] = 10\log\left[\frac{I(\omega)}{I(0)}\right]$$

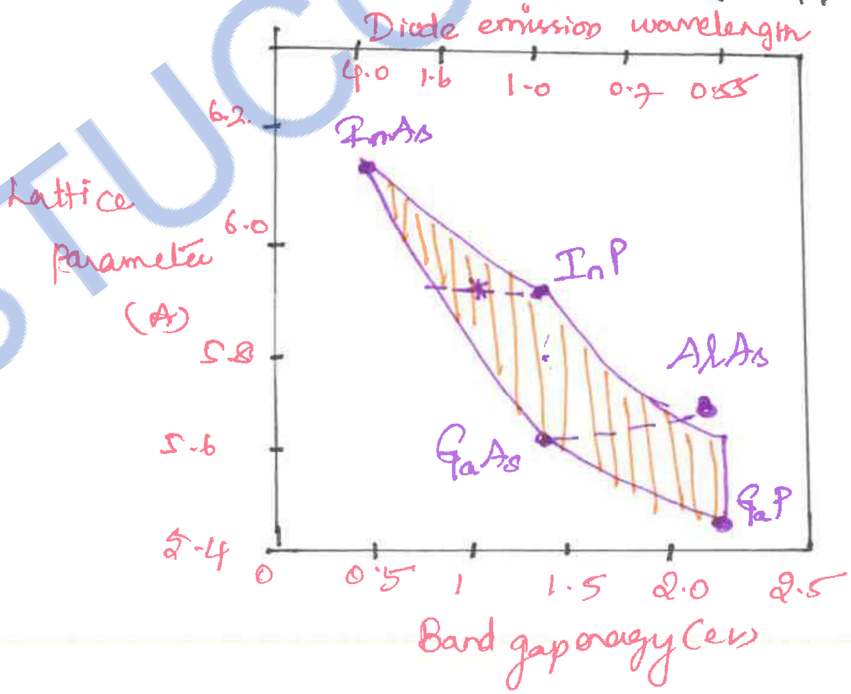


Light Source Materials:

Most of the light sources contain III–V ternary & quaternary compounds.

$Ga_{1-x}Al_xAs$ by varying x it is possible to control the band-gap energy and thereby the emission wavelength over the range of 800 nm to 900nm. The spectral width is around 20 to 40nm.

$In_{1-x}Ga_xAs_yP_{1-y}$ by changing $0<x<0.47$; y is approximately $2.2x$, the emission wavelength can be controlled over the range of 920nm to 1600 nm. The spectral width varies from 70 nm to 180 nm when the wavelength changes from 1300nm to 1600nm. These materials are lattice matched.



LASER (Light Amplification by the Stimulated Emission of Radiation).

LASER is an optical oscillator it comprises a resonant optical amplifier whose output is fed back in to its input with matching phase. Any oscillator contains:

(i) An amplifier with a gain-saturated mechanism
(ii) A feed back system
(iii) A frequency selection mechanism
(iv) An output coupling scheme.

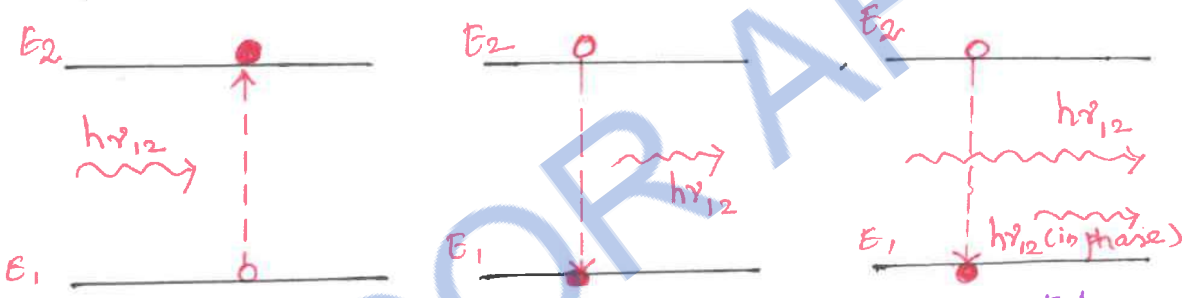
In laser the amplifier is the pumped active medium, such as biased semiconductor region, feedback can be obtained by placing active medium in an optical resonator, such as Fabry-Perot structure, two mirrors seperated by a prescribed distance.

Frequency selection is achieved by resonant amplifier and by the resonators, which admits certain modes. Output coupling is accomplished by making one of the resonator mirrors partially transmitting.

Laser Operations:

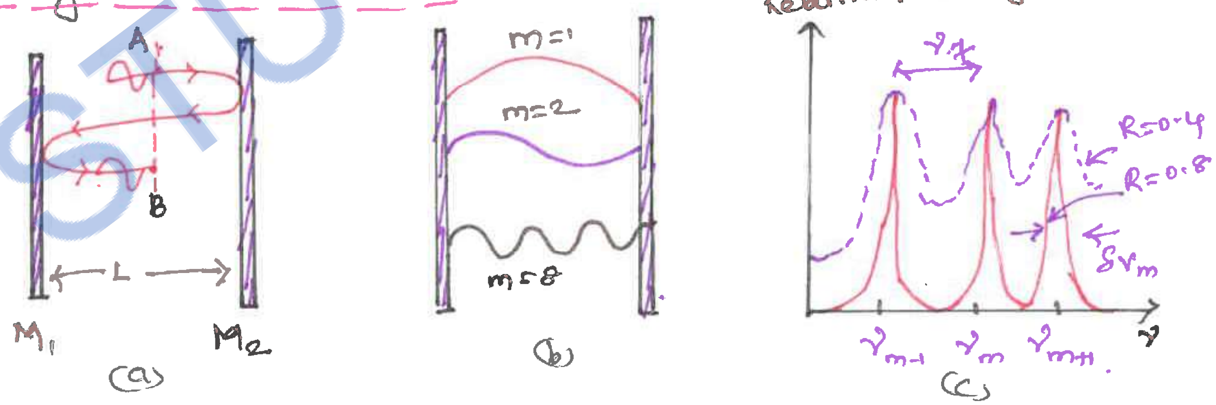
In thermal equilibrium, the stimulated emission is essentially negligible, since the density of electrons in the excited state is small and optical emission is mainly because of the spontaneous emission

Stimulated emission will exceed absorption only if the population of excited states is greater than that of ground state. This condition is known as population inversion. It is achieved by various pumping technique. In Semiconductor laser, population inversion is accomplished by injecting electrons in to the material to fill the lower energy states of the conduction band.



(a) Absorption (b) Spontaneous emission (c) Stimulated emission

Fabry-Perot Resonator :



(a) Reflected waves interfere

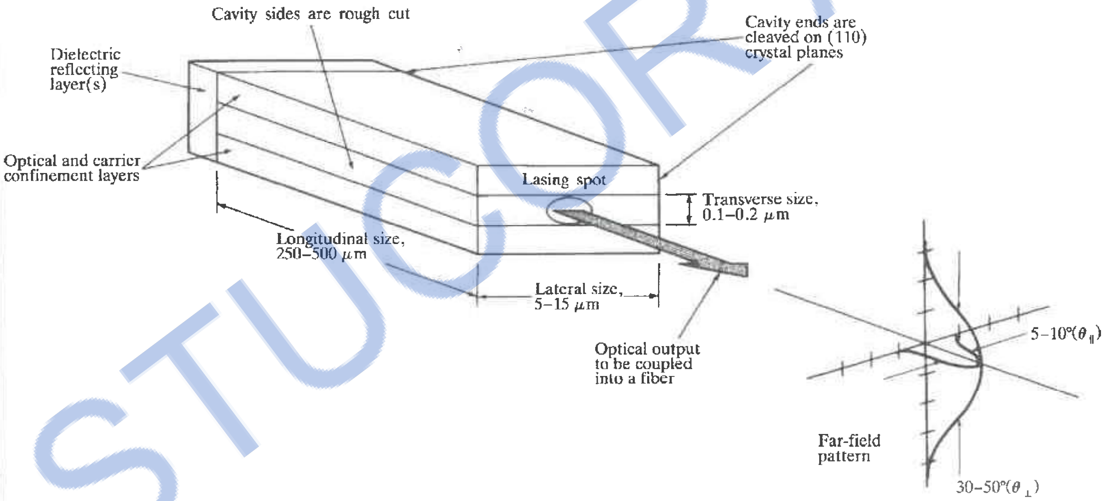
(b) Only Standing EM waves, modes of Certain wavelength are allowed in the cavity

(c) Intensity vs. frequency for various modes.

LASER DIODE:

Laser diode is an improved LED, in the sense that uses stimulated emission in semiconductor from optical transitions between distribution energy states of the valence and conduction bands with optical resonal structure with both optical and carrier confinements.

Laser Diode



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Laser Diode Characteristics:

- * Nano second and even pico second response time.
- * Spectral width of the order of nm or less
- * High output power (tens of mW)
- * Narrow beam (Good coupling to single mode fibers)

Modes and Threshold conditions :

Laser diodes have three distinct radiation modes namely

- * Longitudinal mode.
- * Lateral mode
- * Transverse mode

In LASER diodes, end mirrors provide strong optical feedback in longitudinal direction, so by roughening the edges and cleaving the facets the radiation can be achieved in longitudinal direction rather than lateral direction.

Efficient operation of laser diode requires reducing the no. of lateral modes, stabilizing the gain for lateral modes as well as lowering the threshold current. These are met by structures that confine the optical wave, carrier concentration and current flow in the lateral direction.

Electric field in longitudinal direction is

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

The radiation intensity with respect to lasing cavity is

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

$\bar{\alpha}$ – Effective absorption efficient

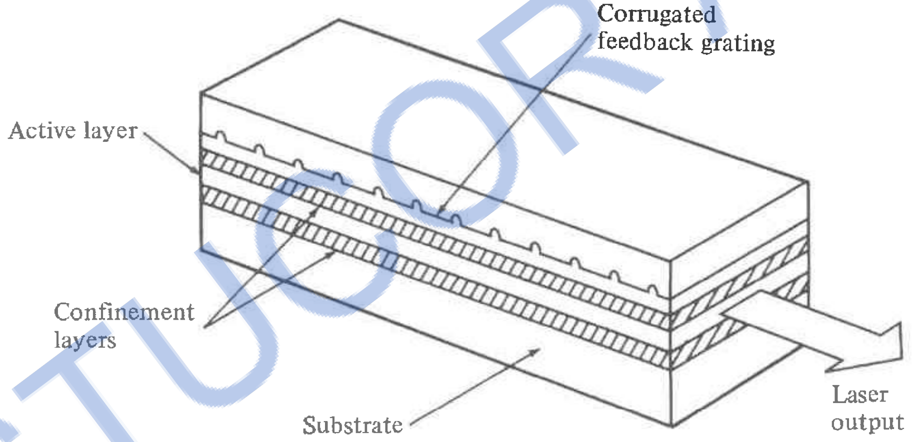
Γ – optical field confinement factor.

The condition to just reach the lasing threshold is the point at which the optical gain is equal to the total loss α_1 in the cavity

$$\Gamma g_{th} = \alpha_1 = \bar{\alpha} + \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right) = \bar{\alpha} + \alpha_{end}$$

Types of LASER diode structure:

DFB(Distributed FeedBack) Lasers



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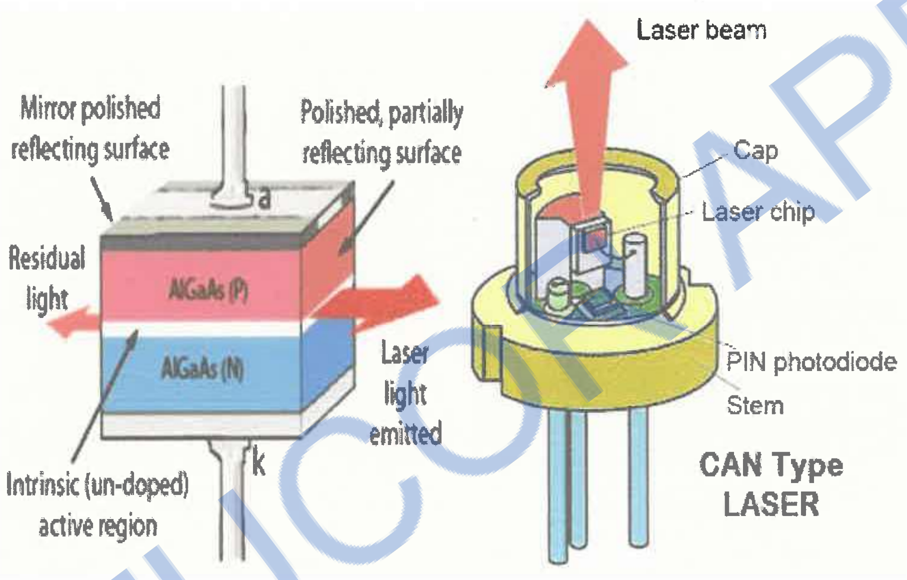
In above DFB laser type, the cleaved facets are not required for optical feed back. The fabrication of this device is similar to the Fabry-Perot type except that the lasing action is obtained from Bragg reflectors (Gratings) or periodic variations of RI.

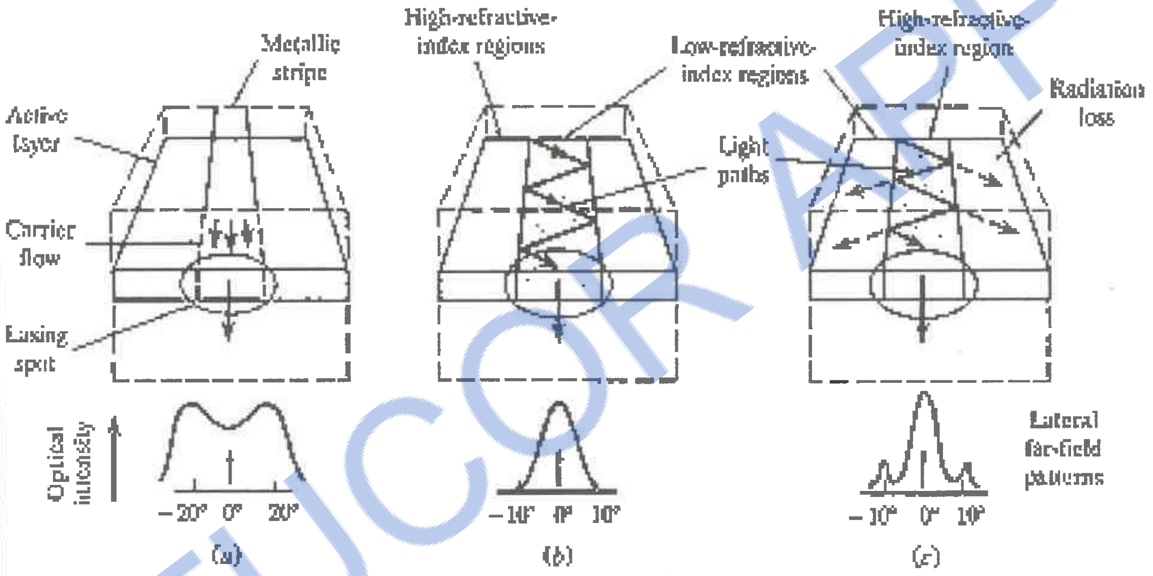
A basic requirement for efficient operation of laser diodes is that, in addition to transverse optical and carrier confinement between heterojunction layers, the current flow must be restricted laterally to a narrow stripe along the lengths of the laser.



Numerous novel methods of achieving this, with varying degrees of success, have been proposed, but all strive for the same goals of limiting the number of lateral modes so that lasing is confined to a single filament, stabilizing the lateral gain, and ensuring a relatively low threshold content.

Optical Confinement methods.

These methods are used for bounding laser light in the lateral direction. Below figure represents three types of optical confinement methods.



(a) gain-induced guide (b)positive-index waveguide (c)negative-index waveguide

(a) A narrow electrode stripe runs along the length of the diode. The injection of electrons and holes into the device alters the refractive index of the active layer directly below the stripe. This injected electrons creates waveguide that confines the light laterally. This type is called "gain-guided laser".

(b) Positive index waveguide: Dielectric waveguide structures are fabricated in the lateral direction. The variations in the real refractive index of various materials will control the lateral modes in laser.

(c) Negative index waveguide: 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 ~~in~~ to the surrounding material and is thus lost.

Index guided lasers can be made using any one of the four fundamental structures.

(1) Buried Hetero structure
(2) Selectively diffused construction
(3) Varying thickness structure
(4) Bent-layer configuration

1) Buried Hetero Structure (BH):

Narrow mesa stripe (1–2 μm wide) is etched in double heterostructure material. The mesa is then embedded in high resistivity lattice matched n-type material with an appropriate band gap and low refractive index.

This configuration thus strongly traps generated light in a lateral waveguide. A number of variations of this fundamental structure have been used to fabricate high performing laser-diode.

Laser Diode with buried heterostructure (BH)

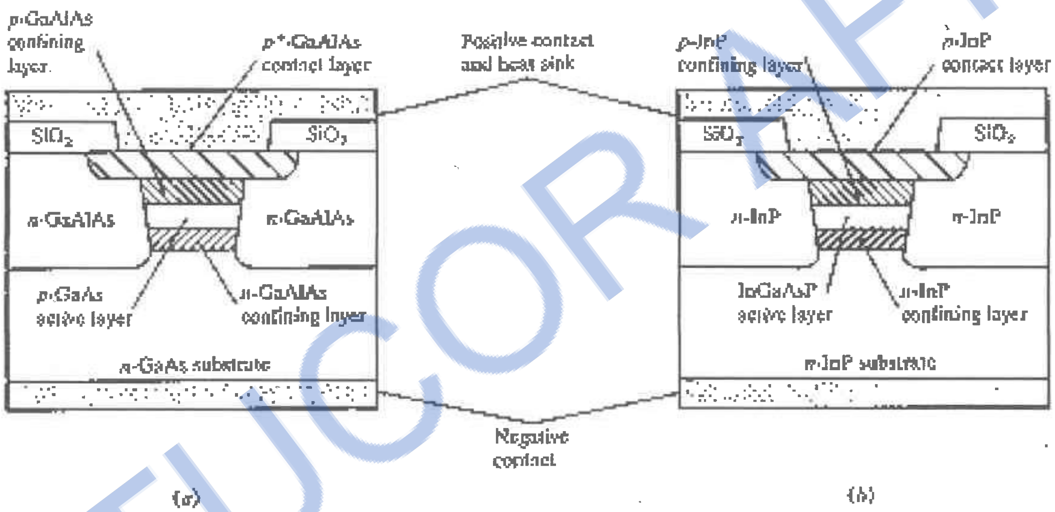
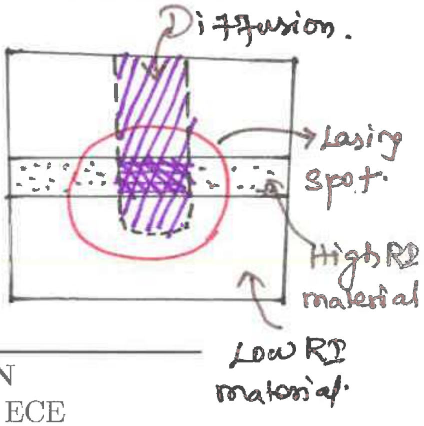


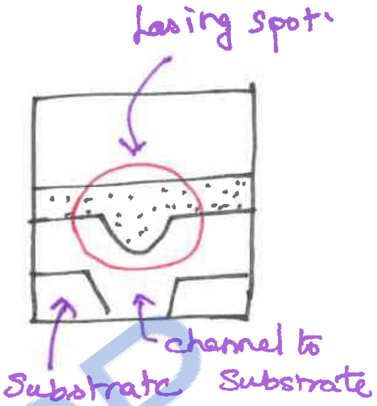
FIGURE 4-23
(a) Short-wavelength (800–900 nm) GaAlAs and (b) long-wavelengths (1300–1600 nm) InGaAsP buried-heterostructure laser diodes.

2) Selected Diffused Construction:



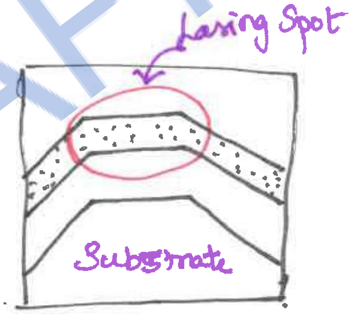
* A chemical dopant such as GaAlAs is diffused in to the active layer immediately below the metallic contact stripe. The dopant changes the refractive index of the active layer to forms a lateral wave guide channel.

(3) Varying thickness structure:



A channel is etched in to the substrate Layers of crystal are then regrown into the channel using liquid phase epitaxy. This process fills in the depressions and partially dissolves the protrusions, thus creating variations in thickness to becom positive index waveguide

(4) Bent-layer structure:



A mesa is etched in to the substreate. Semiconductor material layers are grown on to this structure using vapor phase epitaxy to exactly replicate the mesa configuration.

Single Mode Lasers:

These lasers used for high-speed, long-distance communications. These lasers contain only a single longitudinal mode and a single transverse mode. Consequently the spectral width of the optical emission is very narrow.

One way of restricting a laser to have only one longitudinal mode is to reduce the length L of the lasing cavity to the point where the frequency seperation Δν of the adjacent modes.

VCSEL

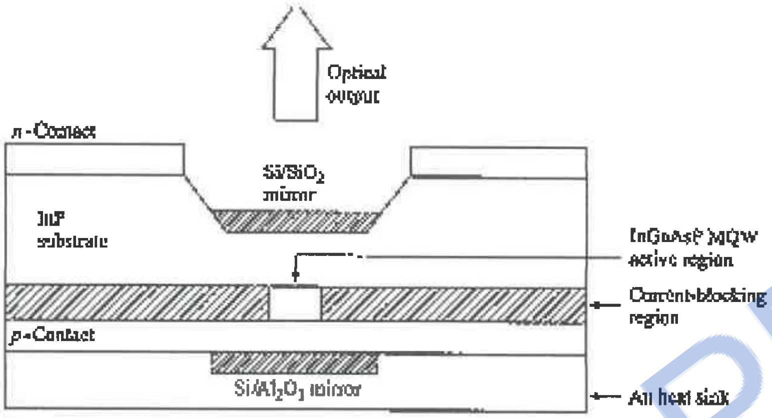
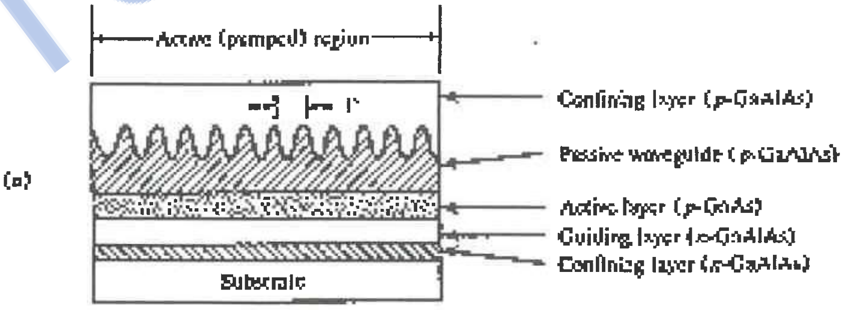


FIGURE 4-27
Basic architecture of a vertical-cavity surface-emitting laser.

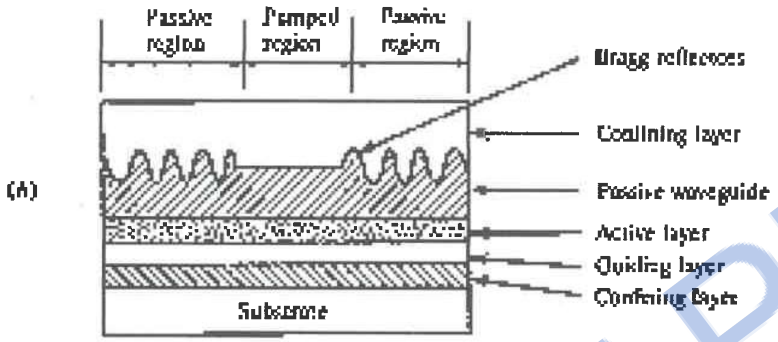
The special feature of a vertical-cavity surface emitting laser (VCSEL) is that the light emission is perpendicular to the semiconductor surface.

Frequency-Selective laser Diodes: Distributed Feedback (DFB) laser



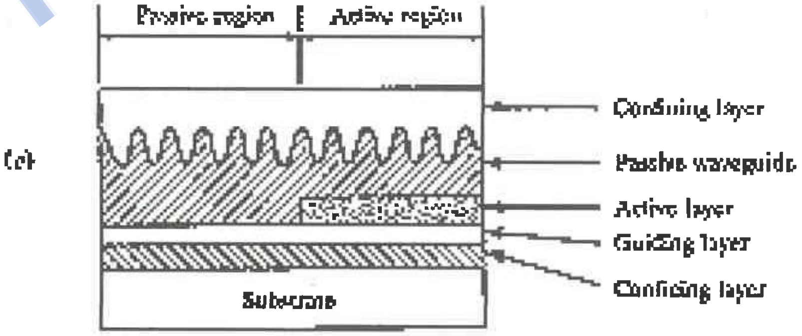
$$\lambda_B = \frac{2n_e\Lambda}{k} \quad [4\text{-}33]$$

Frequency-Selective laser Diodes: Distributed Feedback Reflector (DBR) laser



This feature facilitates the integration of multiple lasers onto a single chip in one- or two dimensional arrays, which makes them attractive for wavelength WDM applications.

Frequency-Selective laser Diodes: Distributed Reflector (DR) laser



For the distributed-Bragg-reflector laser. The gratings are located at the ends of the normal active layer of the laser to replace the cleaved end mirrors used in Fabry-Perot optical resonator. This structure improves the lasing properties of conventional DFB and DBR lasers, and has a high efficiency and high output capability.

Laser Diode Rate Equations:

Rate equations relate the optical output power, of no. of photons per unit volume ϕ, to the diode drive current of no. of injected electrons per unit volume n. For active (carrier confinement) region of depth d, the rate equations are

$$\frac{d\phi}{dt} = Cn\phi + R_{sp} - \frac{\phi}{\tau_{ph}}$$

Photon rate = Stimulated emission + Spontaneous emission + photon loss.

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\phi$$

Electron rate = Injection + Spontaneous recombination + Stimulated emission

C – Coefficient expressing the intensity.

R_{sp} – Rate of Spontaneous emission in to the lasing mode

τ_{ph} – Photon life time

J – Injection current density.

Consider the photon and electron rate equations in the steady state condition at the lasing threshold.

$$\phi \approx 0 \qquad \frac{d\phi}{dt} \geq 0 \qquad R_{sp} \approx 0$$

$$① \Rightarrow \quad Cn\phi - \frac{\phi}{\tau_{ph}} \geq 0$$

$$\Rightarrow \quad \boxed{n \geq \frac{1}{C\tau_{ph}} = n_{th}}$$

The threshold current needed to maintain a steady state threshold concentration of the excess electron, is found from electron rate equation under steady state condition $\frac{dn}{dt} = 0$. when the laser is going to just about to lase.

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

$$\Rightarrow \quad \boxed{\frac{J_{th}}{qd} = \frac{n_{th}}{\tau_{sp}}}$$

By solving the above equations yields the number of photons per unit volume.

$$\boxed{\phi_t = \frac{\tau_{ph}}{qd}(J - J_{th}) + \tau_{ph} R_{sp}}$$

External Quantum Efficiency:

External Quantum Efficiency η_{ext} is defined as. number of photons emitted per radiative electron hole pair recombination above threshold, gives us the external quantum efficiency.

$$\eta_{ext} = \frac{\eta_I (g_{th} - \alpha)}{g_{th}}$$

η_I - Internal quantum efficiency

Experimentally η_{ext} is calculated from the straight-line portion of the emitted optical power P versus drive current I

$$\eta_{ext} = \frac{q}{E_g} \frac{dP}{dI}$$

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

E_g - Band-gap energy in electron volts

dp - Incremental change in the emitted power.

Resonant Frequencies

Resonant frequencies of the laser holds when

$$2\beta L = 2\pi m$$

For propagation constant $m = \frac{L}{\lambda/2n} = \frac{2Ln}{c}\gamma$

The resonant frequency of mth mode is ν_m

$$m = \frac{2Ln}{c}\nu_m$$

The resonant frequency of m-1th mode is ν_{m-1}

$$m-1 = \frac{2Ln}{c}\nu_{m-1}$$

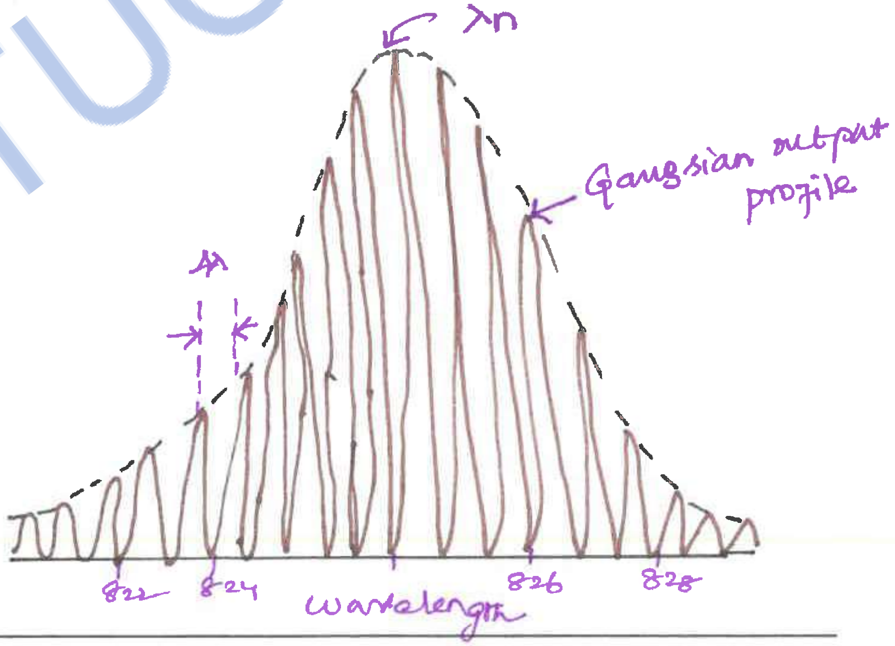
On solving these equations yields.

$$\frac{2Ln}{c}(\nu_m - \nu_{m-1}) = m - m + 1$$

$$\frac{2Ln}{c}(\nu_m - \nu_{m-1}) = 1$$

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

The frequency spacing $\Delta\nu = \frac{c}{2Ln}$.



Modulation of Laser Diodes:

The process of imposing information on a light stream is called modulation. Modulation can be done either by directly varying laser drive current with the information stream to produce a varying optical output power or by using an external modulator to modify a steady power level emitted by the laser.

Internal modulation : Simple but suffers from non-linear effects

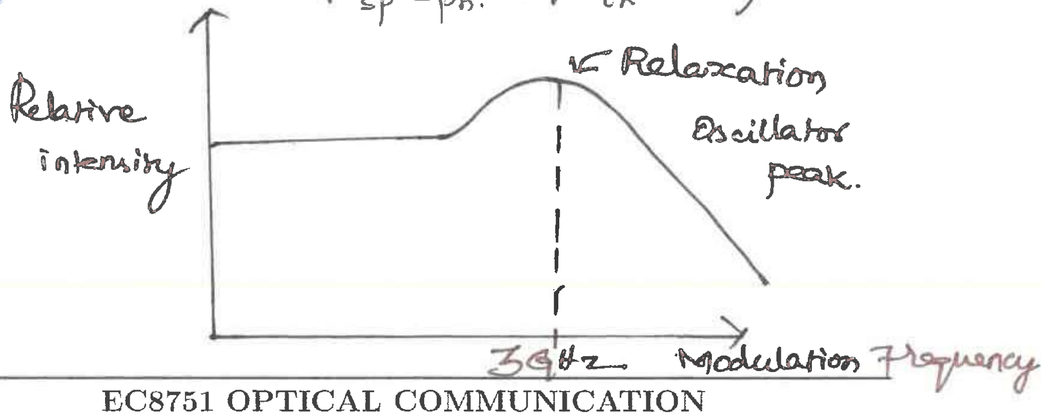
External modulation : For rates greater than 2Gb/s more complex, high performance.

Most fundamental limit for the modulation rate is set by the photon life time in the laser cavity

$$\frac{1}{\tau_{ph}} = \frac{c}{n}\left(\bar{\alpha} + \frac{1}{2L}\ln\frac{1}{R_1R_2}\right) = \frac{c}{n}g_{th}.$$

Relaxation oscillation frequency:

$$f = \frac{1}{2\pi}\frac{1}{\sqrt{\tau_{sp}\tau_{ph}}}\left(\frac{I}{I_{th}} - 1\right)^{1/2}$$



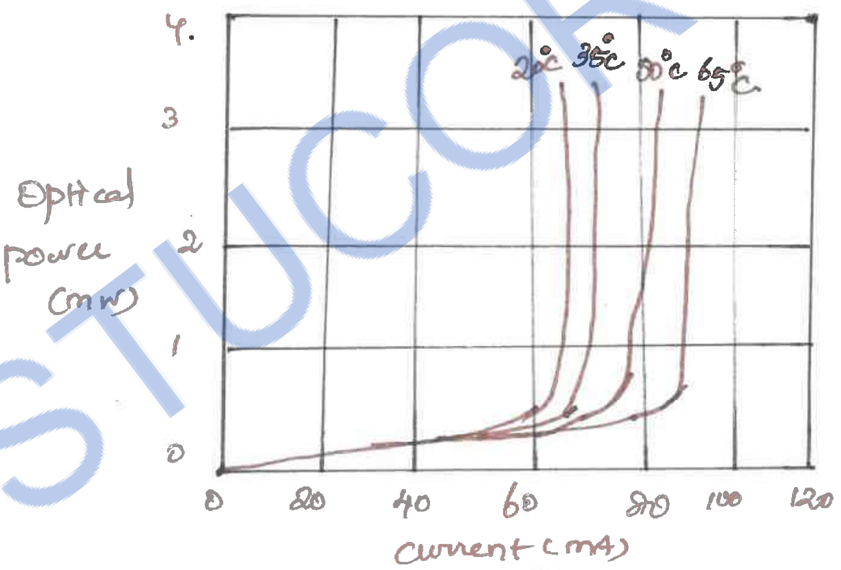
Temperature Effects :

An important factor to consider in the application of laser diodes is the temperature dependence of the threshold current $I_{th}(T)$. The temperature variation of I_{th} can be approximated by the empirical expression

$$I_{th}(T) = I_Z \, e^{T/T_0}$$

T_0 – Relative temperature intensitivity

I_Z – Constant.



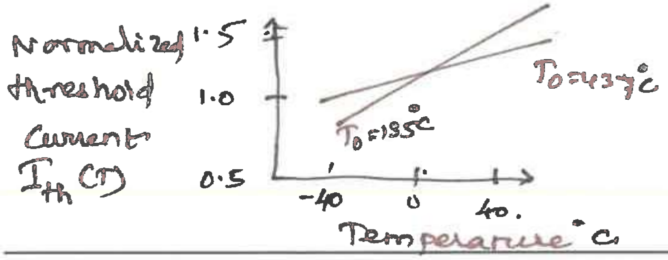


Photo Detectors :

Photo detector senses the luminescent power falling upon it and converts the variation of this optical power in to a correspondingly varying electric current.

Photo dector must have

- * High response or sensitivity in the emission wave length range
- * Fast response speed or sufficient bandwidth to handle the desired data rate.

Many types of photo detectors are existed.

(i) Photo multipliers

(ii) Pyroelectric detectors.

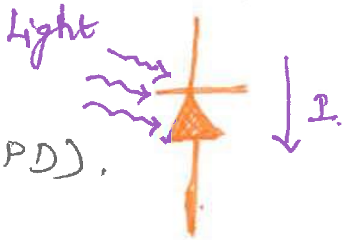
(iii) semiconductor based photo conductors

(iv) Photo transistors.

(v) Photo diodes.

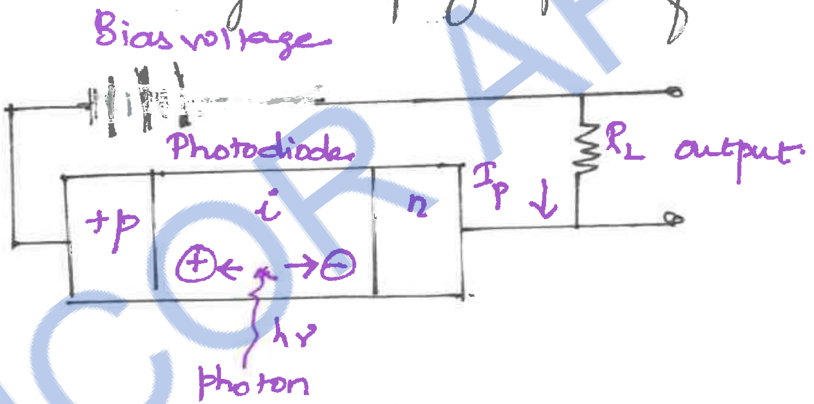
Semiconductor based photodiodes are predominantly used and satisfy above mentioned requirements. Two types commonly used are

- * pin photodetector
- * Avalanche Photodiode (APD).

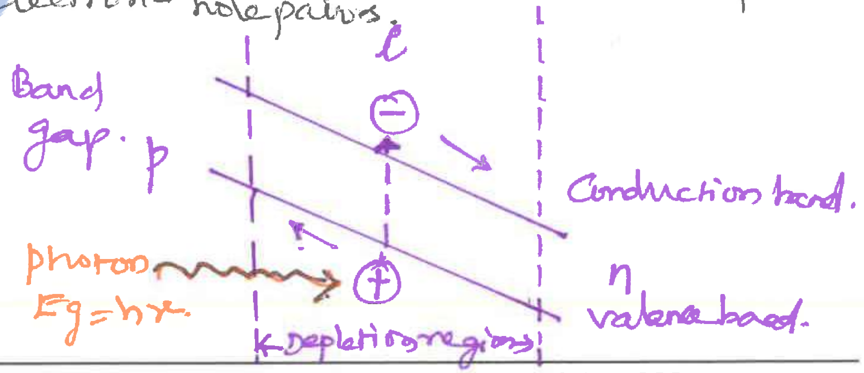


pin Photodetector:

The most common semiconductor photodetector is pin photodiode. The device structure consists of p and n regions separated by very lightly n-doped intrinsic (i) region. In normal operation a sufficiently large reverse-bias voltage is applied across the device, so that the intrinsic region is fully depleted of carriers.



When an incident photon is having energy greater than or equal to band gap energy of the semiconductor material, the photon can give up its energy and excite an electron from the valence band to the conduction band. This process generates free electron-hole pairs.



As the charge carriers flow through the material, some electron-hole pairs will recombine and hence disappear. On the average, the charge carriers move a distance L or Lp for electrons and holes, respectively. This distance is known as diffusion length(τ). The time it takes for an electron or hole to recombine is known as the carrier life time (τ^{1})". The relationship is

$$L_n = (D_n \tau_n)^{\wedge} \quad \text{and} \quad L_P = (D_p \tau_p)$$

D_n, D_p – Electron and hole diffusion coefficient

Optical radiation absorped is

$$P(x) = P_0(1-e^{-\hat{\alpha}_\lambda x})$$

$\hat{\alpha}_\lambda$ – absorption coefficient

P_0 – incident optical power level.

The total power absorpted in the distance w is

$$P(w) = P_0(1-e^{-\alpha_i w})$$

Photocurrent $I_p = \frac{q}{h\nu} P_0(1-e^{-\alpha_i w})(1-R_f)$

Quantum Efficiency (η).

$$\eta = \frac{\text{Number of electron-hole pairs generated}}{\text{Number of incident photon.}}$$

$$\eta = \frac{I_p/q}{P_0/h\nu}$$

I_p – Average steady state photocurrent.

P_0 – Incident photodetector power

Responsivity :

It specifies the photocurrent generated per unit optical power

$$\mathcal{R} = \frac{I_p}{P_0} = \frac{\eta q}{h\nu}$$

Avalanche Photo Diode (APD):

APD's internally multiply the primary signal photocurrent before it enters the input circuitry of the following amplifier.

* In order for carrier multiplication to take place, the photogenerated carriers must traverse a region where a very high electric field is present. In this high field region, a photogenerated electron or hole can gain enough energy so that it ionizes bound electrons in the valence band upon colliding with them. This carrier multiplication mechanism is known as "impact ionization".

* The newly created carriers are also accelerated by the high field thus gaining enough energy to cause further impact ionization. This phenomenon is "avalanche Effect"

* Below the diode "breakdown" a voltage a finite total number of carriers are created, where as above breakdown the number can be infinite

It requires very high reverse bias voltage (100-400V) in order that the new carriers created by impact ionization can themselves produce additional carriers by the same mechanics. Carrier multiplication factor as great as 10^5 may be obtained using defect free materials to ensure uniformity of carriers multiplication over the entire photo sensitive area.

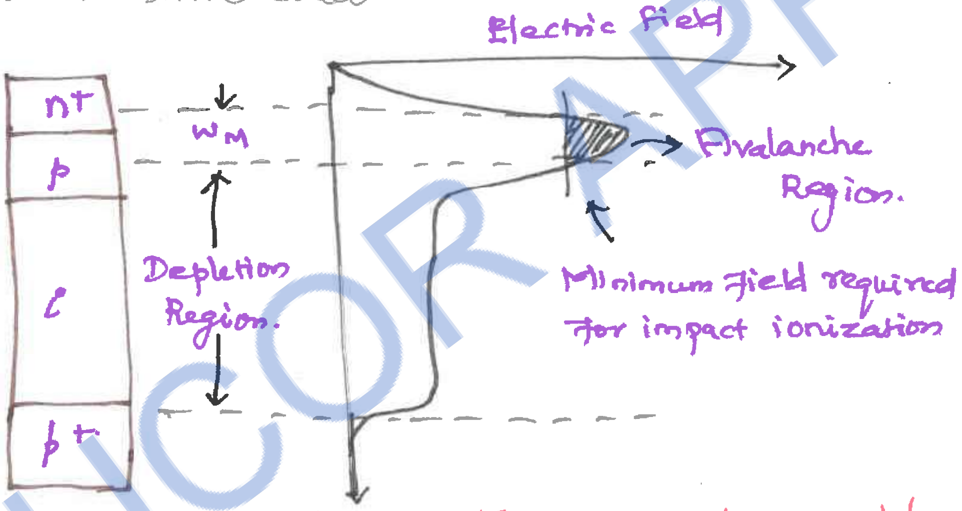


Fig: Reach through Avalanch structure and electric fields.

The multiplication factor M is the measure of internal gain provided by the APD

$$M = \frac{I}{I_p}$$

I – Total Output current at the operating voltage

I_p – Initial or Primary Photo current.

The gain M increases with the reverse bias voltage V_d;

$$M = \frac{1}{1-(V_d/V_{BR})^n}$$

V_{BR} – Break down Voltage

n – Constant

Photo Detector Noise :

The power SNR at the output of an optical receiver is

$$\frac{S}{N} = \frac{\text{Signal Power from Photocurrent}}{\text{Photodetector noise power} + \text{amplifier noise power}}$$

The noise sources in the receiver arises from the photo detector noises resulting from the statistical nature of the photon-to-electron conversion process and the thermal noises associated with the amplifier circuitry.

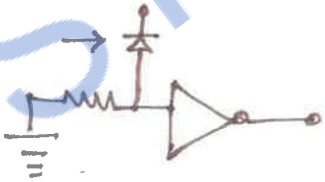
To achieve high SNR following conditions should be met.

(i) The photodetector must have a high quantum efficiency to generate a large signal power.

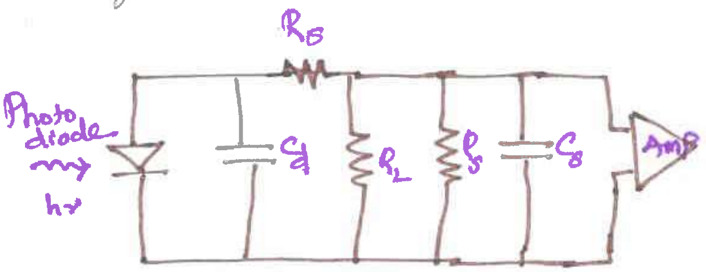
(ii) The photodetector and amplifier noise should be kept as low as possible.

Noise Sources :

To understand SNR effect, the receiver model has to be studied.



Simple model of a Photodetector receiver.



Equivalent Circuit.

If a modulated signal of a optical power P(t) falls on the detector, the primary photocurrent $I_{ph}(t)$ generated is

$$i_{ph}(t) = \frac{\eta q}{h\nu} P(t)$$

For pin photodiodes the mean-square signal current is

$$\langle i_s \rangle^2 = \sigma^2_{t,pin} = \langle i_p^2(t) \rangle$$

For avalanch photodetector

$$\langle i_s^2 \rangle = \sigma^2_{s,APD} = \langle i_p^2(t) \rangle M^2$$

For sinusoidally varying input signal of modulation index m the signal component

$$\langle i_p^2(t) \rangle = \sigma_p^2 = \frac{m^2}{2} I_p^2$$

Noises associated with photodetector that have no internal gain are

- Quantum noise or shot noise.
- Dark current noise generated in the bulk material
- Surfaceleakage current noise

Quantum or Shot Noise :

Arises from the statistical nature of the production and collection of photo electrons. when an optical signal is incident on a photodetector. The quantum noise current is

$$\langle i_Q^2 \rangle = \sigma_Q^2 = 2qI_pBM^2F(M).$$

$F(M)$ is noise figure

B Bandwidth

i_p Photocurrent

Photodiode Dark Current :

Current that continues to flow through the bias circuit of the device when no light is incident on the photodiode. This is the combination of bulk and surface currents. The bulk dark current (I_{DB}) arises from electrons and/or holes which are thermally generated in the pn junction of the photodiode

$$\langle i_{DB}^2 \rangle = \sigma_{DB}^2 = 2qI_D M^2 F(M) B .$$

Surface Leakage current :

The surface dark current (I_{DS}) is referred as surface leakage current or leakage current. It is dependent on surface defects, cleanliness, bias voltage and surface area.

$$\langle i_{DS}^2 \rangle = \sigma_{DS}^2 = 2qI_L B .$$

The effective way to reduce surface dark current is to use of a guard ring structure which shunts surface leakage current away from the load resistor.

The total mean square "photodetector noise current" $\langle i_N^2 \rangle$ is

$$\boxed{\begin{aligned}\langle i_N^2 \rangle = \sigma_N^2 &= \langle i_Q^2 \rangle + \langle i_{DB}^2 \rangle + \langle i_{DS}^2 \rangle \\ &= \sigma_Q^2 + \sigma_{DB}^2 + \sigma_{DS}^2 \\ &= 2q(I_p + I_D) M^2 F(M) B + 2qI_L B .\end{aligned}}$$

The photodetector load resistor contributes a mean-square thermal (Jhonson) noise current

$$\langle i_r^2 \rangle = \sigma_r^2 = \frac{4k_BT}{R_L} B.$$

Signal-to-Noise Ratio (SNR).

Signal power current is $\langle i_s^2 \rangle = \langle i_p^2(t) \rangle M^2$

Noises current are

Photodetector noise current is $\langle i_N^2 \rangle = 2q(I_p + I_D)M^2 F(M)B + 2qI_LB.$

Receiver noise current $\langle i_r^2 \rangle = \frac{4k_BT}{R_L} B.$

The SNR is

$$\frac{S}{N} = \frac{\langle i_p^2 \rangle M^2}{2q(I_p + I_D)M^2 F(M)B + 2qI_LB + 4k_BTB/R_L}$$

Detector Response Time:

The response time of a photodiode together with output circuit depends mainly on the following three factors

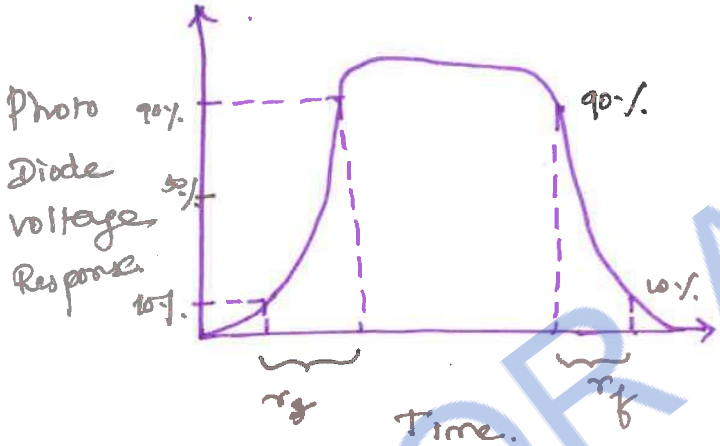
(i) The transit time of the photo carriers in the depletion region.

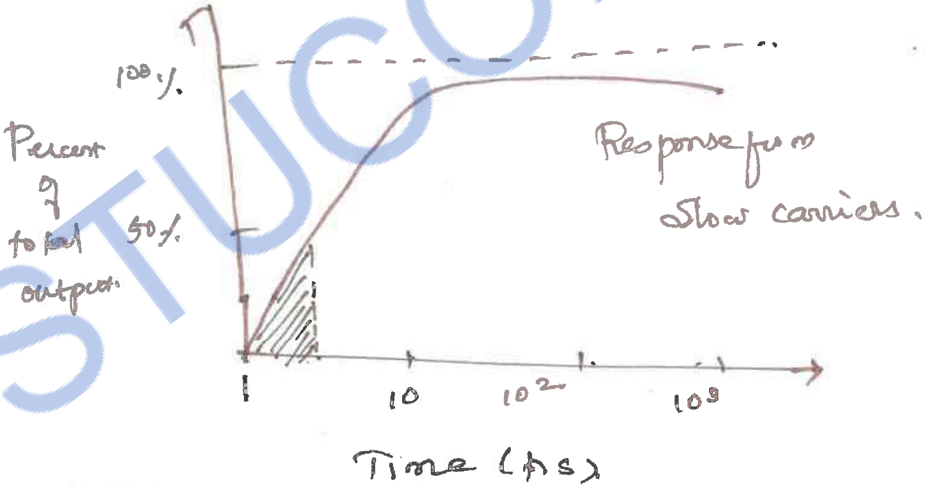
(ii) The diffusion time of the photo carriers generated outside of the depletion region.

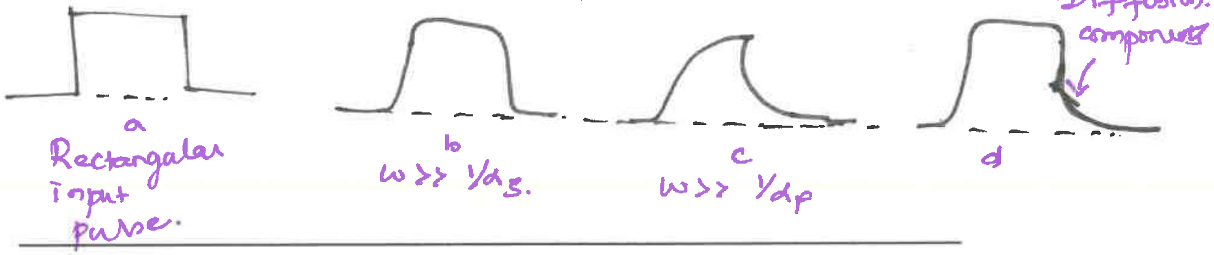
(iii) The RC time constant of the photodiode and its associated circuit.

The transit time t_d depends on the carrier drift velocity V_d and the depletion layer width w_t is

$$t_d = \frac{w}{V_d}$$







Avalanche Multiplication Noise:

The ratio of actual noise generated in an avalanche photodiode to the noise that would exist if all carrier pairs were multiplied by exactly M, is called excess noise factor F and is defined by

$$F = \frac{\langle m^2 \rangle}{\langle m \rangle^2} = \frac{\langle m^2 \rangle}{M^2}$$

This excess noise factor is a measure of the increase in detector noise resulting from the randomness of the multiplication process. It depends on the ratio of the electron and hole ionization rates and on the carrier multiplication.

For injected electrons the excess noise factors are

$$F_e = \frac{k_2 - k_1^2}{1 - k_2} M_e + 2\left[1 - \frac{k_1(1-k_1)}{1-k_2}\right] - \frac{(1-k_1)^2}{M_e(1-k_2)}$$

For injected holes the excess noise factors are

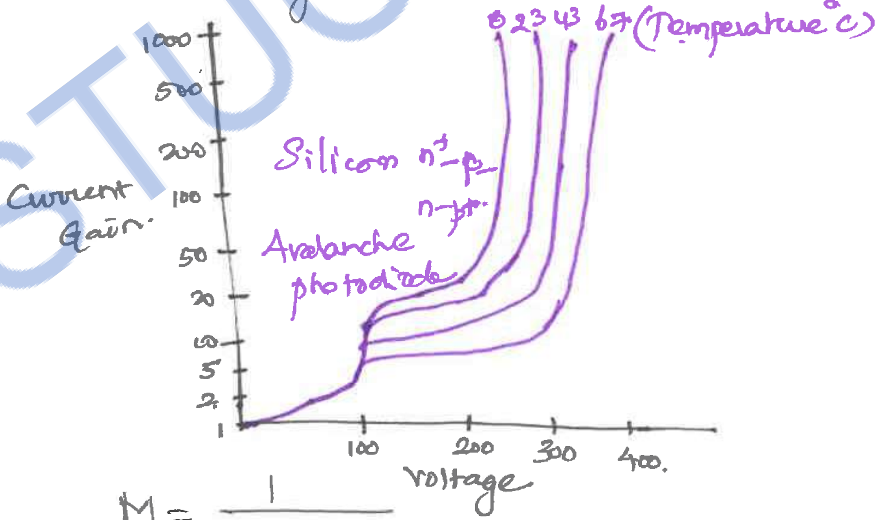
$$F_h = \frac{k_2 - k_1^2}{k_1^2(1-k_2)} M_h - 2\left[\frac{k_2(1-k_1)}{k_1^2(1-k_2)} - 1\right] + \frac{(1-k_1)^2 k_2}{k_1^2(1-k_2) M_h}$$

Here k_1, k_2 are weighted ionization rates.

Temperature Effect on Avalanche Gain :

The gain mechanism of an avalanche photodiode is very temperature sensitive because of the temperature dependance of the electrons and hole ionization rates. This temperature dependence is particularly critical at high bias voltages, where small changes in temperature can cause large variations in gain.

To maintain a constant gain as the temperature changes, the electric field in the multiplying region of the pn junction must also be changed. This requires that the receiver incorporate a compensation circuit which adjusts the applied bias voltage on the photodetector when the temperature changes.



$$M = \frac{1}{1-(V/V_B)^N}$$

V_B - Breakdown voltage

Here $V = V_d - I_M R_M$.

V_d – Reverse bias voltage applied to the detector

I_M – Multiplied Photo current.

R_M – Photodiode Series Resistance.

Breakdown voltage vary with temperature

$$V_B(T) = V_B(T_0)\left[1 + \alpha (T - T_0)\right]$$

Comparison of Photodetectors.

Generic operating Parameters of Si, Ge and InGaAs pin photo diodes."

Parameter	Symbol.	Unit	Si	Ge	InGaAs.
Wavelength range.	λ	nm	400–1100	800–1650	1100–1700
Responsivity	$\mathcal{R}$	A/W	0.4–0.6	0.4–0.5	0.25–0.95
Dark current.	I_D.		1–10	50–500	0.5–2.0
Rise time	τ_s	ns	0.5–1	0.1–0.5	0.05–0.5
Bandwidth	B	GHz.	0.3–0.7	0.5–3	1–2
Bias voltage.	V_B.	V	5.	5–10.	5.

Generic Operating Parameters of Si, Ge, InGaAs "Avalanche Photo diode".

Parameter	Symbol	Unit	Si	Ge	InGaAs.
Wavelength range	λ	nm	400-1100	800-1650	1100-1700
Avalanche gain	M	—	20-400	50-200	10-40
Dark current.	I_D	nA	0.1-1	50-500	10-50
Rise Time	τ_s	ns	0.1-2	0.5-0.8	0.1-0.5
Gain — Bandwidth.	M-B	GHz	100-400	2-10	20-250
Bias voltage	V_B.	V	150-400	20-40.	20-30.

UNIT – I
INTRODUCTION TO OPTICAL FIBERS

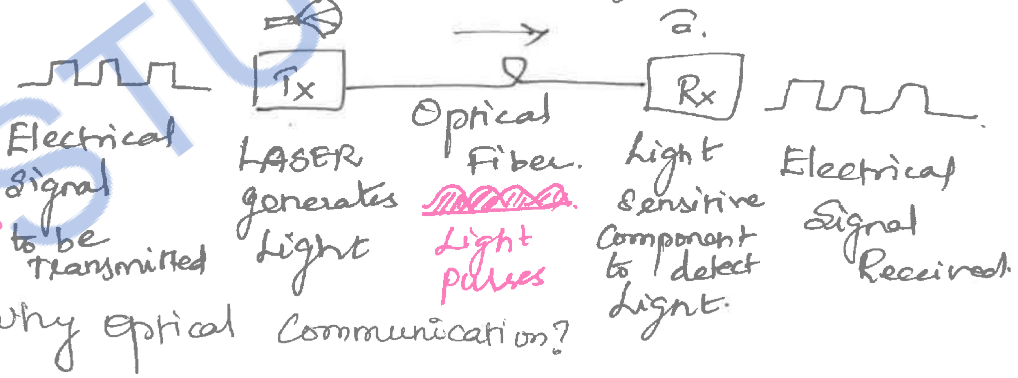
Introduction :

* An optical fiber is a thin, flexible, transparent fiber that acts as waveguide or 'light pipe' to transmit light between the two ends of the fiber.

* Optical fibers are widely used in Fiber-optic Communications, which permits transmission over longer distances and at higher bandwidths (data rates) than other forms of communication.

* Fibers are used instead of metal wires because signals travel along them with less loss and are also imune to electromagnetic interference.

Fig - 1 Optical Transmission



Why optical Communication?

(i) High Bandwidth Transport
(ii) Low Loss
(iii) Compact size
(iv) Immunity to EMI
(v) Cost effective.
(vi) New technology trends.

Evolution of fiber optic system:

(i) The first generation light wave systems uses GaAs semiconductor LASER and operating region was near 0.8 μm. other specifications of 1st generation are

Bit rate – 45 mbps Repeater Spacing – 10km

(ii) The Second generation Systems uses GaAsP lasers which operate wavelength 1.3μm.

Bit rate – 10Mbps Repeater Spacing – 50km

(iii) The Third generation systems operate at 1.5μm wavelength

Bit rate – 10 Gbps Repeater Spacing – 100km

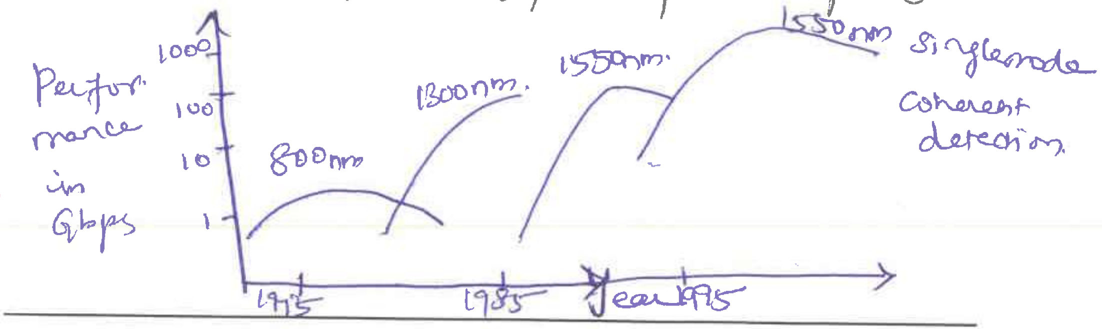
(iv) The Fourth generation systems uses WDM techniques. operates at 1.45 to 1.62 μm wavelength.

Bit rate – 10Tbps Repeater Spacing ≥10,000km

(v) Fifth generation uses Raman amplification technique and optical solitons, operates at 1.53 to 1.57μm

Bit rate – 40 to 60Gbps Repeater Spacing – 24,000km

Fig-2: Optical Evalution.



General Optical Fiber Communication System:

Basic blockdiagram of optical fiber communication system consists of following important blocks

(1) Transmitter

(2) Information channel.

(3) Receiver.

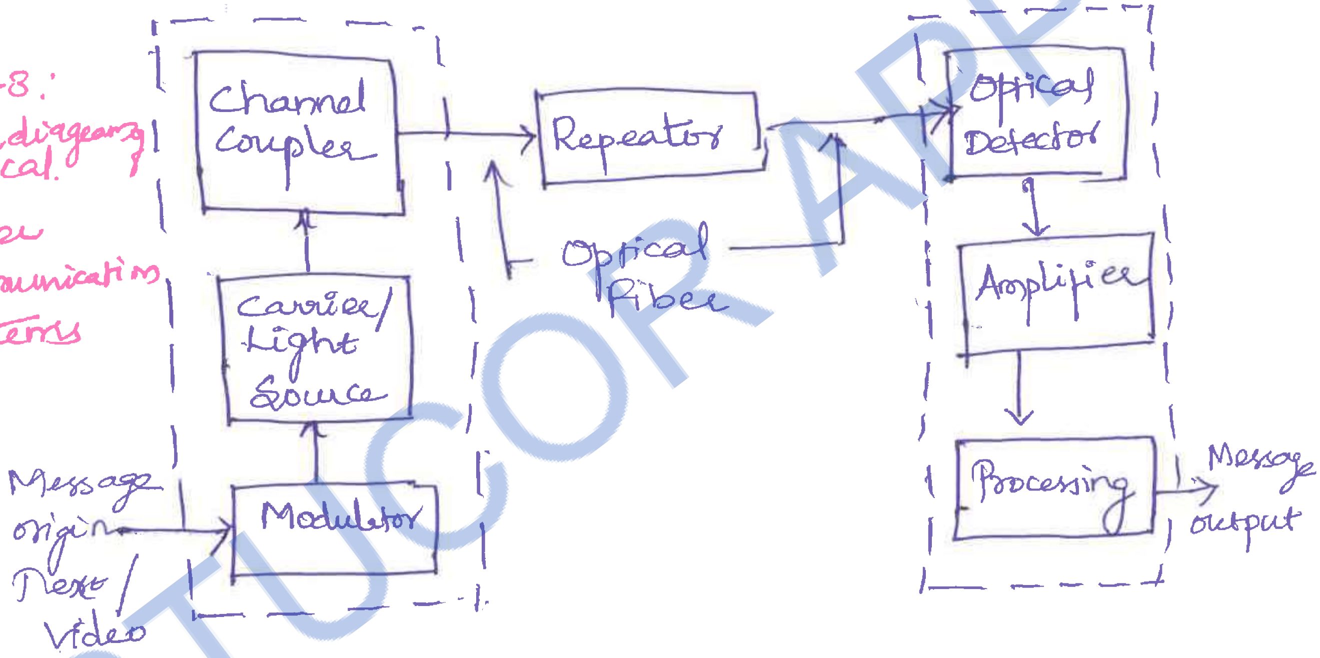


Fig-8: Blockdiagram Optical Fiber Communication Systems

* The light beam pulses are then fed into a fiber-optic cable where they are transmitted over long distances.

* At the receiving end, a light sensitive device known as photocell or light detector is used to detect the light pulses.

*. This photocell or photodetector converts the light pulses in to an electrical signal.

* The electrical pulses are amplified and reshaped back in to digital form. To summarize,

Optical Sources → Provides ~~electrical~~ light signal to a transmitter by providing electrical to light pulse conversion.

Optical Detectors → Converts optical - electrical conversion by PIN/APD diodes.

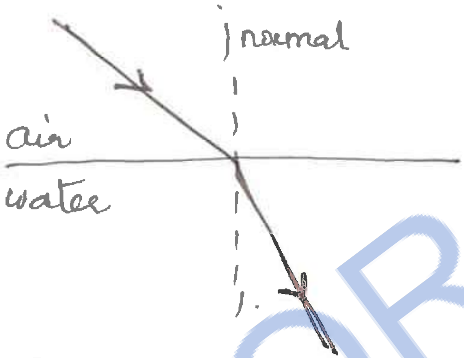
Basic optical laws and definitions:

Ray theory / Geometric optics:

The basic laws of ray theory are quite self-explanatory. In a homogeneous medium, light rays are straight lines. Light may be absorbed or reflected. Reflected ray lies in the plane of incidence and angle of incidence will be equal to the angle of reflection. At the boundary between two media of different refractive indices, the refracted ray will lie in the plane of incidence. Snell's law will give the relationship between the angles of incidence and refraction.

Ray optics – Refraction of light.

As a light ray passes from one transparent medium to another, it changes direction; this phenomenon is called refraction of light. How much that light ray changes its direction depends on the refractive index of the medium.

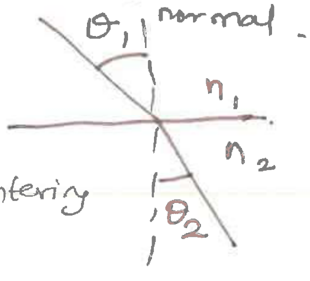


Refractive Index : It measures how much a material refracts light. Refractive index of a normal material abbreviated as n, is defined as ratio between speed of light in a vacuum (c) and speed of light in a material (v)

$$n = c/v.$$

Snell's law: When a light passes from one transparent material to another, it bends according to Snell's law which is defined as

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$



n_1 – Refractive index of medium the light is leaving

n_2 – Refractive index of material the light is entering

θ_1 – Incident angle

θ_2 – Refractive angle

Critical Angle(θ): The critical angle can be calculated from Snell's law putting in an angle of 90° for the angle of refracted ray θ_2 this gives θ_1,

Since $\theta_2 = 90°$

so $\sin\theta_2 = 1$

Then $\theta_c = \theta_1 = \arcsin(n_2/n_1)$

Numerical Aperture (NA): For step-Index multimode model, the acceptance angle is determined only by the indices of refraction

$$NA = n\sin\theta_{max} = \sqrt{n_f^2 - n_c^2}$$

n – Refractive Index of the medium light is traveling before entering the fiber

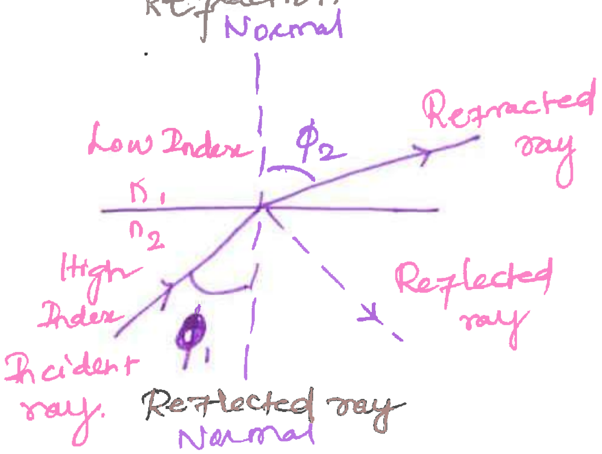
n_f – Refractive Index of the fiber core

n_c – Refractive Index of the cladding

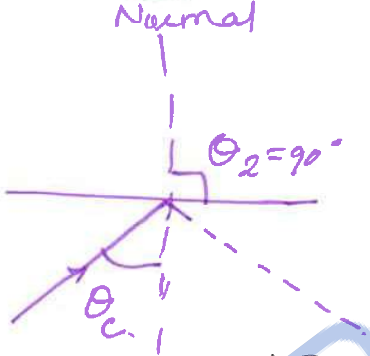
Total Internal Reflection:

When a ray is incident on the interface between two dielectrics of differing refractive indices some portion of ray is reflected and some portion is refracted inside medium when a incident angle is fixed in such a way that refracted portion is nullified and total ray is reflected inside the medium. This is achievable when critical angle(θ_c) > 90°. when $\theta_c = 90°$, refraction occurs parallel to dielectric.

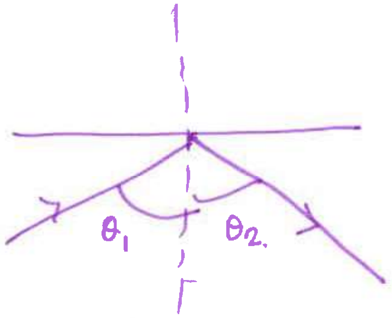
Refraction



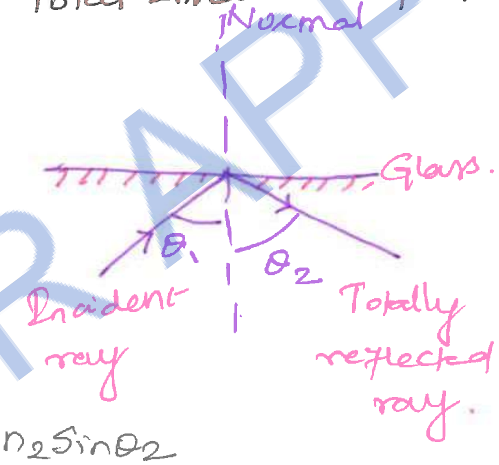
Critical



Reflected ray



Total Internal Reflection



As per Snell's law,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

Critical angle

$$\sin\theta_1 = \sin\theta_2 \left(\frac{n_2}{n_1}\right)$$

for $\theta_2 = 90°$

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

Acceptance angle :

Rays with shallow grazing angle at the core-cladding interface are transmitted by total internal reflection. Meridonial ray A at the critical angle ϕ_c with in the fiber at the core-cladding interface. The ray enters

The fiber core at an angle θ_a. Any ray which are incident in to the fiber core at an angle greater than θ_a will be transmitted to the core-cladding interface at an angle less than will not be totally internally reflected.

Incident ray 'B' at an angle greater than θ_a is refracted in to the cladding and eventually lost. Maximum angle to the axis at which light may enter the fiber in order to be propagated and is often referred to as the acceptance angle θ_a for the fiber.

Numerical Aperture:

NA is the measure of how much light can be collected by an optical system such as an optical fiber or a micro.

At Point 'A' $n_0 \sin\theta_{0(max)} = n_1 \sin\theta_c$ —— ①

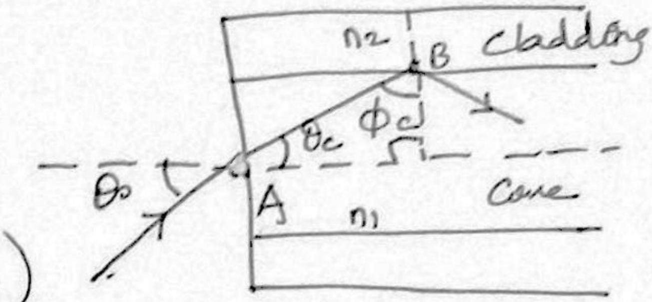
Snell's law at Point B

$$n_1 \sin\phi_c = n_2 \sin 90°$$

$$n_1 \sin\phi_c = n_2$$

$$\sin\phi_c = \frac{n_2}{n_1}$$

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



From ①

$$n \sin\theta_{0(max)} = n_1 \sin(90-\phi_c)$$

$$= n_1 \cos\phi_c$$

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

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

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

$$N_A = n\sin\theta_{0(max)} = \sqrt{n_1^2-n_2^2}$$

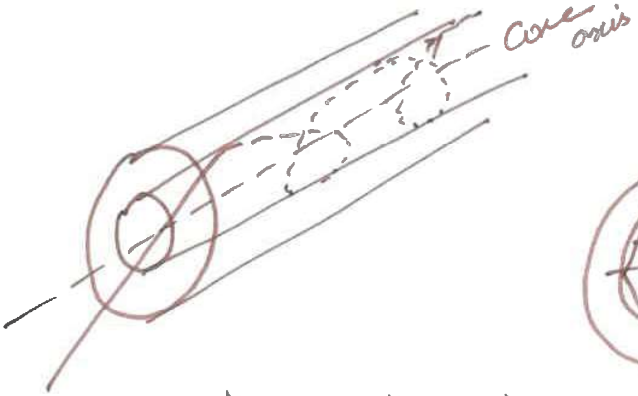
Numerical aperture for step index fiber.

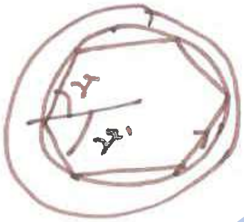
$$N_A = n_1\sqrt{2\Delta}$$

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

Skew ray optics :-

These rays are transmitted without passing through the fiber axis





The helical path traced through the fiber gives a change in direction of 2γ at each reflection where γ angle between the projection of ray and the radius of the fiber core at the point of reflection.

To resolve the ray path AB relative to the radius BR in these two perpendicular planes requires multiplication of $\cos\gamma$ and $\sin\theta$

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

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

Using Snell's law at point A.

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

$$\sin\theta_{as} = \frac{n_1}{n_0}\sin\theta$$

$$= \frac{n_1}{n_0}\,\frac{\cos\phi}{\cos\gamma}$$

$$= \frac{n_1}{n_0\cos\gamma}\left[1-\frac{n_2^2}{n_1^2}\right]^{1/2}.$$

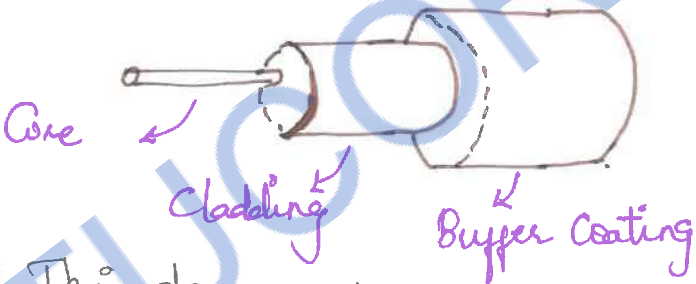
$$\boxed{n_0\cos\gamma\,\sin\theta_{as} = (n_1^2-n_2^2)^{1/2} = NA}$$

Optical Modes and Configurations

Optical fibre is a cylindrical dielectric waveguide that guides the light in a direction to its axis at optical frequencies.

"Optical modes" will describes the nature of propagation of electromagnetic waves in a wave guide i.e., it is the allowed direction whose associated angles satisfy the conditions for total internal reflection and constructive interference.

Optical fiber has three parts Core, cladding, Buffer coating



Core : Thin glass center of fiber where light travels

Cladding : Transparent cladding of slightly lower refractive index n_2

Buffer coating : Plastic coating protects fiber from damages, moisture

Based on the number of modes that propagates through the optical fiber, they are classified as

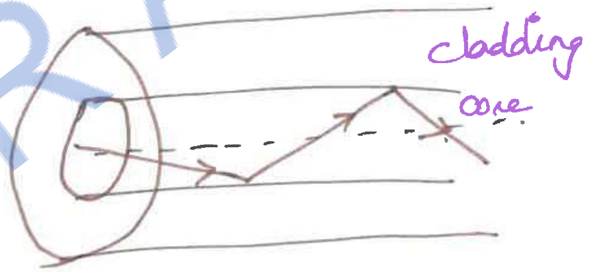
- Single mode fibers
- Multimode fibers.

Single mode fibers:

In a fiber, if only one mode is transmitted through it, then it is said to be a single mode fiber.

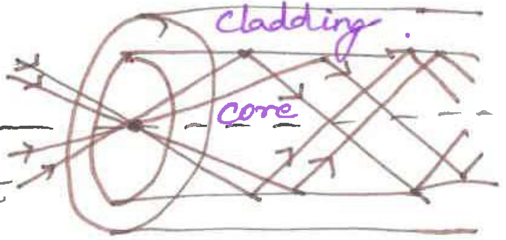
A typical single mode fiber may have a core radius of 3μm and a numerical aperture of 0.1 at a wavelength of 0.8 μm. The condition for the single mode operation is given by V number of the fiber, which is defined as. Such that $V \leq 2.405$.

- * Only one path available
- * V number is < 2.405
- * Core diameter is small
- * No dispersion
- * Higher bandwidth (1000MHz)
- * Used for long haul communication
- * Fabrication is difficult & costly



Multimode fibers:

- * If more than one mode is transmitted through optical fiber then it is multimode fiber.
- * The larger core radii of multimode fibers make it easier for launching optical power in to the fiber and facilitate the end to end connection of similar powers
- * V number is greater than 2.405.



Based on refractive index profile of the core and cladding, the optical fibers are classified into two types:

- * Step - Index fiber.
- * Graded - Index fiber

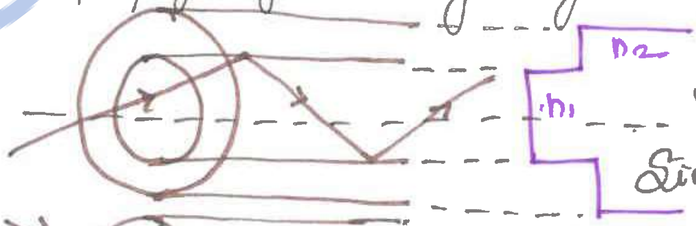
Step - Index fiber (SI)

Core of the fiber's refractive index n_1 is constant and a cladding is slightly lower refractive index n_2

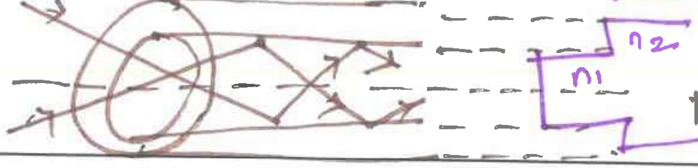
$$n(r) = \begin{cases} n_1, & r < a \text{ core} \\ n_2, & r \geq a \text{ cladding} \end{cases}$$

In Step-index fiber, the refractive index changes in a step fashion, from the centre of the fiber, the core, to the outer shell, the cladding.

The light rays propagating through it are in the form of meridinal rays which will cross the fiber core axis during every reflection at the core-cladding boundary and are propagating in a zig-zag manner.



RI profile.
Singlemode Step Index Fiber



RI profile
Multimode Step-Index Fiber.

Step - Index Multimode fibers

A multimode step index fiber, propagates light in many modes. The total number of modes MN increases with increase in the numerical aperture. For a large number of modes, MN can be approximated as.

$$M_n = \frac{V^2}{2} = 4.9 \left[\frac{d n_1 \sqrt{2\Delta}}{\lambda}\right]^2$$

d - Diameter of fiber.

V - Normalized frequency.

'V' number is a relation relation among the fiber size, the refractive indices and the wavelength. It is given as,

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

a - Fiber core radius.

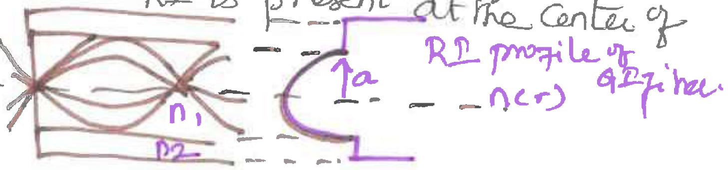
λ - Operating wavelength.

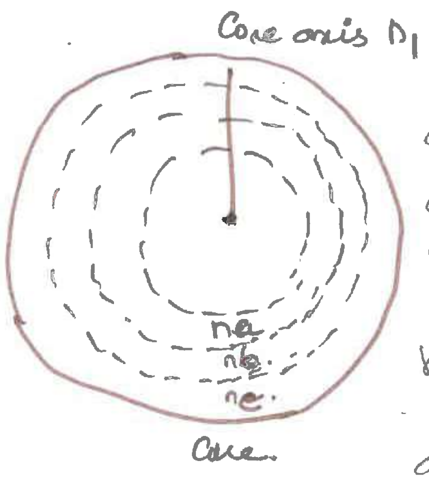
Δ - relative refractive index difference

Graded Index fiber (GI)

Refractive index 'n' in the core varies as we move away from the core. RI is made to vary in the form of parabolic manner such that maximum RI is present at the center of core.

$$n(r) = \begin{cases} n_1\left(1 - 2\Delta (r/a)^2\right)^{1/2} & r < a \\ n_2(1 - 2\Delta)^{1/2} = n_2 & r \geq a \end{cases}$$





Each dashed circle represents a different refractive index, decreasing as we move away from the fiber center.

A ray incident on these boundaries between na – nb, nb – nc is refracted.

Eventually at n_2 the ray is turned around and totally reflected.

- * The light rays will be propagated in the form of skew (or) helical rays which will not cross the fiber axis at any time and are propagating around the fiber axes in a helical or spiral manner.

- * The effective acceptance angle of the graded-index fiber is somewhat less than that of an equivalent step-index fiber. This makes coupling fiber to the light source more difficult.

Concept of Mode:

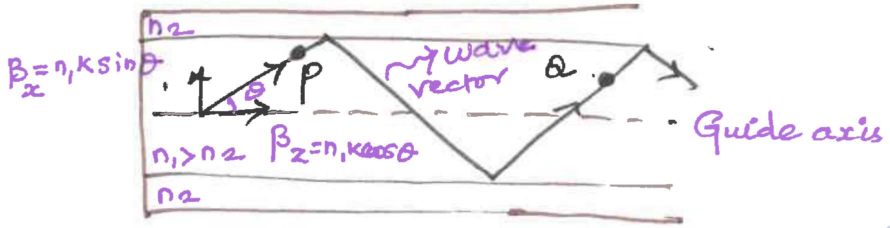
A plane monochromatic wave propagating in direction of ray path within the guide of refractive index n_1 sandwiched between two regions of lower refractive index n_2.

→ Wavelength $= \lambda / n_1$

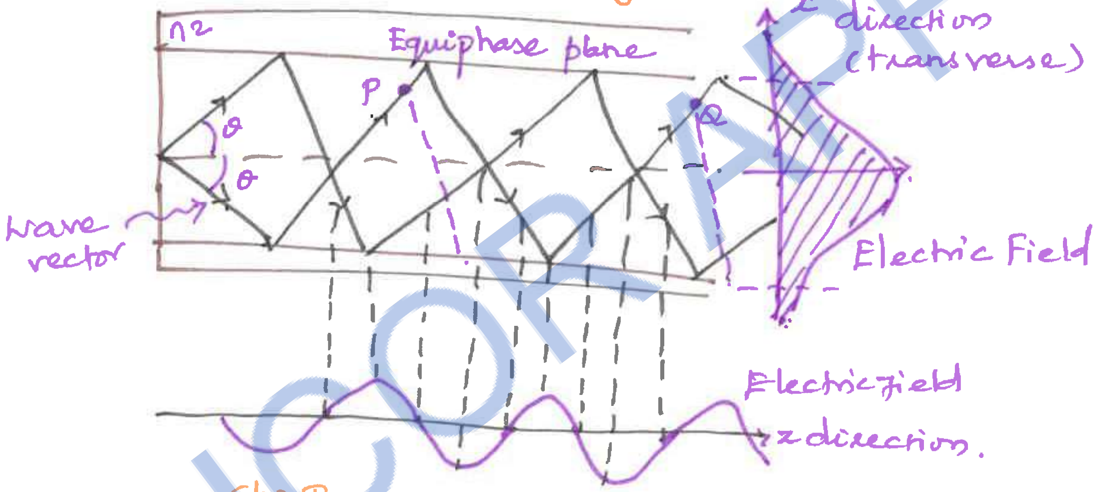
→ Propagation constant $\beta = n_1 k$

→ Components of β in z and x directions $\beta_z = n_1 k \cos\theta$,
$\beta_x = n_1 k \sin\theta$.

→ Constructive interference occurs and standing wave obtained in x-direction



(a) Plane wave propagating in the guide



(b) Interference of plane waves in the guide. (forming lowest order mode m=0)

→ Components of plane wave in x-direction reflected at core cladding interface and interfere may be constructive

→ Stable field distribution in the x-direction with only a periodic z-dependance is known as "Mode"

* Specific mode is obtained only when the angle between the propagation vectors or rays and interface have a particular value discrete modes typified by a distant value of θ.

Modes in Planar waveguides :

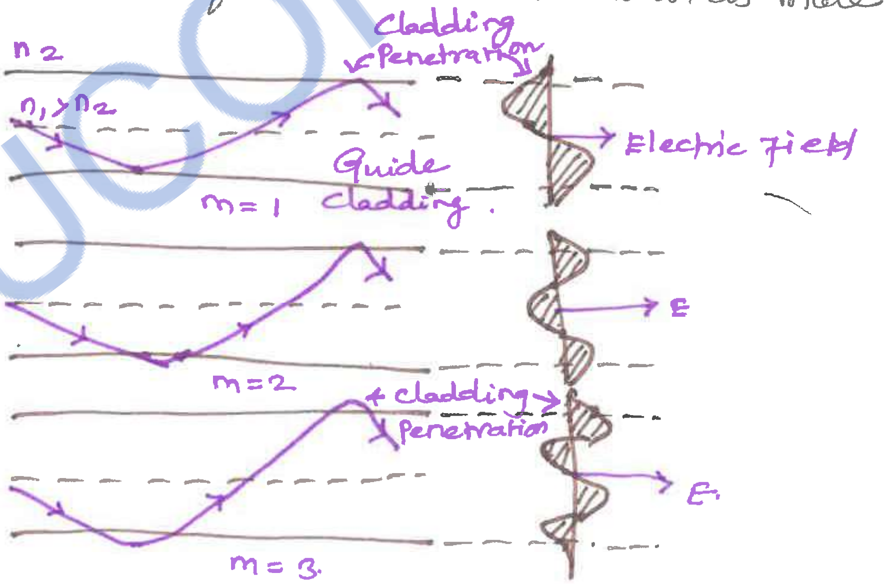
For monochromatic light fields of angular frequency ω, a mode traveling in positive z-direction has a time and z-dependence given by

$$\exp j(\omega t - \beta z)$$

* Dominant modes propagating in z-direction with electric field distribution in x- direction formed by rays. with m=1, 2, 3

* m denotes number of zeros in this transverse pattern

* Also signifies order of the mode and is known as mode number.



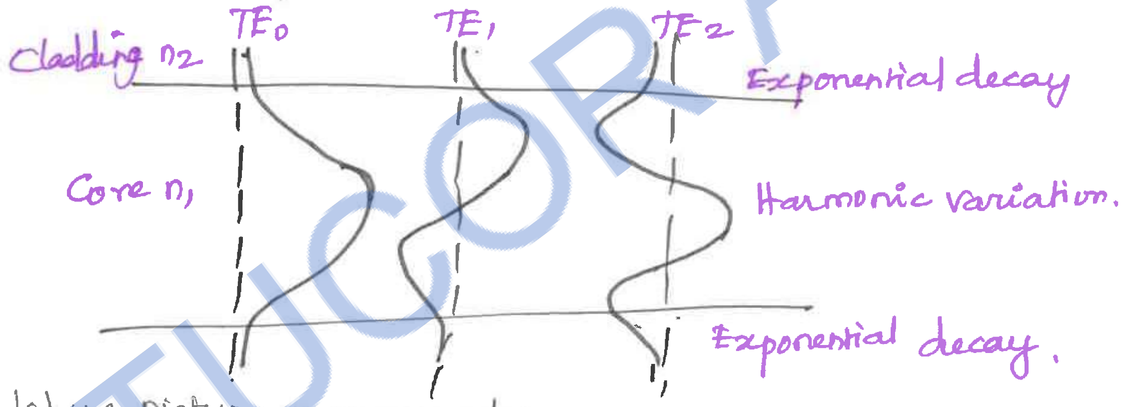
Ray propogation and corresponding TE field patterns of three lower order modes in planar guide.

TE and TM modes:

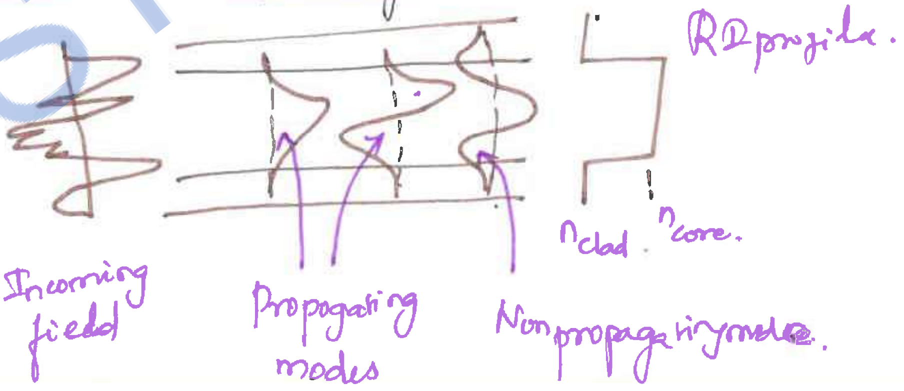
Transverse Electric Mode (TE): Electric field perpendicular to direction of propagation; $E_z=0$, but a corresponding component of magnetic field H is the direction of propagation.

Transverse Magnetic Mode (TM): A component of E field is the direction of propagation but $H_z=0$

Transverse ElectroMagnetic (TEM): Total field lies in the transverse plane in that case both E_z and H_z are zero



Wave picture of waveguides:



- * The Step-index profile provide focusing just like lenses and GRIN materials
- * The guides modes of the fiber are those that propagate without changing their profile
- * The guided modes are those intensity profiles, for which the focusing due to the index profile, exactly matches the diffraction.
- * In the core is small, only one such mode exists (single mode fiber)

Phase velocity : For plane wave, there are points of constant phase, these constant phase points forms a surface referred as wave front. As light wave propagate along a waveguide in the z-direction, wavefront travel at a phase velocity ; $V_p = \omega/\beta = c/n_1$

Here propagation constant $\beta = n_1 k = n_1 \frac{2\pi}{\lambda} = n_1 \frac{\omega}{c}$

Group velocity : Non monochromacity leads a group of waves with closely similar frequencies is called wave packet. wave packet observed to move at a group. velocity

$$V_g = \delta\omega / \delta\beta$$

$$V_g = \frac{c}{\left(n_1 - \lambda \frac{dn_1}{d\lambda}\right)} = \frac{c}{N_g}$$

N_g → Group index of the guide.

Evanescent field : The form of the electric field in the cladding of the guide. The transmitted wave field in the cladding is of the from

$$B = B_0 \exp(-\xi_2 x) \exp j(\omega t - \beta z)$$

The amplitude of the field in the cladding is observed to decay exponentially in the x - direction is called "Evanescent field"

Cylindrical Fiber :

In common with planar waveguide, TE and TM modes are obtained within dielectric cylinder. A cylindrical waveguide is bounded in two dimensions, therefore, two integers l and m to specify the modes.

TE_{lm} and TM_{lm} modes

These modes from meridional rays propagation within guide.

Hybrid modes where E_z and H_z are non zero results from skew ray propagation within the fiber. Designated as,

HE_{lm} and EH_{lm} depending upon whether the components of H or E make larger contribution to transverse field.

Modes in Cylindrical Fibers :

Mode analysis is simplified by considering fibers for communication purposes

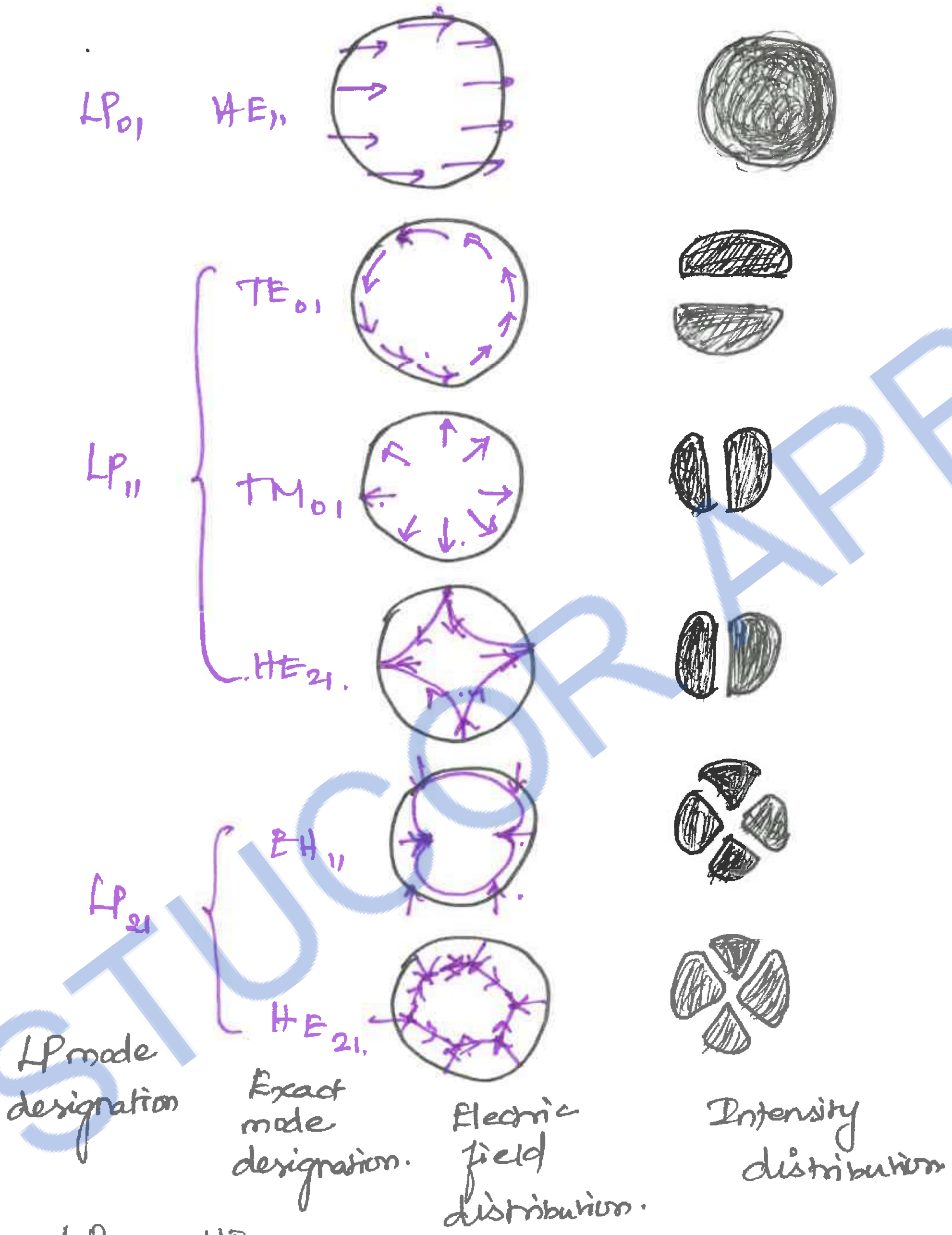
→ Satisfy, weakly guided approximation, Δ<<1, small grazing angles θ.

Approximate solutions for full set of HE, EH, TE and TM modes may be given by two linearly polarized (LP) components.

→ Not exact modes of fiber, except for fundamental mode, however as Δ is very small, HE-EH modes pairs occur with almost identical propagation constants are called as degenerate modes.

→ The superposition of these degenerating modes characterized by a common propagation constant corresponds to particular LP modes regardless of their HE, EH, TE or TM configurations. This linear combination of degenerate modes, a useful simplification in the analysis of weakly guiding fibers. Correspondence between the lower order in linearly polarized modes and the traditional exact modes from which they are formed

Intensity Profiles : Electric field configuration for the three lowest LP modes in terms of their consistent exact modes. Field strength in the transverse direction is identical for the modes



$LP_{01} \rightarrow HE_{11}$

$LP_{11} \rightarrow HE_{21}, TE_{01}, TM_{01}$

$LP_{21} \rightarrow HE_{31}, EH_{11}$

$LP_{02} \rightarrow HE_{12}$

$LP_{31} \rightarrow HE_{41}, EH_{21}$

$LP_{12} \rightarrow HE_{22}, TE_{02}, TM_{02}$

$LP_{lm} \rightarrow HE_{2m}, TE_{0m}, TM_{0m}$

Linearly polarized modes are the lower order modes obtained in a cylindrical homogeneous core waveguide.

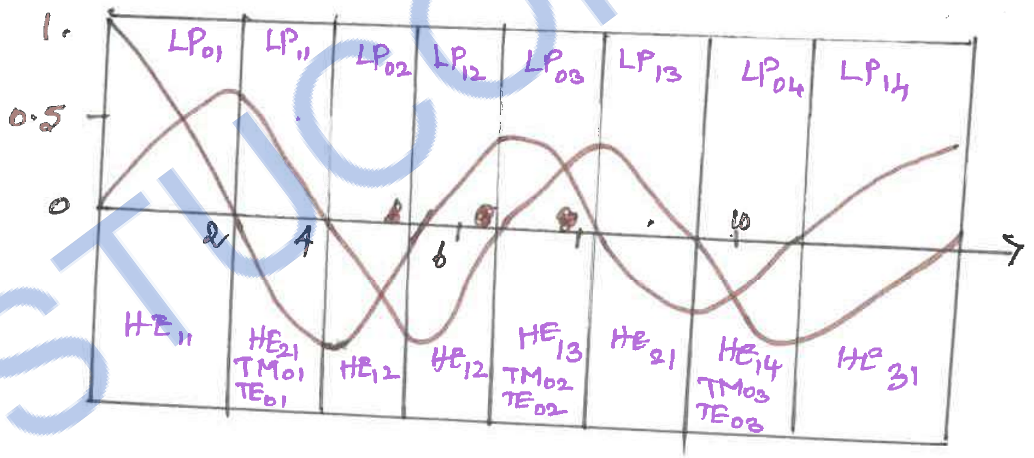
Allowed regions for the LP modes of order $l = 0, 1$ against normalized frequency (V) for a circular optical waveguide with a constant refractive index are (SI)

Value of V, where J_0 and J_1 cross the zero gives the cutoff point for various modes $V = V_c$

V_c is the different for different modes $= 0$ for LP_{01} mode

$= 2.405$ for LP_{11} mode

$= 3.83$ for LP_{02} mode



Fibe Materials :

To selecting materials for optical fibers, a number of requirements must be satisfied, for example

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

Materials that satisfy these requirements are glasses and plastics.

- Glass fibers.
- Active glass fibers
- Plastic optical fibers
- Photonic Crystal fibers. (PCF) → Index-Guiding PCF
  → Photonic Bandgap Fiber.

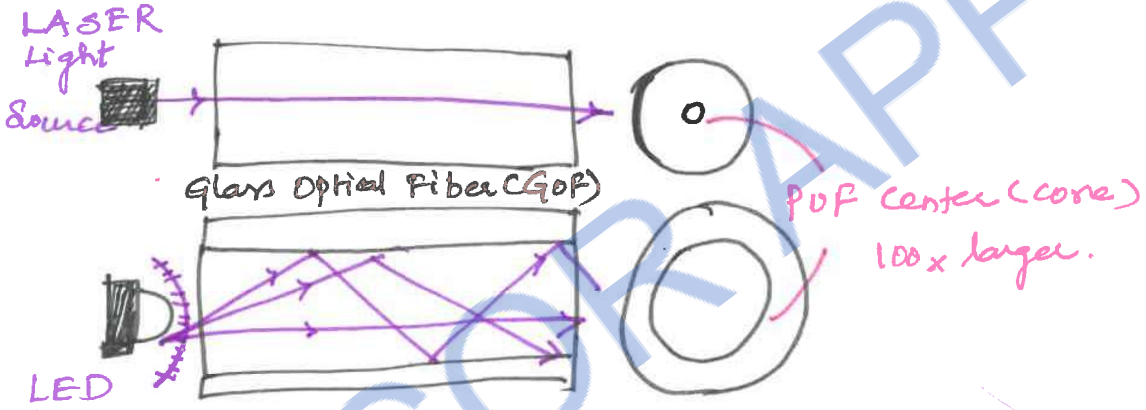
1. Glass Fibers

Glass is made by fusing mixtures of Metal oxides, Sulfides or selenite

Glass fiber is a dimensionally stable enginaring material. Glass fiber does not stretch or shrink. after exposure to extremely high or low temperatures. Glass fibers do not absorb moistures or change physically or chemically when exposed to water

2. Plastic Optical Fibers:

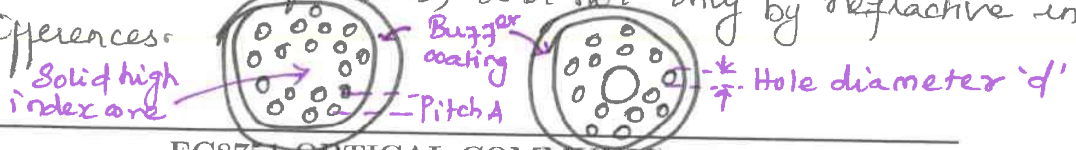
Plastic optical Fiber (POF) is an optical fiber which is made out of plastic. POF standard is based on multi level PAM modulation a frame structure. Plastic fibers are similar to glass fiber but their installation cost is much lesser.



Plastic Optical Fiber (POF)

3. Photonic Crystal Fiber (PCF)

PCF is a new class of optical fiber based on the properties of photonic crystals. PCFs guiding light by a conventional higher-index core modified by the presence of air holes. PCF may be considered a subgroup of a more general class of micro structured optical fibers, where light is guided by structural modifications, and not only by refractive index differences.



Fiber Fabrication :

Two basic techniques are used in the fabrication of all-glass optical wave guides.

* Vapor oxidation process.
* Direct Melt methods.

In, Vapor-phase oxidation process, highly pure vapors of metal halides (eg $SiCl_4$ and $GeCl_4$) react with oxygen to form a white powder of SiO_2 particles. The particles are then collected on the surface of a bulk glass by on of four different commonly used processes and are sintered by one of a variety of techniques to form a clear glass rod or tube. This rods or tube is called a "preform". The preform is precision-fed into a circular heater called the drawing furnace. Here, the preform end is softened to the point where it can be drawn in to a very thin filament, which becomes the optical fiber. The turning speed of the takeup drum at the bottom of the draw tower determines how fast the fiber is drawn.

- * Outside Vapor-Phase Oxidation (OVPO)
- * Vapor phase Axial Deposition (VAD)
- * Modified Chemical Vapor Deposition (MCVD)
- * Plasma Activated Chemical Vapor Deposition (PCDV)
- * Photonic Crystal Fiber Fabrication.

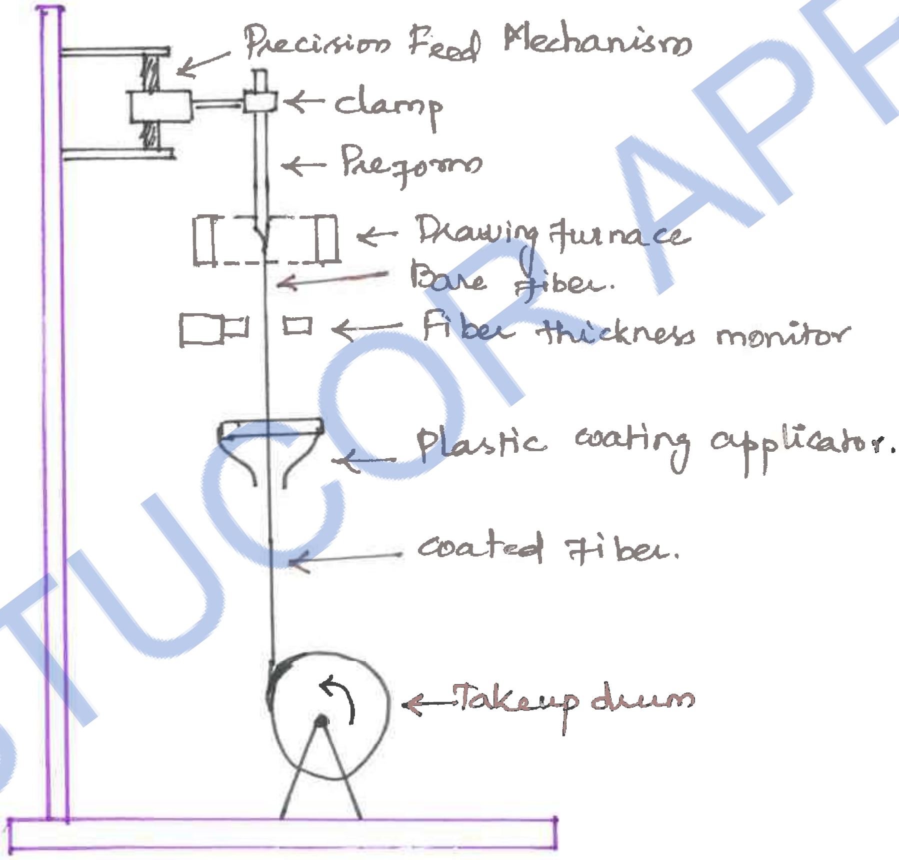


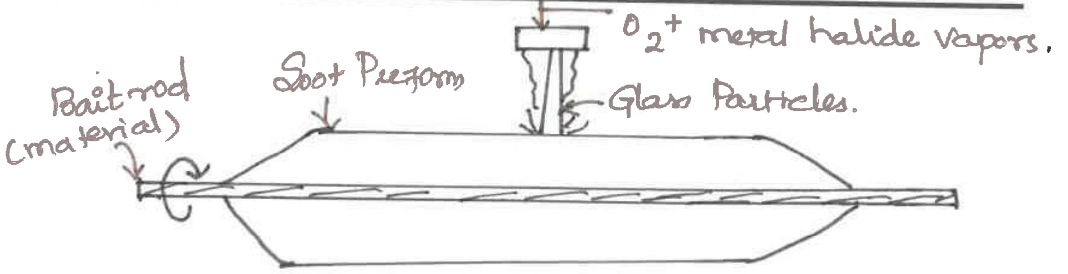
Fig: Schematics of a fiber-drawing apparatus

Outside Vapor-Phase Oxidation:

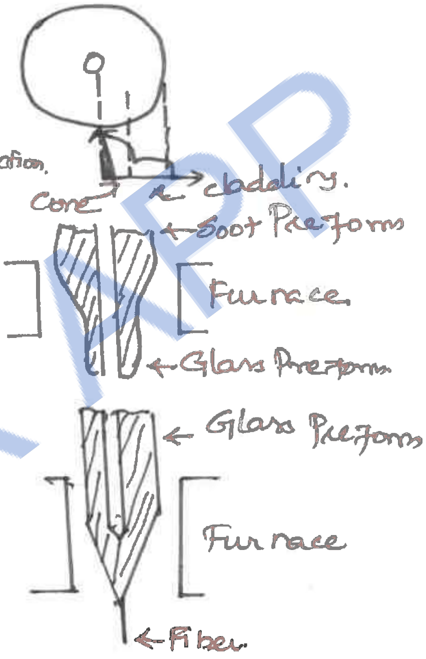
First, a layer of SiO_2 particles called a soot is deposited from a burner onto a rotating graphite or ceramic material. The glass soot adhere to this bait rod and layer by layer, a cylindrical, porous glass preform is built up. By properly Controlling the constituents of the metal halide vapor stream during the deposition process, the glass composition and dimensions desired for the core and cladding can be incorporated into the preform. When the deposition process is completed, the mandrel is removed and the porous tube is then vitrified in a dry atmosphere at a high temperature (above 1400°) to a clear glass preform. This clear preform is subsequently mounted in a fiber-drawing tower and made in to a fiber. The central hole in the tube preform collapses during this drawing process.

Vapor-Phase Axial Deposition;

In this method, the SiO_2 Particles are formed in the same way of OVPD process. As these particles emerge from the torches, they are deposited on to the end surface of a silica glass rod which acts as a seed. A porous preform is grown in the axial direction by moving the rod upward. The rod is also continuously rotated to maintain cylindrical symmetry of the particle deposition. As the porous preform moves upward, it is transformed into a solid, transparent rod preform by zone melting with the carbon ring heater



(a) Soot Deposition



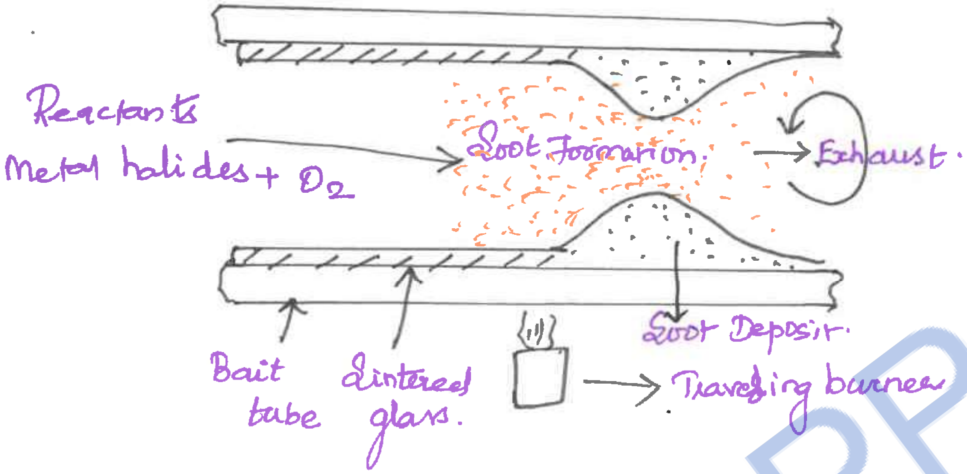
(b) Profiles can be step or graded index — Soot Preform cross section.

(c) Following deposition, the soot preform is sintered in to a clear glass preform

(d) Fiber is drawn from the glass preform.

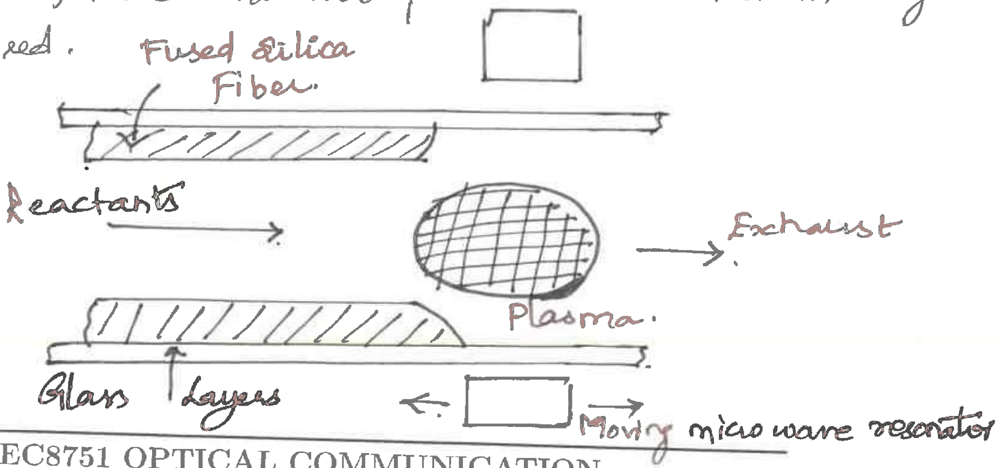
Modified Chemical Vapor Deposition (MCVD) :

It is developed at Bell laboratories and widely adopted to produce very low-loss graded index fibers. The glass vapor particles, arising from the reaction of the constituent metal halide gases and oxygen, flow through the inside of a revolving silica tube. As the SiO_2 particles are deposited. they are sintered to a clear glass layer by an oxy hydrogen torch which travels back and form along the tube. When the desired thickness of glass has been deposited, the vapor flow is shut off and the tube is heated strongly.



Plasma Activated Chemical Vapor Deposition (PCVD)

It is similar to MCVD, However, a non isothermal microwave plasma operating at low pressure initiates the chemical reaction. With the silica tubes held at temperatures in the range of 1000-1200°c to reduce mechanical stresses in the growing glass films, a moving microwave resonator operating at 2.45 GHz generates a plasma inside the tube to activate the chemical reaction. This process deposits clear glass material directly on the tube wall; there is no soot formation. Thus no sintering is required.



Photonic Crystal Fiber Fabrication:

The fabrication of a photonic crystal fiber also is based on first creating a preform. The preform is made by means of an array of hollow capillary silica tubes. To make a preform for an index-guiding fiber the capillary tubes first are bundled in an array around a solid silica rod.

For a photonic bandgap fiber, the hollow core is established by leaving an empty space at the center of the array. Following the array stacking processes, these configurations are fussed together to create a preform and then made in to a fiber using a conventional optical fiber drawing tower.

In the drawing process, the holes keep their original arrangement. This allows the creation of any type of array pattern and hole shape in the final fiber.

Classification of Optical Fibers :

Classified on basis of

→ Core and cladding materials.
→ Refractive index profile
→ Modes of propagation.

Core and Cladding Materials :

(i) Glass core and cladding (SCS: silica-clad-silica)

* Low attenuation & best propagation characteristics
* Least rugged - delicate to handle

(ii) Glass core with plastic cladding (PCS: plastic clad silica)

* More rugged than glass; attractive to military applications
* Medium attenuation and propagation characteris

(iii) Plastic core and cladding.

* More flexible and more rugged.
* Easy to install, better withstand stress, less expensive, weigh 60% less than glass.
* High attenuation limited to short runs.

Based on Refractive index profile → Step Index
→ Graded Index

Based on modes of propagation → single mode
→ Multimode

Graded Index Fiber Structure :

In GI fiber design the core refractive index decreases continuously with increasing radial distance r from the center of the fiber, but is generally constant in the cladding. The most commonly used construction for the refractive index variation in the core is the power law relationship.

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

The RI difference Δ is given as

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} = \frac{n_1 - n_2}{n_1}$$

The local numerical aperture is defined as

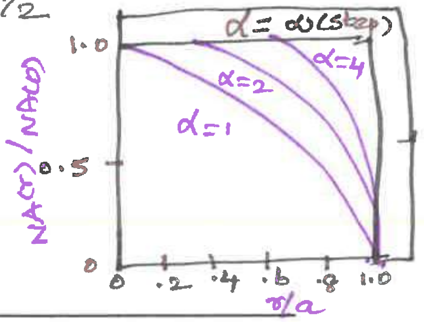
$$NA(r) = \begin{cases} [n^2(r) - n_2^2]^{1/2} \approx NA(0)\sqrt{1-(r/a)^{\alpha}} & \text{for } r \le a \\ 0 & \text{for } r > 0 \end{cases}$$

Where the axial numerical aperture is defined as

$$NA(0) = [n^2(0) - n_2^2]^{1/2}$$

$$= (n_1^2 - n_2^2)^{1/2}$$

$$NA(0) \approx n_1\sqrt{2\Delta}$$



UNIT-2

TRANSMISSION CHARACTERISTIC OF OPTICAL FIBER

Signal attenuation and distortion in optical fiber.

* Signal attenuation largely determines the maximum repeaterless separation between optical transmitter & receiver

* Signal distortion cause that optical pulses to broaden as they travel along a fiber, the over lap between neighboring pulses, creating errors in the receiver output, resulting in the limitation of information-carrying capacity of a fiber.

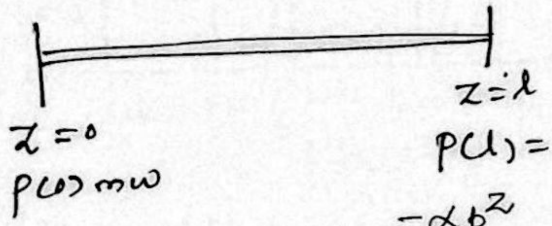
* The transmission characteristics of most interest: "attenuation (loss) and bandwidth"

* Now silica based glass fibers have losses about 0.2dB/km (i.e., 95% launched power remains after 1km of fiber transmission). This is essentially the fundamental lower limit for attenuation in silica based glass fibers.

* Fiber bandwidth is limited by the signal dispersion within the fiber. Band width determines the number of bits of information transmitted in a given time period. Now, fiber band width has reached many 10's Gbits/s over many km's per wavelength channel.

Attenuation :

Signal attenuation with in optical fibers is usually expressed in the logarithmic unit of the decibel. The decibel, which is used for comparing two power levels, may be defined for a particular optical wave length as the ratio of the output optical power from the fiber to the input optical power.



$$P(l) = P(0)\,e^{-\alpha_p l}\ \text{mW}$$

$$P(z) = P(0)\,e^{-\alpha_p z}$$

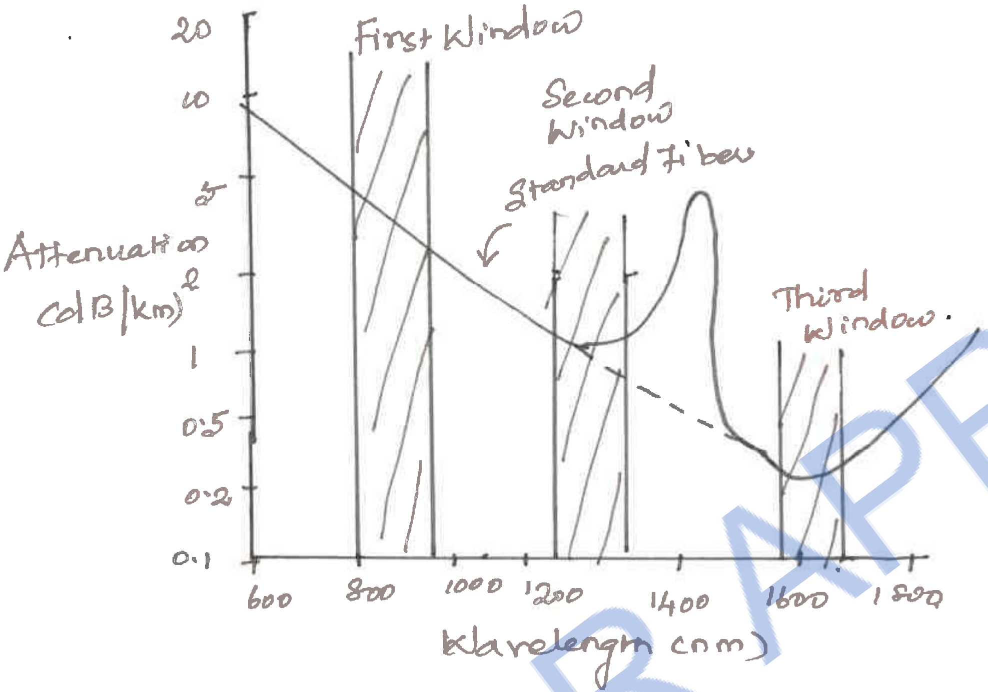
The parameter α_p is called fiber attenuation coefficient in a units of for example (1/km) or (nepers/km). A more common unit is dB/km that is defined by

$$\alpha\,[\text{dB/km}] = \frac{10}{l}\log\left[\frac{P(0)}{P(l)}\right] = 4.343\,\alpha_p\,[1/\text{km}]$$

Fiber loss in dB/km

$$P(l)\,[\text{dBm}] = P(0)\,[\text{dBm}] - \alpha\,[\text{dB/km}] \times l\,[\text{km}]$$

where [dBm] or dB milliwat is 10log(P [mW])



Fiber attenuation mechanisms

1. Material absorption
2. Scattering loss.
3. Bending loss.
4. Radiation losss (due to mode coupling)
5. Leaky modes.

Absorption :

Absorption is caused by three different mechanisms:

(i) Impurities in fiber material : from transition metal ions and OH ions with absorption peaks at wavelengths 2700nm, 400nm, 950nm and 725nm

(ii) Intrinsic absorption (fundamental lower limit) : Electronic absorption band (UV region) & atomic bond (IR region) in basic SiO_2

(iii) Radiation Defects

The light absorption can be intrinsic (due to the material components of the glass) or extrinsic (due to impurities introduced in to the glass during fabrication.

Intrinsic absorption:

Pure silica-based glass has two major intrinsic absorption mechanisms at optical wavelengths.

* A fundamental "UV absorption" edge, the peaks are centered in the ultraviolet wave length region. This is due to the electron transitions within the glass molecules. The tail of this peak may extend into the shorter wavelengths of the fiber transmission spectral window

* A fundamental "infrared and far-infrared absorption" edge, due to molecular vibrations (such as Si-O). The tail of these absorption peaks may extend into the longer wavelengths of the fiber transmission spectral window.

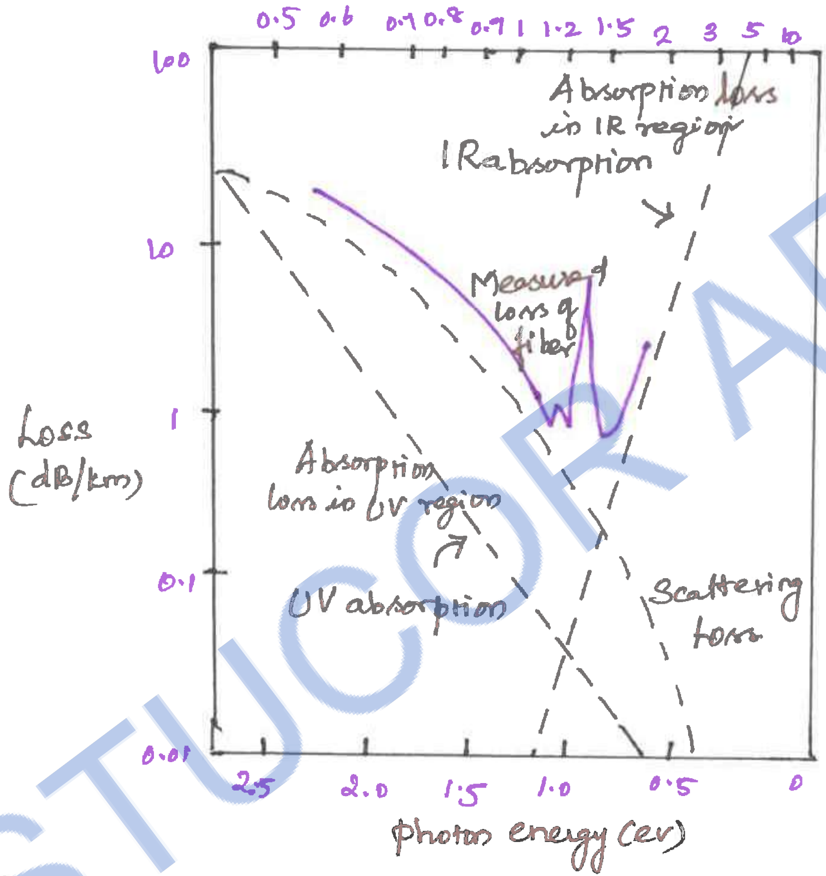
Extrinsic absorption:

* Major extrinsic loss mechanism is caused by absorption due to water introduced in the glass fiber during fiber pulling by means of oxyhydrogen flame.

* These OH- ions are bounded in to the glass structure and have absorption peaks at 1.38μm.

* Since these OH⁻ absorption peaks are sharply peaked, narrow spectral windows exist around 1.3μm and 1.55μm which are essentially unaffected by OH- absorption.

* The lowest attenuation for typical silica-based fibers occurs at wavelength 1.55 μm at about 0.2dB/Km, approaching the minimum possible attenuation at this wavelength.



Scattering Loss:

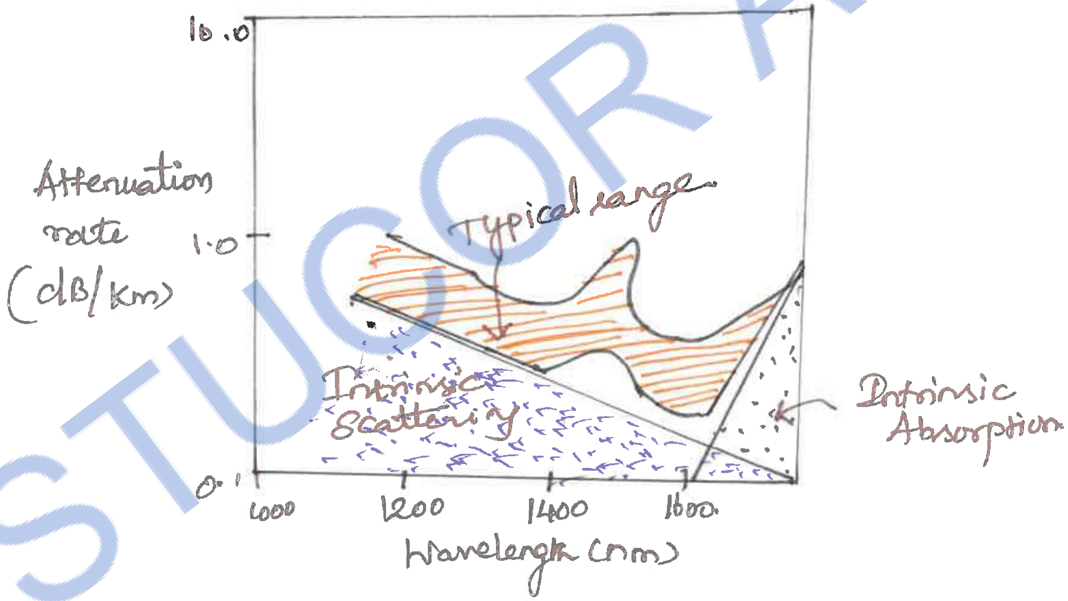
* Scattering results in attenuation (in the form of radiation) as the scattered light may not continue to satisfy the total internal reflection in the fiber core.

* Small variation in material density, chemical composition, and structural inhomogeneity scatter light in other directions and absorb energy from guided optical wave.

The essential mechanism is the Rayleigh Scattering. Since, the black body radiation classically is proportional to λ^{-4}, the attenuation coefficient due to Rayleigh scattering is approximately proportional to λ^{-4}.

$$\alpha_{scat} \propto \lambda^{-5}\left[\exp\left(\frac{hc}{\lambda k_B T}\right)\right]^{-1}$$

$h = 6.626 \times 10^{-34}$ Js, $K_B = 1.3806 \times 10^{-23}$ JK^{-1}



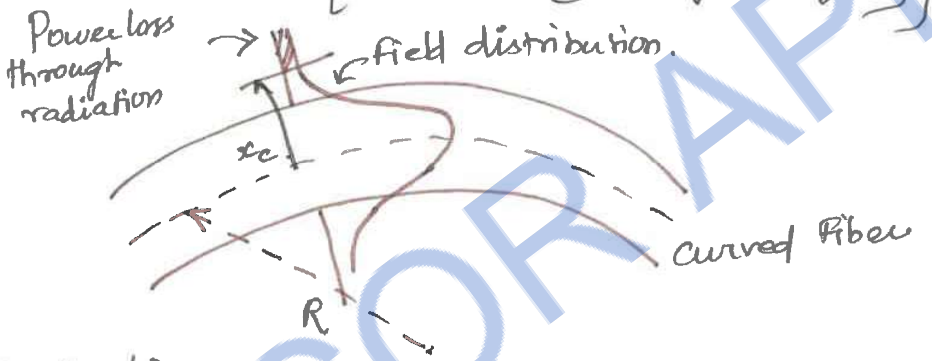
Bending Loss (Macrobending & Microbending)

Macrobending: The curvature of the bend is much larger than fiber diameter. Lightwave suffers sever loss due to radiation of the evanescent field in the cladding region. As the radius of the curvature decreases, the loss increases exponentially until it reaches at a certain critical radius.

For any radius a bit smaller than this point, the losses suddenly becomes extremely large. Higher order modes radiate away faster than lower order modes.

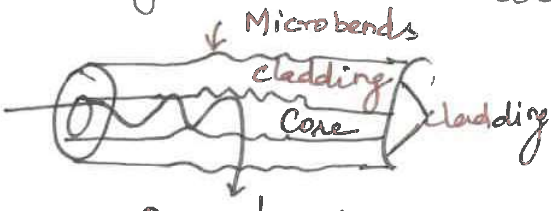
The total number of modes that can be supported by a curved fiber is less than in a straight fiber.

$$M_{eff} = M_{\infty}\left\{1 - \frac{\alpha+2}{2\alpha\Delta}\left[\frac{2a}{R} + \left(\frac{3}{2n_2kR}\right)^{2/3}\right]\right\}$$

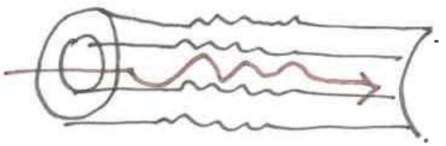


Microbending Loss:

Microscopic bends of the fiber axis that can arise when the fibers are incorporated into cables. This power is dissipated through the microbended fiber, because of the repetitive coupling of energy between guided modes & the leaky or radiation modes in the fiber.



Power loss from higher order modes



Power coupling to higher order modes.

Core and Cladding Loss:

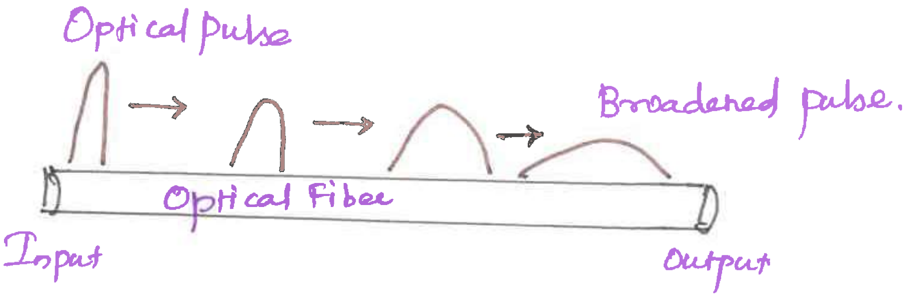
Core and cladding have different refractive indices because they are having different composition.

$$\alpha_{vm} = \alpha_1 + (\alpha_2 - \alpha_1)\frac{P_{clad}}{P}$$

Dispersion in Optical Fibers:

A phenomenon in which the velocity of propagation of any electromagnetic wave is wavelength dependent. In communication, dispersion is used to describe any process by which any electromagnetic signal propagating in a physical medium is degraded because the various wave characteristics of the signal have different propagation velocities within the physical medium.

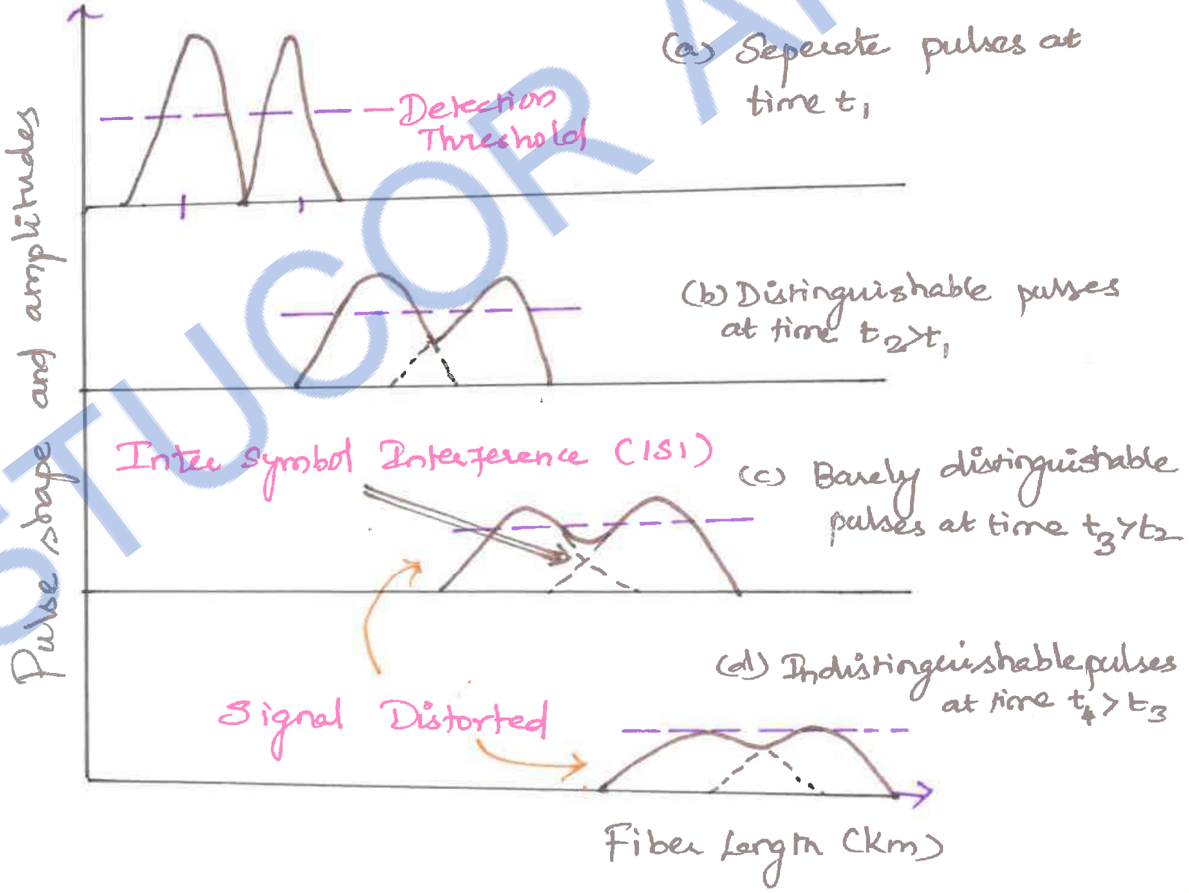
Fiber dispersion results in optical pulse broadening and hence digital signal degradation.



Dispersion Mechanisms

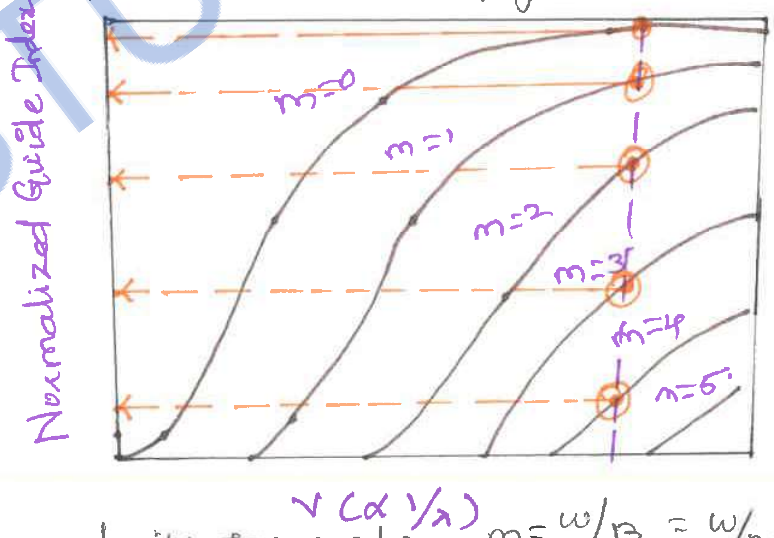
1. Modal (Intermodal) dispersion
2. chromatic dispersion (CD)
3. Polarization mode dispersion (PMD)

Dispersion caused due to pulse broadening is because the increasing number of errors may be encountered on the digital optical channel as the ISI becomes more pronounced.



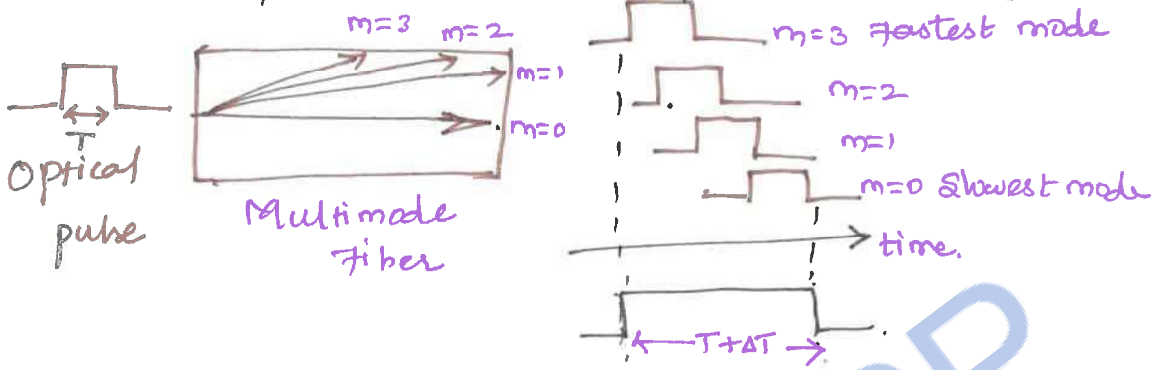
Modal Dispersion :

- When numerous waveguide modes are propagating, they all travel with different net velocities with respect to the waveguide axis.
- An input waveform distorts during propogation because its energy is distributed among several modes, each traveling at a different speed. parts of the wave arrive at the output before other parts, spreading out the waveform. This is thus known as multimode (modal) dispersion.
- Multimode dispersion does not depend on the source line width (even a single wave length can be simultaneously carried by multiple modes in a waveguide).
- Multimode dispersion would not occur if the waveguide allows only one mode to propagate.



Phase velocity for mode $m = \omega/\beta_m = \omega/n_{eff}(m)k_0$

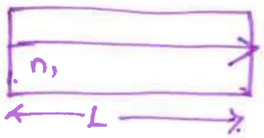
Modal dispersion results in pulse broadening



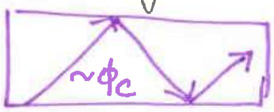
When different modes arrived at the receiver with different delays causes pulse broadening in multimodal fiber.

A zero-order mode traveling near the waveguide axis needs time:

$$t_0 = L/V_{m=0} \approx Ln_1/c \quad (V_{m=0} \approx c/n_1)$$



The highest-order mode traveling near the critical angle needs time: $t_m = L/V_m \approx Ln_2/c \quad (V_m \approx c/n_2)$



The pulse broadening due to modal dispersion

$$\Delta T = t_0 - t_m = (L/c)(n_1 - n_2)$$
$$\approx \left(L/2cn_1\right) NA^2.$$

Information Capacity Determination:

A measure of the information capacity of an optical waveguide is usually specified by the bandwidth-distance product in MHz·km.

The information carrying capacity can be determined by examining the deformation of short light pulses propagating along the fiber.

"Bit rate distance product" (limited by modal dispersion)

$$BL < 2c\, n_{core} / NA^2.$$

This condition provides a rough estimate of a fundamental limitation of step-index multimode fibers. The smaller is the NA, the larger is the bit-rate distance product.

Ex: If a system is capable of transmitting 10Mb/s over a distance of 1km, it is said to have a bit rate distance product of 10Mbps-km. This may be suitable for some Local-area networks (LANs)

Single mode fibers eliminate modal dispersion

The main advantage of single mode fiber is to propagate only one mode so that modal dispersion is absent. However pulse broadening does not disappear altogether. The group velocity associated with the fundamental mode is frequency dependent within the pulse spectral line width because of chromatic dispersion.

Group delay & Group velocity :

As the signal propogates along the fiber, each spectral component can be assumed to travel independently and to undergo a time delay or group delay per unit length in the direction of propagation is given by

$$\boxed{\frac{\tau_g}{L} = \frac{1}{V_g} = \frac{1}{c}\frac{d\beta}{dk} = -\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda}} \quad \text{—} ①$$

L – distance travelled by the pulse

β – Propagation Constant along the fiber axis

$k - \frac{2\pi}{\lambda}$

For a transmission system operation the most important & useful type of velocity is the group velocity, vg. This is the actual velocity which the signal information & energy is traveling down the fiber. It is always less than the speed of light in the medium. The observable delay experiences by the optical signal waveform and energy, when traveling a length of l along the fiber is commonly refered as group delay.

Group velocity is

$$\boxed{V_g = c\left(\frac{d\beta}{dk}\right)^{-1} = \left(\frac{\partial\beta}{\partial\omega}\right)^{-1}} \quad \text{—} ②$$

For spectral components which are $\delta\lambda$ apart and which lie $\delta\lambda/2$ above and below a central wave length λ_0, the total delay difference $\delta\tau$ over a distance L is

from ① ⇒

$$\delta\tau = \frac{d\tau_g}{d\lambda}\delta\lambda$$

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

In terms of angular frequency

$$\delta\tau = \frac{d\tau_g}{d\omega}\delta\omega$$

$$\delta\tau = \frac{d}{d\omega}\left(\frac{L}{V_g}\right)\delta\omega$$

$$\delta\tau = L\left(\frac{d^2\beta}{d\omega^2}\right)\delta\omega \qquad \left[\because \beta_2 = \frac{d^2\beta}{d\omega^2}\right] \quad — \text{④}$$

pulse spreading is approximated by rms pulse width

$$\sigma_g = \left|\frac{d\tau_g}{d\lambda}\right|\sigma_\lambda = \frac{L\sigma_\lambda}{2\pi c}\left|2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right|$$

The modal dispersion parameter

$$\boxed{D = \frac{1}{L}\frac{d\tau_g}{d\lambda} = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right) = \frac{-2\pi c}{\lambda^2}\beta_2}$$

Material Dispersion:

The refractive index of the material varies as a function of wavelength $n(\lambda)$.

The material-induced dispersion of the plane wave propagation in homogeneous medium of refractive index n:

$$\tau_{mat} = L\frac{d\beta}{d\omega} = \frac{-\lambda^2}{2\pi c} L \frac{d\beta}{d\lambda}$$

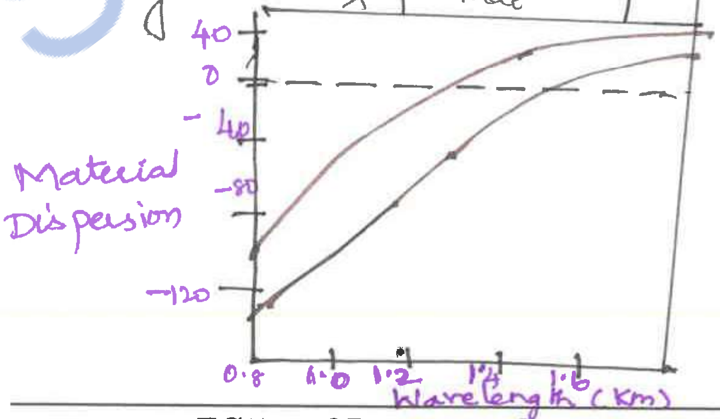
$$= \frac{-\lambda^2}{2\pi c} L \frac{d}{d\lambda}\left[\frac{2\pi}{\lambda} n(\lambda)\right]$$

$$\tau_{mat} = \frac{L}{c}\left(n - \lambda\frac{dn}{d\lambda}\right)$$

The pulse spread due to material dispersion is therefore

$$\sigma_g \approx \left|\frac{d\tau_{mat}}{d\lambda}\right|\sigma_\lambda = \frac{L\sigma_\lambda}{c}\left|\lambda\frac{d^2n}{d\lambda^2}\right|$$

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



Wave guide dispersion :

Waveguide dispersion is due to the dependency of the group velocity of the fundamental mode as well as other modes on the V number. In order to calculate waveguide dispersion, we consider that n is not dependent on wavelength.

Defining the normalized propagation constant b as;

$$b = \frac{\beta^2/k^2 - n_2^2}{n_1^2 - n_2^2} \approx \frac{\beta/k - n_2}{n_1 - n_2}$$

Solving for propagation constant

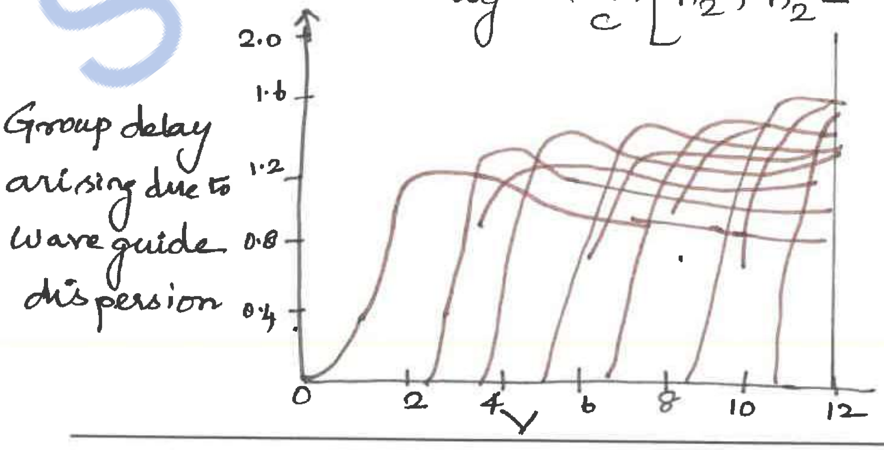
$$\beta \approx n_2 k (1 + b\Delta)$$

Using V number. $V = ka(n_1^2 - n_2^2)^{1/2}$

$$\approx k a n_2 \sqrt{2\Delta}$$

Delay time due to waveguide dispersion can then be expressed as

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



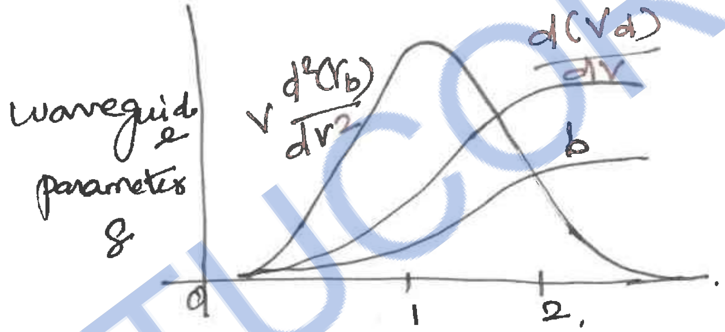
Waveguide dispersion in single mode fibers.

For single mode fibers, wave guide dispersion is in the same order of material dispersion. The pulse spread can be well approximated as.

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

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

$$= \frac{n_2 L \Delta \sigma_\lambda}{c\lambda} V \frac{d^2(Vb)}{dV^2}$$



Group-Velocity Dispersion (GVD):

Consider a light pulse propagates in a dispersive medium of length L

A specific spectral component at the frequency ω (or wave length λ) would arrive at the output end of length L after a time delay

$$T = L/V_g$$

If $\Delta\lambda$ is the spectral width of an optical pulse, the extent of pulse broadening for a material of length L is given by

$$\Delta T = (dT/d\lambda)\Delta\lambda = [d(L/v_g)/d\lambda]\Delta\lambda$$

$$= L[d(1/v_g)/d\lambda]\Delta\lambda$$

Hence the pulse broadening due to differential time delay

$$\Delta T = LD\Delta\lambda$$

where $D = d(1/v_g)/d\lambda$ is called the dispersion parameter and is expressed in units of ps/km-nm.

$$D = d(1/v_g)/d\lambda = c^{-1} dn_g/d\lambda$$

$$= c^{-1} d[n-\lambda(dn/d\lambda)]/d\lambda$$

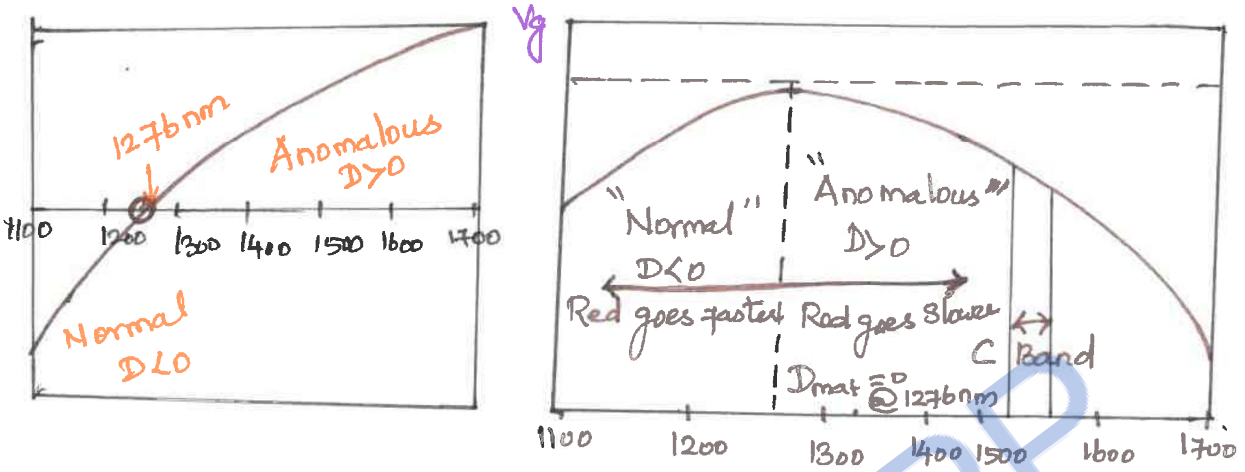
$$= -c^{-1}\lambda\, d^2n/d\lambda^2$$

Zero-dispersion wavelength:

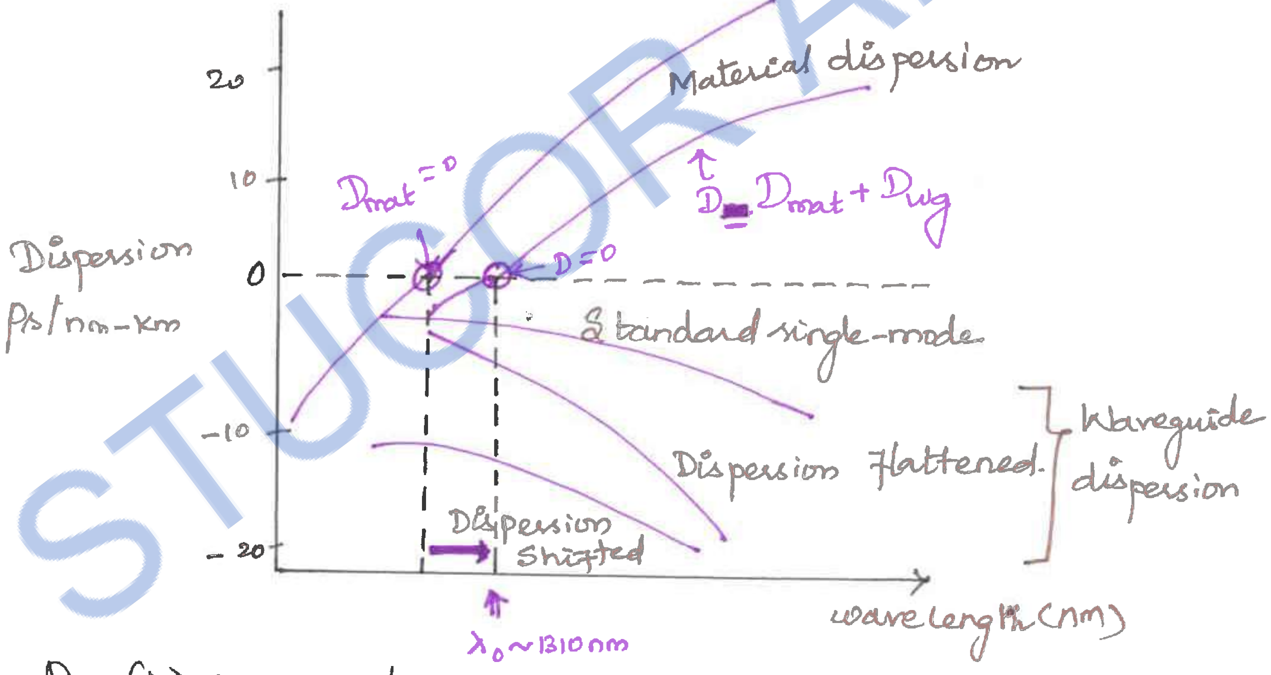
Material dispersion $D_{mat} = 0$ at $\lambda \sim 1276$ nm for fused silica. This λ is referred to as the zero-dispersion wavelength λ_{ZD}. Chromatic or material dispersion $D(\lambda)$ can be zero; or

Negative ⇒ Longer wavelengths travel faster than shorter wavelengths

Positive ⇒ Shorter wavelengths travel faster than longer wavelengths



Variation of Vg with wavelength for fused silica



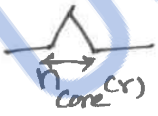
$D_{wg}(\lambda)$ compensate some of the $D_{mat}(\lambda)$ and shifts the λ_{ZD} from about 1276 nm to a longer wavelength of about 1310 nm.

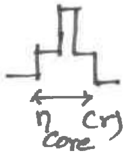
Dispersion Compensation:

1. As the waveguide contribution D_{wg} depends on the fiber parameters such as core radius a and the index difference Δ, it is possible to design the fiber such that λ_{ZD} is shifted in to the neighborhood of 1.55 μm. Such fibers are called "dispersion shifted fibers."

2. It is also possible to tailor the waveguide contribution such that the total dispersion D is relatively small over a wide wavelength range extending from 1.3 to 1.6 μm. Such fibers are called "dispersion-flattened fiber".

The design of dispersion-modified fibers often involves the use of multiple cladding layers and a tailoring of the refractive index profile.





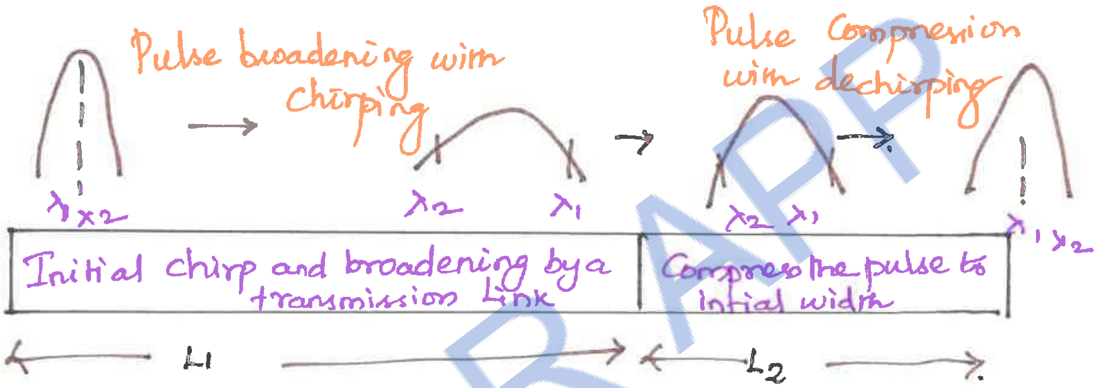
Chromatic dispersion compensation:

chromatic dispersion is time independent in a passive optical link which will allow compensation along the entire fiber span. There are two basic techniques

(i) Dispersion Compensating Fiber (DCF)

(ii) Dispersion Compensating fiber grating

DCF: The basic idea of DCF is, the positive dispersion in a conventional fiber can be compensated for by inserting a fiber with negative dispersion. This is achieved by using span of fiber to compress an initially chirped pulse.



Dispersion Compensated Channel: $D_2L_2 = -D_1L_1$

Typically, only one wavelength can be compensated exactly.

Better chromatic dispersion compensation requires both dispersion and dispersion slope compensation.

For slope compensation $L_2\, dD_2/d\lambda = -L_1\, dD_1/d\lambda$

Dispersion and slope compensation $\dfrac{D_2}{dD_2/d\lambda} = \dfrac{D_1}{dD_1/d\lambda}$

disadvantages of using DCF:

- * Added loss associated with increased fiber span
- * Non linear effects may degrade the signal over the long length of fiber which requires amplifier stage.

Intermodal dispersion:

Propagation delay differences between the modes with in a multimode fiber cause pulse broadening. this dispersion is called as intermodal dispersion. The delay difference between these two rays when travelling in the fiber core allows estimation of the pulse broadening resulting from inter modal dispersion within the fiber.

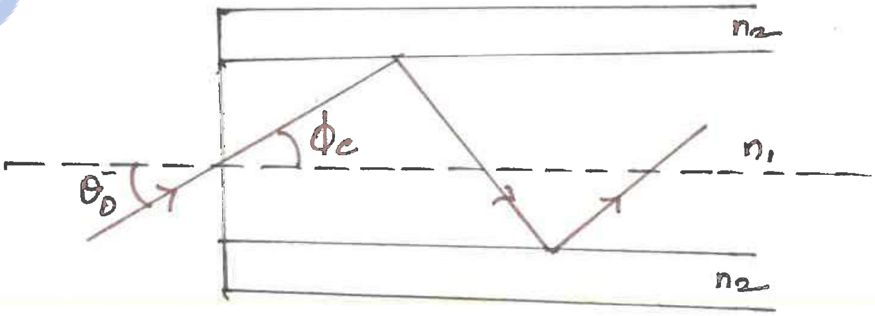
$$T_{min} = \frac{\text{distance}}{\text{Velocity}} = \frac{Ln_1}{c}$$

$$T_{max} = \frac{L/\cos\theta}{dn_1} = \frac{c/n_1}{c\cos\theta}$$

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

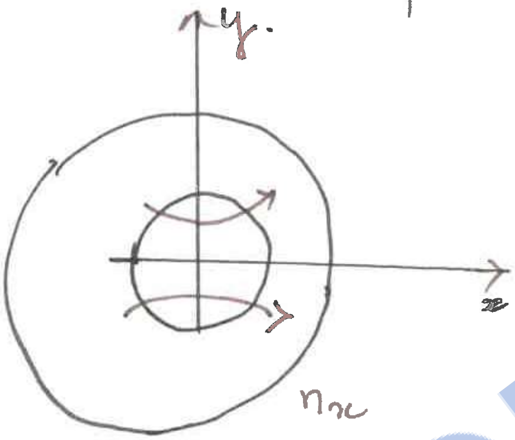
$$\delta T_g = T_{max} - T_{min} = \frac{Ln_1^2 - Ln_1}{cn_2 - c} = \frac{Ln_1^2}{cn_2} \cdot \left(\frac{n_1 - n_2}{n}\right) \approx \frac{Ln_1^2\Delta}{cn_2}$$

$$\delta T_g = \frac{Ln_1\Delta}{c} \;;\; NA = n_1\sqrt{2\Delta} \;;\; \Delta = \frac{NA^2}{2n_1^2}$$

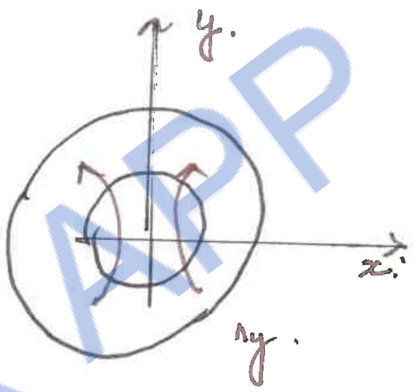


Polarization Mode Dispersion (PMD):

In a single-mode optical fiber, the optical signal is carried by the linearly polarized "fundamental mode" LP_{01}, which has two polarization components that are orthogonal.

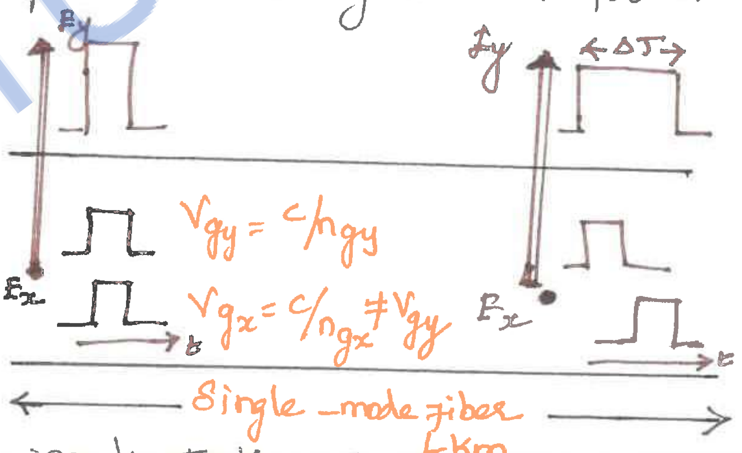


Horizontal mode



vertical mode

In a real fiber (i.e., $n_{gx} \neq n_{gy}$) the two orthogonal polarization modes propagate at different group velocities, resulting in pulse broadening is called Polarization mode dispersion.



Pulse broadening due to the orthogonal polarization modes

(The time delay between the two polarization modes components is characterized as differential group delay (DGD)).

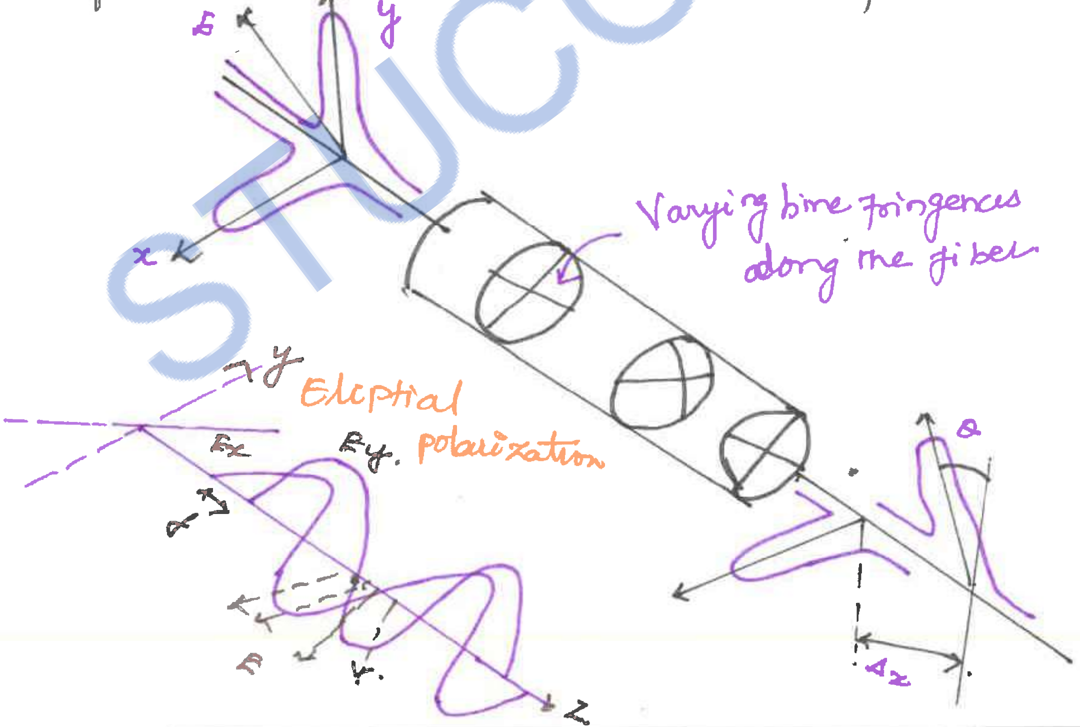
- * Polarization varies along the fiber length
- * PMD is a statiscal process

The refractive index difference in fiber is known as birefringence."

$$B = n_x - n_y.$$

assuming $n_x > n_y \Rightarrow y$ is the fast axis, x is the slow axis

B varies randomly because of thermal and mechanical stresses over time (due to randomly varying environmental factors in terrestrial, arial and buried fiber cables).



The polarization state of light propagating in fibers with randomly varying birefringence will generally be elliptical and would quickly reach a state of arbitrary polarization.

* However the final polarization state is not of concern for most lightwave systems as photodetectors are insensitive to the state of polarization.

* A simple model of PMD divides the fiber into a large number of segments. Both the magnitude of Birefringence B and the orientation of the principal axes remain constant in each section but changes randomly from section to section.

PMD pulse broadening $\Delta T_{PMD} = D_{PMD} \sqrt{L}$

D_{PMD} is the PMD parameter (coefficient) measured in $ps/\sqrt{km}$

$\sqrt{L}$ modes the "random" nature

D_{PMD} does not depend on wavelength

* PMD is relatively small compared with chromatic dispersion. But when one operates at zero dispersion wavelength with narrow spectral width, PMD can become a significant component of the total dispersion.

* There is no simple way to eliminate PMD completely

* The fiber birefringence is enhanced in single-mode polarization persevering fibers.

Signal Distortion in Single mode fiber

Waveguide can of same order of magnitude as material dispersion

$$\sigma_{wg} = \sigma_\lambda \frac{d\tau_{wg}}{d\lambda} = \sigma_\lambda L D_{wg}(\lambda)$$

$$= \frac{-V}{\lambda} \sigma_\lambda \frac{d\tau_{wg}}{dV}$$

$$= -\frac{n_2 L \Delta \sigma_\lambda}{c\lambda} V \frac{d^2(Vb)}{dV^2}$$

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

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

$$\frac{\sigma_{wg}}{L} = \frac{-0.003\sigma_\lambda}{c\lambda}.$$

$$\frac{\sigma_{mat}}{L} = \frac{-0.02\sigma_\lambda}{c\lambda}.$$

It is observed that

* Minimum distortion at wavelength about 1300nm for single mode silica fiber

* Minimum attenuation is at 1550 nm for Single mode silical fiber.

Shifting the zero dispersion to longer wavelength for min. attenuation and dispersion by modifying waveguide dispersion by changing from a simple step-index core profile to more complicated profiles.

Dispersion Optimization of Single Mode Fiber:

The are four major categories of optimization

(i) 1300 nm optimized single mode step-fibers: matched cladding (mode diameter 9.6 μm) and depressed cladding (mode diameter 9 μm)

(ii) Dispersion shifted fibers

(iii) Dispersion-flattened fibers

(iv) large-effective area (LEA) fibers (less non linearities for fiber optical amplifier applications, effective cross section areas are typically greater than 100 μm^2)

Refractive-Index (RI) profiles of single mode fiber

To achieve maximum transmission distance of a high capacity link, the dispersion null should be at the wavelength of minimum attenuation. To achieve this one can adjust the basic fiber parameters to shift the zero dispersion minimum to longer wavelengths.

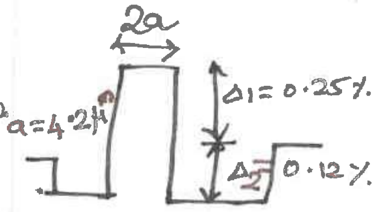
Matched cladding:

- * Uniform RI throughout cladding
- * MFD 9.5 μm.
- * Core to cladding difference 0.37%.

Matched cladding

Depressed cladding:

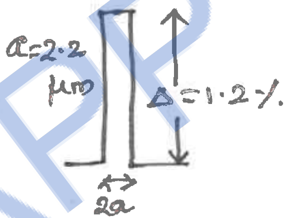
- * Cladding portion next to the core has a lower index than outer cladding region.
- * MFD is 9 μm
- * Positive & negative index differences are 0.25 & 0.12%.



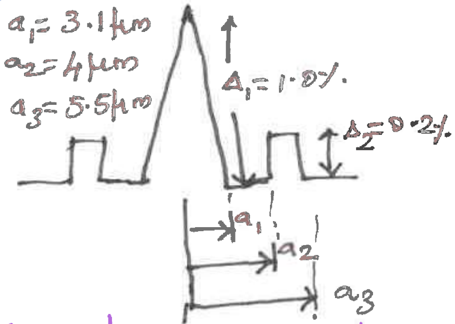
Depressed cladding

Dispersion Shifted Fiber:

By creating a fiber with a larger negative waveguide dispersion and assuming the same values for material dispersion as in a standard single mode fiber, the addition of waveguide and material dispersion can then shift the zero dispersion point to longer wavelengths. This kind of fibers called as dispersion shifted fibers.



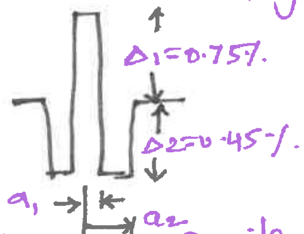
Step -Index



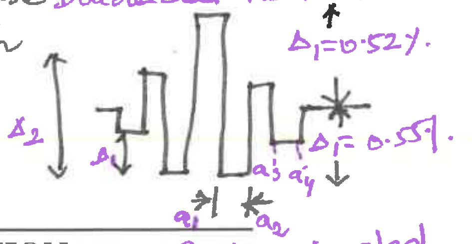
Triangular with annular ring

Dispersion flattening fiber:

- * To reduce the fiber dispersion by spreading the dispersion minimum out over a wide range
- * Dispersion flattened fibers are more complex to design than dispersion shifted fibers, because dispersion must be considered over a much broader range of wavelengths.
- * They offer wide spread of wavelengths.



Double clad RI profile

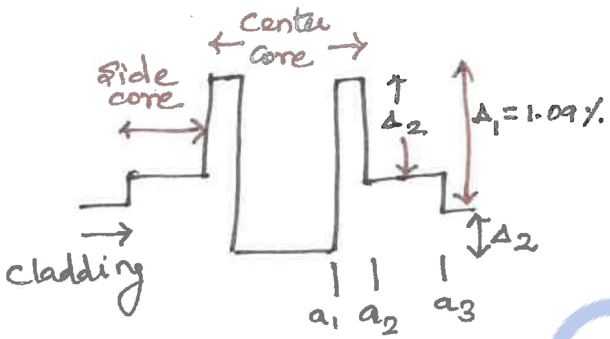


Quadruple clad RI profile

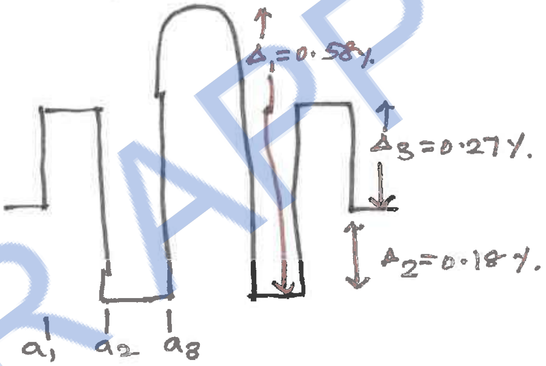
Large Effective Area (LEA) fibers.

* The larger core areas is the need to reduce the effects of fiber non linearities, which limits system capacities.

* The standard single-mode fibers have effective core areas about 55 μm^2, these profiles yield values greater than 100 μm^2.



Large area dispersion shifted



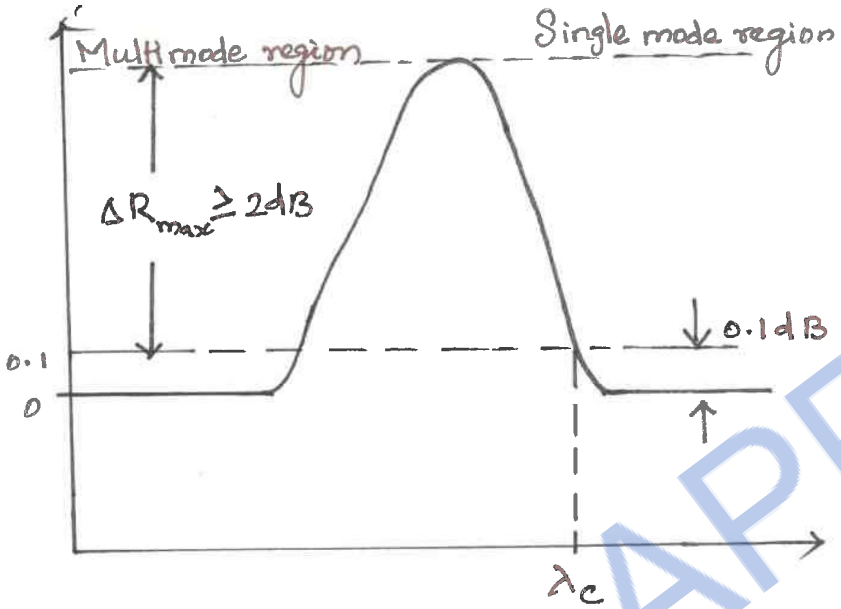
Large area dispersion flattened

Cutoff wavelength:

The cutoff wavelength of any mode is defined as the maximum wavelength at which that mode propagates. It is the value of λ that corresponds to V_c for the mode concerns. For each LP mode, the two parameters are related

$$\lambda_{cth} = \frac{2\pi a}{V_c(lm)} (n_1^2 - n_2^2)^{1/2}$$

For a fiber to operate single mode, the operating wavelength must be longer than the cutoff wavelength for the LP_{11} mode. This is an important specification for a single mode fiber, mentioned as λ_{cth}.



Dispersion Calculations:

Total dispersion in single-mode fibers consists mainly of material and waveguide dispersion

The resultant chromatic or material dispersion is

$$D(\lambda) = \frac{d\tau}{d\lambda} \qquad \tau - \text{Group delay}$$

The broadening of ~~a~~ an optical pulse over a fiber length L is

$$\sigma = D(\lambda) L \sigma_\lambda \qquad \sigma_\lambda - \text{Half power spectral width}$$

Chromatic dispersion is

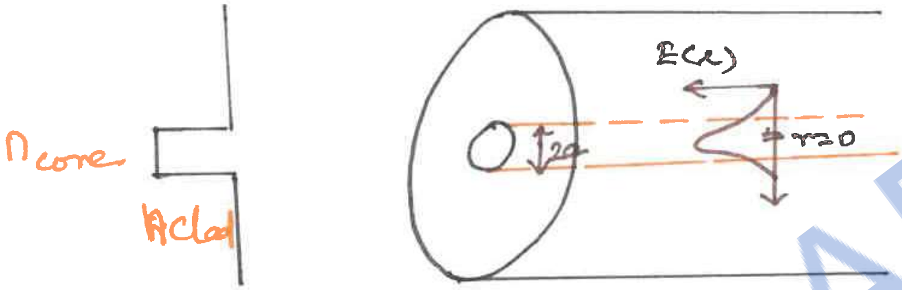
$$D_{ch}(\lambda) \approx |D_{mat} + D_{wg}|$$

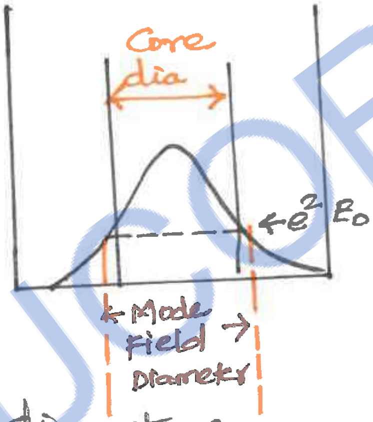
$$\sigma_{ch} = D_{ch}(\lambda) L \sigma_\lambda$$

The total dispersion is the sum of chromatic, polarization dispersion and other dispersion types and the total rms pulse spreading can be given as $D_{total} \approx |D_{ch} + D_{pol} + \dots|$ $\sigma_{total} = D_{total} L \sigma_\lambda$

Mode-Field Diameter (MFD) = $2w_0$ rather than core diameter

MFD characterizes the functional properties of single-mode fibers. Here w_0 is spotsize.





For SMF

9.2 μm at 1310 nm

10.4 μm at 1550 nm.

Core diameter : 8.2 μm

MFD > Core diameter

Mode-field diameter (MFD) can be determined from the mode field distribution of the fundamental fiber mode and is a function of the optical source wavelength. The MFD is used to predict fiber splice loss, bending loss, cutoff wavelength and wave guide dispersion

To find MFD:

(i) A measure of far-field distribution $E^2(r)$

(ii) Calculate MFD by peter mann II equation

$$MFD = 2w_0 = 2\left[\frac{2\int_0^{\infty} E^2(r)\, r^3\, dr}{\int_0^{\infty} E^2(r)\, r\, dr}\right]^{1/2}$$

Splicing loss due to MFD mismatch between two different SMF's.