INTRODUCTION:

- A phenomenal increase in voice data and video communications has caused the demand for more economical and large capacity communications system. This has caused technical revolution in the electronic communications industry.
- Terrestrial microwave systems have long since reached their capacity and satellite systems can provide at best only temporary relief to the ever increasing demand. It is obvious that economical communications systems that can handle large capacities and provide high quality service are needed.
- Communications systems that use light as carrier of information have recently received a great deal of attention.
- Propagating light waves through the earth's atmosphere is difficult and impractical because water vapor, oxygen and particulates in the air absorbs and attenuate the signals at light frequencies.
- Consequently, systems that use glass or plastic fiber cables to contain a light wave and guide it from a source to a destination are presently in great use. Communication systems that carry information through a guided fiber cable are called fiber optic systems.
- The information carrying capacity of a communication system is directly proportional to its bandwidth; the wider the BW, the greater its information carrying capacity
- It is common to express the BW of a system as a percentage of its carrier frequency. For instance, VHF radio system operating at 100 MHz could have a BW equal to 10 MHz (i.e. 10% of the carrier frequency). A microwave radio system operating at 6 GHz will have a BW equal to 600 MHz; thus, higher the carrier frequency, wider the BW possible and consequently greater the information carrying capacity.
- Light frequencies used in fiber optic systems are between 10^{14} Hz to Hz. 10 % of 100.000GHz is 10,000 GHz and is an excessive BW and hence it illustrates the capabilities of Optical Fiber Systems.

OPTICAL FIBER Vs METALLIC CABLE:

Communications through glass or plastic fiber cables have several overwhelming advantages over communications using conventional metallic or coax or waveguide facilities.

1. **Extremely wide system bandwidth:**
    - Fiber systems have greater capacity due to the inherently larger BWs available with optical frequencies. Metallic cables exhibit capacitance between and inductance along their conductors. These properties cause them to act as low pass filters which limit their transmission frequencies and hence bandwidths.
2. **Immunity to electromagnetic interference:**

- Fiber cables are immune to static interference caused by lightning, electric motors, fluorescent light and other external electrical noise sources. This immunity is due to the fact that optical fibers are non-conductors of electricity. Also fiber cables do not radiate RF energy and therefore cannot cause interference with other communication system.

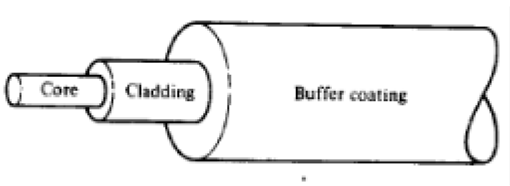
3. **Virtual elimination of crosstalk:**
    - The light on one glass fiber does not interfere with light on an adjacent fiber. Fiber systems are immune to cross talk between cables caused by magnetic induction. Glass or plastic fibers are non-conductors of electricity and therefore do not have a magnetic field associated with them. In metallic cables, the primary cause of cross talk is magnetic induction between conductors located near each other.
4. **Lower signal attenuation than other propagation systems:**
    - Typically attenuation figure of a 1GHz BW signal for optical fibers are 0.03dB per 100 feet compared to 4dB for both coax and an X band waveguide. So, fewer repeater stations are needed as a result of glass fiber.
5. **Security:**
    - Fiber cables are more secure than their metallic counterparts. It is virtually impossible to tap into a fiber cable without the user knowing about it.
6. **Safety:**
    - In many wired systems, the potential hazard of short circuits requires precautionary designs. Additionally, the dielectric nature of optical fiber eliminates the spark hazard.
7. **Substantially lighter weight and smaller size:**
    - Fibers are smaller and much lighter in weight than their metallic counterparts. Fiber cables require less storage space and are cheaper to transport.
8. **More resistive to environmental extremes and non-corrosiveness:**
    - Fiber cables operate over a larger temperature variation than their metallic counterparts and fiber cable are affected less by corrosive liquids and gases. Fibers are used around volatile liquids and gases without worrying about their causing explosions.
9. **Lower cost:**
    - The long term cost of fiber optics system is projected to be less than that of its metallic counterpart as the cost of copper is increasing.
10. **Conservation of the earth's resources:**
    - The supply of copper and other good electrical conductors is limited whereas the principal ingredient of glass is sand and it is cheap and in unlimited supply

DISADVANTAGES OF FIBER SYSTEMS:

1. **Interfacing Costs:**
    - To be practical and useful, they must be connected to standard electronic facilities, which often require expensive interfaces.
2. **Strength:**
    - Optical fibers by themselves have a significantly lower tensile strength than coaxial cable. This can be improved by coating the fiber with a protective jacket of PVC.
3. **Remote electrical power:**
    - Occasionally it is necessary to provide electrical power to remote interface or regenerating equipment. This cannot be accomplished with the optical cable, so additional metallic cables must be included in the cable assembly.
4. **Optical fiber cables are more susceptible to losses introduced by bending the cable:**
    - Bending the cable causes irregularities in the cable dimensions, resulting in a loss of signal power.
5. **Specialized tools, equipment and training:**
    - Optical fiber cables require special tools to splice and repair cables and special test equipment to make routine measurements. Sometimes it is difficult to locate faults in optical cables because there is no electrical continuity.

CONSTRUCTION OF FIBER OPTIC CABLE:

- An optical fiber which is in the form of a cylinder consists of an inner and outer shell. The inner shell is known as core and has high refractive index (n_1), while the outer shell is known as cladding and has low refractive index (n_2).
- The portion of the fiber optic cable that carries the light is made from either glass (silica) or plastic.
- The construction of a fiber optic cable is shown below.



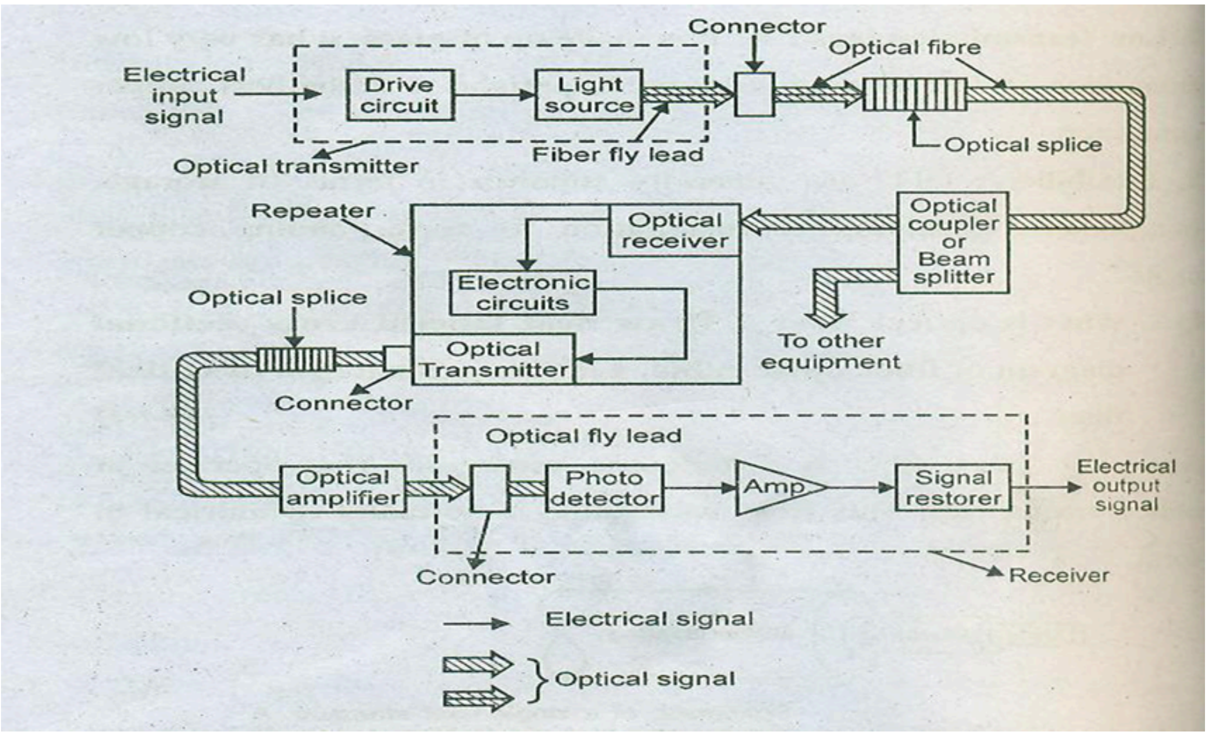
- **Core:**
    - The core is made up of glass or plastic and has a higher refractive index w.r.t cladding. This ensures that light is confined within the core and propagates by total internal reflection.
- **Cladding:**
    - Surrounding the core is cladding which is also made up of glass or plastic. The refractive index of outer cladding (n_2) is slightly less than that of the core (n_1). The functions of the cladding are:
        - It reduces scattering loss resulting from dielectric discontinuities at the core surface.

- It adds mechanical strength to the fiber.
- It protects the core from absorbing surface contamination with which it could come in contact.

- **Jacket:**
  - Over the cladding is usually a plastic jacket similar to the outer insulation on an electrical cable. This outer jacket is made up of some type of plastic, typically, polyethylene, polyurethane or polyvinyl chloride (PVC).
    - It adds strength to the fiber.
    - It mechanically isolates or buffers the fibers from small geometrical irregularities, distortions or roughness of adjacent surfaces.
    - Fibers must be protected from moisture, dirt, temperature variations and other conditions.

BASIC BLOCK DIAGRAM OF FIBER OPTICS SYSTEM:

- An optical fiber is a dielectric waveguide that operates at optical frequencies. This fiber waveguide is normally cylindrical in form which confines electromagnetic energy in the form of light to within its surface and guides the light in the direction parallel to its axis.
- A fiber optics communication system comprises of the elements as shown in the figure below:



Transmitter:

- The transmitter first converts the input voltage to current value which is used to drive the light source. Thus it interfaces the input circuit and the light source.
- The light source is normally an infrared LED or LASER device which is driven by the current value from the V to I convertor. It emits light which is proportional to the

drive current. Thus light which is proportional to the input voltage value is generated and given as input to fiber.

- A source to fiber interface is used for coupling the light source to the fiber optic cable. The light emitted from the source is inserted into the fiber such that maximum light emitted from it is coupled to the fiber.

Optical Splice:

- For creating long haul communication link, it is necessary to join one fiber to other fibers permanently. For this purpose, optical splicing techniques are used to join different fibers.

Optical Coupler/ Beam splitter:

- Optical couplers are used to couple the light output from the fiber end to the device which can be receiver or regenerator.
- Beam splitters are used to split the light beam which can be given to other equipment.

Regenerator/ Repeater:

- After an optical signal is launched into a fiber, it will become progressively attenuated and distorted with increasing distance because of scattering, absorption and dispersion mechanisms in the glass material.
- Therefore repeaters are placed in between to reconstruct the original signal and again retransmit it.
- The signal is processed in electronics domain and hence optical to electrical conversion and electrical to optical conversions are performed in the repeater.

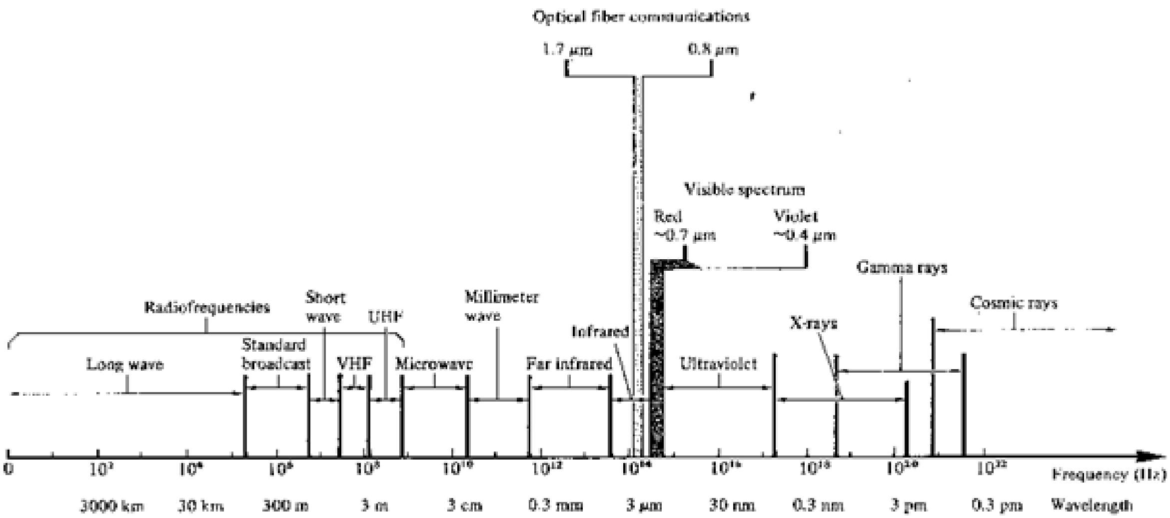
Optical Amplifier:

- After an optical signal has travelled a certain distance along a fiber, it becomes greatly weakened due to power loss along the fiber.
- Therefore, when setting up an optical link, engineers formulate a power loss budget and add amplifiers or repeaters when the path loss exceeds the available power margin.
- The periodically placed amplifiers merely give the optical signal a power boost, whereas a repeater attempts to restore the signal to its original shape.

Receiver:

- At the destination of an optical fiber transmission line there is a coupling device (connector) which couples the light signal to the detector.
- Inside the receiver is a photodiode that detects the weakened and distorted optical signal emerging from the end of an optical fiber and converts it to an electrical signal. (Referred to as photo current).
- I to V convertor produce an output voltage proportional to the current generated by the light detector. Thus, we obtain output value which was given to the system as data input.

OPTICAL SPECTRUM:

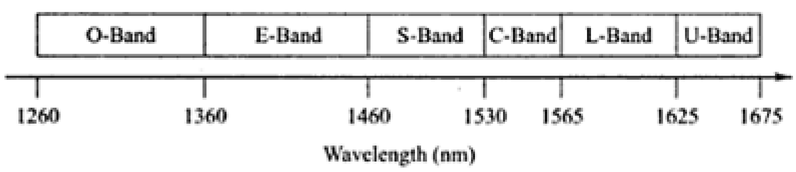


The frequency spectrum extends from subsonic frequencies (a few Hz) to cosmic rays (10^{22} Hz). The light frequency spectrum can be divided into three general bands.

1. INFRARED:
   - Band of light wavelengths that are too long to be seen by the human eye.(1000μm – 0.7μm)
2. VISIBLE:
   - Band of light wavelengths that the human eye will respond to. (0.7μm – 0.4μm)
3. ULTRAVIOLET:
   - Band of light wavelengths that are too short to be seen by the human eye. (0.4μm – 0.01μm)

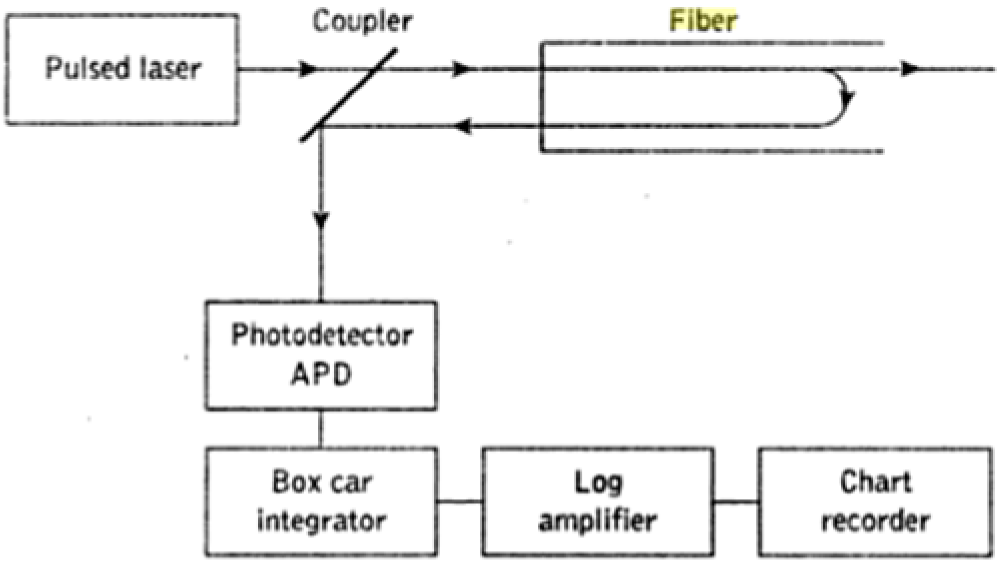
- While dealing with higher frequencies, electromagnetic waves such as light; it is common to use units of wavelength rather than frequency.
- The majority of fiber optic systems use the infrared as opposed to visible light. The range of λ commonly used is 800 nm – 255nm.

Name	*Designation*	*Spectrum (nm)*	*Origin of Name*
Original band	O-band	1260 to 1360	Original (first) region used for single-mode fiber links
Extended band	E-band	1360 to 1460	Link use can extend into this region for fibers with low water content
Short band	S-band	1460 to 1530	Wavelengths are shorter than the C-band but higher than the E-band
Conventional band	C-band	1530 to 1565	Wavelength region used by a conventional EDFA
Long band	L-band	1565 to 1625	Gain decreases steadily to 1 at 1625 nm in this longer wavelength band
Ultra-long band	U-band	1625 to 1675	Region beyond the response capability of an EDFA



OPTICAL TIME DOMAIN REFLECTOMETER (OTDR):

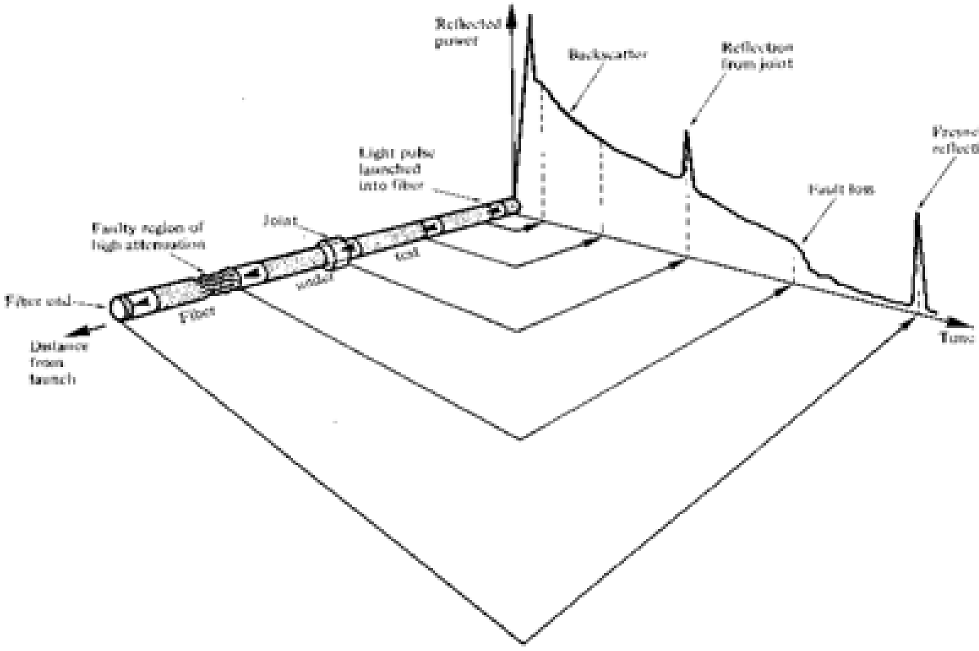
- An OTDR is a versatile portable instrument that is used widely to evaluate the characteristics of an installed optical fiber link.
- In addition to identifying and locating faults or anomalies within a link, this instrument measures parameters such as fiber attenuation, length, optical connector and splice losses and light reflection levels.
- A typical OTDR consists of light source and receiver, data acquisition and processing modules, information storage unit and a display.



BLOCK DIAGRAM EXPLANATION:

- A light pulse is launched into the fiber in the forward direction from an injection laser using either a directional coupler or a system of external lenses with a beam splitter.
- The backscattered light is detected using an avalanche photodiode receiver which drives an integrator.
- Integrator improves the received signal to noise ratio by giving an arithmetic average over a number of measurements taken at one point within the fiber.
- The signal from the integrator is fed through a logarithmic amplifier and averaged measurements for successive points within the fiber are plotted on a chart recorder. This provides location dependent attenuation values which give an overall picture of the optical loss down the link.

OTDR TRACE:



- The scale of vertical axis is logarithmic and measures the returning (back reflected) signal in dB.
- The horizontal axis denotes distance between the instrument and measurement point in the fiber.
- A light pulse is launched into the fiber in the forward direction using an optical circulator.
- The backscattered light is detected using a photodetector.
- The signals are then processed in order to achieve proper S/N ratios and then displayed.
- The plot provides location dependent attenuation values which give an overall picture of the optical loss down the link.
- Initial pulse caused by reflection and backscatter from the input coupler followed by a long tail caused by the distributed Rayleigh scattering from the input pulse as it travels down the link. Also reflections from fiber joint as well as discontinuity due to excessive loss at fiber imperfection or fault. End of fiber link is indicated by a pulse corresponding to Fresnel reflection at output end face of fiber.
- Such a plot yields attenuation per unit length for the fiber by simply computing slope of the curve over the length required. Also the location and insertion losses of joints/faults can be obtained from the power drop at their respective positions on the link. The overall link length can be determined from the time difference between reflections from the fiber input and output end faces.

NATURE OF LIGHT (REFLECTION AND REFRACTION):

In order to understand the propagation of light in a glass fiber, it is necessary to understand the basics of light refraction and reflection.

REFLECTION:

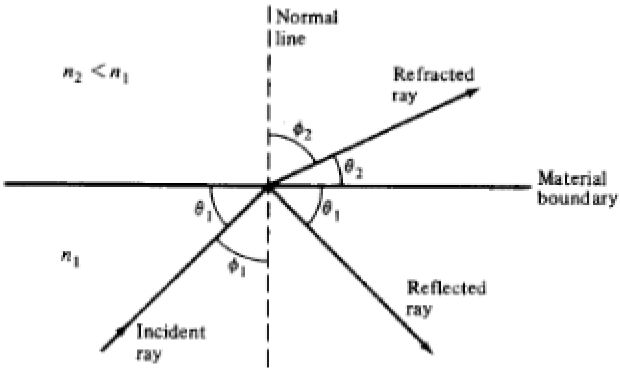
- According to the law of reflection, the angle θ_1 at which the incident ray strikes the interface is exactly equal to the angle the reflected ray makes with the same interface. In addition, the incident ray, the normal to the interface and the reflected ray all lie in the same plane which is perpendicular to the interface plane between the two materials.

REFRACTIVE INDEX:

- The amount of bend provided by refraction depends on the refractive index of the two materials involved. The refractive index η is the ratio of the speed of light in free space to the speed in a given material.
- Typically value of η for free space (vacuum) is 1, while for air it is 1.0003, water it is 1.33 and glass it is 1.5.

REFRACTION :

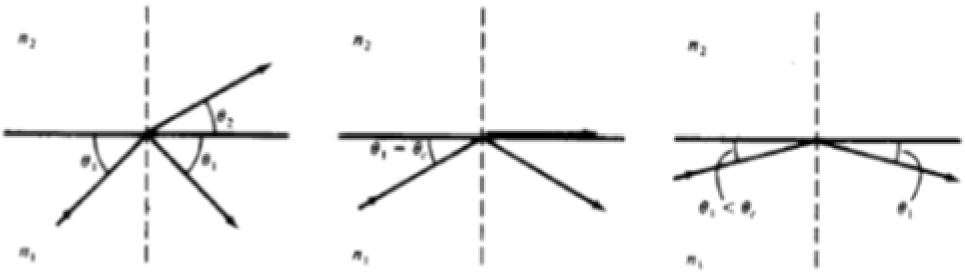
- When a light ray encounters a boundary separating two mediums, a part of the ray is reflected back into the first medium and the remainder is bent (or refracted) as it enters the second material. This is shown in figure below where $_2 < _1$.
- The bending or refraction of the light ray at the interface is a result of the difference in the speed of light in the two materials having different refractive indices.



SNELL'S LAW:

- How a light ray reacts when it meets the interface of two transmissive materials that have different indices of refraction can be explained with Snell's law.
- A refractive index model for Snell's law is shown in figure below.
- At the interface of medium 1 and medium 2, the incident ray may be refracted toward the normal or away from it, depending on whether n_1 is greater than or less than n_2. Hence angle of refraction can be greater or smaller than the angle of incidence, depending on the refractive indices of the two materials.
- The relationship at the interface is known as Snell's law and is given by
  - $n_1 \sin \Theta_1 = n_2 \sin \Theta_2$
  - where the angles are defined in the figure above.

CRITICAL ANGLE:



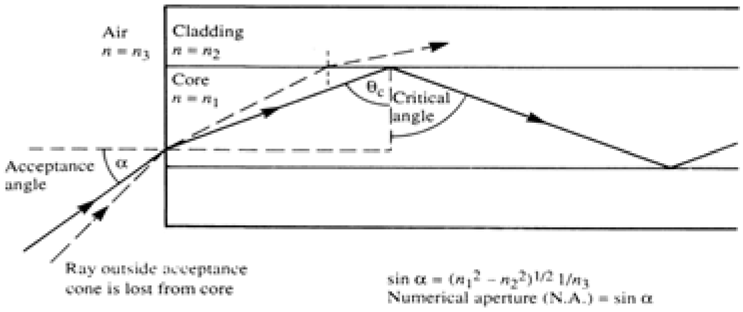
- Above figure shows a glass surface in air. A light ray gets bent towards the glass surface as it leaves the glass in accordance to Snell's law.
- If the angle of incidence θ_1 is decreased, a point is reached where the light ray in air is parallel to the glass surface. This angle is known as the **critical angle of incidence θ_c**.
    - **$\sin \theta_c = n_2/n_1$**

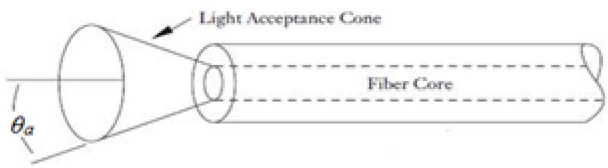
TOTAL INTERNAL REFLECTION:

- When light propagates from denser medium to rarer medium at an angle greater than critical angle with respect to normal (at an angle less than critical angle with respect to boundary separating the two mediums), the light is totally reflected back into the denser medium and this phenomenon is called as total internal reflection.

ANGLE OF ACCEPTANCE / ACCEPTANCE CONE HALF ANGLE:

- It defines the maximum angle in which external light rays may strike the air fiber interface and still propagate down the fiber.
    - **$\Theta_a = \sin^{-1}$(Numerical Aperture)**





- Rotating the acceptance angle around the fiber axis describes the acceptance cone of the fiber input. This is shown in above figure.
- Any light entering the cone of acceptance illustrated will be reflected internally and may propagate down the fiber. Light entering from outside the cone of acceptance will merely be refracted into the cladding and will not propagate.

NUMERICAL APERTURE:

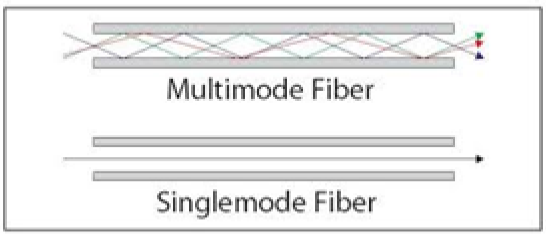
- It is defined as the light gathering ability of an optical fiber and is given by the sine of the maximum angle a ray entering the fiber can have with the axis of the fiber and still propagate by internal reflection.
    - For step index; $\sin\vartheta_{in} = (n_1^2 - n_2^2)^{-1/2}$; ϑ_{in} = *acceptance cone half angle*
    - For graded index; $\sin\vartheta_c$; ϑ_c = *critical angle*
- The larger the magnitude of NA, the greater the amount of light accepted by the fiber from the external light source.
- NA for optical fibers varies from 0.1 to 0.5. The NA is a basic specification of a fiber provided by the manufacturer that indicates its ability to accept light and shows how much light can be off axis and still propagate through the fiber.

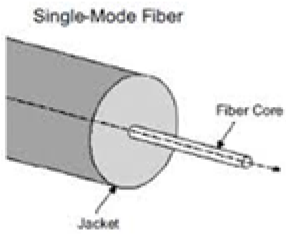
PROPAGATION OF LIGHT THROUGH THE FIBER:

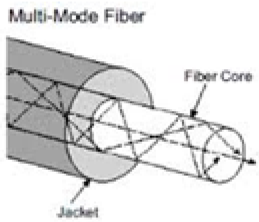
- An optical fiber is a dielectric waveguide that operates at optical frequencies. This fiber waveguide is normally cylindrical in form and confines electromagnetic energy in the form of light to within its surfaces and guides the light in the direction parallel to its axis.
- Light can be propagated down an OFC by either total internal reflection or refraction. The light propagation depends on the mode of propagation and optical fiber configuration (index profile of the fiber).

MODE OF PROPAGATION:

- In fiber optic system, the word mode means path. If there is only one path for light to take down the cable, it is called **single mode**. If there is more than one path, it is called **multimode.** The figure shows single and multimode propagation of light down an optical fiber.

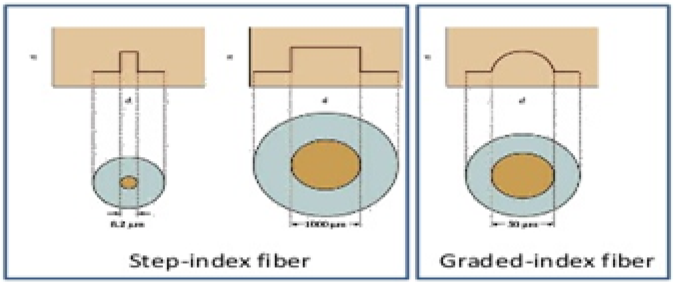






REFRACTIVE INDEX PROFILE:

- The index profile of an optical fiber is a graphical representation of the magnitude of the refractive index across the fiber. The refractive index is plotted on the horizontal axis and the radial distance from the core is plotted on the vertical axis.
- Depending on index profiles, there are two types of fibers:
    - Step index fiber
    - Graded index fiber
- A **step index** fiber has a central core with a uniform and high refractive index throughout and a step jump of refractive index at the core cladding interface.



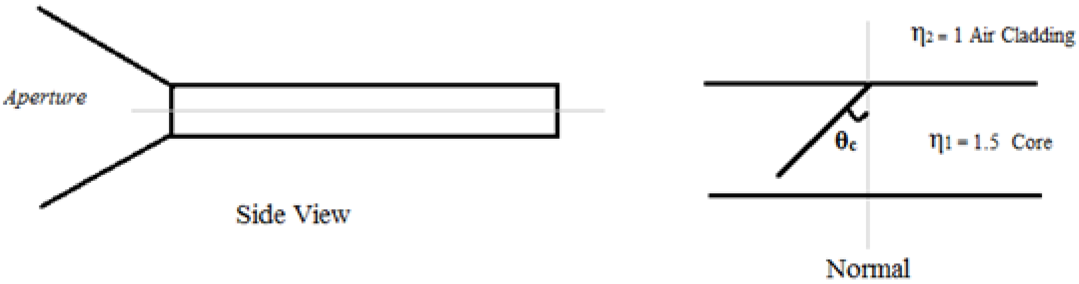
- In the **graded index** fiber, as shown in figure, it can be seen that the refractive index of the core is non-uniform. A fiber in which the refractive index is made to vary as the function of the radial distance from the center of the fiber is known as graded index fiber. The refractive index is highest in the center of the core and decreases gradually with distance towards the outer edge.

OPTICAL FIBER TYPES:

Essentially there are three types of optical fibers:

Single Mode Step Index Fiber:

- A single mode step index fiber has a central core that is sufficiently small (7-10μm) so that there is essentially only one path that the light may take as it propagates down the cable. Since the core refractive index is larger than the cladding index, the electromagnetic energy at optical frequency is made to propagate along the fiber waveguide through internal reflection at the core cladding interface.
- The simplest form of single mode step index fiber is the one in which the outside cladding is simply air as in figure below. The larger difference in refractive index results in a small critical angle (42°) at glass-air interface.



$\theta_c = \sin^{-1}\eta_2/\eta_1 = \sin^{-1}(1/1.5) = 41.8°$

Acceptance angle $= 90° - \theta_c = 48.2°$

- Thus, the fiber will accept light from a wide aperture. This makes it relatively easy to couple light from a source into the cable. The disadvantage is that this type of fiber is very weak and of limited practical use.
- A more practical type of single mode step index fiber is one that has a cladding other than air as shown in figure below. The refractive index of the cladding is slightly less than the refractive index of the central core and is uniform throughout the cladding.
- This type of cable is physically stronger than the air clad fiber but the critical angle is much higher (approx. 77°).

- This results in a small acceptance angle and a narrow source to fiber aperture making it much more difficult to couple light into the fiber from a light source.
- With both types of SMSI fibers, light is propagated down the fiber through reflection. Light rays that enter the fiber propagate straight down the core or are reflected once.
- Consequently, all the light rays follow approximately the same path down the cable and take approximately the same amount of time to travel the length of the cable.

Advantages of SMSI fiber:

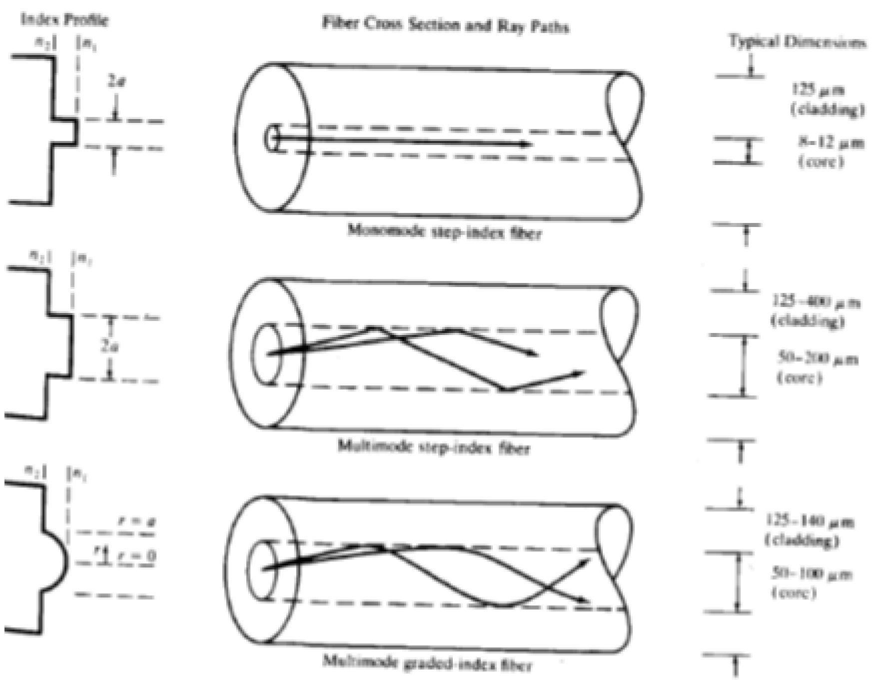
1. There is minimum dispersion, as all the rays propagating down the fiber takes approximately the same path, they take approximately the same time to travel down the cable. Consequently, a pulse of light entering the cable can be reproduced at the receiving end very accurately.
2. Because of higher accuracy in reproducing transmitted pulses at the receiver end, large bandwidths and higher transmission rates are possible with SMSI fibers as compared to other types.

Disadvantages of SMSI fiber:

1. Because the central core is very small, it is difficult to couple light into and out of this type of fiber.
2. Because of small central core, a highly directive light source such as a laser is required to couple light into a single mode step index fiber.
3. SMSI fibers are expensive and difficult to manufacture.

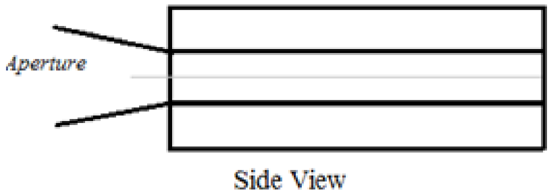
Application:

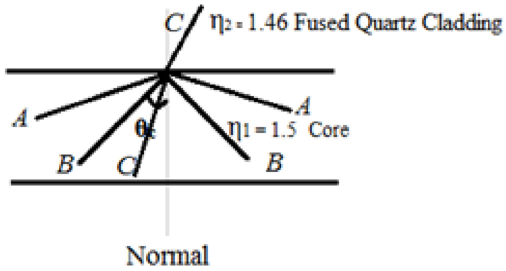
1. Single mode fibers are used for long haul communication used in different applications like telecommunication, CATV, MAN, WAN & data communication



Multimode step index fiber:

- It is similar to SMSI configuration, except that the central core is much larger (50-100μm).
- This type of fiber has a large light to fiber aperture and consequently allows more light to enter the cable. A MMSI fiber is shown in figure below.
- The light rays that strike the core cladding interface at an angle greater than the critical angle (ray A, B) are propagated down the core in a zigzag fashion, continuously reflecting off the interface boundary.
- Light rays which strike the core cladding interface at an angle less than the critical angle (ray C) enter the cladding and are lost. It is seen that there are many paths that a light ray may follow as it propagates down the fiber. As a result, all light rays do not follow the same path and consequently do not take the same amount of time to travel the length of the fiber.





Advantages:

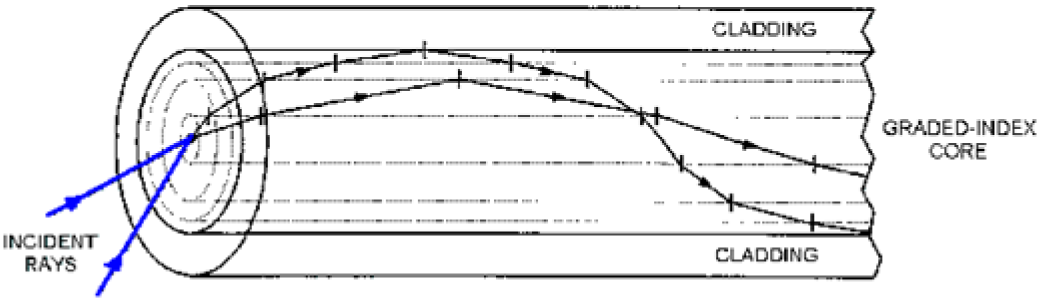
1. MSSI fibers are inexpensive and simple to manufacture and have a long life.
2. It is easy to couple light into and out of multimode step index fibers. They have a relatively large source to fiber aperture and easier for connecting together similar fibers because of large core radii.

Disadvantages:

1. Light rays take many different paths down the fiber, which results in large differences in their propagation times. Because of this, rays traveling down a MMSI fiber have a tendency to spread out (intermodal distortion). Consequently, a pulse of light propagating down a MMSI fiber is distorted more than with the other types of fibers.
2. The bandwidth and rate of information transfer possible with this type of cable are less than the other types.

Multimode Graded index fibers:

- To overcome the pulse dispersion problem, the graded index fiber was developed. The index of refraction is gradually varied with a parabolic profile and is highest at the fiber's center and goes on decreasing gradually towards the cladding.
- Lowest refractive index is farthest from the fiber axis. And thus velocity of propagation increases away from the center.
- Therefore, all modes, even though they take various paths and travel different distances, tend to transverse the fiber length in about the same amount of time.



Advantages and disadvantages (Comparison):

1. They are easier to couple light into and out of than SMSI fibers but more difficult than MMSI fibers.
2. Distortion due to multiple propagation paths is greater than SMSI fibers but less than in MMSI fibers.
3. They are easy to manufacture than SMSI fibers but difficult than MMSI fibers.

Applications:

1. Multimode fibers are used in LAN, data center, in an endoscope and short haul communication.

FIBER ATTENUATION/ FIBER LOSSES:

- Signal attenuation of a light signal as it propagates along a fiber is an important characteristic of the fiber since it plays a major role in determining the maximum transmission distance between a transmitter and receiver.
- Fiber loss is defined as the ratio of the optical output power from a fiber of length L to the optical power P_{in}.
  - α (dB/km)=10/L log(P_{out}/P_{in})
- This power ratio is a function of wavelength. So losses in the fiber results in a reduction in the light power and thus reduce the system bandwidth, information transmission rate, efficiency and overall system capacity. Basic fiber losses are as follows:
  - Absorption losses
  - Material/Rayleigh scattering losses
  - Radiation or bending losses
  - Dispersion losses
  - Coupling losses.

Absorption Loss:

- Absorption loss in optical fiber is analogous to power dissipation in copper cables. Impurities in the fiber absorb light and convert it to heat. Absorption losses in optical fibers are due to three different mechanisms –
  - Absorption by atomic defects in the glass composition.
  - Extrinsic absorption by impurities in the glass material.
  - Intrinsic absorption by the basic constituent atoms of the fiber material.

- Atomic defects are imperfections of the atomic structure of the fiber material such as missing molecules, high density clusters of atom groups or oxygen defects in the glass structure. Usually absorption losses arising from these defects are negligible compared to intrinsic and impurity absorption. So basically absorption losses are categorized into 3 types. They are-

Ultraviolet Absorption:

- This is intrinsic absorption which results from electronic absorption band in the UV region. UV absorption is caused by valence electrons in the silica material from which the fibers are manufactured. Absorption occurs when the photon interacts with the electrons in the valence band and excites it to a higher energy level. The ionization is equivalent to a loss in the total light field and consequently contributes to the transmission losses of the fibers.

Infrared Absorption:

- This is also an intrinsic absorption which results from atomic vibration bonds in the near infrared region. It is associated with the characteristic vibration frequency of a particular chemical bond between the atoms of which the fiber is composed. An interaction between the vibrating bond and the photon of the optical signal results in the transfer of energy from the field to the bond giving rise to absorption. This absorption is quite strong because of the many bonds present in the fiber.

Extrinsic/Ion Resonance Absorption:

- The dominant absorption factor in fibers is the presence of impurities in the fiber material. Impurity absorption results predominantly from OH- ions (water) and transition metal ions (such as iron, cobalt, copper, etc.) This absorption loss occurs either because of electronic transition between the energy levels associated with the incompletely filled inner sub shell of these ions or because of charge transitions from one ion to another.
- The source of OH- ions is water molecules that have been trapped in the glass during the manufacturing process. The presence of water molecules can dominate the extrinsic loss.

Scattering Loss:

Linear Scattering Losses:

- Linear scattering occurs when optical energy is transferred from the dominant mode of operation to adjacent modes. It is proportional to the input optical power injected into the dominant mode.
- Linear scattering is divided into two categories: **Mie scattering** and **Rayleigh scattering.**

Rayleigh scattering:

- Rayleigh scattering arises when the physical size of the inhomogeneities/anomalies within the optical fiber is less than one-tenth of the diameter of the operating wavelength.
- Scattering occurs when the optical wave propagating through the fiber encounters density irregularities i.e. small refractive index fluctuations.
- These Scattering /diffraction cause the light to disperse and spread out in many directions. Some of the diffracted light continues down the fiber and some of it escapes through the cladding. The light rays that escape represent a loss in light power. This is called Rayleigh scattering loss.
- These inhomogeneities cannot be totally eliminated and set the lower limit of the fiber loss.
- Rayleigh scattering loss is proportional to the fourth power of the wavelength and so operation at long wavelengths is desirable.

Mie Scattering:

- Mie scattering arises when the physical size of the inhomogeneities/anomalies within the optical fiber is larger than one-tenth of the diameter of the operating wavelength.
- The inhomogeneities /anomalies results from the non-perfect cylinder structure of the waveguide and due to fiber imperfections such as irregularities in the core-cladding interface, core-cladding refractive index differences along the fiber, diameter fluctuation, bubbles etc.
- These imperfections are the result of improper mixing of fabrication materials during the manufacturing process.
- By advancement in the fiber manufacturing process Mie scattering is almost eliminated.

Non- Linear Scattering Losses:

- Scattering loss in a fiber also occurs due to fiber nonlinearities i.e. if the optical power at the output of the fiber does not change proportionately with the power change at the input of the fiber, the optical fiber is said to be operating in the non-linear mode. Nonlinear scattering is divided into two categories: **Stimulated Raman Scattering** and **Stimulated Brillouin Scattering.**

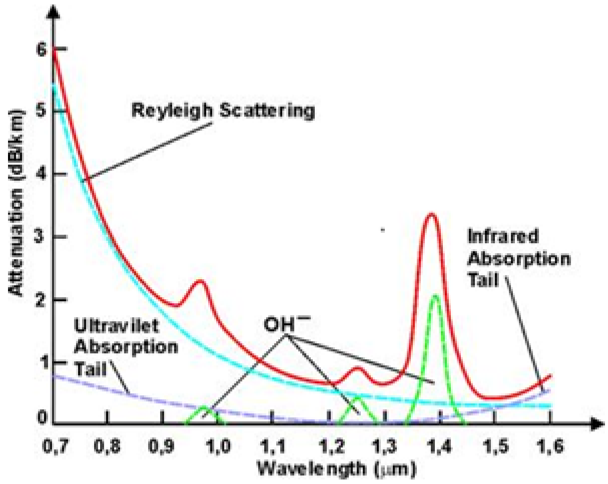
Stimulated Raman Scattering:

- When the vibrating atoms in a crystalline lattice interact with optical waves, the vibrating atoms absorb some of the energy of the optical wave. This absorbed energy plus the vibration energy of the absorbing atom within the crystalline lattice is almost instantaneously re-emitted in the form of photons.
- The re-emitted photons (combined photon/atom vibration energy) are a form of light scattering which results in wavelength shifting.

- Stimulated Raman scattering contributes to signal attenuation at operating wavelength, however the optical amplification is evident at the shifted frequency.

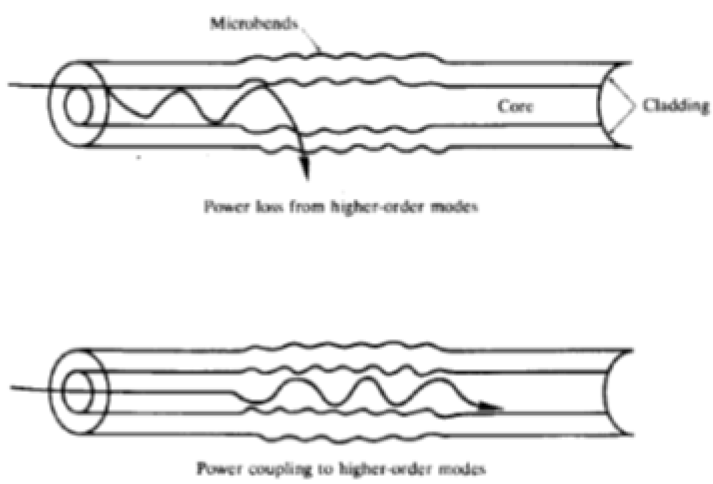
Stimulated Brillouin Scattering:

- When the light wave travels through an electrostrictive material (dielectric material whose refractive index changes under the influence of a strong electric field), it will interact with the acoustic noise generated by the molecular thermal noise. Through this interaction, a portion of the optical wave will be backscattered (called as Stroke light) and travel in the opposite direction from the incident wave. This Strobe light will generate an acoustical wave that stimulates further Brillouin scattering.



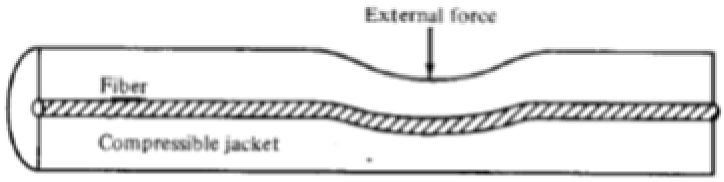
Radiation Losses/ Bending losses:

Radiation losses are caused by small bends and kinks in the fiber. Essentially there are two types of bends: microbends and macro bends (constant radius bends).

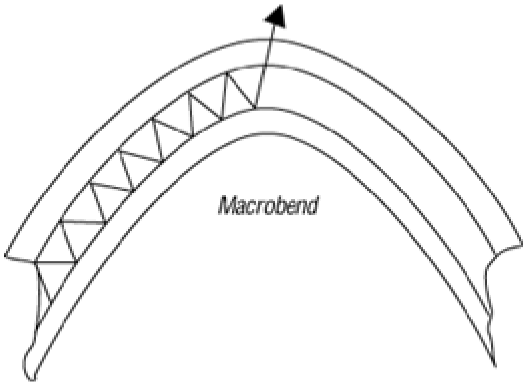


- **Microbending** is due to imperfection in the geometry of the fiber such as core-cladding irregularities, bubbles, diameter fluctuations and axis misalignment. Sometimes microbending arises from external influences such as mechanical stress caused by pressure, tension or twist. Scattering losses due to these mechanisms are called microbending losses.

- These losses can be reduced by increasing the index difference between core-cladding or by careful fiber drawing and cabling or by using compressible jackets for cabling.



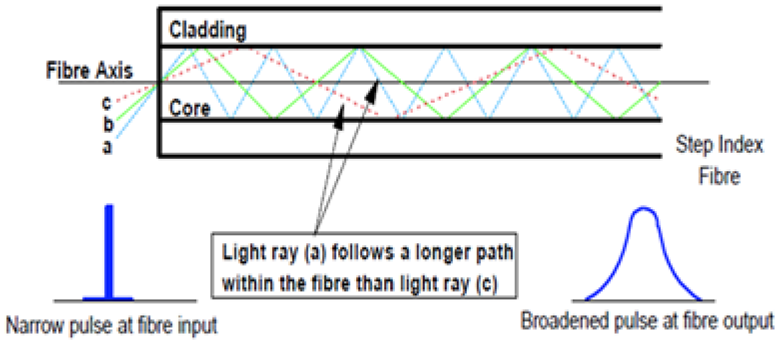
- Fiber subjected to macroscopic bend having radii large as compared to the fiber diameter (Eg: when a fiber cable turns a corner results in large curvature radiation losses called as macro- bending losses.

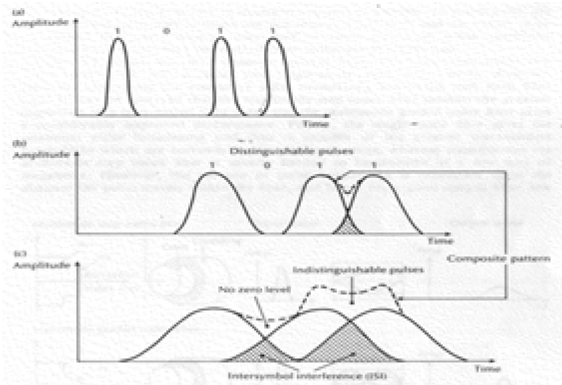


- It is the bend in the entire cable which causes certain modes not to be reflected and therefore causes loss to the cladding. In a typical fiber cable, it is around 0.5dB per bending and fiber bending shall be kept minimum.
- The **macro-bending** loss can be taken care by properly laying the cable in duct or plastic pipes so that macro-bending is within limits as specified by the manufacturer.

Fiber Dispersion:

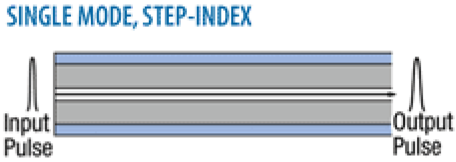
- Dispersion is a measure of the temporal spreading that occurs when a light pulse propagates through an optical fiber. Dispersion is sometimes referred to as delay distortion in the sense that the propagation time delay causes the pulse to broaden.
- The broadened pulse overlaps with its neighbors eventually becoming indistinguishable at the receiver input. This effect is known as intersymbol interference (ISI).
- The signal dispersion alone limits the maximum possible bandwidth or the data rate attainable with a particular optical fiber.
- Three mechanisms are responsible for the pulse broadening in fibers:
- modal (or mode) dispersion, material dispersion and waveguide dispersion. Modal dispersion is referred to as intermodal dispersion. The combination of material and waveguide dispersion is often called as intra-modal or chromatic dispersion because both are dependent on wavelength.



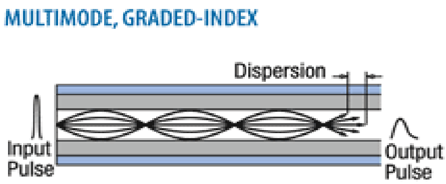


Intermodal dispersion:

- Intermodal or modal dispersion is caused by the difference in the propagation times of light rays that take different paths down the fiber.
- Obviously modal dispersion can occur only in multimode fibers. It can be reduced considerably by using graded index fibers and single mode step index fibers which almost entirely eliminate the modal dispersion.
- In multimode step index fibers, a light that propagates straight down the axis of the fiber takes the least amount of time to travel the length of the fiber.
- A light ray that strikes the core/cladding interface at the critical angle will undergo largest number of internal reflections as shown in the figure below and consequently take the longest time to travel the length of the fiber.
- So if three rays of light were emitted into the fiber at the same time and represented a pulse of light energy, the three rays would reach the far end of the fiber at different times and result in the spreading out of the light energy with respect to time.
- This is called modal dispersion in MMSI and results in a stretched pulse that is also reduced in amplitude at the output of the fiber.
- Modal dispersion is reduced considerably when light rays propagates down a SMSI fiber as shown in the figure below.
- As the radial dimension of the fiber is sufficiently small, there is only a single path for each of the rays to follow as they propagate down the length of the fiber.
- Consequently each ray of light travels the same distance in the given period of time and the light rays have exactly the same time relationship at the far end of the fiber as they had when they entered the cable. The result is no modal dispersion or pulse stretching.



- Other method of reducing the modal dispersion is to use graded index fibers. Figure below shows light propagating down the multimode graded index fiber. Different rays are shown travelling in different mode.
- Each ray travels a different path but they all take approximately the same amount of time to propagate the length of the fiber.
- This is because the refractive index of the fiber decreases with distance from the center and the velocity at which a ray travels is inversely proportional to the refractive index.
- Consequently as rays which travel farther away from the center, the faster they propagate.
- It is seen that as the pulse propagates down the fiber, the light rays that make up the pulse spread out in time which cause a corresponding reduction in the pulse amplitude and stretching the pulse width.
- This is called as pulse spreading or pulse width dispersion.



Intra-modal Dispersion:

- Intra-modal dispersion is pulse spreading that occurs within a single mode. It is a result of the group velocity being a function of the wavelength. Since intra-modal dispersion depends on the wavelength, its effect on signal distortion increases with the spectral width of the optical source. The spectral width is the band of wavelengths over which the source emits light. The two main causes of intra-modal dispersion are-

Material dispersion:

- It arises from the variation of the refractive index of the core material as a function of wavelength. LED's emit light that contain a combination of wavelengths. Each wavelength within the spectral width travels at a different velocity. Consequently, light rays that are simultaneously emitted from the LED and propagated down an optical fiber do not arrive at the far end of the fiber at the same time.
- This results in the distorted received signal, the distortion is called as material or chromatic distortion. It can be eliminated by using a monochromatic light source such as an injection laser diode (ILD).

Waveguide Dispersion:

- It occurs because a single mode fiber only confines about 80% of the optical power to the core.
- Dispersion thus arises since 20% of the light propagating in the cladding travels faster than the light confined to the core.
- The amount of waveguide dispersion depends on the fiber design since modal propagation constant β is a function of where *a* is the core radius.

Coupling Losses/Connector losses:

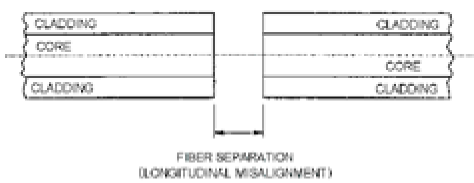
- In fiber cables, coupling losses can occur at any of the following three types of optical junctions- light source to fiber connection, fiber to fiber connections and fiber to photo detector connections. Junction losses are most often caused by one of the following alignment problems:

Lateral Misalignment:

- The lateral or axial displacement between two pieces of adjoining fiber cables is as shown in the figure. The amount of loss can be from a couple of tenth of a decibel to several decibels. This loss is generally negligible if the fiber axes are aligned to within 5% of the smaller fiber diameter.

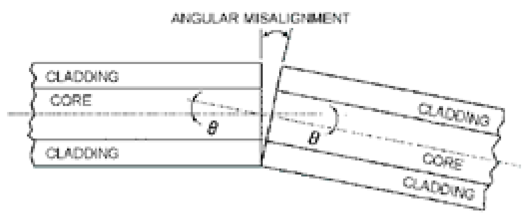
Gap Misalignment:

- This is sometimes called as end separation as shown in figure. When splices are made in OF's, the fibers should actually touch. The farther apart the fibers are, the greater the loss of light. If two fibers are joined with the connector, the ends should not touch. This is because two ends rubbing against each other in the connector could cause damage to either or both fibers.



Angular Misalignment:

- This is shown in figure and is sometimes called angular displacement. If the angular displacement is less than 2°, the loss will be less than 0.5dB.



Imperfect Surface finish:

- This is shown in figure. The ends of the two adjoining fibers should be highly polished and should fit together squarely. If the fiber ends are less than 3° off from the perpendicular, the losses will be less than 0.5dB.

Fibre end not cut square

Fibre end irregular or rough

Splice loss:

- When two fibers are joined together to make long fibers, splice loss occurs. Splice loss adds to the connector loss if there is additional misalignment. Splice loss depends on number of factors. Any imperfections caused during splicing will result in additional power loss. Typical values for splice loss range from 0.1 to 1dB.

OPTICAL SOURCES:

- The principal light sources used for fiber optics communications applications are injection laser diode (ILD) and light emitting diodes (LED). To be useful in an optical link, a light source needs the following characteristics:
- It must be possible to operate the device continuously at a variety of temperatures for many years.
- Their optical power output can be directly modulated by varying the input current to the device and it must be possible to modulate the output power over a wide range of modulating frequencies.
- It must have high efficiency.
- It must have high radiance output.
- Faster speed of response.
- For fiber links, the wavelength of the output should coincide with one of the transmission windows for the fiber type used.
- To couple large amounts of power into an optical fiber, the emitting area should be small.
- To reduce material dispersion in an OF link, the output spectrum should be narrow.
- Both the devices have advantages and disadvantages and the selection of one device over the other is determined by system economic and performance requirements.

LIGHT EMITTING DIODE (LED):

- The semiconductor LED is used for optical communication systems requiring bit rates less than approximately 100 to 200 Mbps together with multimode fiber coupled optical power in tens of microwatts.
- LED's require less complex circuitry and they can be fabricated less expensively with higher fields. To be useful in fiber transmission applications, an LED must have a

high radiance (brightness) output, a fast emission response time and high quantum efficiency.

- Essentially a LED is simply a PN junction diode. It is usually made from a semiconductor material such as Aluminum-gallium-arsenide (AlGaAs) or Aluminum-arsenide-phosphide (AlAsP).
- LED emits light by spontaneous emission. Light is emitted as a result of the recombination of electrons and holes. When forward biased, majority carriers are injected across the PN junction.
- Once across the PN junction, minority carriers recombine with majority carriers and give up energy in the form of light.
- This process is same as in a conventional diode except that in LED's certain semiconductor materials and dopants are chosen such that the process is radiative i.e. a photon is produced.
- The energy gap of a material used to construct a LED determines whether the light emitted by it is invisible or visible and of what color.

Structure:

Following are the different types of structures used in the fabrication of LED:

➔ Planar LED
➔ Dome LED
➔ Surface emitter LED
➔ Edge emitter LED
➔ Super Luminescent LED
➔ Resonant cavity and Quantum Dot LED

Out of which only two types i.e. surface emitters and edge emitters (using double heterojunction) are used extensively in optical fiber communication.

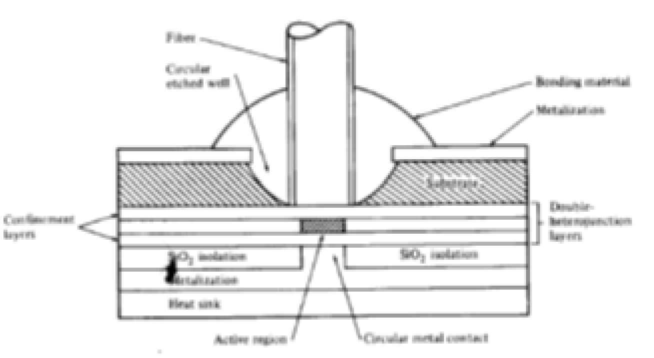
Why Double heterojunction structure:

- This is the most effective structure used in fiber optic system. By means of this sandwich structure of differently composed alloy layers, both carriers and the optical field are confined in the central active layer.
- The band gap differences of adjacent layers confine the charge carrier while the differences in the indices of refraction of adjoining layers confine the optical field to the central active region.
- Hence, this dual confinement leads to both high efficiency and high radiance and hence it is easier to couple its emitted light to fiber and allows the planar heterojunction LED to be used at higher speed.

Surface Emitting LED's:

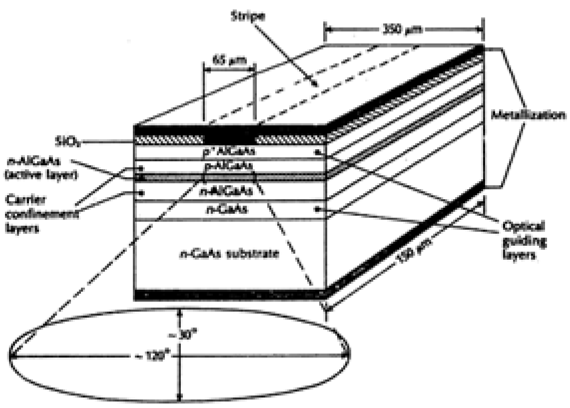
- In surface emitter, the plane of the active light emitting region is oriented perpendicular to the axis of the fiber as shown in figure. In this configuration, a well is etched through the substrate of the device which helps concentrate the emitted light to a very small area.
- This well is used to mount a fiber in order to accept the emitted light.

- The circular active area in practical surface emitters is normally 50μm in diameter and upto 2.5μm thick. The emission pattern is isotropic with a 120° half power beamwidth. These devices are more efficient than the standard surface emitters and they allow more power to be coupled into the optical fiber but they are also more difficult and expensive to manufacture.



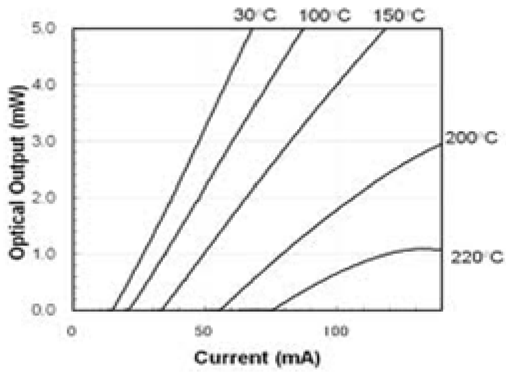
Edge Emitting LED's:

- The edge emitting LED's emit a more functional light pattern than the surface emitting LED's. 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 index of the surrounding material.
- This structure forms a waveguide channel that directs the optical radiation toward the fiber core. The emitting surface is a stripe rather than confined circular area (as in surface emitter).
- The light is emitted from an active stripe and forms an elliptical beam to match the typical fiber core diameters (50 to 100μm), the contact stripe for the edge emitter are 50-70μm wide. The length of the active region is 100 to 150μm.
- Surface emitting LED's are more commonly used than edge emitters because they emit more light. However coupling losses with surface emitters are greater and have narrow bandwidths.



Characteristics:

- The radiant light power emitted from an LED is a linear function of the forward current passing through the device. It can also be seen that the optical output power of an LED is a function of the operating temperature.



LASER DIODES (injection laser diode):

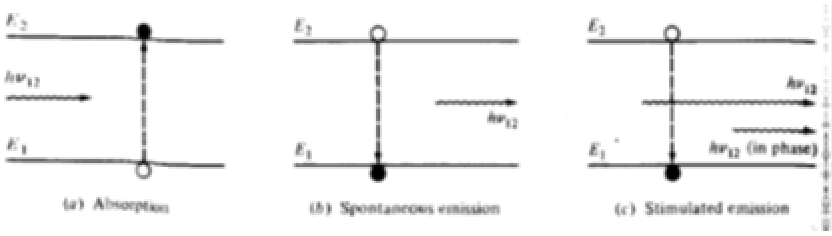
Semiconductor Lasers: These lasers are made from semiconductors p-n junctions and are commonly called injection laser diodes (ILD's). The excitation mechanism is a direct – current power supply that controls the amount of current to the active medium. The output light from an ILD is easily modulated making it very useful in many electronic communications applications.

LASER CHARACTERISTICS:

- ➔ All types of lasers have several common characteristics:
- ➔ They all use an active material to convert energy into laser light.
- ➔ A pumping source to provide power or energy.
- ➔ Optics to direct the beam through the active material to be amplified.
- ➔ Optics to direct the beam into a narrow powerful cone of divergence.
- ➔ A feedback mechanism to provide continuous operation.
- ➔ An output coupler to transmit power out of the laser.

BASIC PRINCIPLE OF LASER DIODES:

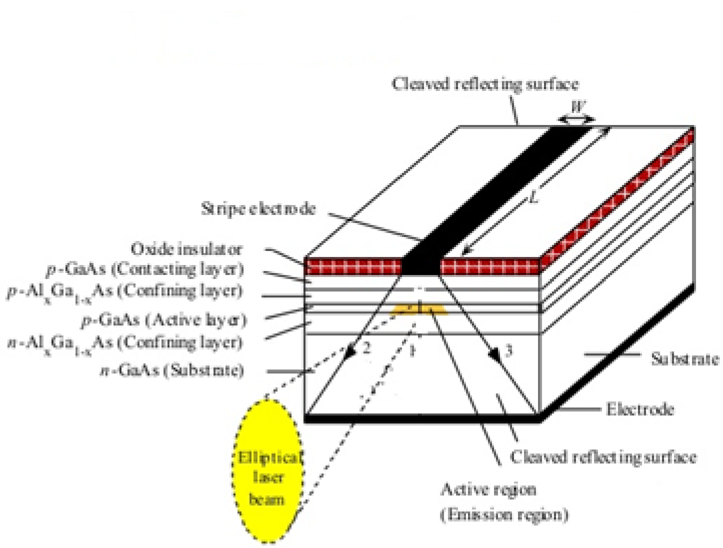
- The term LASER refers to Light Amplification by Stimulated Emission of Radiation. It is a light source that emits coherent monochromatic light. Monochromatic means a single light frequency. Coherent refers to the fact that all light waves emitted are in phase with one another.
- The laser operation is based on stimulated emission.
- The orbit with lower energy E_1 is called the ground state, equilibrium or valence band and the higher energy E_2 the excited state or conduction band. When a photon of energy (E_2 - E_1) impinges on the system, an electron in the state E_1 can absorb the photon energy and be excited to state E_2.



- The electrons can also be induced to make a downward transition from the excited level to the ground level by an external stimulation. If a photon of energy *hv* impinges on the system while the electron is still in the excited state, the electron is immediately stimulated to drop to ground level and give off a photon of energy of *hv.* This emitted photon is in phase with the incident photon and the resultant emission is known as **stimulated emission**. Thus two emissions are additive and this process is called light amplification by stimulated emission of radiation.
- A special requirement for laser action is that there should be more electrons in the excited energy level than in the lower level. This condition is called as population inversion. Population inversion is achieved by various pumping techniques. In a semiconductor laser, population inversion is accomplished by injecting electrons into the material at the device contacts to fill the lower energy states of the conduction band.

CONSTRUCTION:

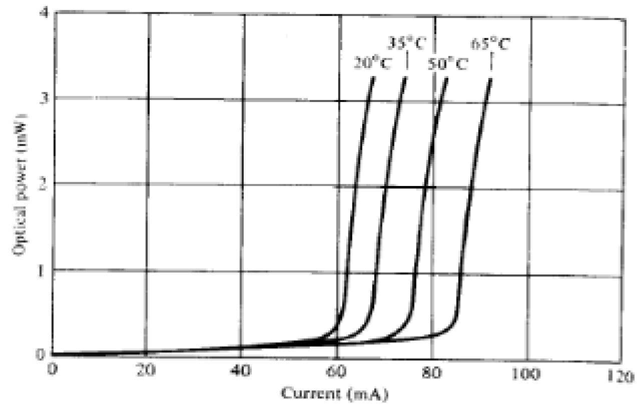
- The construction of a laser diode is similar to that of an LED except that the ends are highly polished. In fact below a threshold current the laser diode operates as an LED.
- Figure shows a simplified cross sectional diagram of a common type of laser diode known as striped heterojunction injection laser.
- This diode has a junction surrounded by material that has a lower refractive index than the material used for the junction.
- Many of the photons produced at the junction remain in the plane of the junction, if they move away from it, they will be reflected in the same way that the light is contained within an optical fiber.
- The ends of the junction have mirrored surfaces with one of the mirrors being partly transmissive so that light can escape in one direction only. The whole junction forms a resonant cavity (at the operating frequency).



OPERATION:

- When a large forward bias is applied, a large number of free holes and electron pairs are created in the immediate vicinity of the junction.
- When a hole and electron pair collide and recombine, they produce a photon of light.
- The P-N junction is sandwiched between layers of material with different optical and dielectric properties. The material that shields the junction has a low refractive index.
- So this difference traps the holes and electrons in the junction region and thereby improves light output. When a certain level of current is reached, the population of minority carriers on either side of the junction increases and photon density becomes so high that they begin to collide with already excited minority carriers.
- This causes a slight increase in the ionization energy level, which makes the carrier unstable. It thus recombines with the carrier of the opposite type at a slightly different (higher) level than if no collision had occurred. When it does, two equal energy photons are released.
- The carriers that are stimulated may reach a density level such that each released photon may trigger several more. This creates an avalanche effect that increases the emission efficiency exponentially with current above the initial emission threshold value.
- This behavior is usually enhanced by placing mirrored surfaces at each end of the junction zone. These mirror like ends trap the photons in the active region and as they reflect back and forth, stimulate free electrons to recombine with holes at high than normal energy level.
- This process is called lasing. The mirrored surface where light emits is partially transmissive.

CHARACTERISTICS:



- The radiant output power of typical ILD is shown in figure. It can be seen that very little output power is realized until the threshold current is reached.
- This is non-coherent radiation caused by spontaneous emission in the recombination layer. Thus the laser diode functions as a LED until its threshold current is reached.
- Threshold currents run from 5 to 250 mA for most diodes. The voltages are of the order of 1.2 to 2V at threshold.
- After lasing begins, the optical output power increases drastically with small increase in drive current.
- At that point the light output becomes coherent. This effect is shown in the figure.
- It can also be seen that laser diodes are much more temperature sensitive than LED's.
- As the temperature increases, the diode's gain decreases so that more current is required before oscillation (lasing) can begin.
- That is, the threshold current becomes greater (by about 1.5%/°C). This occurs because of thermal generation of holes in the n layer and electrons in the p layer. These free charges recombine with free electrons and holes outside the active layer reducing the number of charges reaching that layer and consequently reducing the number of charges available for the production of gain and stimulated emission.
- In addition, thermally generated holes and electrons in the active layer itself recombine non-radiatively, reducing in gain and an increase in threshold current results.

ADVANTAGES OF ILD's OVER LED:

- Because ILD's have a more directive radiation pattern, it is easier to couple their light into an optical fiber. This reduces the coupling losses and allows smaller fiber to be used.
- The radiant output power from an ILD is greater than that for a LED. A typical output power for an ILD is 5 mW (7 dBm) and 0.5mW (-3 dBm) for LED's. This allows ILD's to provide a higher drive power and to be used for systems that operate over longer distances.
- ILD's can be used at higher bitrates than LED's.

- ILD's generate monochromatic light which reduces chromatic/wavelength dispersion.

DISADVANTAGES:

- ILD's are typically on the order of 10 times more expensive than LED's.
- Because ILD's operate at higher powers, they typically have a much shorter lifetime than LED's.
- ILD's are more temperature dependent than LED's. This increases the complexity of transmitter circuitry.
- Their construction is more complicated mainly because of the requirement of current confinement in a small lasing cavity.

DIFFERENCE BETWEEN LED AND LASER:

Characteristics	**LEDs**	**Lasers**
Output Power	Linearly proportional to drive current	Proportional to current above the threshold
Current	Drive Current: 50 to 100 mA Peak	Threshold Current: 5 to 40 mA
Coupled Power	Moderate	High
Switching Speed	Slow	Fast
Beamwidth	Wide	Narrow
Bandwidth	Moderate	High
Wavelengths Available	0.66 to 1.65 µm	0.78 to 1.65 µm
Spectral Width	Wide	Narrow
Fiber Type	Multimode Only	SM, MM
Ease of Use	Easy	Difficult
Lifetime	Long	Short as compared to LED
Cost	Low	High

DETECTORS:

- The devices used to convert the transmitted light back into an electrical signal are a vital link in the fiber optic system. The first element of the receiver is a photo-detector. The photo-detector senses the luminescent power falling on it and converts the variation of this optical power into a correspondingly varying electrical current. Since the optical signal is generally weakened and distorted, when it emerges from the end of the fiber, the photo-detector must meet very high performance requirements. They are –

- ➔ High response or sensitivity in the emission wavelength range of the optical source used.
- ➔ Minimum addition of noise to the system.
- ➔ A fast response speed or sufficient bandwidth to handle the desired data rate.
- ➔ It should be insensitive to variations in temperature.
- ➔ It should be compatible with the physical dimensions of the optical fiber.
- ➔ Should have reasonable cost in relation to the other components of the system.
- ➔ Should have a long operating life.

- Several different types of photodetectors are in existence. Among these are photomultipliers, pyro electric detectors, semiconductor based photo conductors, phototransistors and photodiodes.
- However, many of these detectors do not meet one or more of the foregoing requirements. Of the semiconductor based photodetectors, photodiodes are used almost exclusively for fiber optic systems because of its small size, suitable material, high sensitivity and fast response time.
- The two types of photo-diodes used are the PIN photodiode and avalanche photodiode (APD).

CHARACTERISTICS OF LIGHT DETECTORS:

RESPONSIVITY:

It is the measure of the conversion efficiency of photodetectors. It is the ratio of the output current of a photodiode to the input optical power launched into the diode. It has unit of Amperes/Watts. Responsivity is generally given for a particular wavelength/frequency.

DARK CURRENT:

Dark current is the reverse leakage current that flows through a photodiode with no light input (under dark condition). Dark current is caused by thermally generated carriers in the diode.

TRANSIT TIME:

Transit time is the time it takes a light induced carrier to travel across the depletion region. This determines the maximum bit rate (or data rate) possible with a particular photodiode.

SPECTRAL RESPONSE:

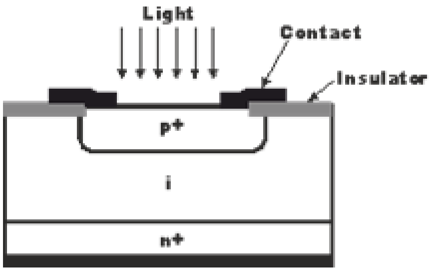
It is the range of wavelength values that can be used for a given photodiode. Generally, relative spectral response is graphed as a function of wavelength or frequency. Figure shown below provides the spectral response vs light wavelength for the typical PIN photodiode. This particular photo detector absorbs energy more efficiently in the range 800 nm to 820 nm.

PIN DIODE:

A PIN diode is a depletion layer photodiode and is probably the most common device used as a light detector in Fiber Optic communication systems.

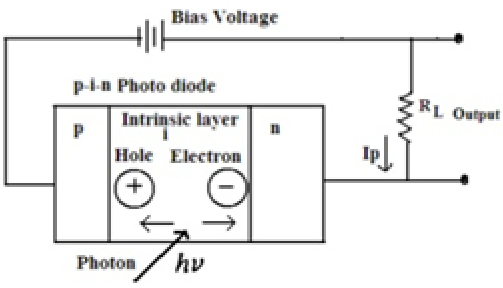
CONSTRUCTION:

- The figure shows the basic construction of PIN diode. The device structure consists of heavily doped P and N regions separated by a very lightly doped (almost pure / intrinsic) layer of N type semiconductor material.



- Light enters the device through a very small window and falls on the carrier void intrinsic material. The intrinsic material is made thick enough so that most of the photons that enter the device are absorbed by this layer.
- In normal operation a sufficiently large reverse biased voltage is applied across the device so that the intrinsic region is fully depleted of carriers.

OPERATION:



- Light entering through the window of a PIN diode is absorbed by the intrinsic material and adds enough energy (an energy greater than or equal to the band gap energy of the semiconductor material) to cause the electrons to move from the valence band to the conduction band.
- This process generates free electron hole pairs which are known as photo-carriers since they are photon-generated charge carriers.
- The photodetector is designed so that these carriers are generated mainly in the depletion region where most of the incident light is absorbed.
- The high electric field present in the depletion region causes the carriers to separate and be collected across the reverse biased junction. This gives rise to current flow in the external circuit.
- This current flow is known as photocurrent and is proportional to the light power absorbed by the diode.
- The ability of an electron hole pair to contribute to current flow depends on the hole and electron being rapidly separated from each other before they collide and cancel each other out.

AVALANCHE PHOTODIODE:

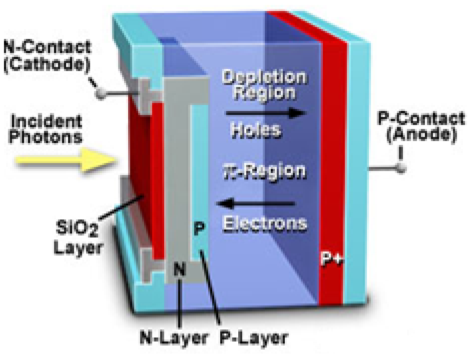
- One of the major parameters of the photodiode is sensitivity – the minimum light power a photodetector can detect. This parameter determines the length of a fiber optics link imposed by a power limitation.
- The more sensitive the photodiode, the longer the link a designer can afford to have with the given losses.
- The remedy for this problem is to use an amplifier to magnify the photocurrent produced by the photodiode. In fact a receiver circuit always includes an amplifier.
- But an amplifier introduces its own noise thus reducing the sensitivity. So, if photocurrent is amplified without an external amplifier and therefore noise associated with the circuitry. That is why Avalanche Photo Diode was invented.

PRINCIPLE:

- A special PIN structure of photodiodes is used. Incident photons generate primary electrons and holes as they do in regular PIN diodes.
- Relatively high (around 20V) reverse voltage is applied to the photodiode. This voltage accelerates photo generated electrons and holes, which thereupon acquire high kinetic energy.
- These electrons and holes strikes neutral atoms separate other bonded electrons and holes.
- These secondary carriers gain enough energy to ionize other carriers causing so called avalanche process of creating new carriers.
- Thus one photon eventually generates many charge carriers which means this photodiode internally amplifies photocurrent.

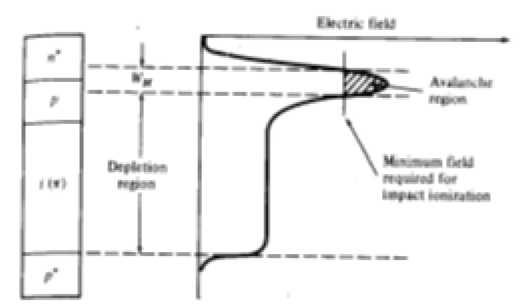
CONSTRUCTION:

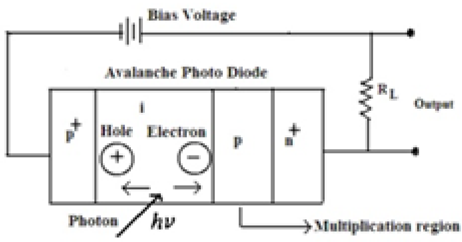
- APD's are usually variation of PIN diodes. The materials used and thus the spectral ranges are the same.
- One form of APD, a reach through diode, is shown in figure.



- It consists of p^+-π-p-n^+ layers. The p^+ and n^+ layers are highly doped, low resistance regions having a very small voltage drop. The π region is lightly doped nearly intrinsic. Most of the photons are absorbed in this layer creating electron hole pairs.

- When the APD is reverse biased, most of the voltage appears across the p-n^+ junction because of negligibly small photocurrent.
- So photoelectrons move to the p region which has been depleted of free charge by the large reverse bias voltage.
- With the increase in the bias voltage level, this electric field at the junction and width of the depletion region increases.
- At a certain voltage level, this electric field is about 10% less than the avalanche breakdown limit and the depletion layer just reaches through to the nearly intrinsic π region.
- Because of this reason, it is referred to as reach through APD.





OPERATION:

- The RAPD is operated in the fully depleted mode. Photons enter the device through the p^+ region and are mostly absorbed by the high resistivity intrinsic p type layer where electron hole pairs are created.
- The relatively weak electric field in this region forces or separates the carriers causing the electrons and holes to drift into the high electric field region.
- The electrons are drifted towards the p-n^+ layer. Because of the high field intensity, electrons are imparted with high kinetic energy.
- The kinetic energy of electrons is greater than bandgap energy of the valence electrons, so the collision can free a bound electron.
- The free electron and hole so created acquire enough kinetic energy to cause further ionization. It results in avalanche with the number of carriers growing exponentially as the process continues.

COMPARISON BETWEEN PIN DIODES AND APD's:

- ➔ The APD is a semiconductor junction detector that has internal gain which increases its responsivity over PIN devices.
- ➔ APD's are more sensitive than PIN diodes so better S/N ratios.
- ➔ APD's have excellent linearity over optic power levels ranging from a fraction of nano watt to several microwatts. If more than a microwatt is available at the receiver, an APD is usually not needed. At this power level PIN diode provides enough responsivity and sufficiently large S/N ratios for most applications.

- ➔ The gain of an APD is temperature dependent and generally decreases as the temperature rises. This occurs because the mean free path between collisions is smaller at higher temperatures. Many of the charge carriers do not get a chance to reach the high velocities required to produce secondary carriers. The PIN diode is less sensitive to temperature.
- ➔ APD's require a high reverse bias voltage as compared to PIN diode.
- ➔ The PIN device is cheaper as compared to APD.

FIBER TO FIBER JOINTS:

- A significant factor in any fiber optics system installation is the requirement of interconnections of fibers in a low loss manner. These interconnections occur at the optical source, at the photodetector, at intermediate points in the link where two cables are connected.
- The particular technique selected for joining the fibers depends on whether a permanent bond or an easily demountable connection is desired.
- A permanent bond is generally referred to a splice whereas demountable joint is known as a connector.
- Every joining technique is subject to certain conditions which can cause various amounts of optical power loss at the joints. These losses depend on parameters such as input power distribution at the joint, the geometrical and waveguide characteristics of the two fiber ends at the joint and the fiber end face qualities.

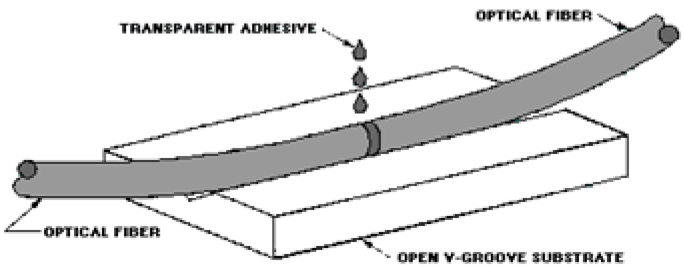
FIBER SPLICING:

- A fiber splicing is the permanent connection of two pieces of optical fiber. These are typically used to create long optical links or in situations where frequent connections and disconnections are not needed.
- In making and evaluating such splices, one must take into account the geometrical differences in the two fibers, fiber misalignments at the joints and the mechanical strength of the splice. Three types of techniques are used – Mechanical, Fusion and Elastic Tube.

MECHANICAL SPLICES:

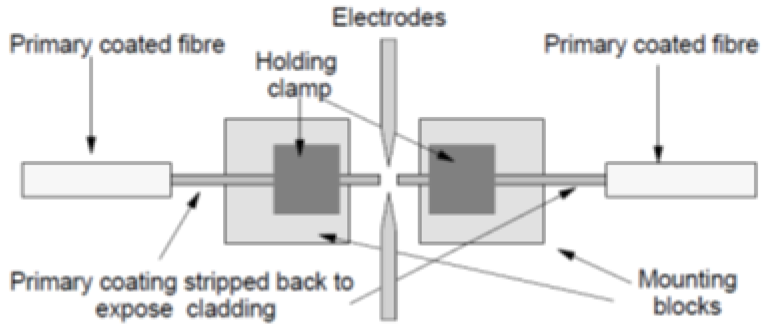
V-Grooved Splices:

- Mechanical splices may also use either a grooved substrate or positioning rods to form suitable V-grooves for mechanical splicing.
- The basic V-grooved device relies on an open grooved substrate to perform fiber alignment. When inserting the fibers into the grooved substrate, the V-groove aligns the cladding surface of each fiber end.
- A transparent adhesive makes the splice permanent by securing the fiber ends to the grooved substrate. Figure below illustrates this type of open V-grooved splice.



FUSION SPLICING:

- A fiber join is a type of weld. The fiber ends are cut, polished, butted up to one another and fused by heat. In practice, a light loss of only 0.1 dB is the current budget for power loss in a single-mode fiber join.
- But it should be realized that 0.1 dB is quite a lot in that it represents the total loss of one half of a kilometer of cable. A device setup for fusion splicing is illustrated in Figure below.

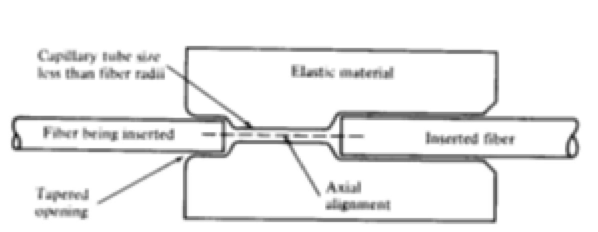


- Each fiber is stripped of its primary coating and the end cleaved such that it is square.
- The fiber ends are positioned a few mm from one another and clamped to positioning blocks. There is often a groove provided in the mounting block to aid in correct alignment.
- The fiber ends are then aligned with one another and brought closer together.
- When alignment is satisfactory an electric arc is started between the two electrodes and the fibers brought into contact. Heat from the arc melts the glass and the join is made.
- This technique can produce very low splice losses (no reflection loss and minimal insertion loss). However care must be taken in this technique since surface damage due to handling, surface defect growth created during heating and residual stresses induced near the joint as a result of changes in chemical composition arising from the material melting can produce a weak splice.

ELASTIC TUBE SPLICE:

- The elastic tube splice shown cross sectionally in the figure below is a unique device that automatically performs lateral, longitudinal and angular alignment.

- It splices multimode fibers with losses in the same range as commercial fusion splices, but much less equipment and skill are needed.
- The splice mechanism is basically a tube made of elastic material. The central hole diameter is slightly smaller than that of the fiber to be spliced and is tapered on each end for easy fiber insertion.
- When the fiber is inserted, it expands the hole diameter so that the elastic material exerts a symmetrical force on the fiber.
- This symmetry feature allows an accurate and automatic alignment of the axes of the two joined fibers.
- A wide range of diameters can be inserted into the elastic tube. Thus the fibers to be spliced do not have to be equal in diameter, since each fiber moves into position independently relative to the tube axis.



FIBER CONNECTORS:

- A connector is used to temporarily connect an optical fiber to another fiber or to a transmitter/receiver. Thus a connection system includes a connector and receptacle whose function is to accept an optical signal with minimum loss.
- For this reason connector is also called as a plug. A wide variety of optical fiber connectors has evolved for numerous different applications.
- Their uses range from simple single channel fiber to fiber connections to multi channel connectors used in harsh military field environments.
- Some of the principal **requirements of a good connector** design are as follows:

Low coupling Loss:
The connector assembly must maintain stringent alignment tolerances to assure low mating losses. These low losses must not change significantly during operation or after numerous connects and disconnects.

Interchangeability:
Connectors of the same type must be compatible from one manufacturer to another.

Ease of Assembly:
A service technician should be readily able to install the connectors in a field environment i.e. in the location other than the connector factory. The connector loss should also be fairly insensitive to the assembly skill of the technician.

Low Environmental Sensitivity:
Conditions such as temperature, dust and moisture should have a small effect on connector loss variations.

Low Cost and Reliable Construction:

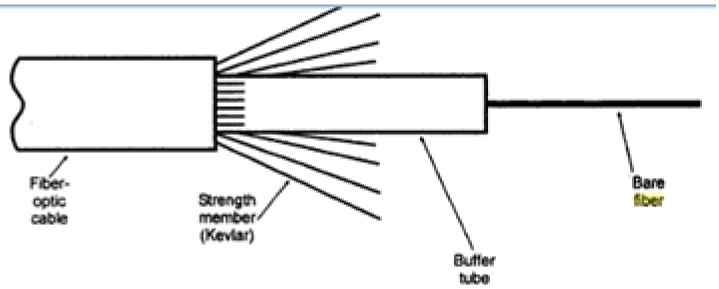
The connectors must have a precision suitable to the application but its cost must not be a major factor in the fiber system.

Ease of Connection:

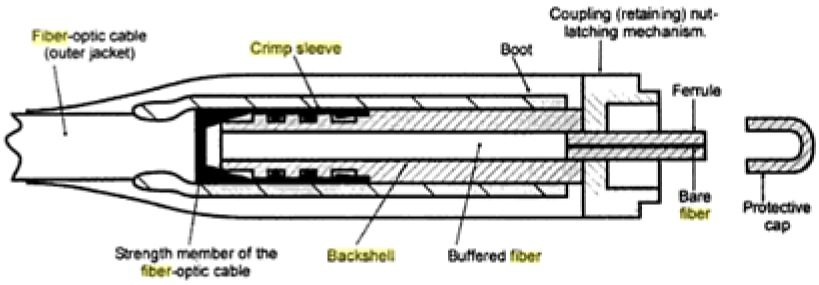
Generally user should be able to mate and demate the connector by hand.

BASIC STRUCTURE OF CONNECTOR:

- There are many types of connectors. But regardless of the specific design, each has the following basic components: a ferrule, a latching mechanism, a backshell, a crimp sleeve and a boot.
- The basic structure of an assembled connector is shown in figure (b).
- Figure (a) shows how a **fiber optic cable is prepared for termination** the outer jacket is stripped, the strength member is revealed and the buffer is stripped to disclose the bare fiber.
- Such a prepared cable end is inserted into the connector so that the ferrule houses the bare fiber.
- The buffer is placed within the backshell as shown. The boot covers the entire assembly from the latching mechanism back to the cable preventing the cable from bending while the technician is working with the connector.
- The cable is affixed with respect to the connector by positioning the strength member between the backshell and the crimp sleeve and the fiber is guided by using ferrule inside.
- A latching mechanism – a coupling or retaining as shown in fig. (b) fixes the connector with respect to the receptacle so that light is transmitted from the fiber cable to the receiver.
- Thus the fiber core is aligned with respect to the ferrule through the ferrule hole, the ferrule is aligned with respect to the latching mechanism and the latter is aligned with respect to the receptacle.
- Connectors come from their manufacturers with protective caps which screen the end face of the ferrule for dust, dirt, scratches and any other possible blemishes.


Fiber-
optic
cable
Strength
member
(Kevlar)
Buffer
tube
Bare
fiber

a)


Fiber-optic cable
(outer jacket)
Crimp sleeve
Boot
Coupling (retaining) nut-
latching mechanism.
Ferrule
Bare
fiber
Protective
cap
Strength member of the
fiber-optic cable
Backshell
Buffered fiber

b)