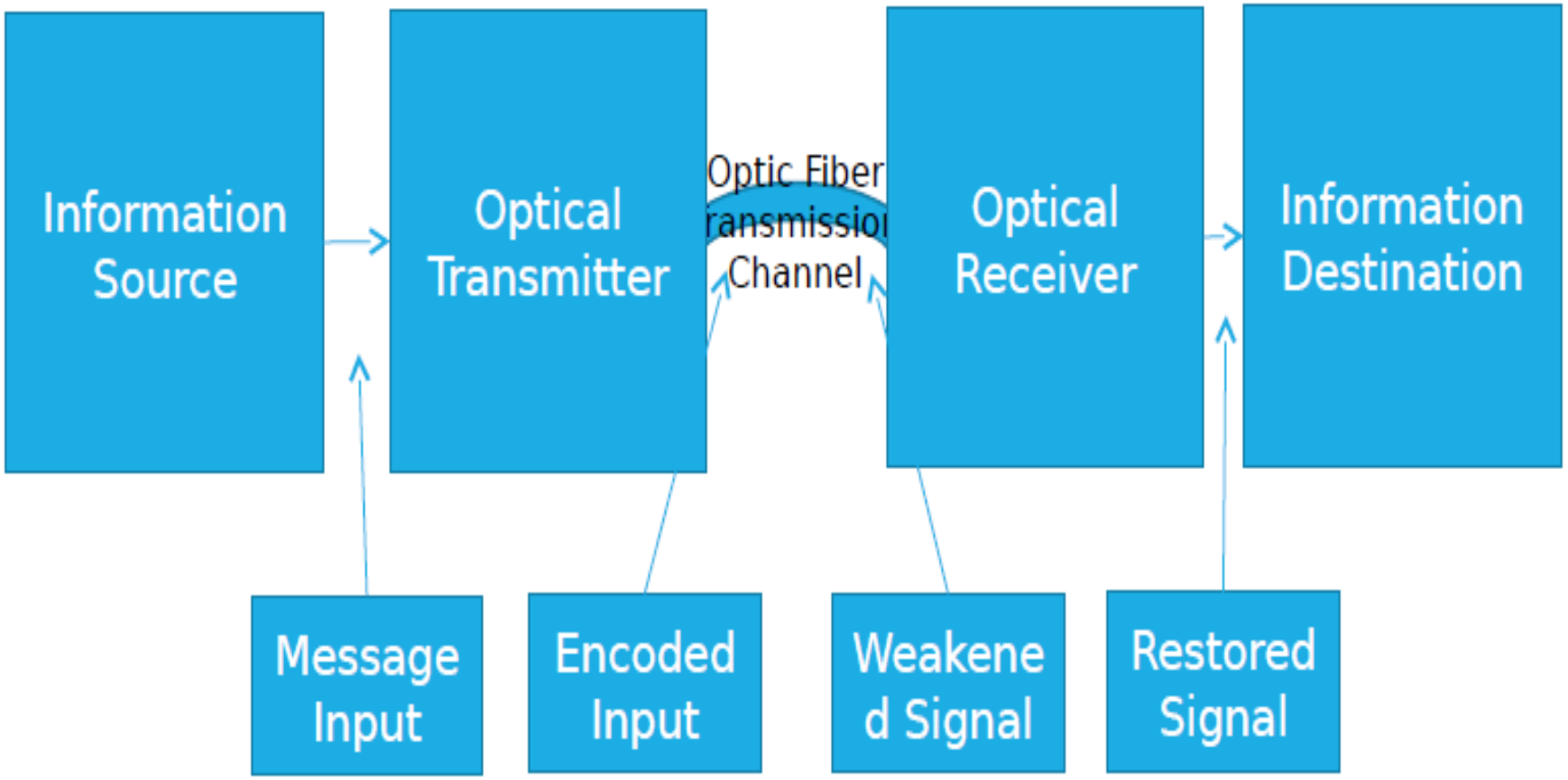
MODULE 1

GENERAL LIGHT WAVE SYSTEM



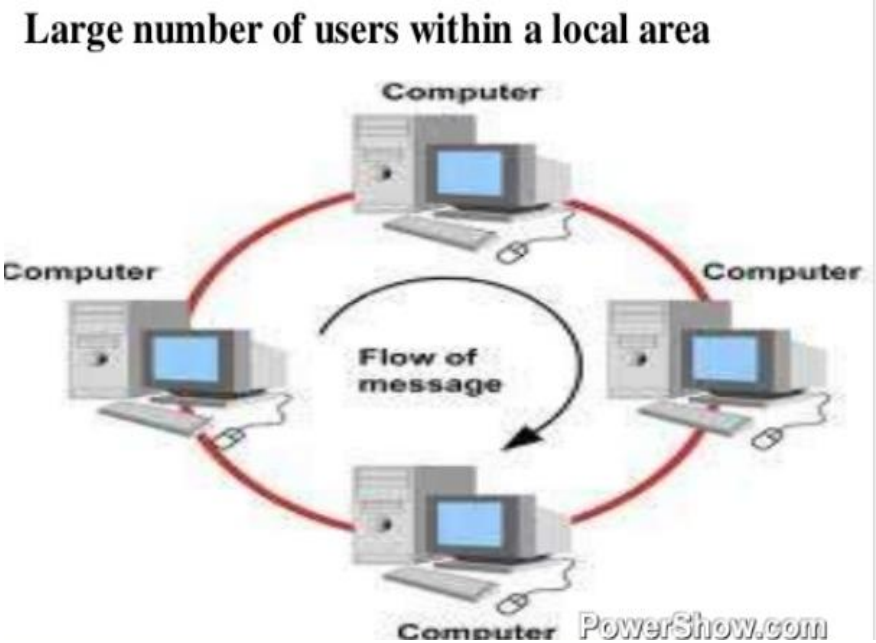
Act

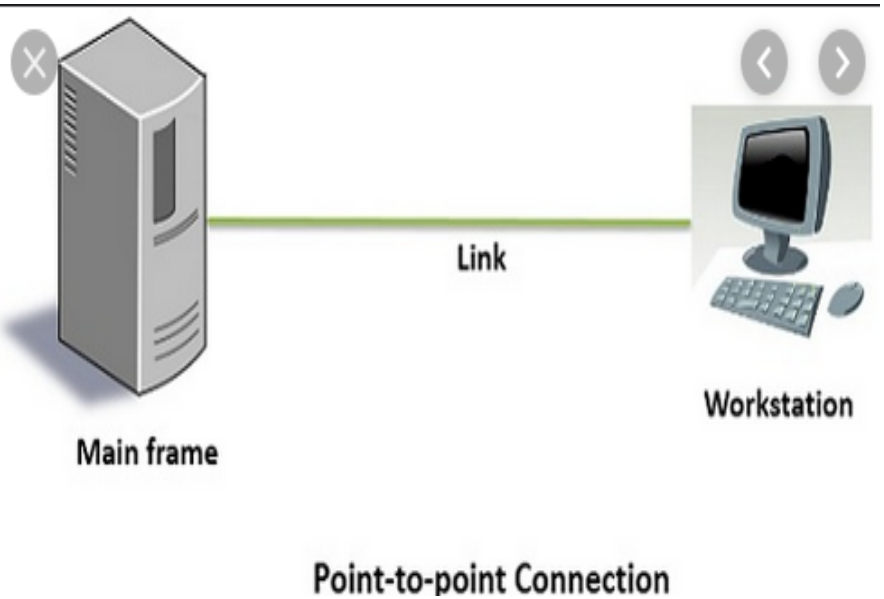
ADVANTAGES OF LIGHT WAVE SYSTEM

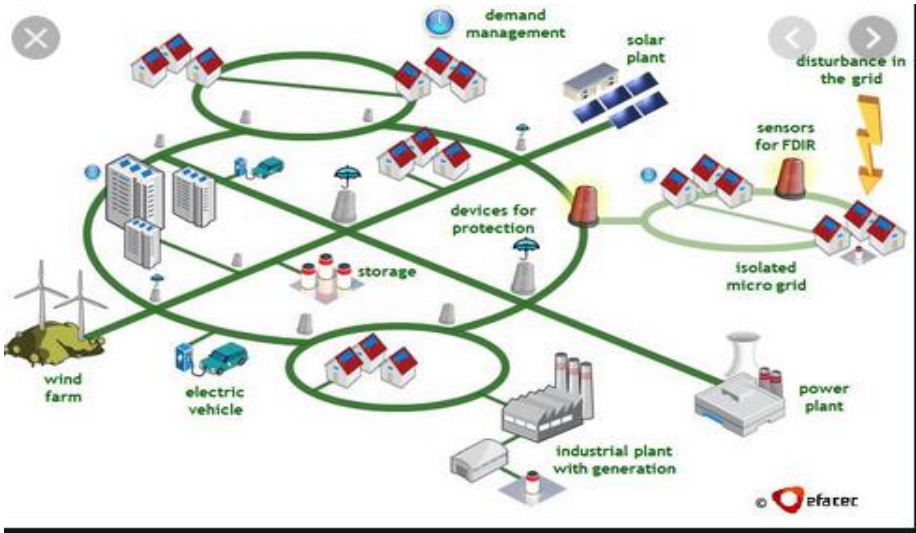
1. Long Distance Transmission
a) Lower Transmission Losses
b) Reduction in number of repeaters
c) Low cost
2. Large Information Capacity
a) Low number of lines
3. Small
4. Immune to electrical interference
5. Enhanced Safety
6. Increased Signal Security

CLASSIFICATION OF LIGHTWAVE SYSTEMS

- POINT TO POINT LINKS
- DISTRIBUTION NETWORKS
- LOCAL AREA NETWORKS





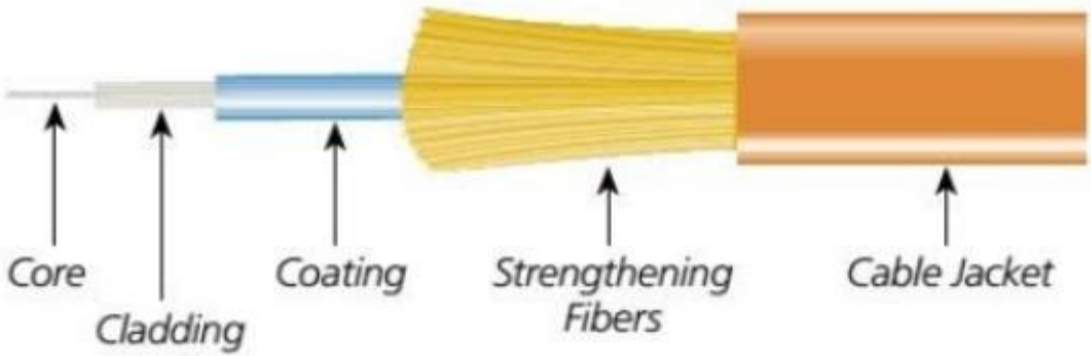


OPTICAL FIBER

- The fiber which are used for optical communication are wave guides made of transparent dielectrics.
- This fiber waveguide is normally cylindrical in form.
- Its function is to guide visible and infrared light over long distance.
- The propagation of light along a fiber can be described in terms of a set of guided electromagnetic waves called modes of the waveguide
- The light in fiber travels by TIR with a velocity of $v=c/n$

FIBER CONSTRUCTION

- The fiber cable consist of a core with refractive index n1 at the center and a cladding with lower refractive index n2 outside the core.
- The buffer jacket provide protection for the fiber from external mechanical influences.
- Surrounding the buffer jacket there is a layer of strengthening fibers called Kevlar which increase the tensile strength of cable.
- Again, an outer protective tube is filled with polyurethane ,which prevents moisture from coming into contact with fiber.



TYPES OF OPTICAL FIBRES

1. Based on material
   - Plastic core with plastic cladding
   - Plastic core with glass cladding
   - Glass core with glass cladding
2. Based on mode of transmission
   - Single mode fiber
   - Multimode fiber
3. Index profile
   - Step-index fiber
   - Graded index fiber

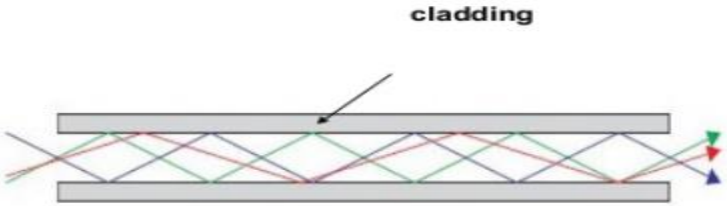
SINGLE MODE FIBER

- In single mode fiber only one mode can propagate through the fiber.
- It has small core diameter (5um) and high cladding diameter (70um).
- Difference between the refractive index of core and cladding is very small.
- There is neither dispersion nor degradation therefore it is suitable for long distance communication.
- The light is passed through the single mode fiber through laser diode.

Singlemode Fiber

MULTIMODE FIBER

- It allows a large number of modes for light ray travelling through the fiber.
- The core diameter is 40um and that of cladding is 70um.
- The relative refractive index difference is also large than single mode fiber.
- There is signal degradation due to multimode dispersion.
- It is not suitable for long distance communication due to large dispersion and attenuation of signal



Multimode Fiber

REFRACTIVE INDEX PROFILE

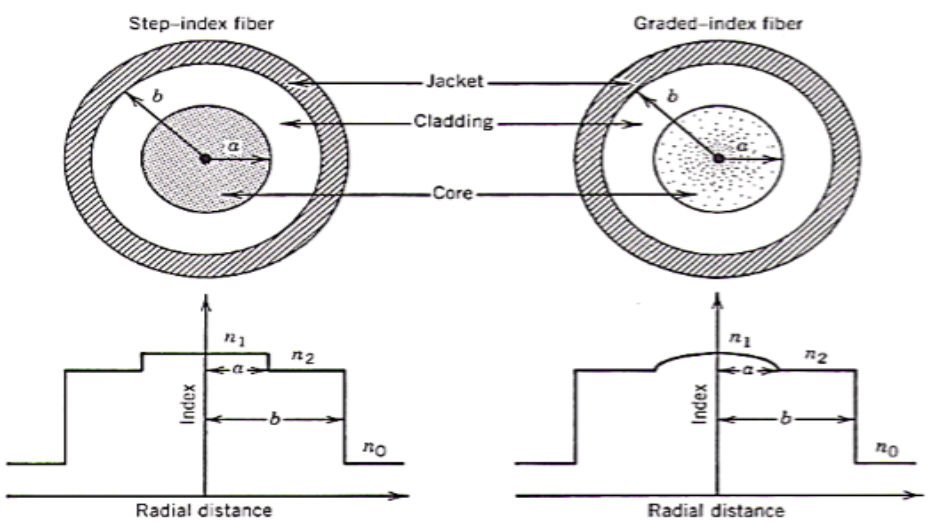
- The refractive index profile describes the relationship between the refractive indices of core and the cladding.
- Variations in the material composition of the core give rise to two commonly used fiber types- step index and graded index fibers

STEP-INDEX FIBER

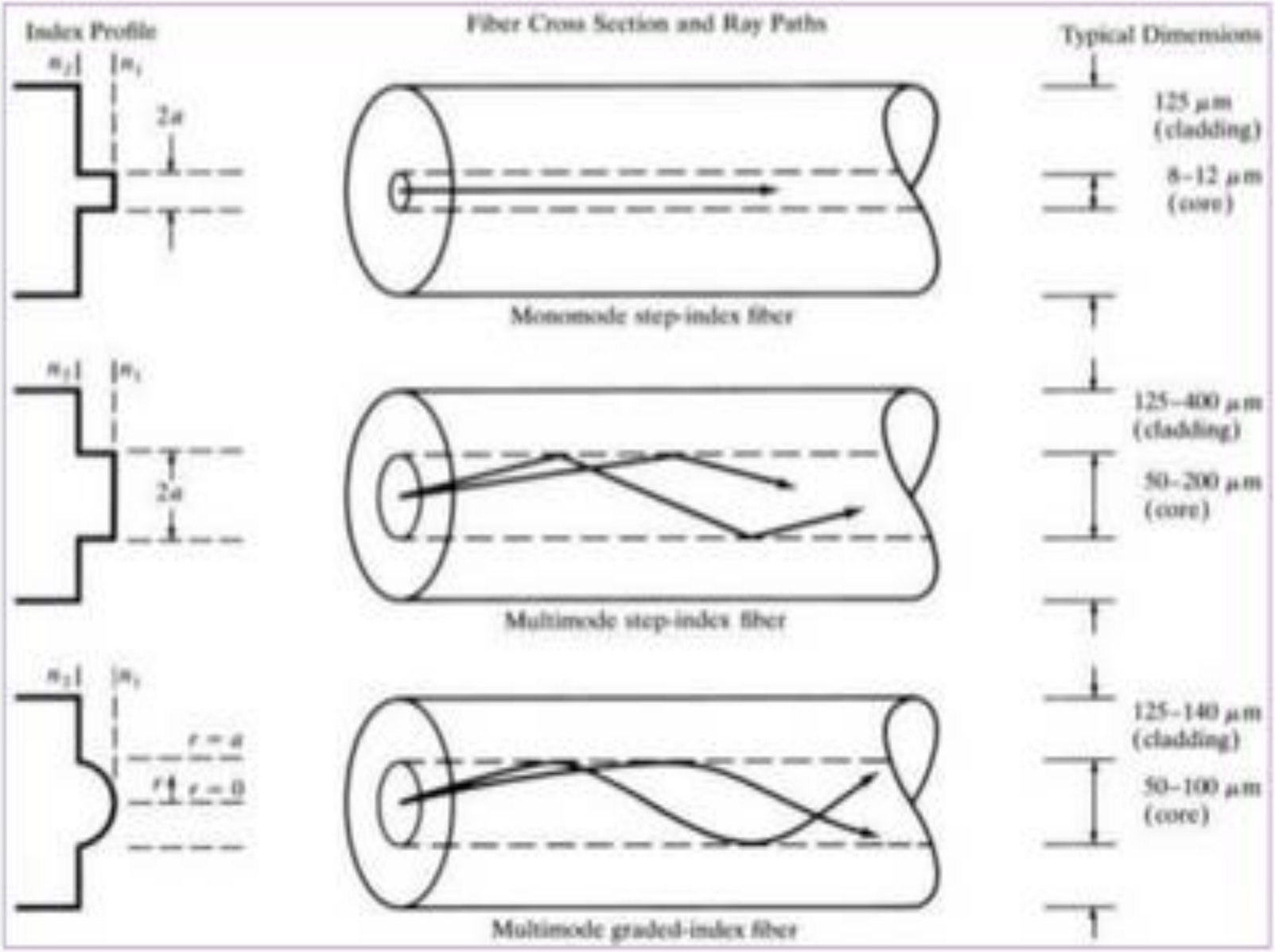
- The refractive index of core and cladding are constant.
- The light ray propagate through it in the form of meridional rays which cross the fiber axis during every reflection at the core cladding boundary.
- Step index fiber is of two types viz; single mode fiber and multi mode fiber.
- The refractive index profile may be defined as: $n(r) = \begin{cases} n_1 & r < a \quad \text{(core)} \\ n_2 & r \geq a \quad \text{(cladding)} \end{cases}$
- Number of modes for step index fiber ,M = $v^2/2$

GRADED INDEX FIBER

- In this type of fiber core has a non uniform refractive index that gradually decrease from the center towards the core cladding interface.
- The cladding has a uniform refractive index.
- The light rays propagate through it in the form of helical rays. They never cross the fiber axis.
- Graded index fiber is of only one type,that is multi mode fiber.
- The refractive index profile may be defined as: $$n(r) = \begin{cases} n_1 \left(1 - 2\Delta \left(\frac{r}{a}\right)^{\alpha}\right)^{1/2} & r < a\,(core) \\ n_1 \left(1 - 2\Delta\right)^{1/2} & r \geq a\,(cladding) \end{cases}$$
- Number of modes for graded index fiber ,M = $v^2/4$



Cross section and refractive-index profile for step-index and graded-index


Index Profile
Fiber Cross Section and Ray Paths
Typical Dimensions
n_2
n_1
$2a$
125 μm (cladding)
8–12 μm (core)
Monomode step-index fiber
125–400 μm (cladding)
50–200 μm (core)
Multimode step-index fiber
$r = a$
$r = 0$
125–140 μm (cladding)
50–100 μm (core)
Multimode graded-index fiber

PROS & CONS

Sl. No	Single Mode Step Index	Multi Mode Step Index	Multi Mode Graded Index
1	Low Intermodal dispersion (Broadening of transmitted light)	Considerable Dispersion	Lowest Dispersion
2	Highest Bandwidth	Low Bandwidth	Medium Bandwidth
3	Coherent sources are must	Use of Incoherent optical sources (LED can be used as source)	>
4	Coupling must be precise	Easy Coupling	>
5	Higher Tolerance	Lower Tolerance	>

MODES IN SI AND GI FIBRES

- The total number of guided modes or mode volume M_s for SI fiber is related to V-number for the fiber by approximate expression

$$M_s \approx V^2/2$$

- where

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

- NA varies from 0.12-0.20 for SMFs and 0.20-0.50 for MMFs

$$NA = \sin\theta_a = \sqrt{n^2_{core} - n^2_{cladding}}$$

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

- The total number of guided modes or mode volume M_g for GI fiber is

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

- Δis relative refractive index difference and α is the profile parameter.

α= ∝; Step index profile

α= 2; Parabolic profile

α =1 Triangular profile

- **For example**: A MM SI fiber of core diameter 80μm, core refractive index 1.48, relative index difference of 1.5% and operating at 850nm

  ⇒ supports 2873 guided modes.

Numerical Aperture (NA):

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

0.12-0.20 for SMF, 0.15-0.25 for MMF

Relative Refractive Index Difference (Δ):

$\Delta = (n_1 - n_2)/n$; n- the average refractive index

<0.4% for SMF, >1% for MMF

Normalized Frequency or **V-Number:**

$$V = [(2\pi a)/\lambda]\, NA$$

$V \leq 2.405$ for SMF; ≥ 10 for MMF

LINEAR AND NON LINEAR EFFECTS IN FIBRES

Linear effects

1) ATTENUATION

- Attenuation means loss of light energy as the light pulse travels from one end of the cable to the other.
- It is also called as signal loss or fiber loss.
- It decides the number of repeaters required between transmitter and receiver.
- Attenuation is directly proportional to the length of the cable.
- Attenuation is defined as the ratio of optical output power to the input power in the fiber of length L.

$$\alpha = 10\log10\ Pi/Po\ [\text{in db/km}]$$

where, Pi= Input Power Po= Output Power, α is attenuation constant

- Attenuation depends on

1. Wavelength (Attenuation decreases with wavelength increases)
2. Type of fiber(MM fibers have more attenuation than SM fibers)

- Causes of fiber attenuation

1. Absorption
2. Scattering
3. Bending

ABSORPTION

- Defines as the portion of attenuation resulting from the conversion of optical power into another energy form.ie Heat
- Cause of absorption is the presence of impurities like metal particles / moisture in the fiber.
- It is influenced by atomic structure, impurities and fiber material.
- Two types

1. Intrinsic absorption
2. Extrinsic absorption

- Intrinsic Absorption occurs when photon interacts with an electron in the valence band & excites it to a higher energy level near the UV region.
- Extrinsic Absorption(Impurity absorption) results from the presence of transition metal ions like iron, chromium etc and absorption due to water dissolved in glass.

SCATTERING

- Scattering Losses occurs due to microscopic variations in the material density, compositional fluctuations, structural in homogeneities and manufacturing defects.
- Linear Scattering

1. Rayleigh Scattering losses (due to microscopic variation in the material of the fiber)
2. Mie Scattering Losses (results from the compositional fluctuations & structural inhomogenetics & defects created during fiber fabrications which causes the light to scatter outside the fiber)
3. Waveguide Scattering Losses (result of variation in the core diameter, imperfections of the core cladding interface, change in RI of either core or cladding)

- Non-linear Scattering

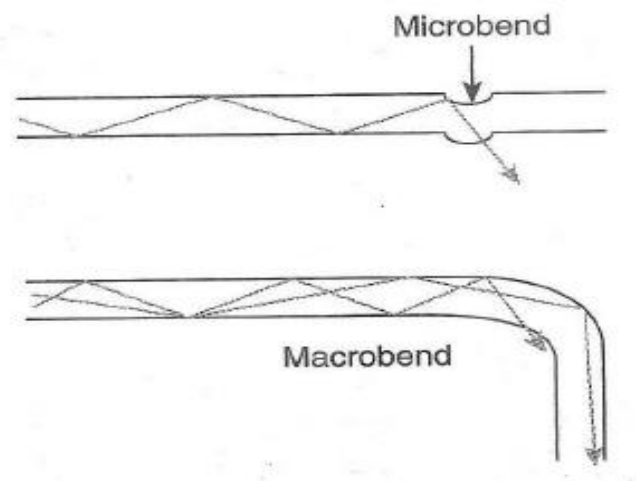
1. Stimulated Brillouin Scattering(SBS) (is the modulation of light through thermal molecular vibrations within the fiber)
2. Stimulated Raman Scattering(SRS) (similar to SBS except that high frequency optical phonon rather than acoustic phonon is generated in

BENDING LOSSES

- Defines as the radiative losses whenever fiber undergoes a bend of finite radius of curvature
- Bending loss is classified according to the bend radius of curvature : 1. Micro bend Loss 2. Macro bend Loss
- Micro bend Loss are caused by small discontinuities or imperfections in the fiber. Uneven coating applications and improper cabling procedure increases micro bend loss. External forces are also a source of micro bends.
- Macro bend Losses are observed when a fiber bend's radius of curvature is large compared to the fiber diameter. These bends are a great source of loss.
- Bending losses can be reduced by

Shortest possible operating wavelength

Fiber with a large refractive index difference



DISPERSION

- Dispersion is broadening of light pulses.
- The physical properties and geometry of the transmission medium are responsible for the dispersion.
- The dispersion cause that optical pulses to broaden as they travel along a fiber, the overlap between neighboring pulses, creating errors in the receiver output, resulting in the limitation of information-carrying capacity of a fiber.
- The higher dispersion the longer the bit interval which must be used.
- Two types

1. Intramodal Dispersion – Material dispersion & Waveguide dispersion.
2. Intermodal Dispersion
3. Polarization mode dispersion

- Disadvantages:

1. Signal Distortion
2. Pulse broadening
3. Inter Symbol Interference
4. Low SNR

INTERMODAL DISPERSION

- In a multimode fiber different modes travel at different velocities. If a pulse is constituted from different modes then intermodal dispersion occurs.
- Intermodal dispersion occurs only in multimode step index fibers.
- The more modes the greater the modal dispersion.
- The time taken by each mode to cover same distance is different in MM fibers which causes pulse broadening.
- Single mode fibers propagate only in fundamental mode and there does not exist intermodal dispersion. Therefore SM fibers exhibit lowest amount of total dispersion and it can be preferred for long haul communication.

INTRAMODAL DISPERSION

- It is pulse spreading that takes place within a single mode.
- In single mode fiber light with different wavelength transmit at different speed which causes pulse broadening.
- The broadened pulse has reduced peak intensity and it becomes difficult to detect. Thus chromatic dispersion is the only limiting factor for high data transmission.
- Also known as Group Velocity Dispersion, since the dispersion is a result of the group velocity being a function of the wavelength.
- Two types

1. Material dispersion
2. Waveguide dispersion

MATERIAL DISPERSION

- Also known as spectral dispersion
- Due to the intrinsic properties of material, glass.
- Results because of Refractive Index variation of core as a function of wavelength
- Various spectral components in the spectral width of optical source travel with different speed, which causes pulse broadening.

WAVEGUIDE DISPERSION

- Occurs because a SM fiber confines only 80% of optical power to the core of fiber.
- Whenever any optical signal is passed through the optical fiber, practically 80% of optical power is confined to core & rest 20% optical power into cladding.
- Dispersion arises because the fraction of light power propagating in the cladding travel faster than the light confined to the core, since the index is lower in the cladding.
- In SM fiber it occurs only in one mode and in MM fiber it occurs in every mode.

POLARIZATION MODE DISPERSION

- Phenomenon that causes a spreading of light pulses as they travel along a network.
- Occurs due to fiber birefringence.
- PMD results from the fact that optical signal at a given wavelength in a SM fiber actually occupies two orthogonal polarization states or modes.
- At the start of the fiber, the two polarization states are aligned.
- Since the fiber material is not perfectly uniform throughout its length, each polarization mode will encounter a slightly different refractive index and each mode will travel at a slightly different velocity.
- The resulting difference in propagation times between the two orthogonal polarization modes will cause pulse broadening.
- PMD varies randomly along the fiber,which is the limiting factor for long haul communication.

MODULE 1

- General light wave system, advantages, classification of light wave systems.
- Fibres: types and refractive index profiles, mode theory of fibres: modes in SI and GI fibres,
- Linear and non linear effects in fibres, dispersion, Group Velocity Dispersion, modal, wave guide and Polarization, Modes, Dispersion,
- Attenuation- absorption, bending and scattering losses.

MODULE 2

FIBRE MATERIALS

- An optical fiber is a hair thin cylindrical fiber of glass or any transparent dielectric medium.
- The fiber material must be -
  - Possible to make long, thin flexible fibers
  - Transparent at a particular optical wavelength to guide light efficiently
  - Physically compatible materials that have slight difference in refractive indices of core and cladding.
- Materials that satisfy these requirements are glasses and plastics.
- Majority of fibers are made of glass consisting of either silica $SiO2$ or silicate.
- Based on material used, two types

1. Glass fiber
2. Plastic fiber

GLASS FIBER

- It is an optical fiber made of glass
- Being a delicate type of optical fiber, it cannot be cut, spliced or repaired.
- more difficult to handle and more delicacy.
- Extremely versatile and robust
- Higher information transmission capacity with lower loss
- Glass fibers can be used with both visible red and infrared light.
- Used for high-speed, long-distance applications.

PLASTIC FIBER

- It is an optical fiber which is made out of plastic [PMMA (acrylic) as the core and fluorinated polymers as the cladding material]
- Boast of simpler and less expensive components.
- Greater flexibility, and resiliency to bending, shock and vibration
- Lighter in weight.
- Lower cost
- Plastic fiber uses harmless green or red light that is easily visible to the eye.
- Used for low-speed, short-distance (up to 100 meters) applications.

FIBER FABRICATION

- Three steps

1. Making a Preform
2. Drawing the Fibers from the Preform
3. Testing the Fiber

- Two basic techniques

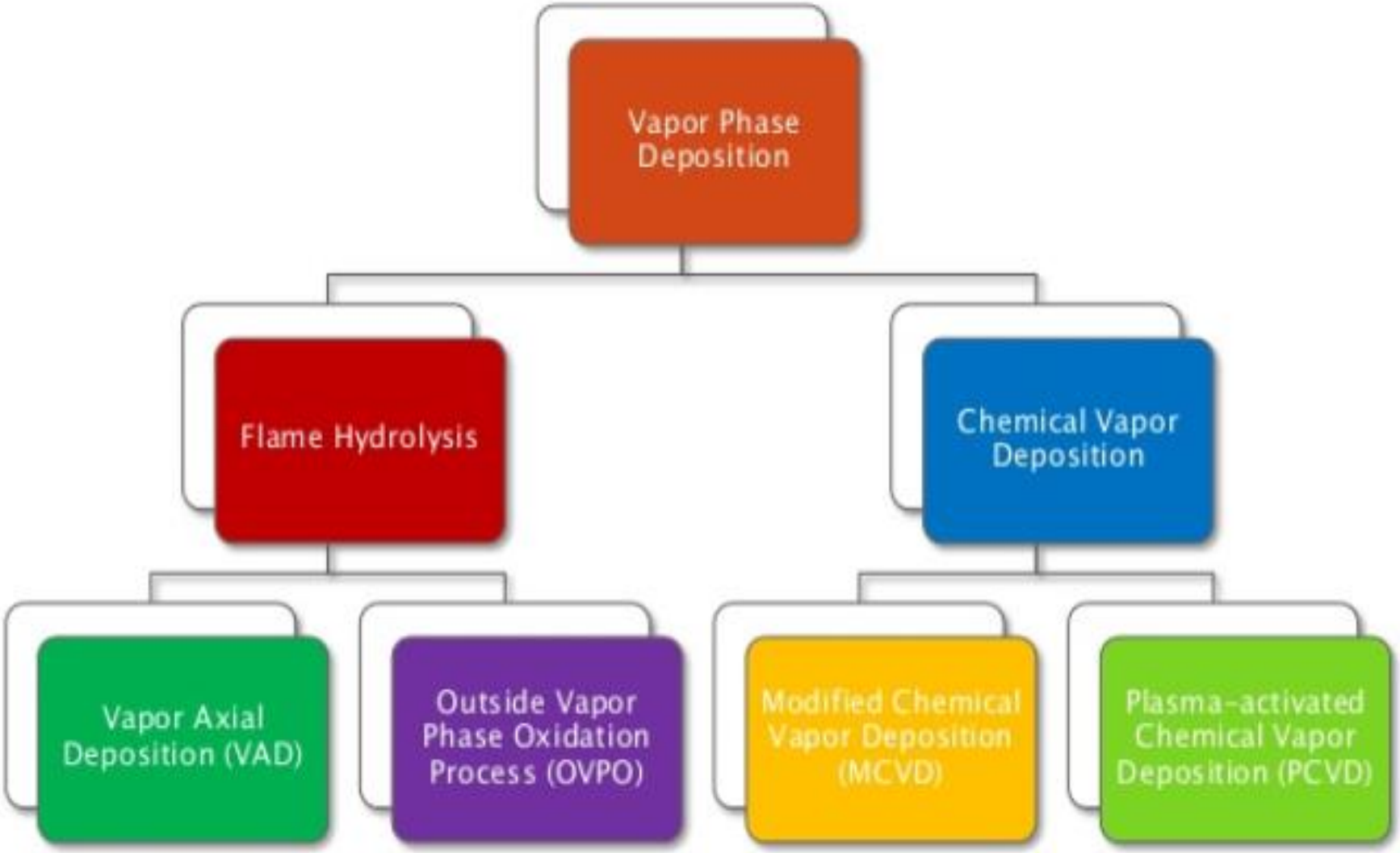
1. Vapor-phase oxidation process
2. Direct melt methods(Traditional method)

VAPOR-PHASE OXIDATION PROCESS

- Method of preparing the extremely pure optical glasses.
- Vapor Phase methods are the ones that are now used to produce silica-based fibers with very low attenuation, highest transparency with the optimal optical properties.

Starting Materials	Dopants
Starting materials are volatile organic compounds such as: ○ $SiCl_4$ ○ $GeCl_4$ ○ SiF_4 ○ BCL_3 ○ O_2 ○ BBr_3 ○ $POCl_3$	Refractive index modification is achieved through the formation of dopants from the non-silica starting materials: ○ TiO_2 ○ GeO_2 ○ P_2O_5 ○ Al_2O_3 ○ B_2O_3 ○ F

CLASSIFICATION



1. Highly pure vapors of metal halides like $SiCl_4$, $GeCl_4$ react with oxygen to form a white powder of SiO_2 particles
2. The particles are then collected on the surface of bulk glass and are then sintered to form a rod or tube (preform)
3. It is 10 to 25mm in diameter and 60 to 120mm long
4. Fibers are then made from this preform using the fiber drawing apparatus
5. Preform is precision fed and heated using a drawing furnace.
6. Here preform is softened to a point where it can be drawn into a very thin filament which becomes the optic fiber
7. Turning speed of the takeup drum determines how fast the fiber is drawn and also thickness of the fiber
8. So a precise rotation rate must be maintained
9. To protect the fiber from external impurities like dust and water, an elastic coating is applied immediately after it is drawn

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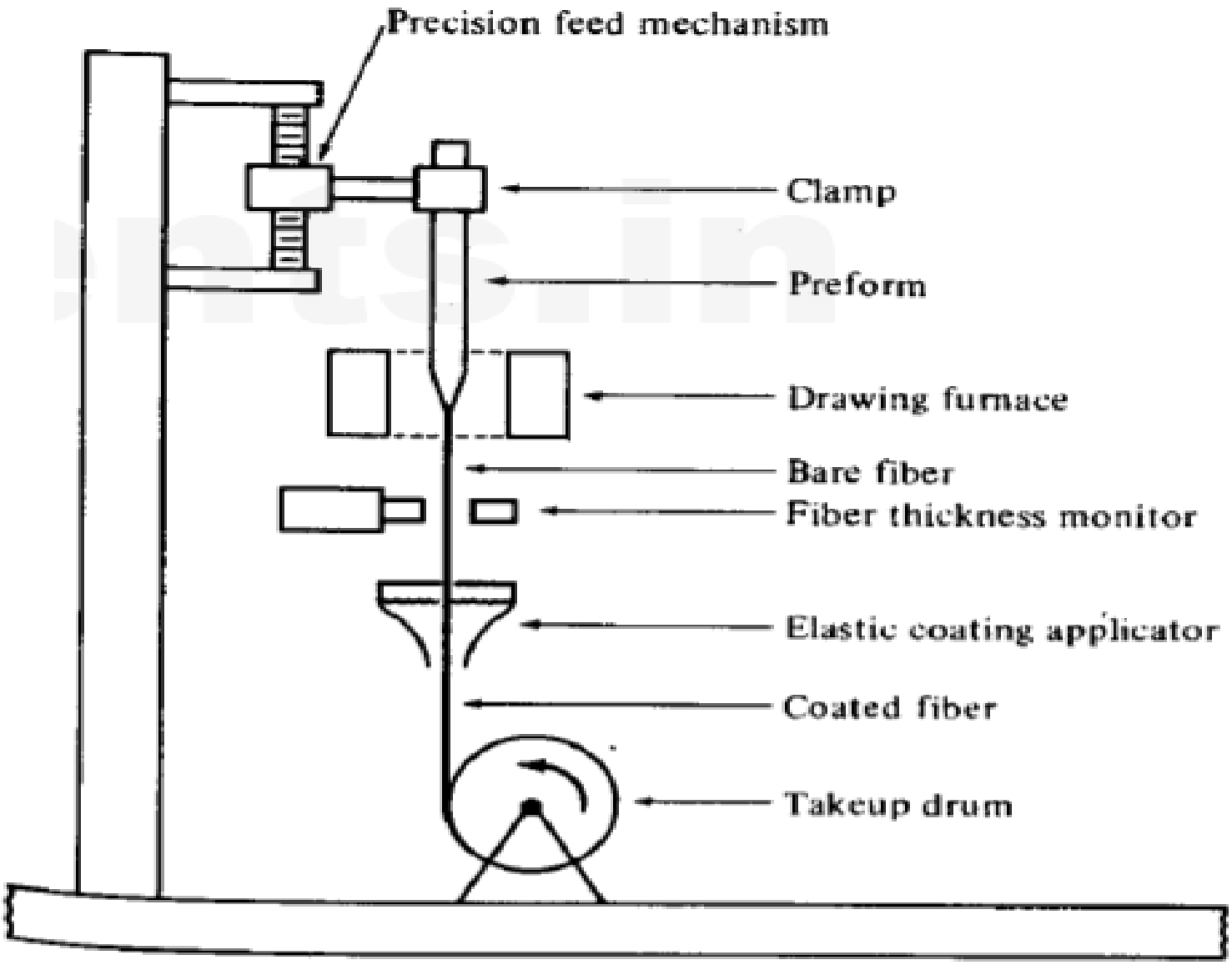

Precision feed mechanism
Clamp
Preform
Drawing furnace
Bare fiber
Fiber thickness monitor
Elastic coating applicator
Coated fiber
Takeup drum

CLASSIFICATION

1) Outside Vapor Phase Oxidation Process (OVPO)

- In this method, a layer of SiO_2 particles called soot is deposited from a burner onto a rotating graphite or ceramic spindle.
- The glass soot adheres to this rod, & layer by layer, a cylindrical porous glass preform is built up.
- When the deposition process is completed, the spindle is removed and the porous tube is then vitrified in a dry atmosphere at a high temperature to a clear glass preform, which be drawn into a fiber by heating it in another furnace.

2) Vapor Phase Axial Deposition (VAD)

- Modified method for continuous production of low-loss fiber in a controlled environment.
- Here, the deposition occurs at the end of the target rod. The rod is continuously pulled away from the burner, and very long preforms can be drawn in the process.The resultant preform can then be drawn into a fiber by heating it in another furnace.

3) Modified Chemical Vapor Deposition (MCVD)

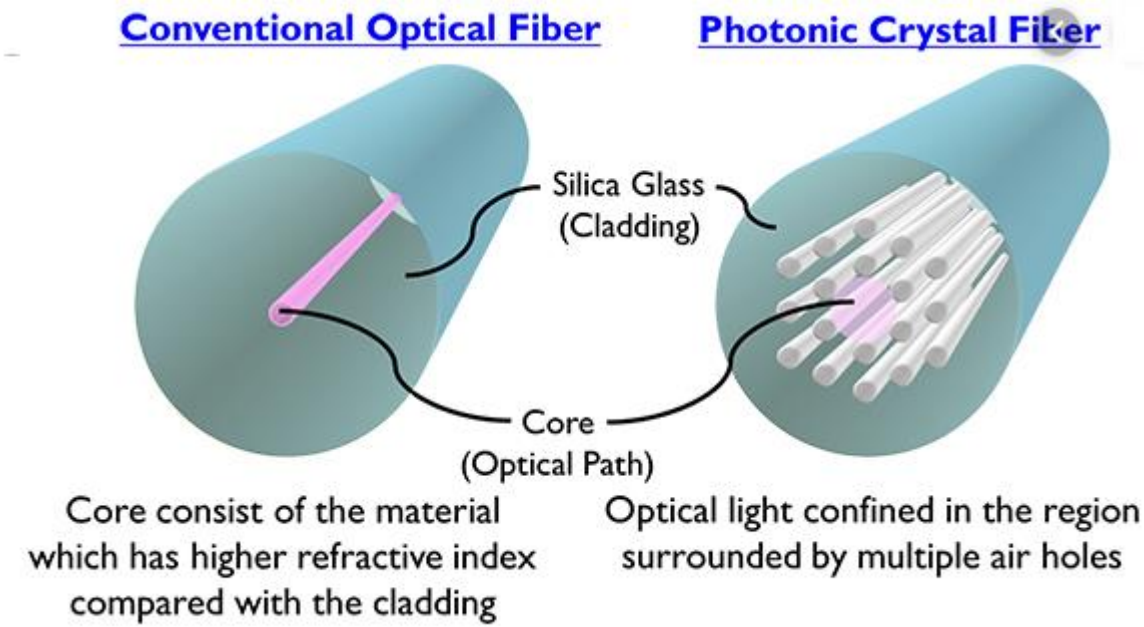
- In this method flow through a revolving silica tube.
- As SiO_2 particles are deposited, they are sintered into a clear glass layer.
- When the desired thickness of glass has been deposited, the vapor flow is shut off and the tube is heated strongly to cause it to collapse in to a solid rod preform.
- Fiber is then drawn from the preform.

4) Plasma-activated Chemical Vapor Deposition (PCVD)

- This method uses non-isothermal low pressure plasma to chemical reaction.
- Microwaves are used in place of burner for heating the deposition region.
- With the silica tube held at temperatures in the range of 1000-1200°C, a moving microwave resonator operating at 2.45 GHz generates a plasma inside the tube to activate the chemical reaction.
- This process deposits clear glass material directly on the tube wall.
- When the desired thickness of glass is deposited, the tube is collapsed into a preform.

PHOTONIC CRYSTAL FIBRE

- A photonic crystal is a periodic optical nanostructure that affects the motion of photons in much the same way that ionic lattices affect electrons in solids
- Photonic crystal fibers combine properties of 2D photonic crystals and classical fibers
- PCFs are optical fibers that employ a long thread of silica glass with a periodic air holes running down its length.

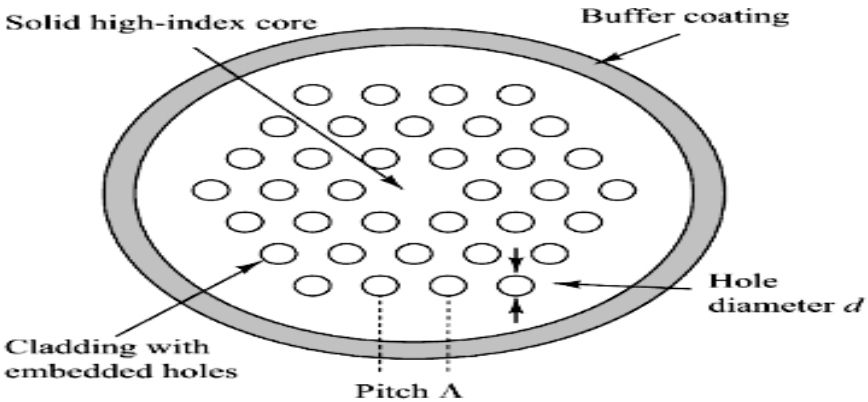


- The size and spacing of the holes in the micro-structure and the refractive index of its constituent material determine the light-guiding characteristics of photonic crystal fibers.
- The comparatively large index contrast between air and glass in PCFs, and the ability to vary the sizes and positions of the air holes means that a much broader range of index profiles becomes possible, resulting in fibers with highly unusual optical characteristics.
- Highly non-linear, possess unusual dispersion or can be highly birefringent
- There are two guiding mechanisms in PCF: index guiding mechanism and the photonic bandgap mechanism.
- Types – High index guiding fiber & Low index guiding fiber

HIGH INDEX-GUIDING /SOLID-CORE PCFS

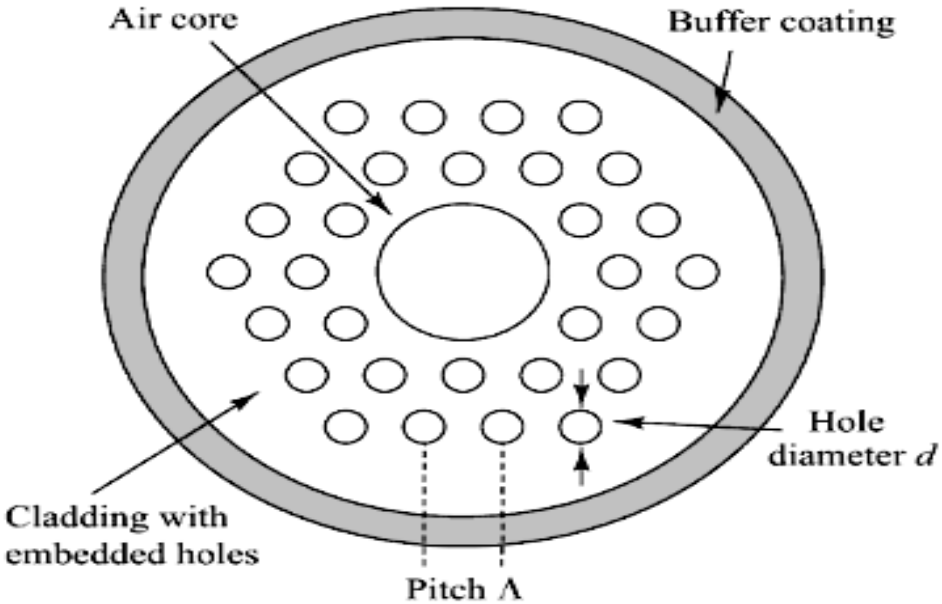
- The fiber has a solid core that is surrounded by a cladding region which contains air holes running along the length of a fiber.
- The holes have a diameter ‘d’ and spacing (pitch) ‘A’.
- solid-core PCF’s guide light by Modified Total Internal Reflection (M-TIR) at the boundary between a low index cladding and a high index core.
- In a PCF the required index difference is achieved by incorporating holes into the cladding.
- The total internal reflection is caused by the lower effective index in the micro structured air-filled region.
- Applications

1. Super continuum generation
2. Power delivery
3. Sensors



LOW INDEX-GUIDING /HOLLOW-CORE PCFS

- The fiber has a hollow core that is surrounded by a cladding region which contains air holes running along the length of the fiber.
- The hollow core fibers have a lower index than the surrounding medium
- The holes in the cladding region have a diameter ‘d’ and spacing (pitch) ‘A’.



- In this fiber, the hollow core acts as a defect in the photonic bandgap structure, which creates a region in which the light can propagate
- Hollow core fibers employ a fundamentally different guiding mechanism ie photonic bandgap mechanism.
- A photonic bandgap in the cladding acts as a virtually loss-free mirror confining light to a core .
- This makes it possible to create low-loss waveguides with gas filled or even evacuated cores at optical wavelength.
- Guiding light in a hollow core holds many applications like high power delivery without the risk of fiber damage, gas sensors or extreme low loss guidance in vacuum.

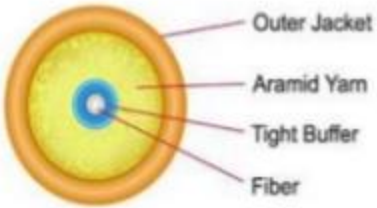
FIBRE CABLES

- A fiber optic cable is a network cable that contains strands of glass fibers inside an insulated casing.
- These cables are designed for long distance and very high bandwidth (gigabit speed) network communications.

- Types of fiber optics cables

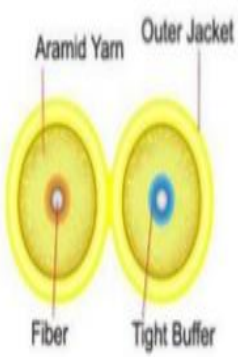
1. Simplex Cable (Single strand of fiber surrounded by a 900 um buffer then a layer of Kevlar and finally the outer jacket)

1. Simplex Cable

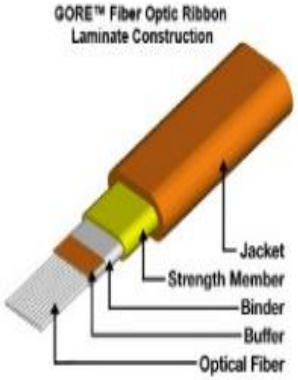


2. Duplex Cable (Two single strands of fiber optic cable attached at the center. Surrounded by a 900 um buffer then a layer of Kevlar and finally the outer jacket)
3. Fiber Optic Ribbon (A coherent optical fiber bundle in which the configuration is flat rather than round, giving an output in a line)
4. Loose Tube (250 um fibers inside of a smooth tube are then surrounded by a water resistant tape and all tubes are incased inside a protective outer jacket)

2. Duplex Cable



3. Fiber Optic Ribbon



4. Loose Tube

ADVANTAGES

- Extremely high bandwidth
- Security
- Immunity and reliability
- Resistance to electromagnetic interference
- Less expensive.
- Less signal degradation
- Non-flammable
- Low power

DISADVANTAGES

- Installation costs
- Special test equipment is often required
- Fragile Fibers can be broken or have transmission loses when wrapped around curves of only a few centimeters radius.

OPTICAL SOURCES

- Convert electrical energy into optical energy
- Requirements
- Size and configuration compatible with launching light into fiber
- Should be linear
- Emit light at wavelengths where fiber has low losses,dispersion
- Capable of direct modulation ranging from audio frequencies to Ghz range.
- Should couple sufficient optical power to overcome attenuation in the fiber

- Should have narrow spectral bandwidth
- Must be capable of maintaining stable optical output
- Should be cheap and highly reliable

- Types

1. Wideband continuous spectra(Incandescent lamps)
2. Monochromatic incoherent(LEDs)
3. Monochromatic coherent (LDs)

LED

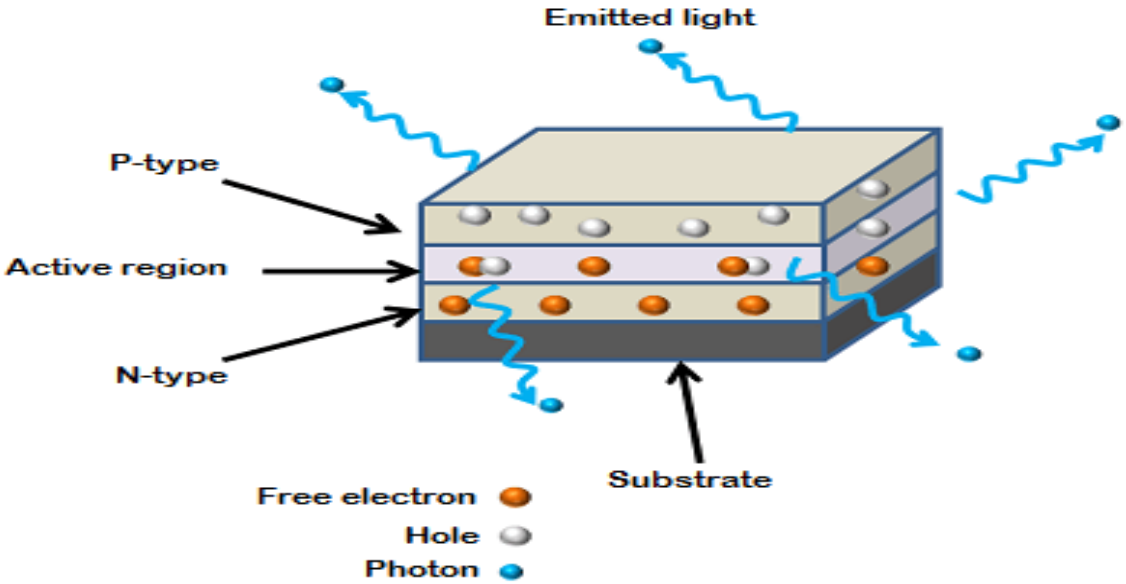
- An optical semiconductor device that converts electrical energy into light energy.
- Light emitting diodes emit either visible light or invisible infrared light when forward biased.
- The LEDs which emit invisible infrared light are used for remote controls.
- When Light Emitting Diode (LED) is forward biased, free electrons in the conduction band recombines with the hole in the valence band and releases energy in the form of light. The process of emitting light in response to the strong electric field or flow of electric current is called electroluminescence.
- LEDs operates only in forward bias condition’

- To be useful in fiber transmission applications, an LED must have high radiance o/p, a fast emission response time & high quantum efficiency.
- An LED which uses the same material on both sides with different conductivity is called a homojunction LED, & has poor radiance and low quantum efficiency
- A heterojunction LED generally consists of a combination of multiple heterojunctions that secure the carriers and the emitted photon.
- The two basic LED configurations used in fiber optics are Surface emitters & Edge emitters.
- In the surface emitter, the plane of the active light-emitting region is oriented perpendicularly to the axis of the fiber.In this configuration, a well is etched through the substrate of the device, into which a fiber is then cemented in order to accept the emitted light.
- The edge emitter consists of an active junction region, which is the source of the incoherent light, and two guiding layers. The guiding layers both have a refractive index which is lower than that of the active region, but higher than the refractive index of the surrounding material.This structure forms a waveguide channel that directs the optical radiation toward the fiber core.

LED construction

- A Light Emitting Diode (LED) consists of three layers: p-type semiconductor, n-type semiconductor and depletion layer. The p-type semiconductor and the n-type semiconductor are separated by a depletion region or depletion layer.
- LED uses gallium, phosphorus and arsenic materials are used for construction instead of silicon or germanium materials since they emit light.
- When LED is forward biased, free electrons from n-type semiconductor and holes from p-type semiconductor are pushed towards the active region.
- When free electrons from n-side and holes from p-side recombine with the opposite charge carriers in active region, an invisible or visible light is emitted.

- The safe forward voltage ratings of most LEDs is from 1V to 3 V and forward current ratings is from 200 mA to 100 mA.
- If the voltage applied to LED is increased to a value greater than 3 volts. The depletion region in the LED breaks down and the electric current suddenly rises which may destroy the device. To avoid this a resistor (R_s) is placed in series with the LED. The resistor placed between LED and voltage source is called current limiting resistor.
- The voltage drop of LED is 2 to 3V whereas silicon or germanium diode is 0.3 or 0.7 V.Therefore, to operate LED we need to apply greater voltage than silicon or germanium diodes. Light emitting diodes consume more energy than silicon or germanium diodes.

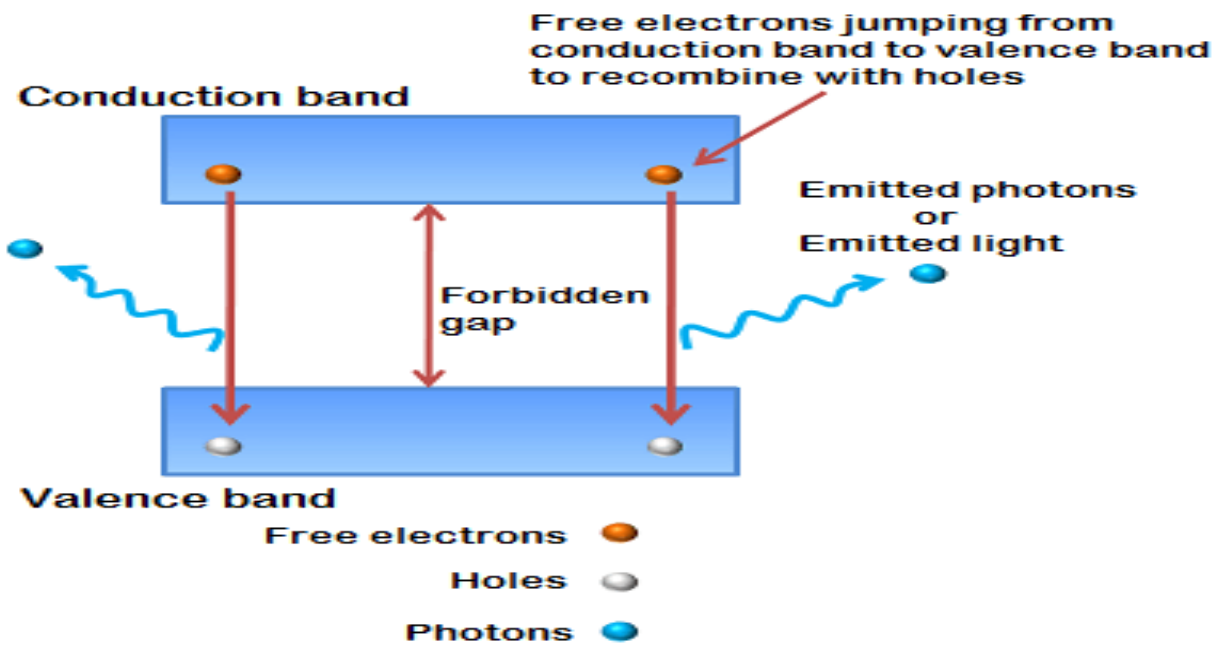


LED - WORKING

- When external voltage is applied to the valence electrons, they gain sufficient energy and left the parent atom with an empty space in the valence shell. This empty space in the valence shell is called a hole.
- The energy level of all the valence electrons is almost same. Grouping the range of energy levels of all the valence electrons is called valence band. In the similar way, grouping the range of energy levels of all the free electrons is called conduction band.
- The energy level of free electrons in the conduction band is high compared to the energy level of holes in the valence band. Therefore, free electrons in the conduction band need to lose energy in order to recombine with the holes in the valence band. Each recombination of charge carrier will emit some light energy.

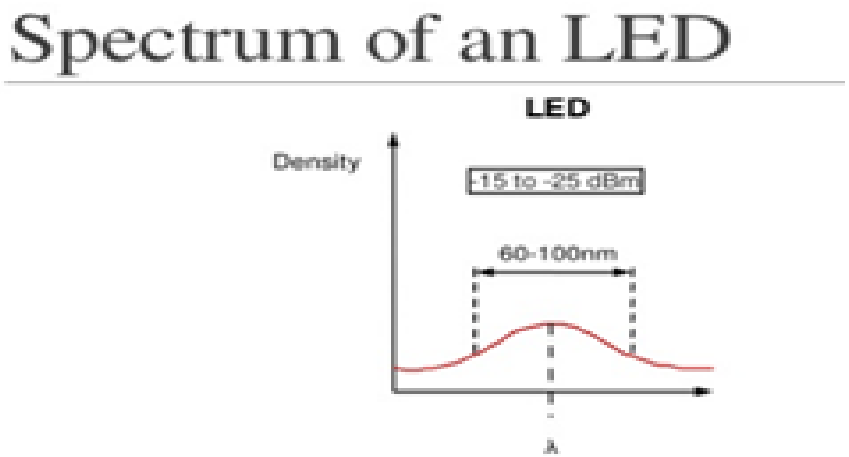
- The intensity of emitted light is depends on the forbidden gap or energy gap between conduction band and valence band.
- The semiconductor device with large forbidden gap emits high intensity light whereas the semiconductor device with small forbidden gap emits low intensity light.
- The efficiency of generation of light in LED increases with increase in injected current and with a decrease in temperature.
- In light emitting diodes, light is produced due to recombination process. Recombination of charge carriers takes place only under forward bias condition. Hence, LEDs operate only in forward bias condition.
- Light emitting diodes can be switched ON and OFF at a very fast speed of 1 ns.

- When light emitting diode is reverse biased, the free electrons from n-side and holes from p-side moves away from the junction. As a result, the width of depletion region increases and no recombination of charge carriers occur. Thus, no light is produced.
- All diodes emit photons or light but not all diodes emit visible light. The material in an LED is selected in such a way that the wavelength of the released photons falls within the visible portion of the light spectrum.



Different materials emit different colors of light.

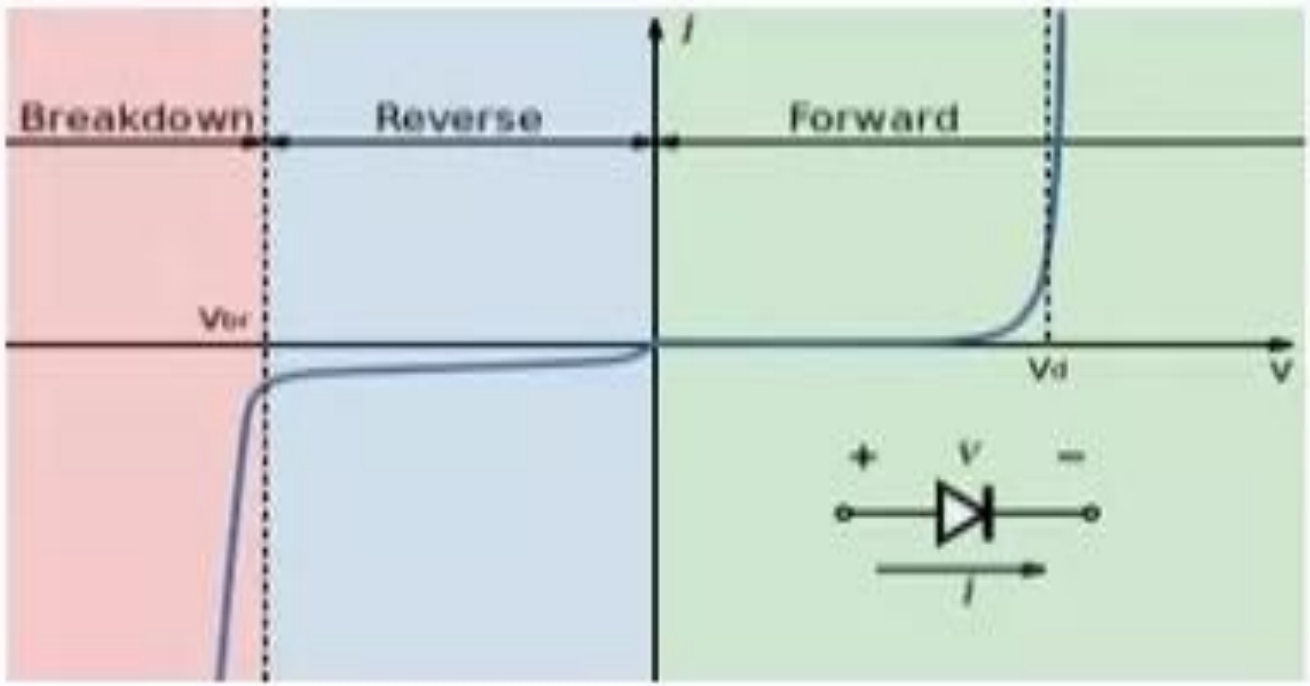
- Gallium arsenide LEDs emit red and infrared light.
- Gallium nitride LEDs emit bright blue light.
- Yttrium aluminium garnet LEDs emit white light.
- Gallium phosphide LEDs emit red, yellow and green light.
- Aluminium gallium nitride LEDs emit ultraviolet light.
- Aluminum gallium phosphide LEDs emit green light.



I-V Characteristics of Light Emitting Diode

- When the light emitting diode is forward biased by applying 2 or 3 volts across its terminals then it emits the visible coloured, invisible infrared or laser light of narrow band width.
- In this condition, it shows that the forward current is almost constant at early stage but when it is fully on then the forward current is increased up constantly shown is figure.
- The light intensity depends upon this current when this current is high then the intensity of output light would be high.
- The voltage at which the current is increased constantly is called forward voltage and is denoted by Vd in figure .

- In reverse bias condition the reverse current or leakage current is almost linearly constant but a point is come when its PN junction is breakdown and reverse current is increased constantly in negative current region.
- The voltage at which the breakdown is occurred is called breakdown voltage and is denoted by Vbr shown is figure.



MODULATION OF LED

- In order to code information as pulses, it is necessary to modulate the output of the LED.This is done by switching the current ON and OFF.
- The frequency response of an LED depends on:

  1- Doping level in the active region

  2- Injected carrier lifetime in the recombination region

  3- Parasitic capacitance of the LED
- If the drive current of an LED is modulated at a frequency of ω the output optical power of the device will vary as:

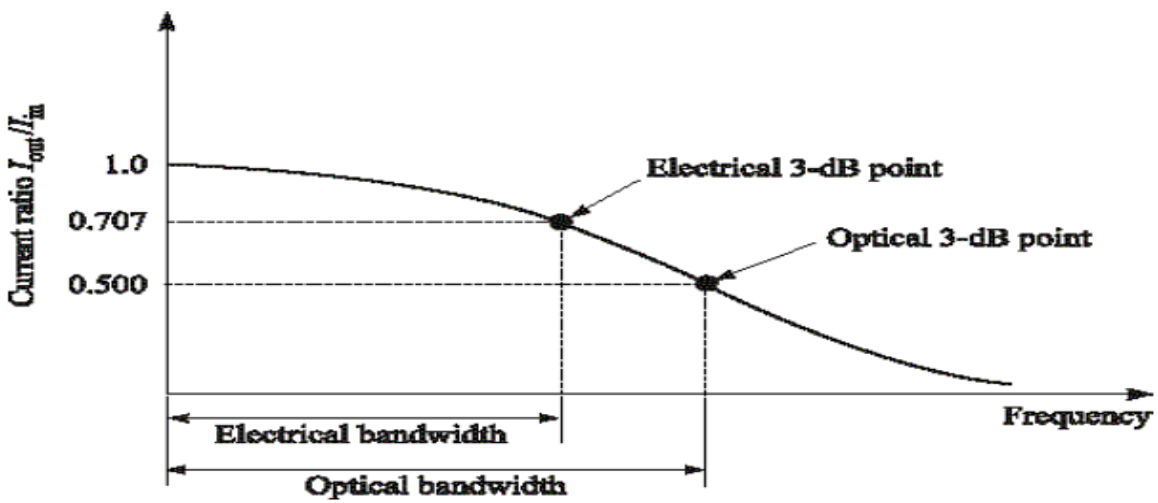
$$P(\omega) = \frac{P_0}{\sqrt{1 + (\omega \tau_i)^2}}$$

- Electrical current is directly proportional to the optical power, thus we can define electrical bandwidth and optical bandwidth, separately

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

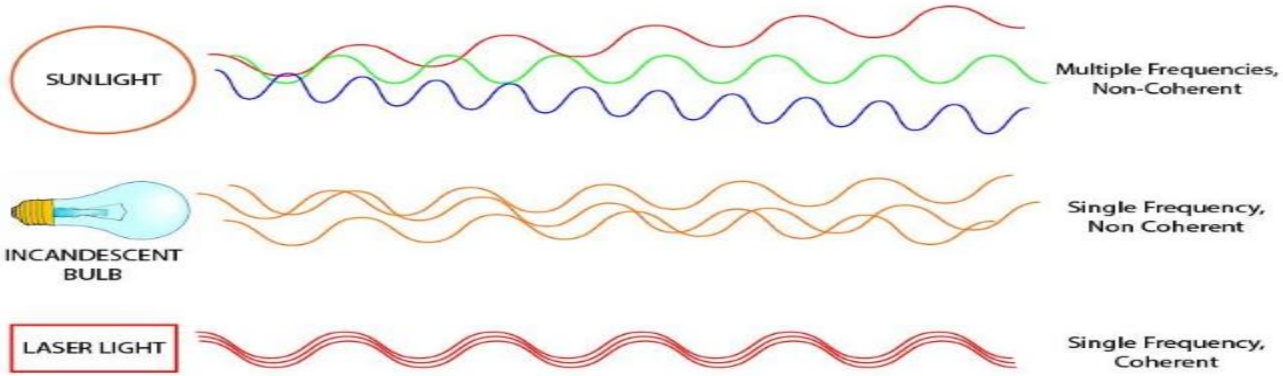
p : electrical power, I : electrical current

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



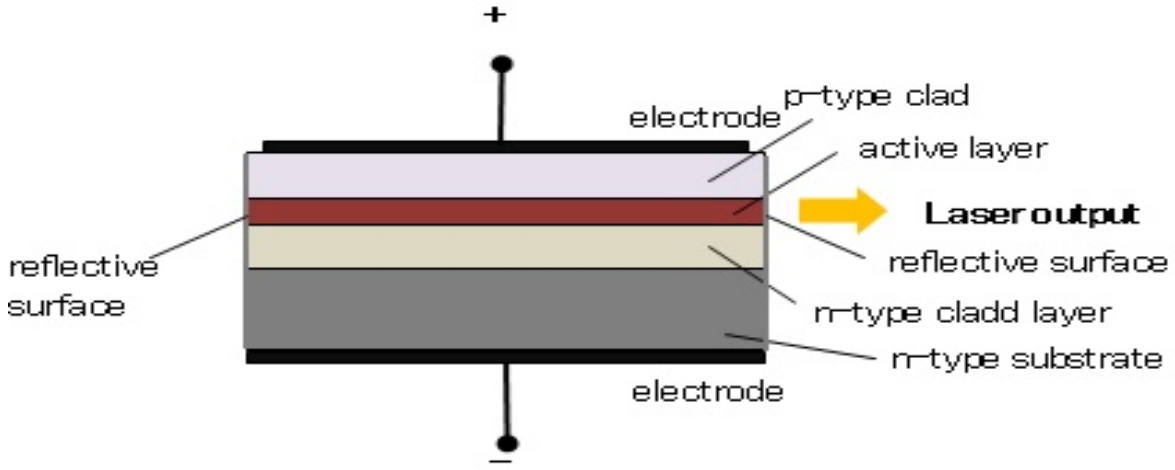
LASER DIODE

- A Laser Diode is a semiconductor device similar to a light-emitting diode (LED).
- It uses p-n junction to emit coherent light in which all the waves are at the same frequency and phase.
- This coherent light is produced by a process termed as "Light Amplification by Stimulated Emission of Radiation", which is abbreviated as LASER.
- And since a p-n junction is used to produce laser light, this device is named as a laser diode.



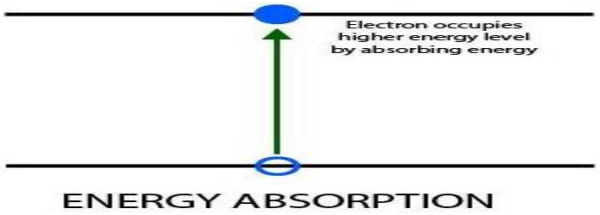
LASER construction

- It uses gallium arsenide doped with elements such as selenium, aluminum, or silicon to produce P type and N type semiconductor materials.
- Laser diode has an additional active layer of undoped (intrinsic) gallium arsenide sandwiched between the P and N layers, effectively creating a PIN diode (P type-Intrinsic-N type).
- Light beam from the laser diode can be further focused using an optical lens. This entire PIN diode (P-type, Intrinsic, N-Type) arrangement is enclosed normally in a metal casing.

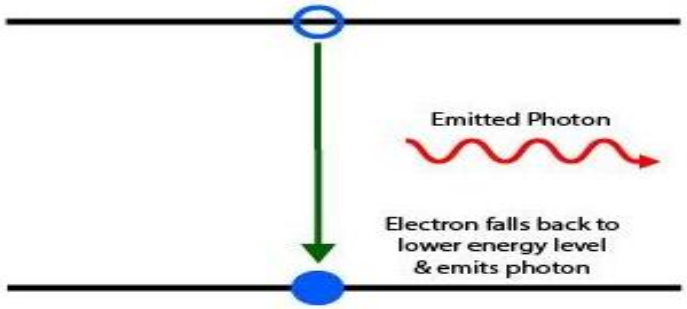


LASER - WORKING

- Laser action is the result of three key processes
  - Energy absorption
  - Spontaneous emission and
  - Stimulated emission
- **Energy Absorption-**When a certain voltage is applied at the p-n junction, the electrons absorb energy and they transition to a higher energy level. Holes are formed at the original position of the excited electron. The electrons stay in this excited state without recombining with holes for a very small duration of time, termed as “recombination time”

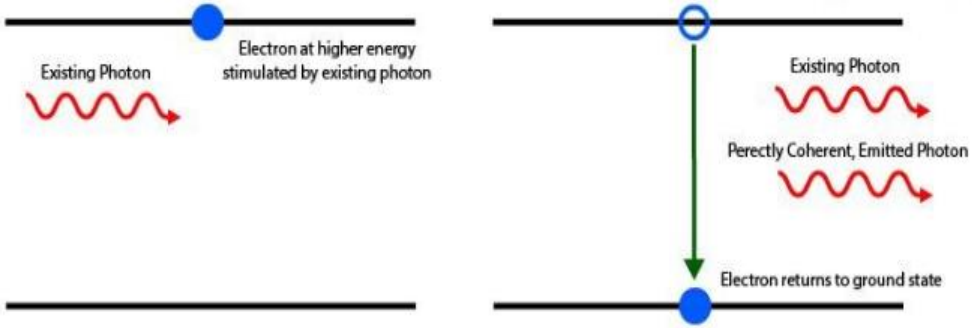


- **Spontaneous Emission-**After the upper-state lifetime of excited electrons, they recombine with holes. As the electrons fall from higher energy level to a lower energy level, the difference in energy is converted into photons or electromagnetic radiation.



SPONTANEOUS EMISSION

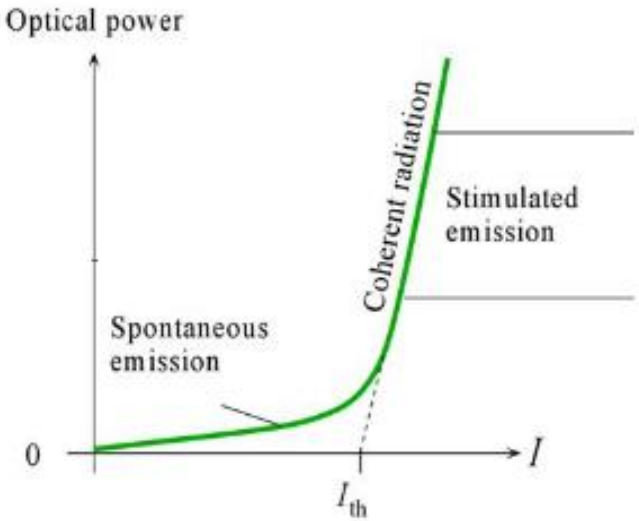
- **Stimulated Emission-**A partially reflecting mirror is used on either side of the diode so that the photons released from spontaneous emission are trapped in the p-n junction until their concentration reaches a threshold value. These trapped photons stimulate the excited electrons to recombine with holes even before their recombination time. This results in the release of more photons so the output gets amplified.



STIMULATED EMISSION

P-V Characteristics of LASER Diode

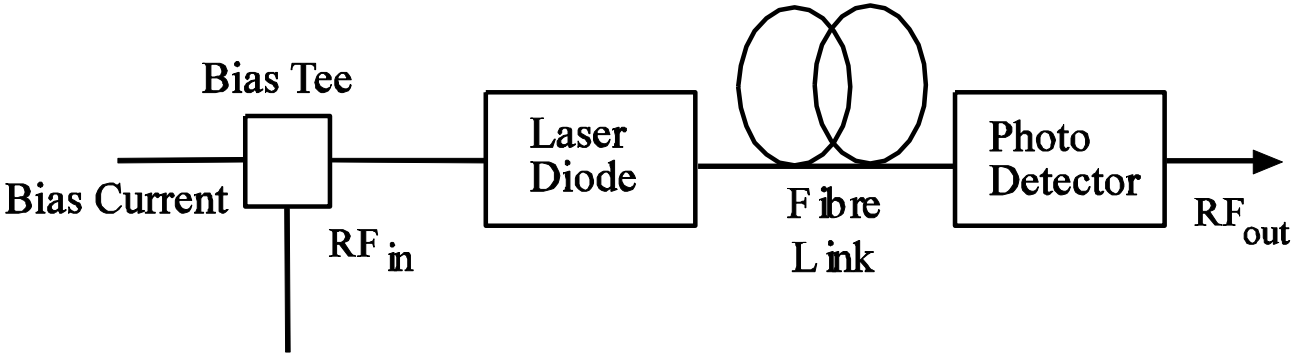
- The laser diode is operated at a much higher current, typically about 10 times greater than a normal LED.
- In a laser diode, however laser light is not produced until the current level reaches the threshold level when stimulated emission starts to occur.
- Above this threshold current, the process of stimulated emission increases.
- This causes the power of output light to increase a lot even for smaller increases in input current.
- The output optical power also depends on temperature and it reduces with decrease in temperature.



MODULATION OF LASER DIODE

- Optical sources can be modulated either directly or externally.
- Direct modulation is done by modulating the driving current according to the message signal (digital or analog)
- In external modulation, the laser is emits continuous wave (CW) light and the modulation is done in the fiber
- For data rates of less than 10 GB/s, direct modulation can be done.
- For higher data rates, a device known as external modulator needs to be used.

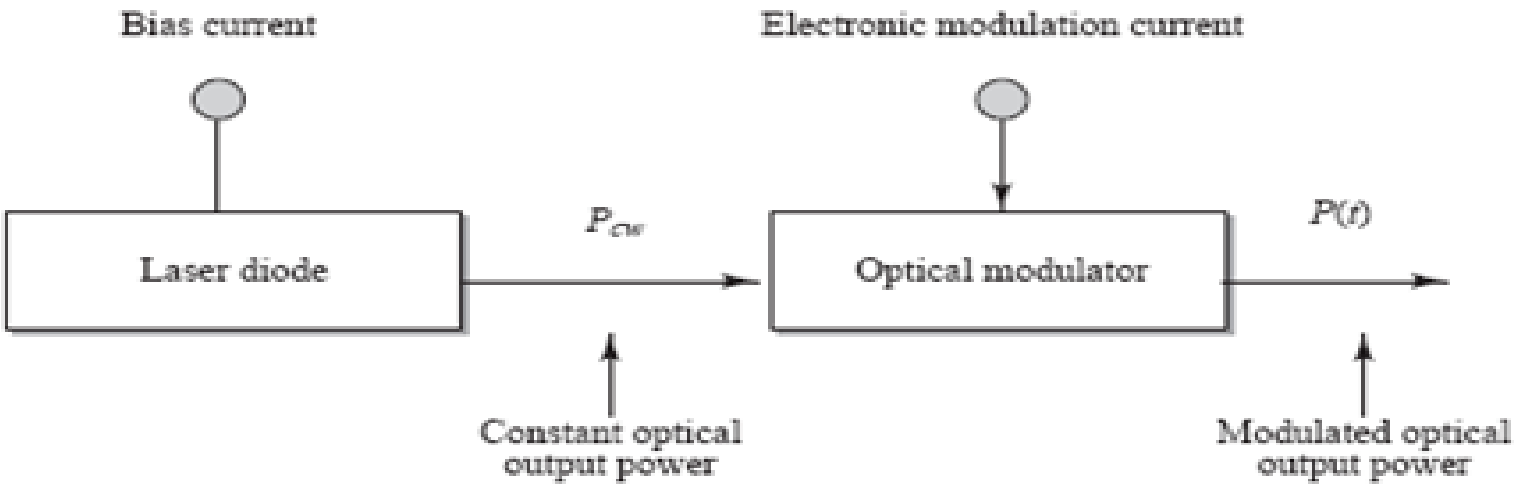
1) Direct Modulation



- The message signal (ac) is superimposed on the bias current (dc) which modulates the laser
- Robust and simple, hence widely used
- Issues: laser resonance frequency, chirp, turn on delay, clipping and laser nonlinearity
- When direct modulation is used in a laser transmitter, the process of turning the laser on and off with an electrical drive current produces a widening of the laser line width.This phenomenon is referred to as **chirp** .

2) External modulation

- In external modulation, the optical source emits a constant-amplitude light signal which enters the external modulator
- In this case,the optical power level that exits the external modulator is changed.This process produces a time-varying optical signal.
- Two main types of external modulators are Electro-optical modulator & Electro-absorption modulator.



NOISE IN LASER DIODES

- “Noise” of lasers is fluctuations of various output parameters. This is a frequently encountered phenomenon which has a profound impact on many applications in photonics, particularly in the area of precision measurements.
- **Types**

1) Modal (speckel) Noise: Fluctuations in the distribution of energy among various modes.

2) Mode partition Noise: Intensity fluctuations in the longitudinal modes of a laser diode, main source of noise in single mode fiber systems.

3) Reflection Noise: Light output gets reflected back from the fiber joints into the laser, couples with lasing modes, changing their phase, and generate noise peaks. Isolators & index matching fluids can eliminate these reflections.

- Minimization of laser noise can be done by

1. Minimization of external noise influences
2. Optimization of laser parameters
3. Use of automatically adjusting feedback system

MODULE 2

- Fibre materials, fabrication of fibres,
- photonic crystal fibre, index guiding PCF, photonic bandgap fibre, fibre cables.
- Optical sources, LEDs and LDs, structures, characteristics,
- Modulators using LEDs and LDs. coupling with fibres,
- Noise inLaser diodes, Amplified Spontaneous Emission noise, effects ofLaser diode noise in fibre communications

Ref 1: BIREFRINGENCE

- Birefringence is the optical property of material having a refractive index that depends on the polarization and propagation direction of light.
- These optically anisotropic material are said to be birefringent.
- The birefringence is often quantified as the maximum difference between effective index of the Fundamental mode(FM).
- Birefringence is responsible for the phenomenon of double refraction.

MODULE 3

OPTICAL DETECTORS

- The function of an optical detector is to convert the optical signal into an electrical signal, which can then be further processed.
- It senses the luminescent power falling upon it and converts the variation of this optical power into a correspondingly varying electric current.
- Characteristics of optical detectors

a. Sensitivity has to be matched to the emission spectra of the optical transmitter

b. Linearity

c. Reliability and Robustness

d. Low Noise

e. Lost Cost

f. High quantum efficiency

g. Fast response time

h. Stability of performance

TYPES OF PHOTO DETECTORS

1. Photomultipliers,
2. Pyroelectric detectors, and
3. Semiconductor-based photoconductors such as phototransistors and photodiodes.

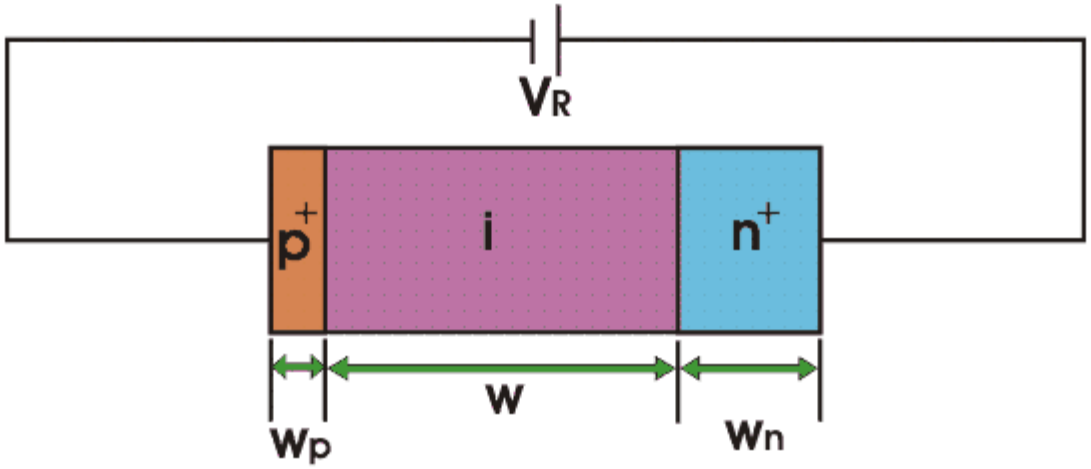
- Photomultipliers consists of a photocathode and an electron multiplier packaged in a vacuum tube. Due to its large size, it becomes un suitable with optical fiber.
- Pyroelectric detectors involve the conversion of photons to heat.
- Of the semiconductor-based photo detectors, the photodiode is used almost exclusively for fiber optic systems.
- The two types of photodiodes used are the pin photodetector (PIN)& Avalanche photodiode (APD).

PIN DIODE

- It is a kind of photo detector which can convert optical signals into electrical signals.
- Most common semiconductor diode

STRUCTURE

- PIN diode consists of heavily doped P and N regions separated by a wide intrinsic region.



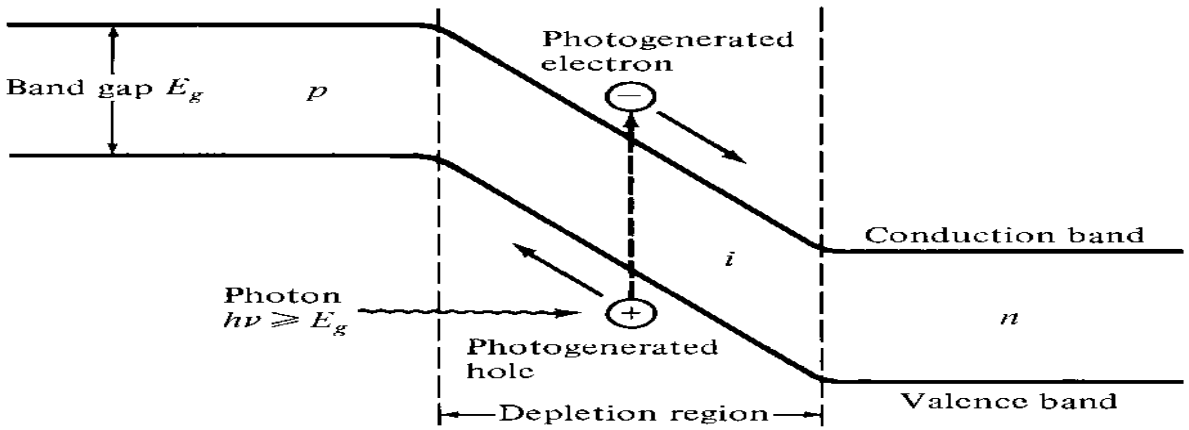
- In P-region the hole is the majority charge carrier while in n-region the electron is the majority charge carrier.
- The intrinsic region has no free charge carrier. It acts as an insulator between n and the p-type region.
- The i-region has the high resistance which obstructs the flow of electrons to pass through it.
- PIN diode works as an ordinary PN junction diode frequencies up to a 100 MHZ. Above 100 MHZ it seizes its operation of rectifier and behaves as a switch or resistance. In reverse bias it acts as a capacitor.

Applications

- High voltage rectifier.
- Ideal radio frequency switch.
- Photo detector

- **UNBIASED** : when the PIN is unbiased there is a diffusion of electron across the junction. Depletion region is formed between PI and IN regions with more penetration in intrinsic region.
- **FORWARD BIAS** : When the diode is forward biased, the injected carrier concentration is typically several orders of magnitude higher than the intrinsic level carrier concentration. Due to this high level injection, which in turn is due to the depletion region , the electric field extends deeply (almost the entire length) into the region. This electric field helps in speeding up of the transport of charge carriers from P to N region, which results in faster operation of the diode, making it a suitable device for high frequency operations. In forward bias the diode behaves as a variable resistance and resistance decreases with increase in forward bias voltage.
- **Reverse Bias** : As the reverse bias voltage is increased the depletion layer thickness increases . The device behaves as a variable capacitor until the intrinsic region becomes free of mobile carriers. This voltage is called swept out voltage . At this voltage the device works as a constant capacitor.

WORKING



- In normal operation, a sufficiently large reverse bias voltage is applied across the device so that the intrinsic region is fully depleted of carriers.
- When an incident photon has energy greater than that or equal to the band-gap energy of the semiconductor material, the photon can give up its energy and excite an electron from the valence band to the conduction band.This process generates electron-hole pairs.These electrons and holes are called photocarriers.

- The photodetector is normally designed so that these carriers are generated mainly in the depleted intrinsic region where most of the incident light is absorbed.
- The high electric field present in the depletion region causes the carriers to separate and be collected across the reverse biased junction.
- This gives to a current flow known as the photocurrent.
- As the charge carriers flow through the material, some electron-hole pairs will recombine and hence disappear.

- On the average, the charge carriers move a distance L_n or L_p for electrons and holes, respectively. The distance is known as diffusion length.
- The time it takes for an electron or hole to recombine is known as the carrier life time and is represented by τ_n and τ_p respectively.
- The lifetimes and diffusion lengths are related by the expressions

$$L_n = (D_n \tau_n)^{1/2} \text{ and } L_p = (D_p \tau_p)^{1/2}$$

Where D_n and D_p are the electron and hole diffusion constants.

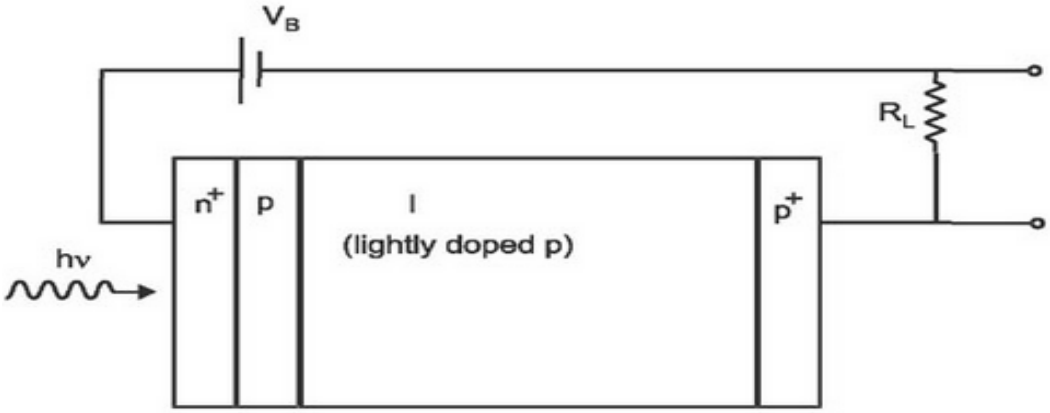
TYPES

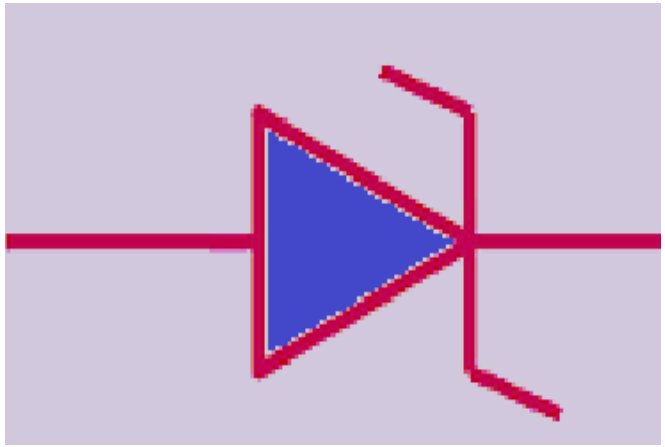
1) FRONT ILLUMINATION PD :- The light passes through the thin p region and generates electron-hole pairs in the thick intrinsic layer

2) REAR-ILLUMINATION PD :- Light enters the active region through a heavily doped n + layer. This layer is transparent to the incident light because its energy gap is larger than the energy of incident photons

AVALANCHE PHOTODIODES

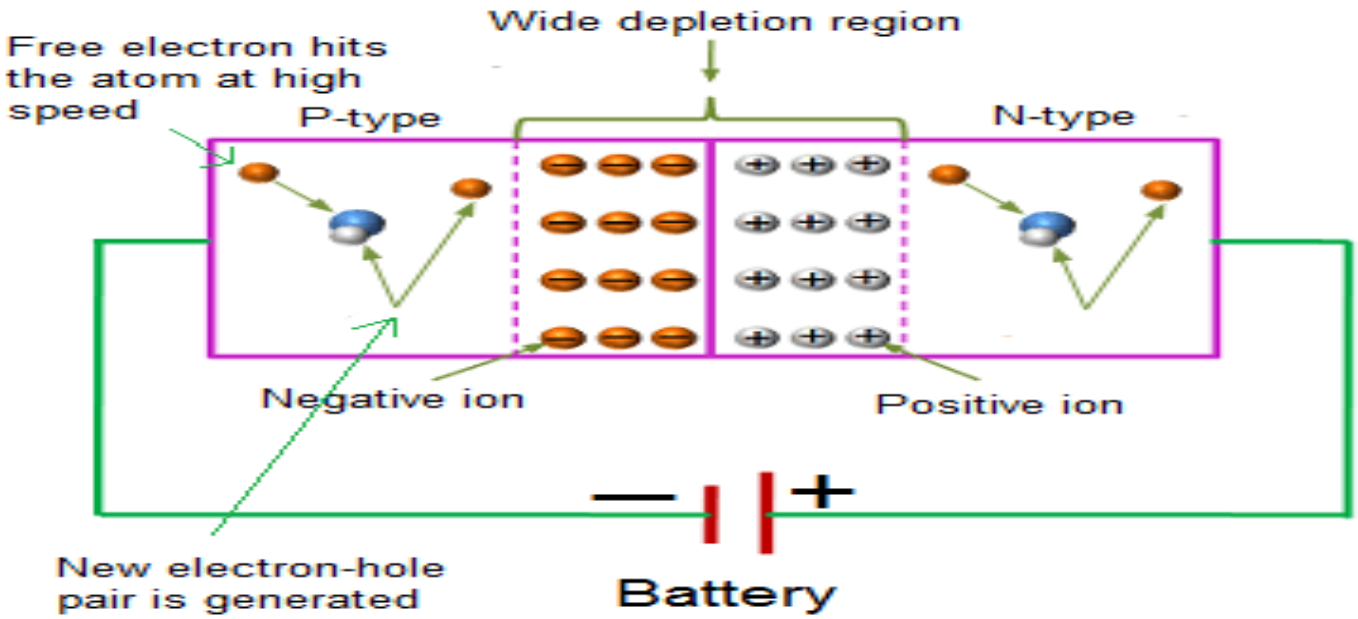
- An avalanche diode is a special type of semiconductor device designed to operate in reverse breakdown region.
- Avalanche diodes are lightly doped. Therefore, the width of depletion layer in avalanche diode is very wide Because of this wide depletion region, reverse breakdown occurs at higher voltages in avalanche diode.
- The operating principle of a APD is based on the avalanche effect, where a highly accelerated electron excites another electron due to “impact ionization”.





WORKING

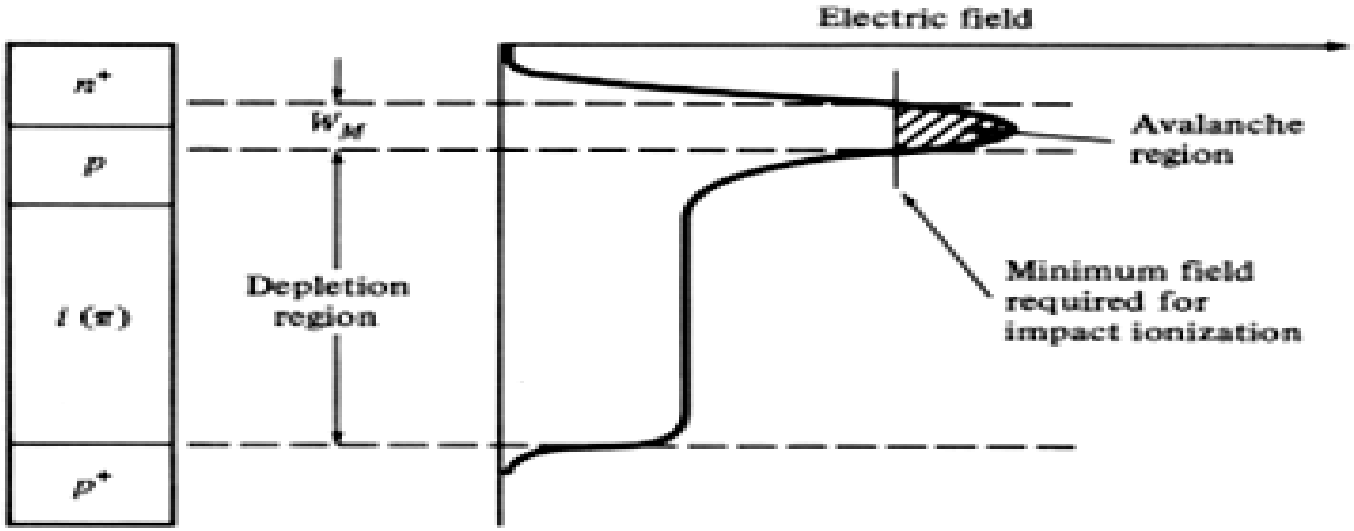
- Avalanche diode allows electric current in both forward and reverse directions.
- When forward bias voltage is applied to the avalanche diode, it works like a normal p-n junction diode by allowing electric current through it.



- When reverse bias voltage is applied to the avalanche diode, the majority carriers are moved away from the junction and the width of depletion region increases.
- However, the minority carriers experience a repulsive force from external voltage and flow from p-type to n-type and n-type to p-type by carrying the electric current.This small electric current carried by minority carriers is called reverse leakage current.
- If the reverse bias voltage applied to the avalanche diode is further increased, the minority carriers will gain large amount of energy and accelerated to greater velocities. These electrons moving at high speed will collide with the atoms and transfer their energy to the valence electrons.

- The valance electrons which gains enough energy and get detached from the parent atom and become free electrons. This carrier multiplication mechanism is known as impact ionization.
- These free electrons are again accelerated. When these free electrons again collide with other atoms, they knock off more electrons.Because of this continuous collision with the atoms, a large number of minority carriers are generated. This phenomenon is known as the avalanche effect.
- When the reverse voltage applied to the avalanche diode continuously increases, at some point the junction breakdown or avalanche breakdown occurs. At this point, a small increase in voltage will suddenly increases the electric current.

- A commonly used structure for achieving carrier multiplication with very little excess noise is the reach-through construction.
- The reach-through avalanche photo diode (RAPD) is composed of a high resistivity p-type material deposited on a heavily doped p-type substrate.
- P-type diffusion is then made in the high resistivity material followed by the construction of an n^+ layer.
- This configuration is referred to as $p^+\pi pn^+$ reach-through structure.
- The π layer is basically an intrinsic material, but actually doped by p-type materials because of imperfect purification.



- When a low reverse bias voltage is applied, most of the potential drop is across the pn^+ junction.
- The depletion layer widens with increasing bias until a certain voltage is reached at which the peak electric field at the pn^+ junction is about 5-10 % below that is needed to cause avalanche breakdown.
- At this point, the depletion layer just ”reaches through” to the nearly intrinsic π region.

- In the normal usage, RAPD is operated in the fully depleted mode. Light enters the device through p^+ region and is absorbed in the π material.
- Upon being absorbed, the photon gives up its energy, thereby creating electron-hole pairs, which are then separated by the electric filed in the π region.
- The photo generated electrons drift through the π region in the pn^+ junction, where a high electric field exists.
- It is in this high-field region that carrier multiplication takes place.
- The average no: of electron-hole pairs created by a carrier per unit distance traveled is called the *ionization rate*.

Applications

- Avalanche diodes can be used as white noise generators.
- Avalanche diodes are used in protecting circuits.

COMPARISON

Sr. No.	PIN photodiodes	Avalanche photodiodes
1.	An undopped intrinsic layer (i) is placed between two highly dopped regions.	Here 'π' layer is placed between p and n regions.
2.	Gain is not provided.	More gain is provided.
3.	Amplifier is required to connect externally.	No external amplifier required.
4.	Response time is less.	More response time.
5.	Output current is small.	More output current is obtained.
6.	Different noise currents are photon noise, shot noise, Johnson noise and generation recombination noise.	Different noise currents are shot noise, thermal noise and avalanche noise.
7.	Shot current is, $I_{shot} = \sqrt{2qI_D B}$	Shot current is, $I_{shot} = \sqrt{2q\,(I_{ph} + I_B + I_D) \cdot G^2 \cdot F \cdot B}$
8.	Sensitivity is less.	Higher sensitivity.
9.	Low reverse bias is required.	High reverse bias is required.
10.	Good temperature stability.	Poor temperature stability.

NOISE IN DETECTORS

- Noise is a term generally used to refer to any undesired disturbances that mask the received signal in a communication system
- Noise is any electrical or optical energy apart from the signal itself.
- An optical signal that is too weak cannot be distinguished from noise.
- The most important noises associated with the photodetector and the receivers are:

1. Shot Noise
2. Dark Current
3. Thermal Noise

SHOT NOISE

- Discrete nature of electrons causes a signal disturbance called shot noise.
- Deviation of the actual number of electrons from the average number is known as shot noise.
- Shot noise arises due to the reason that an electric current is made up of stream of randomly generated electrons.
- The shot noise current has a mean-square value in a receiver bandwidth B_e that is proportional to the average value of photocurrent I_p.
- $\langle i^2_{shot} \rangle = \sigma^2_{shot} = 2q\ I_p\ B_e\ M^2\ F(M)$, where F(M) is a noise figure associated with the nature of the avalanche process & M is the average of the statistically varying avalanche gain

THERMAL NOISE

- It is also known as Nyquist noise or Johnson noise
- It arises due to thermal motion of electron in the load resistor of photodiode circuit.
- This is due to the fact that electrons in any resistor have random motion.
- Since the electron motion is random, the average value of this current is zero.
- The mean square thermal noise current in a load resistor R_L is given by

$$<i^2_{TN}> = (4K_BT_B)/R_L$$

Where K_B is the Boltzmann's constant & is $1.38*10^{-23}$J/K

T_B is the absolute temperature.

DARK CURRENT NOISE

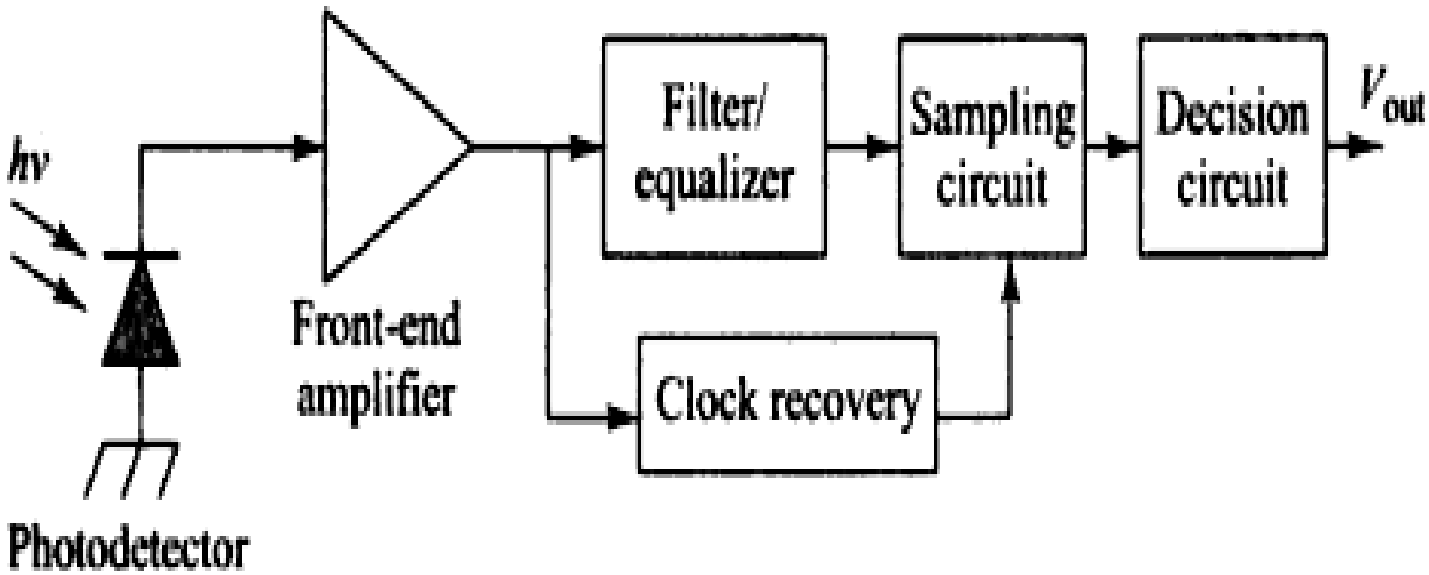
- When there is no incident optical power even then, a small reverse leakage current still flows from the device terminals,called dark current and this contributes to the total system noise.
- It arises from thermally generated carriers.
- It increases with the increase of temperature and dark current noise is given by

$$\langle i_d^2 \rangle = 2q\, B_e I_d\,,$$

where I_d is the dark current.

OPTICAL RECEIVERS

- The function of the receiver is to detect the optical power transmitted through the fiber to the photo detector and to extract the transmitted information.



- The first element is either a pin or avalanche photodiode, which produces an electric current that is proportional to the received power level.
- Since this electric current typically is very weak, a front-end amplifier boosts it to a level that can be used by the following stages.
- After amplification, the electric signal is passed through a low pass filter to reduce the noise that is outside the signal bandwidth.
- The filter can also reshape (equalize) the pulses that have become distorted as they traveled through the fiber.

- In the final optical receiver module, a decision circuit samples the signal level at the midpoint of each time slot and compares it with a certain reference voltage known as threshold level.
- If the received signal is greater than the threshold level, 1 is said be received.
- If the voltage is below the threshold level, 0 is assumed to be received.
- To accomplish this bit interpretation, a periodic waveform called clock is used , and hence the function is called clock recovery or timing recovery.
- The ***Bit Error Rate (BER)*** is the ratio of the no: of errors occurring over a certain time interval ‘t’, to the no: of pulses (ones and zeroes) transmitted during this interval.

$$BER = N_e/N_t$$

QUANTUM LIMIT OF DETECTION.

- Ideal photo detector have unity quantum efficiency and no dark current.
- The quantum efficiency is defined as fraction of incident photons which are absorbed by photoconductor and generated electrons which are collected at the detector terminal.
- Quantum limit is the minimum received power required for a specific BER assuming that the photodetector has a 100% quantum efficiency and zero dark current.

$$P_e = P_1(0) = \exp(-\overline{N})$$

- Where $\overline{N}$ is the average number of electron-hole pairs, when the incident optical pulse energy is E

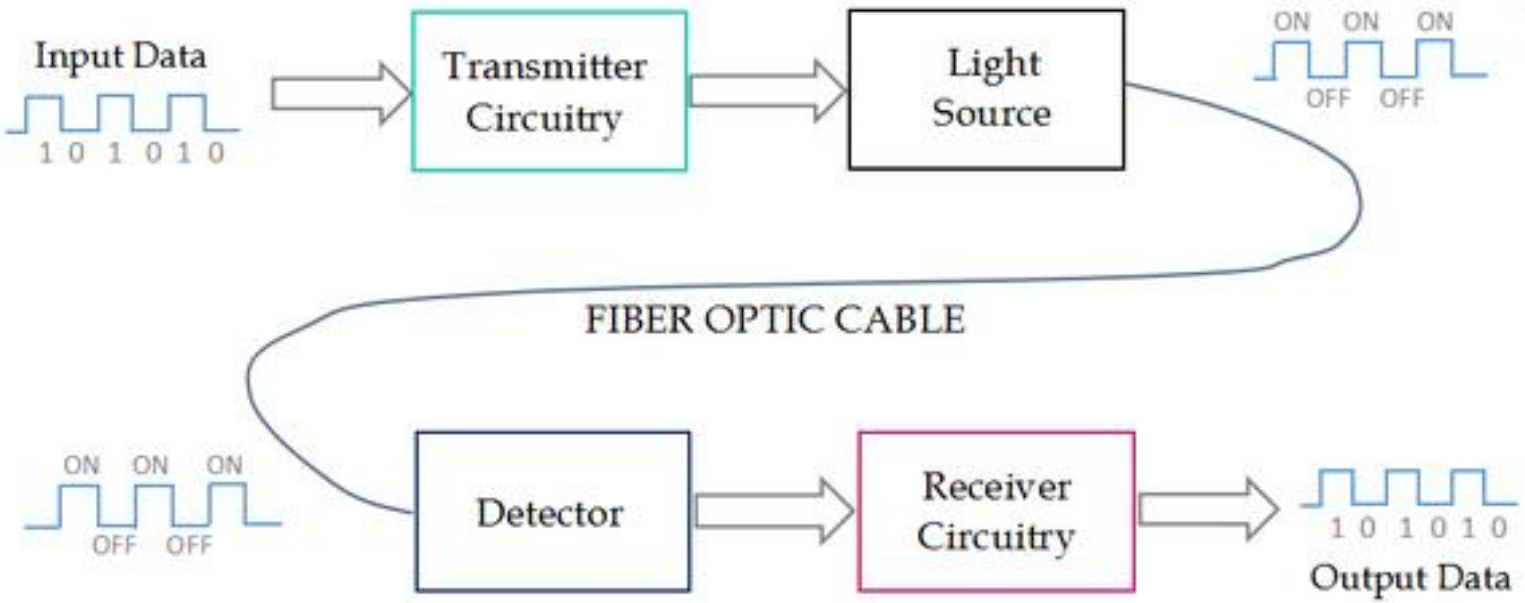
SYLLABUS

- Optical detectors- types and characteristics,
- Structure and working of PIN and APD photodiode
- Noise in detectors
- Comparison of performance.
- Optical receivers
- Ideal photo receiver and quantum limit of detection.

MODULE 4

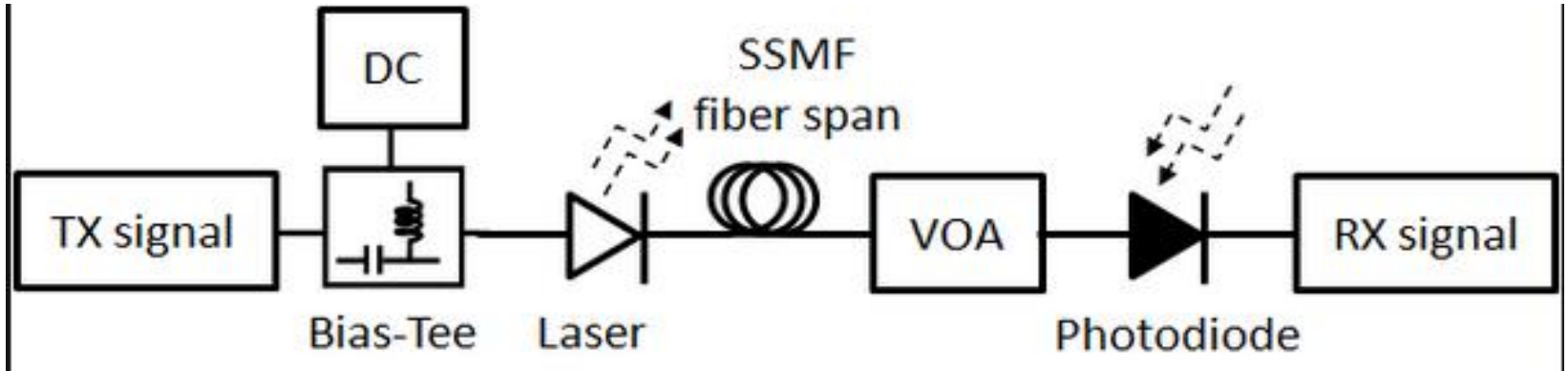
OPTICAL FIBER TRANSMISSION LINK

- Transmission can be analog or digital.
- Digital transmission system provides superior performance over analog system in terms of acceptable SNR, reduced nonlinearities, temperature dependence on optical sources and digital compatibility with digital computing and storage.
- The simplest transmission link is a point-to-point line having a transmitter at one and receiver on the other as shown in below.



IMDD (Intensity modulated direct detection) SYSTEM.

- In order to transmit, it is necessary to modulate the property of light with the information or message signal.
- The Intensity Modulation (IM) is easy to implement.
- In intensity modulation ,an information carrying electrical signal modulates the amplitude of optical signal to be transmitted.
- At the receiver end, a simple Direct Detection (DD) of the intensity-modulated light is carried out by the photodetector to convert the intensity variation into the corresponding electrical signal.
- This form of optical communication system is usually referred to as IMDD system.



DESIGN OF IMDD LINKS

- The design of an optical link involves many interrelated variables among the fiber, source and photodetector operating characteristics.
- The primary design requirements are
  - The desired (or possible) transmission distance
  - The data rate or channel bandwidth
  - The bit-error rate (BER)
  - Cost and Complexity

DESIGN STEPS

STEP 1: Operating wavelength selection

- If the distance over which the data are to be transmitted is not too far, it is decided to operate in the 800 – 900 nm region.
- On the other hand ,if the transmission distance is relatively long ,it may choose wavelengths around 1300 or 1550 nm due to low attenuation and dispersion.

STEP 2:Selection of photodetector

- In choosing a particular photodetector,we need to determine the minimum optical power that must fall on the photodetector to satisfy the bit-error-rate (BER) requirement at the specified data rate.
- PIN diodes are stable and less expensive. But APDs are highly sensitive.

STEP 3: Selection of optical source

- The system parameters involved in deciding between the use of an LED and a laser diode are Signal dispersion, Data rate, Transmission distance and Cost.

STEP 4: Selection of optical fiber

- The choice of fiber depends on the type of light source used and on the amount of dispersion that can be tolerated.
- SMF can be used with Laser and Edge emitting LEDs
- MMF can be used with LEDs.

STEP 5:Two analysis are performed to ensure the required system performance are met.

1. The link power budget analysis
2. The rise-time budget analysis.

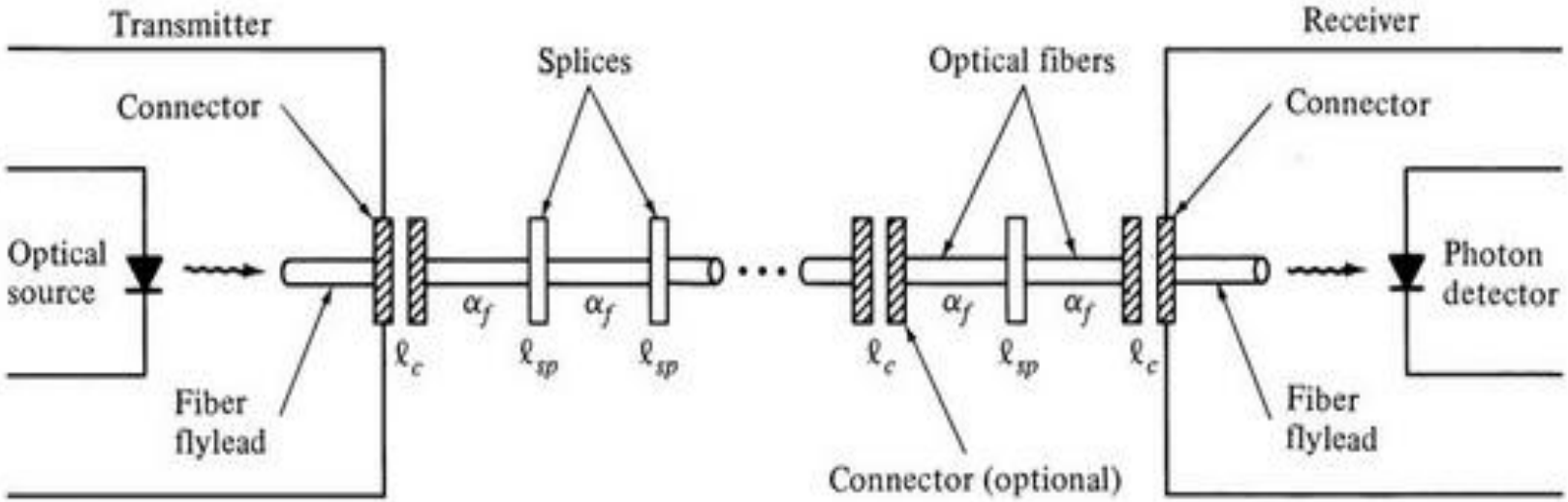
- If the choice of components did not allow the desired parameters,the components are to be changed.

LINK POWER BUDGET

- In the link power budget analysis, one first determines the power margin between the optical transmitter output and the minimum receiver sensitivity needed to establish a specified BER.
- The optical power received at the photodetector depends on the amount of light coupled into the fiber and the losses occurring in the fiber and at the connectors and the splices.
- The link loss budget simply considers the total optical power loss P_T that is allowed between the light source and the photodetector, and allocates this loss to cable attenuation, connector loss, splice loss and system margin.
- If P_S is the optical power emerging from the end of a fiber flyhead attached to the light source, and if P_R is the receiver sensitivity, then $P_T = P_S - P_R$

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

- Optical power loss model for a point to point link is shown .



- per

- During the propagation the light suffers a transmission loss α over fiber length, L. A splicing loss I_S occurs at splices.
- Finally output power P_o reaches the detector.

- Total loss ,$P_t = P_i - P_o$

$$P_t\ (dB) = 10 \log(P_o/P_i)$$

- P_t = Connector loss +Splice loss+ Fiber attenuation + System margin

$$= N_C I_C + N_S I_S + \alpha L + \text{system margin}$$

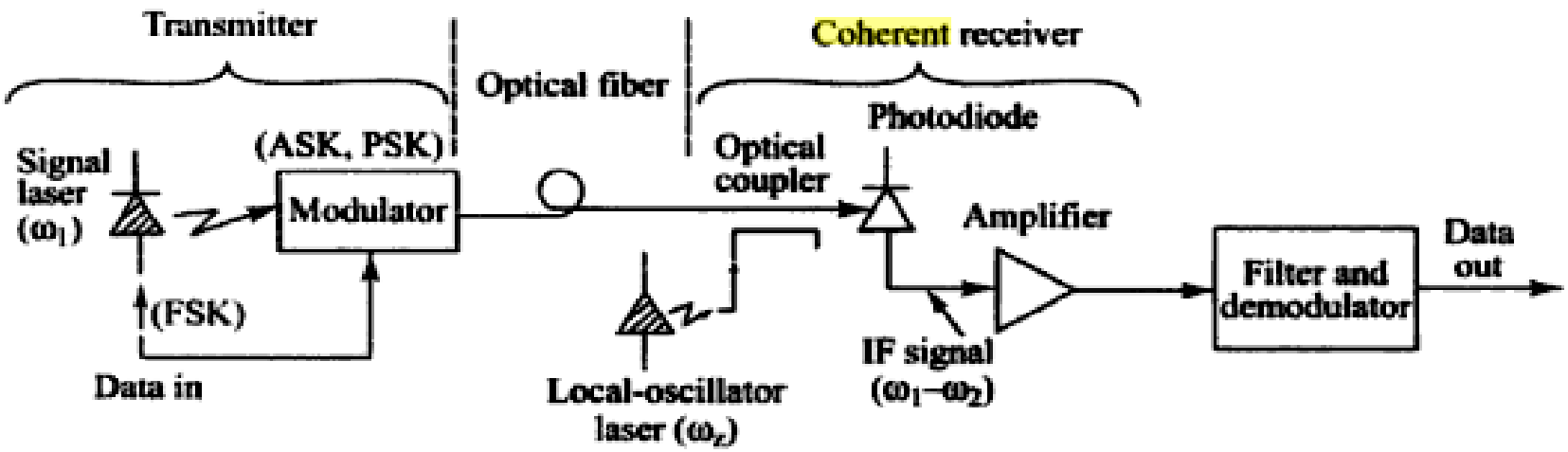
- N_C = No: of connectors
- N_s = No: of splices
- α = attenuation constant for the fiber
- System margin= 6 -8 (usually 6)

RISE-TIME BUDGET

- After establishing link power budget, rise time budget analysis is performed to ensure that the desired overall system performance is satisfied.
- A rise-time budget is a convenient method for determining the dispersion limit of an optical fiber link.
- Rise time is the time taken to attain 90 % of the steady state response.
- System rise time is a combination of source,fiber and detector rise times.
- $T_{SYSTEM} = (T_{TX}^{2} + T_{RX}^{2} + T_{FIBER}^{2})^{1/2}$
- $T_{FIBER}^{2} = T_{MODAL}^{2} + T_{GVD}^{2}$
- $T_{MODAL} =$ rise time from intermodal dispersion
- $T_{GVD} =$ rise time from group velocity dispersion

COHERENT SYSTEMS

- Optical communication systems which use homodyne or heterodyne detection are called Coherent Optical communication systems.
- In coherent detection techniques, light is treated as a carrier medium, which can be amplitude, frequency or phase modulated.
- The figure illustrates the fundamental concept in coherent light wave system.



- The key principle of coherent detection is to provide gain to the incoming signal by combining or mixing it with a locally generated continuous wave (CW) optical field.
- The device used for creating the CW signal is a narrow-line width laser called a local oscillator. (LO).
- The term “mixing” means that when two waves which have frequencies ω_1 and ω_2 are combined, the result will be other waves with frequencies equal to $2\omega_1$, $2\omega_2$ and $\omega_1 \pm \omega_2$.
- To send information, the optical carrier can be amplitude, frequency or phase modulated. Ie ASK,FSK or PSK is used.
- At the receiving end in coherent light wave systems, the receiver first adds a locally generated optical signal to the incoming information-bearing signal and then detects the combination.

- The mixing of the information signal and the local oscillator signal is done on the surface of the photo detector.
- For coherent light wave systems, all frequency components other than ω_1-ω_2 are filtered out at the receiver.
- The detected current is proportional to the square of the total electric field of the signal falling on the photo detector.
- The major advantages of the coherent systems are:
  - ✓Receiver sensitivity improvement
  - ✓Excellent frequency selectivity
  - ✓Possibility of equalization at the intermediate frequency (IF) band.

IMDD SYSTEMS

- In intensity modulation ,an information carrying electrical signal modulates the amplitude of optical signal to be transmitted.
- At the receiver end, a simple Direct Detection (DD) of the intensity-modulated light is carried out by the photo detector to convert the intensity variation into the corresponding electrical signal.
- This form of optical communication system is usually referred to as IMDD system.

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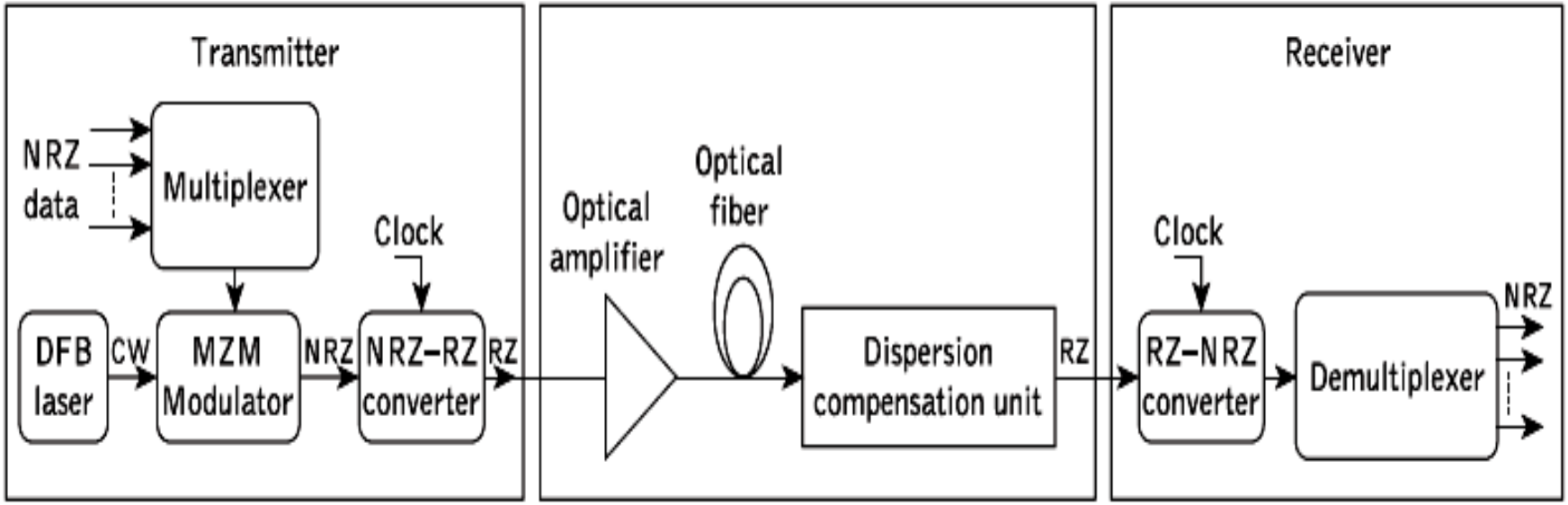
INTRODUCTION TO SOLITON TRANSMISSION

- Solitons are non-linear optical pulses that can propagate undistorted over long distances and remain unaffected after collisions with each other.
- Solitons are very narrow, high intensity stable optical pulses with high peak power and special shapes.
- During propogation,the shape of soliton remains unchanged.
- Soliton pulses reduce the effect of chromatic dispersions.
- Chromatic dispersions:

  1. Group velocity dispersion
  2. Self phase modulation

- Depending on the particular shape chosen, the pulse either does not change its shape as it propagate, or it undergoes periodically repeating change in shape.
- The family of pulse that do not change in shape are called Fundamental Soliton.
- The family of pulse that undergo periodic shape change are called Higher order soliton.
- The block schematic of an optical fiber soliton transmission system is as shown.

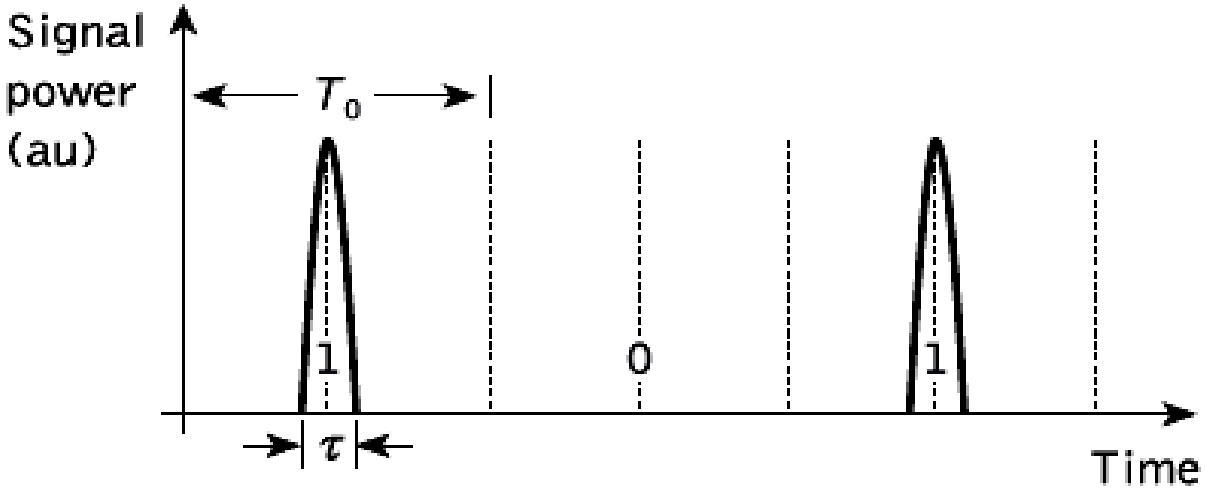


- A simple approach to generate RZ pulses is to employ an optical modulator (Mach–Zehnder modulator) and an NRZ-to-RZ converter which is driven by a DFB laser source.
- At the receiving end the incoming signal requires conversion back from RZ to NRZ and then finally a demultiplexer separates the specific NRZ data for each channel.
- Optical fiber soliton transmission systems can be single-wavelength or multiwavelength channel.
- In a single-wavelength channel system only one transmitter is used to launch the RZ pulses onto the optical fiber.
- Multiwavelength-channel system employ several transmitters simultaneously where the data is multiplexed using WDM.

SOLITON-SOLITON INTERACTION

- A single soliton pulse when propagated over a long transmission distance travels without emitting energy.
- Amplifier noise and chromatic dispersion can cause deterioration of the bit pattern when several soliton pulses are propagating closely following each other.
- In such cases, it is important to maintain a safe distance between two consecutive soliton pulses to avoid any destructive interaction
- The distance between two interacting soliton pulses is commonly referred to as the **strength of interaction**.
- In-phase soliton pulses attract each other and out-of-phase pulses repel each other, whereas when the phase difference is $\pi/2$, the soliton pulses do not interact with each other.
- This phase shift is due to the difference in the velocities of interacting soliton pulses.

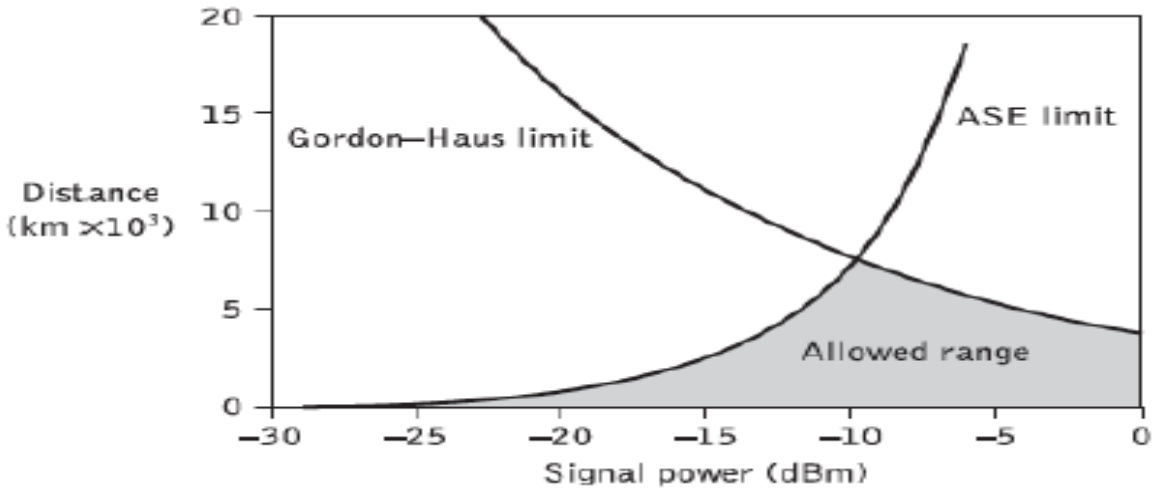
- The figure shows the propagation of soliton pulses where they are shown both maintaining a safe distance and interacting with each other.
- The case where each soliton pulse occupies a small fraction of the bit period in order to maintain a safe distance between neighboring pulses is shown.
- The parameter T_0 represents the duration of the bit period and τ is the soliton pulse width.



GH Effect (Gordon-Haus Effect)

- Optical amplifiers in soliton system contribute towards the amplitude fluctuation in the form of amplified spontaneous emission (ASE) noise.
- ASE noise variations accompanied by dispersion on the fiber gives rise to jitter in the pulse arrival times known as Gordon–Haus jitter and the effect is called Gordon–Haus effect.
- The timing jitter can cause some of the pulses to move out of their correct bit time slots which will then create errors in the soliton transmission.
- ASE noise and Gordon–Haus jitter are the two important phenomena that impose limitations on the maximum permissible transmission distance for an optical soliton transmission system.

- As a result of additive nature of ASE noise ,a large SNR and thus large optical signal power is required for longer transmission distance.
- At such distances GH effect dominates and causes bit errors due to random displacement of pulses.
- A balance between the effect of ASE noise and GH effect is required to enable successful transmission.
- Allowed range depicts the acceptable range of values for the ASE noise and the GH jitter with low BER transmission.



SYLLABUS

- Digital transmission systems
- Design of IMDD links- power and rise time budgets
- Coherent Systems, sensitivity of a coherent receiver, comparison with IMDD systems.
- Introduction to soliton transmission, soliton links using optical amplifier, GH effect,
- Soliton-soliton interaction, amplifier gain fluctuations, and design guide lines of soliton based links.

MODULE 5

OPTICAL AMPLIFIERS

- An optical amplifier is a device which amplifies the optical signal directly without changing it to electrical signal.
- Necessity of Optical amplifiers

➢ To transmit signals over long distances (>100 km)

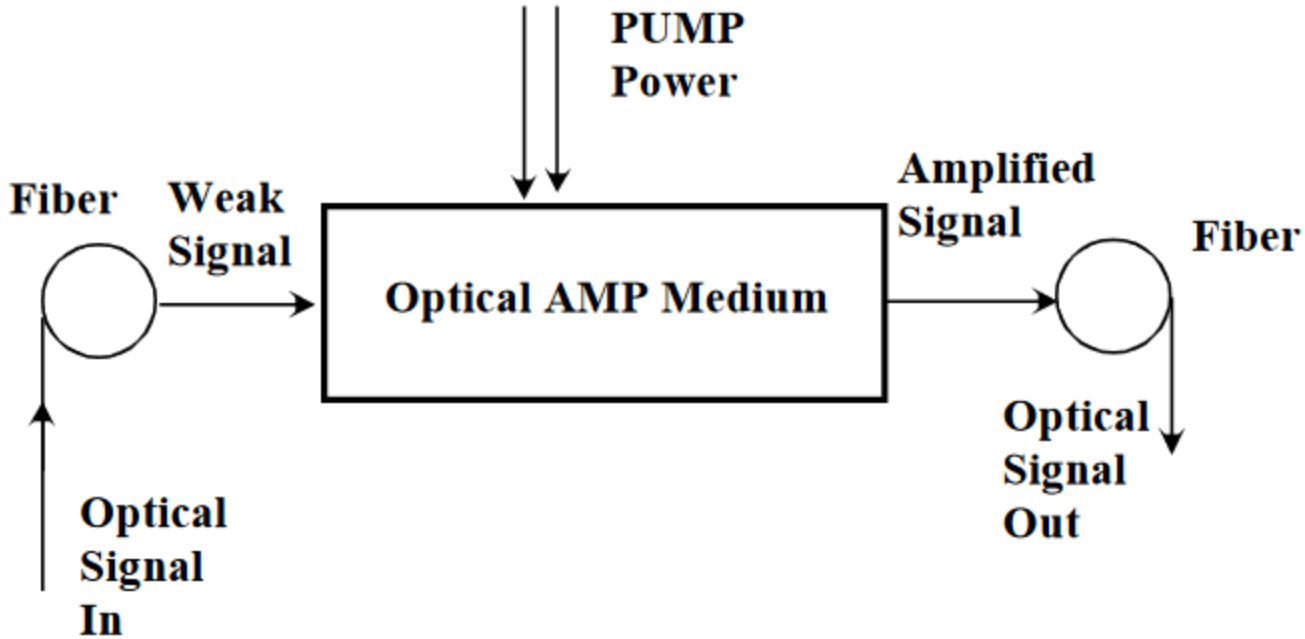
➢ To compensate for attenuation losses within the fiber.

➢ Reliability

➢ Flexibility

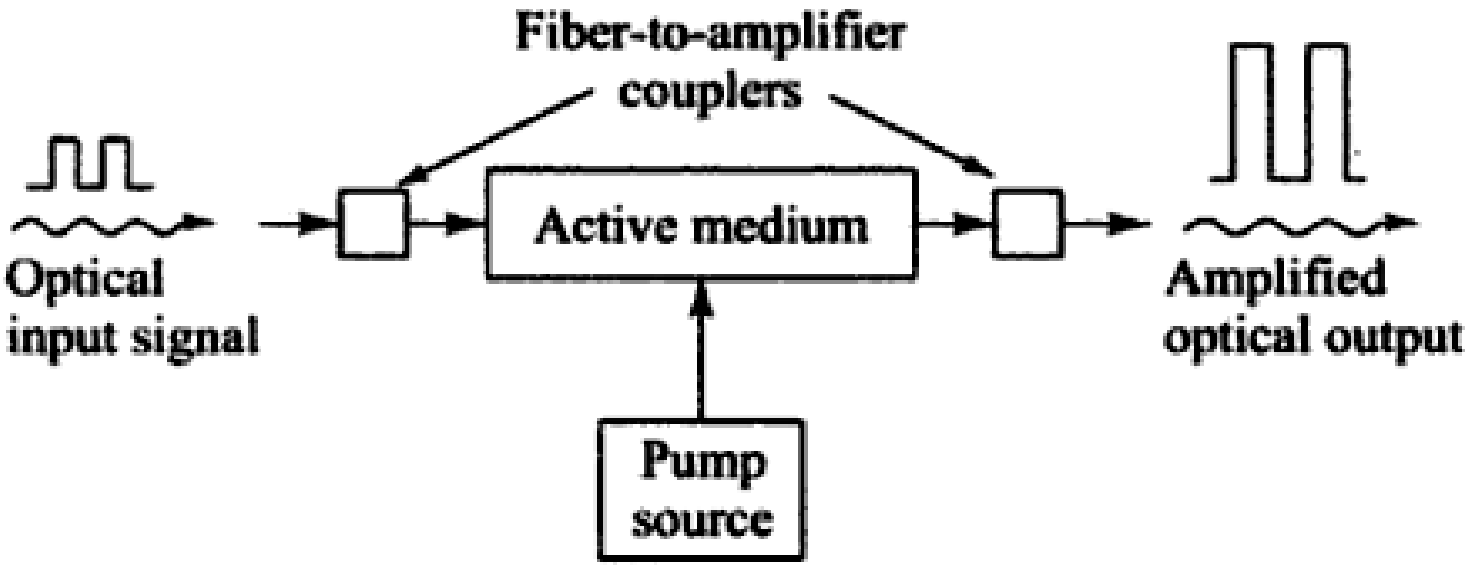
➢ WDM

➢ Low Cost



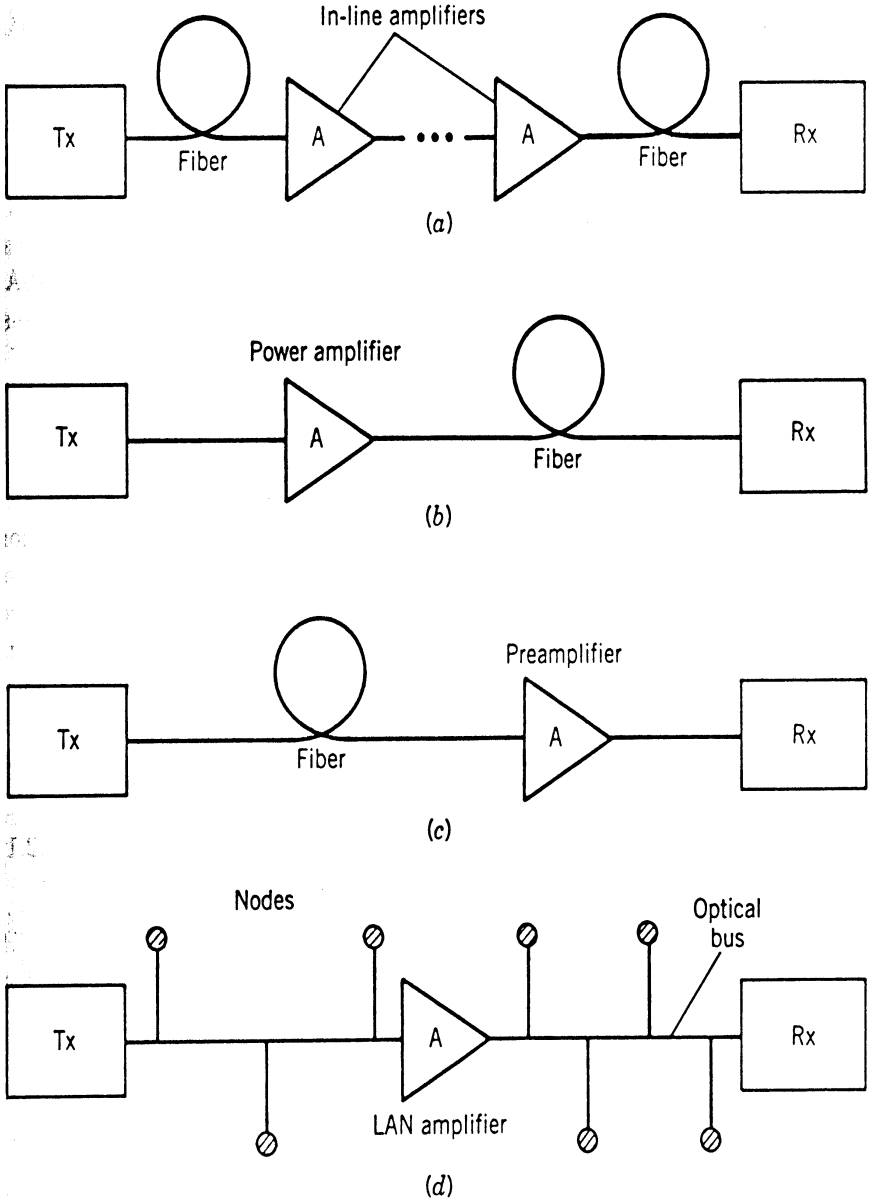
BASIC CONCEPTS

- Most optical amplifiers use stimulated emission
- An optical amplifier is basically a laser without feedback
- An optical amplifier can boost incoming signal levels, but it cannot generate a coherent optical output by itself.
- Here, the device absorbs energy supplied from an external source called pump.



- The pump supplies energy to electrons in an active medium, which raises them to higher energy levels to produce population inversion.
- An incoming photon will trigger these excited electrons drop to lower energy levels through a stimulated emission process.
- Since one incoming trigger photon stimulates many excite electrons to emit photons of equal energy as they drop to ground state, the result is an amplified signal.
- Optical gain is realized when the amplifier is pumped optically (or electrically) to achieve population inversion
- Gain depends on wavelength, internal light intensity and amplifier medium
- Three types based on active medium : Semiconductor optical amplifiers, Raman Amplifiers and Fiber doped amplifiers

APPLICATIONS



- In-line amplifiers
  - replaces regenerators
- Power amplifiers
  - boost signals to compensate fibre losses
- Preamplifiers
  - boost the recieved signals
- LAN amplifiers
  - compensate distribution losses in local-area networks

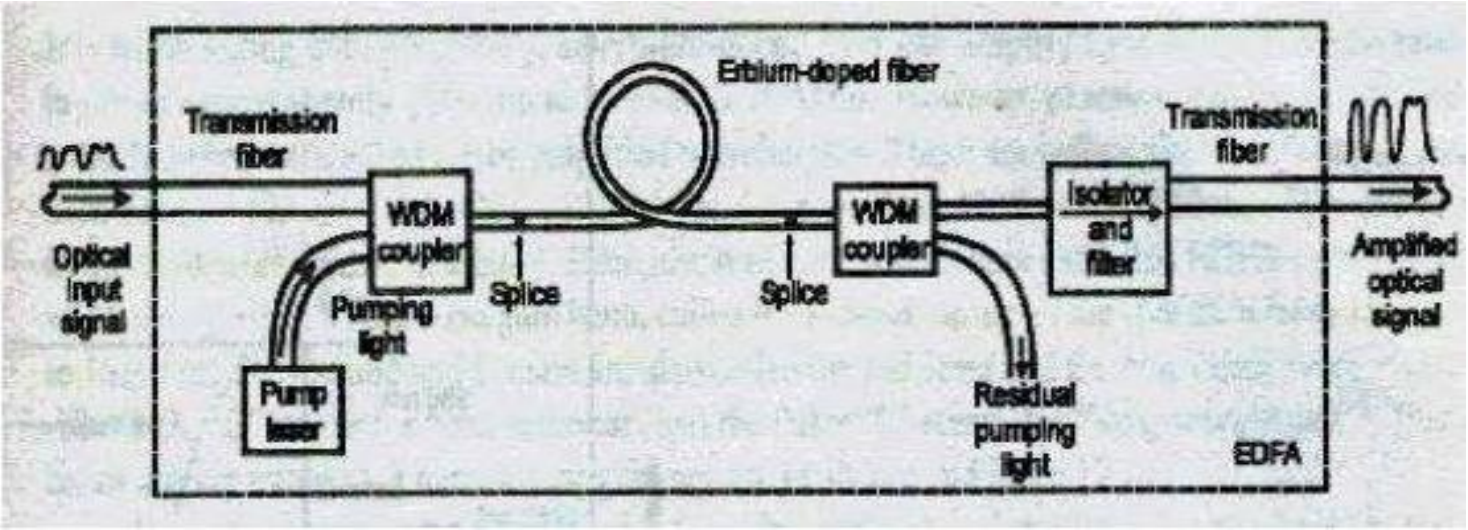
ERBIUM-DOPED FIBER AMPLIFIERS (EDFA).

- Doped fiber amplifiers (DFAs) are optical amplifiers that use a doped optical fiber as active medium to amplify an optical signal.
- The most common example is the Erbium Doped Fiber Amplifier (EDFA)
- A popular material used for long-haul telecommunication applications is a silica fiber doped with erbium, which is known as Erbium-Doped Fiber Amplifiers (EDFA).
- Characteristics

1. Long fiber length (10-30 m)
2. Low coupling loss (+)
3. Transparent to signal format and bit rate
4. No cross talk
5. Broad output spectrum (1530 – 1560 nm)
6. Works only in specific Wavelengths

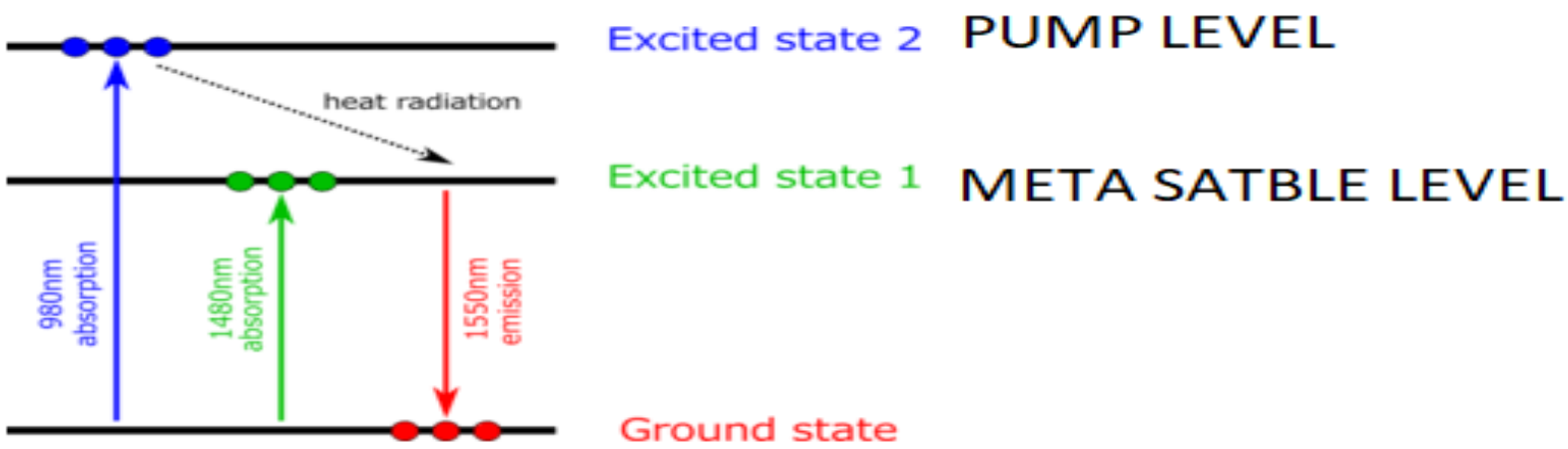
EDFA -ARCHITECTURE

- An optical amplifier consists of a doped fiber, one or more pump lasers, a passive wavelength coupler, optical isolators and tap couplers.
- The tap couplers are wavelength-insensitive and are generally used on both sides of the amplifier to compare the incoming signal with the amplified output.
- The optical isolators prevent the amplified signal from reflecting back into the device.
- The pump light is usually injected from the same direction as the signal flow. This is known as co directional pumping.



EDFA –AMPLIFICATION MECHANISM

- Erbium-doped fiber is usually pumped by semiconductor lasers at 980 nm or 1480 nm.
- The three energy levels that are primarily involved in the stimulated emission process in EDFA are ground level, pump level and metastable level.
- Pump at 980 nm used to create population inversion between levels metastable level and ground level. Stimulated emission between metastable level and ground level leads to amplification.



- Pumping at 1480nm is not efficient as 980nm pumping.
- The degree of population inversion that can be achieved by 1480nm pumping is lower.
- Higher the population inversion the lower the noise figure of the amplifier. Thus 980nm pumping is preferred to realize low noise amplifiers.
- In the absence of any radiation, the ions are in their ground states.
- If a beam of light of appropriate frequency incident on the system, the ions will be excited to the higher levels.
- This radiation, called pump radiation, if chosen at 980 nm, will excite the ions to the pump level.
- The lifetime of the ions in the level is 1μs approximately.
- The ions readily decay from pump level to the metastable level by non-radiative transition, i.e. by releasing heat.
- Pump can also work directly at 1480 nm to excite the ions directly to the metastable level.
- In this case, rapid relaxation would occur to the lowest sub-level within the group of metastable levels from which laser action would take place.
- This is known as spontaneous emission and adds to noise.

ADVANTAGES

- Commercially available in C-band & L-band
- Insensitivity to light polarization state
- High gain
- Low noise figure: 4.5 dB to 6dB
- No distortion at high bit rates
- Simultaneous amplification of wavelength division multiplexed signals
- Immunity to cross talk among wavelength multiplexed channels

DISADVANTAGES

- Pump laser necessary
- Need to use a gain equalizer for multistage amplification
- Difficult to integrate with other components
- Dropping channels can give rise to errors in surviving channels

SEMICONDUCTOR LASER (OPTICAL) AMPLIFIER SLA/SOA

- Widely used optical amplifier

FEATURES

- Small size , electrical pumping
- Broad gain spectrum
- Exploitable nonlinear characteristics
- Compatibility with photonic integrated circuits

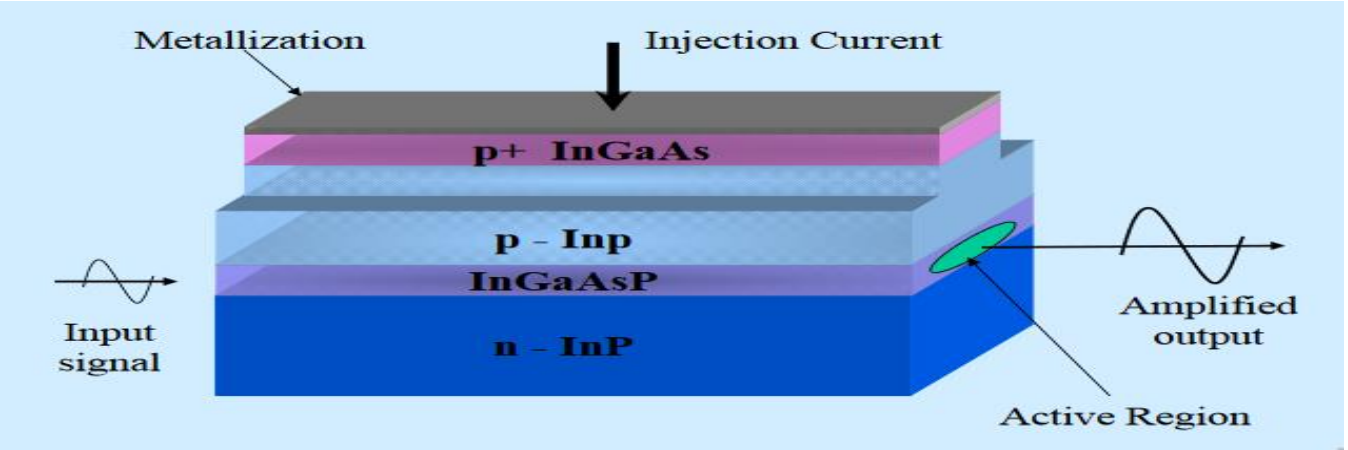
TWO TYPES OF SOAS: -

1. Fabry-Perot amplifiers (FPA)
2. Non-resonant traveling-wave amplifiers (TWA)

- TWA is superior to FPA as it is less dependent on temperature fluctuations and bias fluctuations. It also has better noise characteristics.

SOA –STRUCTURE

- Essentially a Semiconductor Laser diode with Anti-reflection coating on facets
- A typical structure of a InGaAsP/InP SOA is shown in the Figure
- The intrinsic region 9gain region) forms the core of the optical waveguide and the quasineutral regions form the claddings.
- Current injection into the intrinsic region can create a large population of electrons and holes.
- If the carrier density exceeds the transparency carrier density then the material can have optical gain and the device can be used to amplify optical signals via stimulated emission.



SOA –AMPLIFICATION

- Basic working principle is same as the semiconductor laser but without feedback.
- SOA amplify incident light through stimulated emission.
- When the light travelling through the active region it causes these electrons to lose energy in the form of photons and get back to the ground state.
- These stimulated photons have the same wavelength as the optical signal, thus amplifying the optical signal.
- Both edges (or "facets") of the SOA are designed to have very low reflectivity so that there are no unwanted reflections of the signal within the semiconductor itself.
- This is the main difference from regular lasers in order to build up the intensity of light within the semiconductor material.

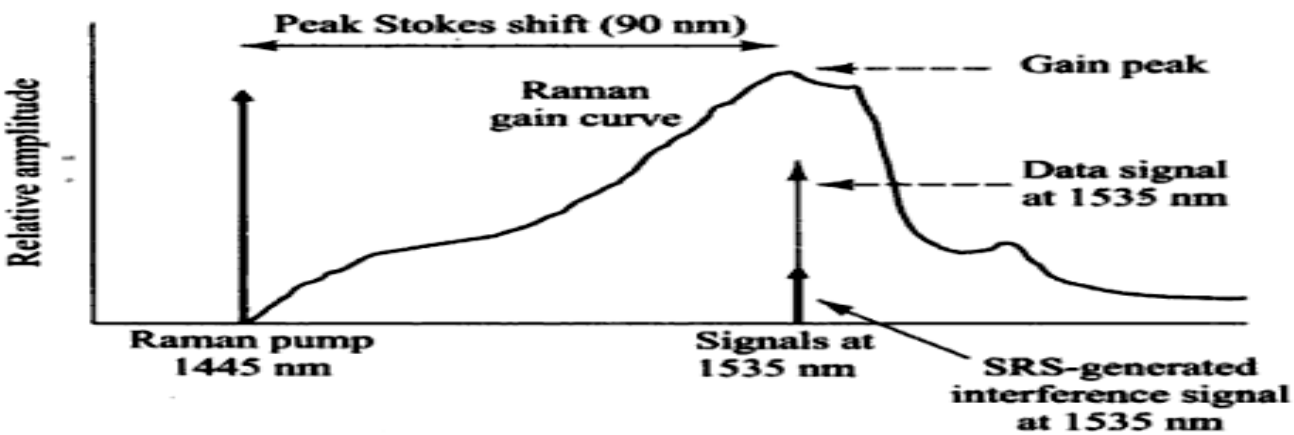
APPLICATIONS

- Power booster
- In-line amplifier
- Detector preamplifier
- Optical switching element
- Wavelength converter

RAMAN AMPLIFIER

- A Raman optical amplifier is based on a nonlinear effect called stimulated Raman scattering (SRS) which occurs in fibers at optical powers.
- An atom first absorbs a photon at a particular energy and then releases another photon at a lower energy, that is, at a longer wavelength than that of the absorbed photon.
- The energy difference between the absorbed and the released photons is transformed into a phonon, which is a vibrational mode of the material.
- The wave which irradiates the material is called the Pump wave, the waves with lower frequencies are called the Stokes waves, and the waves with higher frequency are called the Anti-Stokes waves.
- The shift to a particular longer wavelength is referred to as Stokes shift for that wavelength.

- Raman amplifier makes use of the standard transmission fiber itself as the amplification medium.
- Amplification takes place throughout the length of transmission fiber
- the stimulated process can be used for light amplification.
- If a small signal at Stokes frequency is present along with the pump, the signal gets amplified keeping all the characteristics of the input signal.
- The figure shows the Raman gain spectrum for a pump laser operating at 1445 nm and illustrates the SRS-induced power transfer to a signal at 1535 nm.



ADVANTAGES

- Variable wavelength amplification possible
- Compatible with installed SM fiber
- Can be used to extend EDFAs
- Can result in a lower average power over a span, good for lower crosstalk
- Very broadband operation may be possible

DISADVANTAGES

- High pump power requirements, high pump power lasers have only recently arrived
- Sophisticated gain control needed
- Noise is also an issue

OPTICAL AMPLIFIERS -COMPARISON

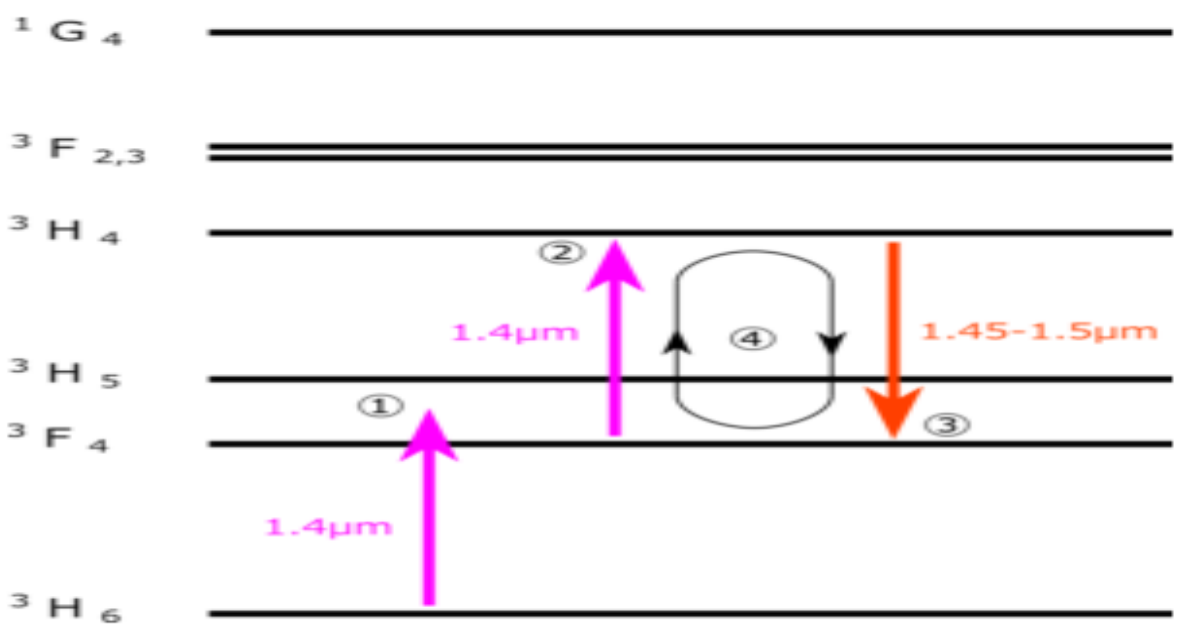
Property	EDFA	Raman	SOA
Gain (dB)	> 40	> 25	>30
Wavelength (nm)	1530-1560	1280-1650	1280-1650
Bandwidth (3dB)	30-60	Pump dependent	60
Max. Saturation (dBm)	22	0.75 × pump	18
Polarization Sensitivity	No	No	Yes
Noise Figure (dB)	5	5	8
Pump Power	25 dBm	>30 dBm	< 400 mA
Time Constant	10^{-2} s	10^{-15} s	2×10^{-9}
Size	Rack mounted	Bulk module	Compact
Switchable	No	No	Yes
Cost Factor	Medium	High	Low

THULIUM DOPED FIBER AMPLIFIER (TDFA)

- S-band optical amplifier
- Used for light amplification in the near infra-red (NIR).
- Thulium (tm) shows a broad emission centered at 1.47 µm, and the spectral range covers the s-band; therefore TDFA has been used in optical communication using the s-band.
- One wavelength for pumping a s-band tdfa is 1.4 µm, where a pump laser diode is commercially available.
- Another choice of pumping wavelength is 1.05 µm.
- The pumping scheme for 1.4 µm is shown in figure 2.
- Thulium ion shows a weak Ground-State Absorption (GSA: $^3H_6 \rightarrow {}^3F_4$) and a strong Excited-State Absorption (ESA: $^3F_4 \rightarrow {}^3H_4$) at 1.4 µm.

- Amplification takes place by the following steps:

1. A small fraction of Tm ions are excited to the $^3F_4$ level (due to weak GSA),
2. Ions at the $^3F_4$ level are mostly excited to the $^3H_4$ level (due to strong ESA),
3. Ions at the $^3H_4$ level emit a photon and drop to the $^3F_4$ level,
4. Repeat the cycle 2 and 3 without returning to the ground state.



- **Applications**

a. Booster and In-line amplifier
b. Metro & long haul networks
c. LAN, MAN and WAN
d. Test & measurement
e. Scientific applications

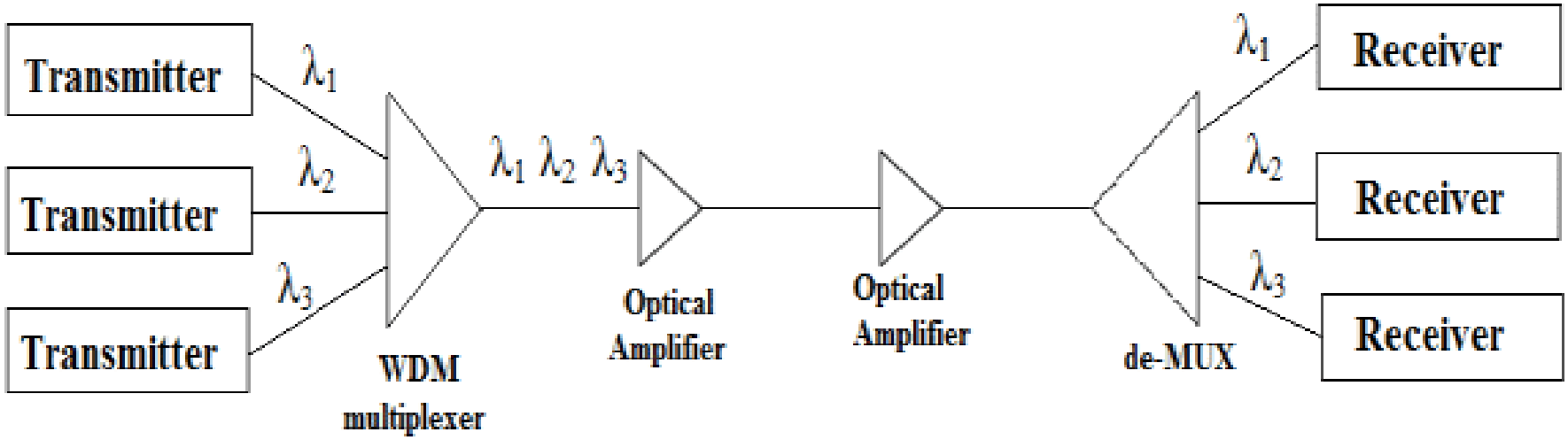
SYLLABUS

- Optical Amplifiers ,basic concept, applications, types.
- Doped fibre amplifiers, EDFA, basic theory, structure and working
- Semiconductor laser amplifier
- Raman amplifiers
- TDFA,amplifier configurations.
- Performance comparison

MODULE 6

WAVELENGTH DIVISION MULTIPLEXING (WDM)

- WDM is a scheme of combining a number of wavelengths over a single fiber.
- Each input is generated by a separate optical source with a unique wavelength.
- An optical multiplexer couples light from individual sources to the transmitting fiber.
- At the receiving station, an optical demultiplexer is required to separate the different carriers before detection.



FEATURES /ADVANTAGES

- Capacity can be upgraded
- Scalable ie no of channels can be increased.
- Transparency (Any channel can carry any transmission format)
- Can carry out wavelength switching and wavelength routing.

WDM COMPONENTS

- Wavelength Selective Splitters
- Wavelength Selective Couplers
- Isolators
- Tunable Optical Filter
- Tunable Source
- Optical amplifier
- Add-drop Multiplexer and De-multiplexer

WDM COMPONENTS

Passive devices:

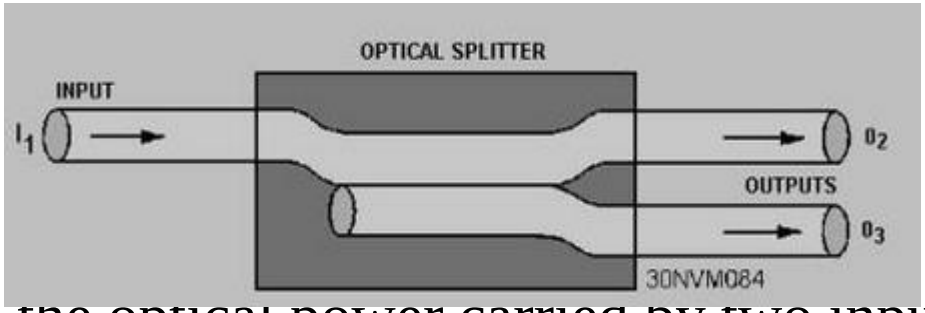
- operate completely in optical domain to split, isolate and combine light streams.
- Couplers, Power splitters, Optical isolators

Active devices :

- controlled electronically
- Tunable sources, Optical amplifiers, Optical filters

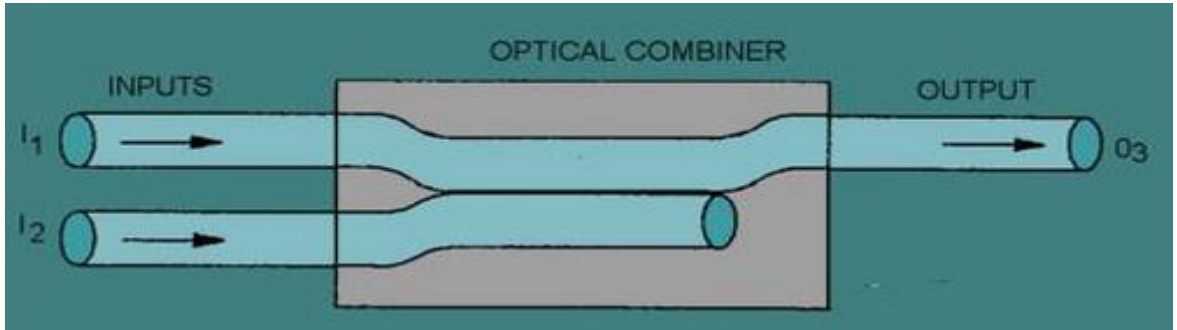
OPTICAL SPLITTER

- A passive device that splits the optical power carried by a single input fiber into two output fibers.
- The input optical power is normally split evenly between the two output fibers. This type of optical splitter is known as a Y-coupler.
- An optical splitter may distribute the optical power carried by input power in an uneven manner. This type of optical splitter is known as a T-coupler, or an optical tap.



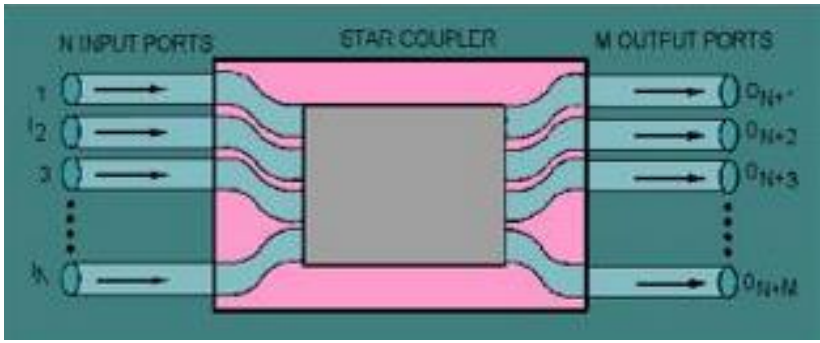
OPTICAL COMBINER

- A passive device that combines the optical power carried by two input fibers into a single output fiber.
- An X coupler combines the functions of the optical splitter and combiner.



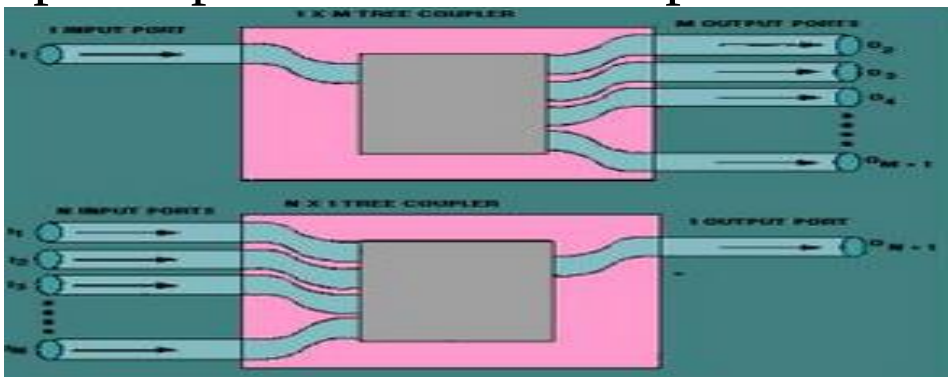
STAR COUPLER

- Multiport couplers that distributes optical power from more than two input ports among several output ports.



TREE COUPLER

- Multiport couplers that splits the optical power from one input fiber to more than two output fibers.



DIRECTIONAL COUPLER

- Directional couplers are fiber optic couplers that prevent the transfer of optical power from one input fiber to another input fiber.

SYMMETRICAL COUPLER

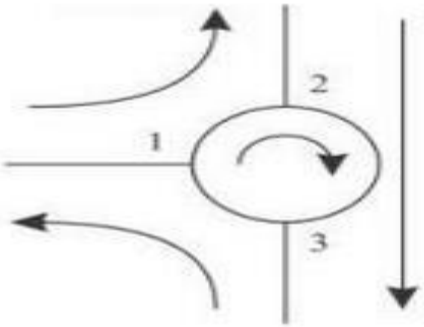
- transmits the same amount of power through the coupler when the input and output fibers are reversed.

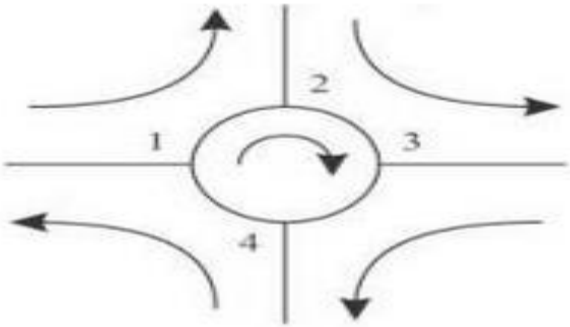
ISOLATOR

- Non-reciprocal => will not work same way if inputs and outputs reversed
- Allow transmission in one direction, but block all transmission in the other

CIRCULATOR

- Similar to isolator, but with multiple ports.
- A non-reciprocal multi-port passive device that directs light sequentially from port to port in only one direction.
- The device is used in optical amplifiers, add/drop multiplexers and dispersion compensation modules.





TUNABLE OPTICAL FILTER

- Operates over a frequency range and is electrically tuned to allow only one optical frequency band to pass through

OPTICAL ADD/DROP MUX (OADM)

- Multiple tunable fiber grating used in conjunction with two optical circulators to add and drop any number of N different wavelength.

FIBER BRAGG GRATING

- FBG is a narrow band reflection filter that is fabricated through a photo imprinting process.
- One can induce a change in the refractive index of the core by exposing it to ultraviolet radiation
- Grating play an important role in Wavelength filtering,Dispersion compensation ,Optical sensing • EDFA Gain flattening • Single mode lasers and many more areas
- formation
- FBG Theory Exposure to the high intensity UV radiation changes the fiber core n(z) permanently as a periodic function of z z: Distance measured along fiber core axis : Pitch of the grating ncore: Core refractive index δn: Peak refractive index

FREE SPACE OPTICS (FSO)

- Optical communication technology that uses light propagating in free space to transfer data.
- Line of sight technology.
- Bandwidth up to 2.5 Gbps
- Uses a directed beam of light radiation between transmitter and receiver.
- An FSO unit consists of

1) Optical transceiver
2) Laser transmitter and receiver

- Maximum range is about 4 kms

- It works in Tera Hertz (THz) spectrum. •
- Wavelength: FSO can operate into two wavelengths:

  1) 800 nm 2) 1550 nm
- 1550 nm wavelengths are more preferred due to its advantages over 800 nm.
- FSO work on simple optical transmission system
- Uses LED or Laser as a light source.
- The receiver detectors are either PIN diodes or Avalanche Photodiode

APPLICATIONS

- Metro Area Networks (MAN)
- Last Mile Access
- Enterprise connectivity
- Fiber backup
- Service acceleration

MERITS

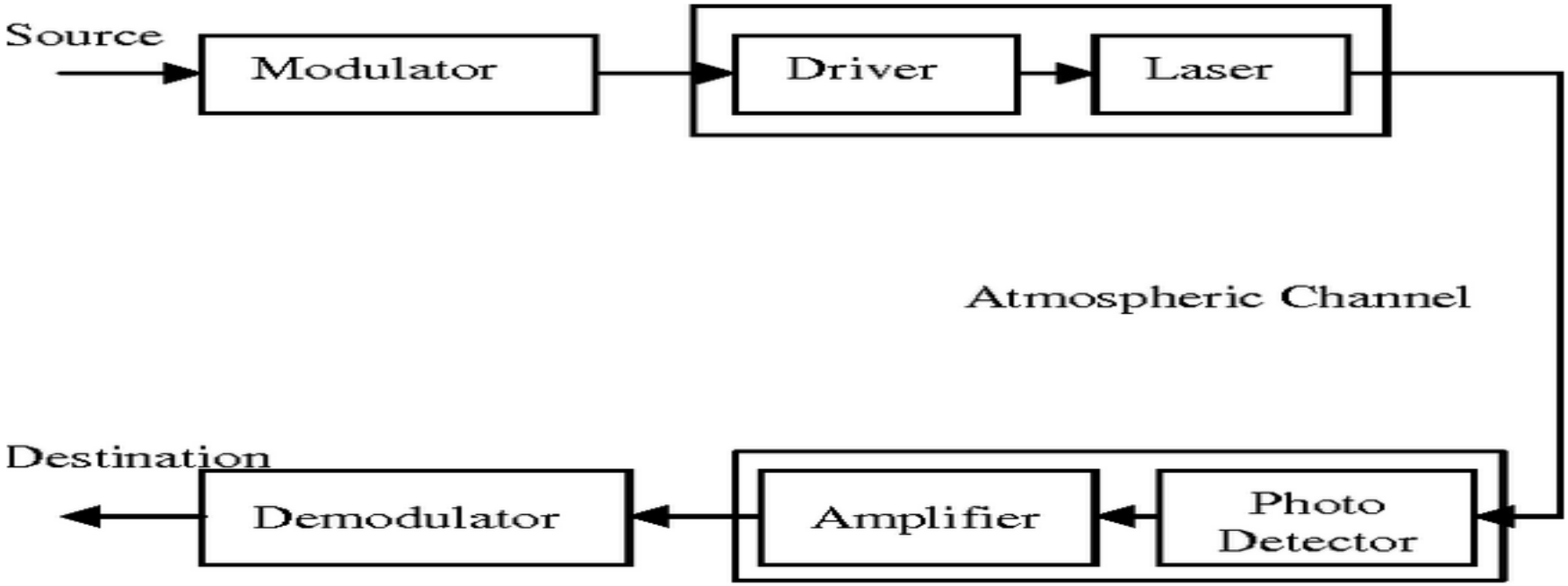
- Flexible network solution over conventional broadband services.
- Straight forward deployment- no licenses required
- Low initial investment
- Ease of installation
- Re-deployability
- High bit rates and low error rates.

DEMERITS

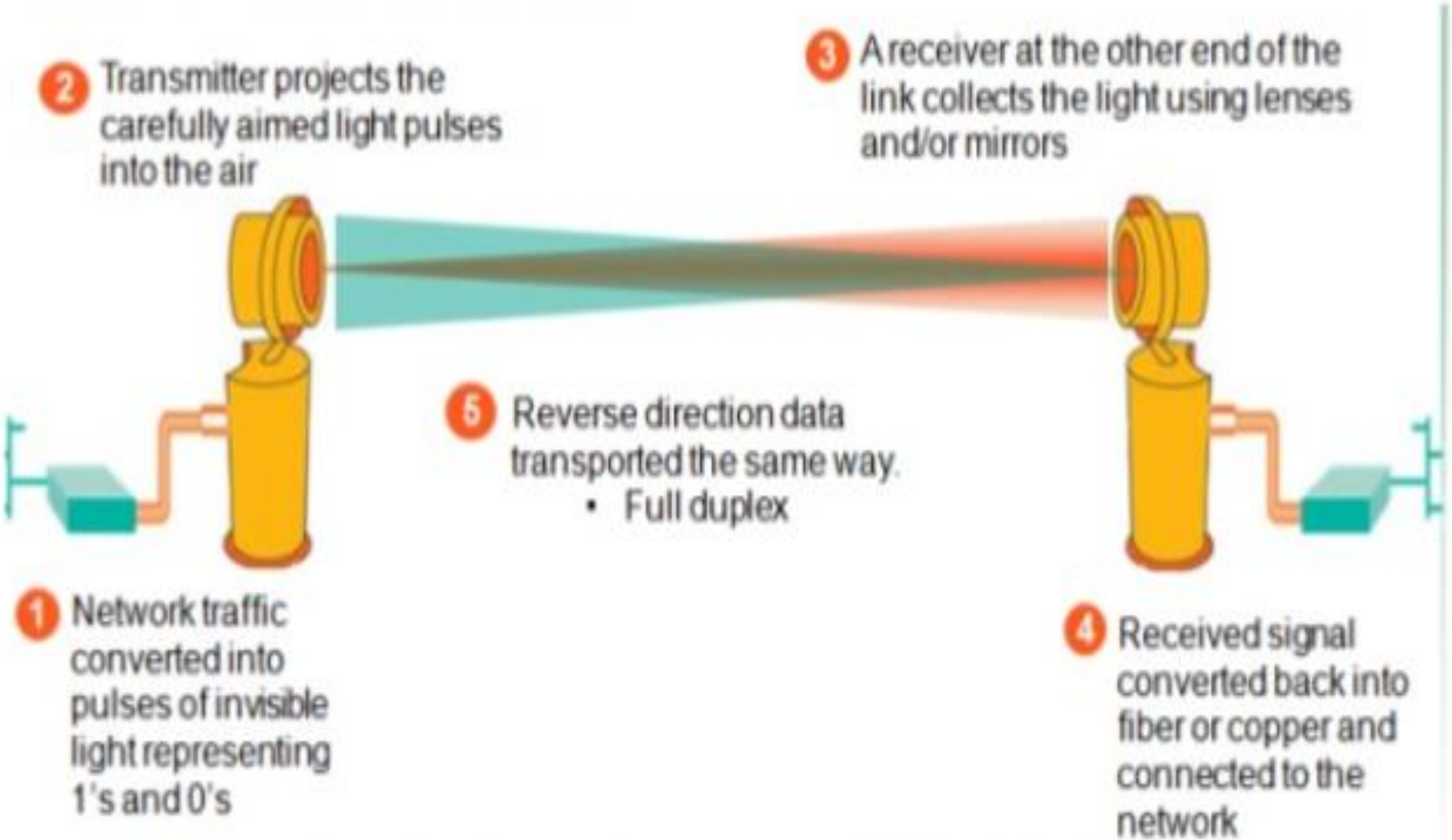
- Fog
- Physical obstructions
- Solar interference
- Scattering
- Absorption

BLOCK DIAGRAM

- A source producing data input is to be transmitted to a remote destination. This source has its output modulated onto an optical carrier; laser or LED, which is then transmitted as an optic al field through the atmospheric channel.
- At the receiver, the field is optically collected and detected, generally in the presence of noise interference, signal distortion, and background radiation.



HOW IT WORKS???


2 Transmitter projects the carefully aimed light pulses into the air
3 A receiver at the other end of the link collects the light using lenses and/or mirrors
5 Reverse direction data transported the same way.
• Full duplex
1 Network traffic converted into pulses of invisible light representing 1's and 0's
4 Received signal converted back into fiber or copper and connected to the network

LIFI TECHNOLOGY

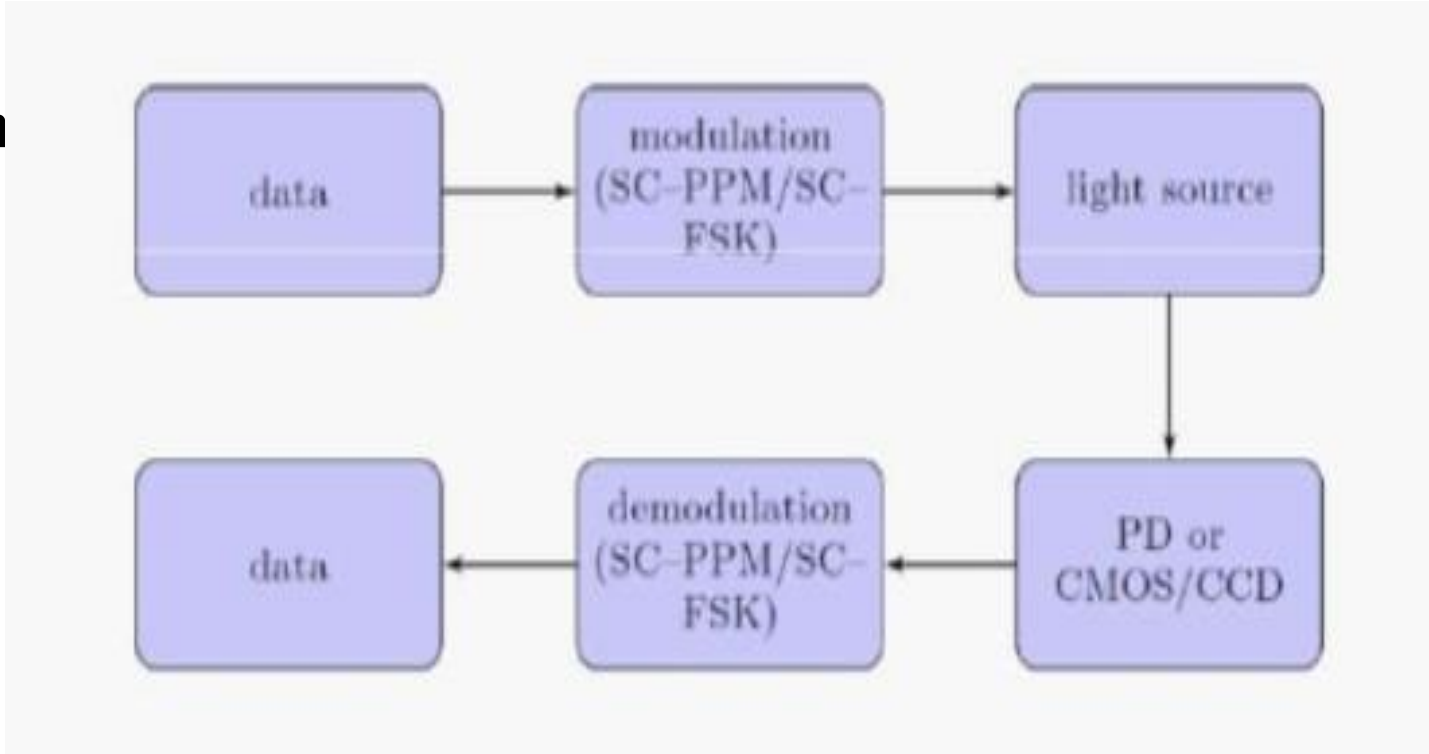
- LIFI –”LIGHT FIDEALITY” is transmission of data through illumination,i.e. sending data through a LED light bulb that varies in intensity faster than human eye can follow.
- Li-Fi is a light based Wi-Fi which uses light instead of radio waves to transmit information.
- Operational procedure is very simple, if the LED is on, you transmit a digit 1, if its off you transmit a digit 0.
- LED’s can be switched on and off quickly. Vary the rate at which the LEDs flicker depending upon the data we want to encode.Thus every light source will work as a hub for data transmission.

LIMITATIONS

- Li-Fi doesn’t work in the dark .
- Li-Fi has a big drawback compared to Wi-Fi, unlike Wi-Fi we cannot move to other rooms unless there are wired bulbs too. ?
- Light can’t pass through the objects.
- Interference from external sources like sun light, normal bulbs, and opaque materials in the path of transmission will course interruption in the communication.
- High installation cost of the VLC systems.
- A major challenge facing Li-Fi is how the receiving device will transmit back to transmitter.

Visible Light Communication (VLC)

- The visible light communication (VLC) refers tothe communication technology which utilizes the visible light source as a signal transmitter, the air as a transmission medium, and the appropriate photodiode as a signal receiving component.
- The visible spectrum covers wave lengths from 380 nm to 750 nm.
- Block diagram



ADVANTAGES

- Large frequency spectrum bandwidth
- There is no EMI.
- Requires much less power compared to RF communication
- Visible light cannot penetrate through the walls, so Indoor Visible light communication is comparatively secure.
- Visible light usually poses no health hazards to human body and eyes.

DISADVANTAGES

- It will only work in places where there are electronic lights
- The bandwidth of LED is limited and so are the data rates.
- It is LOS type of communication and thus blocking could interrupt the signal reception.
- Speed limitations of the opto-electronic devices.

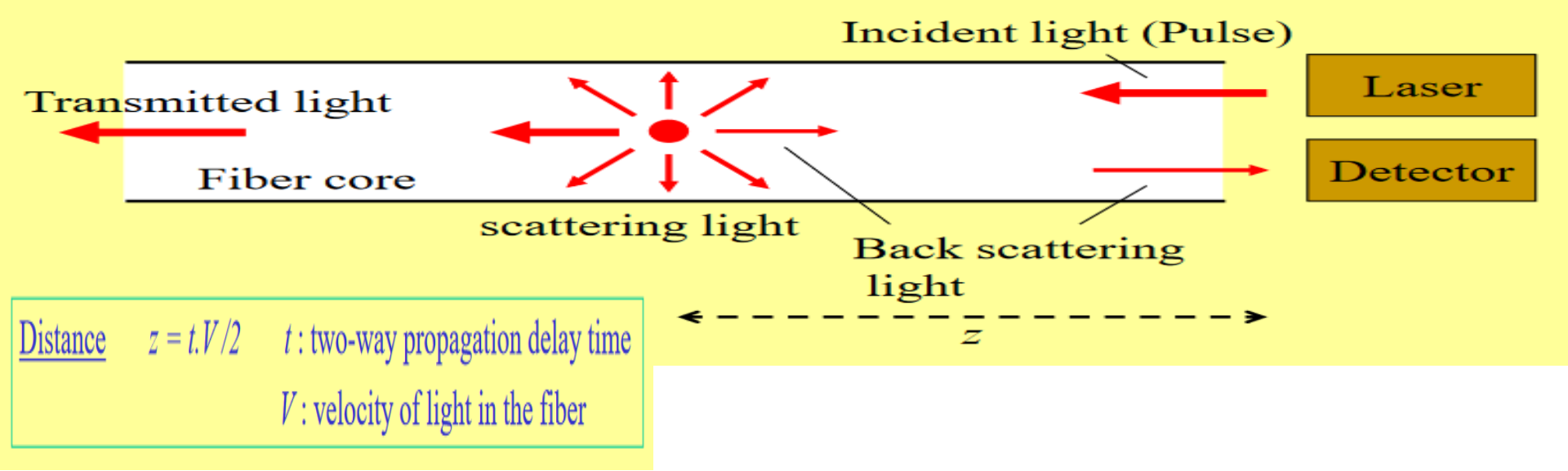
APPLICATIONS

- Mobile-connectivity • Positioning and communications • Illumination and communications • Information display and communications

OPTICAL TIME DOMAIN REFLECTOMETER(OTDR)

- Fundamentally is an Optical RADAR.
- A versatile portable instrument that is used to evaluate the characteristics of an installed fiber optic link.
- It also measures optical fiber parameters such as attenuation, length, optical connector and splices loss.
- OTDR technology is designed to provide a single ended test of any cable.
- It relies upon the measurement & analysis of the fraction of light which is reflected back within the fiber's numerical aperture due to Rayleigh scattering within the fiber.

- A small proportion of the scattered power is collected by the fiber in backward direction and returns to the transmitter, where it is measured by a photodiode.
- In operation, an OTDR launches pulses of light into the line fiber of an optical network and monitors the backscatter signal as a function of time relative to the launch time.
- As the pulse propagates down the fiber it becomes weaker with increasing distance due to power loss, and the measured backscatter signal decreases accordingly.
- The rate of signal decrease for a continuous section of fiber represents the fiber loss and any abrupt drops correspond to losses from the presence of components, terminations or faults which can be readily identified.



- The received backscattered optical power as a function of time 't' down an uninterrupted fiber is given by:

$$P_{Ra}(t) = \frac{1}{2} P_i . S . \gamma_R . w_0 . v_g . \exp(-\alpha v_g t)$$

where;

P_i - optical power launched into the fiber.

S - fraction of captured optical power.

γ_R - Rayleigh scattering coefficient.

w_o - input optical pulse width.

v_g - group velocity in fiber.

α - attenuation coefficient per unit length for the fiber.

- The maximal fiber length that can be measured by OTDR is the function of dynamic range.
- The definition of this parameter is:

$$\frac{P_{\max back}^{[dB]} - NEP_{eff}[dB]}{2} = \frac{P_{bs}(0) - NEP_{eff}[dB]}{2}$$

- where divided by 2 factor is due to the two-way measurement.

$$NEP_{eff} = NEP/n^{1/2},$$

- NEP =Noise Equivalent Power parameter
- n is the number of the averaged samples

OTDR LIMITATIONS

- The limited distance resolution of the OTDR makes it very hard to use in a LAN.
- The OTDR has a great deal of difficulty resolving features in the short cables of a LAN and is likely to show "ghosts" from reflections at connectors, which confuses the user.

SYLLABUS

- The WDM concept,
- WDM standards,
- WDM components, couplers, splitters, Add/ Drop multiplexers, gratings, tunable filters, system performance parameters.
- Introduction to optical networks. Introduction to free space optics
- LiFi technology and VLC.
- Optical Time Domain Reflectometer(OTDR) – fault detection, length and refractive index measurements.