Module 1

Optical Fiber Communications

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* phase & group velocity
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* Fiber Materials
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Historical Development

In 800BC, Greek used fire & smoke signals for sending information during war. In second century, signalling lamps were invented as a part of optical communication methods.

In 1880 Alexander Graham Bell reported the transmission of speech using light beam over a distance of 200m. Further investigations in OFC domain limited the application to mobile due to lack of perfect light sources, detectors & atmospheric disturbances such as rain, snow, fog etc.

Optical communication offers an increase in the Bandwidth over VHF, UHF & MW communications. In 1960, LASER (Light Amplification by stimulated Emission of Radiation) was invented by Maiman. LASER was a powerful coherent light source & provide suitable optical carrier.

Scientists Kao, Hockham & Werts proposed transmission of optical signal through optical dielectric waveguides but these waveguides exhibited very high attenuation around 1000dB/km & of coaxial cable was 10dB/km. In span of 10years, optical fiber loss was reduced to less than 5dB/km

In 1970-80, advancement in semiconductor technology increased the lifetime of LASER 1000hrs to 7000hrs. Semiconductor optical sources & detectors compatible in size with optical fiber were designed & Fabricated

In 1980, optics systems operated at 90Mbps. Today systems operate at 10Gbps & Beyond. with new technologies such as Dense wavelength-division multiplexing (DWDM) & erbium-doped fiber amplifier (EDFA), data rates to beyond terabit per second over distances in excess of 100km is achieved.

Generations of optical communication:

* First Generation (1G):
  - → 1G fiber optic communication system was developed 1975.
  - → Operating wavelength - 800nm
  - → Used GaAs semiconductor laser as source & photo detector.
  - → Bit rate - 30-140Mbps
  - → Repeater length - 40km

* Second Generation (2G)

→ Was developed in early 1980's
→ operating wavelength -1300nm
→ Used GaAsP semiconductor lasers
→ limited to single mode fiber.
→ Repeater length 90km

* Third Generation (3G)

→ Was Developed at wavelength of 1550nm
→ Losses of about 0.2dB/km
→ Bit rate is 10Gb/sec
→ Based on InP/InGaAs Technology

* Fourth Generation

→ Was developed at wavelength of 1450 nm -1620nm
→ Used for optical Amplification & wavelength division multiplexing
→ Bit Rate of 10Tbps
→ Repeaters upto 10000Km

* Fifth Generation:

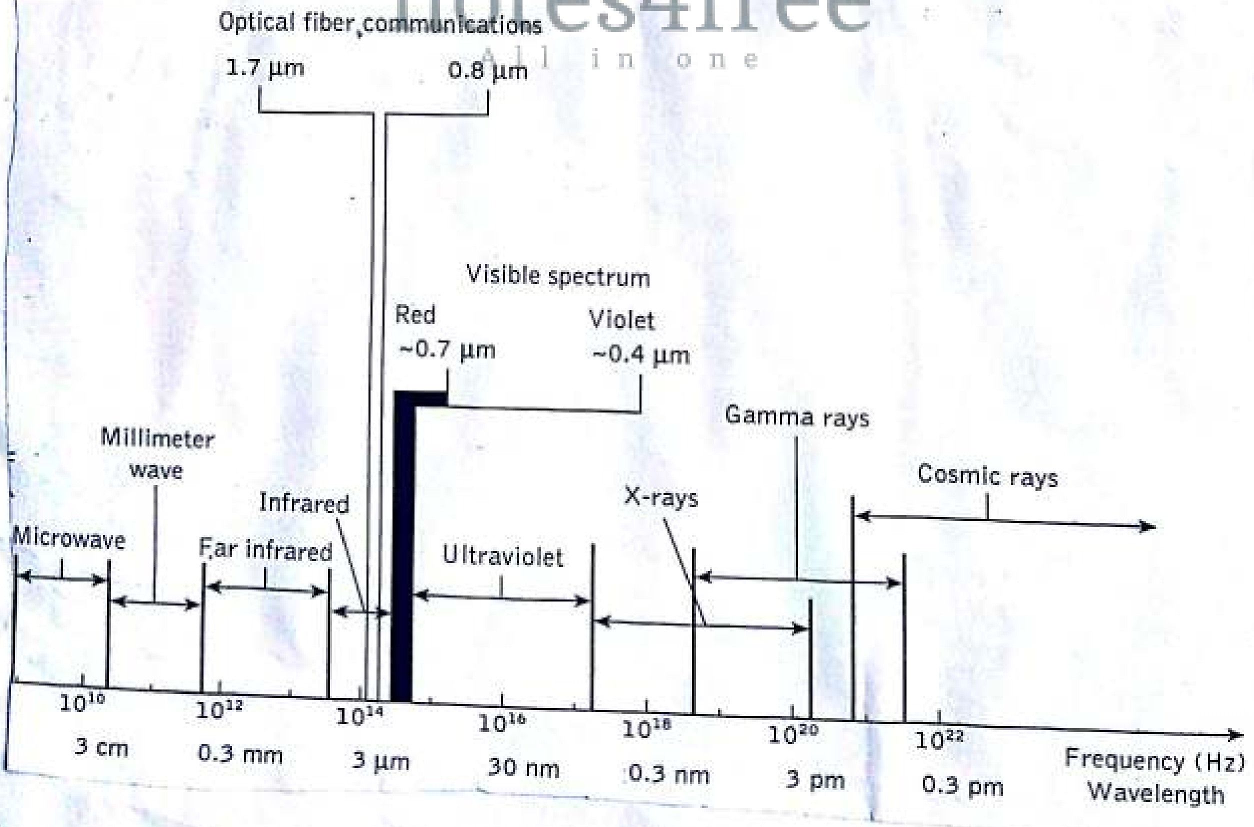
→ $\lambda = 1530 - 1570$
→ 14 Terabits/s.
→ Repeater length = 24000km - 35000Km

Electromagnetic Spectrum:

Radio waves & light waves are electromagnetic in nature. The rate at which they alter in polarity is called their frequency(f) The speed of the electromagnetic wave (v) in free space is $3 \times 10^8 ms^{-1}$

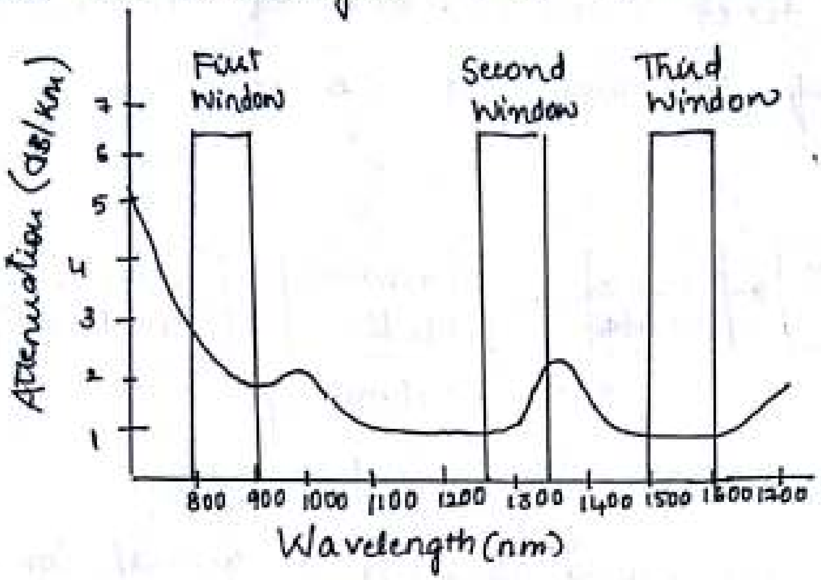
$$\text{Wavelength } (\lambda) = \frac{\text{Speed } (c)}{\text{frequency } (f)}$$

Range of frequencies & wavelengths used for optical fiber communication is shown in electromagnetic spectrum as below.



Optical window:

OFC uses the wavelengths that is near to IR region



The ranges of standard wavelengths used for optical communication at which the fiber operates (with high performance) are called optical windows. & light sources perform their best within one of these windows. Higher wavelengths have lower losses and are used for long distance communications as shown in Above figure (1300nm & 1550nm). The 850nm is still in use because its less expensive & easier to install.

Name	Window Range	operating wavelength
First Window	800nm - 900nm	850nm
Second Window	1260nm - 1360nm	1300nm
Third Window	1500 - 1600nm	1550nm

Table : Transmission window ranges & operating wavelength of optical Fiber

General System

An optical fiber communication system is similar to any type of communication system.

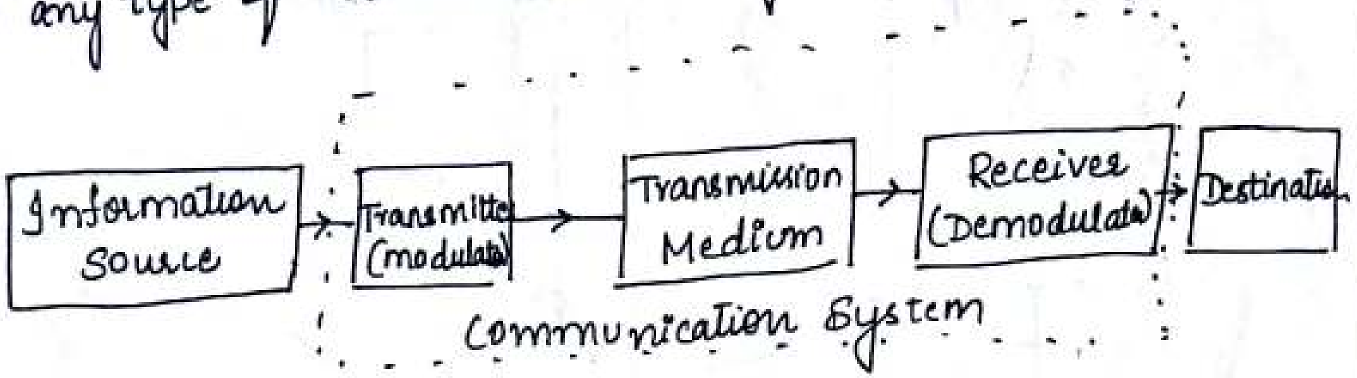


fig a) General Communication System

Fig a) shows the block diagram of general Communication system. The function of the above system is to Convey signal from source over the transmission medium to the destination. Communication system consists of a transmitter comprising electrical & Electronic components which converts the signal into a suitable form for propagation over transmission medium. This is achieved by modulating a carrier. Transmission medium or channel may be a pair of wires or a coaxial cable or a radio link through free space down which the signal is transmitted to reciever, where it is transformed into original Electrical information signal (demodulated) before being passed to destination.

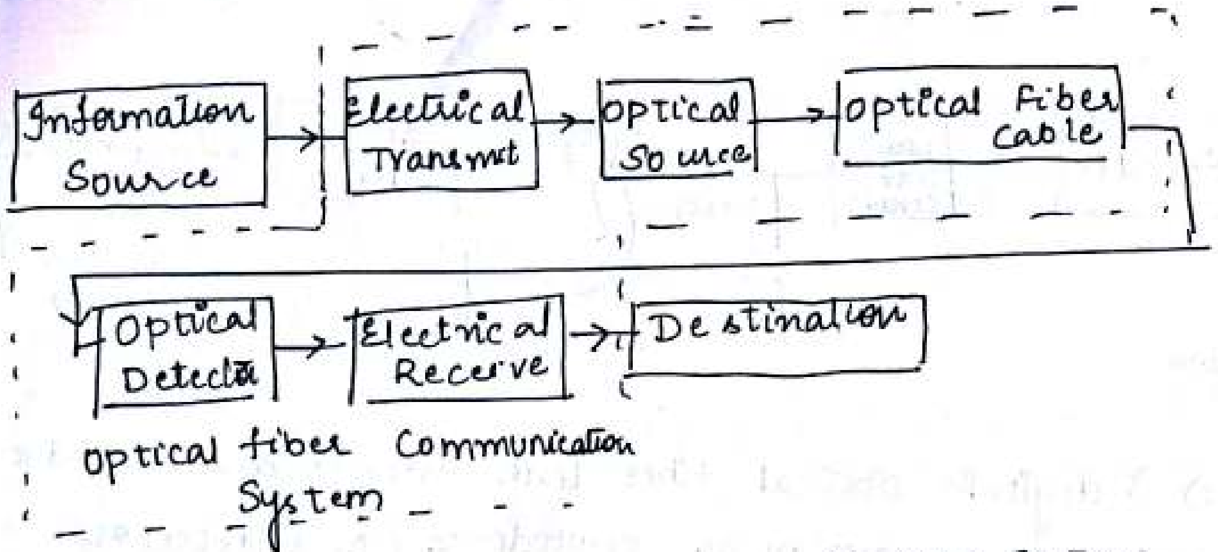


fig b) optical fiber communication system.

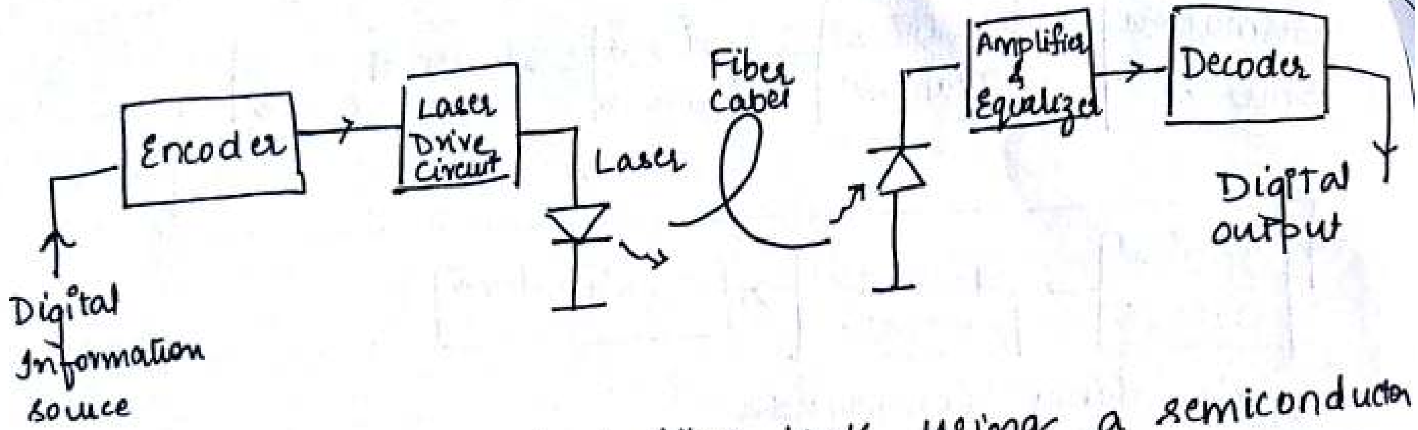
- In optical fiber communication system (as shown in fig b), information source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of the lightwave carrier. optical source can be semiconductor laser or light emitting diode (Electrical - optical Conversion).

* Transmission Medium consists of an optical fiber cable.

* Receiver consists of an optical Detector (photodiode) which drives a Electrical stage & provides demodulation of optical signal & optical-electrical conversion.

* optical carrier may be modulated using either an analog or digital Information signal.

*



fib c) A digital optical fiber link using a semiconductor laser source & an avalanche photodiode (APD) detector.

Fig c) shows a block diagram of digital optical fiber link. Input digital signal from information source is suitably encoded for optical transmission. Laser drive circuit directly modulates the intensity of semiconductor laser with encoded digital signal. Digital optical signal is launched into optical fiber cable. The Avalanche photodiode (APD) detector is followed by a front-end amplifier & equalizer or filter to provide gain as well as linear signal processing & noise bandwidth reduction.

Advantages of optical Fiber communication :

* Enormous potential Bandwidth :

→ 10^{13} to 10^{16} Hz

* Small size & weight

* Electrical Isolation

Optical fibers which are fabricated from glass or plastic polymer are electrical Isolators

* Immunity to cross talk & Interference

Optical fibers form a dielectric waveguide & are free from Electromagnetic interference (EMI)

* Signal security :

Light from fibers do not radiate significantly & provide high degree of signal security

* Low transmission loss

Fibers have been fabricated with losses as low as 0.15dBkm^{-1}

* Ruggedness & Flexibility :

optical fibers are manufactured with very high tensile strength

* System Reliability & ease of maintenance

* potential low cost.

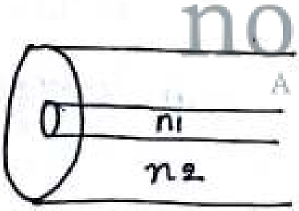
Disadvantage:

- * High Investment cost
- * Difficult to splice
- * Loss of light in fiber due to attenuation & dispersion.

Applications:

- * optical fibers are used as Interconnects
- * Used in Telephone network, cable Television systems (CATV)
- * Optical sensor systems (measure strain, temperature, pressure)
- * Military Applications & Defense.

Structure of optical Fiber



An optical fiber consists of a core, cladding & an outer jacket. Core has an refractive index of n_1 & cladding n_2.

Refractive Index:

$$n = \frac{c}{v} = \frac{\text{Velocity of light in vacuum}}{\text{velocity of light in medium}}$$

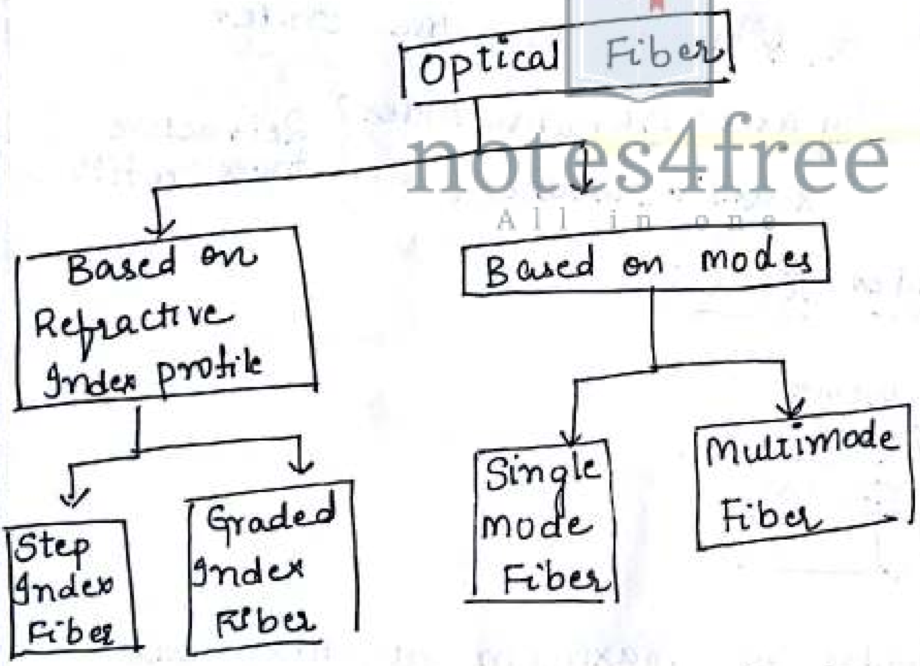
$n = 1 \Rightarrow$ Air
$n = 1.33 \Rightarrow$ Water
$n = 1.5 \Rightarrow$ Glass

Uses of cladding :

Though it does not help in light propagation it is necessary for following reasons :

* Adds Mechanical Strength
* protects core from external Environment
* Restricts light ray to get escaped.

Types of optical Fiber
or
Classification of optical Fiber



Refractive Index profile :

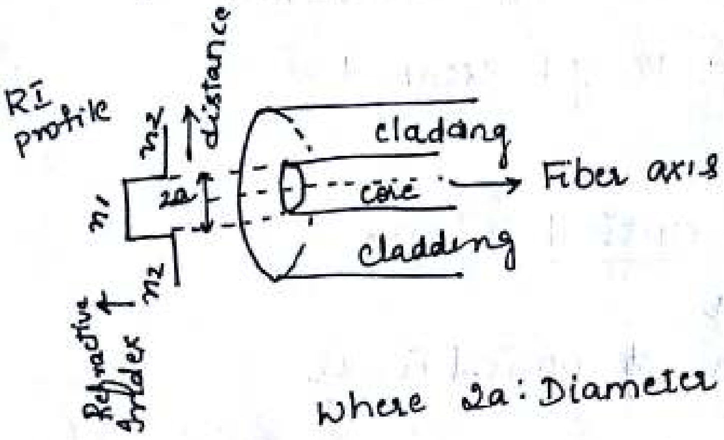
variation of R.I w.r.t distance from the axis of the fiber. $(n_1 > n_2)$ (R.I vs distance)

2 types : Step index
Graded Index

Step Index Fiber :

R·I is uniform, maximum & constant in core & in cladding R·I is minimum. At core cladding interface R·I changes suddenly.

NOTE: RI of core is a function of distance from the fiber axis

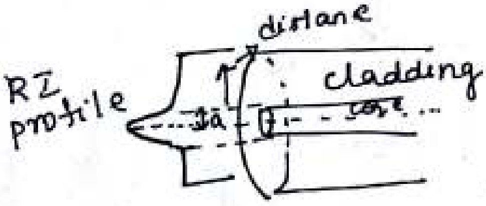


where 2a : Diameter of core

n_1 & n_2 are refractive Index

y axis : Refractive Index } Refractive Index profile
x axis → Distance.

Graded Index Fiber :



Refractive Index is maximum at fiber axis & minimom at core cladding interface.

$$R \cdot I \text{ of core } n(r) = \begin{cases} n_1\left[1-2\Delta\left(r/a\right)^{\alpha}\right]^{1/2} & \text{core } 0 \le r \le a \\ n_1\left[1-2\Delta\right]^{1/2} & r > a \text{ cladding} \end{cases}$$

where Δ → Relative Refractive Index Difference

$\Delta = \frac{n_1 - n_2}{n_1}$, r = distance, measured from center of core along radius, a = core radius

α = Dimensionless parameter that defines shape of refractive index profile

when $\alpha = 1$, the Index profile becomes triangular

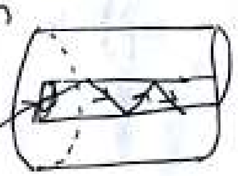
$\alpha = 2$, " " " " parabolic

$\alpha = \infty$, " " " " step index fiber

Fibers Based on no of modes

Single mode fiber or Monomode Fiber

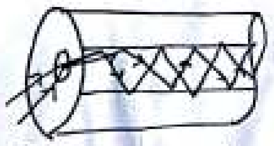
Supports only one mode of propagation



Advantages :
- * No Intermodal Dispersion
- * Higher Bandwidth
- * Easy Fabrication
- * Less manufacturing expense

Disadvantages :
- * Size of core is small, so launching of light into core of fiber is complicated
- * Splicing is difficult
- * Requires high tolerence

Multimode Fiber :



- * Supports more than one mode of propagation
- * Core radius is large

Advantages :

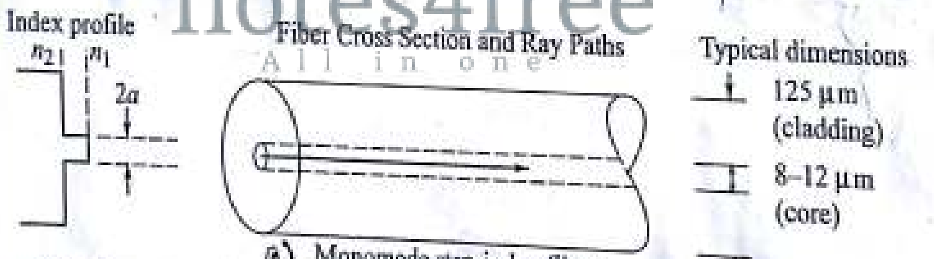
- * Launching of light is easy
- * Splicing is easy
- * Broad source of light can be used

Disadvantage :

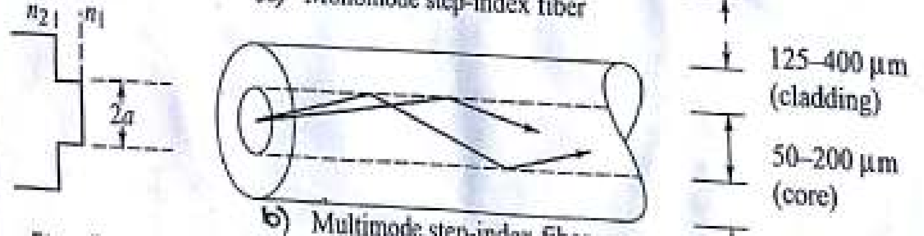
- * Intermodal Dispersion

Fiber Based on RI profile

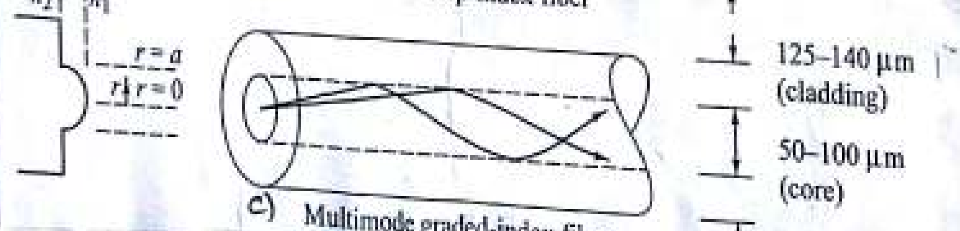
- Step Index
  - Single mode or Monomode Step-Index Fiber
  - Multimode Step-Index Fiber.
- Graded Index
  - Multimode graded Index fiber



a) Monomode step-index fiber



b) Multimode step-index fiber



c) Multimode graded-index fiber

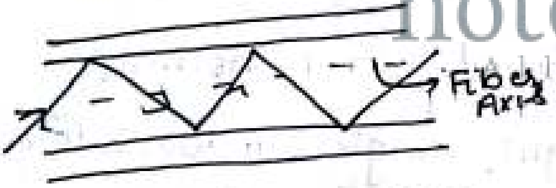
- Single mode/monomode step Index fiber as shown in a) has narrow core & single mode propagation. It is used in submarine cable system

- Multimode Step Index fiber as shown in b) has many mode & used in low Bandwidth Datalinks

- Multimode Graded Index fiber as shown in c) has greater Bandwidth & used for telephone trunk.

Types of Rays :

- Meridional Rays
  - Bound Rays
  - Unbound Rays
- Skew Rays

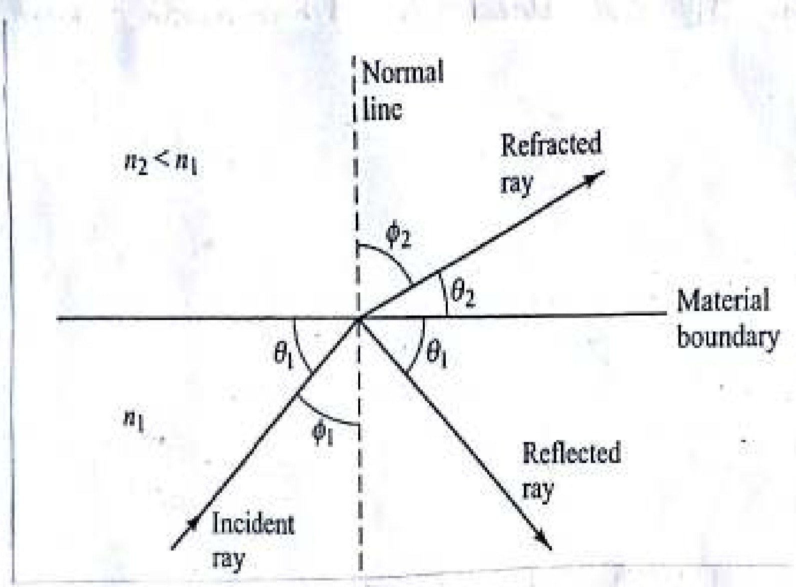


Meridional rays are those rays which are confined to meridional plane of fiber. It passes through fiber axis

Skew rays propagate through core without passing through the fiber axis. It is not confined to single plane

Ray theory or Basic optical Laws.

a) Refractive Index :

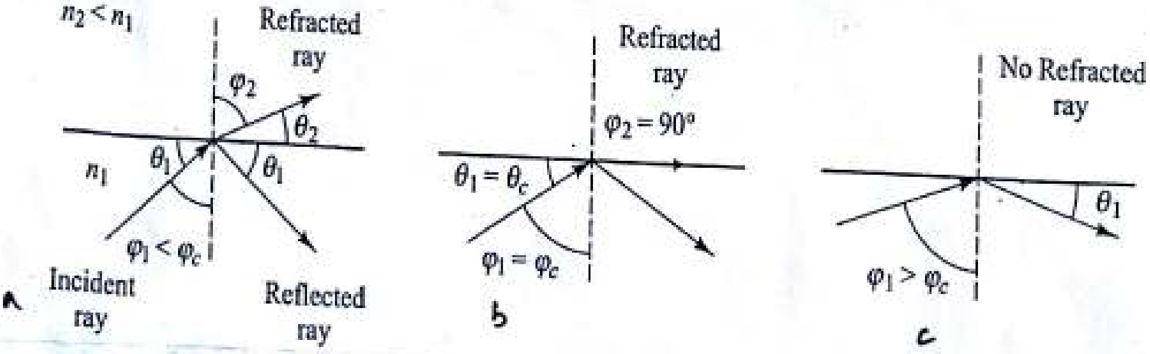


It is defined as ratio of velocity of light in vacum to velocity of light in material

$$n = \frac{c}{v}$$

Angle of rays are measured w.r.t normal This is line drawn at right angle to boundary line b/w two refractive indices. The angles of incoming & outgoing rays are called angle of incidence & refraction respectively

b) Snells Law.



"When a light ray encounters a boundary separating two different media, part of ray is reflected back into first medium & remaining is refracted as it enters second material."

It is shown in fig where $n_2 < n_1$. The relationship at the interface is known as snell's law & is given by $n_1 \sin\phi_1 = n_2 \sin\phi_2$

$n_1 < n_2 \rightarrow$ Bent towards normal

$n_1 > n_2 \rightarrow$ Bent away from normal

Critical Angle:

The Angle of Incidence at which the angle of refraction becomes 90° is called critical angle (fig b)

From snell's law $\phi_1 = \phi_c$, $\phi_2 = 90°$

$$n_1 \sin\phi_c = n_2 \sin 90°$$

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

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

Total Internal Reflection:

If the angle of incidence is beyond (greater) the critical angle, then the entire light ray gets reflected within the denser medium. This is called Total Internal Reflection (TIR) (fig c)

Acceptance cone :

If we rotate acceptance angle around axis of fiber, we get a cone like structure which is called acceptance cone. If cone is large then light can be launched easily into fiber.

The cone of acceptance is the area of light gathering at input side of the optical fiber

Numerical Aperture:

- It is light figure of merit which represents light gathering capacity of Fiber & is a unitless quantity.

$$NA = \sqrt{n_1^2 - n_2^2} = \sin\theta_0$$

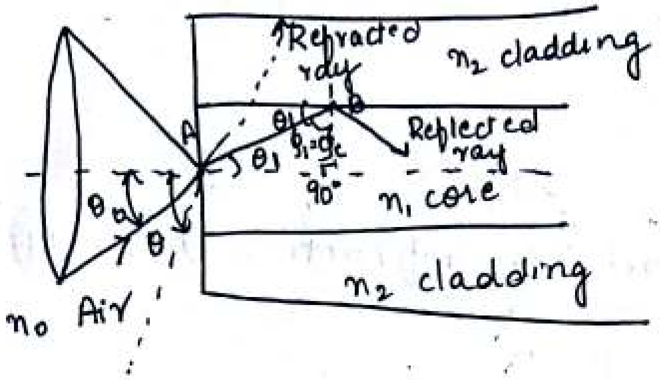
where n_1 & n_2 are refractive Index of core & cladding respectively, θ_0 is Acceptance angle

Acceptance Angle :

The maximum angle at which a light ray be incident upon a fiber core & accept for transmission is called Acceptance angle θ_0

$$\text{Acceptance Angle } \theta_0 = \sin^{-1} NA = \sin^{-1}\sqrt{n_1^2 - n_2^2}$$

Relation b/w Numerical Aperture, refractive Index, Relative refractive Index difference & θ_0 :



When light is outside cone of acceptance then refraction takes place.

When It (ray) is within acceptance cone & if $\phi_1 > \phi_c$ then total internal Reflection takes place.

At point B, $n_1 \sin\phi_1 = n_2 \sin \underbrace{\phi_2}_{90}$

$$n_1 \sin\phi_1 = n_2$$

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

$$n_1 \sin(90-\theta_1) = n_2$$

$$n_1 \cos\theta_1 = n_2$$

$$\cos\theta_1 = \frac{n_2}{n_1} \rightarrow ①$$

At point A, $n_0 \sin\theta_0 = n_1 \sin\theta_1$

$$\sin\theta_0 = \frac{n_1}{n_0} \sin\theta_1$$

$$\sin^2\theta_1 + \cos^2\theta_1 = 1$$

$$\sin\theta_0 = \frac{n_1}{n_0}\sqrt{1-\cos^2\theta_1}$$

$$\sin\theta_1 = \sqrt{1-\cos^2\theta_1}$$

$\sin\theta_0 = \frac{n_1}{n_0}\sqrt{1-\left(\frac{n_2}{n_1}\right)^2}$ from ①

$n_0 = 1$ for air

$\sin\theta_0 = n_1\sqrt{1-\left(\frac{n_2}{n_1}\right)^2}$

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

$\theta_0 = \sin^{-1} NA$

$\Delta = \frac{n_1 - n_2}{n_1} \rightarrow ②$ gives relative refractive Index differenc

$NA = \sqrt{(n_1-n_2)(n_1+n_2)}$

$n_1 \approx n_2$

$= \sqrt{2n_1(n_1-n_2)}$

$\times$ & $\div$ by n_1

$NA = \sqrt{\frac{2n_1(n_1-n_2)n_1}{n_1}} = \sqrt{2n_1^2\Delta}$ from ②

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

Mode Theory

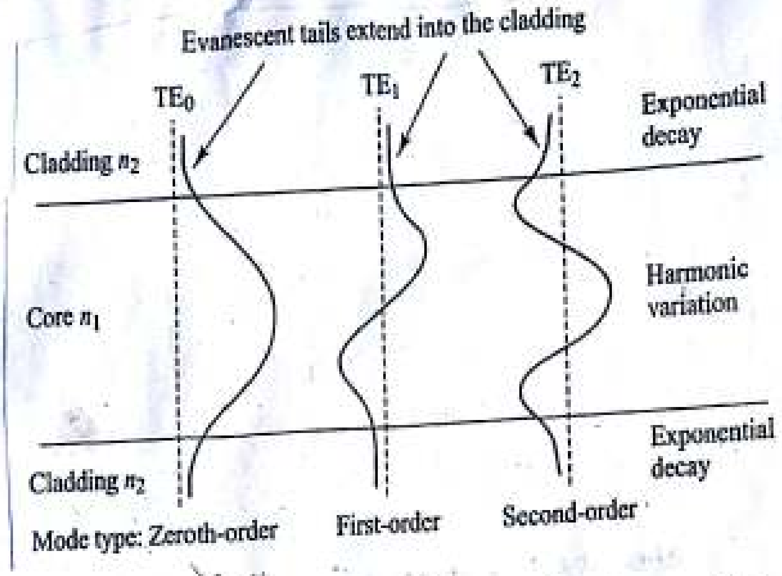


fig: Electric field distribution of lower order guided modes in waveguide.

- Ray analysis gives the concept lightwave through fiber via internal reflection.
- An alternative method of understanding propagation of lightwave through OF is based on electromagnetic theory of maxwell.
- light propagation is described in terms of set of guided electromagnetic field patterns called modes in waveguide.

To understand wave propagation following concepts should be known

a) Order of mode :

No of field becoming zeros across the guide.

Types of modes

- Guided modes
  - Lowest order mode for which field are tightly concentrated at center of core
- Radiation mode
  - When light is launched into fiber at an angle greater than acceptance angle, light will be refracted out of core which is called radiation mode. There will be power loss in core & radiation get trapped in cladding
- Leaky modes
  - Modes that are partially confined to core region & attenuate by continuously radiating power out of core as they propagate along fiber

Mode remains guided as long as propagation factor β satisfies

$$n_2 K < \beta < n_1 K \qquad K = \frac{2\pi}{\lambda}$$

b) V-number :

Important parameter connected to cut-off condition

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

$V \leq 2.405$ → Single mode fiber

$V > 2.405$ → Multimode fiber

a → Radius of core, λ = Operating wavelength

It is also called as normalized frequency & is dimensionless quantity which determines how many modes a fiber can support

Step Index

For multimode fiber no of modes is given by

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

$$= \frac{V^2}{2}$$

V ⇒ Approaches cut off then power leaks in cladding

When V is at cutoff then its radiative mode

When V is far from cut off then fraction of optical power is in cladding (leaky modes)

power for multimode fiber is $\frac{P_{clad}}{P}$ P → Total power of optical signal

For Graded Index fiber, no of modes $M = \left[\frac{\alpha}{\alpha+2}\right]\frac{V^2}{2}$

where α = Index profile & $\alpha = \infty \Rightarrow$ Step Index, $\alpha = 2 \Rightarrow$ parabolic
$\alpha = 1 \Rightarrow$ Triangular

cut off value of Normalized frequency V_c to support single mode in a graded index is given by $V_c = 2.405(1 + 2/\alpha)^{1/2}$

c) Cut off wavelength :

$$\lambda = \frac{2\pi a}{V}\left(\sqrt{n_1^2 - n_2^2}\right)\left[\rightarrow n_1\sqrt{2\Delta} = NA\right]$$

Cut off wavelength is minimum value of wavelength that can be transmitted through optical fiber.

d) propagation constant :

Measure of change undergone by amplitude of wave as it propagates in a given condition

$$\gamma = \frac{\text{Amplitude of light at source}}{\text{Amplitude of light at distance } x}$$

$e^{\gamma x} = A_0/A_x$

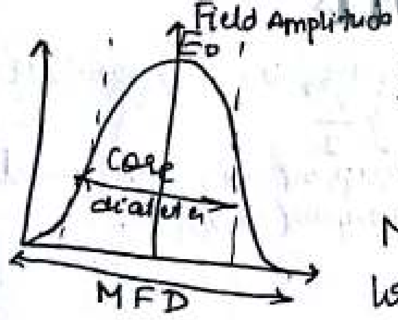
propagation constant $\gamma = \alpha + i\beta \rightarrow$ phase const
$\downarrow$
Attenuation const

Normalized propagation const $\beta = \frac{(n_{ef})^2 - n_2^2}{n_1^2 - n_2^2}$

where $n_{eff} \rightarrow$ Effective RI $= \beta/k_0$

Mode Field Diameter

It describes the signal transmission properties for multimode fibers. It is determined from mode field distribution of fundamental fiber mode. It is a function of optical source wavelength, core radius & RI profile of fiber.



If $V = 2$, then 75% optical power is confined to core.

MFD predicts splice loss, Bending loss, cutoff wavelength & waveguide dispersion

$$MFD = 2W_0 = 2\left[\frac{2\int_0^\infty E^2(r)\, r^3\, dr}{\int_0^\infty E^2(r) \cdot r\, dr}\right]^{1/2}$$

$E(r) \rightarrow$ Field which is gaussian

$E(r) = E_0 \exp[r^2/W_0]^2$

$r \rightarrow$ Radius

Fiber Materials:

Following requirements has to be satisfied when selecting material for optical fiber:

* Must be possible to make long, thin, flexible fibers from the materials.
* Material must be transparent at a particular optical wavelength for the fiber to guide light efficiently
* physically compatible materials that have slightly different refractive indices for core & cladding must be available.

Materials that satisfies above conditions are glass & plastics

* majority of fibers are made of glass consisting silica (SiO_2) or silicate
* plastic fibers are less used because of their high attenuation than glass fiber.
* plastic fibers has high mechanical strength compared to glass fibers

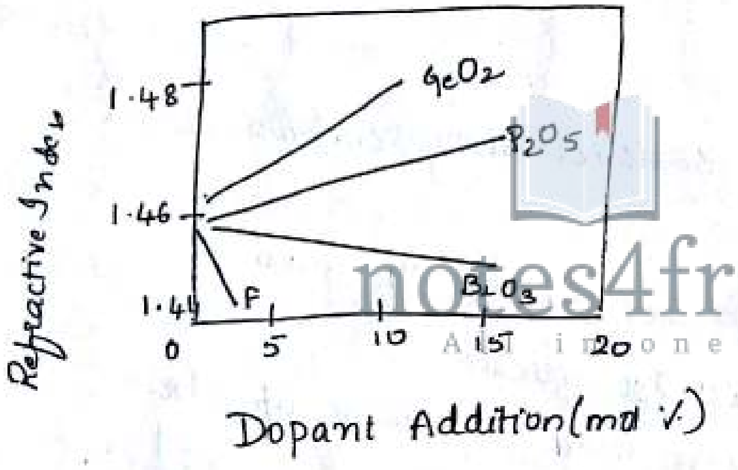
Glass Fibers:

* Glass is made by fusing mixtures of metal oxides, sulfides or selenides. The resulting material is a randomly connected molecular network rather than crystalline material

* Due to random order, glasses do not have well-defined melting points. At very high temperature, glass gradually softens (when heated up from room temperature) & becomes viscous liquid. Melting temperature is commonly used in glass manufacture.

* Largest category of glasses are oxide glasses.

* To produce two similar materials that have slightly different indices of refraction for core & cladding, either fluorine or various oxides (dopants), such as B_2O_3, GeO_2 or P_2O_5 are added to silica.



* As shown in above fig, addition of GeO_2 or P_2O_5 increases R.I & F or B_2O_3 decrease R.I.

Since cladding should have lower RI, combination of dopants are:

1. GeO_2 - SiO_2 core, SiO_2 cladding
2. P_2O_5 - SiO_2 core, SiO_2 cladding
3. SiO_2 - core, B_2O_3 - SiO_2 cladding
4. GeO_2 - B_2O_3 - SiO_2 - core, B_2O_3 - SiO_2 cladding

Active glass fiber :

- Using rare-earth elements (atomic numbers 57-71) into passive glass gives new material with new optical & magnetic properties

* These properties allow material to perform amplification, attenuation & phase retardation on light passing through it.

* Two commonly used materials for fiber lasers are erbium & neodymium.

* Ionic concentration of rare-earth element are low to to avoid clustering effects

*

plastic optical Fiber

* Core of polymer (plastic) optical fibers (POF) is either polymethylmethacrylate or a perfluorinated polymer.

* Fibers are tough & durable

* Compared with silica fibers, core diameters of plastic fibers are 10-20 times larger.

Photonic Crystal Fibers

- It is called as Holey fiber or microstructured fiber.
- Difference between photonic crystal fibers & conventional fibers is that the cladding.
- In some cases, the core region of PCF also contains holes & it runs along the length of the fiber.
- The light guiding characteristics of PCF is determined by size & spacing (known as pitch) of holes in microstructure & R.I of its constituent material.

PCF types

Index Guiding Fiber | Photonic Bandgap Fiber

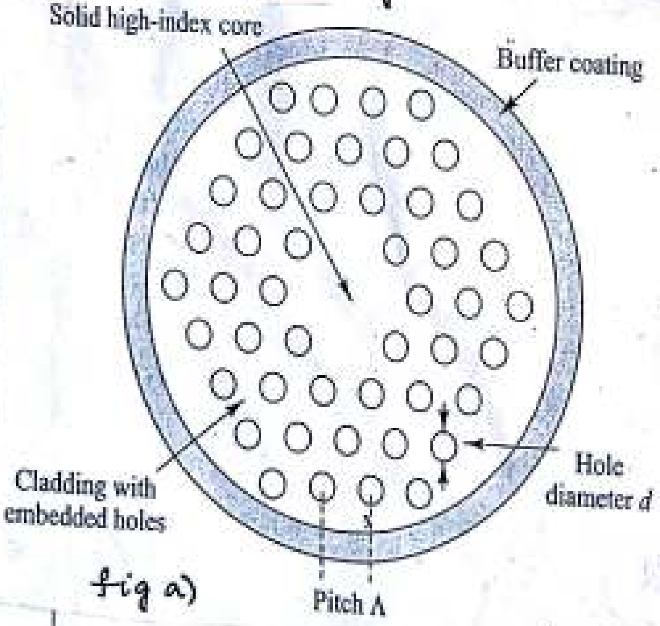


fig a)

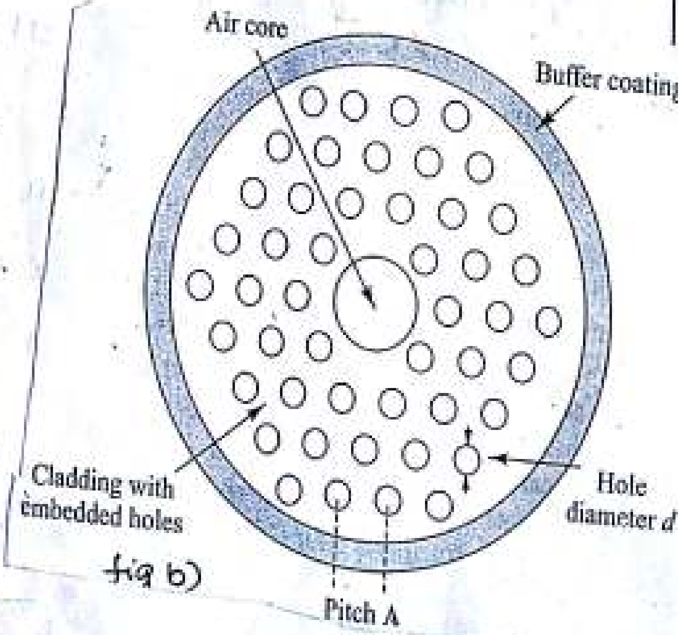


fig b)

Index Guiding Fiber :

* As shown in fig a), fiber has a solid core & cladding contains air holes running along length of the fiber.

* core & cladding are made up of same material Only but holes in cladding has lower the effective R.I of cladding.

* $n_1 = 1.45$ for silica & $n_2 = 1$ for air then microstructure arrangement is equivalent to step index fiber.

* The holes in microstructure arrangement has a diameter 'd' & pitch or distance between two adjacent holes is 'Δ'.

Advantages of pure silica core in Index guiding fiber over conventional are :

→ Very low losses
→ Transmits high optical power
→ High resistance to darkening effect from nuclear radiation.

* It supports single mode operation over 300nm to more than 2000nm wavelength range.

Photonic Bandgap Fiber:

* This fiber has hollow core as shown in fig b). cladding contains air holes running along the length of fiber
* It guides the light by photonic bandgap effect.
* The functional principal is similar to the role of periodic crystalline lattice in a semiconductor
* Hollow core will act as a defect in a photo bandgap structure through which light can propagate.

Fiber optic cables

* In practical Application, fibers need to be incorporated in some type of cable structure.
* Structure of cable depends on whether it is used indoor, outdoor or underwater.

Objectives of cable manufacturer:

→ Cable should be Installable with same equipment, same installation technique, same precautions that is used for conventional wire cable

A silicon optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.5 & a cladding refractive index of 1.47. Determine a) critical angle at core-cladding interface b) NA for fiber c) Acceptance angle in air for fiber.

a) critical angle $\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1.47}{1.50} = 78.5^\circ$

b) $NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.5)^2 - (1.47)^2} = 0.30$

c) Acceptance Angle $\theta_a = \sin^{-1} NA$

$= \sin^{-1} 0.30$

$= 17.4^\circ$

A typical Δ for an optical fiber is 1%.

2. A typical Δ for an optical fiber is 1%. Estimate NA & solid acceptance angle. $n_1 = 1.46$. Further calculate critical angle at core-cladding interface.

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

$= 1.46\sqrt{(2 \times 0.01)}$

$= 0.21$

For small angles, solid acceptance angle is

$\zeta \approx \pi\theta_a^2 = \pi \sin^2\theta_a$

$= \pi(NA)^2$

$= \pi \times (0.21)^2$

$= 0.13$ rad

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

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

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

3. If the core layer of an optical fiber is made from silica with refractive index 1.45 & of cladding is 1% less than that of core. calculate refractive index of cladding, critical angle & NA

$n_2 = 1\%$ saller than n_1

$$n_2 = \frac{99}{100} \times 1.45 = 1.4355$$

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.4355}{1.45}\right) = 81.89^\circ$$

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.45)^2 - (1.435)^2} = 0.2046$$

4. Calculate R.I of core & cladding material of an fiber whose NA=0.35 & Δ=0.01

$$\Delta = \frac{n_1 - n_2}{n_1} \qquad NA = n_1\sqrt{2\Delta}$$

$$n_1 = \frac{NA}{\sqrt{2\Delta}} = \frac{0.35}{\sqrt{2 \times 0.01}} = 2.48$$

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

$$n_2 = n_1(1 - \Delta) = 2.48(1 - 0.01) = 2.45$$

Determine the angle of refraction when a light passes from glass to air at angle of incidence 60°

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

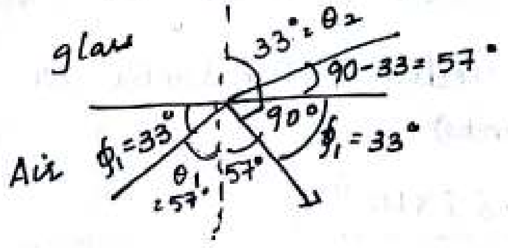
$\underset{(Glass)}{1.5} \sin 60° = \underset{Air}{\overset{\downarrow}{1}} \times \sin\phi_2$

$\sin\phi_2 = 1.5 \times \frac{1}{2} = 0.75$

$\phi_2 = \sin^{-1} 0.75$

$= 48.6°$

6. Light travelling in air strikes a glass plate at an angle $\phi_1 = 33°$, where ϕ_1 measured between the incoming ray & glass surface. Upon striking, the part of beam is reflected & rest refracted. If angle b/w refracted & reflected ray is 90° with each other, what is RI & critical angle for glass?



$n_0 \sin\theta_1 = n_1 \sin\theta_2$

$1 \sin 57° = n_1 \sin 33°$

$n_1 = 1.5398$

$\theta_c = \sin^{-1}\left(\frac{n_0}{n_1} \sin 90\right) = 40.46°$

7 A multimode step index fiber with a core diameter of 80μm & Δ 1.5% is operating at a wavelength of 0.85 μm. If RI of core is 1.48. Estimate
a) Normalized frequency for fiber b) Number of guided modes

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

$$= \frac{2\pi}{0.85\times10^{-6}} \times 40\times10^{-6} \times 1.48 \sqrt{2\times0.015}$$

$$= 75.8$$

$$M_S = \frac{V^2}{2} = \frac{5745.6}{2} = 2873$$

8. Estimate maximum core diameter with $\Delta = \overset{1.4\%}{\underline{\underline{1.5\%}}}$, RI of core $= \overset{1.46}{1.48}$ for SI mode operation. $\overset{\lambda = 0.9\,\mu m}{\lambda = 0.85\,\mu m}$.
Further estimate new max core diameter for single mode operation when Δ is reduced by factor 10

$$a = \frac{V\lambda}{2\pi n_1 \sqrt{2\Delta}} = \frac{\overset{V \text{ for step index}}{2.405} \times 0.85\times10^{-6}}{2\times\pi\times1.48\times(2\times0.015)}$$

$$= 1.3\,\mu m$$

diameter $= 2\times a = 2.6\,\mu m$

if Δ reduce by factor 10. the $\frac{1.5\%}{10} = \frac{0.015}{10} = 0.0015$

$$a = \frac{2.4\times0.85\times10^{-6}}{2\pi\times1.48\times\sqrt{(0.003)}} = 4\,\mu m$$

Diameter $= 2a = 8\,\mu m$

A graded index fiber with a parabolic refractive index profile core has a refractive index of core axis of 1.5 & Δ of 1%. Estimate maximum possible core diameter which allows single-mode operation at a wavelength of 1.3 um

V for single mode in a graded index fiber is

$V = 2.405\sqrt{1+2/\alpha}$

$\alpha = 2$ for parabolic

$V = 2.4(1+2/2)^{1/2}$

$= 2.4\sqrt{2}$

core radius $a = \dfrac{V\lambda}{2\pi n_1\sqrt{2\Delta}}$

$= \dfrac{2.4\sqrt{2}\times 1.3\times 10^{-6}}{2\pi\times 1.5\times\sqrt{2\times 0.01}}$

$= 3.3$ um

diameter $2a = 6.6$ um

10. Determine cut off wavelength for a step index fiber to exhibit single mode operation when core refractive index & radius are 1.46 & 4.5 um respectively & $\Delta = 0.25\% = 0.0025$

$\lambda_c = \dfrac{2\pi a n_1\sqrt{2\Delta}}{V} = \dfrac{2\pi\times 4.5\times 10^{-6}\times 1.46\sqrt{2\times 0.0025}}{2.405} = 1214$ nm

for single mode step index = $V = 2.405$

problems from Exercise.

Calculate the numerical apertue of a step index fiber having $n_1 = 1.48$ & $n_2 = 1.46$. What is maximum entrance angle θ_{0max} for this fiber if the outer medium is air with $n = 1.00$?

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

$= \sqrt{(1.48)^2 - (1.46)^2}$

$= 0.242$

$\sin\theta_0 = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$

$\theta_{0max} = \sin^{-1} NA$

$= \sin^{-1} 0.242$

$= 14.004^\circ$

2. An optical fiber has a numerical aperture of 0.20 & a cladding refractive index of 1.59. Determine:

a) Acceptance angle for fiber in water which has refractive index of 1.33.

b) Critical Angle at core-cladding Interface.

$\sin\theta_0 = \frac{NA}{n_0}$

Ans: a) For water RI = 1.33.

$\therefore \theta_0 = \sin^{-1}\left\{\frac{1}{n_0}\underbrace{\sqrt{n_1^2 - n_2^2}}_{NA}\right\}$

$\theta = \sin^{-1}\left[\frac{NA}{n_0}\right] = \sin^{-1}\left[\frac{0.20}{1.33}\right] = 8.64^\circ$

[$n_0 = 1$ for Air. In this problem, $n_0 = 1.33$ (water]

b) $\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\left(\frac{1.59}{1.6}\right) = 83.59^\circ$

[$NA = \sqrt{n_1^2 - n_2^2}$
$n_1 = \sqrt{NA^2 + n_2^2}$
$= 1.60$]

3. The velocity of light in core of a step Index fiber is $2.01 \times 10^8 ms^{-1}$ and critical angle at the core-cladding interface is 80°. Determine the numerical aperture & Acceptance angle for the fiber in air, assuming it has a core diameter suitable for consideration by ray Analysis. Velocity of light in a vacuum is $2.998 \times 10^8 ms^{-1}$.

Ans $n_1 = \frac{c}{v}$ where c is velocity of light in a vaccu
v is velocity of light in medium (core)

$$n_1 = \frac{2.998 \times 10^8}{2.01 \times 10^8}$$

$$= 1.491$$

$\theta_c = 80°$

$n_2 = ?$

$NA = ?$

$\theta_0 = ?$

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

$\rightarrow$ $n_2 = n_1 \times \sin\theta_c = 1.491 \times \sin(80°) = 1.468.$

$\rightarrow$ $NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.491)^2 - (1.468)^2} = 0.2608$

$\rightarrow$ $\theta_0 = \sin^{-1} NA = 15.11°.$

A step Index fiber with a large core diameter compared with wavelengths of transmitted light has an acceptance angle in air of 22° & a relative refractive index difference of 3%. Estimate numerical aperature & critical angle.

Ans:

$\theta_0 = 22^\circ$

$\Delta = 0.03 = 3\%$

$NA = ?$

$\phi_c = ?$

$\rightarrow NA = \sin\theta_0 = \sin 22 = 0.374$

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

$0.374 = n_1\sqrt{2\times0.03}$

$\rightarrow n_1 = \frac{0.374}{0.244} = 1.532$

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

$n_2 = \sqrt{(1.532)^2 - (0.374)^2}$

$= 1.485$

$\rightarrow \phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\left(\frac{1.485}{1.532}\right)$

$= 75.77^\circ$

5. A graded Index fiber with a core axis RI of 1·5 has a index profile (α) of 1·90, a relative refractive index difference of 1·3% & a core diameter of 40um. Estimate the no of guided modes propagating in the fiber when the transmitted light has a wavelength of 1·55um & determine cut off value of normalized frequency for single mode transmission in fiber.

Ans:

Given $n_1 = 1{\cdot}5$
$a = \frac{40u}{2} = 20um$
$\Delta = 0{\cdot}013$
$\lambda = 1{\cdot}55um$
$\alpha = 1{\cdot}90$

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

$= \frac{2\pi}{1{\cdot}55u} \times 20u \times 1{\cdot}5 \sqrt{2 \times 0{\cdot}013}$

$= 19.59$

No of modes in guided Index fiber $M = \left[\frac{\alpha}{\alpha+2}\right] \frac{V^2}{2}$

where $\alpha = 1{\cdot}9$., $M = \left[\frac{1{\cdot}9}{1{\cdot}9+2}\right]\left[\frac{(19{\cdot}59)^2}{2}\right]$

$= 93{\cdot}4 \approx 94$

For graded Index single mode transmission, cut off value of normalized frequency,

$V_c = 2{\cdot}405 (1 + 2/\alpha)^{1/2} = 2{\cdot}405 (1 + 2/1{\cdot}9)^{1/2} = 3{\cdot}45$.

A graded Index fiber with a parabolic index profile supports propagation of 742 guided modes. The fiber has a numerical aperture in air of 0.3 & a core diameter of 70um. Determine wavelength of light propagating in air.

Estimate the maximum diameter of fiber which gives single mode operation at same wavelength.

Ans: Given : $M = 742$

$NA = 0.3$

$a = \frac{70\mu}{2} = 35\mu m.$

→ NO of modes In graded Index fiber

$$M = \left[\frac{\alpha}{\alpha+2}\right]\frac{V^2}{2}$$

$\alpha = 2$ for parabolic profile

$$742 = \left[\frac{2}{2+2}\right]\left[\frac{V^2}{2}\right]$$

$$\frac{1}{4}V^2 = 742$$

$$V^2 = 2968$$

$$V = 54.4.$$

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

$$\lambda = \frac{2\pi}{V} a \underbrace{n_1\sqrt{2\Delta}}_{} \rightarrow N.A$$

$$= \frac{2\pi}{54.4} \times 35\mu \times 0.3 = 1.212\mu m.$$

7. A step-Index multimode fiber with NA 0.20 supports 1000 modes at 850 nm. What is diameter of core. How many modes does the fiber support at 1320 nm.

→ For step-Index Multimode fiber:

$$m = \frac{V^2}{2}$$

$$1000 = \frac{V^2}{2}$$

$$V = \sqrt{2 \times 1000} = 44.72.$$

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

$$\therefore a = \frac{V\lambda}{2\pi \cdot NA} = \frac{44.72 \times 850 \times 10^{-9}}{2\pi \times 0.20} = 30.26\,um$$

→ Diameter $2a = 2 \times 30.26 \times 10^{-6} = 60.52 \times 10^{-6}$ um.

→ For $\lambda = 1320$nm,

$$V = \frac{2\pi}{1320 \times 10^{-9}} \times 30.26 \times 10^{-6} \times 0.20$$

$$= 28.79$$

→ No of modes at 1320 nm,

$$m = \frac{V^2}{2} = \frac{(28.79)^2}{2} = 411.84 \approx 412 \text{ modes}$$

Module 2

Transmission characteristics of Optical fiber

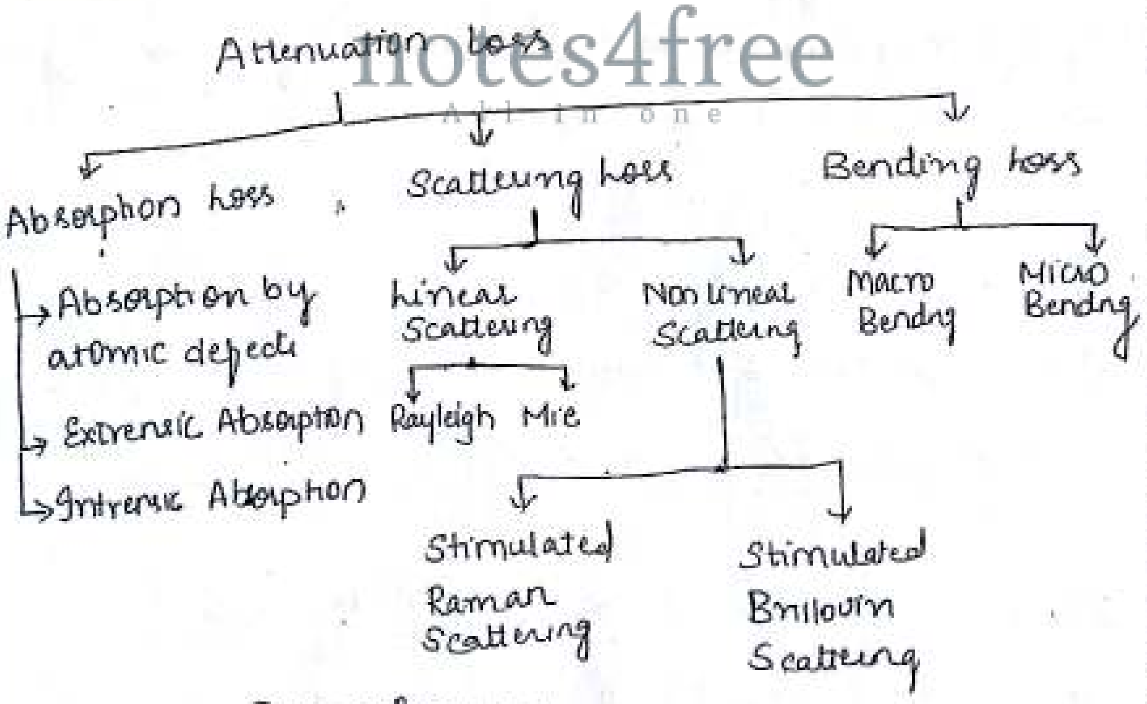
Content

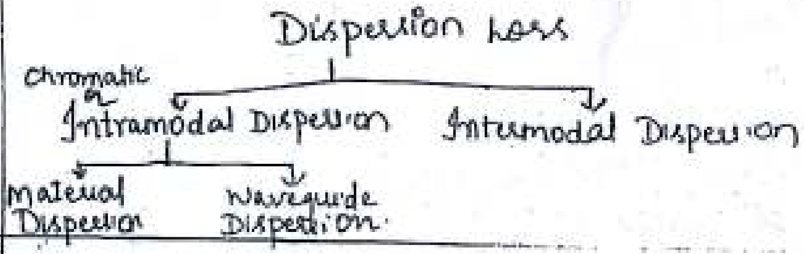
- Attenuation
- Material Absorption losses
- Linear Scattering losses
- Non linear Scattering losses
- Fiber bend loss
- Dispersion
- chromatic dispersion
- Intermodal dispersion: Multimode Step Index fiber

Introduction

Transmission characteristics determine the degradation of optical signals as light propagates along the fiber. The two most important transmission characteristics of an optical fiber are attenuation & dispersion. Attenuation limits optical power transmitted through the fiber while dispersion restricts the bandwidth or rate at which data can be transmitted through a fiber.

optical characteristics & their mechanism is shown below





Attenuation :

Attenuation in an optical fiber decides the maximum transmission distance (b/w transmitter & receiver) without using any repeater.

Attenuation loss is measured in terms of dB. When light travels through optical fiber, power decreases exponentially with distance traversed by light.

Assume an optical fiber through which light propagates along the length (z). If $p(0)$ is optical power launched in a fiber at $z = 0$, the optical power available at distance z away from input end is given by

$$p(z) = p(0)\exp(-\alpha_n z).$$

where α_n = attenuation coefficient of fiber which a function of wavelength

$$\alpha_n = \frac{1}{z}\ln\left[\frac{P(0)}{P(z)}\right] \text{ or } \alpha_n = \frac{1}{L}\ln\left[\frac{P_i}{P_o}\right]$$

where L = length of fiber
P_i = i/p power
P_o = o/p power

Attenuation in dB/km is $\alpha(\text{dB/km}) = \frac{10}{z}\log_{10}\left[\frac{P(0)}{P(z)}\right]$
↓ or
$\frac{10}{L}\log_{10}\left[\frac{P_i}{P_o}\right]$

$$\frac{P(i)}{P(0)} = 10^{\alpha L/10} \text{ or } \frac{P(0)}{P(z)} = 10^{\alpha z/10}.$$

$$\text{power (in dBm)} = 10\log\left(\frac{P}{1\,\text{mW}}\right)$$

where 1mW is reference power

problem

1 When the mean optical power launched into an 8km length of fiber is 120uW, the mean optical power at the fiber output is 3uW.

Determine:

a) The overall signal attenuation or loss in decibels through the fiber assuming there are no connectors or splices.

b) Signal attenuation per kilometer for the fiber

c) Overall signal attenuation for a 10Km optical link using same fiber with splices at 1Km intervals, each giving an attenuation of 1dB.

d) Numerical input/output power ratio in c

Ans: a) Signal attenuation (overall) $\alpha \cdot L$ $= 10\log \frac{P_i}{P_o}$

$$= 10\log\left(\frac{120\times10^{-6}}{3\times10^{-6}}\right)$$

$$= 10\log 40$$

$$= 16dB$$

b) Attenuation per Km

$$\alpha = \frac{10}{L}\log\frac{P_i}{P_o}$$

$$= \frac{10}{8}\log\left(\frac{120\times10^{-6}}{3\times10^{-6}}\right)$$

$$= 2dB/Km.$$

c) $\alpha = 2dBkm^{-1}$, for $L = 10km$, $\alpha_{dB}L \cdot 2\times10 = 20dB$.

The link has nine splices (at 1Km interval) with an attenuation of 1dB. loss due to overall splices is 9dB

Overall signal attenuation = 20+9 = 29 dB

d) To obtain numerical value for the input/ outputpower ratio, $\frac{P_i}{P_o} = 10^{\alpha L/10}$

$= 10^{29/10} = 794.3$

2. Consider a 30km long optical fiber that has an attenuation of 0·8dB/km at 1310nm. Find optical output power Pout if 200uW of optical power is launched into the fiber. Express power in mW

Ans: $P_{i_{dBm}} = 10\log\left[\frac{P_{in}(W)}{1mW}\right]$

$= 10\log\left[\frac{200\times10^{-6}}{1\times10^{-3}}\right]$

$= -7dB$

$\alpha_{dB} = \frac{1}{L} 10\log\frac{P_i}{P_o}$

$P_o = \frac{P_i}{10^{\frac{L\times\alpha}{10}}} = \frac{P_i}{10^{\frac{0.8\times30}{10}}} = \frac{20\alpha\times10^{-6}}{10^{24/10}} = 0.794uW$

$P_{o\text{ in dBm}} = 10\log\left[\frac{0.794\times10^{-6}}{1\times10^{3}}\right]$

9.

Absorption loss :

Absorption is caused by three different mechanisms :

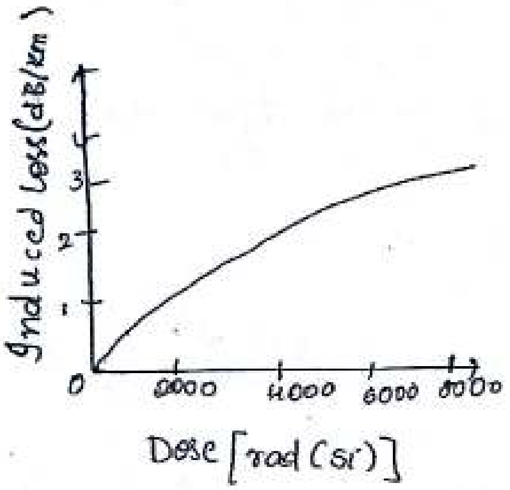
* Absorption by atomic defects in glass composition
* Extrensic Absorption by impurity atoms in glass materials
* Intrensic absorption by basic constituent atoms of fiber material.

Absorption by Atomic defects in glass composition

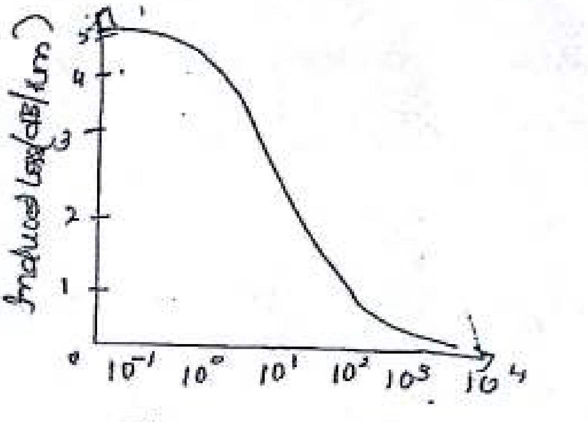
* Atomic defects are imperfections in atomic structure of fiber materials.
ex: missing molecules, high density clusters of atom groups, oxygen defects in glass structure
* Absorption loss caused by atomic defects are negligible compared to intrensic & extrensic methods
* This method becomes significant if fiber is exposed to ionizing radiation, which occurs in a nuclear reactor environment.
* Radiation damages a material by changing its internal structure.
* Damage effects depends on energy of ionizing particles or rays (ex: Electron, neutron), radiation flux (dose rate) & fluence (particles per square centimeter)

Total dose a material re[illegible]s is expressed in units of rad(Si), which is measure of radiation absorbed in bulk silicon.

1 rad (Si) = 100 erg/g = 0.01 J/kg



a)



b)

Higher the radiation level, larger the attenuation as shown in a). The attenuation will relax or anneal out with time.

Extrensic Absorption Loss

It is a dominant absorption loss which occurs due to presence of minute quantities of impurities in fiber materials.

Impurities are OH⁻ ions that are dissolved in glass, & transition metal ions such as iron, copper, chromium & vanadium.

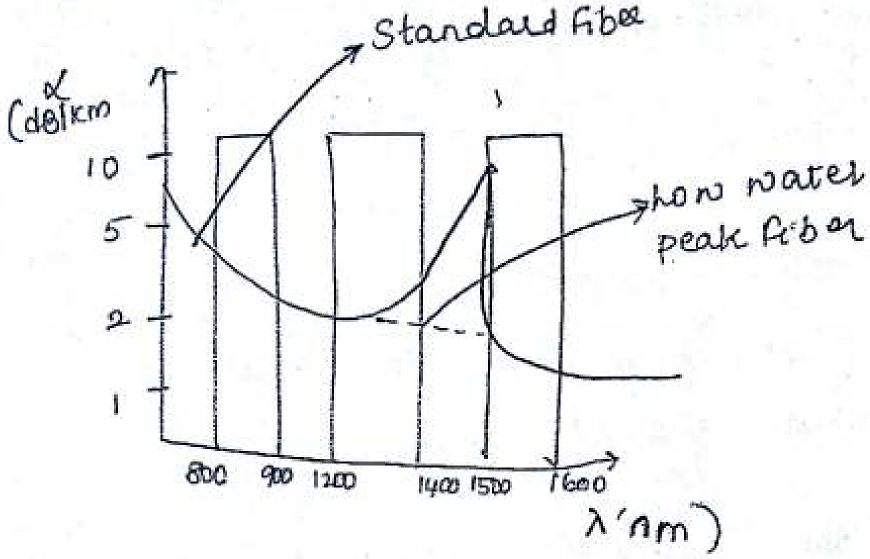
1 parts per million of transition metal ions produces a loss of 4dB/km.

* Extrinsic loss occurs either because of electronic transition between energy levels within these ions or charge transitions between ions. Absorption peak of various transition metal impurities tend to be broad & several peaks may overlap. This further broadens the absorption in specific region.

* Modern vapour phase fiber techniques for producing fiber have reduced the transition metal impurities level by several orders of magnitude. Low impurity levels allows low loss fibers fabrication.

Impurity	Loss due to 1 ppm of Impurity (dB/Km)	Absorption peak (nm)
(Fe^{2+}) Iron	0.68	1100
(Fe^{3+})	0.15	400
Copper (Cu^{2+})	1.1	850
Water OH^-	1	950
OH^-	2	1240
OH^-	4	1380

* Water impurity concentration of less than 1ppb is required to produce attenuation less than 20dB/Km.
* From the above table it is clear that OH ions have absorption peaks at 725, 950, 1240, 1380nm
* It is clear that the region of low attenuation lie between these absorption peaks



Full Spectrum Fibers

By reducing the OH content of fiber below 1ppb single mode fibers have attenuation of 0.4dB/km at 1310nm & < 0.25 dB/km at 1550nm Further elimination of OH^- ions diminishes the absorption peak at 1440nm & thus opens a new E-Band for transmission & fibers that are used in E Band are known as low water peak or full spectrum fibers

Intrinsic Absorption

It is associated with the basic fiber material (Ex: pure SiO_2) & is the principal physical factor that defines transparency window of a material over a specified spectral region

- It occurs when material is in a perfect state with no density variations, impurities, material inhomogeneties etc.

At any wavelength UV loss can be expressed as a function of mole fraction x of GeO_2 as

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

In near infrared region above 1200nm, the optical waveguide loss is predominantly determined by presence of OH ions & inherent infrared absorption of constituent material & is associated with characteristic vibration frequency of particular chemical bond b/w atom of which fiber is composed. Interaction b/w vibrating bond & EM. field of optical signal results in transfer of energy from field to bond, thereby giving rise to absorption. This absorption is quite strong because of many bonds present in fiber α_{IR} for GeO_2-SiO_2 is given by

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

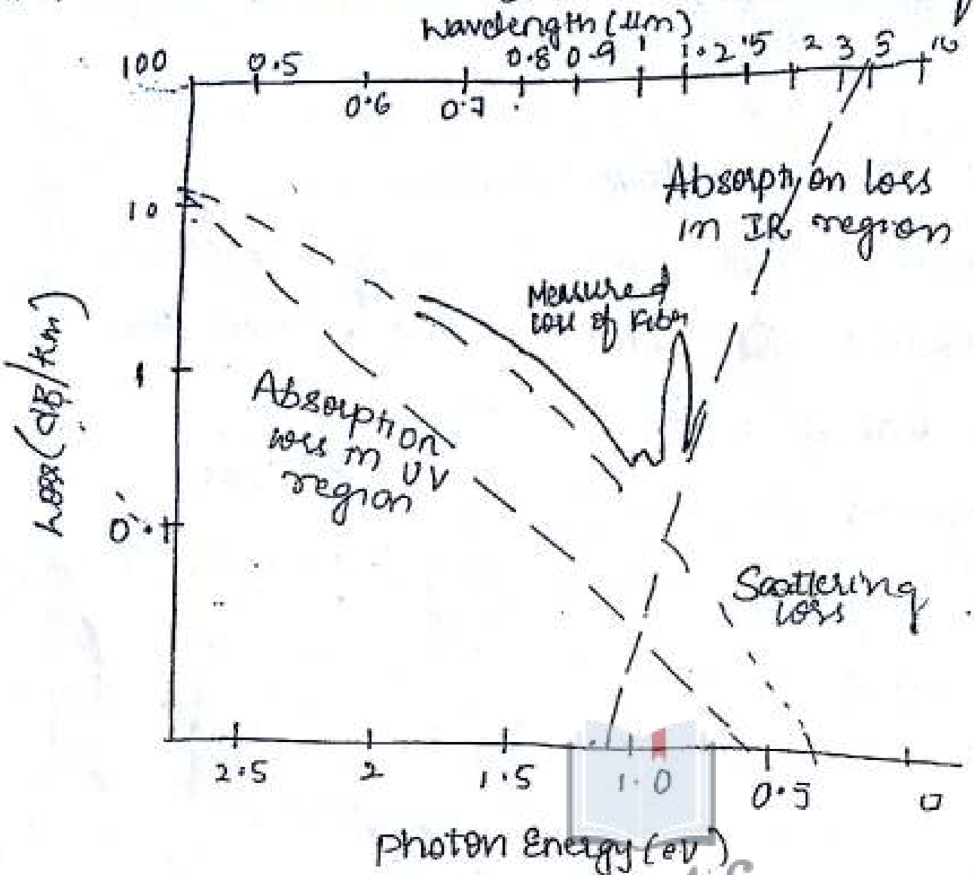
Scattering loss

Scattering loss occur when the propagating light wave interacts with a particle in fiber material & the energy is transfered in different directions.

Scattering occurs because of microscopic variation in material density, structural non homogeneity or compositional variation over distance of order of wavelength of propagating light

Intrinsic absorption is due to ;

- Electronic absorption bands in Ultraviolet region
- Atomic Vibration bands in near-infrared region



Electronic absorption bands are associated with band gaps of amorphous glass materials. Absorption occurs when a photon interacts with an electron in valence band & excites it to a higher energy level. UV edge of electron absorption bands of both amorphous & crystalline materials follow empirical relation $\alpha_{uv} = Ce^{E/E_0}$ which is known as Urbach's rule.

C & E_0 are empirical constants & E is photon Energy. Magnitude & characteristics exponential decay of UV absorption is shown above. E is inversely proportional to wavelength λ & hence UV absorption decays exponentially with increasing wavelength

Scattering is classified as : * Linear Scattering loss
* Non Linear Scattering loss

Linear Scattering loss : → Rayleigh Scattering
→ Mie Scattering.

In linear scattering, the optical power transferred to a different mode is proportional to power contained in the propagation mode. Linear scattering is characterized by fact that there is no change in frequency of scattered wave because of transfer of power from the propagating mode.

Rayleigh Scattering.

Variation of RI within the glass over distance are small compared with wavelength gives rise to Rayleigh scattering. This type of index variation causes light to be scattered in all directions.

It causes loss of power in forward direction.

Loss of power takes place due to variations in density & composition of glass material in fiber that happens during manufacturing. Its dominant loss mechanism in UV region.

Rayleigh scattering is inversely proportional to fourth power of wavelength $(1/\lambda^4)$

$$\gamma_r = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c k T_F$$

λ = optical wavelength, n = R.I of medium.

p = photoelastic coefficient, β = Isothermal compressibility.

T_F = fictive temperature, K = Boltzman constant.

↓

Temp at which
glass can reach
state of thermal
equilibrium or
anneal Temperature.

Transmission loss Factor (Transmissivity) of fiber

$\mathcal{L}_{km} = \exp(-\gamma_R L)$ & Attenuation $= 10\log_{10}(1/\mathcal{L}_{km})$

where L is length of fiber.

problem:

Silica has an estimated fictive temperature of 1400K with an isothermal compressibility of $7\times10^{-11}\ m^2 N^{-1}$. Refractive index & photoelastic coefficient for silica are 1.46 & 0.286 respectively. Determine attenuation in dB/km due to Rayleigh scattering in silica at $\lambda = 0.63$, 1 & 1.3 μm. K = Boltzman's const = $1.381\times10^{-23}\ JK^{-1}$

Ans: $$\gamma_R = \frac{8\pi^3 n^8 p^2 \beta_c k T_F}{3\lambda^4}$$

$$= \frac{8\times(3.14)^3\times(1.46)^8\times(0.286)^2\times 7\times10^{-11}\times 1.381\times10^{-23}\times 1400}{3\lambda^4}$$

$$= \frac{1.895\times10^{-28}}{\lambda^4}\ m^{-1}$$

At $\lambda = 0.63\,\mu m$

$$\gamma_R = \frac{1.895\times10^{-28}}{0.158\times10^{-24}}$$

$$= 1.199\times10^{-3}\,m^{-1}$$

Transmission loss factor for 1 Km:

$$\mathcal{L}_{km} = \exp(-\gamma_R \cdot L)$$

$$= \exp(-1.199\times10^{-3}\times1\times10^{3})$$

$$= 0.301$$

Attenuation in dB/km due to Rayleigh scattering

$$\alpha = 10\log_{10}(1/\mathcal{L}_{km})$$

$$= 10\log_{10}\left(\frac{1}{0.301}\right)$$

$$= 5.2\,dB\,Km^{-1}$$

At wavelength of $1\mu m$:

$$\gamma_R = \frac{1.895\times10^{-28}}{10^{-24}} = 1.895\times10^{-4}\,m^{-1}$$

$$\mathcal{L}_{km} = \exp(-\gamma_R L)$$

$$= \exp(-1.895\times10^{-4}\times10^{3}) = 0.827$$

$$\alpha = 10\log_{10}(1/\mathcal{L}_{km})$$

$$= 10\log_{10}\left(\frac{1}{0.827}\right)$$

$$= 0.8\,dB/km$$

At $\lambda = 1.3\mu m$

$$\gamma_R = \frac{1.895\times10^{-28}}{2.856\times10^{-24}} = 0.664\times10^{-4}\,m^{-1}$$

$$\mathcal{L}_{km} = \exp(-0.664\times10^{-4}\times10^{3}) = 0.936$$

$$\text{Attenuation} = 10\log(1/0.936) = 0.3\,dB/km$$

Mie Scattering

When the scattering inhomogeneity size is comparable or greater than wavelength then mie scattering is significant & scattering is in forward direction.

The inhomogeneities occur due to material improper design, manufacturing defects, Imperfect cylindrical structure of the waveguide (Irregularities at core-cladding interface, core-cladding index difference, diameter fluctuation, etc).

The Inhomogeneities may be reduced by:

a) Removing imperfections due to glass manufacturing process

b) Careful controlled extrusion & coating of fiber

c) Increasing the fiber guidance by increasing relative refractive index difference

Non-Linear Scattering

- Stimulated Brillouin Scattering (SBS)
- Stimulated Raman Scattering (SRS)

Non-Linear scattering results in transfer of power from one mode to another at a different frequency. Optical power may be transferred from a mode in either forward or backward direction. It is called as inelastic scattering & depends on power density within fiber so it is significant above threshold power levels.

Stimulated Brillouin Scattering

SBS occurs from scattering of propagation light by thermal molecular vibrations of material. The interaction of photon with vibrating molecules of the material results in a phonon of acoustic frequency as well as a scattered photon of different energy. For SBS, the frequency shift is maximum in backward direction & zero in forward direction. SBS is viewed as backward process.

The threshold power required for SBS to occur depends on wavelength of operating wavelength & line width of optical source.

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

d & λ are fiber core diameter & operating wavelength respectively measured in micrometers.

α_{dB} is fiber attenuation in dB/km

ν is source Bandwidth in GHz.

Stimulated Raman Scattering

SRS is similar to SBS except that a high-frequency optical phonon is generated in scattering process. SRS occurs in both forward & Backward direction in optical fiber & have an optical threshold of upto three orders of magnitude higher than Brillouin threshold in a particular fiber

SRS Threshold power $P_R = 5.9\times10^{-2} d^2 \lambda \alpha_{dB}$ watts

d & λ are measured in um.

problem

A long single mode optical fiber has an attenuation of 0.5 dBkm⁻¹ when operating at a wavelength of 1.3um. The fiber core diameter is 6um & laser source Bandwidth is 600MHz. Compare the threshold optical powers of SBS & SRS within fiber at wavelength specified.

$P_B = 4.4\times10^{-3} d^2 \lambda^2 \alpha_{dB} \nu$

$= 4.4\times10^{-3}\times 6^2 \times 1.3^2 \times 0.5 \times 0.6$

$= 80.3$ mW

[600M = 0.6 u.
∵ as all other
factors are expressed
in u]

$P_r = 5.9\times10^{-3} d^2 \lambda \alpha_{dB}$

$= 5.9\times10^{-3}\times 6^2 \times 1.3 \times 0.5$

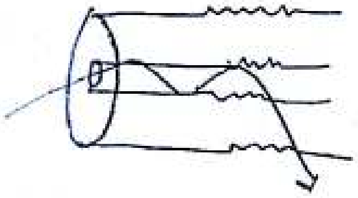
$= 1.38$ W

Bending losses → Micro Bending
→ Macro Bending

It is the radiative loss that occurs when an optical fiber is bent by a finite radius of curvature

MicroBending

Repetative small scale fluctuations in the radius of curvature of fiber axis & Appears randomly along the fiber



power loss from higher order mode

Microbends are created by non-uniformities in the manufacturing process of fiber & lateral pressure created during cabling of fiber.

A compressible jacket around fiber reduces microbending. When external forces are applied to this configuration, jacket will be deformed but fiber will remain straight.

Microbending loss α_m of jacketed fiber is reduced from that of an unjacketed fiber by a factor

$$F(\alpha_m) = \left[1+\pi\Delta^2\left(b/a\right)^4\frac{E_f}{E_j}\right]^{-2}$$

where a = core radius of multimode graded index fiber

b = outer radius

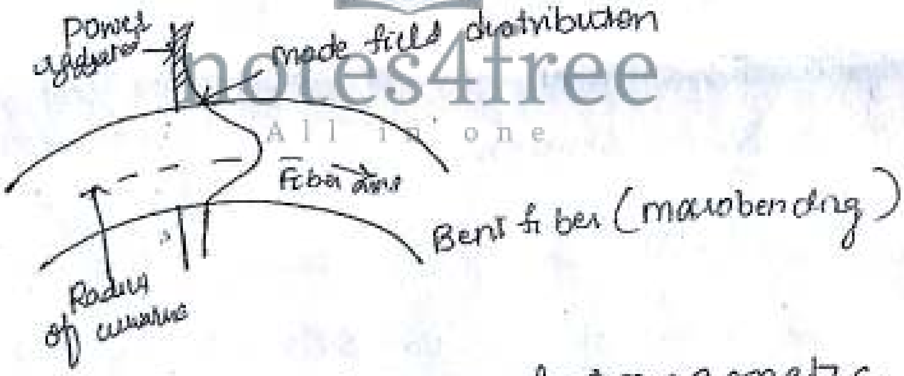
Δ = Relative R.I index difference

E_j & E_f are Young's modulus of the jacket & fiber respectively

Macrobending

Macrobend occurs when a fiber is bent into a relatively large radius of curvature w.r.t fiber diameter. These bends can cause a significant power loss when radius of curvature falls below a certain critical value. Macrobends are formed when fibers are wound in the form of a spool or a fiber cable roll.

Bending loss is primarily due to radiation of energy from fiber when evanescent field fails to keep up pace with part of mode varying harmonically in core as shown below



A mode is considered as an electromagnetic field pattern created in transverse direction which varies harmonically in core region & decay exponentially in cladding region. A mode is considered to be bound when evanescent field tail in the cladding region moves along with the part moving within core. When fiber is bent uniformly, as shown in above figure, field tail on other side of the center of curvature is required to move faster relative to part on inner side in order to keep up with part moving through core region. This is possible upto a critical value of bending decided by radius of curvature of bending. Below critical value, field tail is radiared out of fiber, causing a loss of optical power propagating through fiber.

Bending loss $\alpha_r = c_1 \exp(-c_2 R)$

c_1 & c_2 are empirical constants &

R is radius of curvature of bending.

For a multimode fiber, critical value of Radius of curvature is

$$R_c = \frac{3n_1^2\lambda}{4\pi(\sqrt{n_1^2-n_2^2})}$$

where n_1 & n_2 are refractive Index of core & cladding respectively. λ = operating wavelength

For single mode fiber, critical value of Radius of curvature is

$$R_{cs} = \frac{20\lambda}{\sqrt{n_1^2-n_2^2}}\left(2.748-0.996\frac{\lambda}{\lambda_c}\right)^{-3}$$

where λ_c = cutoff wavelength for single mode fiber

Effective number of modes guided by a curved graded index fiber

$$M_{eff} = M_{\infty}\left[1 - \frac{\alpha+2}{2\alpha\Delta}\left\{\frac{2a}{R} + \left(\frac{3}{2n_2KR}\right)^{2/3}\right\}\right]$$

α = Grade index of GI fiber

Δ = Relative refractive index difference

R = Radius of curvature of bending

$K = \frac{2\pi}{\lambda}$

a = Radius of fiber.

M_{∞} is no of modes through a graded index straight fiber $M_{\infty} = a^2K^2n_1^2\Delta\left(\frac{\alpha}{\alpha+2}\right)$

Problem :

Two step index fibers exhibit the following parameters.

a) Multimode fiber with a core RI of 1.5, a relative refractive index difference of 3%. & $\lambda = 0.82\,\mu m$

b) An 8 µm core diameter single mode fiber with core RI same as a), $\Delta = 0.3\%$ & operating wavelength of 1.55 µm

estimate critical radius of curvature in both cases.

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

$n_2 = 1.05$

$$R_c = \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{1/2}} = \frac{3 \times (1.5)^2 \times 0.82 \times 10^{-6}}{4\pi\sqrt{(1.5)^2 - (1.05)^2}} = 9\,\mu m$$

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

$0.003 = \frac{1.5 - n_2}{1.5}$

$n_2 = 1.115$

Cut-off wavelength for single mode fiber is

$\lambda_c = \frac{2\pi a n_1 \sqrt{(2\Delta)}}{2.405}$ V = 2.405 for single mode fiber

$= \frac{2\pi \times 4 \times 10^{-6} \times \sqrt{2 \times 0.003}}{2.405}$

$= 1.214\,\mu m$

$R_{cs} = \frac{20\lambda}{(n_1 - n_2)^{3/2}} \left(2.748 - 0.996\frac{\lambda}{\lambda_c}\right)^{-3}$

$= \frac{20 \times 1.55 \times 10^{-6}}{(0.043)^{3/2}} \left(2.748 - \frac{0.996 \times 1.55 \times 10^{-6}}{1.274 \times 10^{-6}}\right)^{-3}$

$= 34\,mm.$

2. A 50μm diameter G.I fiber with parabolic index profile has $n_1 = 1.458$, $\Delta = 0.01$. Estimate no of modes at 850nm. If radius of curvature of bent fiber is 2cm, calculate no of modes radiated out of fiber.

No of modes with parabolic index profile $(\alpha = 2)$

Ans: No of modes under normal condition, $M_\infty = a^2 k^2 n_1^2 \Delta \left(\frac{\alpha}{\alpha + 2}\right)$

$= (50 \times 10^{-6})^2 \times \left(\frac{2\pi}{850 \times 10^{-9}}\right)^2 \times (1.458)^2 \times 0.01 \times \left(\frac{2}{2+2}\right)$

$= 170$

$M_{eff} = M_\infty \left[1 - \frac{\alpha + 2}{2\alpha\Delta}\left\{\frac{2a}{R} + \left(\frac{3}{2n_2 kR}\right)^{2/3}\right\}\right] = 170\left[1 - \frac{2+2}{2 \times 2 \times 0.01}\left\{\frac{2 \times 25 \times 10^{-6}}{2 \times 10^{-2}} + \left(\frac{3}{2 \times n_2 \times \frac{2 \times 3.14 \times 2 \times 10^{-2}}{850 \times 10^{-9}}}\right)^{2/3}\right\}\right]$

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

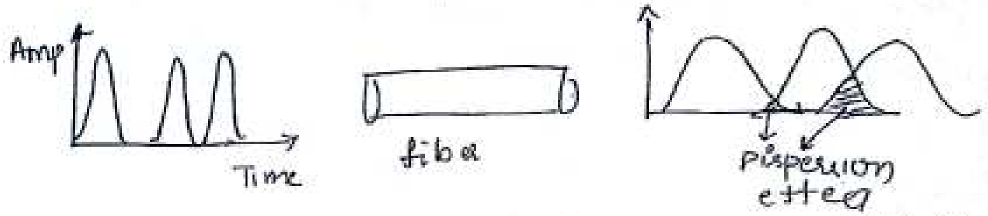
Find n_2 & substitute

Out of 170, only 120 ~~126~~ (modes) will be confined to core, rest will be radiated out

Dispersion

- → Intermodal Dispersion
- → Intramodal Dispersion.

Dispersion is broadening of light pulses & is a critical factor that limits quality of signal Transmission through an optical link. Physical properties & geometry of transmission medium are responsible for dispersion



For no overlapping of light pulse down on a optical fiber link the digital bit rate B_T must be less than reciprocal of the broadened (through dispersion) pulse duration (2τ)

- $B_T \le \frac{1}{2\tau}$.

The maximum bit rate with dispersion may be obtained by considering light pulses at output to have Gaussian shape with an rms width of σ.

$$B_T(max) = \frac{0.2}{\sigma} \text{ bit s}^{-1}.$$

Problem

A multimode graded index fiber exhibits total pulse broadening of 0.1μs over a distance of 15km. Estimate

a) Maximum possible bandwidth assuming no intersymbol interference

b) pulse dispersion per unit length.

c) Bandwidth - length product.

Ans: a) $B_{opt} = B_T = \frac{1}{2\tau} = \frac{1}{0.2\times10^{-6}} = 5MHz$

b) $Dispersion/Km = \frac{0.1\times10^{-6}}{15} = 6.67nsKm^{-1}$

c) $B_{opt}L = 5MHz \times 15Km = 75MHzKm$.

Chromatic Dispersion or Intramodal Dispersion (Group Velocity Dispersion)
- → Material Dispersion
- → Waveguide Dispersion

* chromatic or intramodal dispersion occurs in all types of fibers (more dominant in single mode) & results from finite spectral linewidth of optical source.

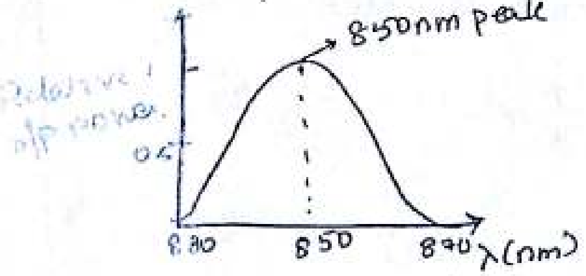


Diagram shows that a source is emitting at 850nm peak with spectral width of 40nm. Intermodal dispersion has high dependency on wavelength & spectral width of source.

Material Dispersion

pulse broadening due to material dispersion results from different group velocities of various spectral components launched into fiber from optical source. It occurs when phase velocity of a plane wave propagating in the dielectric medium varies non-linearly with wavelength. & $d^2n/d\lambda^2 \neq 0$.

pulse spread due to material dispersion may be obtained by considering group delay τ_g

$$\left(\tau_g = \frac{1}{V_g} \rightarrow \text{group velocity}\right)$$

$$\tau_g = \frac{d\beta}{d\omega} = \frac{1}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right)$$ where n_1 = refractive Index of core
$c = 3\times10^8 m/s$

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

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

With rms spectral width σ_λ & mean wavelength λ, rms pulse broadening $\sigma_m = \sigma_\lambda \frac{d\tau_m}{d\lambda} + \sigma_\lambda \frac{2d^2\tau_m}{d\lambda^2} + \dots$

As first term dominates especially for sources operating b/w 0.8 & 0.9 μm wavelength

$$\sigma_m = \sigma_\lambda \frac{d\tau_m}{d\lambda} \rightarrow ①$$

pulse spread considering dependence of τ_m & λ

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

$$= \frac{-L\lambda}{c}\frac{d^2n_1}{d\lambda^2} \rightarrow ②$$

Substituting 2 in ①

$$\sigma_m = \frac{\sigma_\lambda L}{c}\left|\lambda\frac{d^2n_1}{d\lambda^2}\right|.$$

or

$$= \frac{\frac{\sigma_\lambda}{\lambda} L}{c\lambda}\left|\lambda^2\frac{d^2n_1}{d\lambda^2}\right|.$$

Material Dispersion parameter $M = \frac{1}{L}\frac{d\tau_m}{d\lambda} = \frac{\lambda}{c}\left|\frac{d^2n_1}{d\lambda^2}\right|$

Unit is $ps\,nm^{-1}km^{-1}$.

problem

A glass fiber exhibits dispersion given by $|\lambda^2(d^2n_1/d\lambda^2)|$ of 0.025 Determine Material dispersion parameter at wavelength of 0.85um, estimate the rms pulse broadening per kilometer for a good LED source with an rms spectral width of 20nm at this wavelength

$$M = \frac{\lambda}{c}\left|\frac{d^2n_1}{d\lambda^2}\right| = \frac{1}{c\lambda}\left|\lambda^2\frac{d^2n_1}{d\lambda^2}\right| = \frac{0.025}{3\times10^8\times850\times10^{-9}}$$

$$= \frac{0.025}{3\times10^5\times850} s\,nm^{-1}km^{-1} = 98.1\,ps\,nm^{-1}km^{-1}$$

$$\sigma_m = \frac{\sigma_\lambda L}{c}\left|\lambda\frac{d^2n_1}{d\lambda^2}\right|$$

$$\sigma_m = \sigma_\lambda L M$$

$$\sigma_m/km = 20\times1\times98.1\times10^{-12} = 1.96\,ns\,km^{-1}$$

Waveguide Dispersion :

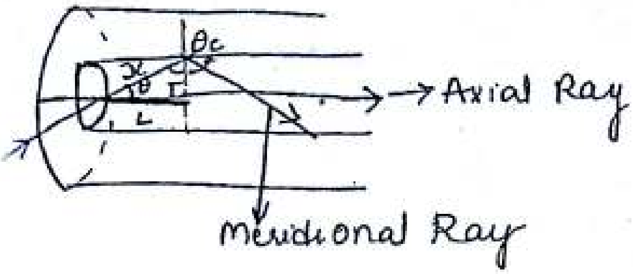
Waveguide dispersion results from variation in group velocity with wavelength for particular mode. Fiber exhibits waveguide dispersion when $d^2\beta/d\lambda^2 \neq 0$. With single-mode fibers, waveguide dispersion are significant.

Intermodal Dispersion

Intermodal dispersion is caused by time delay b/w various modes to travel to destination point & hence found to be present only in multimode fiber. Delay is caused by time difference b/w lowest & highest order modes.

Each mode will have different group velocity at single frequence. Steeper angle of incidence, slow will be group velocity. This give raise to inter modal distortion.

The time Tmax is taken by longest ray congruence path (oblique or meridional ray) & Tmin is taken by shortest ray congruence path (axial ray) & Intermodal dispersion which causes pulse broadening $\Delta T = T_{max} - T_{min}$



$$T_{min} = \frac{\text{Distance}}{\text{Velocity}}$$

Distance = Length of fiber (L)

$$T_{min} = \frac{L}{c/n_1} \quad \left(\because n = c/v \quad v = c/n \right)$$

where c is speed of light

Axial ray travels within core with Tmin given by

$$T_{min} = \frac{Ln_1}{c} \rightarrow ①$$

For meridional ray

$$T_{max} = \frac{\text{Distance}}{\text{velocity}}$$

From diagram, $\cos\theta = \frac{L}{x} \left(\frac{\text{Adjacent}}{\text{Hyp}}\right)$

$$\therefore x = \frac{L}{\cos\theta}.$$

x → distance

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

$$T_{max} = \frac{Ln_1}{c\cos\theta} \rightarrow ②$$

By snell's law for TIR

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

& from diagram $\theta_c = 90-\theta$

$$\sin(90-\theta) = \frac{n_2}{n_1}$$

$$\cos\theta = n_2/n_1 \rightarrow ③$$

substituting 3 in 2

$$T_{max} = \frac{Ln_1}{cn_2/n_1}$$

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

$$\Delta T = T_{max} - T_{min}$$

$$= \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c} \quad \left(\text{For eq1 \& 4} \right)$$

$$= \frac{Ln_1}{c}\left[\frac{n_1}{n_2} - 1\right]$$

$$= \frac{Ln_1}{c}\left[\frac{n_1 - n_2}{n_2}\right]$$

$\times$ & divide by n_1

$$\Delta T = \frac{Ln_1}{c}\left[\frac{n_1 - n_2}{n_2}\right]\frac{n_1}{n_1}$$

$$\delta T_s = \boxed{\Delta T = \frac{Ln_1^2 \Delta}{cn_2}}$$ ⇒ Modal Delay formula

In order for neighbouring pulses to be distinguishable, pulse spread $< 1/B$.

A 6km optical link consists of multimode step index fiber with a core refractive index of ·5 & relative refractive index difference of 1%. Estimate:

a) Delay difference between slowest & fastest modes at fiber output

b) RMS pulse broadening due to Intermodal dispersion

c) Max bit rate assuming only intermodal dispersion

d) Bandwidth-Delay product

Ans:

a) δT_S or $\Delta T_S = \frac{Ln_1\Delta}{c} = \frac{6\times10^3\times1.5\times0.01}{3\times10^8} = 300ns$

b) $\sigma_S = \frac{Ln_1\Delta}{2\sqrt{3}c} = \frac{1}{2\sqrt{3}}\times\frac{6\times10^3\times1.5\times0.01}{3\times108}$

$= 86.7ns.$

c) $B_T = \frac{1}{2\tau} = \frac{1}{2\delta T_S} = \frac{1}{600\times10^{-9}} = 1.7Mbits\,s^{-1}$

(width of pulse window)

or

$B_{T(max)}$ with rms pulse Broadening $= \frac{0.2}{\sigma_S} = \frac{0.2}{86.7\times10^{-9}}$

$= 2.3Mbits\,s^{-1}$

d) $B.W\times L = B_{Tmax}\times L = 2.3MHz\times6km = 13.8MHz\,km$

Overall Fiber Dispersion

Overall dispersion in multimode fiber comprises both chromatic & intermodal terms.

Total rms pulse broadening $\sigma_T = (\sigma_c^2 + \sigma_n^2)^{1/2}$

σ_c = Intramodal or chromatic broadening (consists both material & waveguide)

$\sigma_c \approx \sigma_m$ as waveguide is negligible

σ_n = Intermodal Broadening (consists both multimode step index & graded index) i.e σ_s & σ_g

problem :

$NA = 0.3, n_1 = 1.45, M = 250 \text{ ps nm}^{-1}\text{km}^{-1}$

Estimate a) total Rms pulse broadening per kilometer with spectral width of 50nm.

b) B.W-length product

a) Rms pulse broadening due to material dispersion

$$\sigma_m(1\text{km}) = \frac{\sigma_\lambda L \lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right| = \sigma_\lambda L M = 50 \times 1 \times 250 \text{ ps km}^{-1}$$

$$= 12.5 \text{ ns km}^{-1}$$

$$\sigma_s(1\text{km}) = \frac{L(NA)^2}{4\sqrt{3}\, n_1 c} = \frac{10^3 \times 0.09}{4\sqrt{3} \times 1.45 \times 3 \times 10^8} = 29.9 \text{ ns km}^{-1}$$

$\sigma_c = \sigma_m$ as waveguide dispersion is negligible

& $\sigma_n = \sigma_s$ for multimode step index fiber

$$\sigma_T = \sqrt{(\sigma_m^2 + \sigma_s^2)} = \sqrt{((12.5)^2 + (29.9)^2)} = 32.4 \text{ ns km}^{-1}$$

b) $B_{opt} \times L = \frac{0.2}{\sigma_T} = \frac{0.2}{32.4 \times 10^{-9}} = 6.2 \text{ MHz km}$

Module 3

Optical Source, detectors & Receiver

Characteristics that are considered when choosing optical source compatible with optical waveguide :

- Geometry of source
- Attenuation as a function of wavelength.
- Group delay distortion
- modal characteristics

In the common classification,

LED is used for multimode fibers & LASER is used for both single & multimode fibers.

Differences Between LED & laser

	LED	Laser
1	optical output is incoherent	Optical output is coherent
2	Output has large beam divergence	output is highly monocromatic
3.	Output is not directional	Output is highly directional
4.	optical Energy is not produced in optical cavity	optical Energy is produced through optical resonant Cavity
5.	It is not wavelength selective	It is highly wavelength selective.

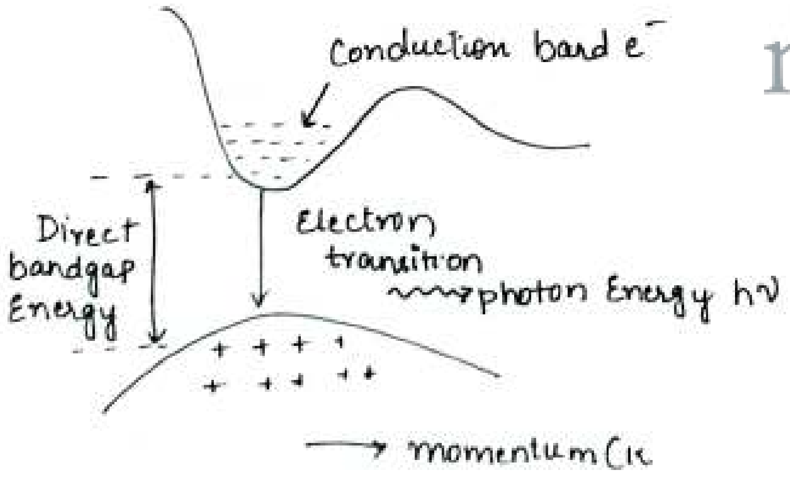
Direct & Indirect Band gaps :

In order for electron transitions to take place to (or) from conduction band with the absorption or emission of photon respectively, both energy & momentum must be conserved.

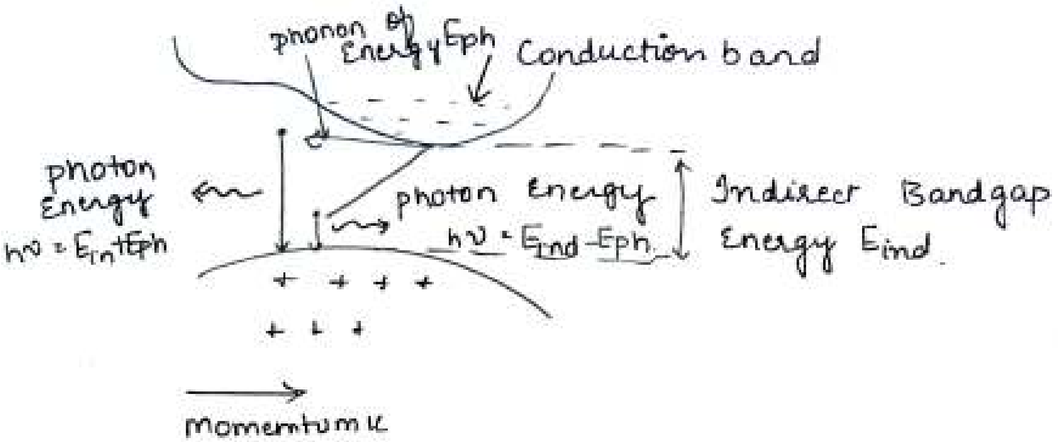
Semiconductors are classified as direct band gap or indirect bandgap based on shape of the bandgap & momentum(K)

Direct Bandgap material :

If the electrons & holes have the same value of momentum then it results in the simplest & most probable recombination process that results in emission of photon.



Indirect Bandgap Material



In this conduction band minimum & the valence band maximum energy levels occur at different values of momentum. Here band-to-band recombination involves a third particle to conserve momentum called phonons.

Light Emitting Diodes (LED)

- LED is used as a source for optical communication system requiring bit rates less than 100-200Mbps with multimode fiber & optical power in the tens of microwatts
- LED requires less complex drive circuitry. does not require thermal or optical stabilization circuits & can be fabricated less expensively with higher yields

LED Structure

LED must have :

- High radiance output : High radiances are necessary to couple sufficiently high optical power levels into a fiber. LED radiance (or brightness) is a measure in Watts, of the optical power radiated into a unit solid angle per unit area of the emitting surface.

- Fast Emission Response Time : Emission response time is the time delay between the application of a current pulse & the onset of optical emission. This time delay limits the bandwidth.

- High Quantum Efficiency : Quantum Efficiency is related to the fraction of injected electron-hole pairs that recombine radiatively.

To achieve a high radiance & a high quantum efficiency, LED structure must provide a means of confining the charge carriers & stimulated optical emission to the active region of the pn junction where radiative recombination takes place.

- Carrier confinement is used to achieve high level of radiative recombination in the active region of the device & high quantum efficiency.
- Optical confinement prevents the absorption of emitted radiation by the material surrounding the pn junction.

To achieve carrier and optical confinement LED can have following configurations:

*Homojunction
*Single or double heterojunction structure.

Most effective configuration is double heterojunction structure.

fig 1 : Cross section of typical GaAlAs double-heterostructure LED

metal Contact	n-type GaAs Substrate	n-type $Ga_{1-x}Al_xAs$ Light guiding & carrier Confinement ~1um	n-type $Ga_{1-y}Al_yAs$ Recombination region ~0.3um	p-type $Ga_{1-x}Al_xAs$ Light guiding & carrier confinement ~1um	p-type GaAs Metal contact improvement layer ~1um	Metal contact

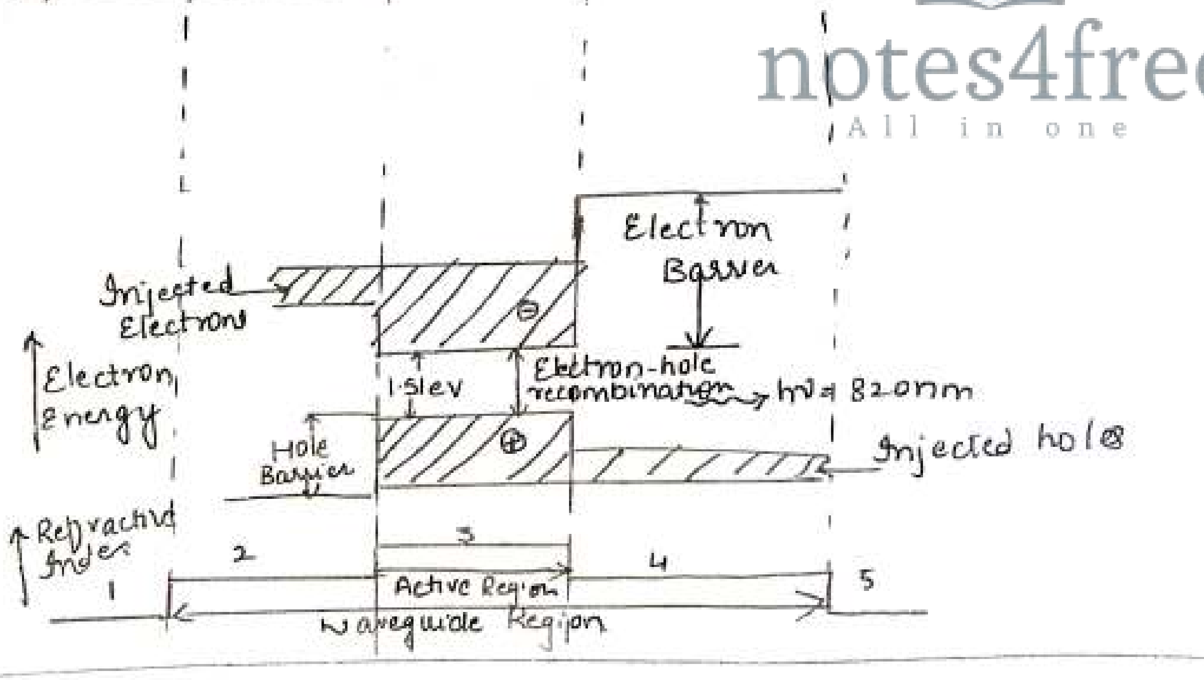


Fig1 shows the double heterojunction structure with two different alloy layers on each side of active region.

- Because of the sandwich structure of differently composed alloy layers both carrier and optical field are confined in central active layer
- Band gap difference of adjacent layers provides carrier confinement.
- Difference in R.I of adjacent layers provides optical confinement

Two basic LED configurations used for optics are

- Surface Emitters
- Edge Emitters

Surface Emitting LED or Burrus or Front Emitters:

- In this configuration, the plane of active light emitting region is oriented perpendicular to the axis of the fiber as shown in fig 2.

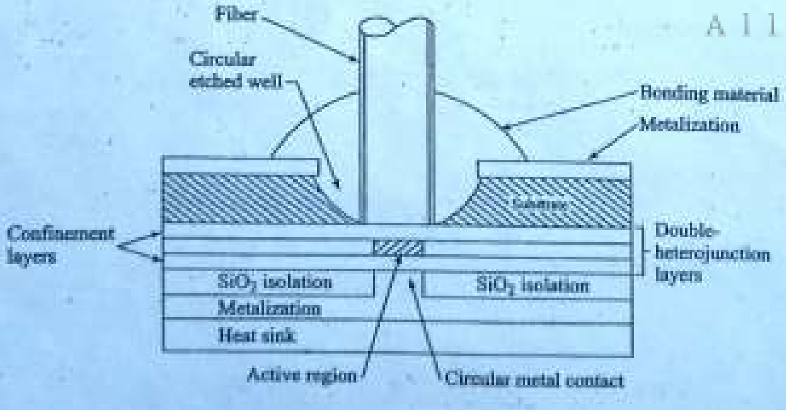


fig 2: Schematic of high radiance surface emitting LED

- A well is etched through the substrate of the device, into which a fiber is cemented in order to accept the emitted light.
- Circular active area in practical surface emitters is 50μm in diameter & 2.5μm thickness.
- The emission pattern is essentially isotropic with 120° Half-power beam width.
- Isotropic pattern from surface emitter is called a lambertian pattern in which source is equally bright when viewed from any direction, but power diminishes as $\cos\theta$, where θ is angle b/w viewing direction & normal to surface. The power is down to 50% of its peak when $\theta = 60°$ & hence total Half power beam width is 120°.

Edge Emitters :

As shown in fig 3, Edge Emitters consists of an active junction region, which is the source of incoherent light & two guiding layers.

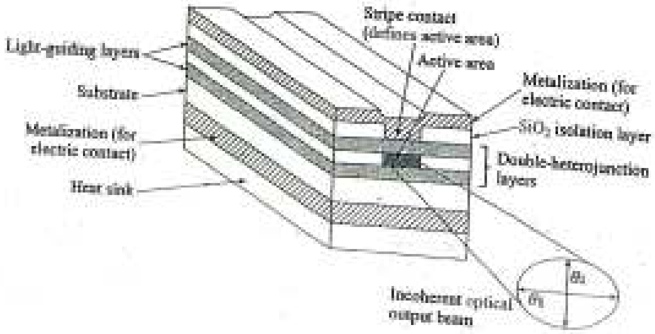


fig 3 : Edge Emitting LED

- Guiding layers both have a R.I which is lower than that of active region but has R.I greater than surrounding material.
- This structure forms a waveguide channel that directs the optical radiation towards the fiber core.
- To match the typical fiber core diameters (50-100 µm), the contact stripes for edge emitters are 50-70 µm wide.
- Length of the active region is 100-150 µm
- In the plane parallel to the junction where there is no waveguide effect, the emitted beam is Lambertian $\theta_{\parallel} = 120^\circ$ (HPBW)
- In the plane perpendicular to the junction $\theta_{\perp}$ can be made as small as $25^\circ - 35^\circ$ by a proper waveguide structure.

Light Source Materials

- Semiconductor material used for active layer of an optical source must have direct bandgap, in which radiative recombination is sufficiently high to produce an adequate level of optical emission.
- Single semiconductor element cannot act as direct bandgap material, but binary compounds act as a direct band gap material.

- Various ternary & quaternary combination of binary compounds are direct band gap materials.
- For 800-900nm spectrum, principle ternary alloy used is $Ga_{1-x}Al_x As$.

where x is mole fraction & dependence with emission wavelength & band gap energy (eV) as shown in fig 4. When $x = 0.08$, peak output power occurs at 810nm as shown in fig 5.

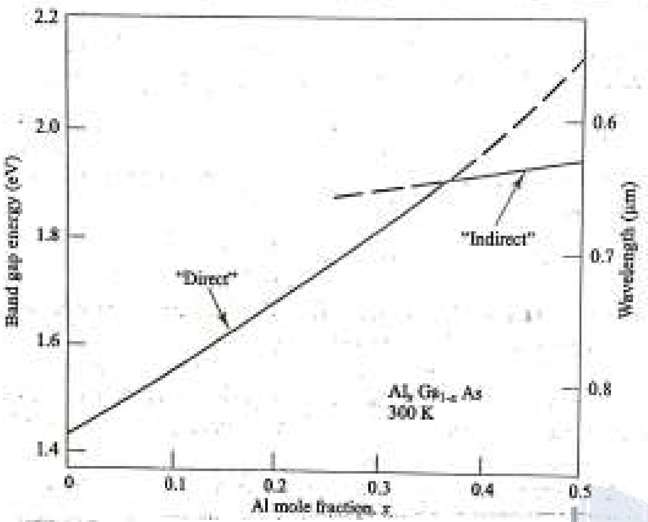


fig 4: Bandgap Energy & output wavelength as a function of aluminum mole fraction x

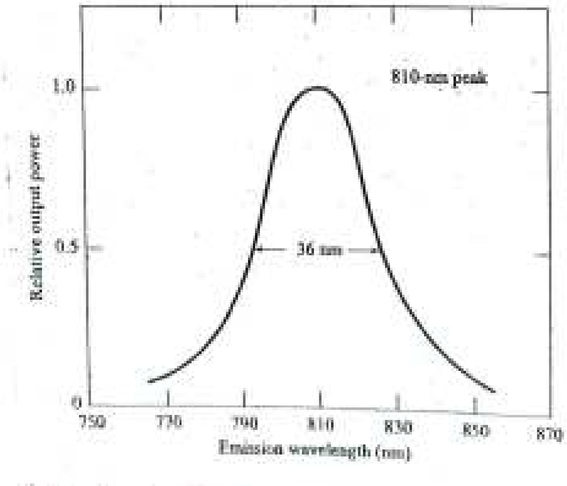


fig 5: Peak power at $x = 0.08$

- For longer wavelength of operation quaternary alloys of semiconductors are preferred
  Ex: $In_{1-x}Ga_xAs_yP_{1-y}$.
- By varying x & y, peak o/p power can be obtained at any wavelength b/w 1.0 & 1.7 um
- GaAlAs & InGaAsP are used as ligh source materials because by using a proper combination of binary, ternary & quaternary materials it is possible to match lattice parameters of hetero structure interface.

Fundamental quantum mechanical relation between Energy E & frequency ν

$\rightarrow 6.62\times10^{-34}$ [illegible]

$$E = h\nu = \frac{hc}{\lambda}$$

$\lambda \rightarrow$ peak Emission wavelength

Wavelength in terms of bandgap Energy Eg in eV is:-

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

Semiconductor Material	Bandgap Energy (ev)
Si	1.12
GaAs	1.43
Ge	0.67
InP	1.35
GaAlAs	1.51
AlAs	2.61

For Ternary Alloys,

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

for values of $x = 0$ to 0.37.

For Quaternary alloys, ($In_{1-x}Ga_xAs_{1-y}P_y$)

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

problem:

1. Compute the emitted wavelength from an optical source having $x = 0.07$.

Soln: $E_g = 1.424 + 1.266x + 0.266x^2$

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

$= 1.513$ eV

$\lambda = \frac{1.24}{E_g}$

$= \frac{1.24}{1.513}$

$\boxed{\lambda = 0.819 \mu m}$

2. For an alloy $In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$ used in LED, find wavelength emitted by the source.

Soln: $In_{1-x}Ga_xAs_yP_{1-y}$ then $x = 0.26$, $y = 0.43$

then $E_g = 1.35 - 0.72y + 0.12y^2$ (For Quaternary)

$= 1.35 - (0.72 \times 0.43) + 0.12(0.43)^2$

$=$

$\lambda = \frac{1.24}{E_g} = 1.062 \mu m$.

Quantum Efficiency & power

The internal quantum efficiency in the active region is the fraction of electron-hole pairs that recombine radiatively. It is the ratio of radiative recombination rate to total recombination rate.

Due to carrier injection an excess of electrons & hole created in p & n material respectively. Excess carrier density decays exponentially with time

$$n = n_0 e^{-t/\tau} \rightarrow ①$$

n_0 : initial injected excess $\bar{e}$ density

τ = Carrier lifetime.

The total rate at which carriers are generated is the sum of externally supplied rate & thermally generated rate.

Externally supplied rate = $\frac{J}{qd}$

where J → current density (A/cm²)
q → Electron charge
d → Thickness of recombination region

Thermally Generated rate = $-\frac{n}{\tau}$

Total rate of carriers

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

For equilibrium condition

$\boxed{n = \frac{J\tau}{qd}}$ Eqn represents steady state electron density in active region when constant current flowing through it

Internal Quantum Efficiency

Internal quantum efficiency is

$$\eta_{int} = \frac{R_r}{R_{nr}+R_r} \rightarrow ①$$

For Exponential decay of excess carriers, the radiative recombination lifetime is given as

$$\tau_r = \frac{n}{R_r} \rightarrow ②$$

where R_r is no of recombinations radiatively per unit time (Recombination rate)
n = charge density

& non-radiative recombination lifetime is given as

$$\tau_{nr} = \frac{n}{R_{nr}} \rightarrow ③$$

R_{nr} = no. of recombinations non-radiatively per unit time (Non-radiative recombination rate)

using ③ & ② in ①

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

$$= \frac{\frac{1}{\tau_r}}{\frac{1}{\tau_r}+\frac{1}{\tau_{nr}}} \rightarrow ④$$

If Total recombination lifetime $\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$ → ⑤

then Eq^n 4 becomes $\eta_{int} = \frac{\frac{1}{\tau_r}}{\frac{1}{\tau}}$

$$\boxed{\eta_{int} = \frac{\tau}{\tau_r}} \rightarrow ⑥$$

η_{int} = 50% for homojunction LED

η_{int} = 60-80% for double Heterojunction LED

If Injected current into LED is I then

$$R_r + R_{nr} = \frac{I}{q}$$

$\left[q = It \right.$

charge quantity = Amount of charge flow over a time $\left. \right]$

Since r_r or r_{nr} is no of recombination per unit time

$\therefore \frac{1}{t} = R$

or $\frac{1}{\tau_r} + \frac{1}{\tau_{nr}} = R_r + R_{nr}$

$$\eta_{int} = \frac{R_r}{I/q} \left[\because \text{of Eq}^n\ 1 \right]$$

$$R_r = \eta_{int} \cdot \frac{I}{q} \rightarrow 6$$

Multiply both sides by $h\nu$ of Eq^n ⑥

$$\underbrace{R_r \cdot h\nu}_{\downarrow \text{power}} = \eta_{int} \cdot \frac{I}{q} \cdot h\nu$$ where $h\nu \rightarrow$ photon Energy

$$\text{power}(P_{int}) = \eta_{int} \cdot \frac{I}{q} \cdot h\nu$$

$$= \eta_{int} \cdot \frac{hcI}{q\lambda}$$

where $h = 6.624 \times 10^{-34}$ J/s

$c = 3 \times 10^{8}$ m/s

$q = 1.602 \times 10^{-19}$ C

Not all internally generated photons will be available from output of device. The external quantum efficiency is used to calculate emitted power. The external quantum efficiency is defined as ratio of photons emitted from LED to the no of photons generated internally

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

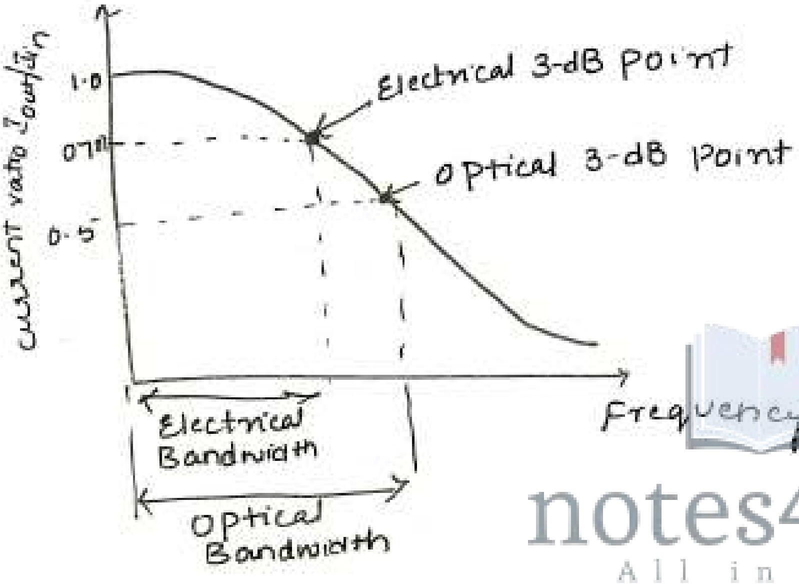
where n is refractive index.

Total power emitted by LED is

$$P = \eta_{ext} \cdot P_{int}$$

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

Modulation of an LED



- In optical communication the modulation bandwidth is defined either in terms of electrical bandwidth or in terms of optical Bandwidth as shown in above figure. Electrical Bandwidth is less than optical Bandwidth.

Modulation Bandwidth of LED is determined by :

- Doping level in active layer
- Injected carrier lifetime τ_i
- parasitic capacitance of device

problems :

1. The radiative & non-radiative recombination lifet of minority carriers in the active region of a double heterojunction LED are 60nsec & 90nsec respectively. Determine the total carrier recombination life time & optical power generated internally if the peak emission wavelength si 870nm & the drive current is 40mA.

Soln: $\lambda = 870nm = 0.87\times10^{-6} m$

$\tau_r = 60nsec$

$\tau_{nr} = 90nsec$

$I = 40mA = 0.04 Amp$

Total carrier recombination life time

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

$$= \frac{1}{60} + \frac{1}{90}$$

$$\frac{1}{\tau} = \frac{150}{5400}$$

$$\tau = 36n\,sec$$

Internal optical power :

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

$$= \left(\frac{\tau}{\tau_r}\right) \frac{hcI}{q\lambda}$$

$$= \frac{36\times10^{-9}}{60\times10^{-9}} \times \left(\frac{6.625\times10^{-34} \times 3\times10^{8} \times 0.04}{(1.602\times10^{-19})(0.87\times10^{-6})}\right) = 34.22mW.$$

A double heterojunction InGaAsP LED operating at 1310nm has radiative & non-radiative recombination times of 30 & 100ns respectively. current injected is 40mA. Calculate Bulk recombination life time, Internal quantum efficiency & Internal power level.

Soln: $\lambda = 1310nm = 1.31\times10^{-6} m$

$\tau_r = 30ns$

$\tau_{nr} = 100ns$

$I = 0.04A$

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

$$= \frac{1}{30} + \frac{1}{100}$$

$\tau = 23.07nsec$

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{23.07\times10^{-9}}{30\times10^{-9}} = 0.769 \text{ or } 76.9\%$$

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

$$= \frac{0.769\times6.625\times10^{-34}\times3\times10^{8}\times0.04}{1.602\times10^{-19}\times0.87\times10^{-6}}$$

$= 2.913mW$

3. With $n = 3.5$, find external quantum efficiency

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

$$= \frac{1}{3.5(3.5+1)^2} :$$

Advantages of LED:

- Simple design
- Easy to manufactue
- Simple System integration
- Low cost
- High reliability

Disadvantages of LED:

- Wide spectral width
- Low Intensity
- poor directiveness
- Incoherent radiated light

To overcome such problems Laser diodes are used

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LASER Diodes:

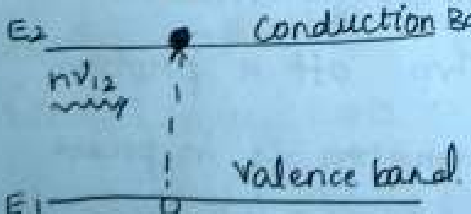
(Light Amplification by stimulated Emission of Radiation - LASER)

- Laser comes in many forms with varying dimensions. Optical fiber system uses semiconductor laser diodes
- Output of laser is highly monochromatic & light beam is very directional.

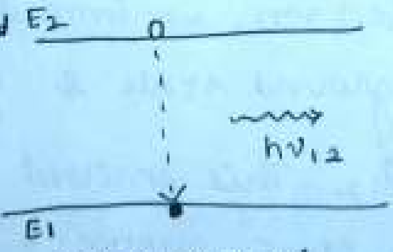
3 basic principle or processes of operation of Laser are:

- photon absorption
- Spontaneous Emission
- Stimulated Emission

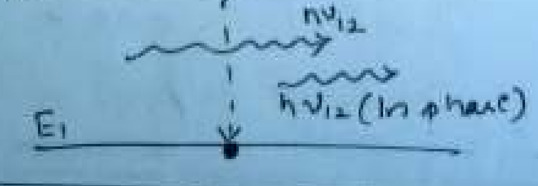
Consider a simple two level energy diagram in which $E_1 \rightarrow$ Ground state Energy & $E_2 \rightarrow$ Excited state Energy.



a) Absorption



b) Spontaneous Emission



- According to plancks law, a transition between E_1 & E_2 states involves absorption or emission of a photon of energy $h\nu_{12} = E_2 E_1$

- Normally system is in ground state. When a photon of Energy $h\nu_{12}$ impinges on system, an electron in state E_1 can absorb the photon energy & be excited to state E_2 as shown in fig a.

- Since this is an unstable state, the electron will shortly return to ground state, thereby emitting a photon of energy $h\nu_{12}$. This occurs without external stimulation & is called spontaneous emission as shown in b).

- Electron can also be induced to make a downward transition from the excited level to ground state level by an external stimulation as shown in fig c. If a photon of energy $h\nu_{12}$ impinges on the system while the electron is still in excited state, the electron is immediately stimulated to drop to the ground state & gives off a photon of Energy $h\nu_{12}$. This emitted photon is in phase with the incident photon & resultant emission is known as stimulated Emission.

Population Inversion :

- Stimulated Emission will exceed absorption only if the population of the excited state is greater than that of the ground state. This condition is known as population Inversion.
- population inversion is not an equilibrium condition & this condition is usually achieved by various pumping techniques.
- In semiconductor lasers, population Inversion is achieved by injecting electrons into the material at device contacts to fill lower Energy states of conduction band

Laser Diode modes & threshold Conditions:

For optical Fiber Communication systems requiring bandwidths greater than 200MHz, the semiconductor injection laser diode is prefered over LED.

characteristics of LASER that makes it as an unique choice for OFC are

- Response time < 1ns
- Spectral width of 2nm or Less
- Power coupled is tens of milliwatts of useful luminescent power.

2 Configuration of LASER :

* Fabry perot Cavity resonator * Distributed Feedback laser

Modes of the cavity :

* optical radiation within the resonance cavity of a laser diode sets up a pattern of electric & magnetic field patterns (or) lines called as modes of cavity
* It can be transverse Electric (TE) or transverse magnetic (TM) mode
* Each set of modes can be described in terms of longitudinal, lateral, transverse variation of EM fields along the major axis of the cavity.

Longitudinal modes :

* Related to length 'L' of cavity
* Determines the principle structure of frequency spectrum of emitted optical radiation
* If length of cavity is larger, so many longitudinal modes exists.

Lateral modes :

* These modes lies in the pn junction
* It depends on the side wall preparation width of the cavity.
* It determines the shape of lateral profile of laser beam

Transverse Mode:

- It is associated with EM field & beam profile in direction perpendicular to the plane of pn junction.
- These modes determine the characteristics of radiation pattern & threshold current density so it is of great importance

Fabry perot Laser

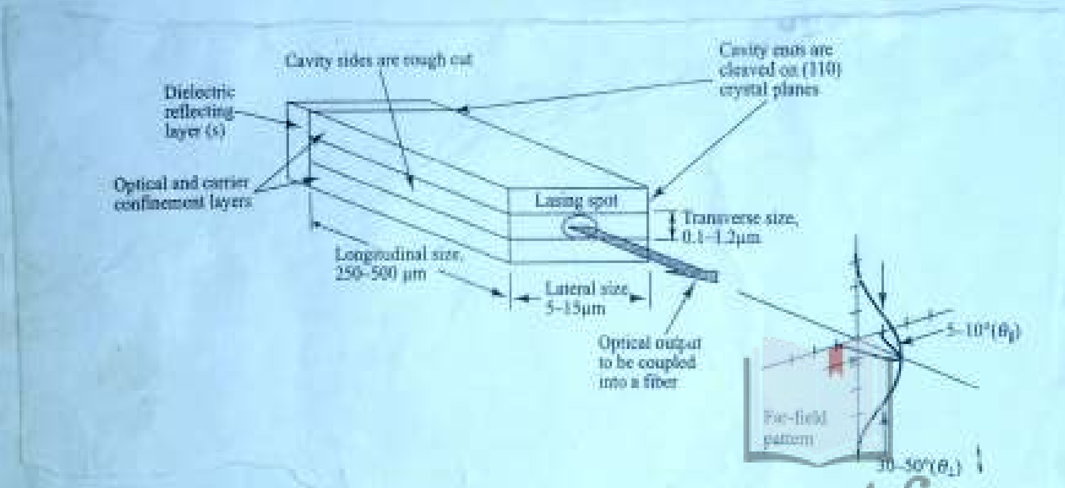


fig Fabry perot resonator cavity for a laser diode

- It is a laser diode configuration as shown in above figure which generates radiation.
- The Cavity has the following small dimensions

Longitudinal dimension : 250-500 um long
Lateral Dimension : 5-15um wide
Transverse Dimension : 0.1 - 0.2 um Thick.

Resonator Cavity:

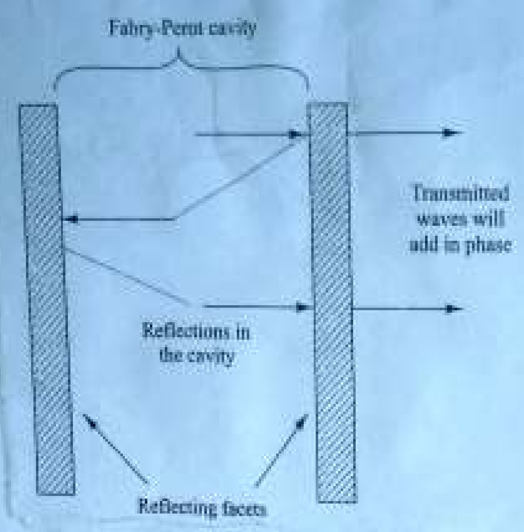


fig: Two parallel light-reflecting mirrored surface.

- Two flat partially reflecting mirrors are directed towards each other to enclose the fabry perot resonator cavity as shown in above figure
- Mirror facets are constructed by making 2 parallel clefts along the natural cleavage planes of semiconductor crystal.
- purpose of mirror is to establish a strong optical feedback in the longitudinal direction.
- Feedback mechanism converts the device into an oscillator & hence a light emitter.
- The unwanted emission in the lateral direction is avoided by roughing the edges of the device.
- Also the gain mechanism compensates for optical losses in cavity at resonant optical frequency

Mechanism:

- Light travels back & forth in the cavity, the electric field of light will interfere on successive round trips.
- Those wavelength that are integer multiples of cavity length interfere constructively, so that their amplitudes will add when they exit the device at right side.
- All other wavelengths interfere destructively, cancels out.
- optical frequencies at which constructive interference occurs are resonant frequencies of the cavity
- Spontaneously emitted photons that have wavelengths at these resonant frequencies reinforce themselves after multiple trips through the cavity so that the optical field becomes very strong.
- The resonant wavelengths are called longitudinal modes of the cavity, since they resonate along the length of cavity.

Figure in the next page (fig a) shows resonant wavelengths for 3 values of mirror reflectivity. from fig it is clear that width of the resonance peaks depends on reflectivity & resonance becomes sharper as reflectivity increases

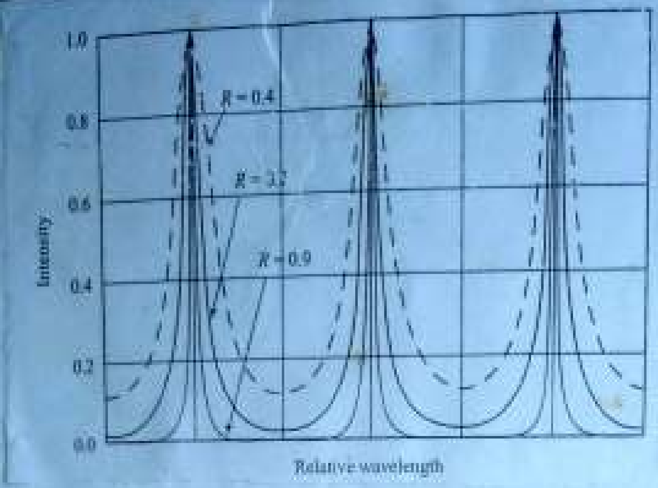


fig a. Behavior of resonant wavelengths in a Fabry-perot cavity for three values of mirror reflectivity.

Distributed Feedback Laser

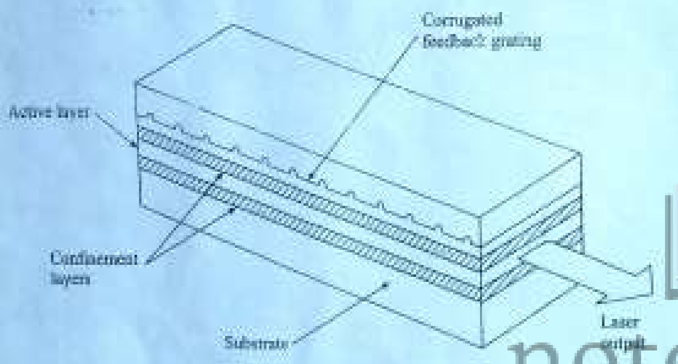


fig: Structure of a distributed-feedback (DFB) laser diode.

- As shown in above fig, the cleaved facets are not required for optical feedback
- Fabrication is similar to fabry perot type except lasing action is obtained from Bragg reflectors (gratings) or periodic variations of refractive index which are incorporated into the

the multilayer structure along the length of diode

- In general, output is needed only from the front facet of laser which is going to be aligned to optical fiber.
- A dielectric reflector can be deposited on the rear laser facet to reduce optical losses in the cavity to reduce threshold current density & increase external quantum efficiency.

Disadvantages of LASER

- Laser are expensive as compared to LEDs
- Amplitude modulation using an analog signal is difficult with most laser because laser output signal power is generally nonlinear with input power.

Photodetectors :-

→ At the output of optical transmission line, there must be a receiving device which interprets the information contained in optical signal.

→ The first element of the receiver is a photodetecto

→ The photodetector senses the luminescent power falling upon it and ~~senses~~ converts the variation of this optical power into a correspondingly varying electric current.

→ Since the optical signal is generally weakened and distorted when it emerges from the end of the fiber, so the photodetectors must meet very high performance requirements.

The foremost of these requirements are

- high response or sensitivity in the emission wavelength range of the optical source that is used
- minimum addition of noise to the system.
- Fast response speed.
- sufficient bandwidth to handle desired data rate.
- It should be insensitive to temperature variations.
- It should be compatible with the physical dimension of optical fiber.
- Resonable cost and long operating life.

Several different types of photodetectors are available. To name a few

- ↳ photo multipliers
- ↳ Pyroelectric detectors.
- ↳ semiconductor based photoconductors.
- ↳ Phototransistors.
- ↳ Photo diodes.

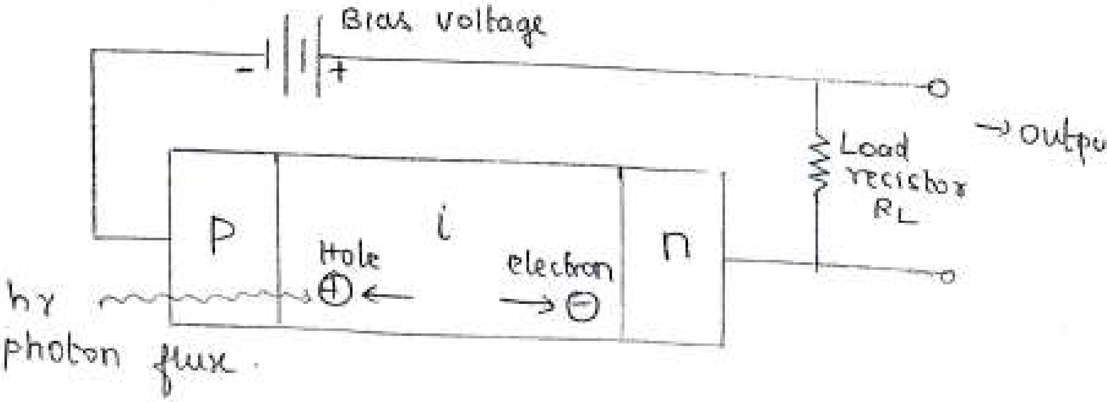
Of the semiconductor based photodectors, photodiodes is used almo for a fiber optic system, because of its high sensitivity and fast response time.

The two types of photodiodes used are

- ↳ pin photodetector.
- ↳ Avalanche photodiode (APD).

Pin Photodetector:-

The device structure consist of p and n region separated by a very lightly doped intrinsic (i) re

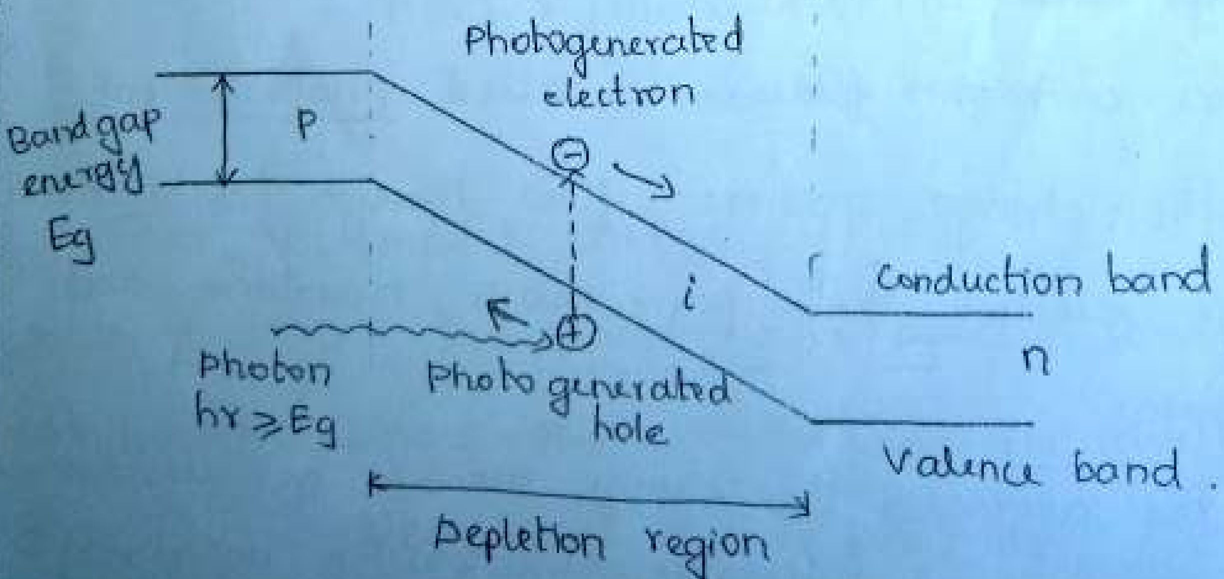


In normal operation, a sufficiently large reverse bias voltage is applied across the device so that the intrinsic region is fully depleted of carriers (ie) the intrinsic n and p carrier concentration are negligibly small in comparison with impurity concentration in this region.

Operation:-

→ When an incident photon has an energy greater than or equal to the band gap energy of the semiconductor material, the photon can give up its energy and excite and electron from the valence band to the conduction band.

→ This process generates mobile electron - hole pairs and these electrons and holes are known as photocarriers.



→ Photon generated carriers are available to pro
a current flow when a bias voltage is appl
across the device.

→ The no. of charge carriers is controlled by the concentration level of impurity elements that are intentionally added to the material.

→ The photodetector is normally designed so that these carriers are generated mainly in depletion region where most of the incident light is absorbed.

→ The high electric field present in the depletion region causes the carriers to separate and be collected across the reverse biased junction.

→ They give rise to a current flow in an external circuit with one electron flowing for every carrier pair generated.

→ This current flow is called photocurrent.

As the charge carriers flow through the material, some electron-hole pairs will recombine and disappear.

Extra

On the average, the charge carriers (ie) electrons and holes moves a distance L_n (or) L_p respectively

This distance is known as diffusion length.

The time that an electron or holes takes to recombine is known as carrier lifetime, and is represented as τ_n and τ_p respectively.

The lifetime and the diffusion lengths are related by the expressions

$$L_n = (D_n \tau_n)^{1/2} \quad \& \quad L_p = (D_p \tau_p)^{1/2}.$$

D_n & D_p → Diffusion coefficients of electron an
hole in cm^2/s.

As a photon flux ϕ penetrates into a semiconduc
it will be absorbed as it passes through the material.

consider if P_{in} → optical power falling on the photodetector at $x=0$.

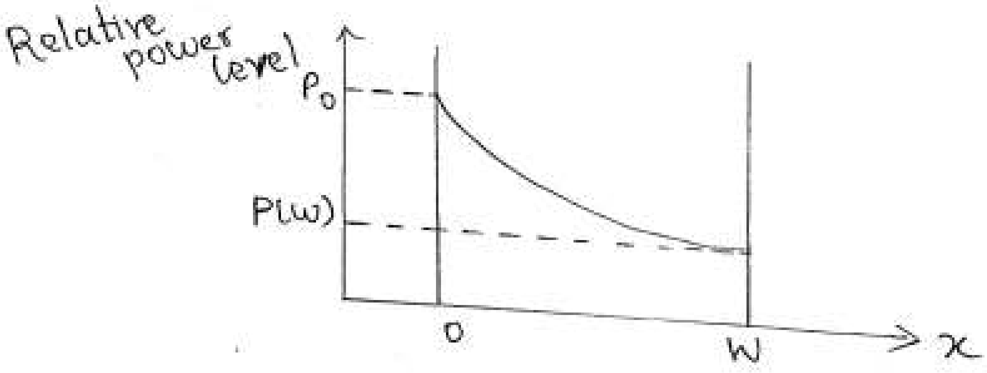
& $P(x)$ → power level at ~~at~~ a distance 'x' into the material.

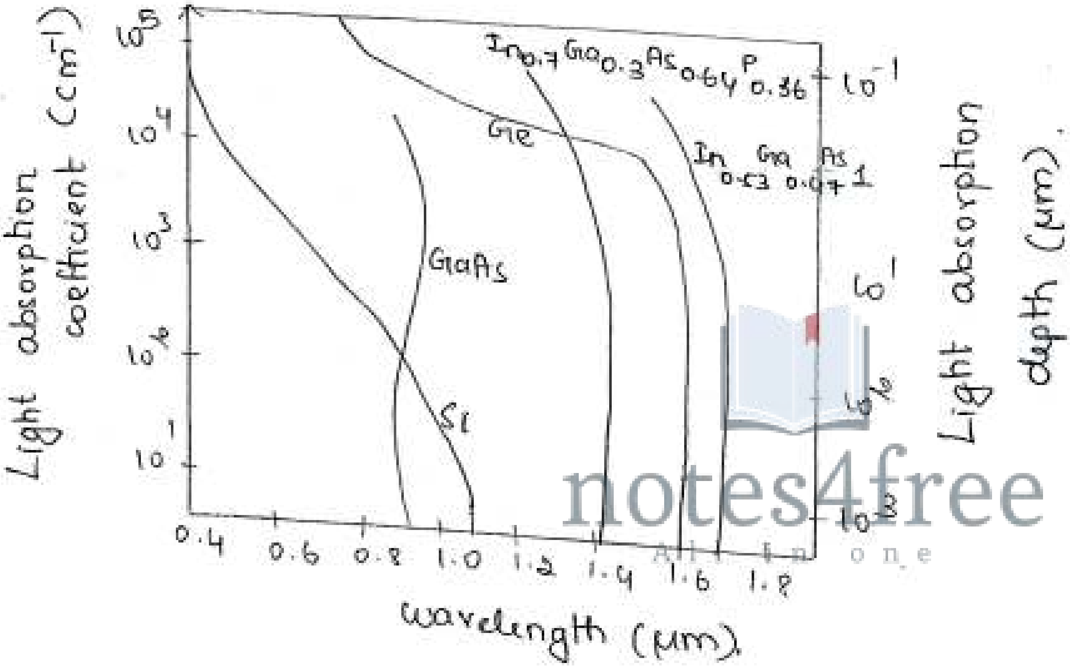
Then incremental change $dP(x)$ in the optical power level as this photon flux passes through an incremental distance 'dx' in the semiconductor is given by $dP(x) = -\alpha_s(\lambda)\, P(x)\, dx$

where $\alpha_s(\lambda) \rightarrow$ photon absorption coefficient at a wavelength (λ)

Integrating the above relationship gives the power level at a distance x into the material as.

$$P(x) = P_{in} \exp(-\alpha_s \cdot x)$$





The above diagram shows the dependence of optical absorption coefficient on wavelength for various photodiode materials.

It is clear that α_s depends strongly on wavelength.

⇒ A particular semiconductor material can be used only over a limited wavelength range. The upper wavelength cut off is determined by the bandgap energy (E_g) of the material.

$$\lambda_c\,(\mu m) = \frac{hc}{E_g} = \frac{1.24}{E_g\,(eV)}.$$

λ_c for Si ⇒ 1.06 μm λ_c for Ge = 1.6 μm.

So it is clear that for longer wavelengths, the photon energy is not sufficient to excite an e^- from valence to conduction band.

Also at lower wavelength end, the photoresponse cuts off for large values of α_s, because photons are absorbed very close to photodetector surface, where the recombination time of generated e^- + hole pairs is short. So they recombine before they can b collected by photodetector circuitry.

If the depletion region has a width (w) then the total power absorbed in the distance w is given by.

$$P(w) = \int_0^w \alpha_s P_{in} \exp(-\alpha_s \cdot x)\, dx \quad P_{in}(1 - e^{-\alpha_s w})$$

If R_f → Reflectivity at the entrance face of the power absorption is given as.

$$I_P = \frac{q}{h\nu} P_{in} \left(1 - e^{-\alpha_s W}\right)(1 - R_f)$$

where P_{in} → optical incident power on the photodetector.

q → electron charge.

$h\nu$ → photon energy.] *Extra

characteristics of photodiode:

The two important characteristics of photo detector are

- Quantum efficiency.
- Response speed.

The two parameters depend majorly on

- material bandgap
- operating wavelength.
- doping & thickness of p, i, n regions of the device.

Quantum efficiency:-

↳ no. of electron-hole pair generated per incident photon of energy $h\nu$

$$\eta = \frac{\text{no. of electron-hole pair generated}}{\text{no. of incident photons}} = \frac{I_P/q}{P_{in}/h\nu}$$

where I_p → photo current generated by a steady state optical power P_{in} that is incident on the photodetector.

Eg: In a photodiode if 100 photons creates 30 to 95 electron hole pairs then η = 30 to 95%

To achieve high quantum efficiency, the depletion layer must be thick enough to permit a large fraction of the incident light to be absorbed.

Thicker depletion layer will make the photogenerated carriers to take longer time to drift across the reverse biased region.

carrier drift time determines response speed so a compromise is done b/w response speed and quantum efficiency.

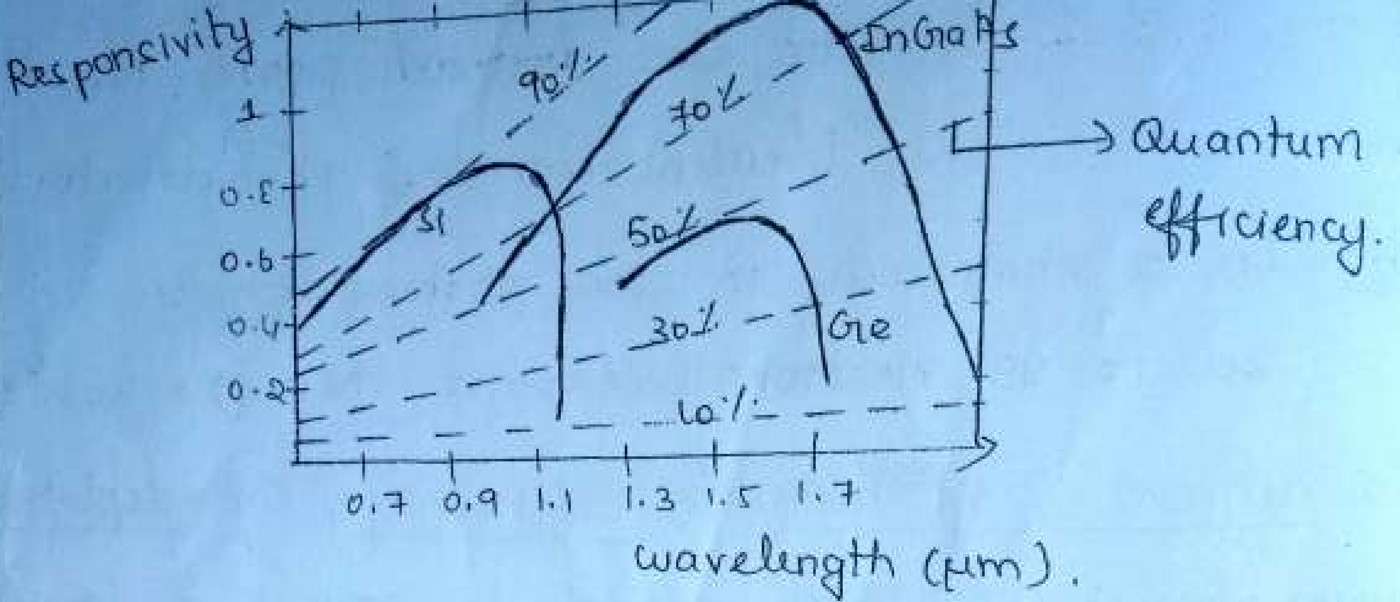
The performance of a photodiode is often characterized by the responsivity "R"

R is related to quantum efficiency as.

$$R = \frac{I_p}{P_{in}} = \frac{\eta q}{h\nu}.$$

This specifies the photocurrent generated per unit optical ~~of~~ power.

The following figure shows comparison of 'η' & 'R' as a function of wavelength (λ).



Note:

→ Quantum efficiency is not constant at all wavelength since it varies according to photon energy.

→ Responsivity falls off rapidly beyond cut off wavelength because photon energy becomes less than that required to excite an ~~photon~~ electron from valence to conduction band.

Avalanche Photodiodes :- (APD)

→ APD internally multiply the primary sgl photocurren before it enters the input circuitry of the amplifier

→ This increases the receiver sensitivity, since the photocurrent is multiplied before encountering the thermal noise associated with receiver circuit.

Basic principle:

→ For carrier multiplication to take place, the photo generated carriers are made to traverse a region where a very high electric field is present.

→ In this high field region, a photogenerated electron or hole gain enough energy so that it ionizes bour electrons in the valence band upon colloiding with them.

→ This carrier multiplication mechanism is known as Impact ionization.

→ The newly created carriers are also accelerated by the high electric field, thus gaining enough energy to cause furthur impact ionization.

→ This phenomenon is called avalanche effect.

→ so below the diode breakdown voltage a finite total no. of carriers are created whereas above the breakdown the no. of carriers can be infinite.

A commonly used structure for achieving car multiplication is called reach through constructi

Construction:-

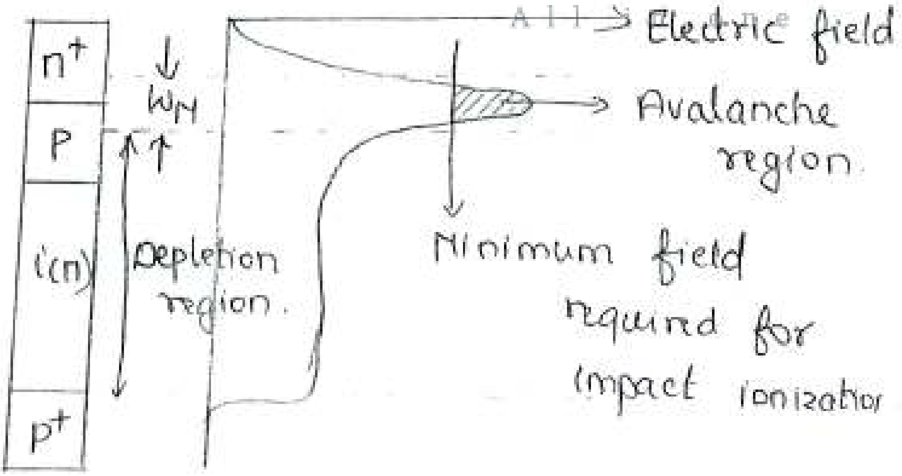
→ The Reach through Avalanche photo Diode (RAPD) is composed of high resistivity p type material deposited as an epitaxial layer ~~of~~ on a p^+ (ie heavily doped p-type) substrate.

→ A p-type diffusion or ion implant is then made in the high resistive material, followed by the construction of an n^+ (heavily doped n-type) layer

→ For silicon, the dopants used to form these layers are normally boron and phosphorus respectively.

→ This configuration is referred to as $p^+ \pi p n^+$ reach through structure.

→ The π layer is basically an intrinsic material that inadvertenty has some p doping because of imperfect purification.



operation:

→ The term reach through arises from the photodiode operation.

→ When a low reverse bias voltage is applied, most of the potential drop ~~act~~ is across pn^+ junction

→ The depletion region widens with increasing bias until a certain voltage is reached at which the peak electric field at the pn^+ junction is about 5-10 % below that needed to cross avalanche breakdown.

→ At this point, the depletion layer just "reaches through" to nearly intrinsic π region.

→ In normal usage, the RAPD is operated in fully depleted mode.

→ Light enters the device through the p^+ region and is absorbed in π-region.

→ Upon being absorbed the photon gives up its energy thereby creating electron-hole pairs.

→ The electron-hole pairs are then separated by the electric field in the π-region.

→ These carriers drift through the π-region in the pn^+ junction where a high electric field exists.

→ It is in this high field region, the carrier multiplication takes place.

→ The average no. of electron-hole pairs created by a carrier per unit distance traveled is called the ionization rate.

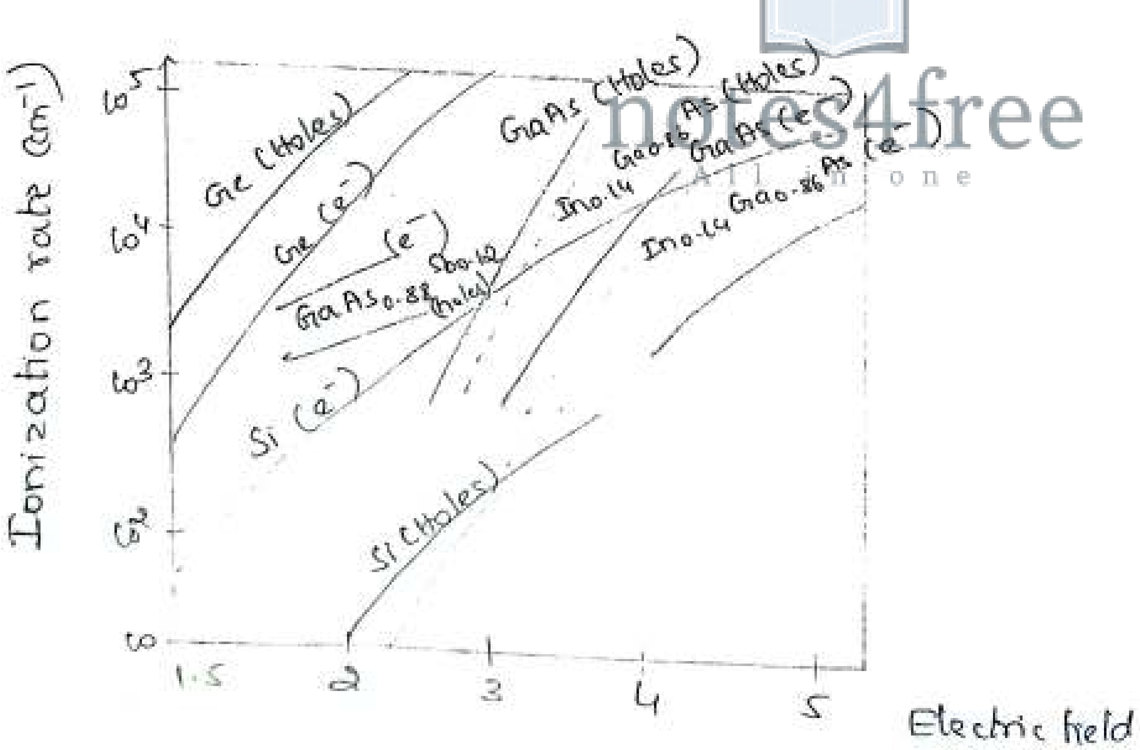
Mostly semiconductor materials exhibit different ionization rate for electron and hole

(ie) $\alpha \rightarrow$ electron ionization rate.

$\beta \rightarrow$ hole ionization rate.

$k = \beta/\alpha$ → measure of photo detector performance

The following diagram shows α and β (experimentally obtained) values for 5 different semiconductor material, and it is obvious that only silicon has significant difference in α and β values.



The multiplication M for all carriers generated in photodiode is defined by

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

where I_M → average value of total multiplied output current.

I_p → primary unmultiplied photo current.

Analogous to the pin photodiode, the performance of an APD is characterized by responcivity, which is given by.

$$R_{APD} = \frac{\eta q}{h\nu} . M$$

$$R_{APD} = R . M$$

where R → unity gain responsivity.

Responce time :-

The response time of a photodiode depends on the following three factors.

→ transit time of photocarriers in the depletion region.

→ Diffusion time of photocarriers generated outside the depletion region.

→ RC time constant of the photo diode and
associated circuit.

The parameters responsible for these three factor
are the

- ↳ absorption coefficient (α_s)
- ↳ depletion region width (w).
- ↳ Photodiode junction capacitance.
- ↳ amplifier capacitance.
- ↳ detector load resistance.
- ↳ amplifier i/p resistance.
- ↳ photo diode series resistance.

~~Transit time of photodectorst~~:-

Transit time of photocarriers in the depletion region:-

The response speed of the photodiode is limite by the time taken by the photo carriers to trave across the depletion region which is known as ~~the~~ transit time.

The transit time ~~dt~~ is given as

$$t_d = \frac{w}{v_d}.$$

where $V_d \rightarrow$ carrier drift velocity

$w \rightarrow$ depletion layer width.

For silicon material the maximum velocities of electrons and holes are

8.4×10^6 cm/s & 4.4×10^6 cm/s.

when the electric field strength $= 2 \times 10^4$ V/cm.

If $w = 10 \mu m$

then a high speed silicon photodiode will have response time limit of 0.1 ns.

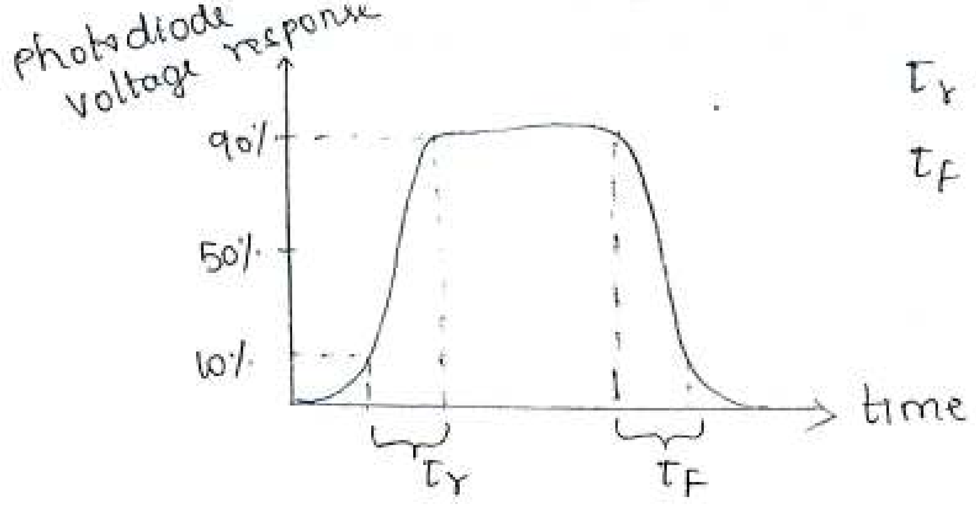
Diffusion time:-

→ In a high field region the diffusion process is slow compared with the drift of carriers.

→ For a high speed photodiode, the photo carriers should be generated in the depletion region or close to it, because of which diffusion time is less than carrier drift times.

→ The effect of long diffusion time can be understood by considering photodiode response time

→ Response time is described by rise time & fall time of detector output when it is illuminated by optical step input.



τ_r → rise time

τ_F → fall time

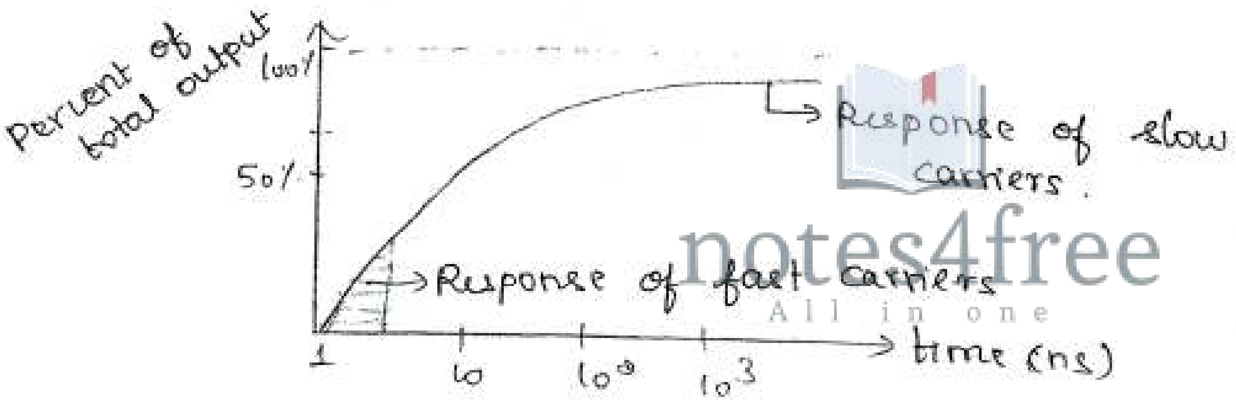
τ_r → 10 to 90% points on the leading edge.

τ_F → 90 to 10% points on falling edge.

For fully depleted photodiodes $\tau_r = \tau_F$.

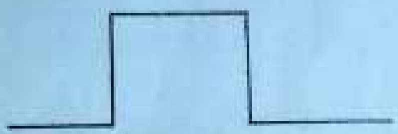
For low bias levels ⇒ photodiodes are not fully depleted so $\tau_r \neq \tau_F$.

The typical response time of partially depleted photodiodes is shown below.

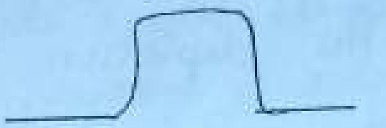


The fast carriers allows the device output to rise to 50% of maximum value in ≃ 1ns, slow carriers causes relatively long delay before the output reaches maximum value.

To achieve high quantum efficiency, one depletion layer width must be much larger than $1/\alpha_s$ (ie) $W >> 1/\alpha_s$, so that most of the light will be absorbed. (provided the capacitance of photodiode is kept low and i/p pulse is rectangula



Rectangular i/p pulse

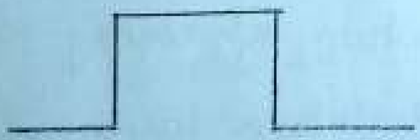


Response of photodiod for $W >> 1/\alpha_s$ & small C_j.

α_s → absorption coefficient

C_j → Junction capacitance.

If photodiode capacitance is larger then the response time is limited by RC time constant of load resistance R_L and photodiode capacitance.

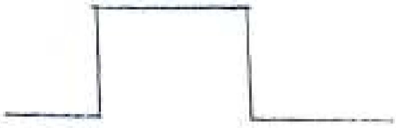


Rectangular i/p pulse

Response of photodiode
$W >> 1/\alpha_s$
large C_j.

If the depletion layer width is small (ie) $W << 1/\alpha_s$. then the photodiode response tend to show distinct fast and slow components.

Rectangular i/p pulse



Photodiode response

$w \leq 1/\alpha_s$

small C_j

The fast component is due to carriers generated in the depletion region.

Slow components arises from diffusion of carriers that are created at a distance L_n ~~far~~ from the edge of depletion region.

If w is too thin then junction capacitance will become excessive

$$C_j = \frac{\varepsilon_s A}{w}$$

where ε_s → permittivity of semiconductor matrix

A → diffusion layer area.

To have resonably high quantum efficiency a compromise in width of depletion layer should be done, as

$$1/\alpha_s < w < 2/\alpha_s.$$

Problems

1. A photodiode has a quantum efficiency of 65% when photons of Energy 1.5×10^{-19} J are incident upon it.

1. At what wavelength is photodiode operating?
2. Calculate incident optical power required to obtain a photocurrent of $2.5\,\mu A$ when the photodiode is operating as described above.

1. $\lambda_c = \frac{hc}{E_g} = \frac{6.624\times10^{-34}\times3\times10^{8}}{1.5\times10^{-19}} = 1.32\,\mu m$

2. $\eta = \frac{I_{ph}\nu}{P_{in} q}$

$$P_{in} = \frac{I_p h c}{\eta q \lambda}$$

$$= \frac{2.5\times10^{-6}\times6.624\times10^{-34}\times3\times10^{8}}{0.65\times1.6\times10^{-19}\times1.32\times10^{-6}}$$

$= 3.6\,\mu W$.

2. Photons of energy 1.53×10^{-19} J are incident on a photodiode which has a responsivity of 0.65 A/W. If the optical power level is $10\,\mu W$. Find Generated photocurrent.

$I_p = R P_{in}$

$= (0.65)(10\mu) = 6.5\,\mu A$

3 In a 100ns pulse, 6×10^6 photons at a wavelength of 1300nm falls on a InGaAs photodetector. On the average, 5.4×10^6 electron hole pairs are generated. Find quantum efficiency.

$$\eta = \frac{\text{no of e-h pair generated}}{\text{no of incident photon}} = \frac{5.4\times10^6}{6\times10^6} = 0.9$$

90% Efficiency

4 A given silicon avalanche photodiode has a quantum efficiency of 65 percent at a wavelength of 900 nm. Suppose 0.5 μW of optical power produces a multiplied photocurrent of 10μA. Find multiplication factor M.

Primary photocurrent $I_p = RP_{in} = \frac{\eta q}{h\nu}P_{in}$

$$= \frac{\eta q\lambda}{hc}P_{in}$$

$$= \frac{0.65\times1.6\times10^{-19}\times0.5\times10^{-6}}{6.625\times10^{-34}\times3\times10^{8}}$$

$= 0.235\mu A$

$$M = \frac{I_m}{I_p} = \frac{10\mu A}{0.235\mu A} = 43$$

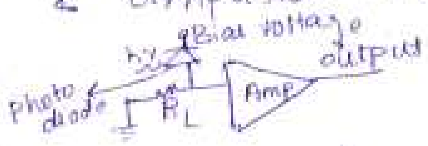
Thus the primary photocurrent is multiplied by a factor of 43.

Photodetector Noise

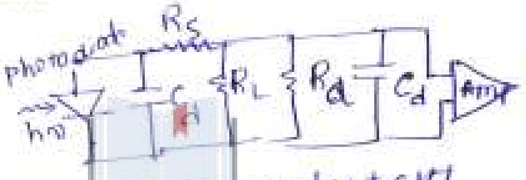
In optic fiber communication system, photodiode is generally required to detect very weak optical signals. Detection of the weakest possible optical signals requires that the photodetector & its following amplification circuitary to be optimized so that a given signal-to-noise ratio to be maintained.

To achieve high SNR, following conditions should be met :

- Photodetector must have a high quantum efficiency to generate a large signal power
- photodetector & amplifier noise should be kept as low as possible



photodetector Receiver



its Equivalent ckt

Noise sources :

principle noises :

principle noises associated with photodetectors that have no internal gain are :

- Quantum noise
- Dark current noise generated in bulk material of photodiode
- Surface leakage current noise

- Quantum or shot noise arises from statistical nature of production & collection of photoelectrons when an optical signal is incident on a photodetector. The short noise current has a mean square value in a receiver Bandwidth B_e which is proportional to average value of photocurrent I_p.

$$\langle i^2_{shot} \rangle = \sigma^2_{shot} = 2q I_p B_e M^2 F(M)$$

where F(M) is noise figure

M is multiplication factor or Gain.

- The photodiode dark current is the current that continues to flow through bias circuit of device when no light is incidence on photodiode. It is combination of bulk & surface current.

- Bulk dark current i_{DB} arises from electrons & holes which are thermally generated in pn junction of photodiode. Mean square value of this current is given by $\langle i^2_{DB} \rangle = \sigma^2_{DB} = 2q I_D M^2 F(M) B_e$

I_D is primary detector Bulk dark current

Surface Dark current or surface leakage current is due to surface defect, cleanliness, bias voltage & surface area & can be reduced through use of guard ring structure which shunts surface leakage current away from load resistor. Mean square value of surface dark current is given by

$$\langle i^2_{DS} \rangle = \sigma^2_{DS} = 2qI_L B_e .$$

where I_L is surface leakage current

photodetector noise current $\langle i^2_N \rangle$ is given by

$$\langle i^2_N \rangle = \sigma^2_N = \langle i^2_{shot} \rangle + \langle i^2_{DB} \rangle + \langle i^2_{DS} \rangle$$

$$= \sigma^2_{shot} + \sigma^2_{DB} + \sigma^2_{DS}$$

$$= 2q(I_P + I_D) M^2 F(M) B_e + 2qI_L B_e$$

problem ;

An InGaAs pin photodiode has $\lambda = 1300\,nm$, $I_D = 4\,nA$, $\eta = 0.9$ $R_L = 1000\,\Omega$ surface leakage is negligible. $P_{in} = 300\,nW$ $B_e = 20\,MHz$. Find various noise terms.

$$P_{in} = \frac{I_p h c}{\eta q \lambda} = .$$

$I_P = 0.282\,uA$

$$\langle I^2_{shot} \rangle = 2qI_P B_e$$

$$= 2 \times 1.6 \times 10^{-19} \times 0.282 \times 10^{-6} \times 20 \times 10^{6}$$

$$= 1.8 \times 10^{-18} A^2$$

$\langle I_{DB}^{2} \rangle = 2q I_D B_e$

$= 2\times1.6\times10^{-19}\times4\times10^{-9}\times20\times10^{6}$

$= 2.56\times10^{-20}\ A^2$

If R_T is combination of load & amplifier input resistance & C_T is sum of photodiode & amplifier capacitance as shown in previous figure, the detector behave like a simple RC low pass filter with B.W

$$B_c = \frac{1}{2\pi R_T C_T}$$

* problem :

1. If the photodiode capacitance is 3pF, Amplifier capacitance is 4pF, load resistor is 1KΩ & amplifier input resistance is 1MΩ. Find circuit Bandwidth.

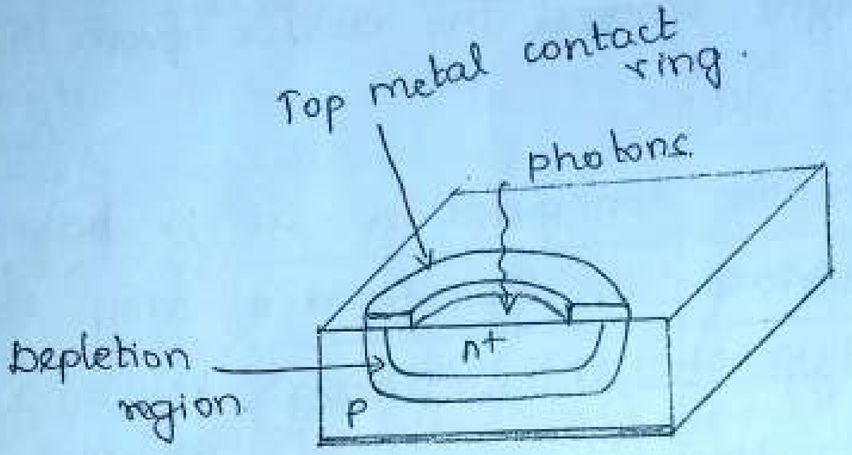
$C_T = 3+4 = 7pF$

$R_T = \dfrac{1K\times1M}{1K+1M} \approx 1K\Omega$

$B_c = \dfrac{1}{2\pi R_T C_T} = \dfrac{1}{2\pi\times7\times10^{-12}\times1\times10^{3}} = 23MHz$

Double hetrostructure photodiodes:-

The performance of pin photodiodes can be significantly increased by using double hetero structure design similar to that employed in semiconductor laser.



→ In this design the central intrinsic layer (the depletion region) is sandwiched b/w differen p-type and n-type semiconductor layers.

→ The bandgap of these layers are choosen such that only intrinsic region absorbs light.

Consider a pin photodiode structure for 1550 laser application uses $In_{1-x}Ga_xAs$ for the intrinsic layer, and InP for adjacent lattice matched p+ n-type layers.

It is known that band gap of InP = 1.35 eV.

so it is transparent to light ~~at~~
$\lambda \geq 920nm$.

when $x = 0.47$

The band gap of intrinsic region is 0.73 eV

$\Rightarrow$ $\lambda = 1700\text{nm}$ in that material.

Operation:-

→ The light enters the device from the top through 'n' layer.

→ A common configuration is to have the top metallic contact in the form of ring, thus enabling light to enter through the ring.

→ Rest of the operation is similar to the normal photodiode operation.

Comparison of photodetectors

Table: Generic operating parameters of Si, Ge & InGaAs pin photodiodes

parameter	Symbol	unit	Si	Ge	InGaAs
Wavelength Range	λ	nm	400-1100	800-1650	1100-1700
Responsivity	R	A/W	0.4-0.6	0.4-0.5	0.75-0.95
Dark current	I_D	nA	1-10	50-500	0.5-2.0
Rise Time	τ_r	ns	0.5-1	0.1-0.5	0.05-0.5
Modulation Bandwidth	B_m	GHz	0.3-0.7	0.5-3	1-2
Bias voltage	V_B	V	5	5-10	5

Table: Generic operating parameters of Si, Ge & InGaAs Avalanche photodiode

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_r	ns	0.1-2	0.5-0.8	0.1-0.5
Gain.Bandwidth	$M \cdot B_m$	GHz	100-400	2-10	20-250
Bias voltage	V_B	V	150-400	20-40	20-30

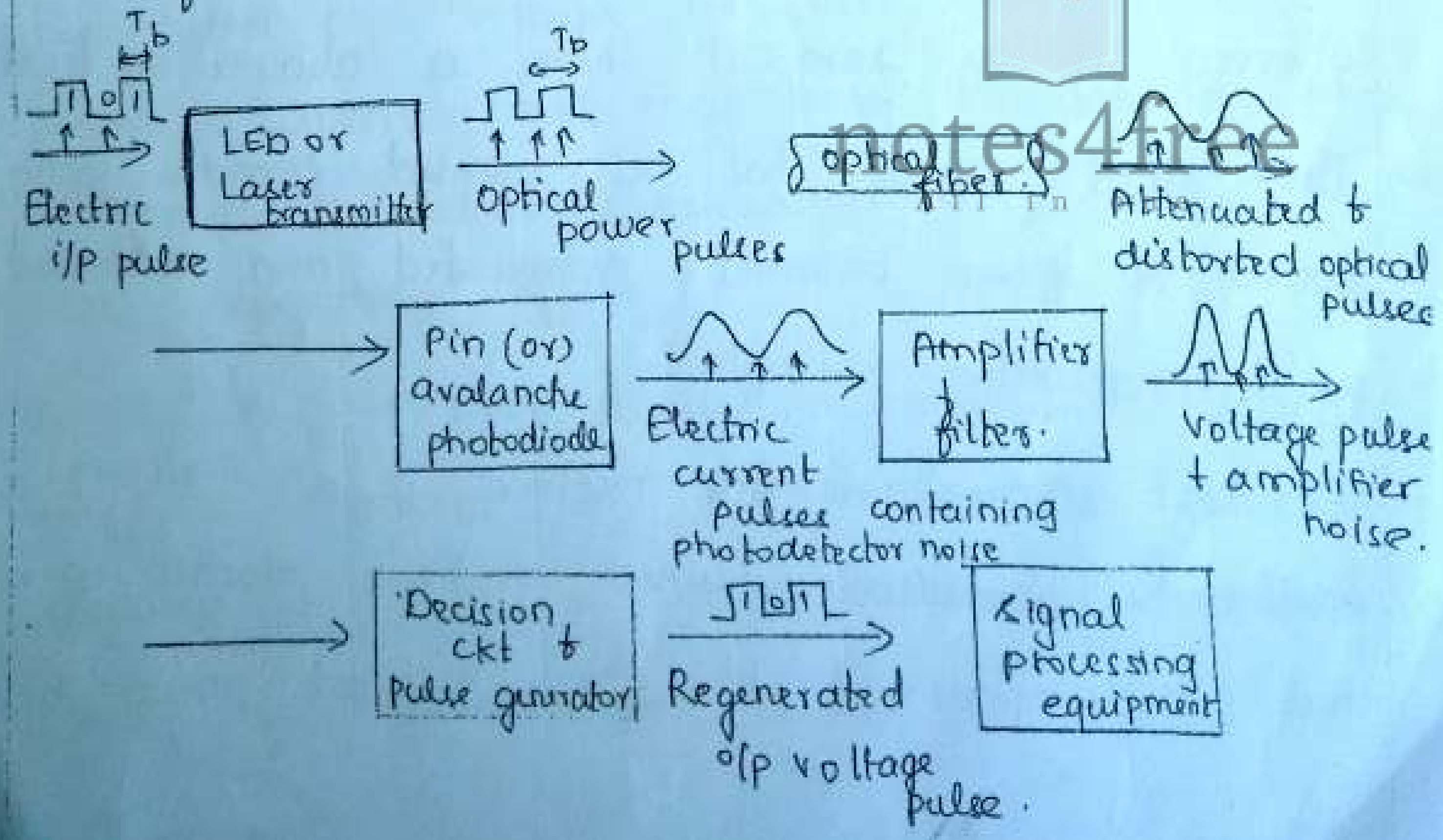
Optical Receiver

Fundamental Receiver operation:-

→The design of an optical receiver is much more complicated than that of an optical transmitter because the receiver must be able to detect weak, distorted signals and make decisions on what type of data was sent

The following diagram illustrates the shape of a digital signal at different points along a optical link.

→The transmitted data is two level binary data stream consisting of either 1 (or) 0 in a time slot of duration "T_b" (bit period).



↑ → denotes the time slot centers.

→ Electrically there are many ways of sending a given digital message, one of the simplest technique is amplitude shift keying. (ASK) or (OOK)

→ In this technique, the voltage level is switched b/w 2 values (ie) 1 (or) 0.

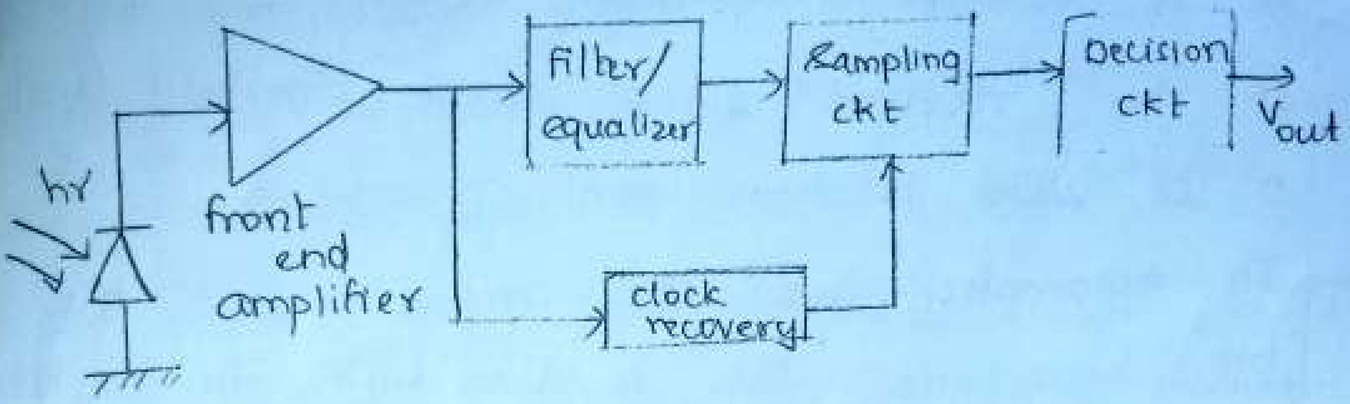
→ The function of optical transmitter is to convert the electrical signal to optical signal.

→ One way of doing this is by directly modulating the light source drive current with the info stream to produce a varying optical o/p power P(t).

→ Thus optical signal from LED (or) Laser is 1 if a pulse of optical power is present for T_b Whereas it is zero if there is absence of light

→ The optical signal that is coupled from the light source to fiber becomes attenuated and distorted as it propagates through it.

→ The first element of the receiver is a PIN (or) avalanche photodiode, which produces electric current that is proportional to the received power level



→ The electric current produced is very weak, so a front end amplifier boosts it to a level that can be used by the following circuitry.

→ After the signal is amplified, it passes through a low pass filter to reduce the noise outside the signal bandwidth. So filter defines the receiver bandwidth.

→ To minimise the effects of Inter symbol interference the filter can reshape the pulses that have become distorted as they travel through the fiber. This process is called equalization. It cancels pulse spreading effects.

→ Finally a decision circuit samples the signal level at midpoint of each time slot and compares it with a certain reference voltage known as threshold level.

- If the received signal is > threshold level, then 1 is said to have been received.
- If the received signal is < threshold level, then 0 is said to have been received.
- To accomplish this, the receiver must the bit boundaries. This is done with the assistance of a periodic waveform called a clock. (periodicity is equal to Tb of transmitted sgl). This process is called clock recovery.

Front end amplifier:-

- Noise sources at the front end of a receiver dominates the sensitivity and bandwidth, so it is necessary to ~~dominate~~ design a low noise front end amplifier.

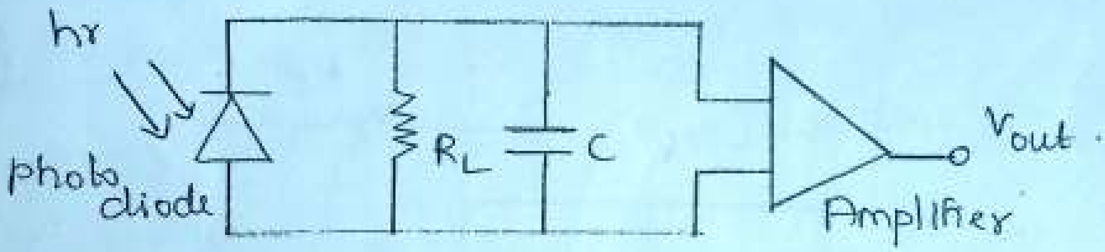
- Front end amplifier is used for.
    - ↳ increasing receiver sensitivity.
    - ↳ maintaining suitable bandwidth.
- Types:
    - ↳ High Impedance design.
    - ↳ Trans Impedance design.

- The important design parameter in front end amplifier is to choosing of R_L (load resistance)

→ Because thermal noise is inversely proportional to R_L (ie) thermal noise $\alpha\ 1/R_L$.

→ so R_L should be as large as possible to minimize thermal noise

High Impedance amplifier:-



→ system Bandwidth is also $\alpha \frac{1}{R_P}$ (R_P → Resistance seen by photodiode)

→ so for this design a trade off must be done b/w noise and bandwidth. ($\because R_P = R_L$)

→ Equalizers can be used to increase the system band width but if bandwidth is less than the bit rate then it is not useful front end amplifier

Trans impedance amplifier:-

→ The drawbacks of the previous amplifier is overcome by using R_L as the negative feedback for an invertion amplifier.

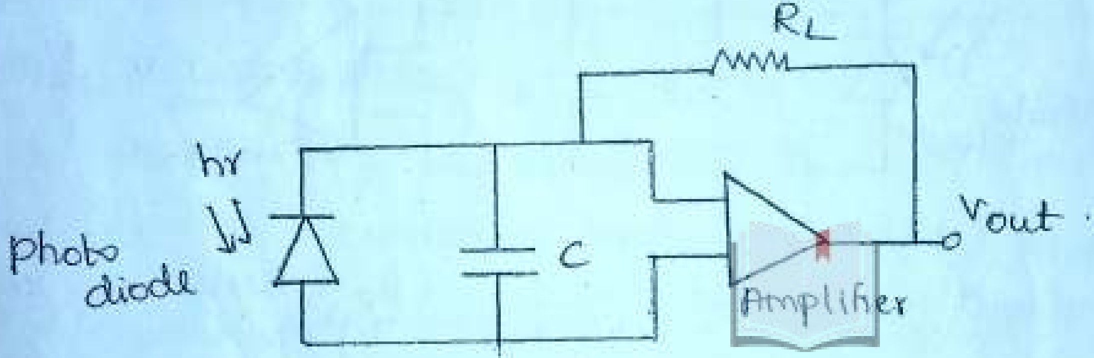
→ Now the effective resistance seen by the photodiod is reduced by a factor of G.

(ie) $R_P = \frac{R_L}{G+1}$ G → gain of amplifier.

→ So the bandwidth increases by a factor "G+1"

→ Also noise is increased but this amount of noise can be tolerated easily.

→ This is the opt choice of amplifier to be used in of optic fiber transmission link.



Receiver Sensitivity:

→ Optical communication systems uses a BER value to specify the performance requirements for a particular transmission link application.

→ To achieve a desired BER at a given data rate, a specific minimum average optical power level must arrive at the photodetector.

→ This minimum power level is called the receiver sensitivity.

→ Two methods of defining receiver sensitivity.

a) Average optical power (Pave) incident on the photodetector.

b) It is the optical modulation amplitude (OMA) given in terms of peak to peak current at the photo detector output.

So Receiver sensitivity is the minimum average power or OMA needed to maintain maximum BER at a specified data rate.

The Q-factor is widely used to specify receiver performance and is associated with signal to noise ratio required to achieve a specific BER.

$$Q = \frac{b_{on} - b_{off}}{\sigma_{on} + \sigma_{off}} \longrightarrow ①$$

where b_{on}, b_{off} → voltage or current from 1 and 0 pulses. ✓

σ_{on}, σ_{off} → Noise current variations.

Now consider I_1 and I_0 are the signal currents from 1 and 0 pulses and σ_1 and σ_0 are their corresponding noise current variations.

then $$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \simeq \frac{I_1}{\sigma_1 + \sigma_0} \rightarrow ②$$

The receiver sensitivity $P_{sensitivity}$ is found from the average power contained in a bit period for specified data rate

$$P_{sensitivity} = \frac{P_1}{2} \rightarrow ⓐ$$

$$P_{sensitivity} = \frac{I_1}{2RM} \rightarrow ③$$

where R → unity gain responsivity.

M → gain of the photodiode.

substitute eqn ② in ③

$$P_{sensitivity} = \frac{Q(\sigma_1 + \sigma_0)}{2RM} \rightarrow ④$$

If there is no optical amplifier in a fiber transmission link,

then thermal and shot noise are the dominant noise effects in the receiver.

thermal noise → independent of incoming optical signal power.

shot noise → dependent on received power.

Assuming there is no optical power in a received zero pulse, the noise variance can be written as

$$\left.\begin{aligned} \sigma_0^2 &= \sigma_T^2 \\ \sigma_1^2 &= \sigma_T^2 + \sigma_{shot}^2 \end{aligned}\right\} \rightarrow ⑤$$

The shot noise variation for a 1 pulse is given as

$$\sigma_{shot}^2 = 2q R P_1 M^2 F(M) B_e \rightarrow ⑥$$

where F(M) → photodiode noise figure

B_e → electrical bandwidth (ie) $B_e = B/2$.

B → Bit rate.

substituting eqn ⓐ in ⑥ we get

$$\sigma_{shot}^2 = 4q R P_{sensitivity} M^2 F(M) B_e \rightarrow ⑦$$

The thermal noise variance is given as

$$\sigma_T^2 = \frac{4k_B T}{R_L} F_n \frac{B}{2} \longrightarrow ⑧$$

where $F_n \rightarrow$ noise figure

$k_B \rightarrow$ Boltzman constant

$T \rightarrow$ absolute temperature.

Now substitute $\sigma_0 = \sigma_T$

$\sigma_1 = (\sigma_T^2 + \sigma_{shot}^2)^{1/2}$ in eqn ④

$$P_{sensitivity} = \frac{Q}{2RM}\left[\sigma_T + (\sigma_T^2 + \sigma_{shot}^2)^{1/2}\right]$$

Solving the above equation we get.

$$P_{sensitivity} = \frac{Q}{RM}\left[\frac{qMF(M)BQ}{2} + \sigma_T\right] \longrightarrow ⑨$$

Eg: consider $R_L = 200\,\Omega$ $T = 300^\circ K$

$F_n = 3$ dB (a factor of 2)

then $\sigma_T = 9.10 \times 10^{-12} B^{1/2}$.

Now for InGaAs $R = 0.95$ A/W

$\lambda = 1550$ nm.

$BER = 10^{-12}$, $Q = 7$

Then $P_{sensitivity} = \frac{7.37}{M}\left[5.6\times10^{-19} M F(M) B + 9.10\times10^{-12} B^{1/2}\right]$

For pin photodiode $M = F(M) = 1$

then $P_{sensitivity} = -31.8$ dBm at 100 Mb/s data rate for 10^{-12} BER requirement.

Quantum limit :-

→ Consider an ideal photodetector which has

a) ~~ideal~~ unity quantum efficiency

b) does not produce dark current [no e^- and hole pairs are produced in the absence of optical pulse

→ For the above condition it is easily possible to find the minimum optical power received for a specific bit error rate performance of a digital system.

→ This minimum received power level is called as quantum limit.

→ Assume that an optical pulse of energy 'E' falls on the photodetector in a time interval "τ"

→ This will be interpreted as '0' pulse, if no e^--hole pairs are generated, with a pulse present.

→ The probability that $n=0$ electrons emitted in a time interval 't" is

$$P_r(0) = e^{-\bar{N}} \longrightarrow ①$$

$$\bar{N} = \eta E / h\nu \longrightarrow ②$$

$\overline{N}$ → average no. of electron and hole pairs.

For a given Pr(0) we can find minimum energy E required at a specific wavelength (λ).

In general, the sensitivity of most receivers is around 20 dB greater than quantum limit because of various non-linear distortion and noise effects in the transmission link.

Eye diagrams :-

→ It is a powerful measurement tool for assessing the data handling ability of digital transmission system.

Eye pattern features :-

→ Eye pattern measurements are made in the time domain and allow the effects of waveform distortion to be shown immediately on the display screen of standard BER test equipment.

→ It is called eye pattern (or) eye diagram.

→ The basic upper and lower bounds are determined by logic one and zero levels, (b_{on} and b_{off}) in the diagram.

Optical Fiber Commonication OFC

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Module 4

WDM Concepts & components

CONTENTS

- WDM concepts
- Overview of WDM operation principles
- WDM Standards
- Mach-Zender Interferometer
- Multiplexer
- Isolators
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- Direct thin Film Filters
- Active optical components
- MEMS Technology
- Variable Optical Attenuators
- Tunable optical Fibers
- Dynamic gain equalizers
- Optical Drop multiplexers
- polarization Controllers
- Chromatic Dispersion compensators
- Tunable light sources

WDM concepts

* Technology of combining a number of independent information-carrying wavelengths onto the same fiber is known as Wavelength Division Multiplexing.

* Applications of WDM techniques are found in all levels of communication links including long-distance terrestrial & Undersea transmission systems, metro networks etc.

* Complex wavelength division multiplexed links design require optical sources with narrow spectral emission bands. optical sources can be a series of individual lasers or variety of wavelength-tunable components which will be discussed in further topics

Overview of WDM

* Use of WDM was to upgrade the capacity of installed point-to-point transmission links: This was achieved with wavelengths that were separated from several tens upto 200nm.

* With the advent of highquality light sources with extremely narrow spectral emission widths, many independent wavelength channels spaced less than a nanometer apart could be placed on same fiber.

Advantages of WDM

* With light sources, the use of WDM allows a dramatic increase in capacity of an optical fiber compared to original simple point-to-point link ~~th~~ carried only a single wavelength.

* Various optical channels support different transmission formats. By using separate wavelengths, different formatted signals at any data rate can be sent simultaneously & independently over same fiber.

Overview of WDM operation principles

* Characteristic of WDM is that discrete wavelengths form an orthogonal set of carriers that can be separated, routed & switched without interfering with each other.

* Implementation of WDM network require passive & active devices to combine, distribute, isolate & amplify optical power at different wavelength

- Passive devices : Do not require external control for their operation & limited in application flexibility Ex: Splitter, combiner etc.
- Active Devices : Require control through electrically or optically, providing large degree of network flexibility. Ex ; Tunable optical filters, Amplifier etc

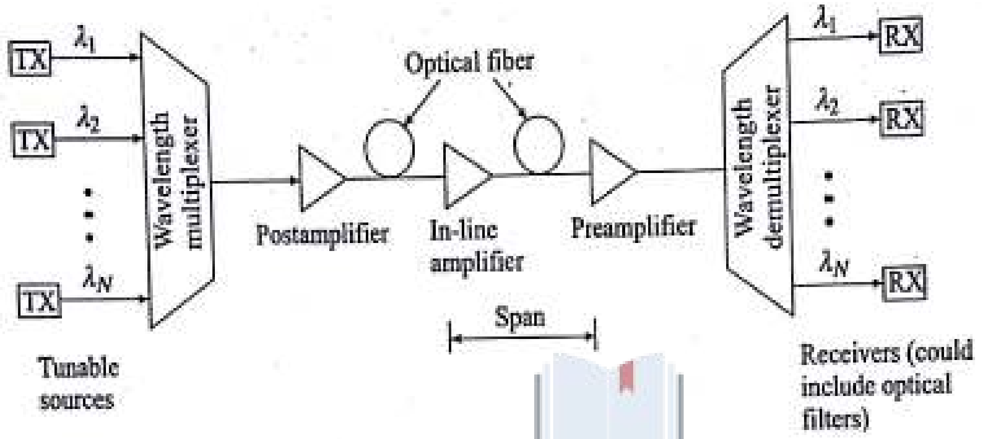
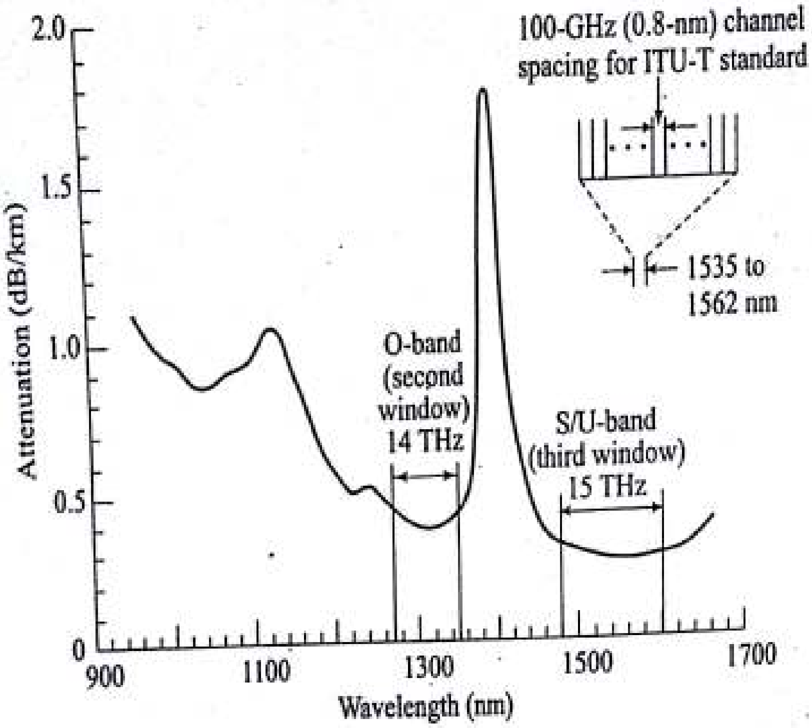


Fig. 10.1 *Implementation of a typical WDM network containing various types of optical amplifiers*

- Above figure shows implementation of passive & active components in a WDM link containing various types of optical Amplifiers.
- multiplexer is needed to combine these optical outputs into a continuous spectrum of signals & couple them onto a single fiber.
- At receiving end a demultiplexer is required to separate the optical signals into appropriate detection channels for signal processing



The transmission-band widths in the O- and C-bands (the 1310-nm and 1550-nm windows) allow the use of many simultaneous channels for sources with narrow spectral widths. The ITU-T G.692 standard for WDM specifies channels with 100-GHz spacings

Above figure shows many independent operating regions across the spectrum ranging from the O-band through L-band in which narrow-linewidth optical sources can be used simultaneously.

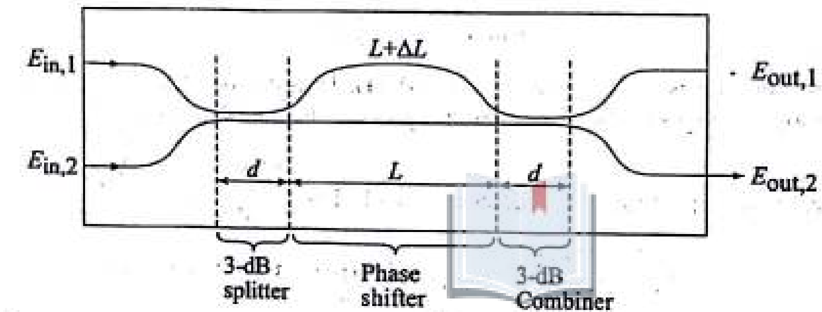
WDM standards

Table 10.1 *Portion of the ITU-T G.694.1 dense WDM grid for 100- and 50-GHz spacings in the L- and C-bands*

L-band				C-band			
100-GHz		50-GHz offset		100-GHz		50-GHz offset	
THz	nm	THz	nm	THz	nm	THz	nm
186.00	1611.79	186.05	1611.35	191.00	1569.59	191.05	1569.18
186.10	1610.92	186.15	1610.49	191.10	1568.77	191.15	1568.36
186.20	1610.06	186.25	1609.62	191.20	1576.95	191.25	1567.54
186.30	1609.19	186.35	1608.76	191.30	1567.13	191.35	1566.72
186.40	1608.33	186.45	1607.90	191.40	1566.31	191.45	1565.90
186.50	1607.47	186.55	1607.04	191.50	1565.50	191.55	1565.09
186.60	1606.60	186.65	1606.17	191.60	1564.68	191.65	1564.27
186.70	1605.74	186.75	1605.31	191.70	1563.86	191.75	1563.45
186.80	1604.88	186.85	1604.46	191.80	1563.05	191.85	1562.64
186.90	1604.03	186.95	1603.60	191.90	1562.23	191.95	1561.83

Mac-Zehnder Interferometer Multiplexer

- Wavelength-dependent multiplexers are designed using Mach-Zender interferometry techniques.
- Devices can be either passive or active.
- Figure shows the 2x2 passive Mac-Zehnder Interferometer (MZI)



Layout of a basic 2 × 2 Mach-Zehnder interferometer

- Above 2x2 MZI consists 3 stages:

→ Initial 3-dB directional coupler/splitter that splits the input signals

→ central section is phase shifter, where one of the waveguide is longer by ΔL to give a wavelength-dependent phase shift between two arms.

→ 3-dB coupler that recombines the signal at the output.

* In the following derivation, the function of MZI Interferometer Multiplexer is, by splitting the input beam & introducing a phase shift in one of the paths. the recombined signals will interfere constructively at one output & destructively at the other. Signals finally emerge from only one output port.

The propagation matrix $M_{coupler}$ for a coupler of length d is

$$M_{coupler} = \begin{bmatrix} \cos kd & j\sin kd \\ j\sin kd & \cos kd \end{bmatrix}$$

where k is coupling coefficient. Since we are considering 3-dB couplers that divide the power equally, then $2kd = \pi/2$, so that

$$M_{coupler} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix}$$

In the central region, when signals in the two arms come from same light source, outputs from two guides have a phase difference $\Delta\phi$ given by

$$\Delta\phi = \frac{2\pi n_1}{\lambda} L - \frac{2\pi n_2}{\lambda}(L+\Delta L) \rightarrow ①$$

when $n_1 = n_2 = n_{eff}$ = effective refractive index in waveguide, eqⁿ 1 becomes,

$$\Delta\phi = \frac{2\pi n_{eff}}{\lambda}(\Delta L) - ②$$

$$= k\Delta L \rightarrow ③$$

where $k = 2\pi n_{eff}/\lambda$.

* Note that the phase difference can arise either from a different path length (ΔL) or through a relative index difference if $n_1 \neq n_2$. We take both arms to have same index & let $n_1 = n_2 = n_{eff}$ (the effective refractive index in the waveguide).

For a given phase difference $\Delta\phi$, propagation matrix $M_{\Delta\phi}$ for phase shifter is

$$M_{\Delta\phi} = \begin{bmatrix} \exp(jk\Delta L/2) & 0 \\ 0 & \exp(-jk\Delta L/2) \end{bmatrix} \rightarrow ④$$

optical output fields $E_{out,1}$ & $E_{out,2}$ from two central arms are Related to input fields $E_{in,1}$ & $E_{in,2}$ by

$$\begin{bmatrix} E_{out,1} \\ E_{out,2} \end{bmatrix} = M \begin{bmatrix} E_{in,1} \\ E_{in,2} \end{bmatrix} \rightarrow ⑤$$

where $M = M_{couplee} \cdot M_{\Delta\phi} \cdot M_{couplee} = \begin{bmatrix} M_{11} & M_{21} \\ M_{12} & M_{22} \end{bmatrix}$

$$= j \begin{bmatrix} \sin(k\Delta L/2) & \cos(k\Delta L/2) \\ \cos(k\Delta L/2) & -\sin(k\Delta L/2) \end{bmatrix} \rightarrow ⑥$$

For MZI multiplexer, a different wavelengths are required at inputs. Let E_{in1} is at λ_1 & $E_{in,2}$ is at λ_2. Then from eq^n ⑤, the output field $E_{out,1}$ & $E_{out,2}$ are each the sum of individual contributions from two input fields.

$$E_{out,1} = j\left[E_{in,1}(\lambda_1)\sin(k_1\Delta L/2) + E_{in,2}(\lambda_2)\cos(k_2\Delta L/2)\right] \rightarrow ⑦$$

$$E_{out,2} = j\left[E_{in,1}(\lambda_1)\cos(k_1\Delta L/2) - E_{in,2}(\lambda_2)\sin(k_2\Delta L/2)\right] \rightarrow ⑧$$

where $k_j = 2\pi n_{eff}/\lambda_j$. output power is found from light intensity, which is square of field strength,

$$P_{out,1} = E_{out,1}\, E^{*}_{out,1} = \sin^2(k_1\Delta L/2) P_{in,1} + \cos^2(k_2\Delta L/2) P_{in,2}$$

$$P_{out,2} = E_{out,2} \cdot E^{*}_{out,2} = \cos^2(k_1\Delta L/2) P_{in,1} + \sin^2(k_2\Delta L/2) P_{in,2}$$

where $P_{inj} = |E_{in,j}|^2 = E_{in,j} \cdot E^{2}_{in,j}$

From eq^n 7 & 8, cross terms are dropped because their frequency, which is twice optical carrier frequency is beyond response capability of photodetector.

From eq^n 7 & 8, if all power from both inputs have to leave same output port, we need to have

$$k_1 \Delta L/2 = \pi \quad \& \quad k_2 \Delta L/2 = \pi/2$$

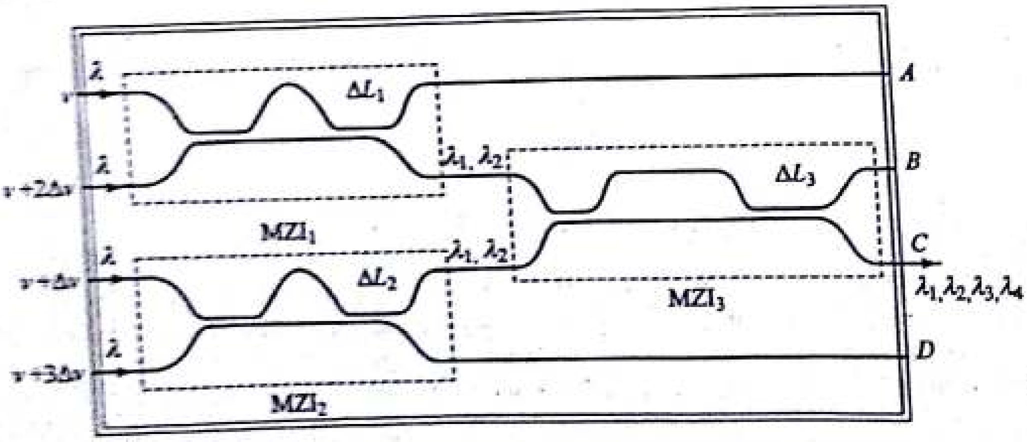
$$(k_1 - k_2)\Delta L = 2\pi n_{eff}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\Delta L = \pi \quad \rightarrow 9$$

The length difference in interferometer arms should be

$$\Delta L = \left[2n_{eff}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\right]^{-1} = \frac{c}{2n_{eff}\Delta\nu}$$

where $\Delta\nu$ is frequency separation of two wavelength

Using 2×2 MZI, Any size N×N multiplexer can be constructed. As shown in below figure, 4×4 multiplexer is designed.



Example of a 4-channel wavelength multiplexer using three 2 × 2 MZI elements

Isolators & Circulators.

- * passive optical devices used in number of applications may be nonreciprocal, that is, it works differently when its inputs & outputs are reversed.

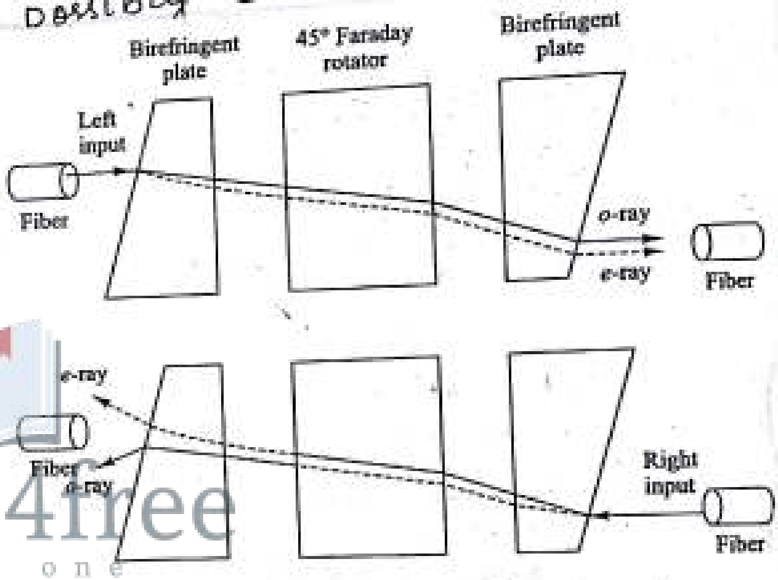
- * Examples: Isolator & Circulators.

Some facts about polarization & polarization-sensitive components:

- * Light can be represented as a combination of a parallel & perpendicular vibrations, which are called two orthogonal plane polarization states of a lightwave.
- * A polarizer is a material or a device that transmits only one polarization component & blocks other.
- * A Faraday rotator is a device that rotates state of polarization (SOP) of light passing through it by a specific angularamount.
- * A device made from birefringent material splits light signal entering it into two orthogonally polarized beams, which then follow different paths through material.
- * A Half-wave plate rotates the SOP clockwise by 45° for signals going from left to right & counterclockwise by 45° for signals propagating in other direction

optical Isolator

- optical isolators are devices that allow light to pass through them in only one direction, & hence prevent scattered or reflected light from traveling in reverse direction.
- Application: laser diode – prevents backward-traveling light entering a laser diode & possibly causing instabilities in optical output



- Above figure shows a design for polarization-independent isolator made
- core of the device consists of 45° Faraday rotator that is placed between two wedges-shaped birefringent plates or walk-off polarizer.
- plates are made of material YVO_4 or TiO_2.
- light traveling in forward direction is separated into ordinary & extraordinary rays by first birefringent plate

* Faraday rotator then rotates polarization plane of each ray by 45°.

* After exiting the rotator, two rays pass through second birefringent plate, the axis of this plate is oriented in such a way that relationship between the two types of rays is maintained.

* When rays exit the polarizer, they both are refracted in identical parallel direction.

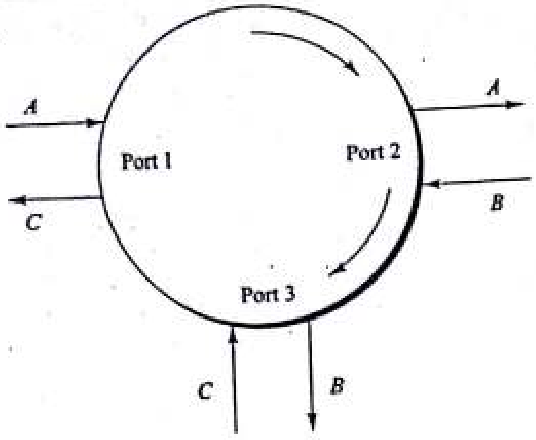
* In reverse direction (right to left), the relationship of ordinary & extraordinary is reversed due to nonreciprocity of faraday rotation & rays diverge when they exit from left-hand birefringent plate & are not coupled to fiber anymore.

optical Circulator

* An optical circulator is a nonreciprocal multiport passive device that directs light sequential from port to port in only one direction.

* Applications: optical Amplifiers, add/drop multiplexers, dispersion compensation modules.

* ~~construction~~ operation same as isolator except that is construction is more complex



Operational concept of a three-port circulator

* As shown in above fig. it consists of number of walk-off polarizer, half wave plates & faradays rotator.

* Consider three port circulator. Here input on port 1 is sent out on port 2, an input on port 2 is sent out on port 3 & input on port 3 is sent out on port 1.

* In a four-port device ideally one could have four inputs & four outputs, but in actual application four port circulator have three inputs & three output ports, making port 1 be an input port only, 2 & 3 being input & output ports, port 4 be an output-port only.

* Advantages:

→ Low insertion loss

→ High isolation over wide wavelength range

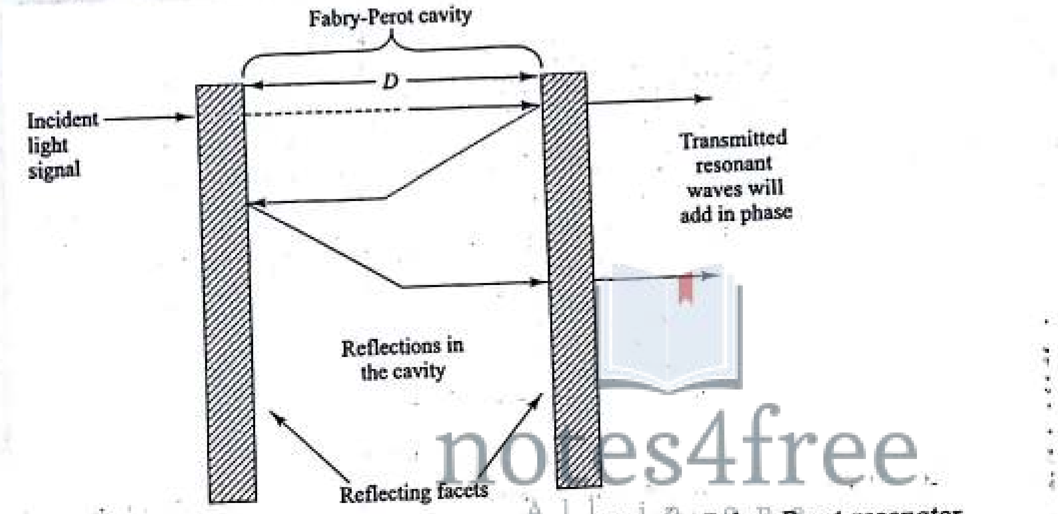
→ Minimal polarization-dependent loss

→ Low plarization-mode dispersion

Dielectric Thin-Film Filters (TFF)

- * TFF is used as an optical bandpass filter which allows particular narrow wavelength band to pass straight through it & reflects all others.

- * Basis of TFF is classical Fabry perot filter structure, which is formed by two parallel highly reflective mirror surfaces shown below.



Two parallel light-reflecting mirrored surfaces define a Fabry-Perot resonator cavity or an etalon

- * Structure is called Fabry-perot interferometer or an etalon or thin film resonant cavity filter.

- * Working :

→ consider a light signal incident on left surface of etalon. After light passes through the cavity & hits inside surface on right, some of light leaves cavity & some reflected

* Amount of light reflected depends on Reflectivity R of surface.

~~of~~ Roundtrip distance between two mirrors is an integral multiple ~~part~~ of wavelength λ then all light at those wavelength add in phase & interfere constructively. & adds to intensity. These wavelengths are resonant wavelengths of cavity. Etalon rejects all other wavelengths.

* Etalon Theory.

The Transmission T of an ideal Etalon in which there is no light absorption by mirrors is an Airy function given by

$$T = \left[1+\frac{4R}{(1-R)^2}\sin^2\left(\frac{\phi}{2}\right)\right]^{-1}$$

where R is reflectivity of mirrors & ϕ is roundtrip phase change of light beam.

Active optical Components

* Active components require some type of external energy either to perform their functions or to be used over a wider operating range than a passive devices, thereby offering greater application flexibility. Ex: Variable optical Attenuator, tunable optical filter. etc

MEMS Technology

* Micro Electro-mechanical systems (MEMS) are miniature devices than can combine mechanical, electrical & optical components to provide sensing & actuation functions.

* MEMS are fabricated using integrated circuit & range in size from micrometers to millimeters

* Applications : Air-bag deployment systems, ink-jet printer heads, biomedical applications, variable optical attenuators, tunable lasers, optical add-drop multiplexers etc.

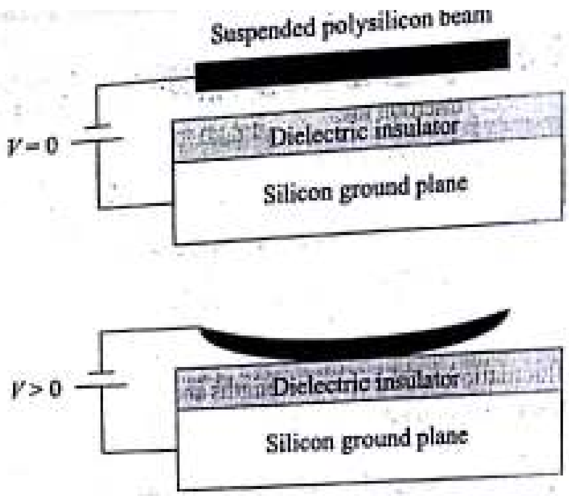


Fig. 10.33 *A simple example of a MEMS actuation method. The top shows an "off" position and the bottom shows an "on" position*

* Above figure shows example of MEMS actuation method.

* At top of device there is a thin suspended polysilicon beam that has typical length, width & thickness dimensions of 80um, 10um & 0.5um respectively.

* At the bottom there is a silicon ground plane that is covered by an insulator material.

* There is a gap of 0.6um between the beam & insulator. When a voltage is applied between silicon ground plane & polysilicon beam, electric force pulls the beam down so that it makes contact with lower structure.

* Initially MEMS devices were based on standard silicon technology, which is stiff material.

* Since some type of electric force typically is used to bend or deflect one of MEMS layer to produce desired mechanical motion, stiffer material require higher voltage to achieve deflection. To reduce required forces, polymeric materials are used which are six orders of magnitude less stiff than silicon. component is compliant MEMS or CMEMS & the elastometric material can be stretched as much as 300 percent, as opposed to less than 1 percent for silicon.

Variable optical Attenuator

* precise active signal-level control is essential for proper operation of DWDM networks.

* A variable optical attenuator (VOA) offers dynamic signal control.

* This device attenuates optical power by various means to control signal levels precisely without disturbing other properties of light signal.

* They are polarization independent, attenuate light independent of wavelength & Have low insertion loss.

* control methods include :

→ Mechanical methods which are reliable but have a low dynamic range & slow response time.

→ Thermo-optic methods that have a high dynamic range, but slow & require thermoelectric cooler (TEC)

→ MEMS technique : An electrostatic actuation method which is most commonly used, since IC processes offer a wider selection of conductive & insulating materials. A voltge change across a pair of electrodes provides an electrostatic actuation force & Require lower power levels than other methods & is fastest.

Below table shows some Representative ~~optical~~ operational parameter values for VOA.

parameter	Specification
Insertion loss	< 1.8 dB
Attenuation Range	> 15 dB
PDL @ 25dB attenuation	< 0.3 dB
Maximum optical power per channel	> 150 mW
Optical return loss	> 42 dB

Table 10.9 *Representative operational parameter values for a typical VOA*

Parameter	*Specification*
Insertion loss	< 1.8 dB
Attenuation range	> 15 dB (up to 60 dB possible)
PDL @ 25 dB attenuation	< 0.3 dB
Maximum optical power per channel	> 150 mW (up to 500 mW possible)
Optical return loss	> 42 dB

When wavelengths are added, dropped, or routed in a WDM system, a VOA can manage the optical power fluctuations of these wavelengths and other simultaneously propagating wavelength signals. Table 10.9 shows some representative operational parameter values for a VOA.

10.8.3 Tunable Optical Filters

Tunable optical filters are key components for dense WDM optical networks. Two main technologies to make a tunable filter are MEMS-based and Bragg-grating-based devices. MEMS actuated filters have the advantageous characteristics of a wide tuning range and design flexibility. One such filter is a tunable variation on the classical structure that has been used widely for interferometer applications. The MEMS-based device consists of two sets of epitaxially grown semiconductor layers that form a single Fabry-Perot cavity. The device operation is based on allowing one of the two mirrors to be moved precisely by an actuator. This enables a change in the distance between the two cavity mirrors, thereby resulting in the selection of different wavelengths to be filtered (see Sec. 10.5).

Fiber Bragg gratings are wavelength-selective reflective filters with steep spectral profiles, as shown in Fig. 10.34. Tunable optical filters based on fiber Bragg gratings involve a stretching and relaxation process of the spacing in the fiber grating, that is, in the periodic variation in the refractive index along the core. Since glass is a slightly stretchable medium, as an optical fiber is stretched with the grating inside of it, the spacing of the index perturbations and the refractive index will change. This process induces a change in the Bragg wavelength thereby changing the center wavelength of the filter. Before it is stretched, the center wavelength

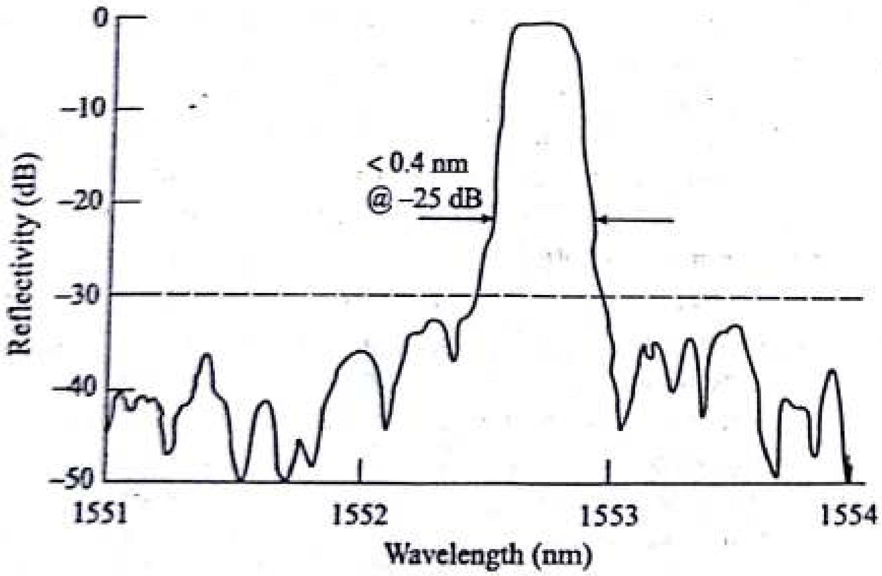


Fig. 10.34 *Example of the reflection band and steep spectral profiles for a 50-GHz fiber Bragg grating filter*

λ_c of a fiber Bragg grating filter is given by $\lambda_c = 2n_{\text{eff}}\Lambda$, where n_{eff} is the effective index of the fiber containing the grating and Λ (*lambda*) is the period of the index variation of the grating. When elongating the fiber grating by a distance ΔΛ, the corresponding change in the center wavelength is $\Delta\lambda_c = 2n_{\text{eff}}\Delta\Lambda$. Such optical filters can be made for the S-, C-, and L-bands and for operation in the 1310-nm region.

The stretching can be done by thermo-mechanical, piezoelectric, or stepper-motor means, as shown in Fig. 10.35. The thermo-mechanical methods might use a bimetal differential-expansion element that changes its shape as its temperature varies. In the figure the high-expansion bar changes its length more with temperature than the low-expansion frame, thereby leading to temperature-induced length variations in the fiber grating. This method is inexpensive but it is slow, takes time to stabilize, and has a limited tuning range. The *piezoelectric technique* uses a material that changes its length when a voltage is applied. Although this method provides precise wavelength resolution, it is more expensive, complex to implement, and has a limited tuning range. The stepper-motor method changes the length of the fiber grating by pulling or relaxing one end of the structure. It has a moderate cost, is reliable, and has a reasonable tuning speed.

Table 10.10 lists representative performance parameters of a tunable optical filter. Applications of these devices include gain-tilt monitoring in optical fiber amplifiers, optical performance monitoring in central offices, channel selection at the receive side of a WDM link, and suppression of amplified spontaneous emission (ASE) noise in optical amplifiers (see Chapter 11).

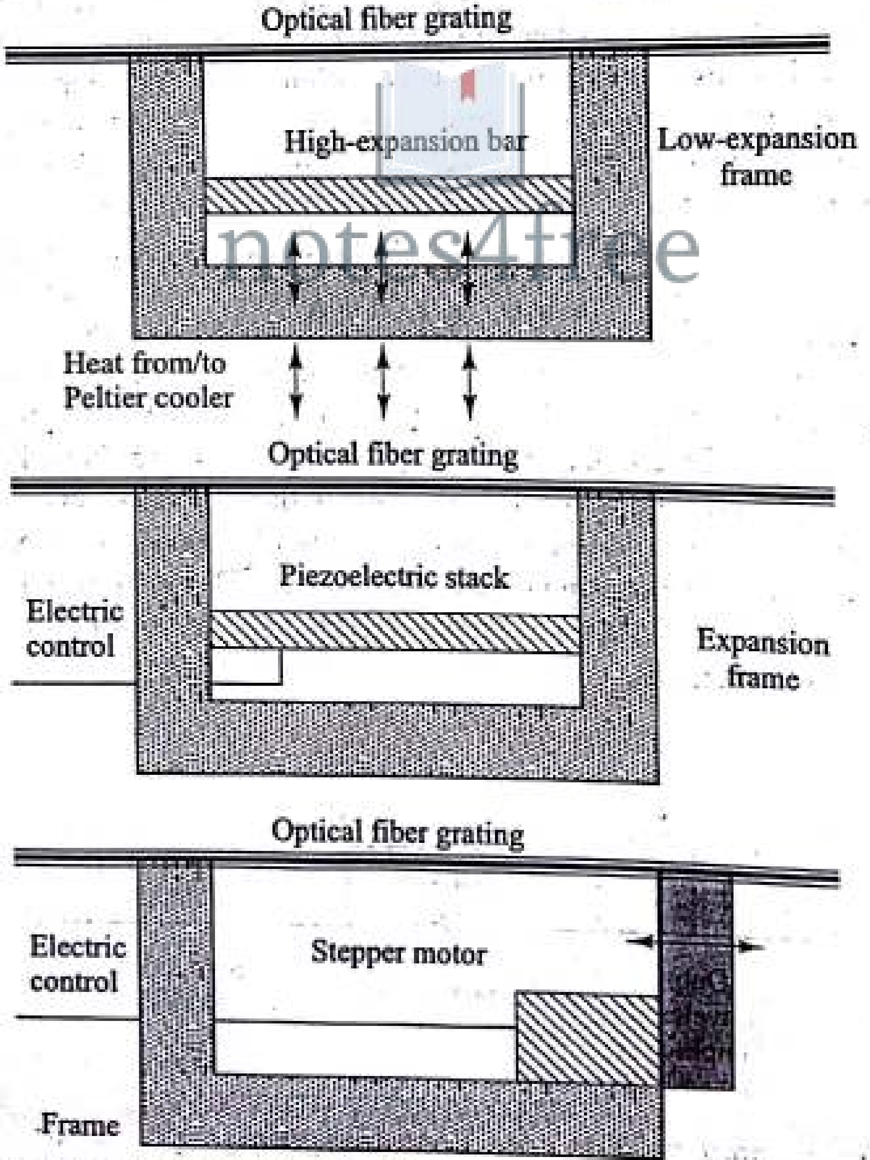


Fig. 10.35 *Three methods for adjusting the wavelength of a tunable Bragg grating*

Table 10.10 *Typical performance parameters of a tunable optical filter*

Parameter	Specification
Tuning range	40 nm typical
Channel selectivity	100, 50, and 25 GHz
Bandwidth	< 0.2 nm
Insertion loss	< 3 dB across tuning range
Polarization dependent loss (PDL)	< 0.2 dB across tuning range
Tuning speed	Technology dependent
Tuning voltage	12 to 40 V

10.8.4 Dynamic Gain Equalizers

A *dynamic gain equalizer* (DGE) is used to reduce the attenuation of the individual wavelengths within a spectral band. These devices also are called *dynamic channel equalizers* (DCE) or *dynamic spectral equalizers.* The function of a DGE is equivalent to filtering out individual wavelengths and equalizing them on a channel-by-channel basis. Their applications include flattening the nonlinear gain profile of an optical amplifier (such as an EDFA or the Raman amplifier described in Chapter 11), compensation for variation in transmission losses on individual channels across a given spectral band within a link, and attenuating, adding, or dropping selective wavelengths. For example, the gain profile across a spectral band containing many wavelengths usually changes and needs to be equalized when one of the wavelengths is suddenly added or dropped on a WDM link. Note that component vendors sometimes distinguish between a DGE for flattening the output of an optical amplifier and a DCE, which is used for channel equalization or add/drop functions. Depending on the application, certain operational parameters such as the channel attenuation range may be different.

These devices operate by having individually tunable attenuators, such as a series of VOAs, control the gain of a small spectral segment across a wide spectral band, such as the C- or L-band. For example, within a 4-THz spectral range (around 32 nm in the C-band) a DGE can individually attenuate the optical power of 40 channels spaced at 100 GHz or 80 channels spaced at 50 GHz. For example, Fig. 10.36 shows how a DGE equalizes the gain profile of an erbium-doped fiber amplifier. The operation of these devices can be controlled electronically and configured by software residing in a microprocessor. This control is based on feedback information received from a performance-monitoring card that provides the parameter values needed to adjust and adapt to required link specifications. This allows a high degree of agility in responding to optical power fluctuations that may result from changing network conditions.

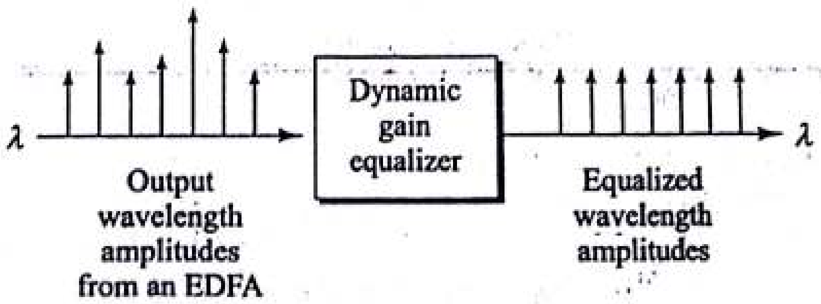


Fig. 10.36 *Example of how a DGE equalizes the gain profile of an erbium-doped fiber amplifier (EDFA)*

Optical Add/Drop Multiplexer (OADM)

* Function of OADM is to insert (add) or extract (drop) one or more selected wavelength at a designated point in an optical network

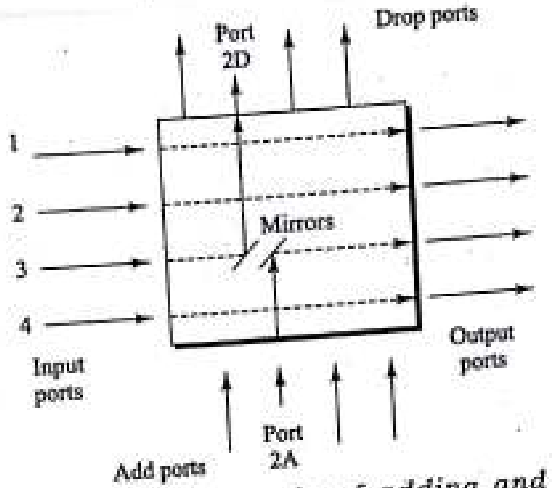


Fig. 10.37 *Example of adding and dropping wavelengths with a 4×4 OADM device that uses miniature switching mirrors*

* Above figure shows a simple OADM which has four input & four output ports.

* In this case, add & drop functions are controlled by MEMS based miniature mirrors that are activated separately & selectively to connect the desired fiber paths

* When no mirrors are activated, each incoming channel passes through switch to output port.

* Incoming signals can be dropped from traffic flow by activating appropriate mirror pair.

* Example : To have signal carried on wavelength λ_3 entering port 3 be dropped to port 2D, mirrors are

are activated as shown in figure. when an optical signal is dropped, another path is established simultaneously allowing a new signal to added from port 2A to traffic flow. OADM is independent of wavelength, data rate & signal format.

polarization controller

- * polarization controller offer high-speed real-time polarization control in a closed-loop system that includes a polarization sensor & control logic
- * These devices dynamically adjust any incoming state of polarization to an arbitrary output state of polarization.
- * Applications : polarization mode dispersion (PMD) compensation, polarization scrambling & multiplexing.
- * For Example, the output could be a fixed, linearly polarized state. Nominally this is done through electronic control voltages that are applied independently to adjustable polarization - retardation plates

Chromatic Dispersion compensators

- A critical factor in optical links operating above 2.5 Gb/s is compensating for chromatic dispersion effects.

- This phenomenon causes pulse broadening, which leads to increased bit-error rates.

- An effective means of meeting the strict narrow dispersion tolerances for such high-speed network is to start with a first order dispersion management method, such as dispersion compensating fiber. Then fine tuning is carried by means of tunable dispersion compensator that works over a narrow spectral band to correct for any residual & variable dispersion

- Device for fine tuning is dispersion compensating module (DCM) which is tuned manually, remotely or dynamically.

→ Manual tuning is done by a network technician prior to or after installation of module in telecommunication rack

→ By using network management software it can be adjusted remotely from central management by network operator if this feature is included in its design

→ Dynamic tuning is done by module itself without any human intervention

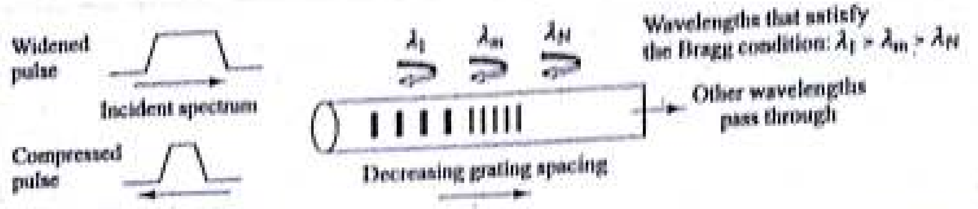


Fig. 10.38 *Dynamic chromatic dispersion may be accomplished with a chirped fiber Bragg grating*

- As shown in above figure, dynamic chromatic dispersion is achieved through use of chirped fiber bragg grating.
- Here grating spacing varies linearly over length of grating, which creates chirped grating.
- This results in a range of wavelengths that satisfy Bragg condition for reflection.
- In configuration shown, the spacing decreases along fiber, Bragg wavelength decreases with distance along the grating length
- Consequently, shorter-wavelength components of a pulse travel farther into fiber before being reflected & experience more delay than longer-wavelength components.
- The relative delays induced by grating on different frequency components of pulse are opposite of delays caused by fiber.
- This results in dispersion compensation because it compresses pulse.

Tunable Light Sources

* Light sources must be carefully controlled & monitored to ensure that their wavelengths do not drift with time & temperature into spectral region of adjacent sources.

* A more flexible implementation is to have tunable laser.

* The fundamental concept to making such a laser is to change the cavity length in which the lasing occurs in order to have device emit at different wavelengths. Basing tuning options are :

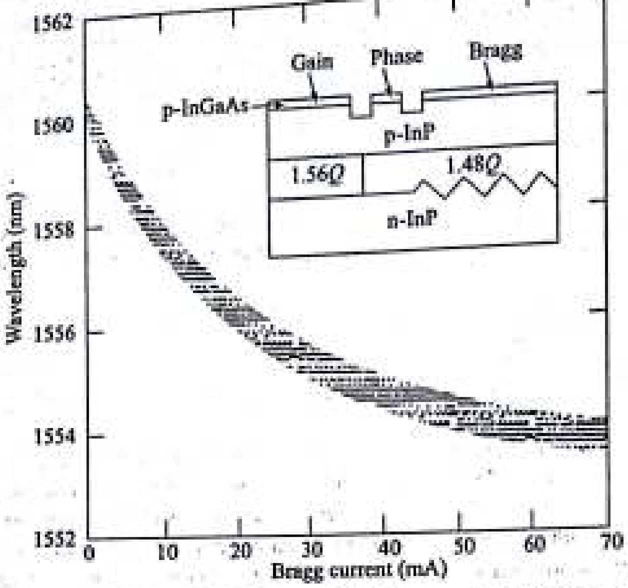
→ wavelength tuning of a laser by means of temperature or current variations

→ Use of a specially designed wavelength tunable laser

→ Frequency locking to a particular lasing mode in a Fabry-perot laser.

→ Spectral slicing by means of a fixed or tunable narrow-band optical filter & a broadband LED.

* With frequency tunable laser, one needs only one source. These devices are based on DFB or DBR structure



Tuning range of an injection-tunable three-section DBR laser. (Reproduced with permission from Staring et al.,[75] © 1994, IEEE)

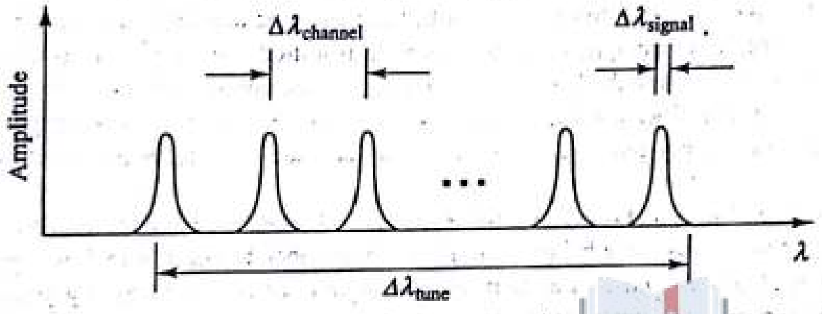
- Above figure shows the tuning range of an injection-tunable three-section DBR lasers.
- Frequency tuning is achieved either by changing temperature of device or by altering injection current into the active section or passive section.
- In above, latter method is used which results in a change in the effective refractive index, which causes a shift in peak output wavelength.
- The maximum tuning range depends on the optical output power, with larger output level resulting in a narrower tuning range.
- The tuning range $\Delta\lambda_{tune}$ can be estimated by

$$\frac{\Delta\lambda_{tune}}{\lambda} = \frac{\Delta n_{eff}}{n_{eff}}$$

where Δn_{eff} = change in the effective refractive index

- practically the maximum index change is around 1 %, resulting in a tuning range of 10 - 15 nm.

- Below figure depicts relationship between tuning range, channel spacing & source spectral width.



Relationship between tuning range, channel spacing, and source spectral width

- To avoid crosstalk between adjacent channels, a channel spacing of 10 times the source spectral width $\Delta\lambda_{signal}$ is specified.

That is, $\Delta\lambda_{channel} \simeq 10\Delta\lambda_{signal}$.

Thus, the maximum number of channels N that can be placed in tuning range $\Delta\lambda_{tune}$ is

$$N = \frac{\Delta\lambda_{tune}}{\Delta\lambda_{channel}}$$

Example 10.15

Suppose that the maximum index change of a particular DBR laser operating at 1550 nm is 0.65 percent. Then, the tuning range is

$$\Delta\lambda_{\text{tune}} = \lambda\frac{\Delta n_{\text{eff}}}{n_{\text{eff}}} = (1550\text{ nm})(0.0065) = 10\text{ nm}$$

If the source spectral width $\Delta\lambda_{\text{signal}}$ is 0.02 nm for a 2.5-Gb/s signal, then using Eqs. 10.68 and 10.69 the number of channels that can operate in this tuning range is

$$N = \frac{\Delta\lambda_{\text{tune}}}{\Delta\lambda_{\text{channel}}} = \frac{10\text{ nm}}{10(0.02\text{ nm})} = 50$$

External-cavity laser designs include the use of Littman and Littrow cavities. The *Littman cavity* scheme uses a grating and a MEMS-based tuning mirror to deliver a high level of side-mode suppression (typically 60 dB) with a narrow linewidth (0.3–5 MHz). The *Littrow cavity* method uses a grating to offer an increase in optical output power but with a slight reduction in side-mode suppression (40 dB). In both devices coarse tuning is achieved by manual adjustment of a high-precision adjuster and further fine tuning is achieved by means of a piezoelectric actuator. Various multiple-section tunable lasers have been examined. These designs can include a distributed Bragg reflector, a gain portion, a passive phase-correction section, and a coarse-tuning section. Modulating the Bragg-grating reflector provides a series, or comb, of wavelength peaks. By using an external control current, the coarse tuner then selects one of these peaks. Such a device can be tuned over a 32-nm range, which covers the entire C-band.

Other designs utilize an integrated combination of an optical source (either a broadband laser diode or LED), a waveguide grating multiplexer, and an optical amplifier.[76–80] In this method, which is known as *spectral slicing*, a broad spectral output (for example, from an amplified LED) is spectrally sliced by the waveguide grating to produce a comb of precisely spaced optical frequencies, which become an array of constant-output sources. These spectral slices are then fed into a sequence of individually addressable wavelength channels that can be externally modulated.

X

Unit 8: Optical Amplifiers and Optical Networks

Introduction:-

optical amplifiers are used as pre-Amplifiers, post amplifiers, In-line amplifiers and boosters. There is no need for conversion of optical signal into electrical signal & then back to optical signal when optical amplifiers are used.

Semiconductor optical amplifier (SOA) and Erbium doped fiber amplifiers (EDFA) are the two widely used optical amplifiers. EDFA is more popular optical amplifier.

synchronous optical NETwork (SONET) and synchronous Digital Hierarchies (SDH) are the two frame structures used in optical networks. These two are compatible to each other.

Basic Rate of SONET is 51.84 Mbps and that of SDH is 155.52 Mbps. SONET streams are designated as STS-1, 2, 3 etc. SDH streams are designated as STM-1, STM-4, 16 etc.

Unidirectional path switching rings [UPSR] and Bidirectional line switching rings [BLSR] are two types of SONET/SDH rings. The networks operating at 10 Gbps or more called high speed light wave systems.

V.T.U 8.1 optical amplifiers:- ** [Types & Applications]

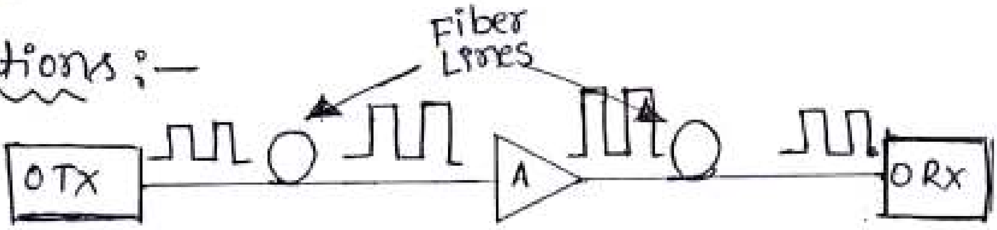
* Types of optical amplifiers :-

There are three fundamental types of optical amplifiers namely.

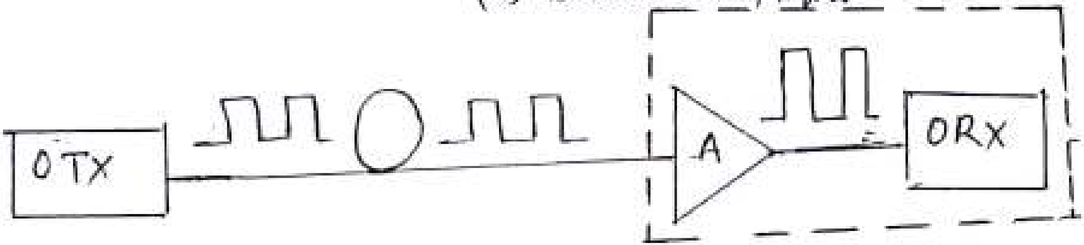
(i) Semiconductor optical Amplifier (SOA)
(ii) Erbium Doped Fiber Amplifiers [EDFA]
(iii) Raman Amplifiers.

- Semiconductor optical Amplifiers & Erbium doped fiber amplifiers works on the principle of population Inversion
- In Raman Amplifiers, No population inversion process is needed.

Applications :—

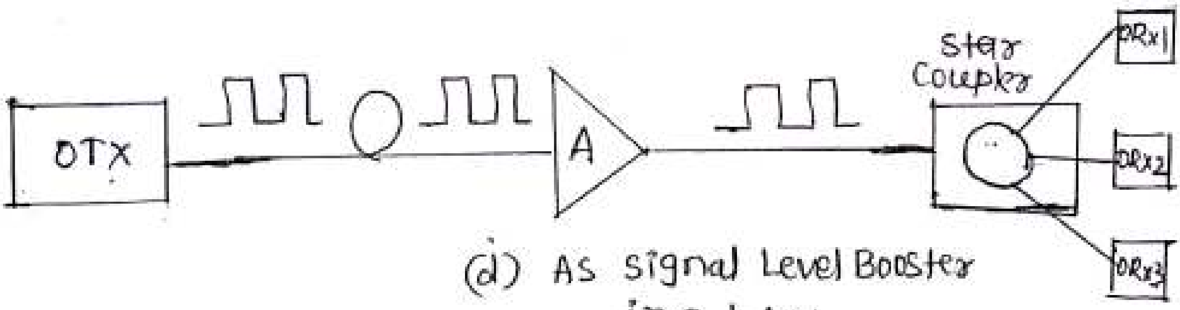


(a) As Inline Amplifier



(b) As Pre-Amplifier

(c) As post Amplifier



(d) As signal Level Booster
in a LAN

Figure 8.1 : Applications of optical Amplifiers

optical amplifiers can be used in Four applications

(i) As a Inline Amplifier

(ii) As a pre Amplifier

(iii) As a post amplifier

(iv) As a signal level booster

- → Figure 8.1(a), shows the application of optical amplifier as a Inline amplifier. This compensates for transmission losses and increases the distance between regenerative repeaters in a single mode link.

- → Figure 8.1(b), shows the application of a pre-amplifier for an "optical receiver". Here signal to Noise Ratio(SNR) is improved by amplifying a weak optical signal before photo detection.

- → Figure 8.1(c), shows the application of a optical amplifier as a " post amplifier for transmitter". This is placed immediately after the optical transmitter.

- → Figure 8.1(d), illustrates the way in which, optical Amplifier is used as a signal level booster in a LAN.

* * *

8.2 Semiconductor Optical Amplifier (SOA):-

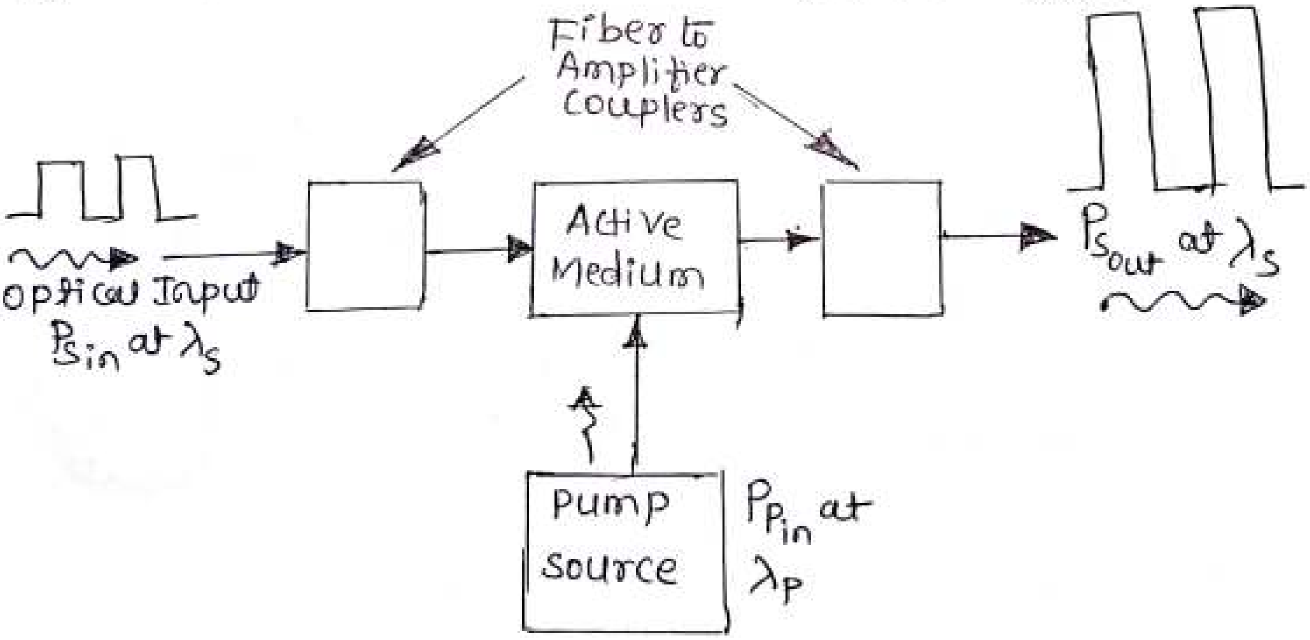


Figure 8.2: Semiconductor Optical Amplifier

Semiconductor optical Amplifier (SOA), shown in figure 8.2 works on the principle of population Inversion.

→ Mechanism for creating population inversion is similar to that of a laser diode. Therefore power Level of incident light input ($P_{s_{in}}$) is increased by stimulated emission.

→ pump source supplies energy to the active medium. The active medium absorbs this energy.

→ This ~~supplied energy~~ supplied energy raises the electrons in an active medium to the higher energy levels. This produces "population Inversion".

→ Active medium is made up of Alloys of semiconductor materials such as Phosphorous (P), Gallium (Ga), Indium (In) and Arsenic (As).

→ amplifier Gain is Given by

$$G = \frac{P_{s_{out}}}{P_{s_{in}}}.$$

→ The no. of photons generated, i.e, photon Density in SOA is given by

$$N_{ph} = \frac{P_s}{v_g \times E_p \times w \times d}.$$

where P_s = source input power

v_g = group velocity

E_p = photon energy = $h\nu = \frac{hc}{\lambda}$

w = width of Active medium

d = deapth of Active medium.

Problems on SOA :-

① An InGaAsP Semiconductor optical Amplifier (SOA) with $w = 5\mu m$ and $d = 0.5\mu m$ has group velocity $v_g = 2\times10^8 ms^{-1}$. If $1\mu W$ optical signal at 1550nm enters the device, find photon Density.

Ans :-

Given data:

$w = 5\mu m$

$d = 0.5\mu m$

$v_g = 2\times10^8 ms^{-1}$

$P_s = 1\mu W = 1\times10^{-6} W$

$\lambda = 1550\times10^{-9}$

$N_p = ?$

We know that photon Density in SOA is

$$N_{ph} = \frac{P_s}{V_g \times E_p \times (w \times d)}$$

$$N_{ph} = \frac{P_s}{V_g \times \left(\frac{hc}{\lambda}\right) \times w \times d}$$

$$N_{ph} = \frac{(1\times10^{-6})}{\left(2\times10^{8} \times \left(\frac{6.625\times10^{-34} \times 3\times10^{8}}{1550\times10^{-9}}\right)(5\times10^{-6}\times0.5\times10^{-6})\right)}$$

$$\boxed{N_{ph} = 1.56\times10^{16} \text{ photons}/m^3}$$

Repeated in VTU Q papers

Working & Architectures (10m)

8.3 Erbium Doped Fiber Amplifier [EDFA] * * * * * *

- Erbium doped fiber amplifier consists of a length of silica fibers.
- The core of silica fibers is coated with ionised atoms, Er_{3+}, of the rare element erbium.
- The Energy levels of Erbium ions in silica fiber are shown in figure 8.3.

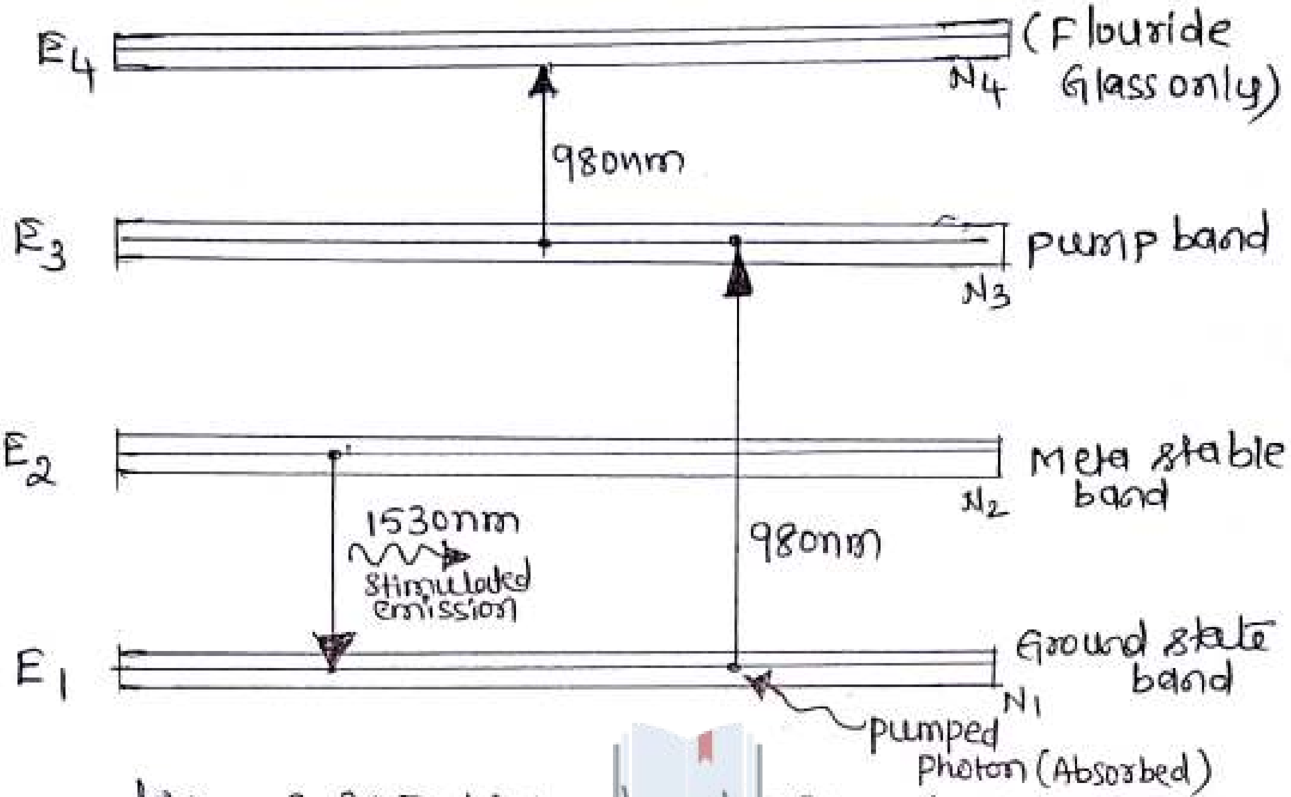


figure 8.3: Erbium doped Fiber Amplifier:-

⇒ Let E_1, E_2, E_3 & E_4 be the four energy levels with $E_1 < E_2 < E_3 < E_4$ and let the corresponding ionic populations is N_1, N_2, N_3 & N_4 respectively.

→ Each Energy Level is split into multiple energy levels due to Erbium ions Er_{3+}. This process is known as stark splitting.

→ Within each energy band, the Erbium ions are distributed in the various levels within the band in a non-uniform manner.

→ Due to this an EDFA is capable of amplifying several wavelengths simultaneously.

→ If optical power (pump) at $\lambda_p = 980nm$ is injected into the amplifier it will cause transitions from E_1 to E_3. This is called "pumping"

→ The Ions raised to 'E_3', will quickly transit to level E_2

by spontaneous emission process.

→ Therefore population inversion takes place between E_2 & E_1.

→ EDFA can amplify any wavelength in the range from λ_s (1520 nm to 1580) nm for pump wavelength $\lambda_p \simeq 980$ nm.

EDFA Architectures :-

There are 3-types of EDFA architectures namely

(i) Co-Directional pumping

(ii) Counter directional pumping

(iii) Dual pump scheme, these architectures are depending on the direction of signal flow and direction of pump power as shown in fig 8.4.

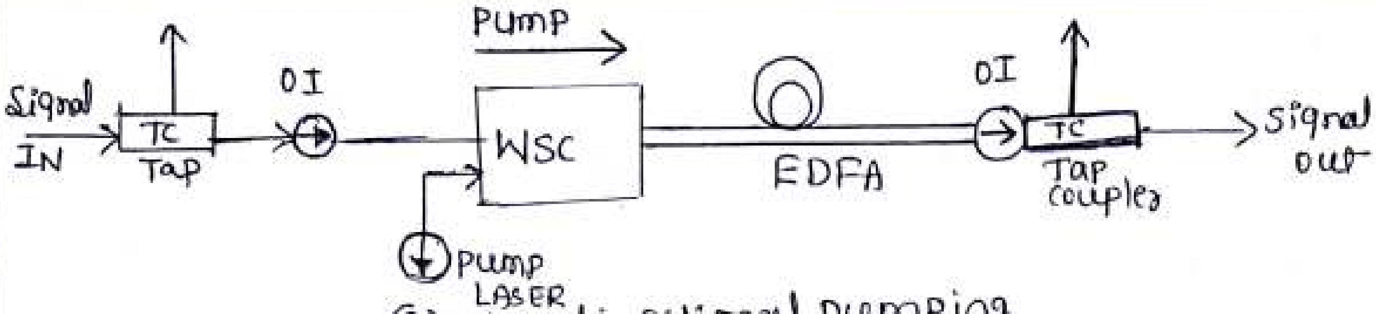
→ In co-directional pumping, pump power signal is injected from the same direction as the signal power flow as shown in fig 8.4 (a).

→ In counter-directional pumping, ~~pow~~ pump power signal is injected from the opposite direction to the signal power flow, as shown in fig 8.4 (b).

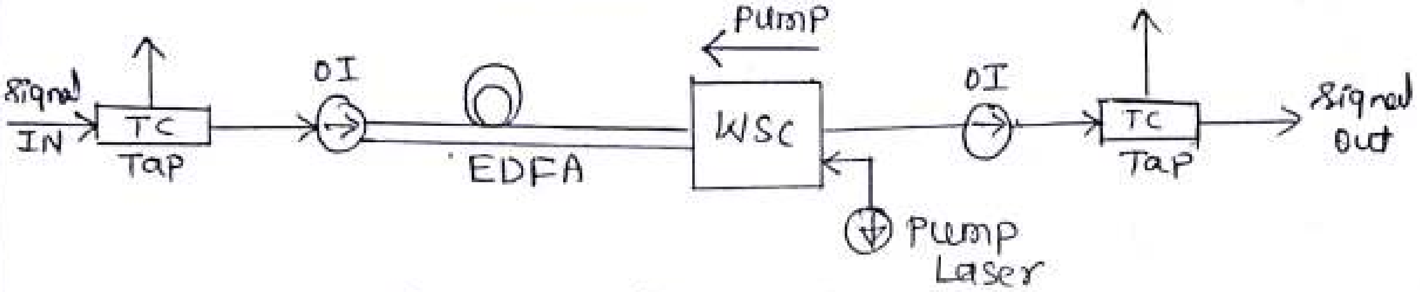
→ In Dual pump scheme, Two pump LASER sources are used on the either side of the amplifier / signal power flow as shown in figure 8.4 (c).

Along with Amplifier (EDFA), these architectures uses

- One or Two pump Lasers
- passive wavelength selective coupler [WSC]
- Optical Isolators (OI) and
- Tap couplers (Tap)



(a) co-directional pumping



(b) counter directional pumping

(c) Dual pump scheme :-

Figure 8.4: EDFA Architectures

→ For Erbium Doped Fiber Amplifier, 980nm pump source is preferred, since it produces less noise and achieves large population Inversion.

Problems on EDFA :-

List - of Formulae :-

(i) power Conversion Efficiency (PCE) = $\dfrac{P_{S_{out}} - P_{S_{in}}}{P_{P_{in}}}$

(ii) Quantum Conversion Efficiency (QCE) = $\dfrac{\lambda_S}{\lambda_P} \times PCE$.

(iii) Gain = $G = \dfrac{P_{S_{out}}}{P_{S_{in}}}$

(iv) $P_{S_{in}} = \dfrac{\left(\frac{\lambda_P}{\lambda_S}\right) P_{P_{in}}}{(G-1)}$

Note ① Conversion of power gain in 'dB' to normal value.

- $G = 10^\wedge\left[\frac{G_{dB}}{10}\right]$

② Conversion from 'dBm' power to Normal value is:

$$P_{dBm} = 10 \log\left(\frac{P}{1mW}\right)$$

$$\therefore P = 1mW\left(10^\wedge\left(\frac{P_{dBm}}{10}\right)\right)$$

③ power is usually mentioned in dBm instead of watts, so before substituting in formula's convert dBm to watts.

④ Gain is usually mentioned in 'dB', so convert it to its Normal value. & then use in formulas.

V.T.U

① An EDFA is being pumped at 980nm with a 30mW pump power. If the gain at 1550nm is 20dB find the maximum input and output powers.

Ans:- Given $\lambda_p = 980nm$; $\lambda_s = 1550nm$; $G = 20dB$; $P_{p_{in}} = 30\times10^{-3} W$

$P_{s_{in}} = ?$ $P_{s_{out}} = ?$

$G = 20dB$ ∴ Its normal ratio is

- $\boxed{G = 10^\wedge\left[\frac{20dB}{10}\right] = 10^\wedge 2 = 100}$

We know that
- $P_{s_{in}} = \frac{\frac{\lambda_p}{\lambda_s} P_{p_{in}}}{(G-1)} = \frac{\left(\frac{980}{1550}\right)(30\times10^{-3})}{(100-1)}$

∴ $\boxed{P_{s_{in}} = 190\mu W}$

- To find $P_{s_{out}}$: W.K.T $G = \frac{P_{s_{out}}}{P_{s_{in}}}$

∴ $P_{s_{out}} = G \times P_{s_{in}} = 100\times190\times10^{-6} W$

$\boxed{P_{s_{out}} = 19mW}$

② Assume that we have an EDFA amplifier that produces $P_{s_{out}} = 27dBm$ for input level of 2dBm at 1542nm.

(a) find the amplifier Gain

(b) What is the minimum pump power required

(c) PCE & QCE of EDFA (Assume $\lambda_p = 980nm$)

→ Given data:-
- $P_{s_{out}} = 27dBm = 1mW\left(10^\wedge\left(\frac{27}{10}\right)\right) = 501.19mW$
- $P_{s_{in}} = 2dBm = 1mW\left(10^\wedge\left(\frac{2}{10}\right)\right) = 1.58mW$
- $\lambda_p = 980nm$ (Default value)
- $\lambda_s = 1542nm$

(i) Amplifier Gain: $G = \frac{P_{S_{out}}}{P_{S_{in}}} = \frac{501.19\times10^{-3}}{1.58\times10^{-3}} = \underline{\underline{317.21}}$

$G_{dB} = 10\log(317.21) \approx 25dB$

(ii) Minimum pump power required $(P_{P_{in}})$:-

W.K.T $P_{S_{in}} = \frac{\left(\frac{\lambda_P}{\lambda_S}\right) P_{P_{in}}}{(G-1)}$

$$\therefore \quad P_{P_{in}} = \frac{(G-1)\, P_{S_{in}}}{\left(\frac{\lambda_P}{\lambda_S}\right)} = \frac{(317.21-1)(1.58\times10^{-3})}{\left(\frac{980n}{1540n}\right)}$$

$P_{P_{in}} = 785\times10^{-3} W = 785 mW$

(iii) • Power Conversion Efficiency (PCE) :-

$$PCE = \frac{P_{S_{out}} - P_{S_{in}}}{P_{P_{in}}} = \frac{(501.19 - 1.158)\times10^{-3}}{785\times10^{-3}}$$

$PCE =$

$\% PCE = \quad \times 100 \quad =$

• Quantum Conversion efficiency is

$$\% QCE = \frac{\lambda_s}{\lambda_p} PCE \times 100$$

$$QCE = \left(\frac{1540}{980}\right)\times \qquad \times 100$$

$QCE = 99.9\%$

V.T.U completion

8.4 : Optical NETWORKS :-

10 Marks

8.4.1 : SONET - SDH Multiplexing hierarchy :-

The two standardised hierarchies for optical networks are

<i> Synchronous optical NETWork (SONET)

<ii> Synchronous Digital Hierarchy (SDH)

SONET is mostly used in North America & SDH is used in all other countries. Both these are compatible with eachother.

<i> SONET Frame structure :-

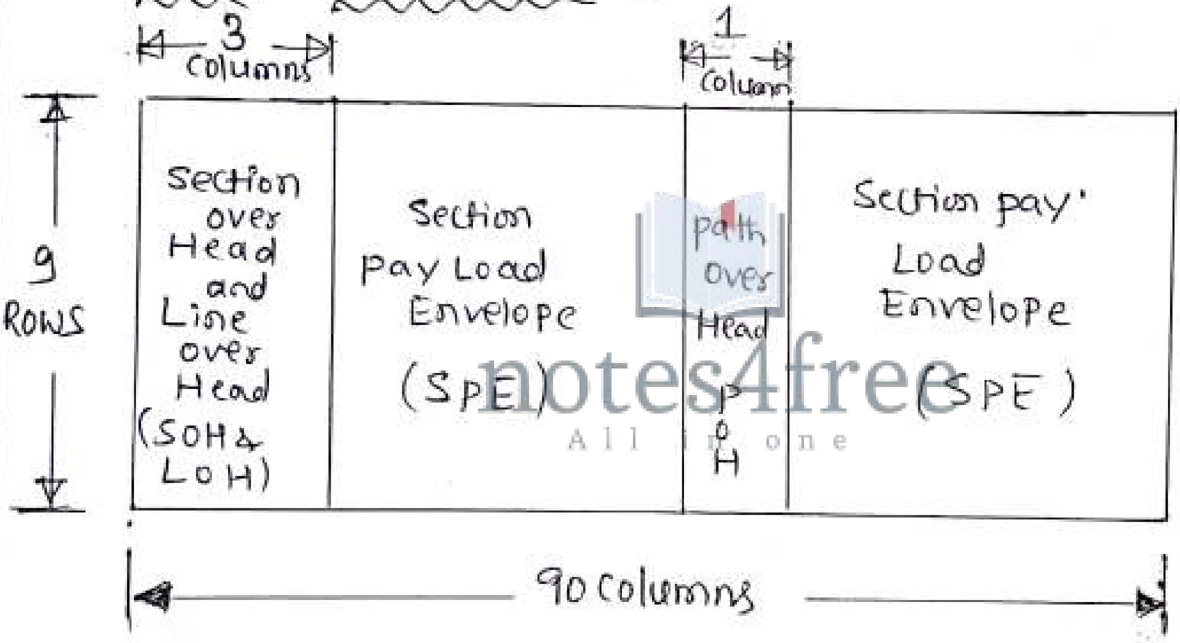


figure 8.5 : SONET Frame structure.

It is a two dimensional structure. It has 90 columns and 9 rows, which are organized as follows.

1. Section & Line overhed [SOH & LOH] requires 3 columns.
2. path overhead (POH) requires 1-column.
3. Synchronous pay Load Envelope (SPE) requires 86 columns.

One Row & one column element constitutes 8 bits.

∴ Total number of bits frame = $90 \times 9 \times 8$ bits

$= \underline{\underline{6480}}$ bits

Duration of each frame = 125 µs.

Hence number of bits/sec = Bit Rate = $\frac{\text{Total No. of bits frame}}{\text{Time duration}}$.

i.e., $\boxed{\text{Bit Rate of SONET} = \frac{6480}{125 \times 10^{-6}} = 51.84 \text{ Mbps}}$ *

∴ The Bit rate of a basic SONET frame structure is 51.84 Mbps. The Basic bit rate of a SONET structure is known as " Synchronous transport signal - 1 (STS-1). all other SONET signals have integer multiples of this rate.

Ex:- STS-N bit rate is N-times the bit rate of STS-1 signal bit rate 51.84 Mbps.

STS-3 bit rate 3×51.84 Mbps = 155.52 Mbps //

→ Line ~~ead~~ over Head <LOH> connects two SONET devices together.

→ path over-Head (POH) provides end-end connection.

→ A fundamental SONET frame has a duration of 125 µs.

→ The SONET structures are designated as STS-1, STS-2, STS-3, . . . , STS-N.

→ When an optical signal is modulated by STS-N i.e. the optical signal formed is known as '<u>OC-N</u>'.

OC → optical carrier.

<ii> SDH-Frame structure :-

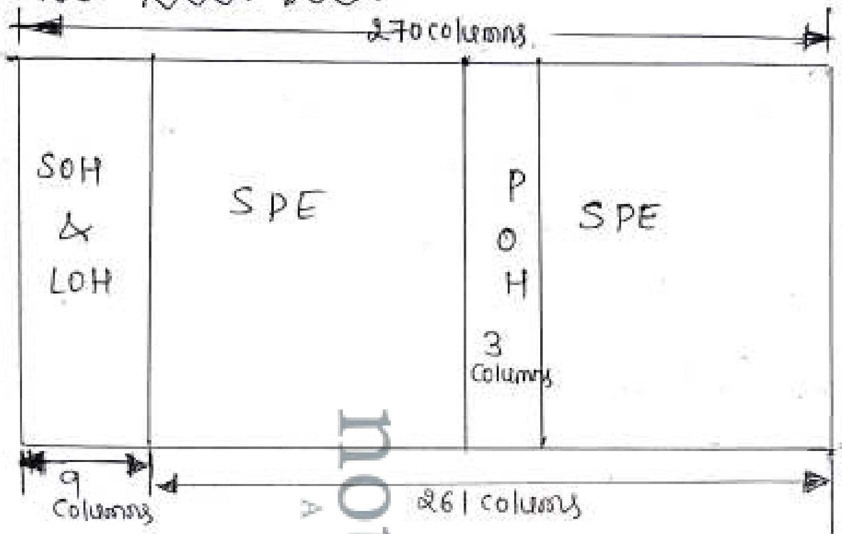


figure 8·6: SDH Frame structure :-

→ The SDH frame structure has 270 columns and 9 ROWS. This is similar to SONET structure except the No. of colums is multiplied by '3'.

→ The Basic Bit rate of SDH $\Big\} = \frac{270 \times 9 \times 8}{125 \times 10^{-6}} = 155.52$ Mbps.

→ The Basic signal bit rate in SDH, is called synchronous transport module 1 (STM-1).

→ In General STM- streams are designated as STM-M. Where M = 1, 4, 16, 64 . . . . .

→ It is clear that $\boxed{\left.\begin{matrix}\text{STM-1'}\\ \text{Bit rate}\end{matrix}\right\} = 3 \times \underset{\text{Bit rate}}{\text{STS-1}}}$ &

∴ A translation mechanism may be needed to interconnect SONET & SDH equipments.

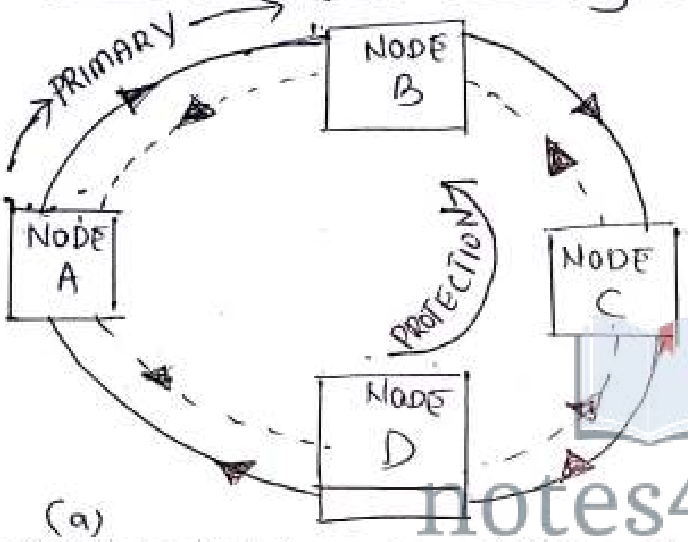
8.5. SONET/SDH Rings :-

SONET/SDH rings are called as self healing rings. ~~These~~ Depending upon the method of switching from primary to protection path/Line, there are two types of RINGS

(i) Unidirectional path switching Rings [UPSR]

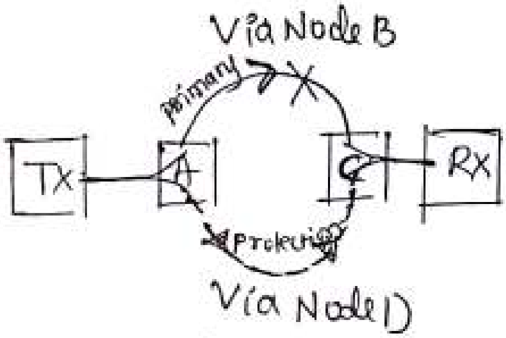
(ii) Bidirectional line switching Ring [BLSR]

(i) Unidirectional path switching Rings [UPSR]



(a)

Fig 8.7: Unidirection path switching Ring (UPSR)



(b)

Fig 8.7: Auto switching to protection path when a link fails in primary path.

- Figure 8.7 (a) & (b), shows schematic diagram of a 2-fiber UPSR. Two fibers are used one for primary path and the other for the protection path.

→ The primary path is clockwise direction & protection path is anticlockwise direction.

→ Suppose a connection is made between Node A & Node C. By default 'NODE A' transmits s/l to Node C in primary path via node B. (A→B→C). This condition is called Normal condition.

*→ When any of the link fails (or) degraded, this is automatically detected by the Reciever (RX) and the connection now is switched over to the protection path via the Links A→D→C in the anticlockwise direction as shown in figure(b).

(ii) Bidirectional Line Switching Ring:- [BLSR]

→ figure 8.8, shows a schematic diagram of BLSR. In this arrangement there are four fibers two each for primary & secondary loop as shown.

→ $(P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow P_4)$ are the primary Links used in clock wise direction

→ $(P_5 \rightarrow P_6 \rightarrow P_7 \rightarrow P_8)$ are the ~~se~~ primary Links used in Anticlock-wise direction.

→ Similarly $(S_1 \rightarrow S_2 \rightarrow S_3 \rightarrow S_4)\}$ → Secondary Links in clockwise dirn
$S_5 \rightarrow S_6 \rightarrow S_7 \rightarrow S_8$ → Secondary Links in Anticlockwise direction

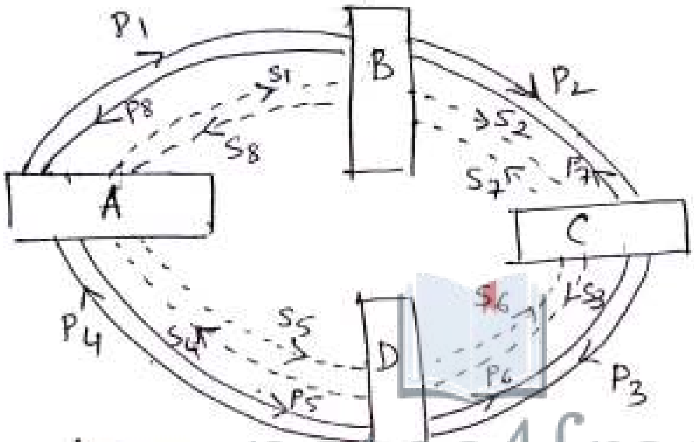


figure 8.8: Schematic of BLSR:-

→ signal will be normally passing through primary loop. Secondary loop is a stand by loop.

→ Any segment (line) can be used as protection link when there is a failure ⓞ degradation in corresponding Link.

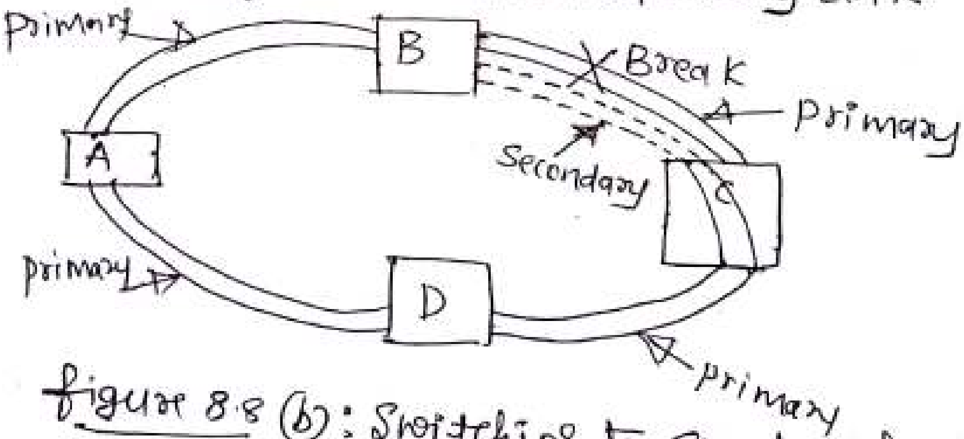
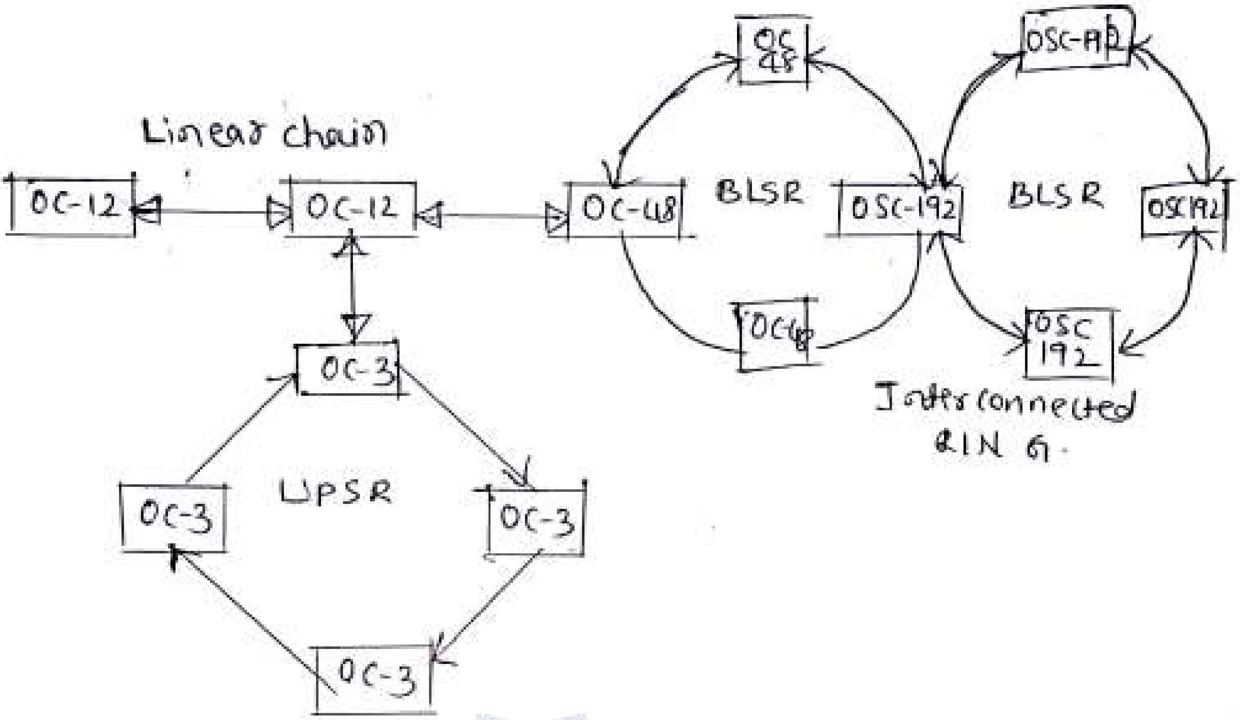


figure 8.8 (b): Switching to Secondary Link during Break

→ Figure 8.8(b) illustrates how a connection is switched over to Secondary Link, when primary Link Between Node B & Node C' is failed/degraded/Broken.

8.6 SONET/SDH Rings:-



-: figure: 8.8: various types of SONET/SDH networks:-

SONET	Electrical	SDH	Bit Rate MbPS
OC-1	STS-1		51.84
OC-3	STS-3	STM1	155.52
OC-12	STS-12	STM4	622.08
OC-48	STS-48	STM16	2488.32
OC-192	STS-192	STM-64	9953.28

Table1: SONET/SDH Bit rates.

→ figure 8.3 shows the various types of SONET/SDH networks, their interconnections & the type of rings used.

→ OC- standsfor optical carries which is equivalent to STS-signal bit rate.

→ The various networks used are OC-3, OC-12 (UPSR), OC-48 (BLSR), OSC-192 (BLSR) & their bit rates, SDH|SONET signals are indicated in Table1.

→ It is noted that each individual Ring has its own failure recovery methodology and management procedures.

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8.7: High Speed Light Wave-guides :- (or) High-speed Light Wave signals

→ The systems operating at 10 Gbps and above are called as "High Speed Light Wave systems".

Ex:- systems operating at 10Gbps, 40Gbps, 160Gbps.

→ These systems use a variety of transceivers in which both transmitters and receivers are incorporated in a single unit

Several types of 10 Gbps systems in use are

(i) Fiber channel connections for storage area network.

(ii) 10 Gigabit Ethernet usually designated as 10-GbE (or) 10 GigE.

* (iii) SONET/SDH OC-192/STM-64, terrestrial & metrolinks.

→ There are 3-classifications of multimode fibers used in high-speed light wave systems shown in Table 2.

optical Mode-Fiber	wavelength	Bandwidth x Lenght
OM_1- Grade Fiber	1310nm	(160 - 200) MHz-Km
OM_2 Grade Fiber	1310nm	(400 - 500) MHz-KM
OM_3- Grade Fiber	1310nm	(2000) MHz - km.

→ Ideally all segments of a link should use same grade of multimode fibers. But this is not practicable in all situations.

→ We may find a mixture of OM2 & OM3 fibers spliced together.

→ In such cases it is necessary to find maximum link length that is feasible. this is done by using the formula

$$L_{max} = L_{OM_2} \frac{BW_{OM_2}}{BW_{OM_3}} + L_{OM_3}$$

Ex:- If $L_{OM_2} = 40m$; $L_{OM_3} = 120m$; $BW_{OM_2} = 500MHz$ & $BW_{OM_3} = 2000MHz$; Then $\boxed{L_{max} = 40 * \frac{2000}{500} + 120m = 280m}$

8.8 Optical Interfaces:-

The optical Interfaces Recommended by ITU(T) are

(i) 8.4.1 ITU(T) - G.957:-

This optical interface standard specifies, "optical interface parameters for equipments & systems based on SDH to enable transmission capability.

This falls in the following categories.

(a) Graded index multimode in the 810nm window [O-band]

(b) Conventional non-dispersion shifted single-mode for the 1310nm & 1550nm windows. [O band & C-band]

(c) Dispersion shifted single mode for the 1550nm window [C-band]

-*- This system objective is to achieve a bit-error-rate (BER) of less than 10^{-10} for lower rate system (< Gb/s) and 10^{-12} for higher rate systems.

(ii) ITU(T) G.691:-

- Optical interface for single channel STM-64 and other SDH systems with optical amplifiers ITU(T) G.692.
- Multimode/channel systems with optical amplifiers G.652, G.653, G.655 specifies the fiber cables.
- The transmission distances are specified for these cables, depending on the distance.
- The Sonet destinations are given as short reach, Intermediate reach, long-reach & very long reach.
- The SDH destinations are Intra-office, short haul, long haul and ultra long haul.

— * — * end-of-unit 8 — ←