Page 2

OPTICAL FIBER COMMUNICATION

Receiver configurations
Point to Point Links:
System considerations
Link power budget
Rise time budget
SLE: Burst mode receivers

- UNIT 5: Analog Systems and Optical Amplifiers Pg 93
  - Overview of analog links
  - Basic applications and
  - Types of optical amplifiers
  - Semiconductor optical amplifiers
  - Erbium doped fiber amplifiers
  - SLE: Wide band optical Amplifiers

- UNIT 6: Optical Networks: Pg 111
  - SONET / SDH
  - Broadcast and select WDM networks
  - Nonlinear effects on network performance
  - SLE: High speed Light wave links

TEXTBOOK:

"Optical Fibre Communication", 'Gerd Keiser', MGH, 3th Ed, 2008.

UNIT-1

The Overview of Optical Fibre Communications

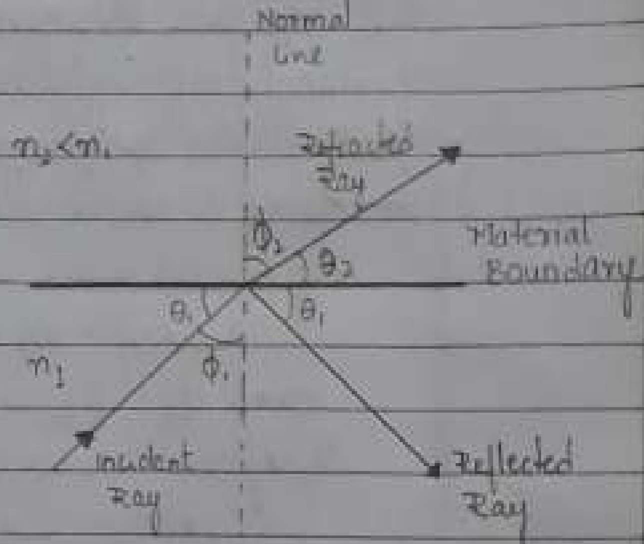
- **Basic Optical Laws and Definitions:**

- Refractive Index (RI):

The ratio of the speed of light in a vacuum to speed of light in matter is called Refractive Index or Index of Refraction.

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

$n = 1.45$ (silica glass)
$n = 2.42$ (diamond)



Reflection and Refraction of a light ray at a material boundary

When a light ray is incident on the interface between the dielectrics differing refractive indices "refraction" occurs.

If $n_2 < n_1$, then the refraction angle ϕ_2 will be, $\phi_2 > \phi_1$

Here,
ϕ_1: angle of incidence
ϕ_2: angle of refraction

By Snell's law of refraction, the RI of two materials are related to each other.

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

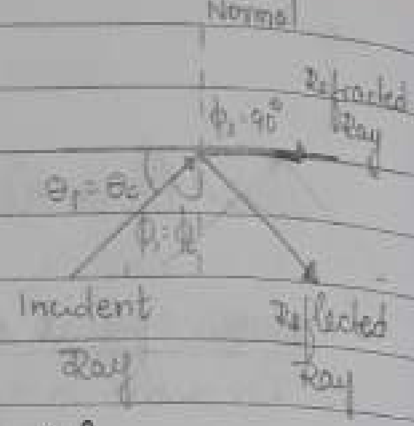
At the boundary between two media of different refractive indices, the refracted ray will lie in the plane of incidence.

Reflected ray lies in the plane of incidence and angle of incidence will be equal to the angle of reflection.

Partial Internal Reflection: A small amount of light is reflected back into the originating medium. By law of reflection,

$\theta_1 = \theta_1$ ie, $\phi_1 = \phi_1$

- As $n_2 < n_1$, the angle of reflection is always greater than the angle of incidence. Thus when the angle of refraction is 90° and refracted ray emerges parallel to the interface between the dielectrics, the angle of incidence must be less than 90°. This is the limiting case of refraction and the angle of incidence is known as the "critical angle"



By Snell's Law, wkt

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

Here $\phi_1 = \phi_c$ and $\phi_2 = 90^\circ$

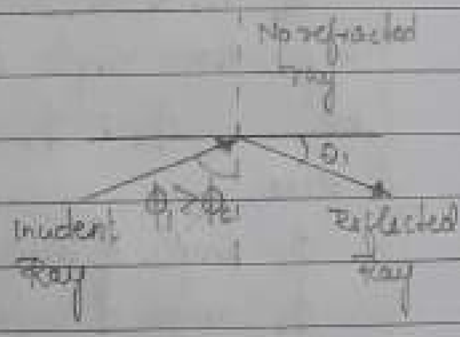
Therefore, $n_1 \sin\phi_c = n_2 (1)$

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

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

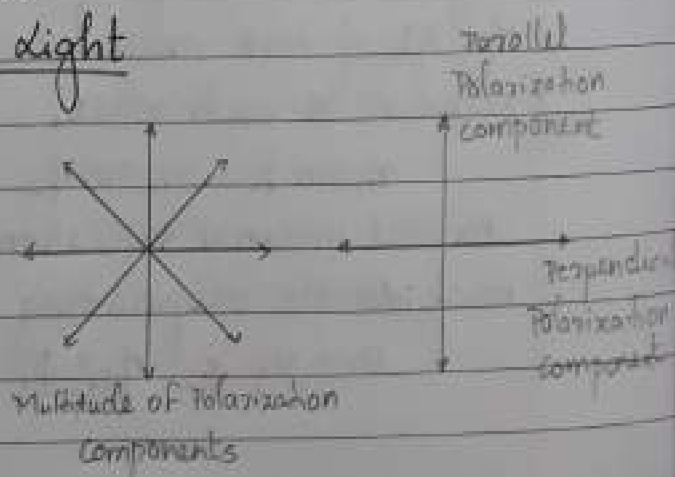
- Total Internal Reflection

The angle of incidence should be greater than the critical angle to get reflected back into the originating medium completely. This phenomena is called the Total Internal Reflection (TIR)



- Polarization components of Light

An ordinary light wave consists of many traverse electromagnetic waves vibrating in variety of directions. (unpolarized light)

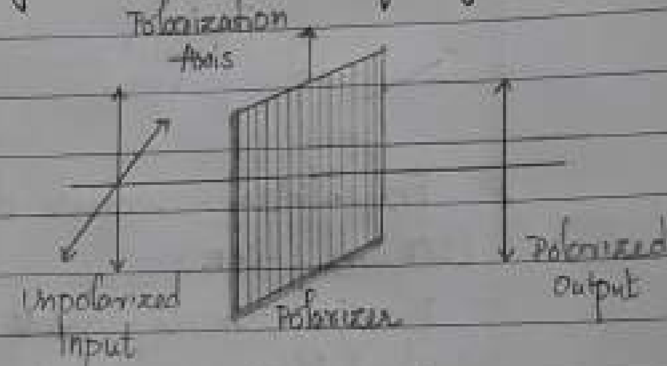


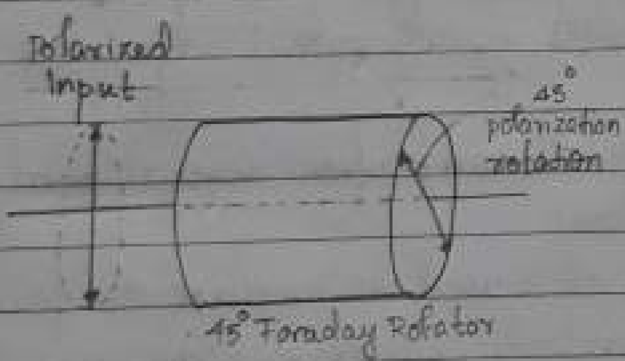
Any directions of vibrations can be represented by combination of parallel polarized component and perpendicular polarized component. When all the electric field components of the different traverse waves are aligned parallel to each other then the light wave is said to be linearly polarized.

Polarization sensitive materials:

Optical Fiber communication uses optical isolators and optical filters which are made by using polarization sensitive materials. Ex: Polarizer, faraday rotator and birefringent crystals

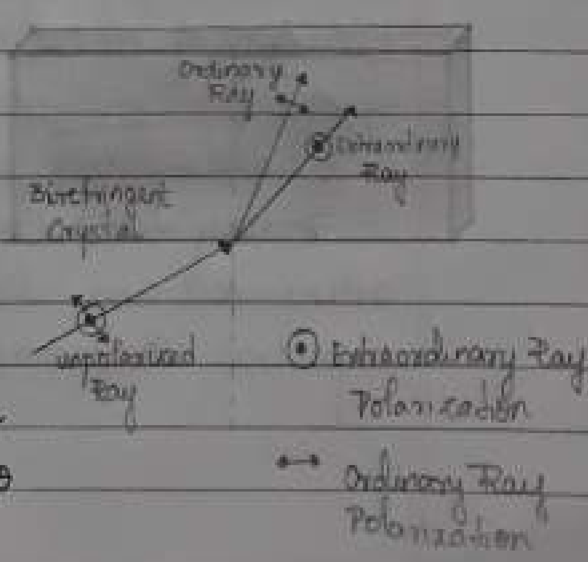
Polarizer: A device that transmits only one polarization component and blocks the others. Ex- sunglasses





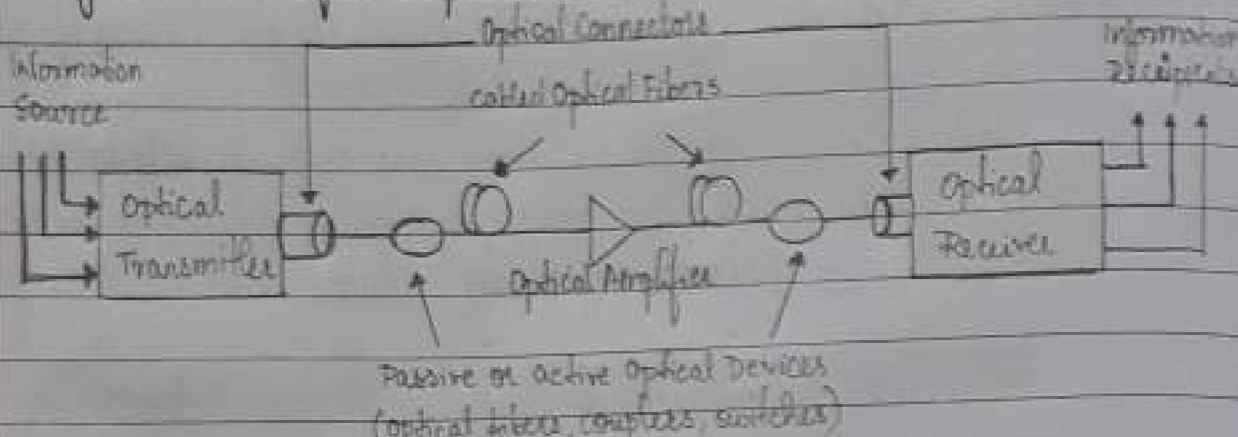
Faraday Rotator: A device that rotates the state of polarization of light passing through it by a specific amount. The rotation is independent of the state of polarization of input light.

Birefringent or Double Refractive Crystal: Double Refraction occurs when indices of refraction are slightly different along two perpendicular axes of the crystal. A device which is made up of such materials is called as a spacial walkoff Polarization (SWP). It splits the light entering into



orthogonally polarized beams. One is ordinary-ray and second beam is extraordinary ray.

- key Elements of an Optical Fiber communication link:



Transmitter: consists of light source and modulation circuitry (LED and LASER).

Passive elements: assist in controlling and guiding the light (optical filters, optical splitters and optical multiplexers).

Active elements: (modulators, variable optical attenuators and optical switches.

Optical Fiber: Its length will range from several hundred meters to several kilometers.

Amplifiers or Repeaters: It is used to increase the power margin.

Receiver: contains photodiode, electronic drive circuit and electrical amplification.

Aim of an optical fiber communication link is to transport signal from one location to another location with high degree of reliability and accuracy.

During transmission, the signal will get progressively attenuated and distorted due to scattering, absorption and dispersion. Performance of OFC link is error probability and SNR.

Advantages:

- Enormous potential bandwidth: optical carrier frequency 10^{13} to 10^{15} (Hz)
- Small size and weight: diameter in μm.
- Electrical isolation: As they are insulators there is no earth looping or interference problems.
- Immunity to interference and crosstalk: because they form a waveguide and are free from EMI, RFI etc.
- Low transmission loss: 0.15 dB/km
- System is reliable and easy to maintain.

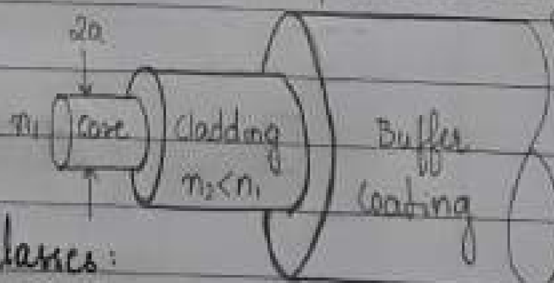
Disadvantages:

- Problem of joining and repairing of cable.
- Cost effective only for long haul links.

- <u>Optical Fiber Modes and Configurations:</u>

Optical fibers can be classified in terms of material, bandwidth, operating classes and refractive index (RI):

Core: carries light (high RI)
Cladding: confines light to core (lower RI)
Buffer: protects core and cladding from damage



Classification based on operating classes:
- Single mode
- Multimode

Classification based on refractive index (RI):
- Step Index
- Graded index

The propagation of light along a wave guide can be described in terms of a set of guided electromagnetic waves called the <u>modes of the waveguide.</u>

Some of the main types of fibers in OFC are:

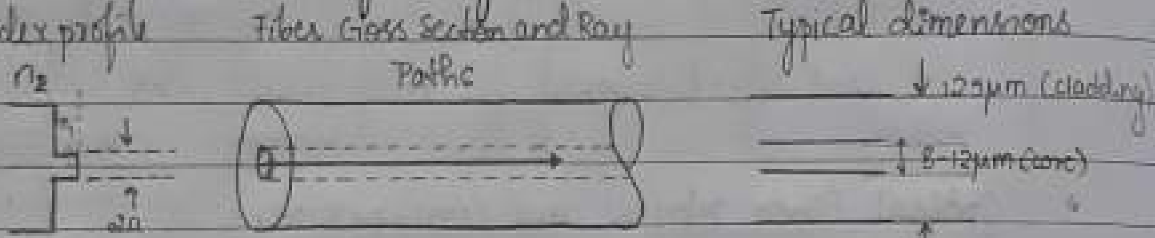
1. Single mode step index fiber
2. Multimode step index fiber
3. Multimode graded index fiber.

Step Index Fibers:

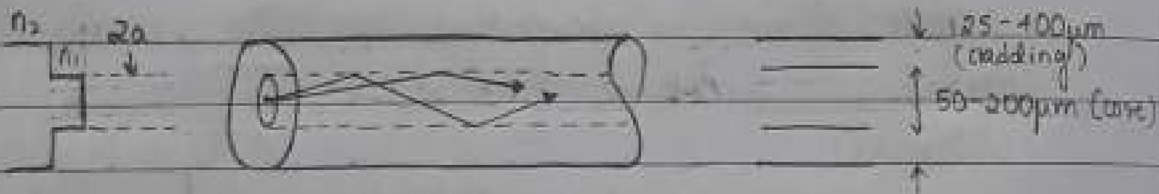
In step index fibers the RI of the core is constant and the index changes abruptly at the core-cladding interface. The RI of core is n_1 and RI of cladding is n_2 which is slightly higher.

$$n(r) = \begin{cases} n_1 & r < a \text{ core} \\ n_2 = n_1(1-\Delta) & r \geq a \text{ cladding} \end{cases}$$

where Δ : core-cladding index difference.
(1 to 3% for multimode)
(0.2 to 0.1% for single mode)



SINGLE MODE STEP INDEX FIBER



MULTIMODE STEP INDEX FIBER

single mode step index fiber: allows the propagation of only one transverse electromagnetic mode

Multimode step index fiber: is large enough to allow the propagation of many modes within the fiber core.

The total number of guided modes or mode volume (M_s) for step index fiber is:

$$\boxed{M_s = \frac{v^2}{2}} \quad \text{where } V = \frac{2\pi a n_1 \sqrt{2\Delta}}{\lambda}$$

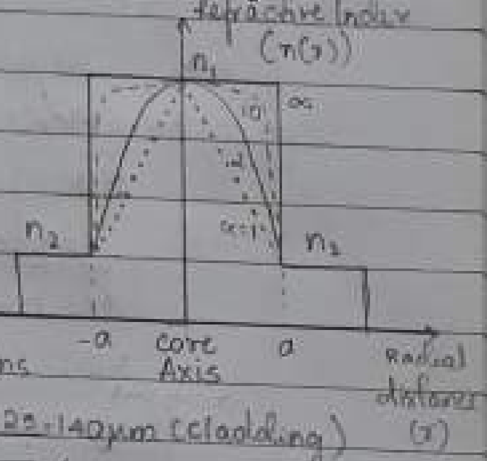
step index fibers are well suited to applications requiring high-power densities such as delivering laser power for medical and industrial applications.

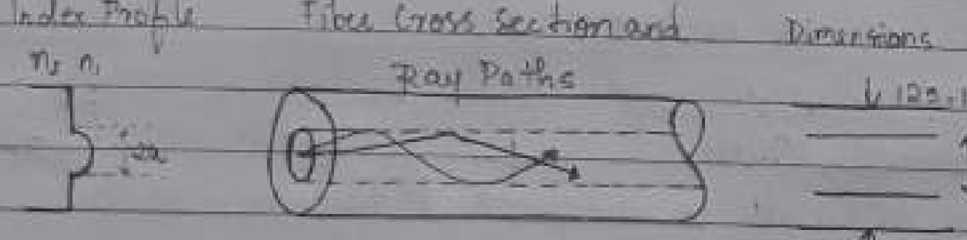
- Graded Index Fibers:

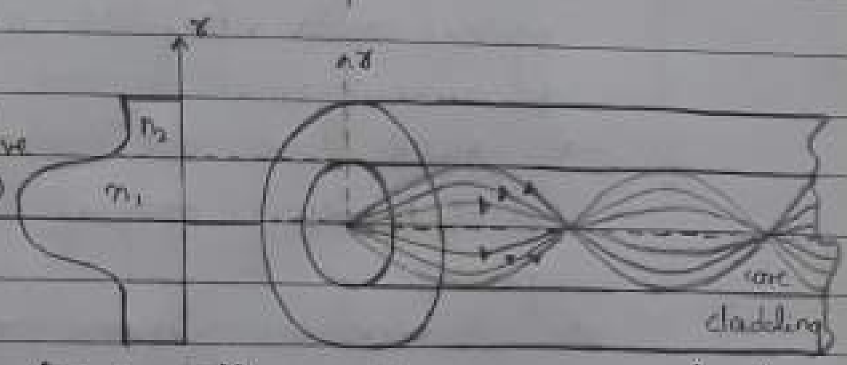
Graded Index Fibers do not have a constant RI in core but a decreasing core index $n(r)$ with radial distance from a maximum value of n_1 at the axis to a constant value n_2. The RI profile can be defined as

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

where Δ : relative RI difference
α : profile parameter
$\alpha = \infty$: step index profile
$\alpha = 2$: parabolic profile
$\alpha = 1$: triangular profile







The curved paths through the fiber core is because the gradual decrease in RI from the centre of the core creates many refractions with ever increasing angle of incidence, until the condition for TIR are met and ray travels back towards the core axis again being continuously refracted.

The total number of guided modes or mode volume (M_g) for graded index fiber is

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

$\alpha = 2$ for parabolic $\quad v = \frac{2\pi a n_1\sqrt{2\Delta}}{\lambda}$

- Difference between step index and graded index

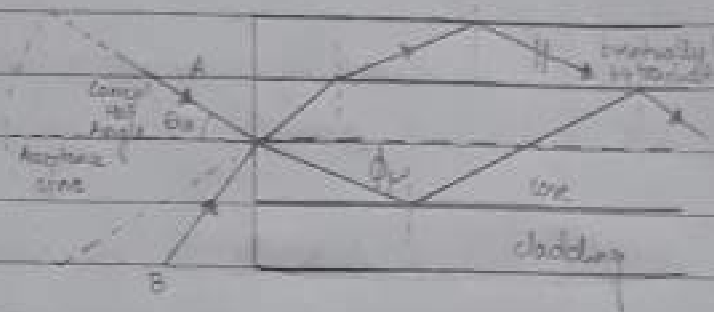
Step Index	Graded Index
→ RI of the core is uniform throughout and changes abruptly at the cladding	→ RI of the core is fuction of the radial distance from the fiber center.
→ They may have band width of 50MHz.	→ They may have band width of 200, 400, 600 MHz.
→ Smaller numerical aperture.	→ Larger numerical aperture.
→ Typical core size for SMSI is 8-12μm MMSI is 50-200μm.	→ Typical core size for GI is 50-100μm.
→ Cladding for SMSI is 125μm MMSI is 125-140μm.	→ Cladding for MMGI is 125-140μm

- Difference between single mode and multimode

Single Mode	Multimode
→ It is difficult to launch optical power into fiber because of small core size.	→ It is easier to launch optical power into optical fiber because of large core size.
→ LASER diodes are used to launch optical power	→ LED are generally used to launch optical power.
→ It sustains only one mode of propagation	→ It allows hundreds of modes of propagation
→ These fibers do not suffer from inter modal dispersion.	→ These fibers suffer from inter modal dispersion.
→ Higher bandwidth are possible.	→ The bandwidth is limited.

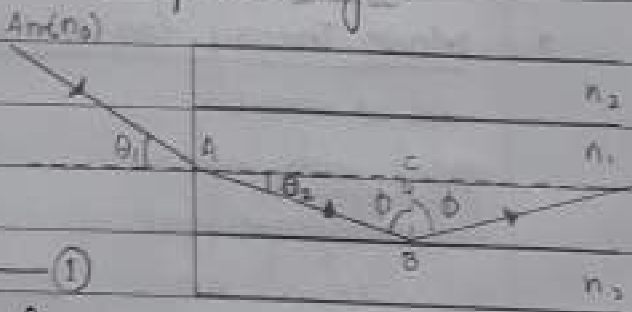
- Ray Optics Representation

A light ray undergoes its first refraction at the air core interface. The angle at which this refraction occurs is crucial because this angle will dicate whether the subsequent internal reflections will follow the principle of Total Internal Reflection. This angle at which the light ray first encounters the core of an optical fiber is called Acceptance Angle.



Numerical Aperture:

considering refraction at the air core interface.



By Snell's Law

$$n_0 \sin\theta_1 = n_1 \sin\theta_2 \quad \text{--- (1)}$$

considering right angle triangle ABC

$$\phi = 90^\circ - \theta_2 \quad \text{--- (2)}$$

Substituting eq (2) in eq (1)

$$n_0 \sin\theta_1 = n_1 \sin(90^\circ - \phi)$$

$$n_0 \sin\theta_1 = n_1 \cos\phi \quad \text{--- (3)}$$

$$n_0 \sin\theta_1 = n_1 (1 - \sin^2\phi)^{1/2} \quad \text{--- (4)}$$

By considering the limiting case

$$\phi = \phi_c \text{ and } \theta_a = \theta_1 \quad \text{--- (5)}$$

Substituting (5) in eq (4)

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

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

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

$$n_0 \sin\theta_a = \cancel{n_1}\left(\frac{\sqrt{n_1^2 - n_2^2}}{\cancel{n_1}}\right)$$ here $n_0 = 1$ (air)

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

In terms of relative refractive index:

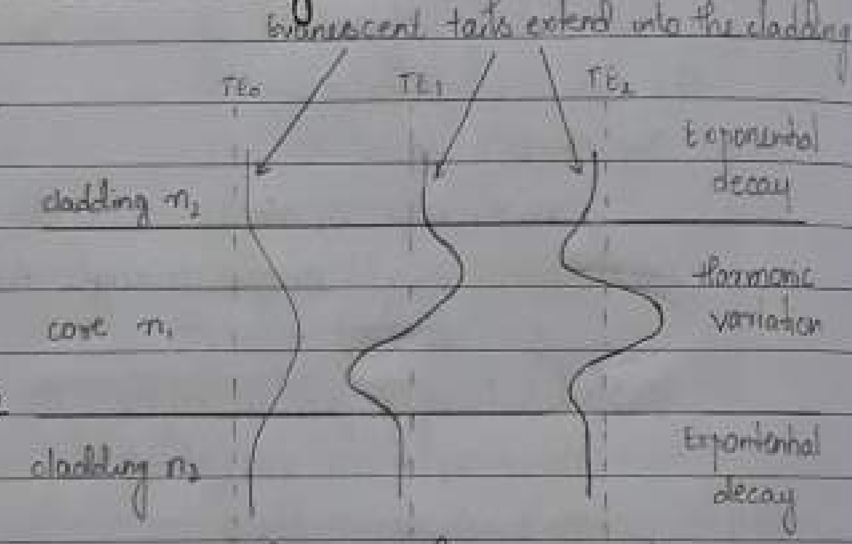
$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \quad \text{or} \quad 2n_1^2\Delta = n_1^2 - n_2^2$$

$$\Delta \simeq \frac{n_1 - n_2}{n_1} \quad \text{for } \Delta << 1$$

$$\therefore \boxed{\sin\theta_a = n_1\sqrt{2\Delta}}$$ Numerical Aperture in terms of relative RI

- **Mode Theory for circular waveguides:**

Let us consider modal fields in planar dielectric wave guide to understand mode theory in circular optical fibers. The optical fiber structure is considered as optical waveguide.



The figure shows the field patterns of several low order transverse electric (TE) modes. The order of the mode is equal to the number of field zeros that are present across the guide.

The plot shows that the electric fields of the guided modes are not completely confined to the core but instead they extend partially into the cladding. The fields vary harmonically in the guiding region of the core and decay exponentially outside this region.

For lower order modes the fields are tightly concentrated near the center at the slab with little penetration into the cladding region on the other hand, for higher order modes, the fields are distributed more towards the edges of the guide and penetrate into the cladding region.

In optical fiber, wave guides have infinite radiation modes that are not trapped in the core.

In addition to bound and refracted modes, a third category of modes called leaky modes are present in optical fibers.

A mode remains guided as long as it satisfies the following condition:

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

where: $k = \frac{2\pi}{\lambda}$

β: propagation constant

cutoff condition – $\beta = n_2 k$ for guided modes and leaky modes
↳ (boundary between truly guided modes and leaky modes)

As soon as $\beta < n_2 k$, power leaks out of the core into the cladding region.

- **Summary of key modal concepts:**

– V number

An important parameter connected with cutoff condition is the V-number. It is a dimensionless quantity the determines how many modes a fiber can support. It is defined as:

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

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

V - number

The V-number can be used to express the number of modes M in a multimode fiber when V is large.

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

Number of modes in a multimode fiber

When the V-number approaches cutoff for any particular mode, more of the mode power is in the cladding.

For large values of V (far from cutoff), the fraction of the average optical power residing in the cladding can be estimated by:

$$\frac{P_{clad}}{P} \simeq \frac{4}{3\sqrt{M}}$$

where P : total power in the fiber.

Since M is proportional to V^2, the power flow in the cladding decrease as V increases. This increases the number of modes in the fiber, which is not desirable for a high bandwidth capability.

- **Problems:**

Q1: A step index multimode fiber with a numerical aperture of 0.20 supports approximately 1000 modes at an 850-nm wavelength.

a. What is the diameter of its core?
b. How many modes does the fiber support at 1320 nm?
c. How many modes does the fiber support at 1550 nm?

- Given: Step index multimode fiber

$NA = 0.20 \quad M = 1000$ at $\lambda = 850\,nm$

a. Diameter of its core:

The number of modes in a multimode fiber is given by

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

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

$$1000 = \frac{1}{2}\left(\frac{2\pi a}{850\times10^{-9}}\right)^2 (0.2)^2$$

$$a = 30.25 \times 10^{-6} = 30.25\,\mu m$$

$\therefore$ diameter : $D = 2a = 60.5\,\mu m$

b. Number of modes supported by the fiber at 1320 nm

The number of modes in a multimode fiber is given by

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

$$M = \frac{1}{2}\left(\frac{2\pi \times 30.25 \times 10^{-6}}{1320 \times 10^{-9}}\right)^2 (0.2)^2$$

$$M = 414.66 \simeq \underline{415 \text{ modes}}$$

c. Number of modes supported by the fiber at 1550 nm

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

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

$$M = \frac{1}{2}\left(\frac{2\pi \times 30.25 \times 10^{-6}}{1550 \times 10^{-9}}\right)^2 (0.2)^2$$

$$M = 300.73 \simeq \underline{301 \text{ modes}}$$

Q2: a. Determine the normalized frequency at 820 nm for a step index fiber having a 25 μm core radius, $n_1 = 1.48$ and $n_2 = 1.46$

b. How many modes propagate in this fiber at 820 nm?

c. How many modes propagate in this fiber at 1320 nm?

d. How many modes propagate in this fiber at 1550 nm?

e. What percent of the optical power flows in the cladding in each case?

Given: Note: normalized frequency: V-number

$n_1 = 1.48$; $n_2 = 1.46$

$a = 25 \mu m$

a. Normalized frequency at 820 nm.

The V-number is given by

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} = \frac{2\pi (25 \times 10^{-6})}{820 \times 10^{-9}}\sqrt{1.48^2 - 1.46^2}$$

$\underline{V = 46.45}$ ~~is~~ the normalized frequency at 820 nm.

b. Number of modes in the fiber at 820nm

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

as we know V for 820nm

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

$$\therefore M = \frac{(46.45)^2}{2} = 1078.8 \simeq \underline{1079 \text{ modes}}$$

c. Number of modes in the fiber at 1320nm

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

$$M = \frac{1}{2}\left(\frac{2\pi \times 25\times10^{-6}}{1320\times10^{-9}}\right)^2 (1.48^2 - 1.46^2)$$

$$M = 416.33 \simeq \underline{416 \text{ modes}}$$

d. Number of modes in the fiber at 1550nm

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

$$M = \frac{1}{2}\left(\frac{2\pi \times 25\times10^{-6}}{1550\times10^{-9}}\right)^2 (1.48^2 - 1.46^2)$$

$$M = 301.94 \simeq \underline{302 \text{ modes}}$$

e. Percentage of optical power flowing in the cladding at each case:

CASE 1: at 820 nm : M = 1079 modes

$$\frac{P_{clad}}{P} = \frac{4}{3\sqrt{M}} = \frac{4}{3\sqrt{1079}} = \underline{4.05\%}$$

CASE 2: at 1320nm : M = 416 modes

$$\frac{P_{clad}}{P} = \frac{4}{3\sqrt{M}} = \frac{4}{3\sqrt{416}} = \underline{6.54\%}$$

CASE 3: at 1550 nm : M = 302 modes

$$\frac{P_{clad}}{P} = \frac{4}{3\sqrt{M}} = \frac{4}{3\sqrt{302}} = 7.67\%$$

Q3: Find the core radius necessary for single mode operation at 1320nm of a step-index fiber with $n_1 = 1.480$ and $n_2 = 1.478$. What are the numerical aperture and maximum acceptance angle of the fiber?

- Given: single mode step-index fiber.

$\lambda = 1320$ nm

$n_1 = 1.480$ and $n_2 = 1.478$.

- Core Radius:

The v-number for single mode step index fiber is given by the following condition:

$$V \leq 2.405$$

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

$$\therefore \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \leq 2.405$$

$$a \leq \frac{2.405\lambda}{2\pi\sqrt{n_1^2 - n_2^2}}$$

$$a \leq \frac{2.405 \times 1320 \times 10^{-9}}{2\pi\sqrt{1.480^2 - 1.478^2}}$$

$$\therefore a \leq 6.57 \times 10^{-6}$$

Hence $a = 6.57\mu m$ is the core radius necessary.

- Numerical Aperture:

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

$$NA = \sqrt{1.480^2 - 1.478^2}$$

$NA = 0.077$ is the numerical aperture.

- Maximum acceptance angle of the fiber:

$$\sin \theta_a = NA$$

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

$$\theta_a = \sin^{-1}(0.077)$$

$\theta_a = 4.42^\circ$ is the maximum acceptance angle

- **SLE: Fiber Fabrication:**

- Fiber Materials:

In selecting materials for optical fibers a number of requirements needs to be satisfied. Some of them are:

- Must be possible to be drawn into long, thin, flexible fibers
- The material must be transparent at a particular optical wavelength in order to guide effectively.
- It must be physically compatible to be available in slightly different refractive indices for the core and cladding.

- Types of Fibers:

1. Glass fibers: Glass is made by fusing mixtures of metal oxides, sulfides or selenite. The most common glass is silica (SiO_2) which has a refractive index of 1.458 at 850 nm.
2. Plastic Optical Fiber / Polymer Optical Fiber: It is an optical fiber which is made out of plastic.
3. Photonic Crystal Fibers: This optical fiber is based on the properties of photonic crystals.

- Process of Fabrication:

a. Preform: Primary process of making optical fiber and it is made by chemical vapour deposition.
b. Drawing: Process of extracting optical fiber from its preform.
c. Coating: After drawing, coating is done by a lower refractive index optical cladding

- Types of Fabrication:
  - Outside Vapour - Phase Oxidation: A layer of SiO_2 particles called a soot is deposited from a burner onto a rotating graphite or ceramic mandrel.
  - Vapor-phase Axial Deposition: This process consist of four phases: laydown, consolidation, drawing and measurement
  - Modified Chemical Vapor Deposition: widely accepted for production of gradex-index fiber.
  - Plasma - Activated Chemical Vapor Deposition: It differs from MCVD by its method of heating the reaction zone.

UNIT - 2

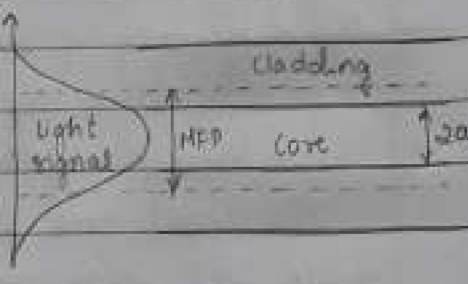
Signal Degradation in Optical Fibers

- **Single Mode Fibers:**

In single mode fibers the geometric distribution of light gives the predicting performances to characterise these fibers.

Mode Field Diameter (MFD) is a measurement of light intensity in a single mode fiber cross section. It can be determined by mode field distribution of fundamental mode.

MFD is larger than the core diameter as the light in the core also propagates through a portion of the cladding.



MFD is a function of wavelength of optical source, core radius and $n(r)$.

MFD is used to predict fiber properties like splice loss, bending loss, cutoff wavelength and waveguide dispersion.

Models used to characterize and measure MFD are far field scanning, near field scanning, transverse offset, knife edge and mask methods (optical power distribution).

A standard technique to find MFD is to measure the far field intensity and then calculate MFD using the following equation:

$$MFD = 2W_0 = 2\sqrt{\frac{2\int_0^{\infty} E^2(r)\, r^3\, dr}{\int_0^{\infty} E^2(r)\, r\, dr}}$$

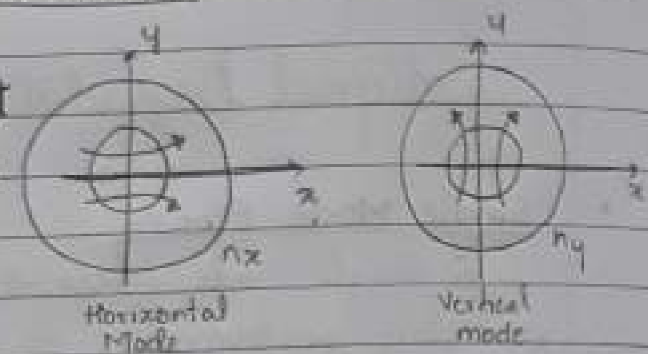
where $2W_0$: spot size

For calculation simplicity the field can be approximated by gaussian function.

$$E(r) = E_0 \exp\left(\frac{r^2}{W_0^2}\right)$$

- Propagation modes in single mode fibers:

In ordinary single mode fibers there are two independent degenerative propagation modes. We arbitarally choose one of the modes along x direction and other mode along y direction.



Because of asymmetries in refractive indices for the two degenerate modes (horizontal and vertical polarizations) are different, the difference is referred to as birefringence (Bf)

$$Bf = n_y - n_x$$

or $\beta = k_0 (n_y - n_x)$

The length over which the phase difference between x and y is 2π, the polarized waves is called beat length.

$$L_p = \frac{2\pi}{\beta} = \frac{2\pi}{k B_f} = \frac{\lambda}{B_f}$$

- **Fiber Materials:**
  - Requirements of fiber materials
    - It must be possible to make long, thin, flexible fibers
    - The material must be transparent at a particular optical wavelength in order to guide effectively
    - It should have physical characteristics such that the manufacturer can manufacture slightly different refractive indices for the core and cladding.
  - Glass Fibers
    - Large category of optical fibers are made by glass
    - These glasses are made by fusing mixtures of metal oxides, sulfides or selenides.
    - The most common glass is silica (SiO_2) which has RI

of 1.45 at 850nm.

- This can be doped with fluorine or various oxides such as B_2O_3, GeO_2 or P_2O_5.

  Ex: $GeO_2 - SiO_2$ core ; SiO_2 - cladding
  $P_2O_5 - SiO_2$ core ; SiO_2 - cladding
  SiO_2 core ; $B_2O_3 - SiO_2$ - cladding
  $GeO_2 - B_2O_3 - SiO_2$ - core ; $B_2O_3 - SiO_2$ - cladding

– Active Glass Fibers

- Doping rare earth materials into normal glass gives new optical and magnetic properties.
- These new materials are capable to perform amplification, attenuation and phase retardation on the light passing through it.

Ex: Fiber doped with erbium and neodymium used in LASER for amplification.

– Plastic Optical Fibers

- Growing demand of high speed services led fiber developers to create high bandwidth Graded index polymer (plastic) optical fibers (POF).

- **Attenuation:**

Attenuation of light signal occurs as it propagates along the fiber. The degree of attenuation determines maximum distance between the transmitter and receiver or inline amplifier.

Attenuation mechanisms are absorption, scattering and bending loss.

As light travels along the fiber, its power decreases exponentially with distance. If P(0) is the power at the origin, then the power P(z) is the power at a distance z.

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

where $\alpha_p = \frac{1}{z} \ln \frac{P(0)}{P(z)}$ km^{-1} attenuation constant.

To calculate optical attenuation in decibels per kilometer (dB/km) we use:

$$\alpha\ (dB/km) = \frac{10}{z} \log \frac{P(0)}{P(z)}$$

- Problems:

Q1. A certain optical fiber has an attenuation of 0.6 dB/km at 1310 nm and 0.3 dB/km at 1550 nm. Suppose the following two optical signals are launched simultaneously into the fiber: an optical power of 150 μW at 1310 nm and an optical power of 100 μW at 1550 nm. What are the power levels in μW of these two signals at

a. 8 km   b. 20 km

- Given:

At 1310 nm: $\alpha_{(dB/km)} = 0.6$
$P(0) = 150\mu W$

At 1550 nm: $\alpha_{(dB/km)} = 0.3$
$P(0) = 100\mu W$

The optical attenuation in dB/km is given by

$$\alpha_{(dB/km)} = \frac{10}{z} \log \frac{P(0)}{P(z)}$$

a. At 8 km

For 1310 nm

$$0.6 = \frac{10}{8} \log \frac{150\times10^{-6}}{P(z)}$$

$$P(8km) = \frac{150\times10^{-6}}{10^{0.48}} = 50\times10^{-6} = \underline{50\mu W}$$

For 1550 nm

$$0.3 = \frac{10}{8} \log \frac{100\times10^{-6}}{P(z)}$$

$$P(8\ km) = \frac{100\times10^{-6}}{10^{0.24}} = 57.54\times10^{-6} = \underline{57.54\mu W}$$

Total at 8 km
$= 50\mu + 57.54\mu$
$= \underline{107.54\mu W}$

b. At 20 km

For 1310 nm

$$0.6 = \frac{10}{20} \log \frac{150\times10^{-6}}{P(z)}$$

$$P(20km) = \frac{150 \times 10^{-6}}{10^{1.2}} = \underline{9.45\mu W}$$

Total at 20km
$= 9.45\mu + 25.12\mu$
$= \underline{34.57\mu W}$

For 1550nm

$$0.3 = \frac{10}{20} \log \frac{100 \times 10^{-6}}{10^{0.6}} = \underline{25.12\mu W}$$

Q2 A continuous 40 km long optical fiber link has a loss of 0.4dB/km

a. What is the minimum optical power level that must be launched into the fiber to maintain an optical power level of 2.0 μW at the receiving end?

b. What is the required input power if the fiber has a loss of 0.6 dB/km?

– Given:

$z = 40km$

a. The optical attenuation in dB/km is given by:

$$\alpha(dB/km) = \frac{10}{z} \log \frac{P(0)}{P(z)}$$

$$0.4 = \frac{10}{40} \log \frac{P(0)}{2 \times 10^{-6}}$$

$$P(0) = 10^{1.6} \times 2 \times 10^{-6} = \underline{79.62\mu W}$$

Hence 79.62μW is the minimum optical power level that must be launched to maintain 2.0μW at the receiving end

b. The optical attenuation in dB/km is given by:

$$\alpha(dB/km) = \frac{10}{z} \log \frac{P(0)}{P(z)}$$

$$0.6 = \frac{10}{40} \log \frac{P(0)}{2 \times 10^{-6}}$$

$$P(0) = 10^{2.4} \times 2 \times 10^{-6} = \underline{502.37\mu W}$$

Hence 502.33μW is the required input power if the fiber has a loss of 0.6dB/km

Q3. The numerical input/output mean optical ratio in a 1km length of optical fiber is found to be 2.5. Calculate the received mean optical power when a mean optical power of 1mW is launched into a 5km length of the fiber.

Given:

$P(0) = 1\,mW \quad \frac{P(0)}{P(z)} = 2.5$

$z = 5\,km$

The optical attenuation in dB/km is given by:

For 1km: $\alpha\,(dB/km) = \frac{10}{z} \log \frac{P(0)}{P(z)}$

$$\alpha = \frac{10}{1} \log 2.5 = \underline{3.98\ dB/km}$$

For 5km: $3.98 = \frac{10}{5} \log \frac{1 \times 10^{-3}}{P(z)}$

$$P(5km) = \frac{1\times10^{-3}}{10^{1.99}} = \underline{10.23\,\mu W}$$

Q4: A 15km optical fiber link uses fiber with loss of 1.5dB/km. The fiber is joined every kilometer with connector's which give an attenuation of 0.8 dB each. Determine the minimum mean optical power which must be launched into the fiber inorder to maintain a mean optical power level of 0.3µW at the detector.

Given:

$z = 15\,km$ joints at every kilometer with attenuation of 0.8dB each

$\alpha = 1.5\,dB/km$

$P(z) = 0.3\,\mu W$

Total loss $= \alpha_{dB}(z) + \text{connector loss}$

$= 1.5(15) + 0.8(14)$

$= 22.5 + 11.2$

$\alpha_{dB/km} z = \underline{33.7\,dB}$

wkt

$$\alpha_{dB/km} = \frac{10}{z} \log \frac{P(0)}{P(z)}$$

$$\therefore \alpha_{dB/km}\, z = 10 \log \frac{P(0)}{P(z)}$$

$$\therefore 33.7 = 10 \log \frac{P(0)}{0.3 \times 10^{-6}}$$

Hence $P(0) = 10^{3.37} \times 0.3 \times 10^{-6} = \underline{703.27\,\mu W}$

1. Absorption:

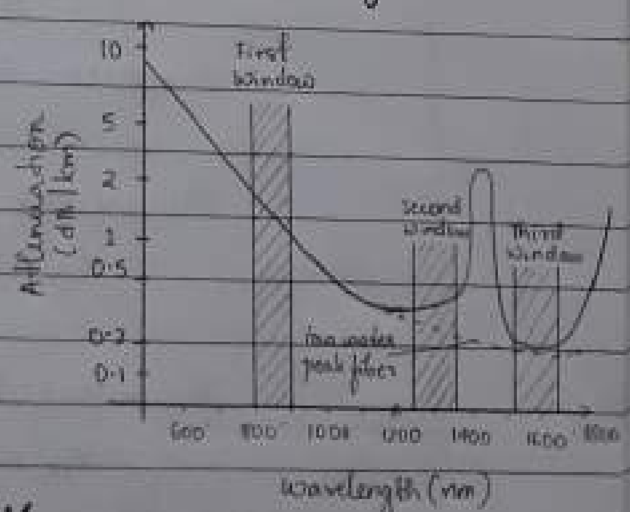
Absorption is caused by three different mechanisms:

a. Absorption by atomic defects in glass composition

Atomic defects are imperfections in the atomic structure of the fiber materials. For example, missing molecules, high density clusters of atom groups or oxygen defects in fiber. The losses due to absorption are negligible, however it may be significant if the fiber is exposed to ionizing radiations.

b. Extrinsic Absorption by impurity atoms in the glass

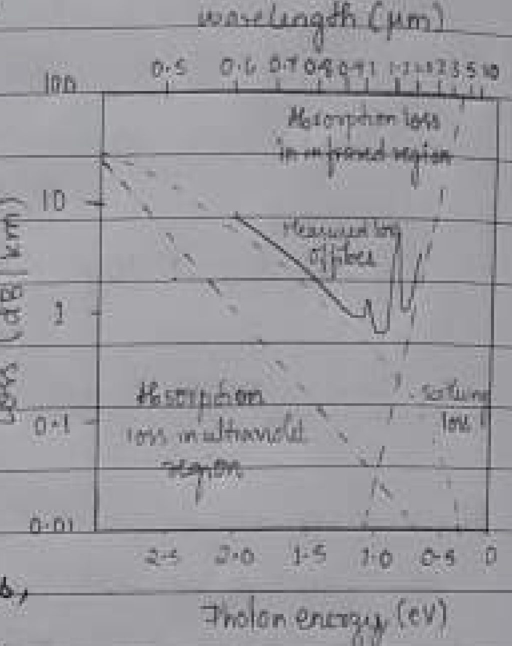
The extrinsic absorption is due to impurity atoms. For example, these impurity atoms consists of OH^- ions and transition metals such as iron, copper, chromium and vanadium.



The transition metals impurity level of 1 ppm in glass results in losses ranging from 1 to 4 dB/km. The impurity absorption loss occur because of electron or charge transition.

c. Intrinsic absorption by the basic constituent atoms of the fiber material:

Intrinsic loss is associated with the basic material SiO_2 and transparency of material over a specified wavelength. It occurs when the material is in a perfect state with no density variations, no impurities and so on.



Intrinsic absorption results from electronic absorption in UV region and atomic vibrations in the near infrared region. Absorption occurs when a photon interacts with an electron in the valence band and excites into a higher energy level.

The UV absorption follows the following emperical relationship:

$$\alpha_{uv} = Ce^{E/E_0}$$

where C and E_0 are constants

E is photon energy.

The UV loss at any wavelength is given by

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

The infrared absorption loss is given by

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

Q5: Consider two silica fibers that are doped with 6 percent and 18 percent mole fraction of GeO_2, respectively. Compare the ultraviolet absorptions at wavelengths of $0.7\mu m$ and $1.3\mu m$.

CASE 1: $\lambda = 0.7\mu m = 0.7 \times 10^{-6}$

For $x = 6\% = 0.06$

The ultraviolet absorption is given by:

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

$$\alpha_{uv} = \frac{154.2(0.06)}{46.6(0.06)+60} 10^{-2} \exp\left(\frac{4.63}{0.7}\right)$$

$$\underline{\alpha_{uv} = 1.10 \text{ dB/km}}$$

For $x = 18\% = 0.18$

The ultraviolet absorption is given by:

$$\alpha_{uv} = \frac{154.2(0.18)}{46.6(0.18)+60} 10^{-2} \exp\left(\frac{4.63}{0.7}\right)$$

$$\underline{\alpha_{uv} = 3.03 \text{ dB/km}}$$

CASE 2: $\lambda = 1.3\mu m$

For $x = 6\% = 0.06$

The ultraviolet absorption is given by:

$$\alpha_{uv} = \frac{154.2(0.06)}{46.6(0.06)+60} 10^{-2} \exp\left(\frac{4.63}{1.3}\right)$$

$$\underline{\alpha_{uv} = 0.07 \text{ dB/km}}$$

For $x = 18\% = 0.18$

The ultraviolet absorption is given by:

$$\alpha_{uv} = \frac{154.2(0.18)}{46.6(0.18)+60} 10^{-2} \exp\left(\frac{4.63}{1.3}\right)$$

$$\underline{\alpha_{uv} = 0.19 \text{ dB/km}}$$

2. **Scattering Losses:**

Scattering losses in glass arise from microscopic variations in the material density, from compositional fluctuations and structural inhomogeneities or defects occurring during fiber manufacture.

The variations in material density and compositional fluctuations gives rise to refractive index variations over a distance, these index variations cause a Rayleigh type of scattering.

For single component glass the scattering loss due to density fluctuations is

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

where n: refractive index

k_B: Boltzmann's constant

T_f: fictive temperature (temperature at which the density fluctuations are frozen into the glass as it solidifies)

β_T: isothermal compressibility of the material

Alternatively,

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

where p: photoelastic coefficient.

For multicomponent glasses the scattering at a wavelength λ (in μm) is given by

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

where the square of the mean square refractive index fluctuation $(\delta n^2)^2$ over a volume δV is

$$(\delta n^2)^2 = \left(\frac{\partial n^2}{\partial \rho}\right)^2 (\delta \rho)^2 + \sum_{i=1}^{m}\left(\frac{\partial n^2}{\partial C_i}\right)(\delta C_i)^2$$

where $\delta\rho$: density fluctuation

δC_i: concentration fluctuation of i^{th} glass component

NOTE:

For wavelengths below about $1\mu m$ it is the dominant loss mechanism in a fiber and gives the attenuation-vs-wavelength plots their characteristic downward trend with increasing wavelength. At wavelengths longer than $1\mu m$, infrared absorption effects tend to dominate optical signal attenuation.

Q6. For silica the fictive temperature T_f is 1400K, the isothermal compressibility β_T is $6.8 \times 10^{-12}\ cm^2/dyn = 6.8 \times 10^{-11}\ m^2/N$ and the photoelastic coefficient is 0.286. Estimate the scattering loss at a 1.30μm wavelength where $n = 1.450$.

– Given: $T_f = 1400K$ $\quad p = 0.286 \quad n = 1.450$

$\beta_T = 6.8 \times 10^{-12} \quad \lambda = 1.30\mu m$

The scattering loss is given by

1 neper/km = 4.343 dB/km

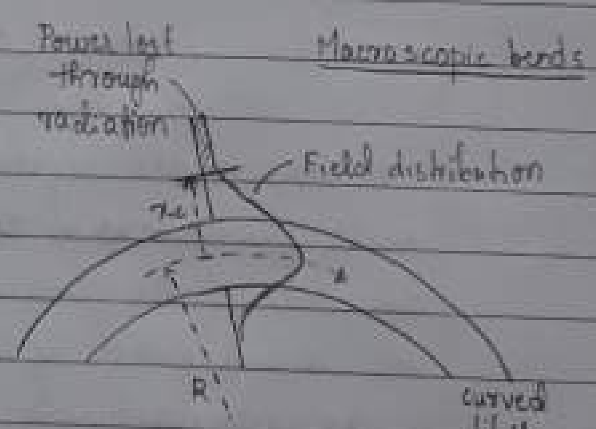
$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 k_B T_f \beta_T$$

$$\alpha_{scat} = \frac{8\pi^3}{3(1.30 \times 10^{-6})^4} (1.45)^8 (0.286)^2 (1.38 \times 10^{-23})(1400)(6.8 \times 10^{-12})$$

$$\alpha_{scat} = 6.08 \times 10^{-2} \text{ nepers/km} = \underline{0.26 dB/km}$$

3. Bending Losses:

Radiative losses occur whenever an optical fiber undergoes a bend of finite radius of curvature.



a) Macroscopic bends: have radii that are large compared to the fiber diameter, such are those that occur when a fiber cable turns a corner

b) Microscopic bends: bends of fiber axis that can arise when the fibers are incorporated into cables

Macroscopic bends

For a small bend the loss is extremely small and unobservable. For large bend or small radius, losses become extremely large.

When the fiber is bent, the field tail on the far side must move faster to keep up the field in core. At a certain critical distance x_c, the field tail would have to move faster than the core field, since this is not possible, the field tail beyond x_c radiates away, i.e., called bending losses.

The higher order modes are less bound to core because they radiate more into the cladding. Thus the total number of modes can be supported by bend or curved fiber is less than in straight fiber.

The effective number of modes M_{eff} that are guided by a curved multimode fiber of radius a is:

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

where: α : graded index profile

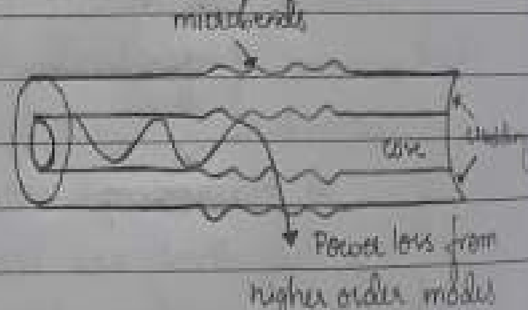
Δ : core-cladding index difference

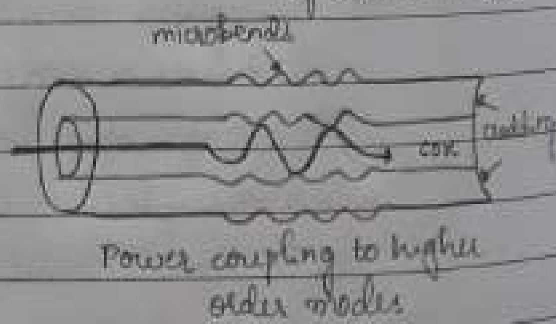
n_2 : cladding refractive index

$k = \frac{2\pi}{\lambda}$: wave propagation constant.

$M_{\infty} = \frac{\alpha}{\alpha+2}(n_1ka)^2\Delta$: total number of modes in a straight fiber.

Microbends are repetitive small scale fluctuations in the radius of curvature of the fiber axis. They are caused either by nonuniformities in the manufacturing of the fiber or by nonuniform lateral pressures created during the cabling of the fiber. It can be minimized by extruding a compressible jacket over the fiber.





Q7. Consider a graded index multimode fiber for which the index profile $\alpha = 2.0$, the core index $n_1 = 1.480$, the core-cladding index difference $\Delta = 0.01$ and the core radius $a = 25\mu m$. If the radius of curvature of the fiber is $R = 1$ cm, what percentage of the modes remain in the fiber at 1300 nm wavelength?

Given: $\alpha = 2.0$ $\quad a = 25\mu m$ $\quad \Delta = \frac{n_1 - n_2}{n_1} \Rightarrow 0.01 = \frac{1.48 - n_2}{1.48}$

$n_1 = 1.48$ $\quad R = 1\,cm$

$\Delta = 0.01$ $\quad \lambda = 1300nm$ $\quad \therefore n_2 = 1.465$

The percentage of modes at a given curvature R is given by:

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

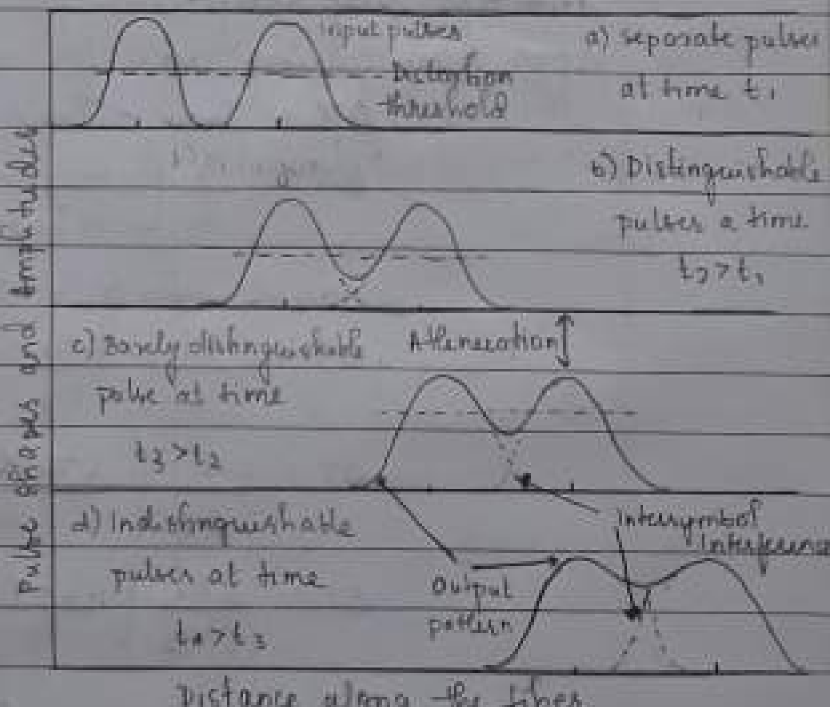
$$\frac{M_{eff}}{M_\infty} = 1 - \frac{2+2}{2(2)(0.01)}\left[\frac{2(25\times10^{-6})}{1\times10^{-2}} + \left(\frac{3(1300\times10^{-9})}{2(1.465)2\pi(1\times10^{-2})}\right)^{2/3}\right]$$

$$\frac{M_{eff}}{M_\infty} = 0.42$$

Thus 42% of the modes remain in this fiber at 1cm bend radius.

- ## Signal Dispersion in Fibers:

An optical signal weakens from attenuation mechanisms and broadens due to dispersion effects as it travels along the fiber. Eventually these two factors will cause neighboring pulses to overlap. After a certain amount of overlap occurs, the receiver can no longer distinguish the individual adjacent pulses and errors arise when interpreting the received signal.



Signal dispersion is a consequence of factors such as intermodal delay, intramodal dispersion, polarization mode dispersion and higher order dispersion effects. These distortions can be explained by examining the behavior of the group velocities of the guided modes. The group velocity is the speed at which energy in a particular mode travels along the fiber.

- Intermodal delay / modal delay:

It appears only in multimode fibers. Modal delay is a result of each mode having a different value of the group velocity at a single frequency.

The steeper the angle of propagation of the ray congruence the higher is the mode number and consequently, the slower the axial group velocity. This variation in the group velocities of the different modes results in a group delay spread, which is the intermodal dispersion.

The maximum pulse broadening arising from the modal delay is the difference between the travel time T_{max} of the longest ray congruence paths and the travel time T_{min} of the shortest ray congruence paths. This broadening is obtained from ray tracing and for a fiber of length L is given by:

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

$$\Delta T = \frac{n_1}{c}\left(\frac{L}{\sin\phi_c} - L\right)$$

because $\sin\phi_c = n_2/n_1$

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

$$\Delta T = \frac{L n_1^2}{c n_2}\left(1 - \frac{n_2}{n_1}\right)$$

$$\Delta T = \frac{L n_1^2}{c n_2}\left(\frac{n_1 - n_2}{n_1}\right)$$

wkt for $\Delta \ll 1$; $\Delta = \frac{n_1 - n_2}{n_1}$

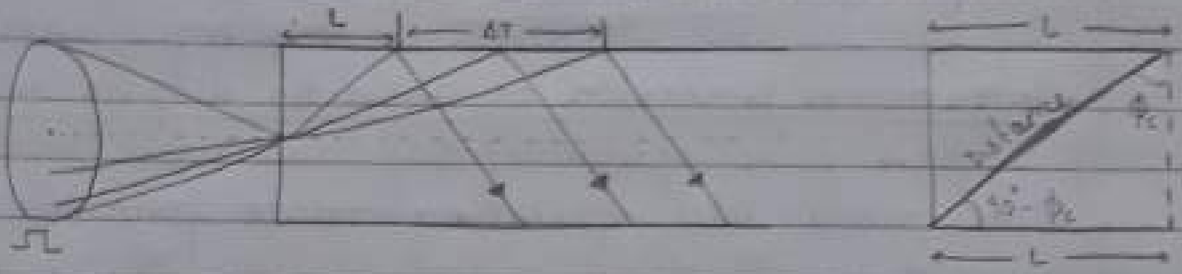
$\therefore$ $\boxed{\Delta T = \frac{L n_1^2}{c n_2}\Delta}$ is the delay required to avoid overlapping.

In order for neighboring signals pulses to remain distinguishable at the receiver, the pulse spread should be less than $1/B$, which is the width of a bit period

In general we need to have $\Delta T < 1/B$. This gives the bit rate distance product

$$\Delta T < \frac{1}{B} \Rightarrow \frac{L n_1^2}{c n_2}\Delta = \frac{1}{B}$$

Therefore, $\boxed{BL = \frac{c n_2}{\Delta n_1^2}}$ Information capacity interms of bit rate distance product



$$\cos(90^\circ - \phi_c) = \frac{L}{\text{Distance}} \Rightarrow \sin\phi_c = \frac{L}{\text{distance}}$$

$$\therefore \text{ distance} = \frac{L}{\sin\phi_c}$$

wkt $\text{velocity} = \frac{\text{distance}}{\text{time}} \Rightarrow \text{distance} = \text{velocity} \times \text{time}$

$$\therefore \frac{L}{\sin\phi_c} = v\,T_{max}$$

$$\Rightarrow T_{max} = \frac{L}{v.\sin\phi_c}$$ but $RI = \frac{c}{v} \Rightarrow n_1 = \frac{c}{v}$

Hence $T_{max} = \frac{L n_1}{c \sin\phi_c}$ $\quad \therefore v = \frac{c}{n_1}$

and $T_{min} = \frac{L n_1}{c}$

Q5: Consider a 1-km long multimode step-index fiber in which $n_1 = 1.480$ and $\Delta = 0.01$, so that $n_2 = 1.465$. What is the modal delay per length in this fiber.

– Given: $n_1 = 1.480 \quad \Delta = 0.01$

$n_2 = 1.465 \quad L = 1\text{km}$

Modal delay per length is given by:

$$\frac{\Delta T}{L} = \frac{n_1^2}{c n_2}\Delta$$

$c = 3\times10^8\ m/s$

$c = 3\times10^5\ km/s$

$$\frac{\Delta T}{L} = \frac{(1.48)^2}{3\times10^5(1.465)}(0.01)$$

$$\frac{\Delta T}{L} = \underline{\underline{49.8\ ns/km}}$$

This means that a pulse broadens by 50 ns after traveling a distance of 1km

- Intramodal Dispersion or Chromatic dispersion:

It is pulse spreading that takes place within a single mode. This spreading arises from the finite spectral emission width of an optical source. The phenomenon is also known as group velocity dispersion, since the dispersion is a result of the group velocity being a function of the wavelength.

- Group Delay:

consider an electrical signal that modulates an optical source. Assuming that the modulated optical signal excites all modes equally at the input of the fiber. Each waveguide thus carries an equal amount of energy through the fiber.

Each mode contains all the spectral components in the wavelength band over which the source emits. As the signal propagates along the fiber, each spectral component can be assumed to travel independently and to undergo a time delay or group delay per unit length in the direction of propagation given by:

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

(because $k = 2\pi/\lambda \Rightarrow d\left(\frac{2\pi}{\lambda}\right) = -2\pi\left(\frac{1}{\lambda^2}\right)$)

where L: distance travelled by the pulse

β: propagation constant along the fiber axis

V_g: group velocity

From eq ①

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

Group velocity is given by:

$$V_g = c\left(\frac{d\beta}{dk}\right)^{-1} = \left(\frac{\partial\beta}{\partial\omega}\right)^{-1} \quad \text{——— ③}$$

It is the velocity at which the energy in a pulse travels along a fiber.

To find the amount of pulse spreading that arises from the group delay variation is required.

The delay difference per unit wavelength along the propagation path is approximately: $\frac{d\tau_g}{d\lambda}$

The total delay difference is:

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

$$\partial\tau = \frac{d}{d\lambda}\left(\frac{-L\lambda^2}{2\pi c}\frac{d\beta}{d\lambda}\right)\partial\lambda \quad (\text{From eq ②})$$

$$\partial\tau = \frac{-L}{2\pi c}\left(2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right)\partial\lambda \quad \text{——— ④}$$

If the spectral width $\delta\lambda$ of an optical source is characterized by its rms value σ_λ, then the pulse spreading can be approximated by the rms pulse width,

$$\sigma_g = \left|\frac{d\tau_g}{d\lambda}\right|\sigma_\lambda$$

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

The factor $D = \frac{1}{L}\frac{d\tau_g}{d\lambda} = \frac{d}{d\lambda}\frac{1}{V_g} = \frac{d}{d\lambda}\left(\frac{d\beta}{d\omega}\right)$ ——— ⑤

From eq ①:

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

$$d\lambda = \frac{-\lambda^2}{2\pi} dk$$

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

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

Substituting in eq ⑤, we get;

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

$$\therefore D = \frac{-2\pi c}{\lambda^2} \beta_2 \text{ ——— ⑥ } \text{(in ps/(nm·km))}$$

The factor D is designated as dispersion. It defines the pulse spread as a function of wavelength. It is a result of material and waveguide dispersion ($D = D_{mat} + D_{wg}$)

The $\beta_2 = \frac{d^2\beta}{d\omega^2}$ is the GVD parameter, which determines how much a light pulse broadens as it travels along an optic fiber.

The two main causes of intramodal dispersion are:

1. Material Dispersion:

It arises due to the variations of the refractive index of the core material as a function of wavelength. It is also known as chromatic dispersion, since it is the same effect by which a prism spreads out a spectrum.

To calculate material-induced dispersion, we consider a plane wave propagating in an infinitely extended dielectric medium that has a refractive index $n(\lambda)$ equal to that of the fiber core. The propagation constant is given as

$$\beta = \frac{2\pi}{\lambda} n(\lambda) \text{ ——— ⑦}$$

From eq ① we have: $\tau_g = \frac{-\lambda^2 L}{2\pi c} \frac{d\beta}{d\lambda}$

by substituting eq (7)

$$\therefore \tau_{mat} = \frac{-\lambda^2 L}{2\pi c} \frac{d}{d\lambda}\left(\frac{2\pi}{\lambda} n(\lambda)\right)$$

$$\tau_{mat} = \frac{-\lambda^2 L}{2\pi c} 2\pi \left[\frac{-1}{\lambda^2} n(\lambda) + \frac{1}{\lambda}\frac{d}{d\lambda}(n(\lambda))\right]$$

$$\tau_{mat} = \frac{L}{c}\left[n - \lambda \frac{dn}{d\lambda}\right] \quad \text{——— (8)}$$

$$\therefore \frac{d\tau_{mat}}{d\lambda} = \frac{L}{c}\left[-\lambda \frac{d^2 n}{d\lambda^2}\right] \quad \text{——— (9)}$$

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

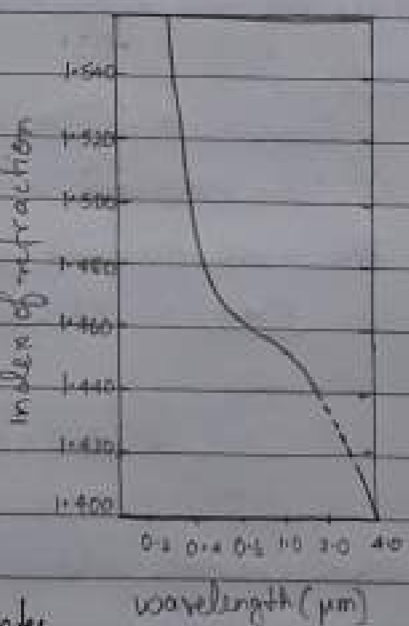
$$\sigma_{mat} = \frac{\sigma_\lambda L}{c}\left|\lambda \frac{d^2 n}{d\lambda^2}\right| = \sigma_\lambda L \left|D_{mat}(\lambda)\right| \quad \text{——— (10)}$$

where material dispersion is $D_{mat}(\lambda)$ which varies with λ and $\frac{d^2n}{d\lambda^2}$. The $\frac{d^2n}{d\lambda^2}$ is the second order derivative of $n(\lambda)$.

$\frac{d^2n}{d\lambda^2}$ is the curvature shape of variation of refractive index with wavelength.

Thus,

$$\boxed{D_{mat}(\lambda) = \frac{\lambda}{c}\left|\frac{d^2n}{d\lambda^2}\right|} \quad \text{——— (11)}$$



At wavelength 1300nm the $\frac{d^2n}{d\lambda^2} = 0$. Thus, if operating wavelength is 1300nm eliminates the material dispersion

Q9: A manufacturer's data sheet lists the material dispersion D_{mat} of a GeO_2 doped fiber to be 110 ps/(nm km) at a wavelength of 860 nm. Find the rms pulse broadening per kilometer due to material dispersion if the optical source is a GaAlAs LED that has a spectral width σ_λ of 40 nm at an output wavelength of 860 nm.

- Given: GeO_2 doped fiber

$D_{mat} = 110 \text{ ps/(nm·km)}$ $\quad \sigma_\lambda = 40 \text{ nm}$

$\lambda = 860 \text{ nm}$

The rms material dispersion per kilometer is given by:

$$\frac{\sigma_{mat}}{L} = \sigma_\lambda D_{mat}$$

$$\frac{\sigma_{mat}}{L} = (40 \times 10^{-9})(110 \text{ ps/(nm km)})$$

$$= \underline{4.4 \text{ ns/km}}$$

Q10. The manufacturer's data shows that the same fiber as in previous problem has a material dispersion D_{mat} of 15 ps/(nm km) at a wavelength of 1550nm. However, now suppose we use a laser source with a spectral width σ_λ of 0.2nm at an operating wavelength of 1550nm. What is the rms pulse broadening per kilometer due to material dispersion?

- Given:

$D_{mat} = 15 \text{ ps/(nm·km)}$ $\quad \sigma_\lambda = 0.2 \text{ nm}$

$\lambda = 1550 \text{ nm}$

The rms material dispersion is given by:

$$\frac{\sigma_{mat}}{L} = \sigma_\lambda D_{mat}$$

$$\frac{\sigma_{mat}}{L} = (0.2 \times 10^{-9})(15 \text{ ps/(nm·km)})$$

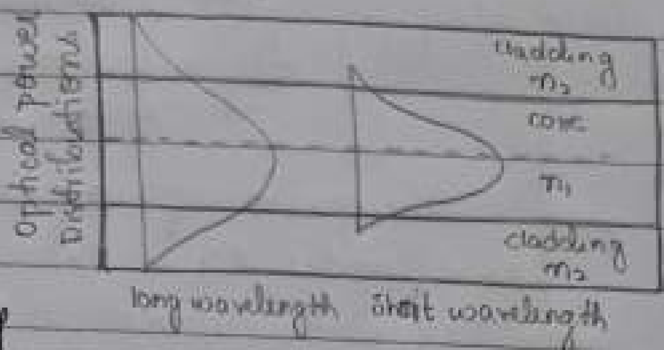
$$= \underline{3 \text{ ps/km}}$$

This example shows that a drastic reduction in dispersion can be acheived by operating at longer wavelengths with laser sources.

2. Waveguide Dispersion:

It causes pulse spreading because only part of the optical power propagating along a fiber is confined to the core. In single propagating mode, shorter wavelengths are more completely confined to the fiber core whereas a larger portion of the optical oper at longer wavelengths propagates in the cladding. As the refractive index is lower in the cladding than in the core, so the fraction of light power propagating in the cladding travels faster than the light confined to the core.

Thus dispersion arises because the difference in core-cladding spatial power distributions, together with the speed variations of the various wavelengths, causes a change in propagation velocity of each spectral component.



Waveguide dispersion can be approximated in the absence of material dispersion.

The normalized propagation constant in terms of group delay is given by:

$$b = 1\left(\frac{ua}{V}\right)^2 = \frac{\beta^2/k^2 - n_2^2}{n_1^2 - n_2^2} \quad \text{——— (1)}$$

For small values of the index difference $\Delta = \frac{n_1 - n_2}{n_1}$, the eq (1) can be approximated as

$$b \simeq \frac{\beta/k - n_2}{n_1 - n_2}$$

$$\Rightarrow \beta = n_2 k (b\Delta + 1) \quad \text{——— (2)}$$

Using eq (2) and using the assumption that n_2 is not a function of wavelength, we find that the group delay τ_{wg} arising from waveguide dispersion is given by:

$$\tau_{wg} = \frac{L}{c}\frac{d\beta}{dk}$$

$$\tau_{wg} = \frac{L}{c}\frac{d}{dk}\left[n_2 k (b\Delta + 1)\right]$$

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2\Delta\frac{d(kb)}{dk}\right] \quad \text{——— (3)}$$

wkt the normalized frequency is given by

$$V = ka\sqrt{n_1^2 - n_2^2}$$

$$V \simeq kan_1\sqrt{2\Delta} \quad \text{—— (4)}$$

which is valid for small values of Δ, to write the group delay in eq (3) in terms of V instead of k, which gives:

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d(Vb)}{dV}\right] \quad \text{—— (5)}$$

The pulse spread σ_{wg} occurring over a distribution of wavelengths σ_λ is obtained from the derivative of the group delay with respect to wavelength.

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

$$\sigma_{wg} = L\left|D_{wg}(\lambda)\right| \sigma_\lambda \quad \text{—— (6)}$$

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

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

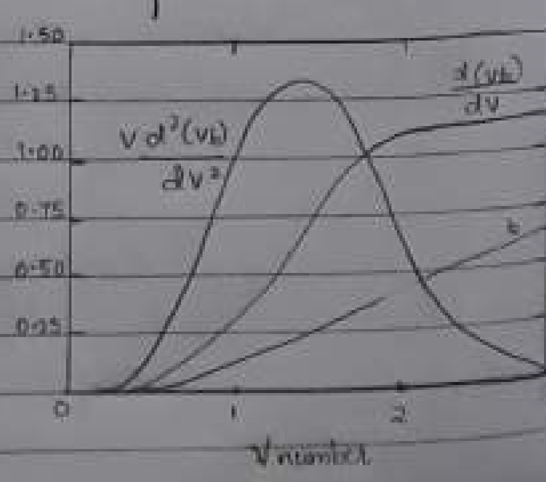
$$\sigma_{wg} = L\left[\frac{-n_2 \Delta V}{c\lambda} \frac{d^2(Vb)}{dV^2}\right] \sigma_\lambda \quad \text{—— (7)}$$

comparing eq (6) and eq (7) we get,

$$\boxed{D_{wg}(\lambda) = \frac{-\Delta n_2 V}{c\lambda} \frac{d^2(Vb)}{dV^2}}$$ is the waveguide dispersion.

From the graph,

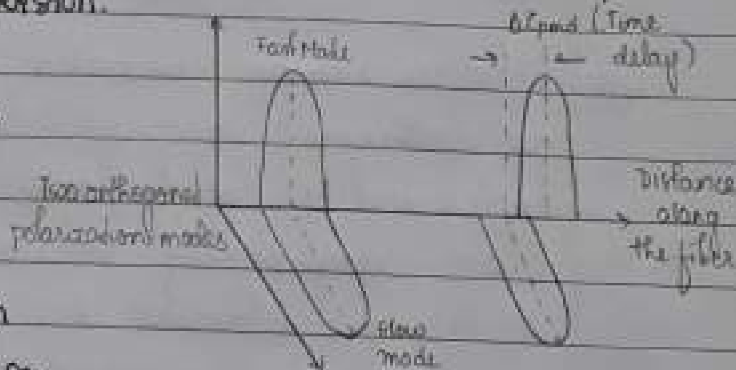
Dwg peak is at 1.2, so the V should be greater than 1.2. Also to maintain single mode operation, V should be less than 2.4.



- Polarization mode dispersion:

Since fiber material is not perfectly uniform throughout its length, each polarization mode will encounter a slightly different refractive index. Consequently each mode will travel at a slightly different velocity. The resulting difference in propagation times between the two orthogonal polarization modes will cause pulse spreading is polarization mode dispersion.

The effects of fiber birefringence on the polarization states of an optical signal are another source of pulse broadening. This is critical in high rate long haul transmission links. Birefringence can result from geometric irregularities of the fiber core, internal stress and also from external factors like bending, twisting or pinching of the fiber.



If the group velocities of the two orthogonal polarization modes are V_{gx} and V_{gy}, then the differential time delay $\Delta \tau_{pmd}$ between the two polarization components during propagation of the pulse over a distance L is

$$\Delta \tau_{pmd} = \left| \frac{L}{V_{gx}} - \frac{L}{V_{gy}} \right|$$

- **Problems:**

Q1: The mean optical power launched into an optical fiber link is 1.5 mW and the fiber has an attenuation of 0.5 dB/km. Determine the maximum possible link length without repeaters when the minimum mean power level required at the detector is 2 μW.

- Given:

$P(0) = 1.5\,mW$ $\quad \alpha = 0.5\,dB/km$

$P(x) = 2\,\mu W$

The optical attenuation in dB/km is given by:

$$\alpha_{(dB/km)} = \frac{10}{z}\log_{10}\frac{P(0)}{P(z)}$$

$$0.5 = \frac{10}{z}\log\left(\frac{1.5\times10^{-3}}{2\times10^{-6}}\right)$$

$z = 57.5$ km is the length required.

Q12: Silica has an estimated fictive temperature of 1400K with an isothermal compressibility of $7\times10^{-11}\ m^2N^{-1}$. The refractive index and the photoelastic coefficient for silica are 1.46 and 0.286 respectively. Determine the theoretical attenuation in decibels per kilometer due to the fundamental Rayleigh scattering in silica at optical wave lengths of 0.63, 1.00 and 1.3 μm. Boltzmann's constant is 1.381×10^{-23} J/k.

→ Given:

$T_f = 1400K$ $\quad$ $p = 0.286$

$\beta_T = 7\times10^{-11}\ m^2/N$ $\quad$ $k_B = 1.381\times10^{-23}$ J/k

$n = 1.46$

- For wavelength of 0.63μm, 1μm and 1.3μm

The scattering loss is given by:

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4}n^8p^2k_BT_f\beta_T$$

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

CASE 1: $\lambda = 0.63\mu m$

$\therefore \alpha_{scat} = 1.199\times10^{-3}/m$

Transmission loss factor for 1 km of fiber is obtained from

$$L_{km} = \exp(-\alpha_{scat}L)$$

$$L_{km} = \exp(-1.199\times10^{-3}\times10^3) = 0.301$$

$$\text{Attenuation} = 10\log\left(\frac{1}{L_{km}}\right) = 10\log\frac{1}{0.301} = 5.2\ dB/km$$

CASE 2: $\lambda = 1\mu m$

$\therefore \alpha_{scat} = 1.889 \times 10^{-4} /m$

Transmission loss factor for 1 km

$L_{km} = \exp(-\alpha_{scat} L) = \exp(-1.889 \times 10^{-4} \times 10^{3})$

$L_{km} = 0.83$

Attenuation $= 10 \log \frac{1}{L_{km}} = 10 \log \frac{1}{0.83} = \underline{0.81 \text{ dB/km}}$

CASE 3: $\lambda = 1.3\mu m$

$\therefore \alpha_{scat} = 0.662 \times 10^{-4} /m$

Transmission loss factor for 1km

$L_{km} = \exp(-\alpha_{scat} L) = \exp(-0.662 \times 10^{-4} \times 10^{3}) = 0.936$

Attenuation $= 10 \log \frac{1}{L_{km}} = 10 \log \frac{1}{0.936} = \underline{0.29 \text{ dB/km}}$

Q8 A glass fiber exhibits material dispersion given by $\left|\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right|$ of 0.025. Determine the material dispersion at a wavelength of 0.85µm and estimate the rms pulse broadening per kilometer for a good LED source with an rms spectral width of 20nm at this wavelength.

– Given:

$\left|\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right| = 0.025$ $\lambda = 0.85\mu m = 850 \text{ nm}$

$\sigma_\lambda = 20 \text{ nm}$ $c = 3 \times 10^5 \text{ km/s}$

Material dispersion is given by:

$$D_{mat}(\lambda) = \frac{\lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right|$$

$$\therefore D_{mat}(\lambda) = \frac{\lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right|\frac{\lambda}{\lambda} = \frac{1}{c\lambda}\left|\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right|$$

$$D_{mat}(\lambda) = \frac{0.025}{3 \times 10^5 \times 850} = \underline{98.04 \text{ ps/(nm km)}}$$

The rms pulse broadening per kilometer is:

$\sigma_{mat} = \sigma_\lambda L D_{mat}$

$\sigma_{mat} = 20 \times 1 \times 98.04 \times 10^{-12} = \underline{1.96 \text{ ns/km}}$

Q14: Find the radius of curvature R at which the number of modes decrease by 50% in a graded index fiber. For this fiber $\alpha = 2$, $n_2 = 1.5$, $\Delta = 0.01$, $a = 25\mu m$ and let the wavelength of the guided light be $1.3\mu m$.

→ Given:

$\alpha = 2$ $\quad \Delta = 0.01$ $\quad \lambda = 1.3\mu m$ $\quad k = \frac{2\pi}{\lambda}$

$n_2 = 1.5$ $\quad a = 25\mu m$ $\quad M_{eff} = 0.5 M_\infty$

The effective number of modes is given by

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

$$0.5 \cancel{M_\infty} = \cancel{M_\infty} \left\{ 1 - \frac{2+2}{2(2)0.01} \left[\frac{2(25\times10^{-6})}{R} + \left(\frac{3(1.3\times10^{-6})}{2(1.5)2\pi R} \right)^{2/3} \right] \right\}$$

$$0.5 = 1 - \frac{1}{0.01} \left[\frac{50\times10^{-6}}{R} + \frac{34.98\times10^{-6}}{R^{2/3}} \right]$$

$$0.5 = \frac{10^{-6}}{10^{-2}} \left[\frac{50 + 34.98 R^{1/3}}{R} \right]$$

$$0.5R = 50\times10^{-4} + 34.98\times10^{-4} R^{1/3}$$

$$0.5R - 34.98\times10^{-4} R^{1/3} - 50\times10^{-4} = 0$$

$$0.125 R^3 - 4.28\times10^{-8} R - 1.25\times10^{-7} = 0$$

$$\therefore \underline{\underline{R = 0.01m = 1cm}}$$

Q15: Let $n_2 = 1.48$ and $\Delta = 0.2\%$ at $V = 2.4$ from the expression $V \frac{d^2(Vb)}{dV^2} = 0.26$. Assume $\lambda = 1320 nm$ Calculate waveguide dispersion.

→ Given:

$n_2 = 1.48$ $\quad V \frac{d^2(Vb)}{dV^2} = 0.26$

$\Delta = 0.2\%$

$V = 2.4$ $\quad \lambda = 1320 nm$

Waveguide dispersion is given by:

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

$$D_{wg}(\lambda) = -\left(\frac{0.2}{100} \times \frac{1.48}{3\times10^5} \times \frac{1}{1320} \times 0.26\right)$$

$$D_{wg}(\lambda) = -1.94 \ ps/(nm\ km)$$

Q16 The optical power loss resulting from Rayleigh scattering in a fiber can be calculated from either of the two equations. Compare these two equation for silica ($n = 1.460$ at 630nm) given that the fictive temperature T_f is 1400k, the isothermal compressibility β_T is 6.8×10^{-12} cm²/dyne and the photoelastic coefficient is 0.286. How does this agree with measured values varying from 3.9 to 4.8 dB/km at 630 nm?

→ Equation 1

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

$$\alpha_{scat} = \frac{8\pi^3}{3(630\times10^{-9})^4}(1.46^2-1)^2(1400)(1.38\times10^{-23})(6.8\times10^{-12})$$

$$\alpha_{scat} = 0.883/km = 3.83\ dB/km$$

Equation 2

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

$$\alpha_{scat} = \frac{8\pi^3}{3(630\times10^{-9})^4}(1.46)^8(0.286)^2(1.381\times10^{-23})(1400)(6.8\times10^{-12})$$

$$\alpha_{scat} = 1.162/km = 5.05\ dB/km$$

• SLE: Characteristics of Single Mode Fibers:

1. Refractive Index Profiles:

Dispersion limits long distance and high speed transmission. At 1310 nm the dispersion is less but is not suitable for longer distance transmission. To transmit longer distance 1550 nm is suitable but dispersion is high.

Thus the fiber designers deviced methods for adjusting the fiber parameters to shift to zero dispersion at longer wavelengths.

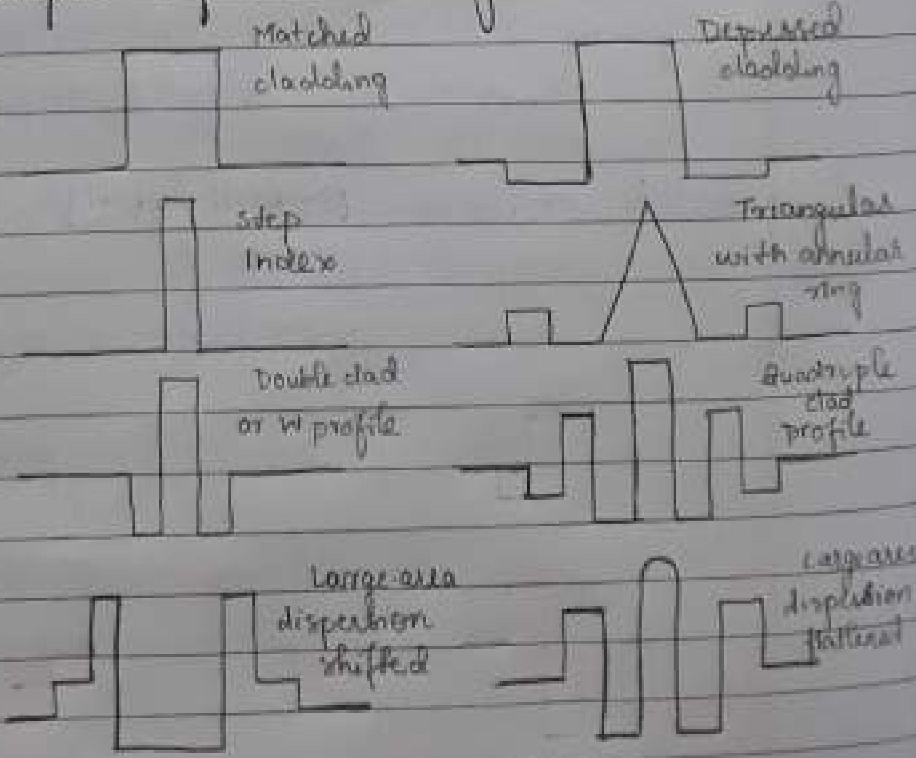
The dispersion is sum of material and waveguide dispersion. It is hard to alter material dispersion where as it is possible to modify the waveguide dispersion. As the waveguide dispersion is a function of core radius, refractive index profile and refractive index difference, by creating a fiber with a negative waveguide dispersion equal to the material dispersion makes the dispersion zero at longer wavelengths. This can be done by changing simple step index design into complex step index design.

a) 1310 nm optimized fibers

b) dispersion shifted fibers

c) dispersion flattened fibers

d) large-effective-core-area fibers



2. Cutoff wavelength:

To operate in single mode operation, the cut off wavelength should be greater than

$$\lambda_c = \frac{2\pi a}{V}\sqrt{(n_1^2 - n_2^2)} \simeq \frac{2\pi a}{V} n_1\sqrt{2\Delta} = \frac{2\pi a}{V}(NA)$$

with $V = 2.405$ for step index fibers.

3. Dispersion calculations:

The total dispersion in single mode fibers consists mainly of material and waveguide dispersion and it is given by

$$D(\lambda) = \frac{1}{L}\frac{d\tau}{d\lambda} \qquad \tau \rightarrow \text{group delay}$$

The broadening σ of an optical pulse over a fiber of length L is given by:

$$\sigma = D(\lambda)\, L\, \sigma_\lambda \qquad \sigma_\lambda \rightarrow \text{half power spectral width of the optical source}$$

4. Mode-Field Diameter:

Mode-field diameter describes the functional properties of single mode fiber. It takes into account the wavelength dependent field penetration into the cladding region.

5. Bending Loss:

The bending loss is a function of the Mode-Field diameter. smaller the Mode-Field Diameter, smaller the bending loss. This is true for both matched and depressed cladding fibers.

UNIT - 3

Optical Sources and Detectors

- **Introduction:**

Light is abundant in nature but not all sources are suitable for optical fiber communication as they may have the following characteristics:

- Large spectral width
- Many sources can not be switched ON and OFF rapidly.

- Desirable Characteristics of Optical sources:
  - Emission with low loss window
  - Narrow spectral width
  - Ease of linear modulation
  - High modulation speed
  - capabity to couple adequate power

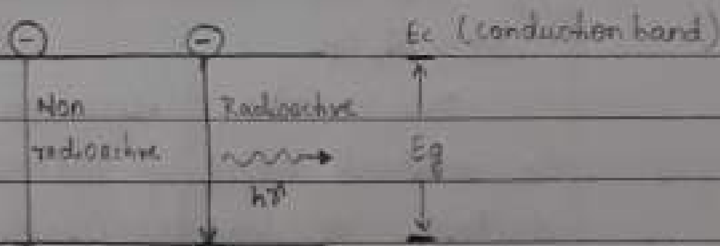
Ex: Gas sources and semiconductor sources

Gas sources: (LASER)
- High power
- Narrow spectral width
- Highly directional

Semiconductor sources: (LED)
- Low power
- Large spectral width
- Non directional

Gas sources are very large in size, so they are difficult to integrate with electronic circuits. Thus semiconductor sources are used

Semiconductor material characteristics can be characterised by bandgap energy diagram.



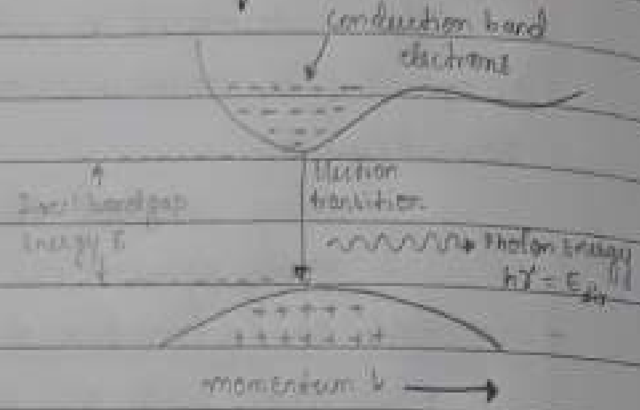
There are two possibilities when e-h combine:

1. Radiative recombination: produces photon of energy ($h\nu$)
2. Non-Radiative recombination: energy may not be photon, it may go into another form.

Semiconductor material can be classified as:

- Direct band gap:

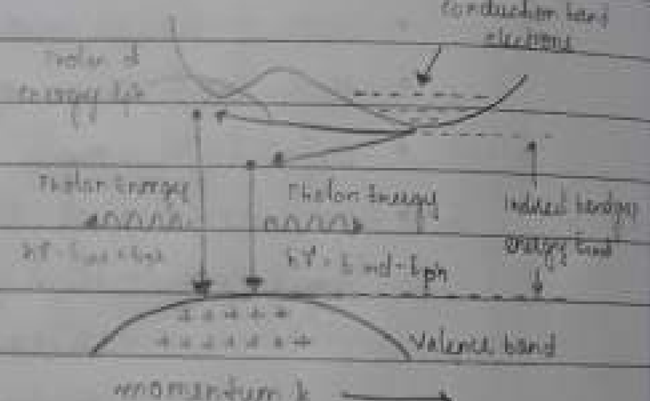
Here the material bottom of conduction band and maximum of valence band are aligned in same momentum. It involves only one process involved in e-h recombination. Ex: GaAs



(a)

- Indirect band gap:

Here the material bottom of conduction band and maximum of valence band are not aligned in same momentum but are in different momentum.



In this case the e-h recombination takes place due to:

a) electron should release momentum
b) e-h recombination

The semiconductor material can also be characterized by energy and momentum space diagram.

Ex: Si, Ge

Due to this, generation of photon energy is much smaller in indirect bandgap material. Thus direct band gap material are suitable for sources (with high efficiency of photon-generation)

Ex: GaAs

Although none of the single semiconductors are direct band gap, by combining many binary compounds we use in optical communication.

- To calculate wavelength of material

$$E = E_2 - E_1 = h\nu = \frac{hc}{\lambda} \qquad \text{For GaAs : } E = 1.4\,eV$$

$$\lambda(\mu m) = \frac{1.24}{E(eV)} \qquad \lambda(\mu m) = 0.8\,\mu m$$

1st window is $0.8\,\mu m$ – material is GaAs.

Ternary semiconductor material $Ga_{1-x}Al_xAs$:

$0 < x < 0.37 \quad E(eV) = 1.424 + 1.266x + 0.266x^2$

for operation in $0.8\,\mu m$ to $0.9\,\mu m$

Quaternary semiconductor material $In_{1-x}Ga_xAs_yP_{1-y}$:

$0 < x < 0.47 \quad y = 2.20x$

$E(ev) = 1.35 - 0.72y + 0.12y^2$

for operation in $0.92\,\mu m$ to $1.65\,\mu m$

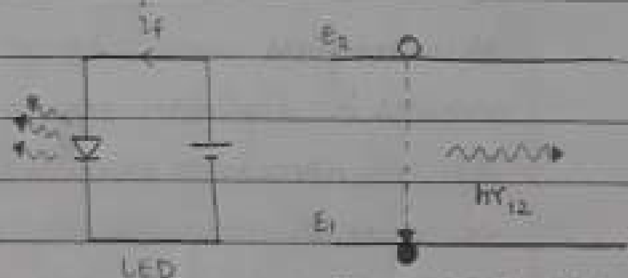
- Basic building blocks of optical fiber communications

1. Absorption:

photo detector   Absorption

When a photon of energy $h\nu$ impinges on the system, an electron in the state E1 can absorb the photon energy and be excited to stat E2, this process is called absorption. This mechanism used in photo detector helps to convert optical signal into electrical signal.

2. spontaneous emission:



LED   Spontaneous Emission

The higher energy state E2, is an unstable state; the electron will shortly return to the ground state E1, thereby emitting a photon of energy, $h\nu$. This occurs without any external simulation and is called as spontaneous emission. This mechanism uses LED to emit light.

3. Stimulated Emission

If a photon of energy hν impinges on the system while the electron is still in its excited state, the electron is immediately stimulated to drop to ground and gives off a photon of energy hν. This emitted photon is in phase with the incident photon and the resultant emission is known as stimulated emission. This mechanism is used in LASER.

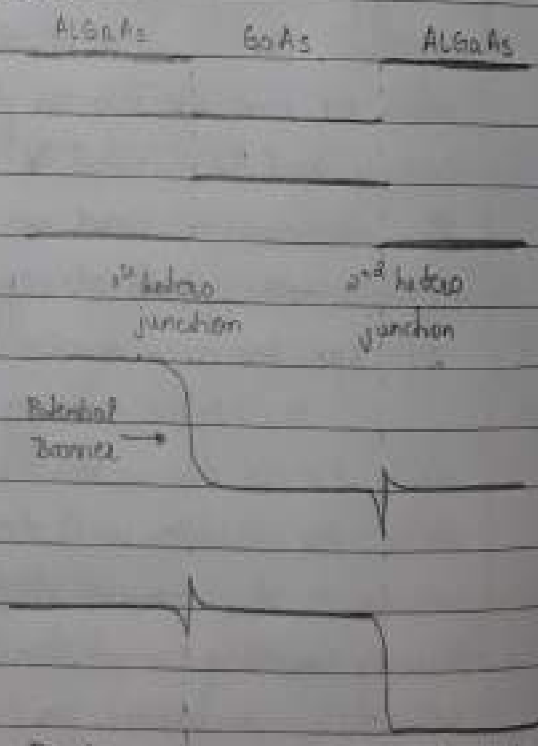
- P-N Junctions Structures:

P-n junctions can be classified based on structure as follows:

- Homo junction: Junction between same material but n-doped and p-doped.
- Hetero junction: Junction between dissimilar material with different band gap.
- Schottky junction: Junction between metal and semiconductor.

In homo-junction structures there is no potential barrier in depletion region. But in hetero junction structures potential barriers are created. This confines more charge carriers in depletion region. This phenomenon is called the carrier confinement.

Optical sources like LED and injection LASER uses double hetero junction structures.



Bandgap diagram of double hetero junction

- **Light Emitting Diodes : (LED)**

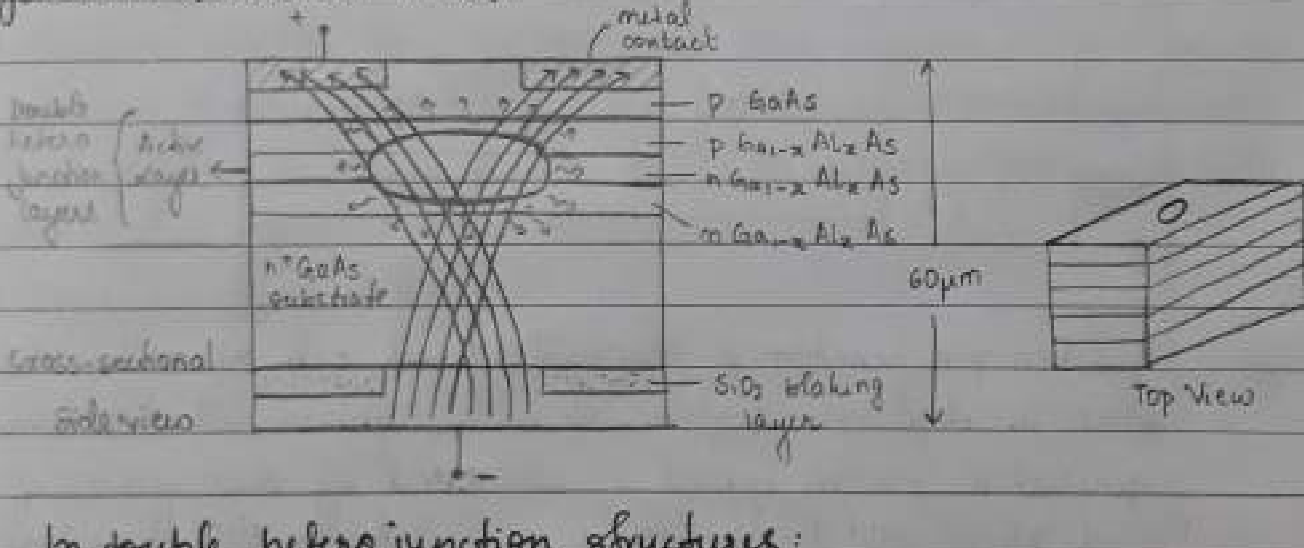
For optical systems requireng bit rates less than 100-200 Mbs with multimode optical fiber which requires optical power in µW, then LEDs are the best sources.

Some of the characteristics that are required in LED are:

- High radiance : Optical power radiated into a unit solid angle per unit surface emitting area.
- Fast Emission Response Time : Time delay between application of electric current pulse to optical emission
- High Quantum Efficiency :

To achieve high radiance and high quantum efficieny, the LED structure must have carrier confinement, optical confinement and less absorption loss.

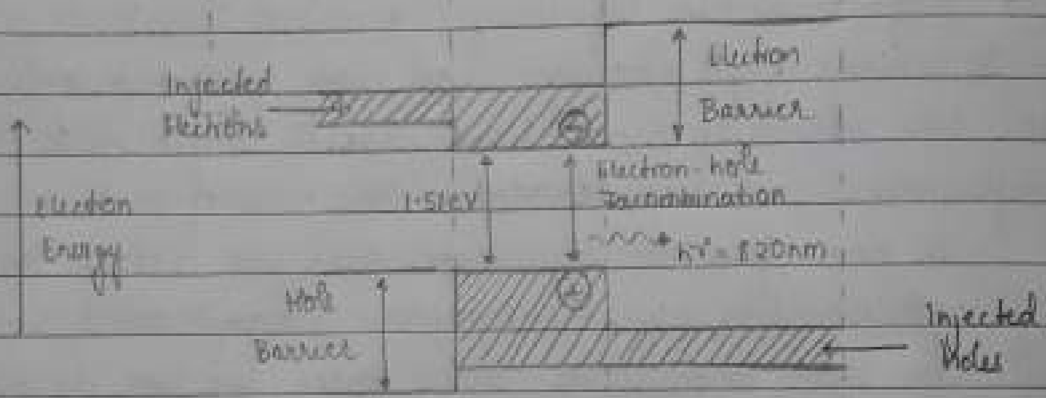
In homo junction structures there are certain losses such as high reflection loss, high reabsorption loss and total internal reflection loss. To overcome these losses we use double hetero junction structures in LED.

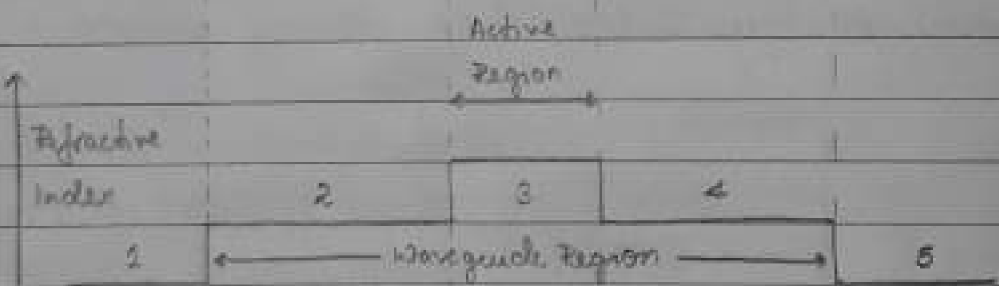


In double hetero junction structures:

1. High band gap energy reduces reabsorption loss.
2. Use of guiding layers gives carrier confinement and also reduces the reflection coefficient.

Metal contact	n-type GaAs substrate	n-type $Ga_{1-x}Al_xAs$	n-type $Ga_{1-x}Al_xAs$	p-type $Ga_{1-x}Al_xAs$	p-type GaAs	Metal contact
		Light guiding and carrier confinement	Recombination region	Light guiding and carrier confinement	Metal contact improvement Layer	
		~ 1μm	~ 0.3μm	~ 1μm	~ 1μm	



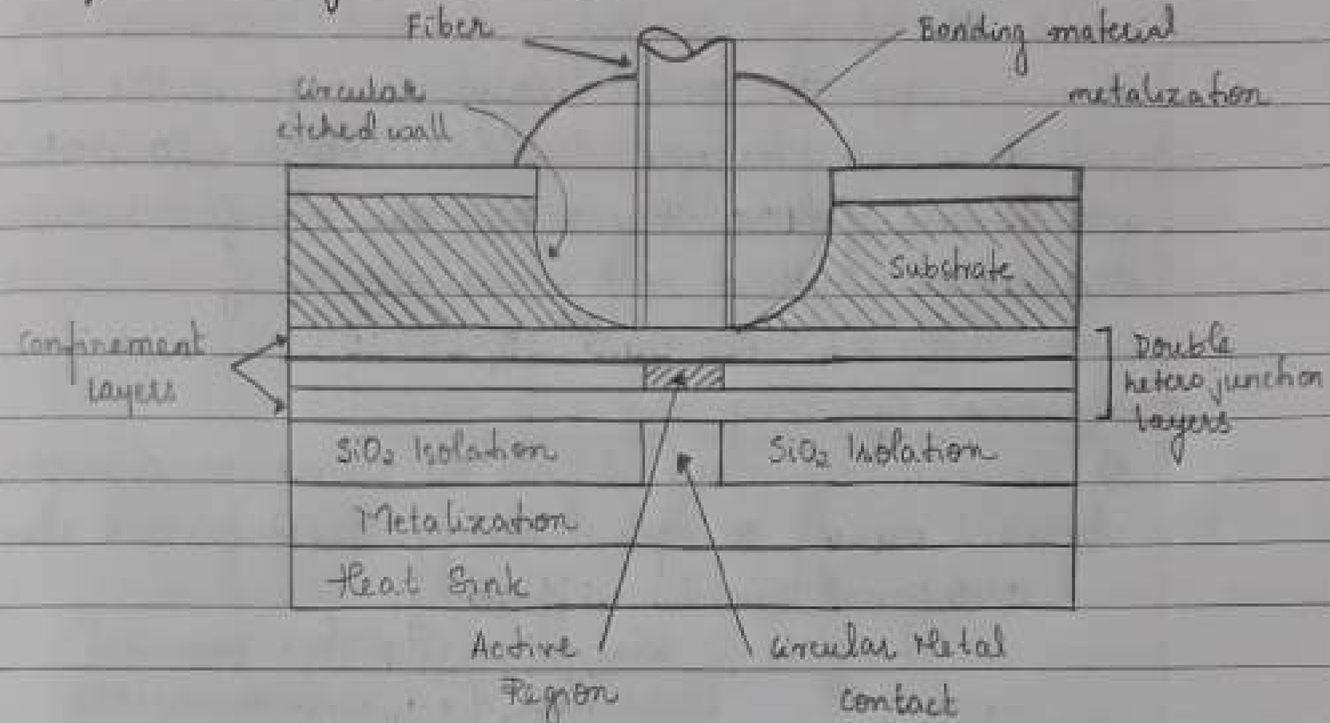


When p-n junction is forward biased e-h recombination takes place in depletion region. It emits light in all directions. The generated photon cannot be absorbed by that material due to high band gap energy, thus reducing reabsorption loss.

The RI of semiconductor material is 3.2 to 3.6. Use of the guiding layers gives carrier confinement and also reduces the reflection coefficient.

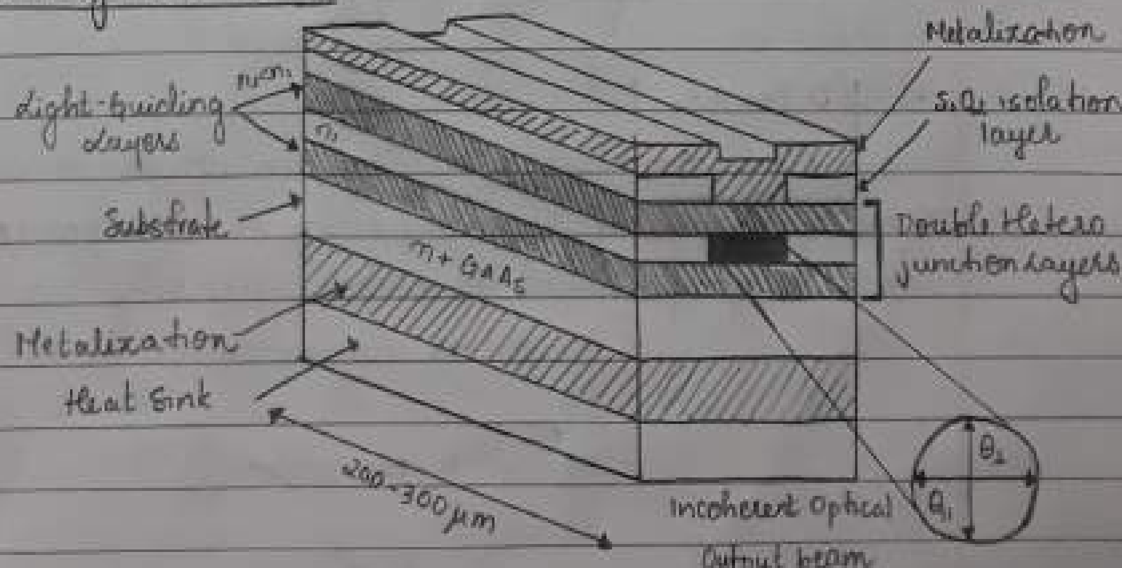
The LEDs can be classified as

1. <u>Surface Emitting LED: (SLED)</u>



In SLED only photons emitted in the top are used for communication. The optical fiber is mounted perpendicular to the active region. In order to mount, a well is etched through the substrate in order to accept the light. The circular active are is normally of 50μm diameter. The emitted light is isotropic with 120° half power beam width and this isotropic pattern is called Lambertian pattern.

2. <u>Edge Emitting LED: (ELED)</u>



The disadvantage of optical confinement is made use in ELED. This structure also uses double hetero junction structure. Here the photons emitted in the sides are used for communication. The active region in edge emitter are 50-70μm wide to match fiber core diameters. High culminated beam gets in case of ELED than SLED. The emitted beam is Lambertian with a half power width of

$$\theta_{\parallel} = 120 \quad \text{and} \quad \theta_{\perp} = 25-35$$

- Quantum Efficiency and LED power

a) Quantum efficiency defines the conversion efficiency of electrical energy to optical energy. This is further classified into

• Internal Quantum Efficiency

$$\eta_{int} = \frac{\text{Total number of photons generated}}{\text{Total number of e-h recombinations}}$$

(this gives the number of photons generated)

• External Quantum Efficiency

$$\eta_{ext} = \frac{\text{Total photons guided to fiber}}{\text{Total photons generated}}$$

(this gives the number of photons captured into optical fiber)

Thus the product of Internal Quantum Efficiency and External Quantum Efficiency gives the Total Quantum Efficiency

$$\eta = \eta_{int} \times \eta_{ext}$$

b) LED Power

Let us consider a region, in which 'n' carriers are injected. Rate of change of recombination or disappearance of carriers would be proportional to carrier density.

$$-\frac{\partial n}{\partial t} \propto n \quad \text{——— (1)}$$

$$-\frac{\partial n}{\partial t} = \frac{n}{\tau} \quad \text{——— (2)}$$

solving eq① gives us:

$$n(t) = n_0 e^{-t/\tau} \quad \text{——— (3)}$$

where τ: life time of carrier against e-h recombination.

n_0: Initial inject carrier density.

Initially injected carriers disappear exponentially in depletion region because of two processes: Radiative recombination and Nonradiative recombination. These two processes act simultaneously.

τ_{rr}: life time against radiative recombination

τ_{nr}: Life time against nonradiative recombination.

Therefore,

Total rate of recombination = Total rate of Radiative recombination + Total rate of Nonradiative Recombinatio

$$-\frac{\partial n}{\partial t}\Big|_{total} = -\frac{\partial n}{\partial t}\Big|_{rad} + -\frac{\partial n}{\partial t}\Big|_{nonrad} \quad \text{——— (4)}$$

$$\frac{n}{\tau} = \frac{n}{\tau_{rr}} + \frac{n}{\tau_{nr}}$$

$$\frac{1}{\tau} = \frac{1}{\tau_{rr}} + \frac{1}{\tau_{nr}} \quad \text{——— (5)}$$

also $$\tau = \frac{\tau_{rr}\tau_{nr}}{\tau_{rr}+\tau_{nr}} \quad \text{——— (6)}$$

wkt, internal quantum efficiency is

$$\eta_{int} = \frac{-\partial n/\partial t|_{rad}}{-\partial n/\partial t|_{tot}} = \frac{n/\tau_{rr}}{\frac{n}{\tau_{rr}} + \frac{n}{\tau_{nr}}} = \frac{1}{1+\frac{\tau_{rr}}{\tau_{nr}}} \quad \text{——— } \boxed{A}$$

or $$\eta_{int} = \frac{n/\tau_{rr}}{n/\tau} = \frac{\tau}{\tau_{rr}} \quad \text{——— } \boxed{B}$$

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

$$\frac{I}{q} = -\frac{\partial n}{\partial t}\Big|_{rad/sec} + -\frac{\partial n}{\partial t}\Big|_{nonrad/sec}$$

but, $\eta_{int} = \dfrac{-\frac{\partial n}{\partial t}\Big|_{rad/sec}}{I/q}$

$$-\frac{\partial n}{\partial t}\Big|_{rad/sec} = \eta_{int}\frac{I}{q}$$ Total number of photons generated per second

$$-\frac{\partial n}{\partial t}\Big|_{rad/sec} \times h\nu = P_{int}$$

Therefore,

$$\boxed{P_{int} = \eta_{int}\frac{I}{q}h\nu = \eta_{int}\frac{I}{q}h\frac{c}{\lambda}}$$ in watt (W)

Q1: A double heterojunction InGaAsP LED emitting at a peak wavelength of 1310nm has radiative and nonradiative recombination times of 30 and 100ns, respectively. The drive current is 40 mA. Find

a) the bulk recombination time
b) the internal quantum efficiency
c) the internal power level

→ Given: Double heterojunction InGaAsP LED

$\lambda = 1310nm$ $\tau_{nr} = 100ns$

$\tau_{rr} = 30ns$ $I = 40mA$

a) the bulk recombination time is given by:

$$\tau = \frac{\tau_{rr}\tau_{nr}}{\tau_{rr}+\tau_{nr}} = \frac{(30\times10^{-9})(100\times10^{-9})}{30\times10^{-9}+100\times10^{-9}}$$

$$\tau = \frac{3000\times10^{-9}}{130} = 23.1\times10^{-9} = 23.1\,n\,sec$$

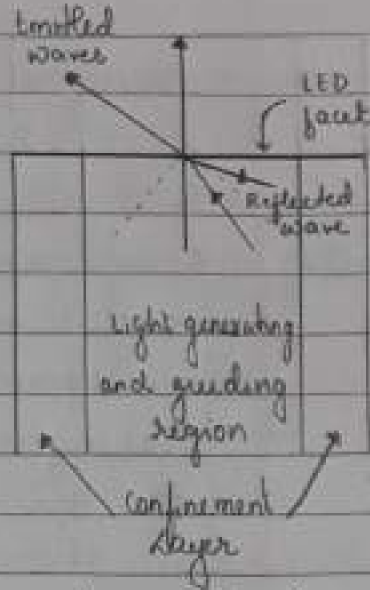
b) the internal quantum effeciency is given by:

$$\eta_{int} = \frac{\tau}{\tau_{rr}} = \frac{23.1\times10^{-9}}{30\times10^{-9}} = 77\% = 0.77$$

c) the internal power level is given by:

$$P_{int} = \eta_{int}\frac{I}{q}\frac{hc}{\lambda}$$

$$P_{int} = 0.77\times\frac{40\times10^{-3}\times6.6256\times10^{-34}\times3\times10^{8}}{1.602\times10^{-19}\times1310\times10^{-9}} = 29.2\,mW$$



As we already know that,
External Quantum Efficiency gives how many photons captured into the optical fiber. This is defined as ratio of the photons emitted from LED to number of internally generated photons

$$\eta_{ext} = \frac{\text{Photon collected over this solid angle}}{\text{Total photons emitted isotropically solid angle}}$$

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

$$\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = 16^\circ$$

$$\eta_{ext} = \frac{1}{2}\left[1 - \cos\phi_c\right] T(\phi)$$

Due to interface at Si-Air, only fraction of energy is transmitted:

$$T(\phi) = 1 - R = 1 - \left(\frac{n_1 \cos\theta_1 - n_2 \cos\theta_1}{n_1 \cos\theta_1 + n_2 \cos\theta_1}\right)^2$$

For normal incidence

$$T(0) = 1 - R = 1 - \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 = \frac{4 n_1 n_2}{(n_1 + n_2)^2}$$

Substituting we get

$$\eta_{ext} = \frac{1}{2}\left[1 - \cos\phi_c\right] \frac{4 n_1 n_2}{(n_1 + n_2)^2}$$

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

For small angle

$$\cos\phi_c \simeq 1 - \frac{\sin^2\phi_c}{2}$$

$$\cos\phi_c = 1 - \frac{n_2^2}{2n_1^2}$$

$$\eta_{ext} = \frac{1}{2}\left[\cancel{1} - \cancel{1} + \frac{n_2^2}{2n_1^2}\right] \frac{4 n_1 n_2}{(n_1 + n_2)^2}$$

$$\eta_{ext} = \frac{n_2^2 \cancel{n_1} n_2}{n_1^2 (n_1 + n_2)^2}$$

Here $n_2 = 1$

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

Therefore, the optical power emitted from the LED is

$$\boxed{P = P_{int}\,\eta_{ext} = \frac{P_{int}}{n_1(n_1+1)^2}}$$

Q2: Assume a typical value of $n = 3.5$ for the refractive index of an LED material what percent of the internally generated optical power is emitted into an air medium?

- Taking the condition for normal incidence, the percent of the optical power that is generally internally in the device that is emitted into an air medium is

$$\eta_{ext} = \frac{1}{n(n+1)^2} = \frac{1}{3.5(3.5+1)^2} = \underline{\underline{1.41\%}}$$

This shows that only a small fraction of the internally generated optical power is emitted from the device.

- Modulation Bandwidth of LED

Modulation bandwidth of LED is limited by: carrier recombination time and RC time constant.

The RC time constant limits the modulation bandwidth because the diode is equivalent to series resistance and capacitance.

$$f_c = \frac{1}{2\pi RC} \qquad R = 10\Omega \quad C = 100\,pF$$

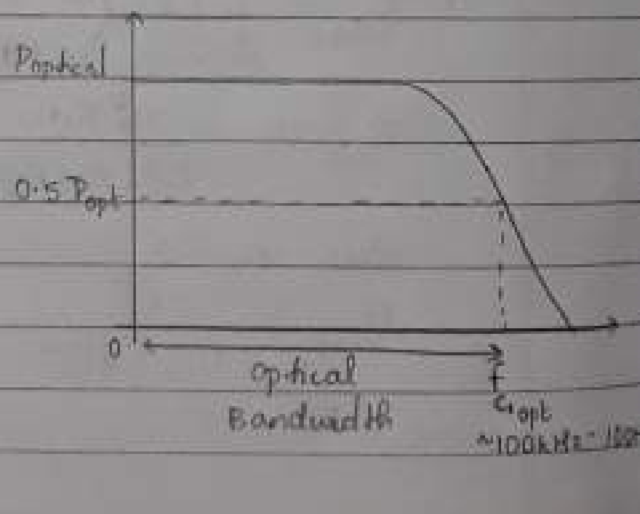
$$\therefore f_c = 100\,MHz$$

Recombination time

$$\tau = 10^{-6} - 10^{-9} = 1\mu s - 1ns$$

The frequency response of LED.

As frequency increases initially the output amplitude of the power remains constant. As frequency increases further it drops to zero.



- **<u>LASER Diodes</u>**: (Light Amplification by Stimulated Emission of Radiation)

LASER is a source of monochromatic coherent radiation on the range of 0.2μm to 20μm. It gives light by stimulated emission. It is analogous to oscillator that comprises amplifier and feedback.

The three components of LASER are:

1. The gain medium or active device which gives gain when powered by power supply.
2. Pump or power supply.
3. Optical feedback unit (optical resonator) which provides feedback to resonant signals.

Coherency is classified as:

- coherency in time - temporal coherency
- coherency is space - spatial coherency

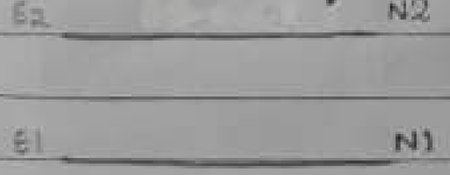
There is coherency between two photons if they have

- Same energy
- Same phase
- Same momentum vector or same direction
- Same polarizations

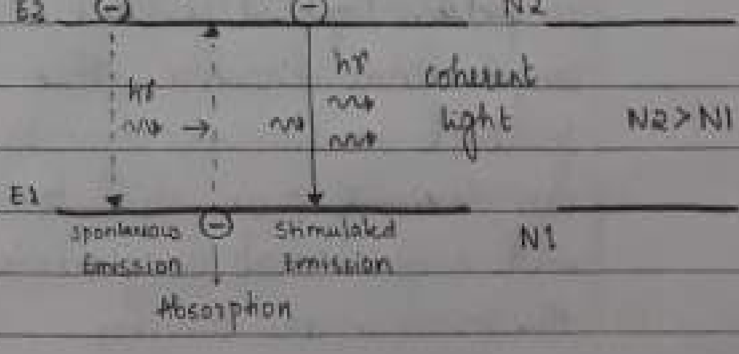
Three key transition processes in LASER action: (Pg 51)

1. Absorption
2. Spontaneous emission
3. Stimulated emission

At thermal equilibrium



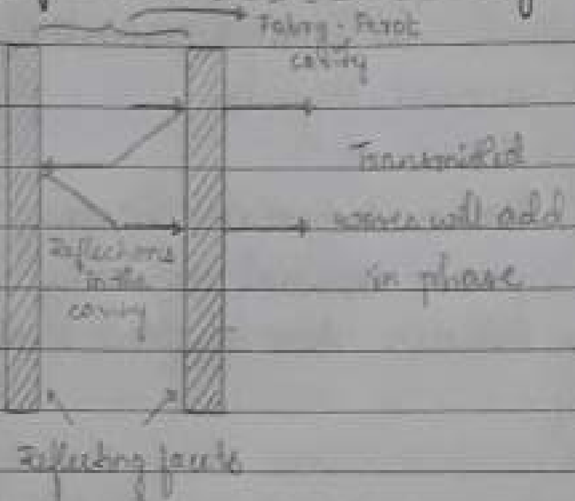
At stimulated emission it requires N2 > N1, it is created by population inversion



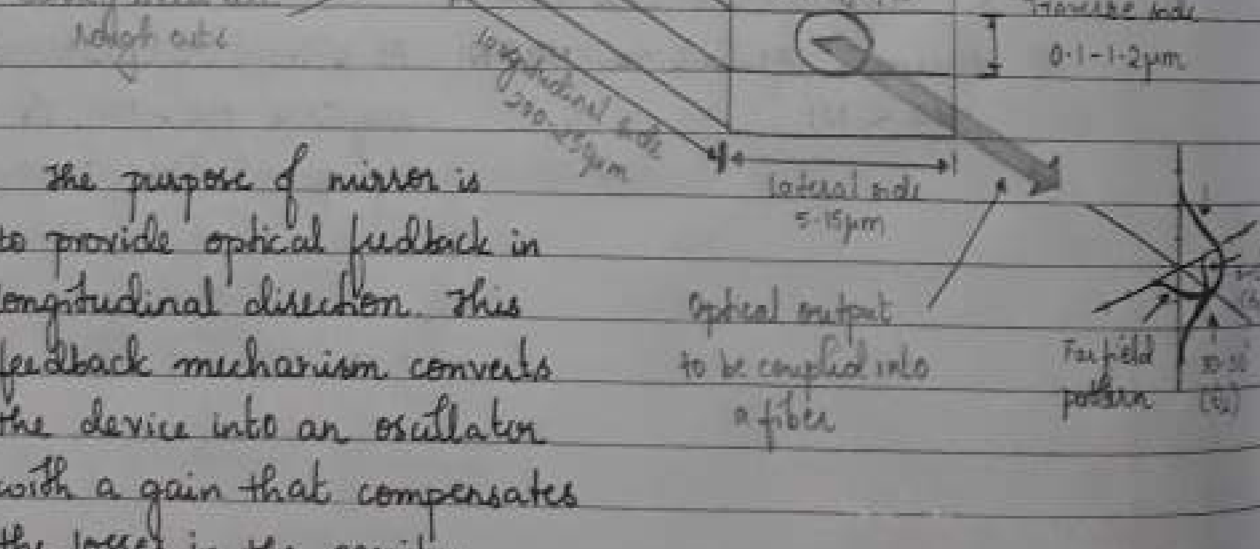
- <u>Laser Diode Modes</u>

For optical communication systems requiring BW > 200MHz, response time < 1ns, spectral width ≤ 2nm and capable of coupling several tons of milliwatts of optical power for optical fibers with small cores use LASER over LED. Lasers use double hetero junction structure because of carrier and optical confinement.

- <u>Fabry - Perot Resonator Cavity</u>



Simulated emission in semiconductor laser is due to optical transitions between valence and conduction states. One such configuration is in Fabry - Perot Resonator cavity.



The purpose of mirror is to provide optical feedback in longitudinal direction. This feedback mechanism converts the device into an oscillator with a gain that compensates the losses in the cavity.

As light reflects back and forth within the cavity, the electric field of the light interfere on successive round trips. Those wavelengths that are integer multiples of cavity length interfere constructively so that their amplitudes add when they exit the device through the right hand face. All other wavelengths interfere destructively by cancelling themselves. These resonant wavelengths are called longitudinal modes of the cavity.
Since the entire output is required at the front face of the laser, the rear face is deposited with dielectric medium.

- Threshold Conditions:

Threshold condition is the minimum gain to start stimulated emission. Electromagnetic wave propagating in longitudinal direction can be represented as:

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

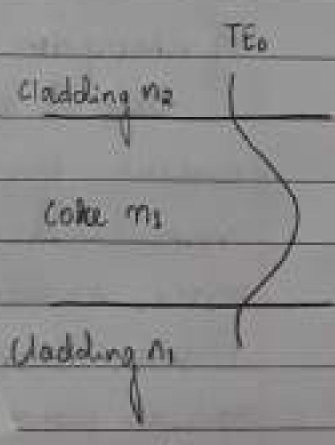
where $I(z)$: Optical Field Intensity or amplitude of EM.

The optical field intensity varies exponentially with distance z

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

where $\bar{\alpha}$: Absorption coefficient
g : gain
Γ : confinement factor
Γg : confined field gain

In cavity, electromagnetic wave travels as modes and only part of the energy is confined.



Assume gain exceeds the loss at one round trip ($z = 2L$) propagation and only fractions of R1 and R2 optical radiations are reflected. Then the optical field intensity after one round trip propagation is

$$I(2L) = I(0)\, e^{[\Gamma g(h\nu) - \bar{\alpha}(h\nu)]2L} \cdot R_1 R_2 \quad \text{——— (2)}$$

At lasing threshold, a steady state of oscillation takes place. Also the magnitude and phase of the returned wave must be equal to those of the original wave (i.e., same amount of photons should return and the reflected wave must interfere constructively with the original wave)

$$\therefore \quad I(2L) = I(0) \quad \text{and} \quad e^{-j\beta 2L} = 1$$

By substituting in eq ②, we get:

$$1 = \exp\left(\Gamma g(h\nu) - \bar{\alpha}(h\nu)\right) 2L \cdot R1 \cdot R2$$

By solving the above equation, we get:

$$\boxed{\Gamma g_{th} = \bar{\alpha} + \frac{1}{2L} \ln\left(\frac{1}{R1 \cdot R2}\right) = \bar{\alpha} + \alpha_{end}}$$

ie, gain = absorption loss + reflecting mirror loss = loss

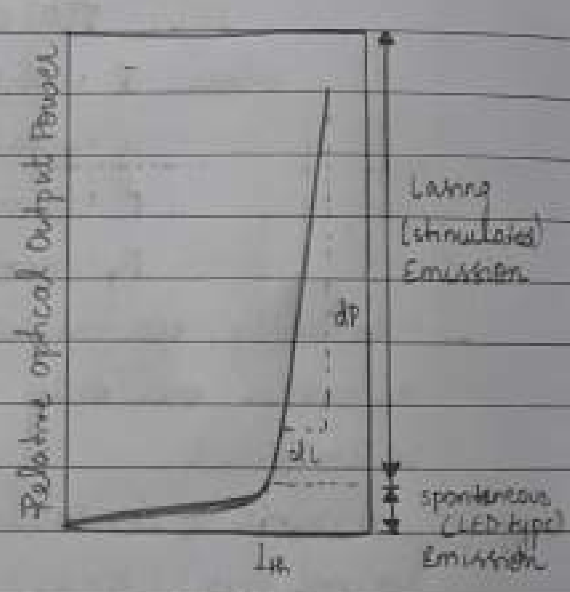
Thus for lasing to occur, the following condition is required:

$$\boxed{g > g_{th}}$$

- Optical Output Power versus laser drive current:

For low currents, the spontaneous emission takes place so the device acts like LED ie., linear relationship. But slope of this characteristics is small because of absorption loss (OFF state = Logic 0)

Once it reaches certain threshold current, beyond this current the stimulated process over comes the losses, suddenly the lasing action starts. Then the increase of optical power occurs with high efficiency (ON state = Logic 1).



Relationship between Optical Output Power and Laser diode drive current.

Due to this switching action, at I_{th} laser can be used with digital modulation. Below I_{th}, LASER is OFF and above I_{th}, LASER is ON.

Laser emits light at single frequency or single wavelength thus giving narrow band spectrum. From the output characteristics we can see that laser has high efficiency, so laser optical sources are suitable for long distance communication.

Q3: Assume for GaAs that $R_1 = R_2 = R = 0.32$ for uncoated facets (i.e., 32 percent of the radiation is reflected at a facet) and $\bar{\alpha} = 10\,cm^{-1}$. What is the gain threshold for a 500 μm long laser diode?

– Given:

$R_1 = R_2 = R = 0.32$ $\quad L = 500\,\mu m = 500 \times 10^{-6}\,m = 500 \times 10^{-4}\,cm$

$\bar{\alpha} = 10\,cm^{-1}$

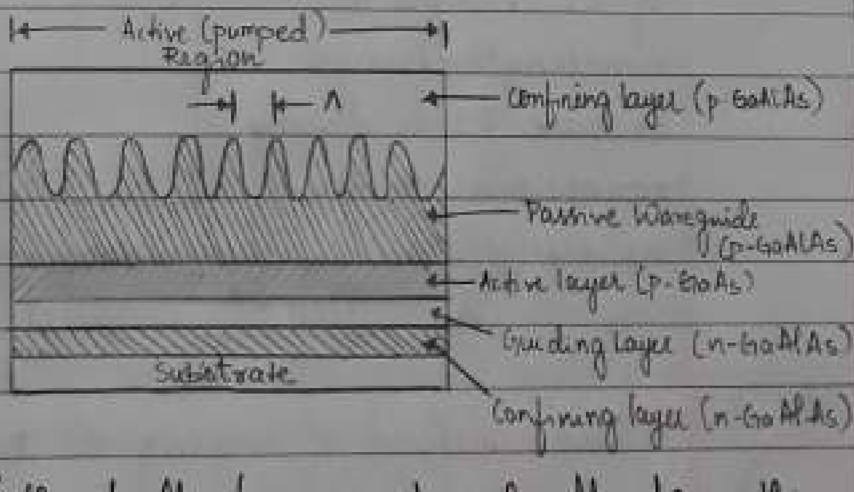
The gain threshold for the laser diode is given by

$$\Gamma g_{th} = \bar{\alpha} + \frac{1}{2L} \ln\left(\frac{1}{R1 \cdot R2}\right)$$

$$\Gamma g_{th} = 10 + \frac{1}{2(500 \times 10^{-4})} \ln\left(\frac{1}{(0.32)(0.32)}\right) = \underline{\underline{32.78\,cm^{-1}}}$$

– Single Mode Lasers or Distributed feedback Laser (DFB)

For high speed long distance communication single mode lasers are needed because it contains only one longitudinal mode with narrow spectral width.

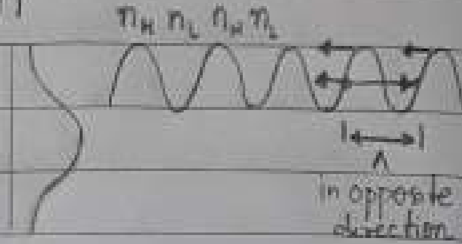


Instead of having feedback at the ends, if the feedback is employed all along the length of the cavity laser then it is called Distributed Feedback Laser. In this structure, the EM wave travels as modes. In this mode, the evanescent field continuously sees the congrugated feedback which is called Bragg grating. The evanescent field continuously sees reflection because of constructive interference, highly coherent radiation emits in opposite direction

$\beta \eta_{eff} \cdot 2\Lambda = q\, 2\pi$

$\frac{2\pi}{\lambda} \eta_{eff}\, 2\Lambda = q\, 2\pi$

$$\boxed{\lambda_B = \frac{\eta_{eff}\, 2\Lambda}{q}}$$



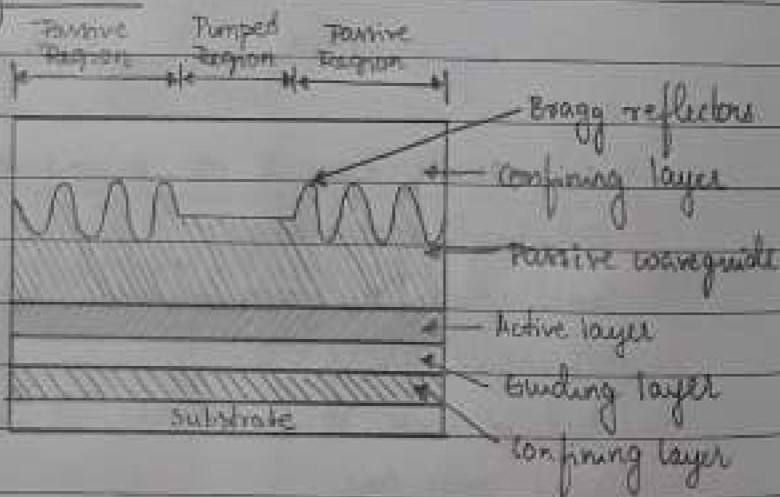
For example: to have highly coherent radiation at $\lambda = 1.55\,\mu m$, $q = 1$

$\Lambda = \frac{\lambda_B q}{2\eta_{eff}} = \frac{1.55\times10^{-6}\times 1}{2\times 3.5} = 0.23\,\mu m$

Thus by maintaining $0.23\,\mu m$ corrugated structure, we get highly coherent radiation at $\lambda = 1.55\,\mu m$.

- Distributed Bragg Reflector:

When current 'i' injects, the RI of medium changes. If RI changes then wavelength changes because RI is directly proportional to the wavelength.



$\therefore \lambda_B = \frac{\eta_{eff}\, 2\Lambda}{q}$ Therefore DFB gives an unstable output.

Thus, instead of having the Bragg grating throughout the length, if we have the Bragg grating at the ends then it gives more stable output.

- Comparison between LED and LASER:

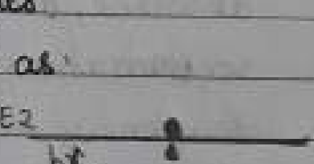
LED	LASER
• Low efficiency	• High efficiency
• Low bit rate	• High bit rate
• Low launch power (in μW)	• High launch power (in mW)
• Slow response time	• Fast response time (in ns)
• Simpler construction	• Complex construction
• Used for small distance communication	• Used for long distance communication
• Output beam is incoherent.	• Output beam is coherent
• Life time is more.	• Life time is less
• Dispersion is more.	• Dispersion is less

• **Principles of Photodiodes:**

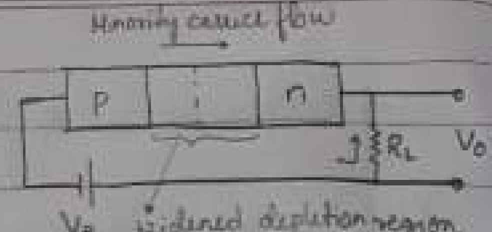
The first element of receiver is a photodetector. It converts optical power into electrical current. Out of many types of photodetectors, optical fiber communication system uses semiconductor photodiodes because of their small size, suitable material, high sensitivity and fast respones.

Semiconductor photodiodes are classified as

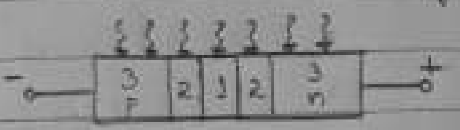
1. PIN Photo diode:



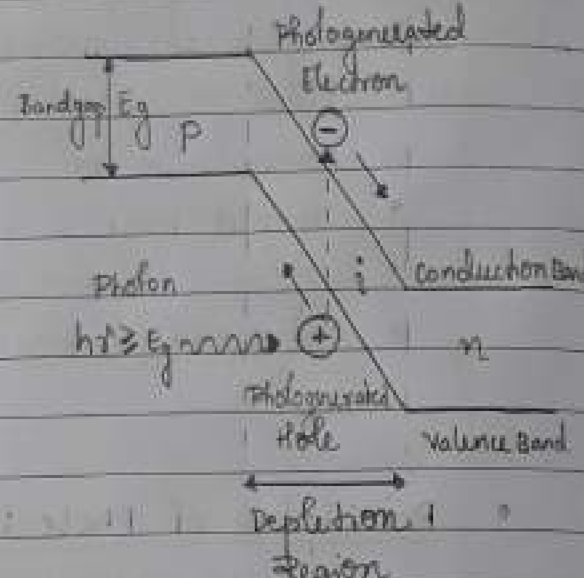
When a photon incidents on an electron in lower energy state, it gives off its energy making an electron transition from E1 to E2. This process creates e-h pair which are called as photocarriers. The p-n junction diode is used in reverse bias to get photo carriers. The e-h pair are called as photocarriers because they are produced due to photon.



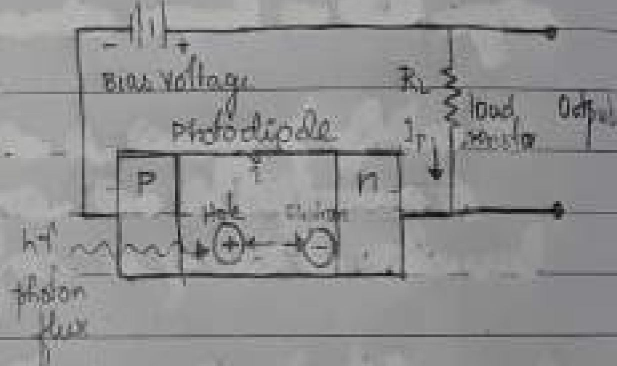
The p-n junction diode is reverse biased by applying reverse bias voltage V_B and the output V_0 is measured across the load resistance R_L.



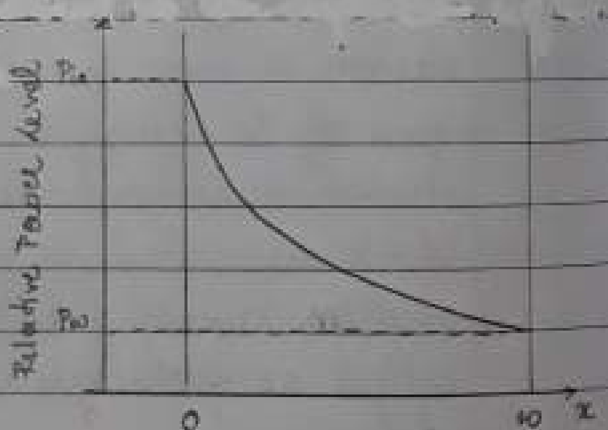
When photon incidents on region 1, energy of photon is absorbed, hence generating e-h pair in the depletion region. Due to built in potential the e-h swept apart gives photocurrent.



When photon incidents on region 3, energy of photon is absorbed, hence generating e-h pair. But due to no influence of electric field these e-h pair wander around in that region and may recombine again.



When photon incidents on region 2, energy of photon is absorbed, hence generating e-h pair. Due to difference in concentration, these e-h pair diffuse to p and n sides and they may recombine.



Therefore only the photon incident on the depletion region (region 1) gives photocurrent.

Practically, p-n junction diode have depletion width in the order 1μm, so photon capture width is less. To increase photon capture width we use PIN photodiode.

PIN photodiode consists of p and n regions separated by a very lightly doped intrinsic (i) ~~n~~ layer.

When photon incidents i layer
it creates e-h pair. Under the influence of electric field this e-h pair is swept apart which gives photo current.

If Pin power illuminates PIN photodiode, then Pin power is exponentially absorbed as shown in the graph. Then the power at distance x is given by:

$$P(x) = P_{in}\, e^{-\alpha x}$$

Q4: If the absorption coefficient of $In_{0.53}Ga_{0.47}As$ is $0.8 \mu m^{-1}$ at 1650 nm, what is the penetration depth at which $\frac{P(x)}{P_{in}} = \frac{1}{e} = 0.368$?

– Given: $\alpha = 0.8 \mu m^{-1}$

$$\frac{P(x)}{P_{in}} = e^{-\alpha x}$$

$$0.368 = e^{-0.8x}$$

Therefore,

$$-0.8x = \ln 0.368$$

$$\underline{x = 1.25 \mu m}$$

Q5: A high speed $In_{0.53}Ga_{0.47}As$ pin photodetector is made with a depletion layer thickness of 0.15μm. What percent of incident photons are absorbed in this photodetector at 1310 nm if the absorption coefficient is $1.5 \mu m^{-1}$ at this wavelength?

– Given:

$\alpha = 1.5 \mu m^{-1}$ $\quad x = 0.15 \mu m$

$$\frac{P(x)}{P_{in}} = e^{-\alpha x} \Rightarrow \frac{P(0.15)}{P_{in}} = e^{-(1.5 \times 0.15)} = \underline{0.8}$$

Therefore only 20% of the incident photons are absorbed

PIN photodiodes are characterized by two important parameters:

1. Quantum Efficiency

$$\eta = \frac{\text{number of e-h pair generated}}{\text{number of photons incident}} = \frac{I_p/q}{P_{in}/h\nu} = \frac{I_p h\nu}{P_{in} q}$$

2. Response speed or Responsivity

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

Q6: In a 100 ns pulse, 6×10^6 photons at a wavelength of 1300 nm fall on an InGaAs photodetector. On the average, 5.4×10^6 electron hole (e-h) pairs are generated. Find quantum efficiency.

– Given:

e-h pairs generated $= 5.4 \times 10^6$

photons incident $= 6 \times 10^6$

Therefore, Quantum efficiency is given by:

$$\eta = \frac{\text{number of e-h pairs generated}}{\text{number of photons incident}}$$

$$\eta = \frac{5.4 \times 10^6}{6 \times 10^6} = \underline{\underline{0.9}}$$

Thus the quantum efficiency at 1300 nm is 90%.

Q7: 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 10μW, find the photocurrent generated.

– Given:

$R = 0.65$ A/W

$P_{in} = 10\,\mu W$

The photocurrent generated is given by:

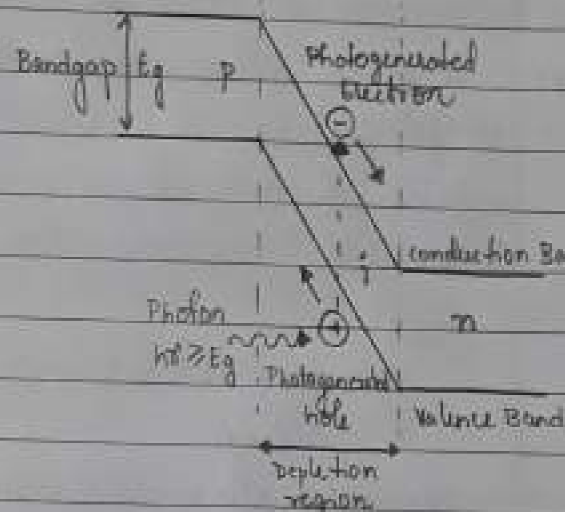
$I_p = R P_{in}$

$I_p = 0.65 \times 10 \times 10^{-6} = \underline{\underline{6.5\,\mu A}}$

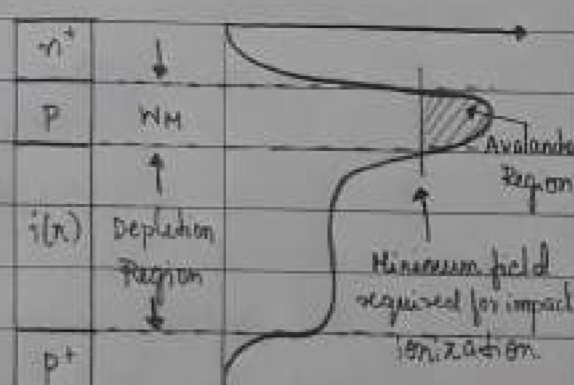
2. Avalanche Photodiodes (APD)

Avalanche photodiodes are PIN diodes with very large reverse bias voltage. It has built in gain due to avalanche multiplication. Typical gain is M~ 10-100. They have high sensitivity but are more noisy.

When photons are incident, e-h pair are generated. Because of large potential slope, the electron goes down the slope. As it is travelling, it gets accelerated due to kinetic energy. Then it may knock down another electron from a bound electron, this creates e-h pair. The same mechanism also occurs for holes. Due to these two processes, avalanche multiplication leads to high gain.



Efficient avalanche multiplication occurs due to electrons. So it uses a new configuration called Reach through APD.



• Reach Through APD

Reach-through APD contains p^+, $i(\pi)$, p, n^+ layers.

The light enters the device through p^+ region and is absorbed in π region. This creates e-h pairs which are swept to p and n side. The electron moving towards n^+ side enters high electric field zone. This electron knocks down another electron creating e-h pairs which are called secondary carriers. This process continues in high electric field zone and then the generated e-h pairs when swept across p and n sides give high gain photocurrent.

This multiplication, M for all carriers generated in photodiode is given by:

$$I_m = M I_p$$

The performance of APD is characterized by its responsivity.

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

Q8: A given silicon avalanche photodiode has quantum efficiency of 65 percent at a wavelength of 900nm. Suppose 0.5μW of optical power produces a multiplied photocurrent of 10μA. What is the multiplication M?

— Given:

$\eta = 65\% = 0.65$ $\quad P_{in} = 0.5\mu W$

$\lambda = 900nm$ $\quad I_m = 10\mu A$

The primary photocurrent is

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

$$I_p = \frac{0.65 \times 1.6 \times 10^{-19} \times 900 \times 10^{-9}}{6.625 \times 10^{-34} \times 3 \times 10^{8}} \times 0.5 \times 10^{-6}$$

$$\underline{I_p = 0.235 \mu A}$$

The multiplication is given by:

$$I_m = M I_p$$

$$M = \frac{I_m}{I_p} = \frac{10 \times 10^{-6}}{0.235 \times 10^{-6}} = \underline{\underline{43}}$$

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

• **Problems:**

Q9: A photodiode is constructed of GaAs which has a bandgap energy of 1.43eV at 300k. Find the longer cut off wavelength (λ_c)

— $$\lambda_c = \frac{hc}{E_g} = \frac{6.625 \times 10^{-34} \times 3 \times 10^{8}}{1.43 \times 1.6 \times 10^{-19}} = \underline{\underline{868.66 \text{ nm}}}$$

- **SLE: Photodetector noise and Avalanche Multiplication Noise**

– **Photodetector Noise:**

In fiber optic communication systems, the photodiode is generally required to detect very weak optical signals.

Detection of weak optical signals requires that the photodetector and its amplification circuitry be optimized to maintain a given signal-to-noise ratio.

The power signal-to-noise ratio S/N (also designated by SNR) at the output of an optical receiver is defined by

$$SNR = \frac{S}{N} = \frac{\text{signal power from photocurrent}}{\text{photodetector noise power + amplifier noise power}}$$

SNR cannot be improved by amplification.

To achieve a high SNR

- photodetector must have high quantum efficiency to generate large signal power.
- photodetector and amplifier noises must be as low as possible

– **Avalanche Multiplication Noise:**

The measured gain of an avalanche photodiode is the mean or average gain experienced by the ensemble of free carriers. This variation in gain manifests itself as an extra noise source usually called the excess noise or multiplication noise. In many application this limits the maximum useful gain of an Avalance photodiode.

The amount of multiplication noise depends on many factors such as the magnitude of reverse voltage, material properties and the device design. It increases with increasing amplification factor, as obtained for increasing reverse voltage. Therefore, the reverse voltage is often chosen such that the multiplication noise approximately equals to the noise of the electronic amplifier, because that setting minimizes the overall noise

UNIT 4:

Optical Receiver and Digital Transmission System

- **Introduction:**

An optical receiver consists of a photodetector, an amplifier and signal processing circuitry. The receiver first converts the optical energy into an electrical signal which is then amplified to certain level so that it can be processed by the following circuitry.

Digital links are characterised by bit error rate (BER) in terms of average error probability and analog links are characterised by fidelity in terms of SNR.

- **Fundamental Receiver Operation:**

The design of an optical receiver is complicated than the optical transmitter because it should detect weak and distorted signal based on amplified and reshaped signal.

Here we consider Intensity Modulated Direct Detect (IMDD) system which uses binary digital signal as input

- Digital Signal Transmission:

• Binary data stream consisting of either 0 or 1 in a time slot of duration T_b is given as input to optical transmitter. One of the simplest technique for generating binary data stream is ASK

• The function of the optical transmitter is to convert the electrical signal to optical signal. This is done by directly modulating the light source drive current with data stream

• The optical signal is then coupled from light source to optical fiber. As the signal propagates it becomes attenuated and distorted.

• The function of optical receiver is to convert optical signal back into an electrical signal

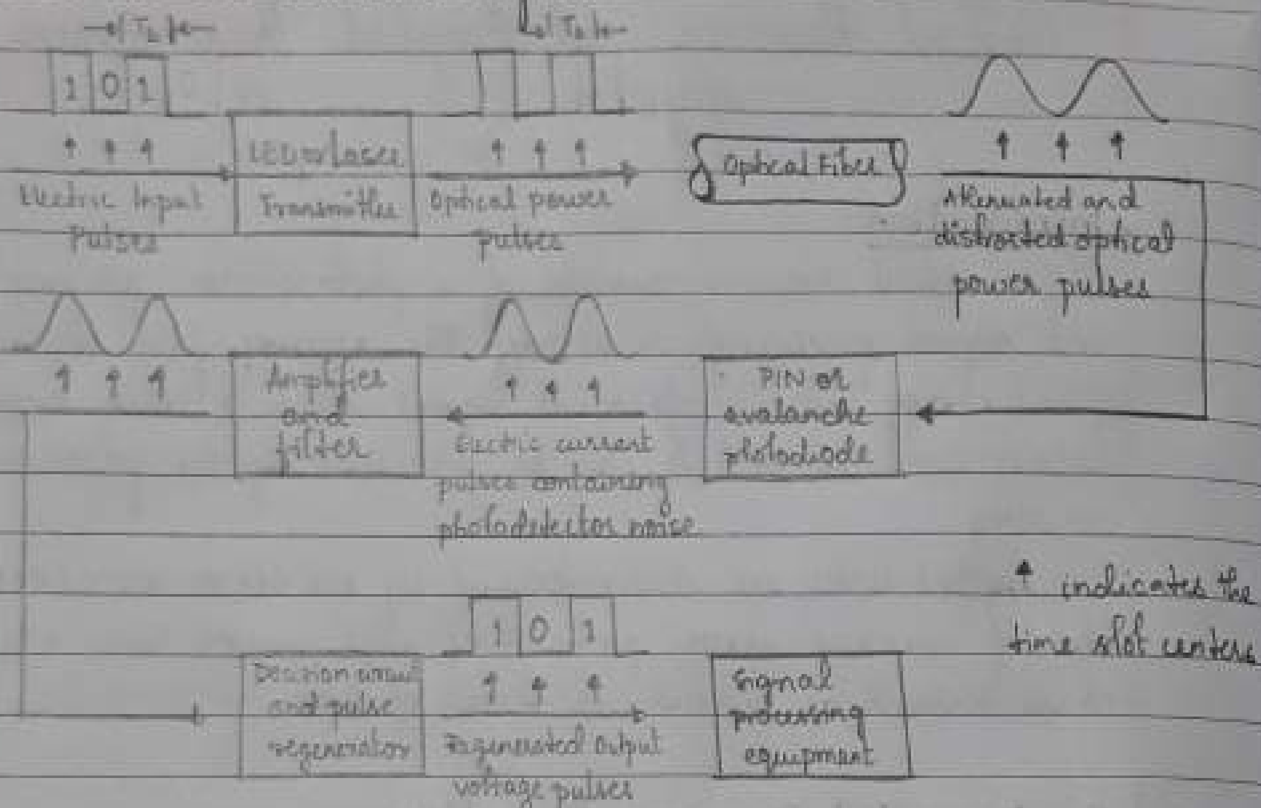
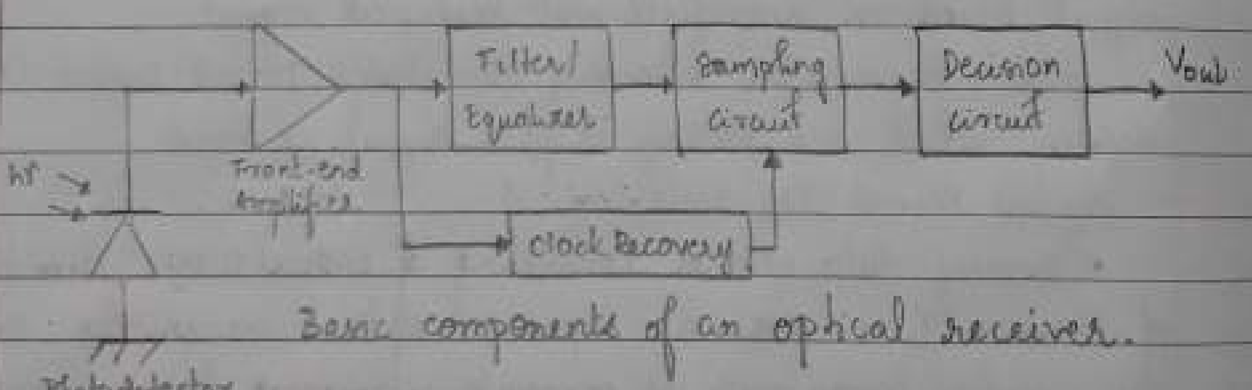


Figure : Illustrates the shape of the digital signal at different points along an optical link.



Basic components of an optical receiver.

The first element is either PIN or APD photodiode which produces electric current proportional to received power. The electric current is then amplified by the amplifier.

The signal is then passed through a low pass filter to reduce noise. This filter defines the receiver bandwidth. In addition to minimizing the effects of ISI, the filter can reshape the pulse that are distorted. This function is called equalization since it cancels or equalizes the pulse spreading effects.

The final module of the optical receiver samples the signal at the midpoint and then by comparing the signal with threshold it detects the received signal (signal greater than threshold level → 1, signal lesser than threshold level → 0).

To sample at mid point the receiver should know the bit boundaries. This is performed with the help of periodic waveform. Thus the function is called clock recovery or timing recovery.

- Error Sources:

Error in the detection mechanism arise from various noises and disturbances. Noise is unwanted signal which disturbs the transmission and processing of signal. There are two types of noises: Internal noise and External noise.

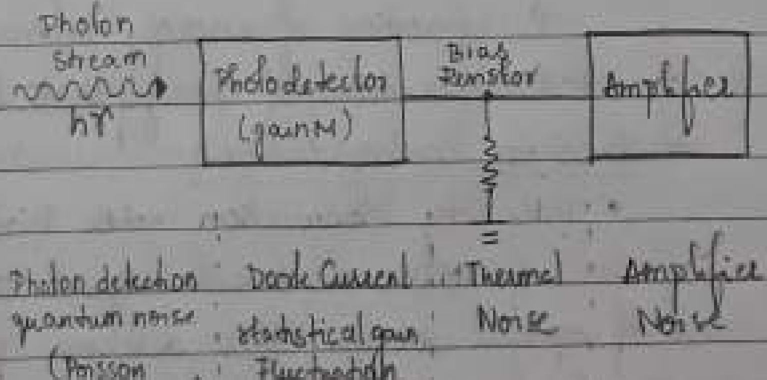
Considering internal noises, the main types of receiver noises are:

1. Quantum Noise / Shot Noise

The random arrival rate of photons produces a quantum noise or a shot noise.

2. Dark Current Noise

During the absense of light, the ambient light falls on the photodetector and produces current that is called Dark Current Noise.



3. Thermal Noise

The random motion of electrons in detector load resistor and amplifier circuitry gives thermal noise.

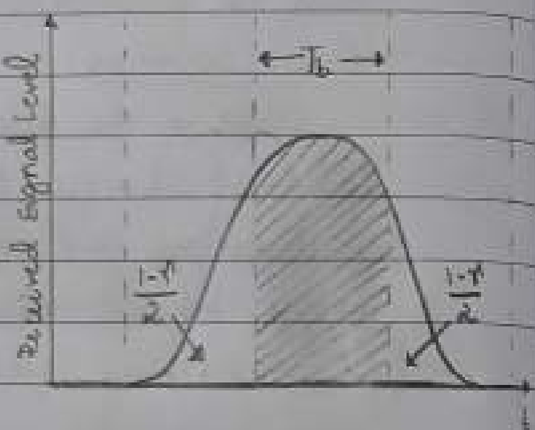
The primary photocurrent generated by the photodiode is a time varying Poisson process.

If the detector is illuminated by an optical signal $p(t)$ then the average number of e-h pairs $\overline{N}$ generated in a time τ is

$$\overline{N} = \frac{\eta}{h\nu}\int_0^{\tau} P(t)\,dt = \frac{\eta E}{h\nu}$$

The probability of 'n' electrons emitted in interval τ is

$$P_{\tau}(n) = \overline{N}^{n}\frac{e^{-\overline{N}}}{n!}$$



Further error source is Inter Symbol Interference (ISI). When a pulse is transmitted in a given time slot due to pulse spreading induced by the fiber some of the transmitted energy will progressively spread into neighboring time slots. The presence of this energy in adjacent time slots is termed as Interfering signal. This mechanism is known as Inter Symbol Interference (ISI).

γ : fraction of energy remaining in the time slot T_b

$1-\gamma$: fraction of energy that has spreaded.

- Receiver configurations:

• Intensity Modulation with Direct Detection system (IM/DD):

In IMDD, electrical signal linearly modulates the intensity of optical source. This scheme pays no attention to the frequency and phase of the optical carrier. Since a photodiode responds only to changes in the power level of light that falls on it, these IMDD methods offer system simplicity and relatively low cost but they suffer from limited sensitivity.

Let us consider the electric field of the transmitted optical field as:

$$E_s = A_s \cos(\omega_s t + \phi_s(t)) \quad \text{--- (1)}$$

where A_s: Amplitude
ω_s: carrier frequency
$\phi_s(t)$: phase

In direct detection system, the receiver produces electric current based on the optical power that falls on the photodiodes. The directly detected current is proportional to intensity I_{DD} which is given as

$$I_{DD} = E_s E_s^* = A_s \cos(\omega_s t + \phi_s(t)) . A_s \cos(\omega_s t + \phi_s(t))$$

$$I_{DD} = A_s^2 \frac{(1 + \cos 2(\omega_s t + \phi_s(t)))}{2} \quad \text{--- (2)}$$

The term involving $\cos 2(\omega_s t + \phi_s(t))$ gets eliminated, then from eq (2) we get

$$I_{DD} = E_s E_s^* = \frac{A_s^2}{2}$$

- Coherent Light Wave Communication System:

In coherent light wave communication system homodyne or heterodyne detection is used since their implementation depends on phase coherence of the optical carrier.

In coherent detection incoming signal is mixed with the locally generated continuous wave to provide gain to the incoming signal.

When two waves are mixed or combined, the resulting waves will be $2\omega_1$, $2\omega_2$, $\omega_1 + \omega_2$ and $\omega_1 - \omega_2$. The coherent light wave system filters all frequencies except $\omega_1 - \omega_2$ to detect information.

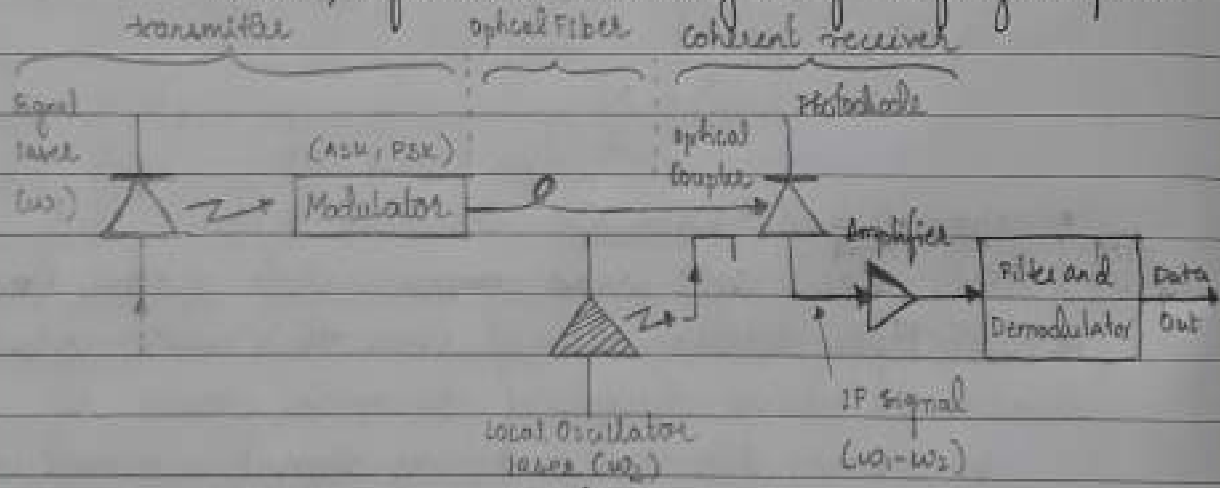
Let us consider the electric field of the transmitted optical field as:

$$E_s = A_s \cos(\omega_s t + \phi_s(t)) \quad \text{--- (1)}$$

where : A_s : amplitude
ω_s : carrier frequency
$\phi_s(t)$: phase

To send information we can modulate the amplitude, frequency or phase of the carrier. Thus one of the following modulation technique can be implemented.

1. Amplitude shift keying (ASK or OOK)
   In this case ϕ_s is constant and amplitude A_s takes one of the two values of 0 and 1.
2. Frequency shift keying (FSK)
   In FSK, A_s is constant and ω_s takes $\omega_1 t$ or $\omega_2 t$ for 0 and 1.
3. Phase shift keying (PSK)
   In PSK, information is conveyed by varying the phase



If the local oscillator field is in the form :

$$E_{LO} = A_{LO} \cos(\omega_{LO} t + \phi_{LO}(t)) \quad (2)$$

where : A_{LO} : Amplitude
ω_{LO} : frequency
ϕ_{LO} : phase

Then detected current is proportional to square of the total electric field falling on photo detector

$$I_{coh}(t) = (E_s + E_{LO})^2 = E_s^2 + E_{LO}^2 + 2E_sE_L$$

$$I_{coh}(t) = A_s^2 \cos^2(\omega_s t + \phi_s(t)) + A_{LO}^2 \cos^2(\omega_{LO} t + \phi_{LO}(t))$$
$$+ 2A_s \cos(\omega_s t + \phi_s(t)) A_{LO} \cos(\omega_{LO} t + \phi_{LO}(t))$$

$$I_{coh}(t) = \frac{1}{2} A_s^2 + \frac{1}{2} A_{LO}^2 + 2A_s A_{LO} \cos\left[(\omega_s - \omega_{LO})t + (\phi_s(t) - \phi_{LO}(t))\right] \cos\theta(t)$$

where $\phi(t) = \phi_s(t) - \phi_{LO}(t)$: Phase difference

$\cos\theta(t) = \frac{E_s E_{LO}}{|E_s||E_{LO}|}$: Polarization misalignment

$$I_{coh}(t) = \frac{A_s^2}{2} + \frac{A_{LO}^2}{2} + \cos\left[(\omega_s - \omega_{LO})t + \phi(t)\right] \cos\theta(t) \quad \text{--- (3)}$$

The optical power $P(t)$ proportional to the intensity, then we have:

$$P(t) = P_s + P_{LO} + 2\sqrt{P_s P_{LO}} \cos\left[(\omega_s - \omega_{LO})t + \phi(t)\right] \cos\theta(t) \quad \text{--- (4)}$$

There are four basic demodulation formats:
- depending on how the optical signal is mixed with the local signal: homodyne and heterodyne
- depending on how the electrical signal is detected: asynchronous and synchronous.

Homodyne Detection:

When the signal carrier frequency is equal to local carrier frequency, $\omega_{IF} = 0$ or $\omega_1 - \omega_2 = 0$. This is called homodyne detection.

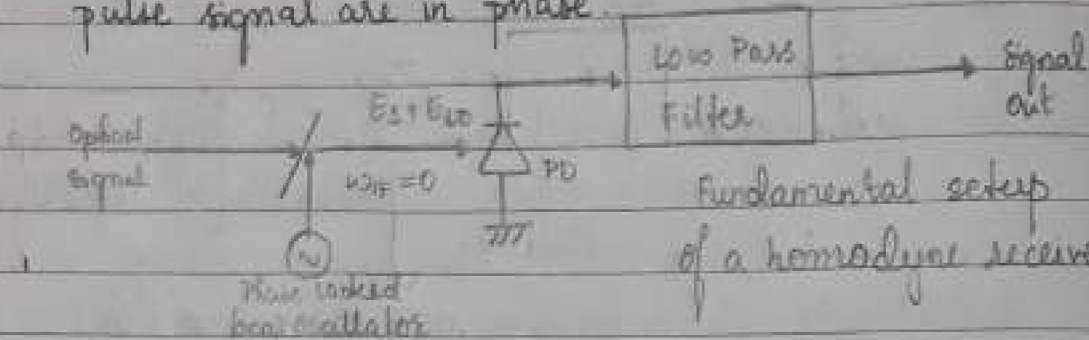
$$\therefore P(t) = P_s + P_{LO} + 2\sqrt{P_s P_{LO}} \cos\phi(t) \cdot \cos\theta(t) \quad \text{--- (5)}$$

Heterodyne Detection:

In heterodyne detection, the output is detected at intermediate frequency $\omega_{IF} \neq 0$. Thus from eq (4) one can employ OOK, FSK or PSK modulation techniques.

PSK Homodyne System:

The incoming optical signal is first combined with a strong optical wave from a local oscillator which is done by using either fiber directional coupler or partially reflecting plate called beam splitter. In PSK, the information is sent by changing the phase of the transmitted wave. For '0' pulse, the signal and local oscillator are out of phase. and for '1' pulse signal are in phase.



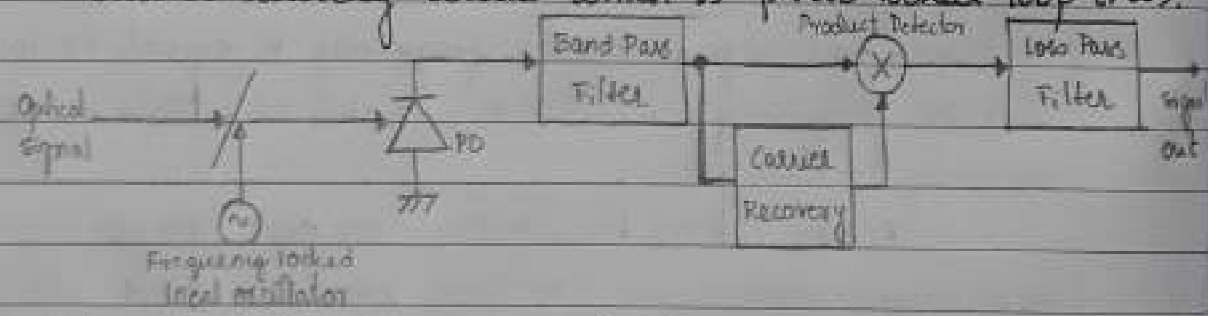
Fundamental setup of a homodyne receiver

Heterodyne Detection Schemes:

The analysis of heterodyne detection method is difficult because the output appears at an intermediate frequency ω_{IF}. Heterodyne receiver can employ either synchronous or asynchronous detection.

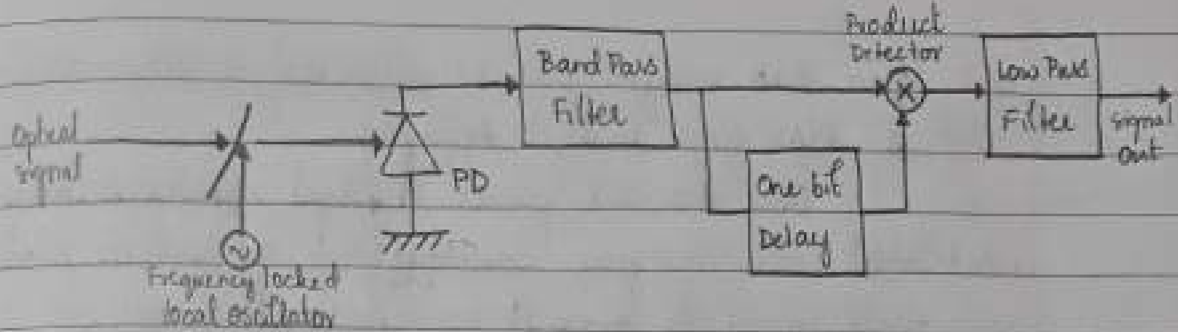
- Heterodyne Synchronous Detection

In synchronous PSK detection, the intermediate frequency signal is mixed with output of PLL to detect phase. To generate local phase reference one uses a carrier recovery circuit which is phase locked loop (PLL).



- Heterodyne Asynchronous Detection

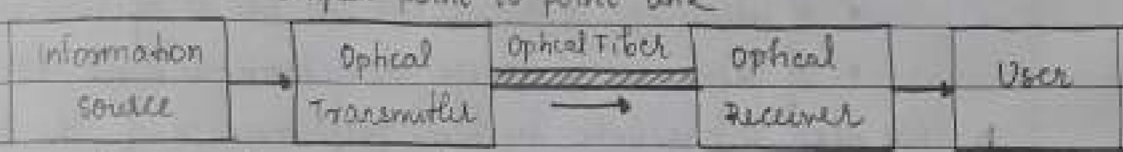
In asynchronous detection, carrier recovery is replaced by a simple one bit delay line. This technique is called differential PSK or DPSK. In this method, information is encoded by the means of phase of the received signal that has changed from the previous bit.



- **Point to Point Links:**

The simplest transmission link is a point to point link. It has a transmitter on one end and a receiver on the other.

Simplex point to point link



Optical link design involves interrelation of many variables of fiber, source and photodetector. The key system requirements are:

- The desired transmission distance
- The data rate or channel bandwidth
- The bit error rate (BER)

To fulfil these requirements the designer has a choice of following components and associated characteristics.

1. Multimode or Single Mode fiber	2. LED or LASER	3. PIN or APD
a. Core size	a. Emission wavelength	a. Responsivity
b. Core RI profile	b. Spectral Linewidth	b. Operating wavelength
c. Bandwidth	c. Output Power	c. Speed
d. Attenuation	d. Emission Pattern	d. Sensitivity
e. Numerical Aperture	e. Number of modes	

Two analysis are usually carried out. They are

1. Link Power Budget

In link power budget analysis, the power margin between the optical transmitter output and minimum receiver sensitivity is determined, which is needed to establish desired

BER. Then this margin can be allocated to other link components.

2. Rise time budget Analysis:

Once the link power budget analysis has been established, the designer can perform a system rise time analysis to meet the overall system performance.

- System Considerations:

a. In carrying out a link power budget; we first decide at which wavelength we need to transmit and then choose components operating in this region.
    - If distance is small we decide to operate in 770-910nm
    - If distance is large we choose O-band to U-band.

b. We next interrelate system performances of the three major optical link block: transmitter, receiver and optical fiber. The procedure we shall follow here is first we select photodetector and then we choose the optical source.

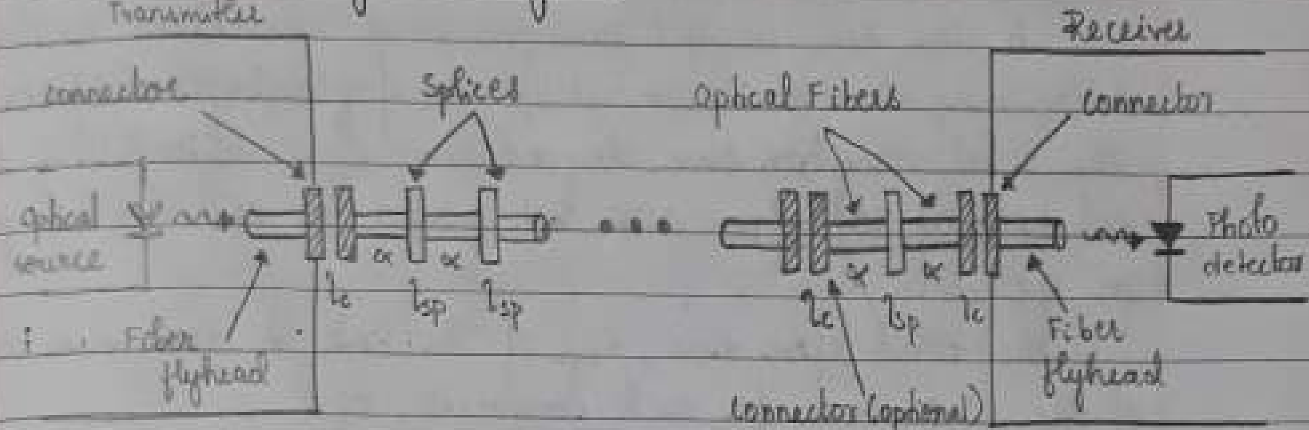
c. In choosing a particular photodetector, we mainly need to determine the minimum optical power that fall on the photodetector to satisfy the BER at the specified data rate.

d. In making the choice, the designer can choose PIN or APD. A pin photodiode is simpler, more stable and less expensive than Avalanche photodiode.

e. The system parameter involved in deciding between LED and LASER are dispersion, data rate, transmission distance and cost.

f. For optical fiber, we have a choice between single mode and multimode either of which could be step or graded index core. This choice depends on the type of light source used. LED can be used with multimode optical fiber and LASER is suitable for high data rate single mode optical fiber.

- Link Power Budget Analysis:



The optical power received at the photodetector depends on the amount of light coupled to fiber and losses occuring in fiber, connector and splices. Loss of each component is expressed in dB

$$\text{Loss} = 10 \log_{10} \frac{P_{out}}{P_{in}}$$

where P_{out}: Optical power leaving the element
P_{in}: Optical power entering the element.

In addition to link loss, a link power margin is normally provided to compensate for component aging, temperature fluctuations and losses arising in future. A link margin of 6-8 dB is generally used for the systems.

The total power loss P_T is loss between the source and photodiode occuring due to attenuation of cable, connector and splice.

$$\therefore \; P_T = P_S - P_R$$

$$P_T = 2l_c + \alpha L + \text{system margin}$$

where P_S: optical power emerging from the end of flyhead
P_R: Receiver sensitivity
l_c: connector loss
α: fiber attenuation (dB/km)
L: transmission distance.

Rise Time Budget Analysis:

A rise time budget analysis is a convenient method for determining the maximum dispersion of an optical fiber link. The total transition time degradation of a digital link should not exceed 70% of an NRZ bit period or 35% of a bit period for RZ data.

The total rise time, t_{sys} of the link is root sum square of the rise times for each component, t_i.

$$\therefore t_{sys} = \left(\sum_{i=1}^{N} t_i^2\right)^{1/2} \quad \text{--- (1)}$$

The four basic elements that may significantly limit system speed are:

- transmitter rise time : t_{tx}
- group velocity dispersion (GVD) rise time of the fiber : t_{GVD}
- modal dispersion rise time : t_{mod}
- receiver rise time : t_{rx}

Single mode fibers do not experience modal dispersion, hence the rise time in these fibers are only related to GVD.

The transmitter rise time is caused due to light source and drive circuitry.

The receiver rise time results from the photodetector response and 3 dB electrical bandwidth of the receiver.

$$\therefore \underset{(\text{in ns})}{t_{rx}} = \frac{350}{B_{rx}} \quad \text{--- (2)}$$

B_{rx} : 3 dB electrical BW of the receiver.

The fiber rise time t_{GVD} resulting from GVD over a length L is given as:

$$t_{GVD} = |D| L \sigma_\lambda \quad \text{--- (3)}$$

where σ_λ : half power spectral width of the source

D : dispersion.

The modal dispersion rise time is given as

$$t_{mod} = \frac{440}{B_m} = \frac{440L^q}{B_0} \quad \text{--- (4)}$$

where B_M : Bandwidth of link length L
B_0 : Bandwidth of 1 km

Substituting eq ②, eq ③ and eq ④ in eq ①, we get

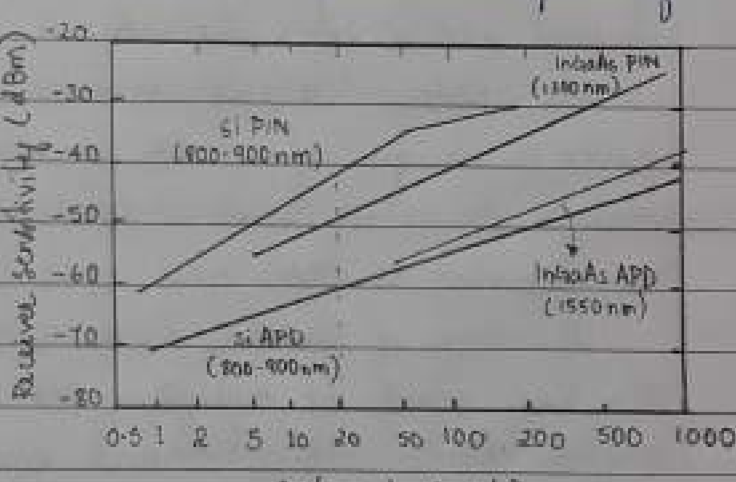
$$t_{sys} = \left[t_{tx}^2 + t_{mod}^2 + t_{GVD}^2 + t_{rx}^2 \right]^{1/2}$$

$$t_{sys} = \left[t_{tx}^2 + \left(\frac{440 L^q}{B_0} \right)^2 + D^2 L^2 \sigma_\lambda^2 + \left(\frac{350}{B_{rx}} \right)^2 \right]^{1/2}$$

- **Problems:**

Q1: To illustrate how a link loss budget is set up.

We begin by specifying a data rate of 20 Mb/s and a bit error rate of 10^{-9} (i.e., at most one error can occur for every 10^9 bits sent). For the receiver we choose a silicon PIN photodiode operating at 850 nm.

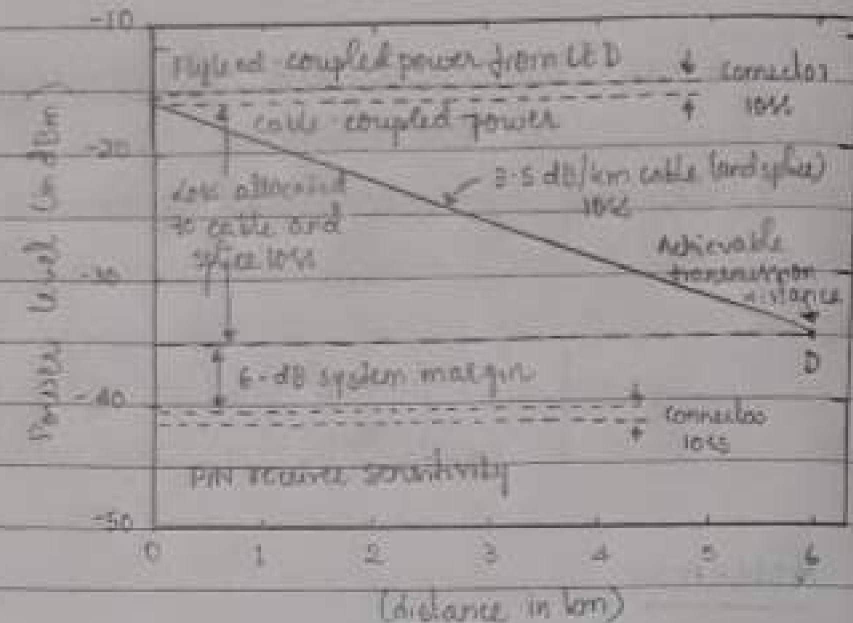


From graph, the required receiver input signal is -42 dBm. We next select a GaAlAs LED that can couple a 50 μW (-13 dBm) average optical power level into a fiber flylead with a 50 μm core diameter. Thus we have a 29 dB allowable power loss. Assume further that a 1 dB loss occurs when the fiber flyhead is connected to the cable and another 1 dB connector loss occurs at the cable-photodetector interface. Including a 6-dB system margin, the possible transmission distance for a cable with attenuation α can be found from:

$$P_T = P_S - P_R = 29\,dB = 2(1\,dB) + \alpha L + 6\,dB$$

If $\alpha = 3.5$ dB/km, then a 6.0 km transmission path is possible.

Graphical representation of a link loss budget for an 850 nm LED/PIN system operating at 20 Mb/s.



The vertical line represents the optical power loss allowed between the transmitter and the receiver. The horizontal axis gives the transmission distance.

Here, we show a silicon PIN receiver with a sensitivity of -42 dBm (at 20 Mb/s) and an LED with an output of -13 dBm coupled into a fiber flylead.

We subtract a 1 dB connector loss at each end, which leaves a margin of 27 dB. Subtracting a 6 dB system safety margin leaves us with a tolerable loss of 21 dB that can be allocated to cable and splice loss.

The slope of the line is the 3.5 dB/km cable and splice loss. This line starts at -14 dBm point (which is the optical power coupled into the cable fiber) and ends at the -35 dBm level (the receiver sensitivity minus a 1 dB connector loss and a 6-dB system margin). The intersection point D then defines the maximum possible transmission path length.

Q2: Make a graphical comparison and a spreadsheet calculation of the maximum attenuation - limited transmission distance of the following two systems operating at 100 Mb/s:

System one operating at 850 nm

a) GaAlAs laser diode: fiber coupled power 0 dBm

b) Silicon avalanche photodiode : −50 dBm sensitivity
c) Graded index fiber : 3.5 dB/km attenuation at 850 nm
d) 1 dB/connector loss

System two operating at 1300 nm :
a) InGaAsP LED : fiber coupled power : −13 dBm
b) InGaAs PIN photodiode : −38 dBm sensitivity
c) Graded index fiber : 1.5 dB/km attenuation at 1300 nm
d) 1 dB/connector loss

Allow 6 dB system margin in each case.

− System 1

The total optical power loss allowed between the light source and the photodetector is

$$P_T = P_S - P_R = 0\,dBm - (-50\,dBm) = 50\,dB$$
$$50\,dB = 2(l_c) + \alpha L + \text{system margin}$$
$$50\,dB = 2(1\,dB) + (3.5\,dB/km)L + 6\,dB$$
$\therefore$ $\underline{L = 12\,km}$ for maximum transmission distance

System 2

The total optical power loss allowed between the light source and the photodetector is

$$P_T = P_S - P_R = -13\,dBm - (-38\,dBm) = 25\,dB$$
$$25\,dB = 2l_c + \alpha L + \text{system margin}$$
$$25\,dB = 2(1\,dB) + (1.5\,dB/km)L + 6\,dB$$
$\therefore$ $\underline{L = 11.33\,km}$ for maximum transmission distance.

Q2 For a 20 Mb/s NRZ data stream multimode fiber link following parameters are used. LED together with its drive circuit has a rise time of 15 ns. Taking a typical LED spectral width of 40 nm, we have a material-dispersion-related rise-time degradation of 21 ns over the 6-km link. Assuming the receiver has a 25 MHz bandwidth. If the fiber we select has a 400 MHz km bandwidth-distance product and with q = 0.7, then calculate the system rise time.

- Given:

Rise time of LED and its drive circuit : $t_{tx} = 15ns$

link length : $L = 6km$

$B_0 = 400 \text{ MHz km}$ $\qquad B_{rx} = 25 \text{ MHz}$

$q = 0.7$ $\qquad t_{mat} = 21ns$

The system rise time is given by:

$$t_{sys} = \left[t_{tx}^2 + \left(\frac{440L^q}{B_0}\right)^2 + D^2L^2\sigma_\lambda^2 + \left(\frac{350}{B_{rx}}\right)^2 \right]^{1/2}$$

Here, $t_{mod} = \frac{440L^q}{B_0} = \frac{440(6)^{0.7}}{400 \times 10^6 \times 10^3} = \underline{3.8 nsec}$

$t_{rx} = \frac{350}{B_{rx}} = \frac{350}{25 \times 10^6 \times 10^3} = \underline{14ns}$

$\therefore t_{sys} = \sqrt{(15\times10^{-9})^2 + (3.8\times10^{-9})^2 + (21\times10^{-9})^2 + (14\times10^{-9})^2}$

$\underline{t_{sys} = 29.6 nsec}$ The value falls below the maximum allowable 35ns rise time degradation for 20Mb/s NRZ data stream.

Q4: For an optical link parameters are given as:

Optical power launched = 6 dBm

Receiver sensitivity = -25 dBm

Source to detector loss = 1dB

Fiber cable length = 100 km

Cable attenuation = 0.1dB/km

Jumper cable loss = 3 dB

Connector loss at each joint = 1dB

Assume two jumper cables and two cable points. Compute the link power margin.

- wkt : $P_T = P_S - P_R = 6 - (-25) = \underline{31dB}$

$P_T = 2l_c + \alpha L + \text{system margin} + 2l_j + 2l_{c_j}$

$31 = 2(1) + 0.1(100) + \text{system margin} + 2(3) + 2(1)$

system margin = 11 dB//

- **SLE: Burst Mode Receivers:**

The amplitude and phase of packets received in successive time slots from different user locations can vary widely from packet to packet.

Since a conventional optical receiver is not capable of instantaneously handling rapidly changing differences in signal amplitude and clock phase alignment, a specially designed burst-mode receiver is needed. These receivers can quickly extract the decision threshold and determine the signal phase from a set of overhead bits placed at the beginning of each packet burst.

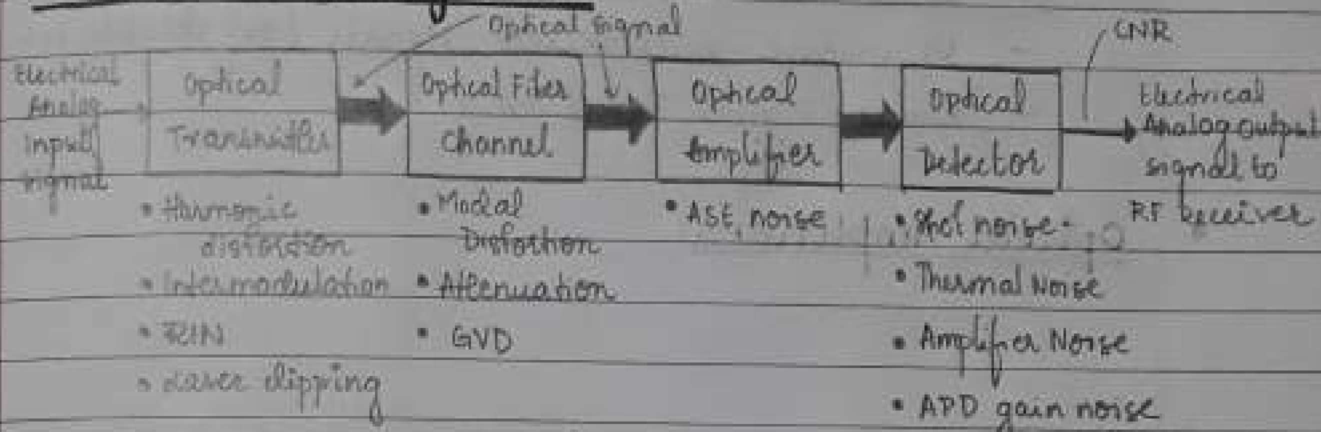
The key requirements of a burst-mode receiver are high sensitivity, wide dynamic range, and fast response time.

The use of a conventional ac coupling method is not possible in a burst-mode receiver, since the residual charge in a coupling capacitor following any particular burst cannot dissipate fast enough in order not to affect the initial conditions of the next burst. The burst-mode receiver therefore requires additional circuitry to accomodate dc-coupled operation. Such receivers now are incorporated into standard commercially available OLT equipment.

UNIT - 5

Analog Systems and Optical Amplifiers

- **Overview of Analog Links:**



The Basic Elements of an Analog Link

The transmitter consists either an LED or LASER diode as optical source.

In analog applications, one first sets a bias point on the source approximately at the midpoint of the linear output region.

The analog signal can then be sent using one of several modulation techniques. The simplest form for optical fiber links is direct intensity modulation, where the optical output from the source is modulated simply by varying the current around the bias point in proportion to the message signal level. Thus the information signal is transmitted directly in the baseband.

Some of the signal impairments in the optical source are harmonic distortions, intermodulation products, relative intensity noise (RIN) in laser and laser clipping.

Some of the signal impairments in the optical fiber are modal distortion, attenuation and GVD.

The use of amplifier leads to an additional noise known as amplified spontaneous emission (ASE). In the optical receiver, the principle impairments are quantum/shot noise, APD gain noise and thermal noise.

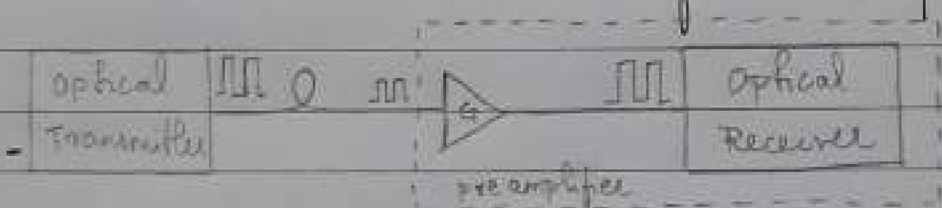
- **Basic Applications and Types of Optical Amplifiers:**

- General Applications:

a)

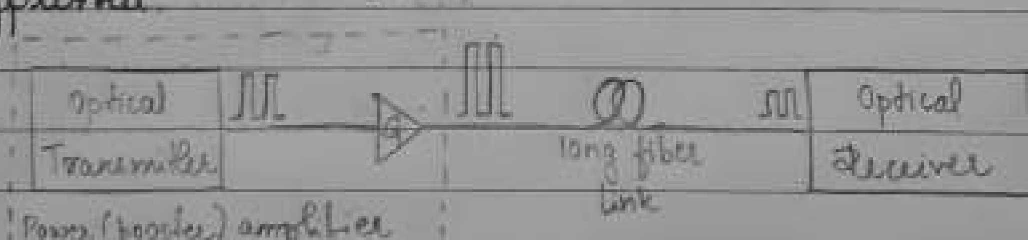
In-line Amplifier: In single mode link, the effects of fiber fiber dispersion may be small so the main limitation to repeater spacing is fiber attenuation. Since such a link does not necessarily require a complete regeneration of the signal, simple amplification of the optical signal is sufficient. Thus an in-line amplifier can be used to compensate for transmission loss and increase the distance between regenerative repeaters.

b)

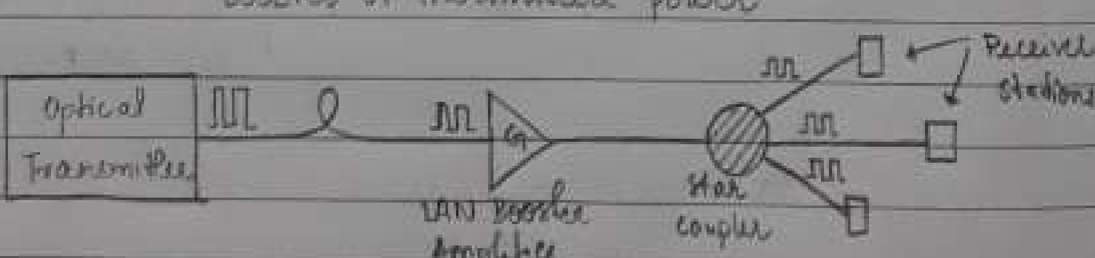


Preamplifiers: In the figure, an optical amplifier is being used as a front end preamplifier for an optical receiver. Thereby a weak signal is amplified before photodetection so that the SNR degradation caused by thermal noise in the receiver can be suppressed.

c)



Booster of transmitted power



Booster of signal level in a local area network

Power Amplifier: Power or booster amplifier is immediately placed after an optical transmitter to boost the transmitted power. This serves to increase the transmission distance by 10-100 km depending on the amplifier gain and fiber loss.

An optical amplifier can also be employed in a local area network to compensate for coupler-insertion loss and power splitting loss. Ex: Boosting the optical signal in front of a passive star coupler so that sufficient power arrives at each receiver.

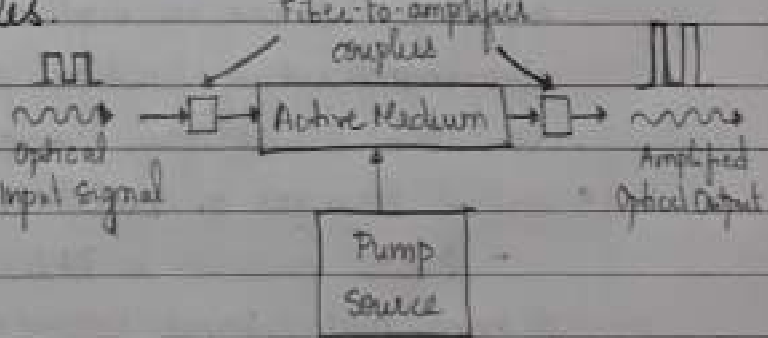
- Types of Optical Amplifiers:

Optical amplifiers operate in the optical domain to boost the power levels. Optical amplifiers can be classified as the following types:

1. Semiconductor Optical Amplifiers (SOA).
2. Doped-Fiber Amplifier (DFA)
3. Raman Amplifier

All optical amplifiers increase the power level of incident light through stimulated emission or power transfer process. In SOAs and DFAs the mechanism for creating the population inversion that is needed for stimulated emission to occur is the same as used in laser diodes.

Although the structure is similar to that of a laser, it does not have the optical feedback mechanism. Thus it can boost the incoming signal levels but it cannot generate a coherent optical output by itself.



Basic Operation of a generic optical amplifier (Amplification Mechanism)

The device absorbs energy supplied from an external source called pump. The pump supplies energy to electrons in active medium, which raises them to excited state to produce a population inversion. An incoming photon will trigger these excited electrons to drop to lower levels through a stimulated emission process. Since one incoming trigger photon stimulates a cascade effect in which many excited electrons emit photons of equal energy as they drop to the ground state. This results as an amplified optical signal.

In contrast to SOA and DFA, Raman amplification is a transfer of optical power from a high power pump wavelength to lightwave signals at longer wavelengths. Thus Raman amplification mechanism is done without the need for a population inversion process.

- Salient features of semiconductor optical amplifier
  - Active medium in SOAs are semiconductor materials from group III and V (Ex: phosphorous, gallium, indium and arsenic)
  - The devices can be made to work in the O-band (around 1310nm) as well as in the C-band.
  - When compared with DFA, SOAs consume less electrical power, have fewer components and are more compact.
  - SOA's have more rapid gain response (Advantage and disadvantage) advantage: It can be implemented when both switching and signal processing functions are called for in optical network. limitation: causes gain fluctuations at a particular wavelength.
- Salient features of Doped-Fiber Amplifier
  - Active medium in DFA's operate in the S band (around 1460), C band and L band (around 1565). The active medium is created by lightly doping silica or tellurite fiber core with rare earth elements such as thulium (Tm), erbium (Er) or ytterbium (Yb).
  - DFAs have the ability to pump at several different wavelengths.
  - DFAs have low coupling loss to the compatible-sized

fiber transmission medium and very low dependence of gain on light polarization.

- They are highly transparent to signal format and bit rate since they exhibit slow gain dynamics.

• Salient features of Raman Optical Amplifier:

- It is based on a nonlinear effect called stimulated Raman scattering (SRS), which occurs in fibers at high optical powers.

- Raman amplification takes place within a standard transmission fiber.

- Raman gain mechanism can be achieved through either a lumped amplifier or distributed amplifier type.

• **Semiconductor Optical Amplifiers:**

A semiconductor optical amplifier is essentially an InGaAsP laser that is operating below its threshold point.

The peak of gain of an SOA can be selected in any narrow wavelength band extending from 1280 nm in the O-band to 1650 nm in the U-band by varying the composition of the active InGaAsP material.

Most SOAs belong to the traveling wave (TW) amplifier category where the optical signal travels through the device only once. During this single passage the signal gains energy and emerges intensified at the other end of the amplifier.

- External Pumping:

External current injection is the pumping method used to create the population inversion needed for having a gain mechanism in SOAs. It is similar to the operation of laser diodes, thus the sum of injection, stimulated emission and spontaneous recombination rates gives the rate equation that governs the carrier density $n(t)$ in the excited state.

$$\frac{\partial n}{\partial t} = R_p(t) - R_{st}(t) - \frac{n(t)}{\tau_r} \quad \text{--- } ①$$

where • $R_p(t) = \frac{J(t)}{qd}$ $\boxed{A}$: external pumping rate from the injection current density $J(t)$ into an active layer of thickness d.

• τ_r : combined time constant coming from spontaneous emission and carrier recombination

• $R_{st}(t) = \Gamma a V_g (n - n_{th}) N_{ph} = g V_g N_{ph}$ $\boxed{B}$
stimulated emission rate

• V_g : group velocity of the incident light
• Γ : optical confinement factor.
• a : gain constant
• n_{th} : threshold carrier density
• N_{ph} : photon density
• g : overall gain per unit length.
• w and d : width and thickness of optical amplifier

The photon density is given by:

$$N_{ph} = \frac{P_s}{V_g (h\nu)(wd)} \quad \text{--- } \boxed{C}$$

where P_s : optical signal power
$h\nu$: photon energy
wd : area of the optical amplifier

In the steady state,

$\frac{\partial n(t)}{\partial t} = 0$, therefore from eq ①, we get:

$$R_p(t) = R_{st}(t) + \frac{n(t)}{\tau_r} \quad \text{--- } ②$$

substituting eq $\boxed{A}$ and $\boxed{B}$ into eq ②, we get:

$$\frac{J(t)}{qd} = \Gamma a V_g (n - n_{th}) N_{ph} + \frac{n}{\tau_r}$$

$$\frac{J(t)}{qd} = g V_g N_{ph} + \frac{n}{\tau_r} \quad \text{--- } ③$$

From eq $\boxed{B}$,

$$\Gamma a \cancel{V_g} (n - n_{th}) \cancel{N_{ph}} = g \cancel{V_g} \cancel{N_{ph}}$$

$$\Gamma a (n - n_{th}) = g$$

$$n = \frac{g}{\Gamma a} + n_{th} \quad \text{----} \quad \boxed{D}$$

substituting eq $\boxed{D}$ in eq ③, we get

$$\frac{J}{qd} = g V_g N_{ph} + \frac{1}{\tau_r}\left(\frac{g}{\Gamma a} + n_{th}\right)$$

$$\frac{J}{qd} = g V_g N_{ph} + \frac{g}{\tau_r \Gamma a} + \frac{n_{th}}{\tau_r}$$

$$\frac{J}{qd} - \frac{n_{th}}{\tau_r} = g\left[V_g N_{ph} + \frac{1}{\tau_r \Gamma a}\right]$$

Therefore,

$$g = \frac{\frac{J}{qd} - \frac{n_{th}}{\tau_r}}{V_g N_{ph} + \frac{1}{\tau_r \Gamma a}} = \frac{g_0}{1 + \frac{N_{ph}}{N_{ph,sat}}} \quad \text{———} \quad ④$$

where, $N_{ph,sat} = \frac{1}{\Gamma a V_g \tau_r}$: saturation photon density

$g_0 = \Gamma a \tau_r \left[\frac{J}{qd} - \frac{n_{th}}{\tau_r}\right]$: medium gain per unit length in the absence of signal input.

zero signal or small-signal gain per unit length

g : internal gain per unit length

- Amplifier Gain

Signal gain or amplifier gain G is given by

$$G = \frac{P_{s,out}}{P_{s,in}} = \frac{\text{output power}}{\text{input power}}$$

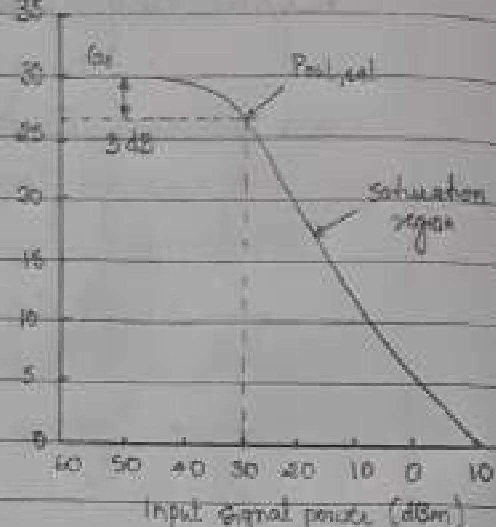
The single pass gain in active medium of the SOA is:

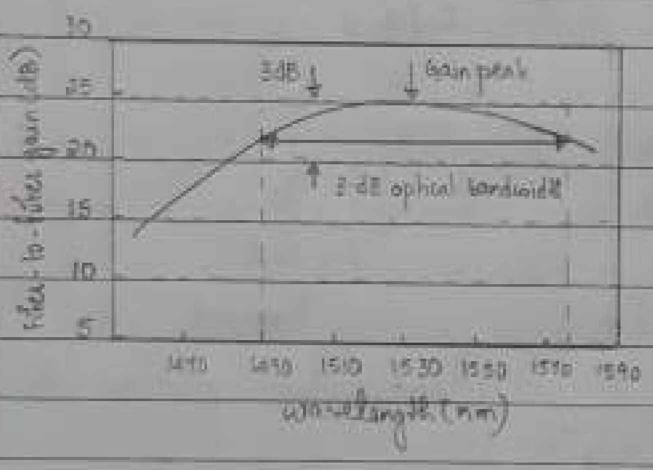
$$G = e^{(\Gamma g_m - \bar{\alpha})L} = e^{g(z)L}$$

where $g(z) = \frac{g_0}{1 + \frac{P_s(z)}{P_{amp,sat}}}$: overall gain per unit length

g_m: material gain coefficient
α: effective absorption coefficient of the material in the optical path
L: amplifier length

Amplifier gain is limited by internal gain because the carrier density decreases with increase in input signal level. At saturation there are no enough excited carriers to provide stimulated emission.





Ex: A typical gain versus wavelength characteristic for a device with a peak gain of 25 dB at 1530 nm. The wavelength span over which the gain decreases by less than 3 dB with respect to the maximum gain is known as the gain bandwidth or the 3-dB optical bandwidth.

Q1: Consider an InGaAsP SOA with $w = 5\mu m$ and $d = 0.5\mu m$. Given that $V_g = 2\times10^8$ m/s, if a $1.0\mu W$ optical signal at 1550 nm enters the device, what is the photon density?

— Given:

$w = 5\mu m$; $d = 0.5\mu m$; $V_g = 2\times10^8$ m/s

$P_s = 1\mu W$; $\lambda = 1550$ nm

The photon density is given by

$$N_{ph} = \frac{P_s}{V_g(h\gamma)(wd)} = \frac{1\times10^{-6}}{2\times10^8 \frac{(6.625\times10^{-34})(3\times10^8)}{1550\times10^{-9}} (5\times10^{-6})(0.5\times10^{-6})}$$

$$\underline{N_{ph} = 1.56\times10^{16} \text{ photons/m}^3}$$

Q: consider the following parameters for a 1300nm InGaAsP SOA:

symbol	Parameter	Value
w	Active area width	$3\mu m$
d	Active area thickness	$0.3\mu m$
L	Amplifier length	$500\mu m$
Γ	confinement factor	0.3
τ_r	time constant	1 nsec
a	Gain coefficient	$2\times10^{-20} m^2$
n_{th}	Threshold density	$1\times10^{24} m^{-3}$

a) What is the pumping rate for the SOA?
b) What is the zero signal gain?

- If a 100mA bias current is applied to the device,

a) the pumping rate is given by:

$$R_p = \frac{J}{qd} = \frac{I}{qdwL}$$

$$R_p = \frac{100\times10^{-3}}{1.6\times10^{-19}\times0.3\times10^{-6}\times3\times10^{-6}\times500\times10^{-6}} = 1.39\times10^{33} (\text{electrons}/m^3)/s$$

b) The zero signal gain is given by:

$$g_0 = \Gamma a \tau_r \left[\frac{J}{qd} - \frac{n_{th}}{\tau_r}\right]$$

$$g_0 = 0.3(2\times10^{-20})(1\times10^{-9})\left[1.39\times10^{33} - \frac{1\times10^{24}}{1\times10^{-9}}\right]$$

$$g_0 = 2340\ m^{-1} = 23.4\ cm^{-1}$$

- **Erbium - Doped Fiber Amplifiers:**

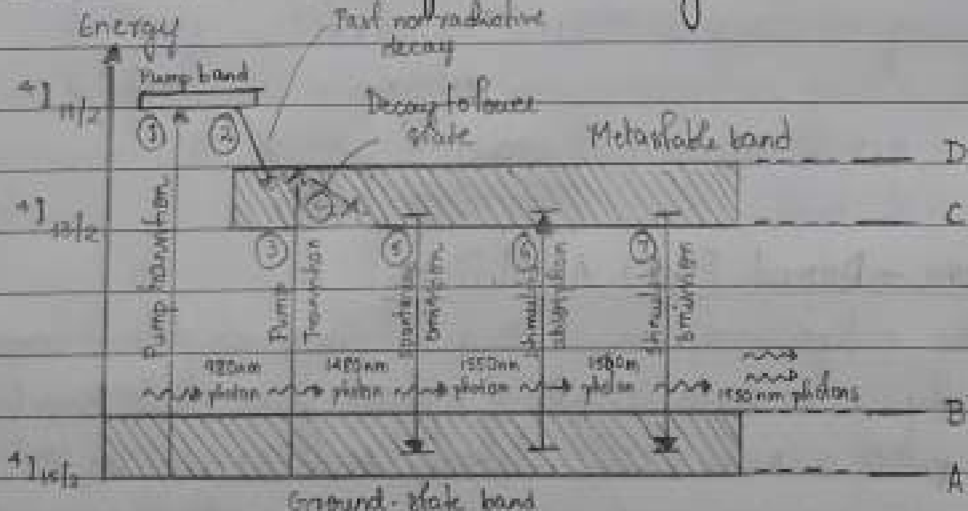
The active medium of optical fiber amplifier consists of a nominally 10 to 30 m length of optical fiber that has been lightly doped with a rare earth element such as erbium (Er), ytterbium (Yb), thulium (Tm) or praseodymium (Pr). The host fiber material can be standard silica, a fluoride-based glass or a tellurite glass.

A popular material for long-haul telecommunication applications is a silica fiber doped with erbium, which is known as an erbium-doped fiber amplifier (EDFA). The operation of a standard EDFA normally is limited to the 1530 to 1565 nm region.

- Amplification Mechanism:

EDFA uses optical pumping to excite electrons to higher energy levels. In this process photons are directly used to raise electrons into excited states.

The optical pumping process requires three or more energy levels. The top energy level to which the electron is elevated initially must lie energetically above the desired final emission level. After reaching its initial state, the electron must quickly release some of its energy and drop to a slightly lower energy level. A signal photon can then trigger the excited electron sitting in this lower level into stimulated emission, whereby the electron releases its remaining energy in the form of a new photon with a wavelength identical to that of signal photon. Since the pump photon must have a higher energy than the signal photon, the pump wavelength is shorter than the signal wavelength.



EDFA working: The erbium atoms in silica are Er^{3+} ions which are the erbium atoms that have lost three of their outer electrons. The above figure shows a simplified energy level diagram and various energy level processes of these Er^{3+} ions in silica glass.

The two principal levels for telecommunication applications are a metastable level ($^4I_{13/2}$ level) and the pump level ($^4I_{11/2}$ level)

The term 'metastable' means that the lifetimes for transitions from this state to the ground state are very long compared with the lifetimes of the states that led to this level.

The metastable, the pump and the ground state levels are actually bands of closely spaced energy levels.

To understand the various energy transitions and photon emission ranges, consider the following conditions:

- The pump band exists at a 1.27eV separation from the bottom of the $^4I_{15/2}$ ground state. This energy corresponds to a 980 nm wavelength.
- The top of the $^4I_{13/2}$ metastable band (level D) is separated from the bottom of the $^4I_{15/2}$ groundstate (level A) by 0.841eV. This energy corresponds to a 1480 nm wavelength
- The bottom of the $^4I_{13/2}$ metastable band (level C) is separated from the bottom of the $^4I_{15/2}$ groundstate (level A) by 0.814eV. This energy corresponds to a 1530 nm wavelength
- The bottom of the $^4I_{13/2}$ metastable band (level C) is separated from the top of $^4I_{15/2}$ ground state band (level B) by about 0.775eV. This energy corresponds to a 1600 nm wavelength.

This means that the possible pump wavelengths are 980 and 1480 nm. The photons emitted during transitions of electrons between possible energy levels in the metastable and ground state bands can range from 1530 to 1600 nm.

→ Transition process 1: In normal operation, a pump laser emitting 980 nm photons is used to excite ions from the ground state to the pump level.

→ Transition process 2: These excited ions decay very quickly from the pump band to the metastable band during which the excess energy is released as photons or equivalent mechanical vibrations in the fiber

→ Transition Process 3: Another possible pump wavelength is 1480 nm. The energy of these pump photons is very similar to the signal-photon energy but slightly higher. The absorption of a 1480 nm pump election from the ground state directly to the lightly populated top of the metastable state

→ Transition process 4: These electrons then tend to move down to the more populated lower end of the metastable level.

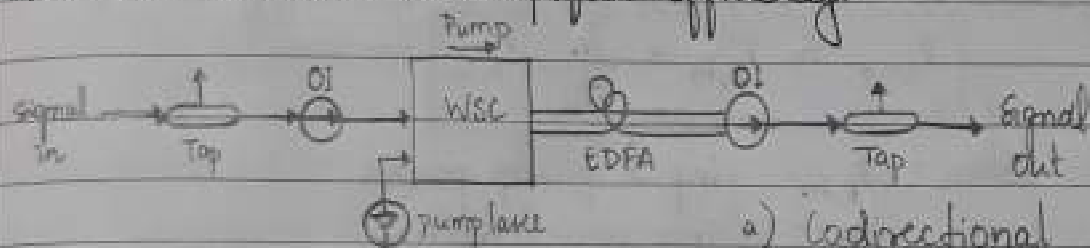
→ Transition process 5: Some of the ions sitting at the metastable level can decay back to the ground state in the absence of an externally simulating photon flux. This decay phenomenon is known as spontaneous emission and adds to the amplifier noise. Two more transitions take place when signal photons pass through the device.

→ Transition process 6: A small portion of the external photons will be absorbed by ions in the ground state, which raises these ions to the metastable level

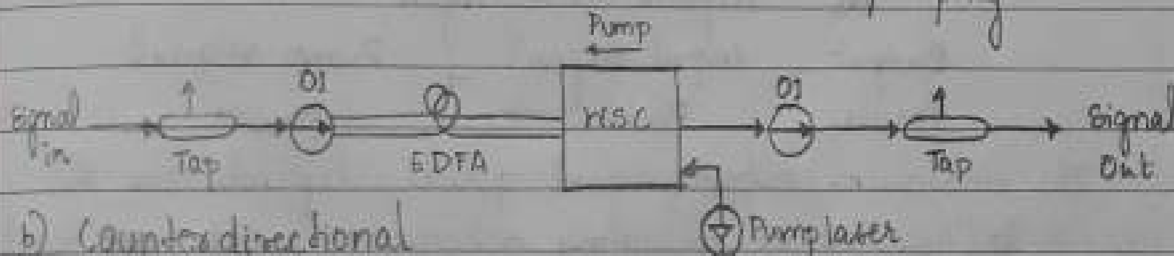
→ Transition process 7: In the stimulated emission process, a signal photon triggers an excited ion to drop to the ground state, thereby emitting a new photon of the same energy, wavevector and polarization as the incoming photon. The widths of the metastable and ground-state levels allow high levels of stimulated emissions to occur in the 1530 nm to 1560 nm range

- EDFA Architecture:

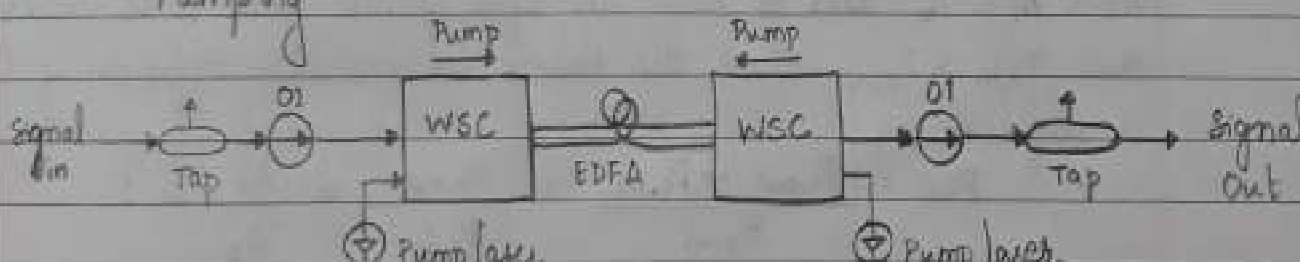
An optical fiber amplifier consists of a doped fiber, one or more pump lasers, a passive wavelength couplers, optical isolators and tap couplers. The dichroic (two wavelength) coupler handles either 980/1550 nm or 1480/1550 nm wavelength combinations to couple both the pump and signal optical powers efficiently into the fiber amplifier. The tap couplers are used on both sides of the amplifier to compare the incoming signal with the amplified output. The optical isolators prevent the amplified signal back into the device, where it could increase the amplifier noise and decrease the amplifier efficiency.



a) Codirectional Pumping



b) Counterdirectional Pumping



c) Dual Pumping

OI : Optical isolator and WSC : wavelength-selective coupler

The pump light is usually injected from the same direction as the signal flow. This is known as codirectional pumping.

It is also possible to inject the pump power in the opposite direction to the signal flow, which is known as counterdirectional pumping.

One can either employ a single pump source or use dual pump schemes, with the resultant gains typically being +17dB and +35 dB respectively.

Counterdirectional pumping allows higher gains but codirectional pumping gives better noise performance. In addition pumping at 980nm is preferred since it produces less noise and achieves larger population inversions than pumping at 1480nm.

- EDFA Power-Conversion Efficiency and Gain:

The input and output signal powers of a EDFA can be expressed in terms of the principle of energy conservation:

$$\boxed{P_{s,out} \leq P_{s,in} + \frac{\lambda_P}{\lambda_s} P_{P,in}} \quad \text{--- } (1)$$

where: $P_{P,in}$: input pump power
λ_P : pump wavelength
λ_s : signal wavelength

Output Power = Input signal Power + Pump signal Power

The maximum output signal power depends on the ratio λ_P/λ_s. For the pumping scheme to work, we need to have $\lambda_P < \lambda_s$ and to have an appropriate gain it is necessary that $P_{s,in} \leq P_{P,in}$. Thus the Power Conservation Efficiency (PCE) is defined as:

$$PCE = \frac{P_{s,out} - P_{s,in}}{P_{P,in}} \approx \frac{P_{s,out}}{P_{P,in}} \leq \frac{\lambda_P}{\lambda_s} \leq 1$$

For absolute reference purposes, it is helpful to use the Quantum Conversion Efficiency (QCE), which is wavelength independent and is defined by:

$$QCE = \frac{\lambda_s}{\lambda_P} PCE$$

The maximum value of QCE is unity, in which case all the pump photons are converted to signal photons.

Dividing eq (1) by $P_{s,in}$ gives amplifier gain G

$$\boxed{G = \frac{P_{s,out}}{P_{s,in}} \leq 1 + \frac{\lambda_P}{\lambda_s} \frac{P_{P,in}}{P_{s,in}}} \quad \text{--- } (2)$$

When the input signal power is very large so that $P_{s,in} \gg \frac{\lambda_p}{\lambda_s} P_{p,in}$, then the maximum amplifier gain is unity. This means that the device is transparent to the signal.

In order to achieve a specific maximum gain G, the input signal power cannot exceed a value given by:

$$\boxed{P_{s,in} \le \frac{(\lambda_P/\lambda_S)\, P_{p,in}}{G-1}} \quad (3)$$

Q3. Consider an EDFA being pumped at 980 nm with a 30 mW pump power. If the gain at 1550 nm is 20 dB, what are the maximum input and output powers?

- Given: EDFA

$\lambda_P = 980\ nm$ $\lambda_s = 1550\ nm$

$P_{p,in} = 30\ mW$ $G = 20\ dB$

The maximum input power is given by:

$$P_{s,in} \le \frac{(\lambda_P/\lambda_S)\, P_{p,in}}{G-1}$$

$$P_{s,in} \le \frac{(980n/1550n) \times 30 \times 10^{-3}}{100-1}$$

$$\therefore P_{s,in} \le 191.59\ \mu W$$

$G = 10 \log P$

$20 = 10 \log P$

$\log P = 2$

$P = 10^2 = 100$

The maximum output power is given by:

$$P_{s,out}(max) = P_{s,in}(max) + \frac{\lambda_P}{\lambda_s} P_{p,in}$$

$$P_{s,out}(max) = 191.59 \times 10^{-6} + \frac{980n}{1550n} \times 30 \times 10^{-3}$$

$$P_{s,out}(max) = 191.59 \times 10^{-6} + 18967.74 \times 10^{-6}$$

$$\therefore P_{s,out}(max) = 19.16\ mW = 12.8\ dBm$$

- **SLE: Wideband Optical Amplifiers:**

Wideband Optical Amplifiers operate over several wavelength bands to handle a large number of wavelength division multiplexing (WDM) channels simultaneously.

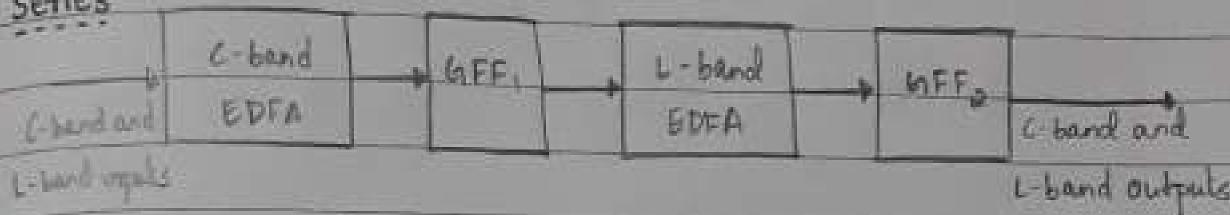
Ex: A combination of two amplifier types can provide effective amplification in both the C and L-bands or in the S and C-bands. This can be extended to use of three amplifier types as well. The individual amplifiers could be based on thulium-doped silica fibers for the S-band, standard EDFAs for the C-band, gain shifted EDFAs for the L-band and different versions of Raman amplifiers.

The amplifier combinations can be in parallel or in series.

- Parallel:

- Wideband demultiplexer splits the incoming signal spectrum into two wavelength bands.
- The two bands then pass through corresponding optical amplifiers after which a wideband multiplexer recombines the two spectral bands.
- It requires use of a guard band (several nanometers) between the two spectral regions to prevent amplification overlap between the different paths and also to prevent noise power originating in one amplifier from interfacing with signal amplification in an adjacent amplifier. (disadvantage: unusable wavelength band)
- Another disadvantage is that two WDM devices is needed before and after each amplifier which adds to the system insertion loss.

- Series:



- Series configuration - also known as a seamless wideband optical amplifier. This is because it does not require splitting the signals into separate paths.
- It avoids noise figure degradations of wavelength couplers and the additional costs of the couplers
- It can be constructed either from a concatenation of two or more doped-fiber amplifiers or from a combination of a fiber amplifier or a Raman amplifier
- The gain characteristics of the different amplifier segments must be matched carefully.

UNIT-6

Optical Networks

- **SONET / SDH :**

SONET – Synchronous Optical Network – is widely used in telephone network and is one of the first large scale optical transmission systems. Digital information is sent through optical fibers using a LED or a laser source.

SONET/SDH are standard signal format used in digital TDM technique. SONET is primarily used in the North America while Europe and Japan use modified version called the SDH - Synchronous Digital Hierarchy.

These techniques make it possible to transfer multiple bit stream synchronously over optical fiber.

- **Transmission Formats and Speeds:**

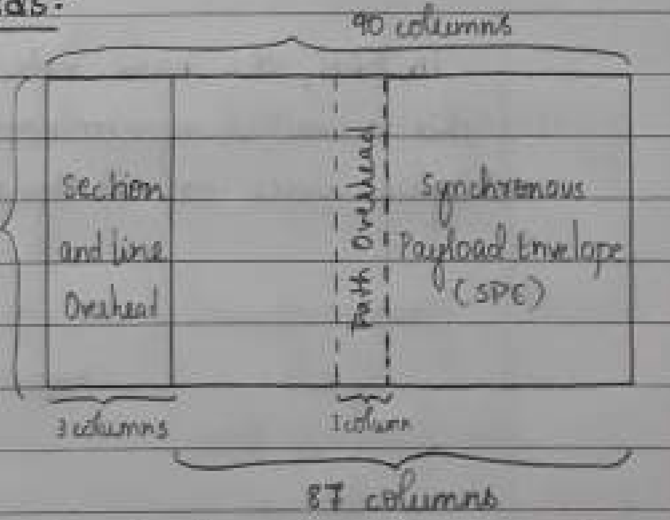
The basic structure of a SONET frame is a two dimensional structure consisting of 90 columns by 9 rows of bytes.

i.e., 90 x 9 = 810 bytes

where 9x3 = 27 bytes are transport overhead

9x1 = 9 bytes are path overhead

and remaining 774 bytes are data.



Basic Structure of an STS-1 SONET frame

Section: connects adjacent pieces of equipment (portion from Mux to repeater)

Line: longer link that connects two SONET devices (T. MUX to R. DEMUX)

Path: complete end-to-end connection (source user to destination user)

The fundamental SONET frame has a 125 μs duration.

Thus the transmission bit rate of the basic SONET signal is

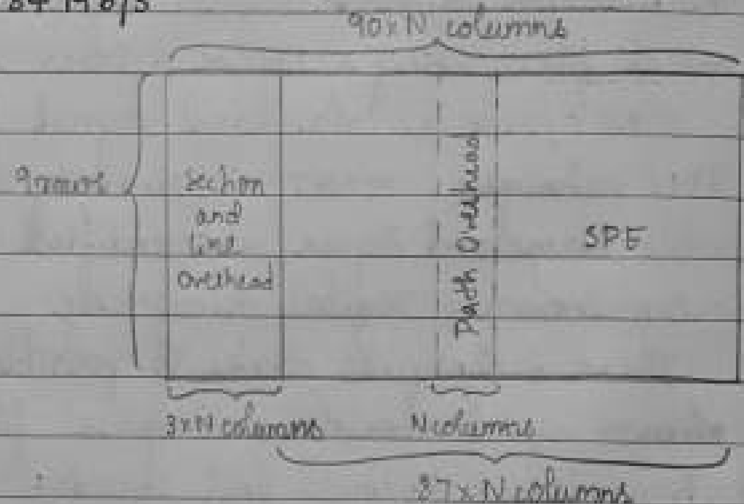
$$STS\text{-}1 = \frac{\frac{90 \text{ bytes}}{\text{row}} \times \frac{9 \text{ rows}}{\text{frame}} \times \frac{8 \text{ bits}}{\text{byte}}}{\frac{125\,\mu\text{sec}}{\text{frame}}} = 51.84 \text{ Mb/s}$$

STS: Synchronous Transport Signal.

All other SONET signals are integral multiples of 51.84 Mb/s

$STS\text{-}N = N \times 51.84$ Mb/s

Basic format of an STS-N SONET frame



In SDH, the basic rate is equivalent to STS-3 or 155.52 Mb/s. This is called synchronous transport module-level 1 (STM-1). Higher rates are designed as STM-N.

Basic format of an STM-N SDH frame

When an STS-N or STM-N signal is used to modulate an optical source, it produces a physical layer optical signal which is called OC-N signals, where OC stands for optical carrier.

Commonly used SONET and SDH Transmission Rates

SONET level	Electrical level	SDH Level	Line rate (Mb/s)	Common rate name
OC-N	STS-N	—	N × 51.84	—
OC-1	STS-1	—	51.84	—
OC-3	STS-3	STM-1	155.52	155 Mb/s
OC-12	STS-12	STM-4	622.08	622 Mb/s
OC-48	STS-48	STM-16	2488.32	2.5 Gb/s
OC-192	STS-192	STM-64	9953.28	10 Gb/s
OC-768	STS-768	STM-256	39813.12	40 Gb/s

- SONET / SDH Rings:

A key characteristic of SONET and SDH is that they are configured as either a ring or mesh architecture. This is done to create loop diversity for uninterrupted service protection purposes in case of link or equipment failures. These rings are also called self-healing rings because the traffic flowing along a certain path can automatically be switched to an alternate or standby path following failure or degradation of the link segment.

Three main features, each with two alternatives, classify all the SONET/SDH rings, thus yielding eight possible combinations of ring types.

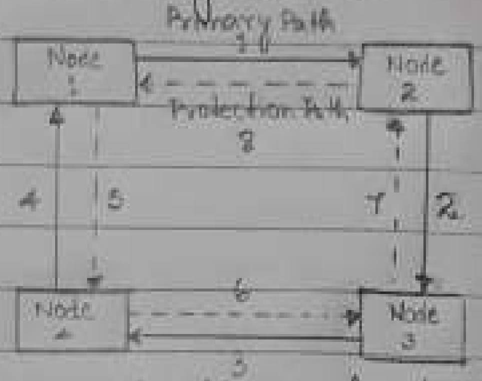
1. There can be either two or four fibers running between the nodes of a ring.
2. The operating signals can travel either clockwise (unidirectional ring) or in both directions around the ring (bidirectional ring).
3. Protection switching can be done either via a line-switching or a path-switching scheme.

Out of the eight possible combinations of ring types, the following two architectures have become popular for SONET/SDH network

- two fiber, unidirectional, path switching ring (two-fiber UPSR)
- two fiber or four fiber, bidirectional, line switching ring (two fiber or four fiber BLSR)

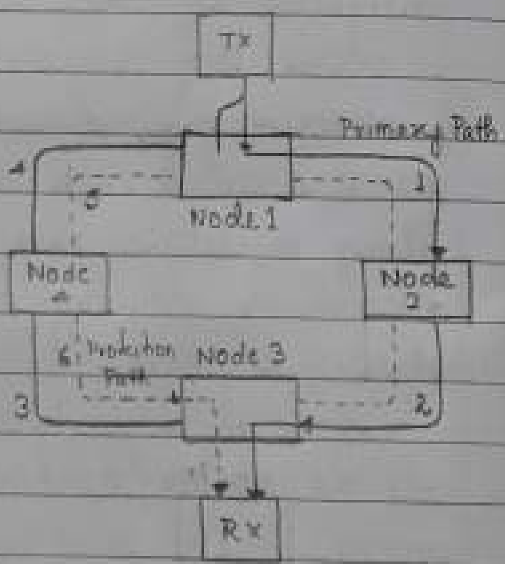
Two-Fiber unidirectional path switched ring network:

By convention, in a unidirectional ring the normal working traffic travels clockwise around the ring, on the primary path. (Ex: connection from node 1 to 3 uses links 1 and 2 whereas traffic from 3 to 1 uses links 3 and 4). Thus two communicating nodes use a specific bandwidth capacity around the entire perimeter of the ring.



Generic two-fiber unidirectional path switched ring (UPSR) with a counter rotation protection path

In case of link failure or node failure, the traffic flows in counterclockwise direction i.e., protection path (from node 1 to node 3 via links 5 and 6). To achieve protection, the signal from a transmitting node is dual fed into both the primary and protection fibers.



Flows of primary and protection traffic from node 1 to node 3

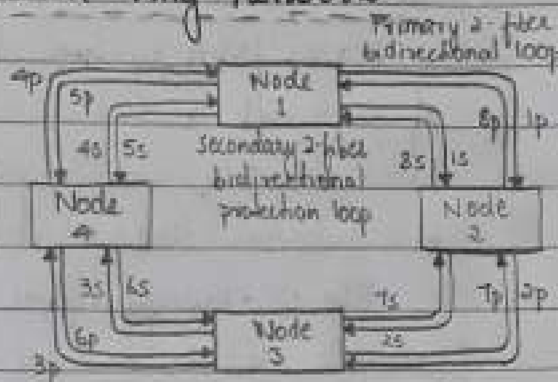
Two identical signals from a particular node arrive at their destination from opposite direction, usually with different delays. The receiver normally selects the signal from the primary path but it continuously compares the fidelity of each signal and chooses the alternate signal in case of severe degradation or loss of the primary signal i.e., called path switching.

Thus each path is individually switched based on the quality of the received signal. Ex: If path 2 breaks or equipment in node 2 fails, then node 3 will switch to the protection channel to receive signals from node 1.

Four-fiber bidirectional line switched ring network:

Two primary fiber loops: 1p to 8p are used for normal bidirectional communication.

Two secondary fiber loops: 1s to 8s are standby links for protection purposes.

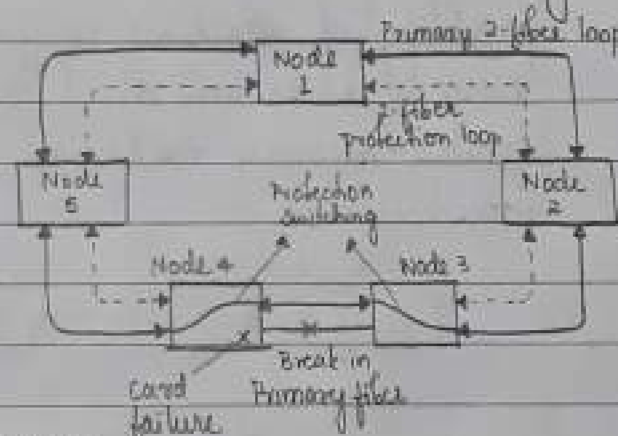


Architecture of a four-fiber bidirectional line-switched ring (BLSR)

Ex: connection between node 1 to node 3 uses 1p and 2p links. Traffic from node 3 to node 1 uses 7p and 8p links for bidirectional traffic flow.

CASE 1: Transmitter or receiver circuit card on the primary ring fails in either node 3 or node 4.

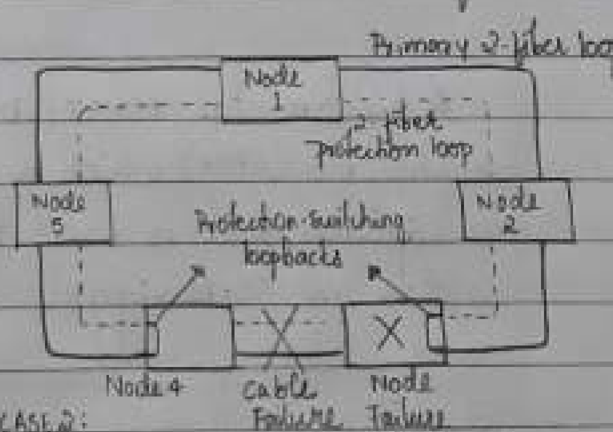
The affected nodes detect a loss of signal condition and switch both primary fibers connecting these nodes to the secondary pair. The protection segment between node 3 and node 4 becomes part of the primary bidirectional loop. Exactly same reconfiguration will occur when the primary fiber connecting node 3 and node 4 breaks.



CASE 1:

Reconfiguration of a four fiber BLSR under transceiver or line failure

CASE 2: Either node fails or both primary or secondary fibers fail.



CASE 2:

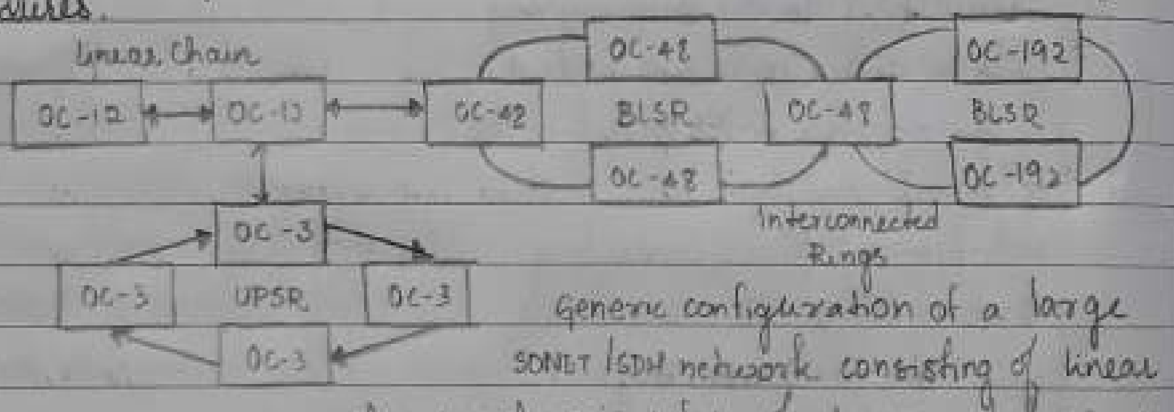
Reconfiguration of a four fiber BLSR under node or fiber cable failure

The nodes on either side of the failed internodal span internally switch the primary-path connections from their receivers and transmitters to protection fibers, in order to loop traffic back to the previous node.

- SONET / SDH Networks

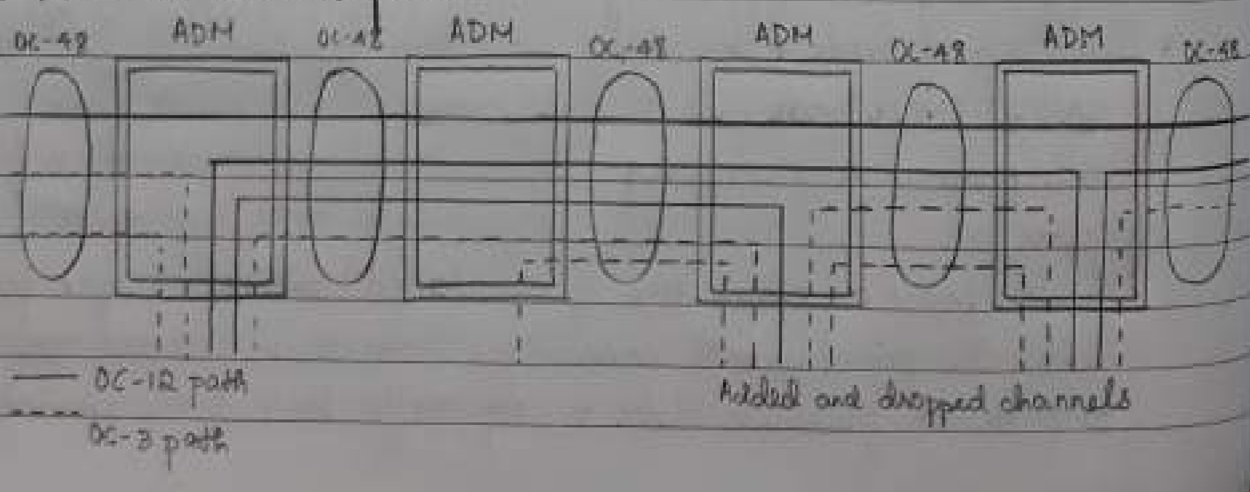
SONET / SDH equipment allows the configuration of a variety of network architectures. Ex: One can build point-to-point links, linear chains, unidirectional path-switched rings (UPSR), bidirectional line-switched rings (BLSR) and interconnected rings.

The OC-192 four fiber BSLR could be a large national backbone network with a number of OC-48 rings attached in different cities. The OC-48 rings can have low capacity localized OC-12 or OC-3 rings or chains attached to them, thereby providing the possibility of attaching equipment that has an extremely wide range of rates and sizes. Each of the individual rings has its own failure-recovery mechanism and SONET / SDH network management procedures.



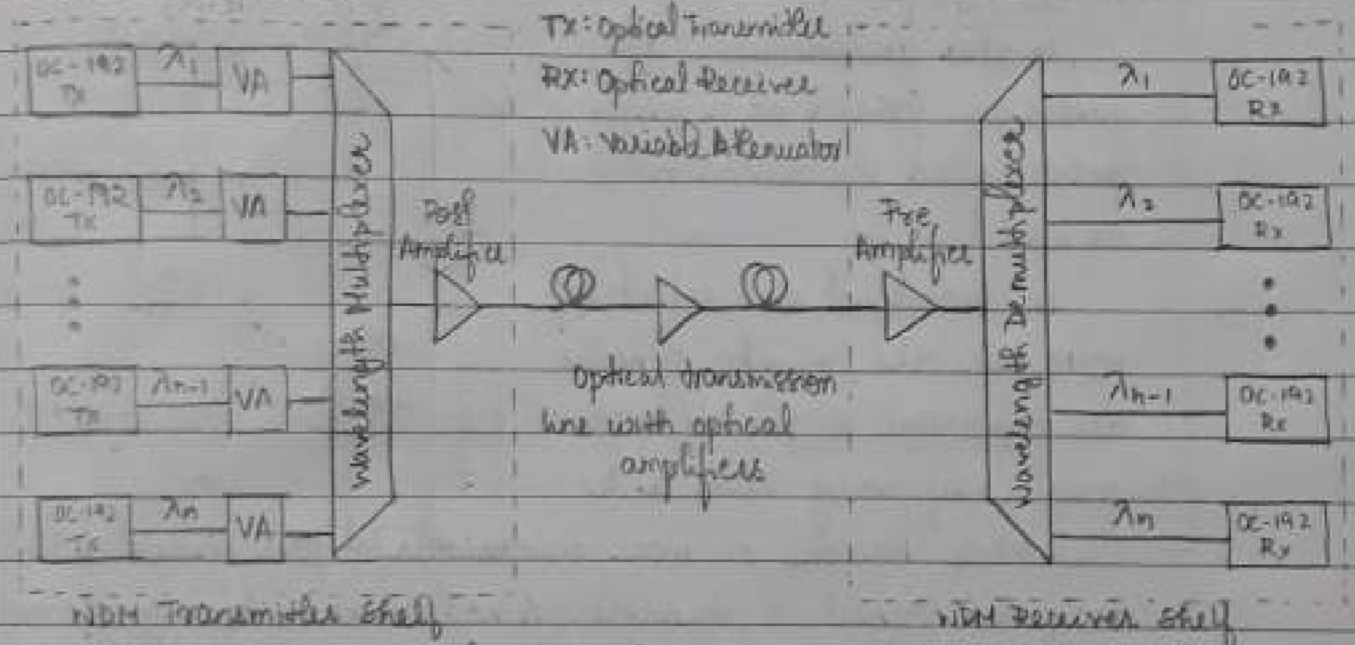
Generic configuration of a large SONET / SDH network consisting of linear chains and various types of interconnected rings

A fundamental SONET / SDH network element is the add / drop multiplexer (ADM) which is fully synchronous, byte-oriented multiplexer that is used to add and drop subchannels within an OC-N signal.



Various OC-12s and OC-3s are multiplexed into an OC-48 stream. Upon entering an ADM, these subchannels can be individually dropped by the ADM and others can be added.

Ex: One OC-12 and two OC-3 channels enter the left most ADM as part of an OC-48 channel. The OC-12 is passed through and the two OC-3s are dropped by the first ADM. Then two more OC-12s and one OC-3 are multiplexed together with the OC-12 channel that is passing through and the aggregate OC-48 is sent to another ADM node down stream.



DWDM deployment of n wavelengths in an OC-192/STM-64 trunk ring

The SONET/SDH architectures can also be implemented with multiple wavelengths. The different wavelength outputs from each OC-192 transmitter are passed first through a variable attenuator to equalize the output powers. These are then fed into a wavelength multiplexer, possibly amplified by a post-transmitter optical amplifier, and sent out over the transmission fiber. Additional optical amplifiers might be located at intermediate points and/or at the receiving end.

- <u>WDM Network Architectures:</u>

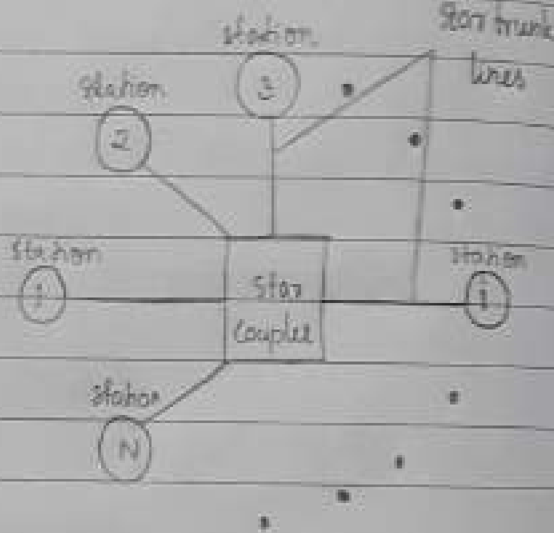
WDM networks can be broadly classified into two categories

1. <u>Broadcast and select WDM Networks:</u>

A broadcast and select WDM uses common transmission medium and employs simple transmission broadcasting mechanism for transmitting and receiving signal.

The most popular topologies for a broadcast and select WDM networks are:

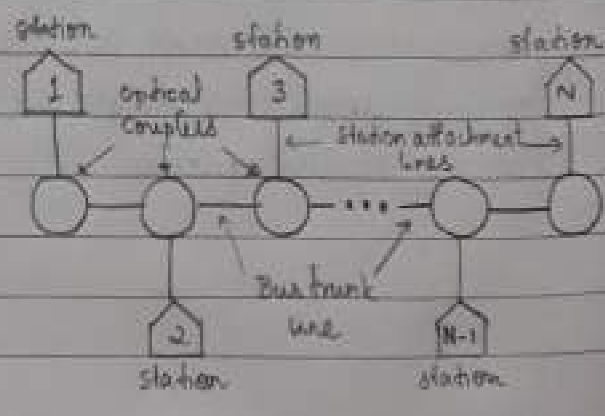
a. <u>Star topology:</u>



In star architecture, all nodes are joined at a single point called the central node or hub.

In broadcast and select WDM networks, number of nodes are connected to passive WDM coupler by using WDM links. Each node has one or more transmitter or receiver which can be fixed tuned or tunable. A node transmits signal on the available wavelength. Here different nodes can transmit their signal on different wavelength simultaneously and independently. The star coupler receives and combines all the signals and broadcast them to all the nodes in the network. To receive signal, a node tunes to its one of the wavelength on which the signal is transmitted.

b. <u>Bus topology:</u>



In bus topology, the nodes are connected to a bus through 2×2 couplers by WDM links. Each node transmits its signal to bus on an available wavelength through the coupler and receives a signal from the bus through another coupler.

Advantages: Simple broadcasting capability.

Disadvantages: 1. Wavelength should be used only once so large number of wavelengths are required as a result the network becomes unscalable. 2. The transmitted power from a node splits among all the nodes in the network. Hence each node can only receive a very small fraction of power, thus it is most suitable for LAN or MAN.

2. Wavelength-Routed WDM networks:

A WDM network that employs wavelength routing to transfer data traffic is called wavelength routed WDM networks. It contains routing nodes interconnected by links in an arbitrary mesh topology.

- **Nonlinear Effects on Network Performance:**

The design of lightwave transmission system requires careful planning of factors such as fiber selection, choice and tuning of optoelectronic components, optical amplifier placement and path routing. The goal of planning is to create a network that meets the design criteria, is reliable and is easy to operate and maintain. The design process must take into account of all power penalties associated with optical signal-degradation process.

It seems natural that the input optical power must be as large as possible to overcome the power pentalties to meet the link design goal. However, this works only if the fiber is in linear medium i.e, the loss and RI are independent of the input power.

In actual fiber several different nonlinear effects start to appear as the optical power level increases. These nonlinearities arise when several high-strength optical fields from different signal wavelengths are present in a fiber at the same time and when these fields interact with acoustic waves and molecular vibrations.

Optical nonlinearities can be classified into two general categories:

1. Encompasses the nonlinear inelastic scattering processes
   Ex: • Stimulated Raman Scattering (SRS)
   • Stimulated Brillouin Scattering (SBS)
2. Arises from intensity dependent variations in the refractive index in a silica fiber: known as Kerr Effect.
   Ex: • Self-phase modulation (SPM)
   • Cross-phase modulation (XPM/CPM)
   • Four-wave mixing / Four-photon mixing (FWM/FPM)

SBS, SRS and FWM result in gains or losses in a wavelength channel. They provide gains to some channels while depleting power from others, thereby producing crosstalk between the wavelength channels.

SPM and XPM affect only the phase of signals, which causes chirping in digital pulses.

When any of these nonlinearities contribute to signal impairment, an additional power is needed to maintain same BER as in their absence. This additional power (in dB) is known as the power penalty for that effect.

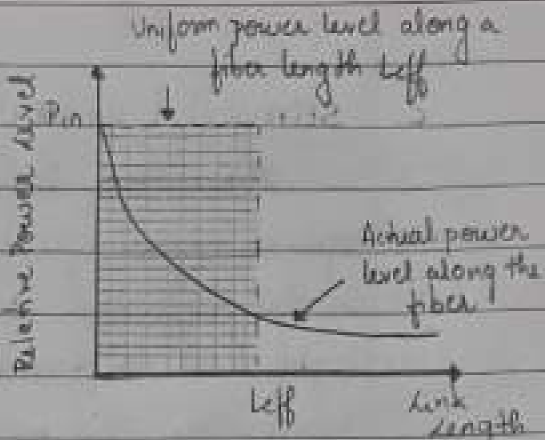
– Different factors influencing nonlinearity that affects optical fiber link performance

a. Effective length and area:

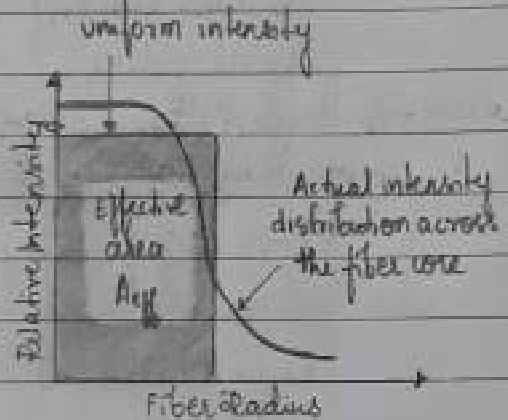
The nonlinear effects depends on the transmission length, the cross-sectional area of the fiber and the optical power level in the fiber. The impact of the nonlinearity on signal fidelity increases with distance. However this is offset by the continuous decrease in signal power along the fiber due to attenuation.

One can use a simple but sufficiently accurate model that assumes the power is constant over a certain fiber length, which is less than or equal to the actual fiber length. This effective length L_{eff}, takes power absorption along the length of the fiber into account.

The area designated by the shaded pattern is equal to the area under the power distribution curve.



The effects of nonlinearities increase with the light intensity in a fiber. For a given optical power, this intensity is inversely proportional to the cross-sectional area of the fiber core. Although the intensity is not distributed uniformly across the fiber-core area, for practical purposes one can use an effective cross-sectional area A_{eff}, which assumes a uniform intensity distribution across most of the core.



b. Stimulated Raman Scattering (SRS):

Stimulated Raman scattering is an interaction between lightwaves and the vibrational modes of silica molecules. If a photon with energy $h\nu_1$ is incident on a molecule having a vibrational frequency ν_m, the molecule can absorb some energy from the photon. In this interaction, the photon is scattered, thereby attaining a lower frequency ν_2 and a corresponding lower energy $h\nu_2$. The modified photon is called a Stokes photon. Because the optical signal wave that is injected into a fiber is the source of the interacting photons, it is called the pump wave because it supplies power for the generated wave.

This process generates scattered light at a wavelength longer than that of the incident light. If another signal is present at this longer wavelength, the SRS light will amplify it and the pump wavelength signal will decrease in power.

c. Stimulated Brillouin Scattering (SBS):

Stimulated Brillouin scattering arises when a strong optical signal generates an acoustic wave that produces variations in the refractive index. These refractive index variations cause lightwaves to scatter in the backward direction toward the transmitter. This backscattered light experiences gain from the forward-propagating signals, which leads to depletion of the signal power.

d. Self-Phase Modulation (SPM).

The nonlinearity in the refractive index is known as the Kerr Nonlinearity. This nonlinearity produces a carrier-induced phase modulation of the propagating signal, which is called the Kerr Effect. In single wavelength links, this gives rise to self phase modulation (SPM), which converts optical power fluctuations in a propagating lightwave to spurious phase fluctuations in the same wave.

e. Cross-Phase Modulation (CPM/XPM):

Cross-phase modulation appears in WDM systems and has a similar origin as SPM. The refractive index nonlinearity converts optical intensity fluctuations in a particular wavelength channel to phase fluctuations in another copropagating channel.

In addition, since the refractive index seen by a particular wavelength is influenced by both the optical intensity of that wave itself and also by the optical power fluctuation of neighbouring wavelengths, SPM is always present when XPM occurs.

f. Four-Wave Mixing (FWM):

Four wave Mixing is a third order ~~non~~-linear effect that is caused by dependence of refractive index on the intensity of the optical power. It is most serious in closely spaced WDM systems. The three optical frequencies mix to produce a fourth intermodulation product. It can cause severe cross talk in the transmission window.

- **SLE: High Speed Light Wave Links:**

A challenge to create efficient and reliable optical networks that satisfy an ever-growing demand for bandwidth is the development of high speed optical fiber transceivers. A variety of transceivers exist that incorporate both an optical transmitter and receiver in the same miniaturized package.

Ex: Small form factor pluggable (SFP) transceiver.
- used for DWDM application
- hot-pluggable capacity: they can be inserted and removed from transmission equipment line cards without turning the electric power off
- they incorporate sophisticated wavelength control into the package.

- Links operating at 10 Gb/s:
  - Fiber channel connections for storage area network
  - 10 Gb ethernet lines for local area and metro networks.
  - SONET/SDH OC-192/STM-64 terrestrial and undersea long haul lines.

As a result of product improvement efforts, several multimode fibers with different bandwidth grades exist for 10 Gb/s use. The multimode fiber classifications are as follows:
- OM1 grade fiber (original/legacy): designed to be used with LEDs
- OM2 grade fiber: improved bandwidth, distance over 82 m
- OM3 grade fiber: higher bandwidth, distance upto 300 m
- OM4 grade fiber: bandwidth: 4700 MHz-km, increases the transmission distance to 550 m.

- Links operating at 40 Gb/s:

New challenges at 40 Gb/s data rate:
- Transceiver response characteristics
- Chromatic dispersion control
- Polarization mode dispersion compensation.

Therefore alternate modulation scheme besides OOK have been considered. One method is differential binary phase shift keying DBPSK/DPSK. The most widely accepted format has been RZ-DPSK for which transceiver modules that can interface to SONET/SDH equipment are available.

- OTDM links operating at 160 Gb/s

160 Gb/s over a single wavelength using G.652 single mode fiber are tested. These test link used the concept of Optical Time Division Multiplexing (OTDM) to form 160 Gb/s data stream, since electronic devices that are needed for carrying out signal processing at these rates were not available.

One option is to use bit-interleaved OTDM. This multiplexing technique is similar to WDM in that the access nodes share many small channels operating at a peak rate that is a fraction of the media rate.

Several field trials have demonstrated the feasiblity of long haul 160 Gb/s transmission systems.

Germany: researchers achieved repeaterless error free transmission.

Japan: to cope with transmission impairments from CD and PMD researches investigated the use of 2 bit/symbol encoding techniques such as DQPSK and simultaneous ASK and DPSK. 160 Gb/s signal was composed of eight 20 Gb/s channels.

United Kingdom: The impact of chromatic and polarization mode dispersion was examined on 275 and 550 km links of installed SSMF. The 160 Gb/s signal was created by time interleaving sixteen channels operating at 10 Gb/s each.