Optical Fiber

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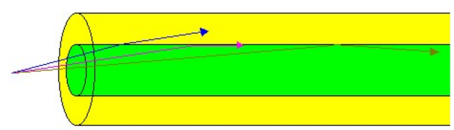
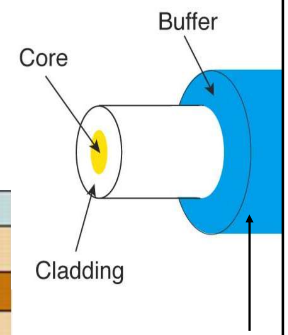
Introduction

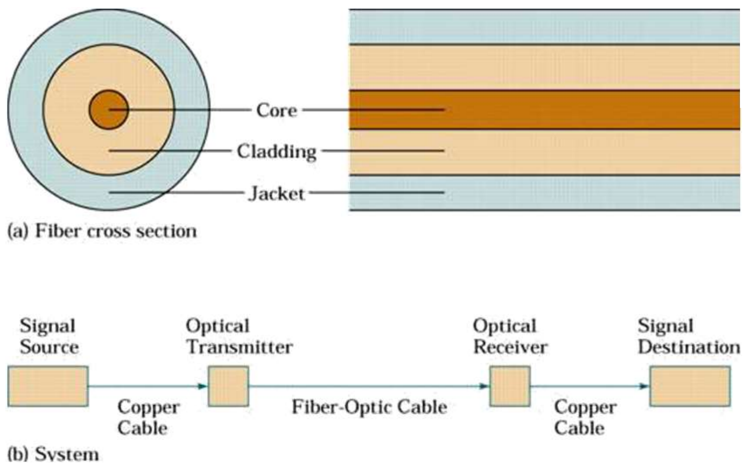


- An optical fiber is essentially a waveguide for light.
- It consists of a **core** and **cladding** that surrounds the core.
- The **index of refraction** of the cladding is less than that of the core, causing rays of light leaving the core to be refracted back into the core.
- A light-emitting diode (LED) or **diode laser** can be used as the source.
- Advantages of optical fiber include:
  - Greater bandwidth than copper
  - Lower loss
  - Immunity to **crosstalk**
  - No electrical hazard

Structure of Optical Fiber

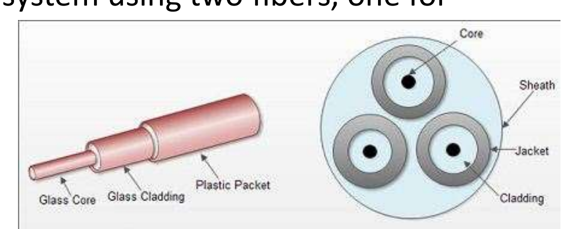


Molten Silica (SiO_2)
+
GeO_2



Structure of Optical Fiber

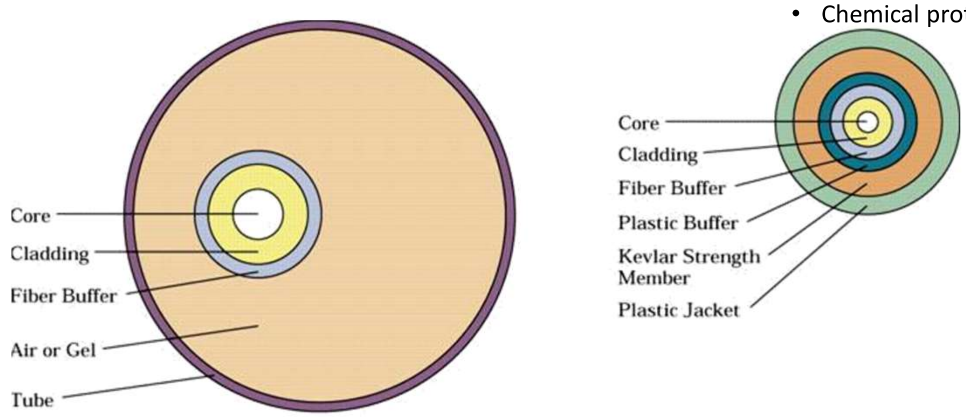
- Optical fiber is made from thin strands of either **glass or plastic**.
- It has little mechanical strength, so it must be enclosed in a **protective jacket**.
- Often, **two or more fibers** are enclosed in the same cable for increased bandwidth and redundancy in case one of the fibers breaks.
- It is also easier to build a full-duplex system using two fibers, one for transmission in each direction.



(a)Optical fibre (b) Bundle of 3 fibers with outer steath

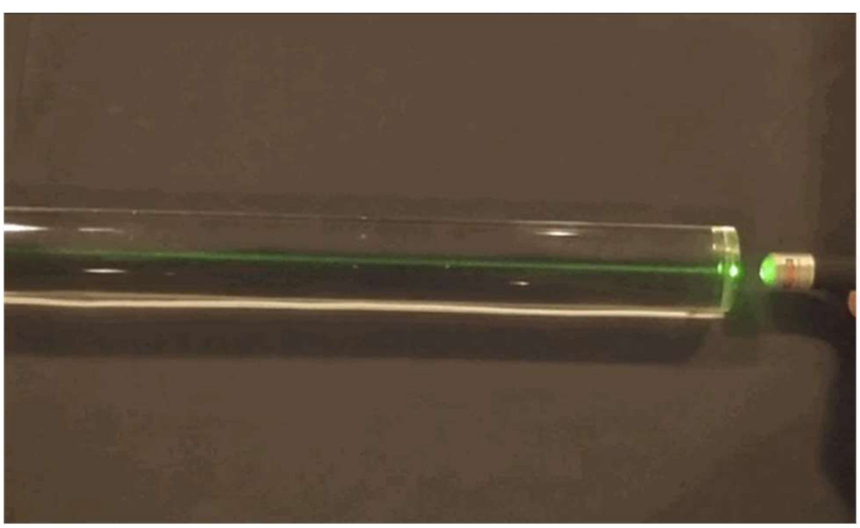
Structure of Optical Fiber

Strengthening and Buffering materials for;
- Mechanical protection
- Moisture protection
- Chemical protection



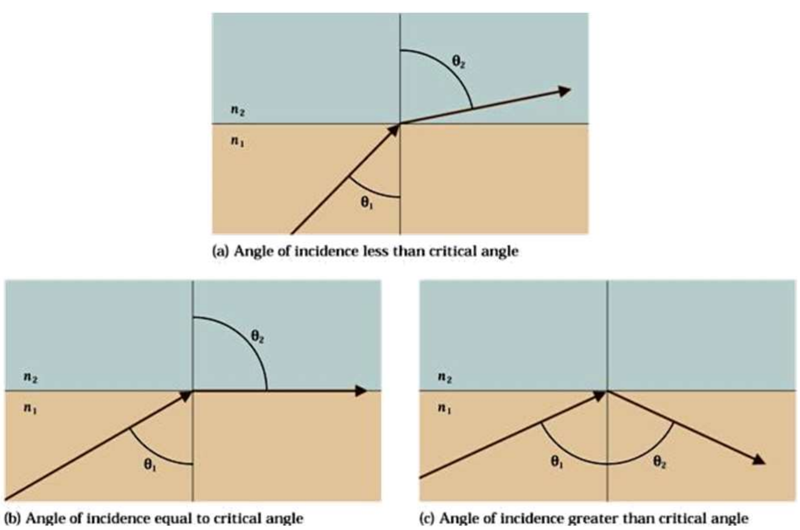
(a) Loose-tube construction (b) Tight-buffer construction

How Optical Fiber Works?



Total Internal Reflection

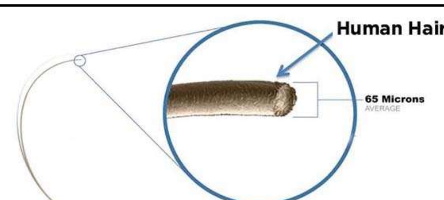
Total Internal Reflection



Total Internal Reflection

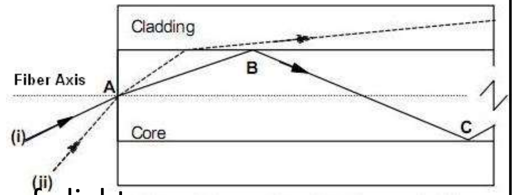
- Optical fibers work on the principle of **total internal reflection**
- The **angle of refraction** at the interface between two media is governed by Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$
- If, $\theta_2 \geq 90$ $\theta_1 = \theta_c \geq \sin^{-1}\frac{n_2}{n_1}$
- If $n_1 = 1.54$, $n_2 = 1.51$ then $\theta_c \geq 79°$

Optical Fiber



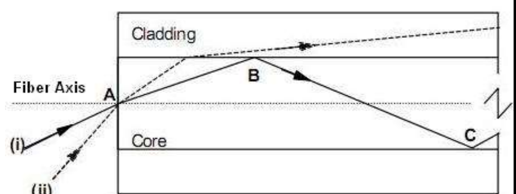
- Optical fibers are mostly have roughly the diameter of a **human hair**, and they may be many miles long.
- Light is transmitted along the center of the fiber from one end to the other, and a **signal may be imposed**.
- Fiber optic systems are superior to metallic conductors in many applications. Their greatest advantage is **bandwidth**.
- Because of the wavelength of light, it is possible to transmit a signal that contains considerably **more information** than is possible with a metallic conductor — even a coaxial conductor.

Light Propagation



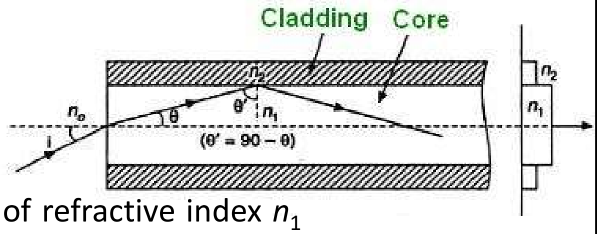
- In order to understand the propagation of light through an optical fiber, consider a light ray entering the core at a point A, travelling through the core until it reaches the core cladding boundary at point B.
- As long as the light ray intersects the core-cladding boundary at a *small angles*, the ray will be reflected back in to the core to travel on to point C where the process of reflection is repeated, i.e., **total internal reflection** takes place.
- Total internal reflection occurs only when the angle of incidence is greater than the critical angle.

Light Propagation



- If a ray enters an optic fiber at a steep angle, when this ray intersects the core-cladding boundary, the angle of intersection is too large.
- So, reflection back in to the core does not take place and the light ray is lost in the cladding.
- This means that to be guided through an optic fiber, a light ray must enter the core with an angle less than a particular angle called the **acceptance angle (**or **angle of acceptance)** of the fiber.
- A ray which enters the fiber with an angle greater than the acceptance angle will be lost in the cladding.

Numerical Aperture

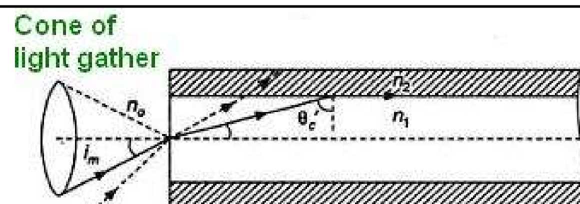


- Consider an optical fiber having a core of refractive index n_1 and cladding of refractive index n_2.
- Let the incident light makes an angle i with the core axis, then the light gets refracted at an angle θ and fall on the core-cladding interface at an angle θ' where, $\theta' = (90 - \theta)$.
- By Snell's law at the point of entrance of light in to the optical fiber we get,

$$n_0 \sin i = n_1 \sin \theta$$

- where n_0 is refractive index of medium outside the fiber. For air n_0 = 1.

Numerical Aperture



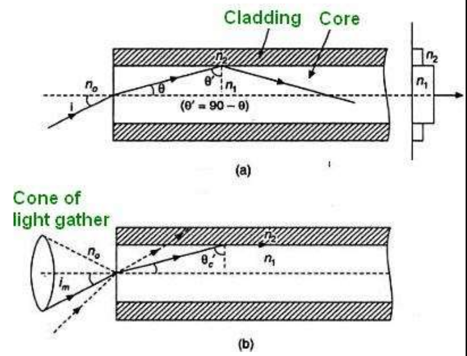
- When light travels from core to cladding it moves from denser to rarer medium and so it may be totally reflected back to the core medium if θ' exceeds the critical angle θ_C'.
- The critical angle is that angle of incidence in denser medium (n_1) for which angle of refraction become 90°.
- Using Snell's laws at core cladding interface,

$$n_1 \sin \theta_C' = n_2 \sin 90$$

or $$\sin \theta_C' = \frac{n_2}{n_1}$$

Numerical Aperture

- Therefore, for light to be propagated within the core of optical fiber as guided wave, the angle of incidence at core-cladding interface should be greater than θ_C'.
- As i increases, θ increases and so $\theta'(= 90 - \theta)$ decreases.
- Therefore, there is maximum value of angle of incidence beyond which, it does not propagate rather it is refracted in to cladding medium.
- This maximum value of i, say i_m is called maximum **angle of acceptance** and $n_0 \sin i_m$ is termed as the **numerical aperture** (NA).



Numerical Aperture

$$NA = n_0 \sin i_m = n_1 \sin\theta = n_1 \sin(90 - \theta_c')$$

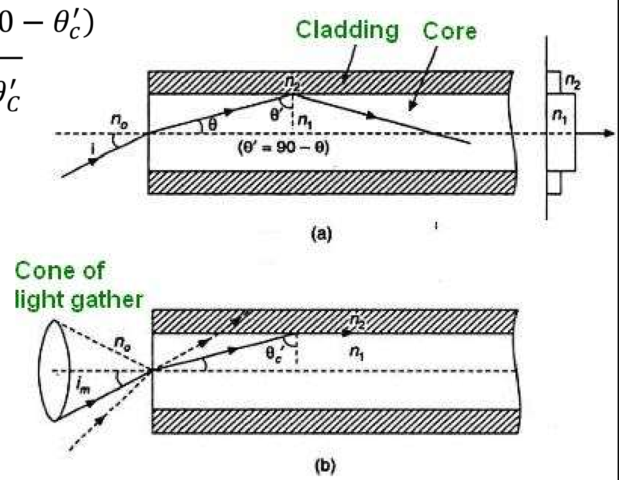
$$NA = n_1 \cos\theta_c' = n_1\sqrt{1 - \sin^2\theta_C'}$$

Since, $\sin\theta_C' = \frac{n_2}{n_1}$

$$NA = n_1\sqrt{1 - \frac{n_2^2}{n_1^2}}$$

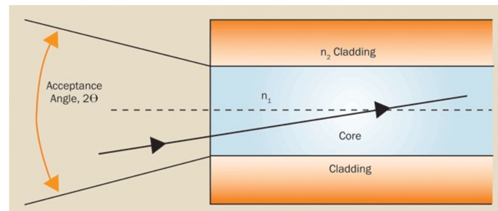
$$NA = \sqrt{n_1^2 - n_2^2}$$

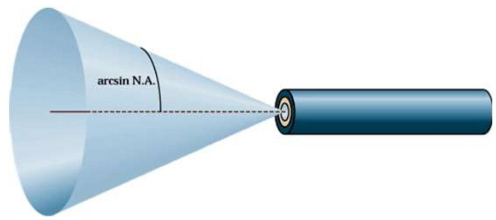
$$NA = \sqrt{n_{core}^2 - n_{cladding}^2}$$



Numerical Aperture

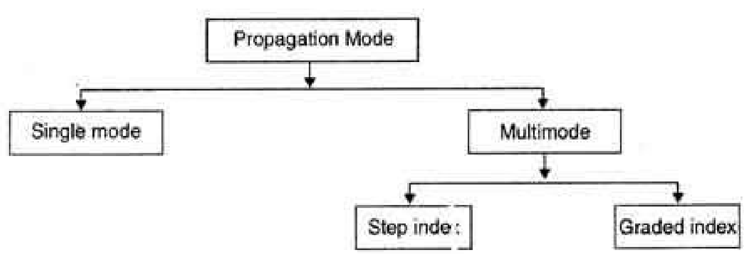
- The significance of *NA* is that light entering in the cone of semi vertical angle i_m only propagate through the fiber.
- The higher the value of i_m or *NA* more is the light collected for propagation in the fiber.
- Numerical aperture is thus considered as a *light gathering capacity* of an optical fiber.
- Numerical Aperture is defined as the sin of half of the angle of fiber's light acceptance cone, i.e., $NA = \sin i_m$ where i_m, is called acceptance cone angle.





Classification of Optical Fibres

- Single mode Step-index Fibre
- Multimode Step-index Fibre
- Multimode Graded-index Fibre

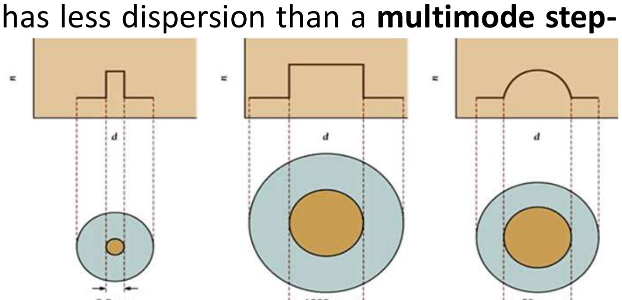


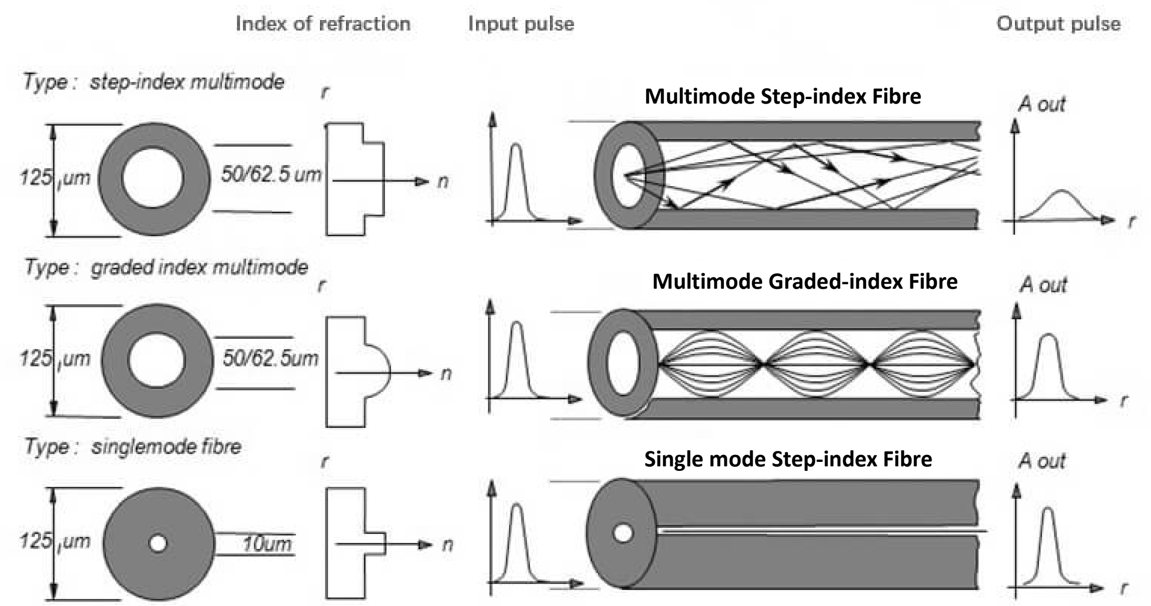
Modes

- Since optical fiber is a waveguide, light can propagate in a number of modes.
- If a fiber is of large diameter, light entering at different angles can accommodate **multiple modes** while narrow fiber may only accommodate **one mode**.
- **Single mode** fiber has much less dispersion but is more expensive to produce. Its small size, together with the fact that its numerical aperture is smaller than that of **Multimode** fiber, makes it more difficult to couple to light sources.
- Multimode propagation will cause **dispersion**, which results in the spreading of pulses and limits the usable bandwidth.

Index

- Both types of fiber described earlier are known as **step-index** fibers because the index of refraction changes radically between the core and the cladding
- **Graded-index** fiber is a compromise multimode fiber, but the index of refraction gradually decreases away from the center of the core
- **Multimode graded-index** fiber has less dispersion than a **multimode step-index** fiber.





Single Mode Fiber (SMF)

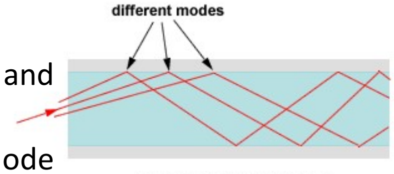
- As its name suggests, in single-mode fiber, only one mode can propagate through the fiber.
- In this, the diameter of the small core is 5 – 10 μm, and the diameter of cladding is 70 – 100 μm. Also, the difference between the refractive indexes of core and cladding is minimal.
- Fiber glass has lower density (index of refraction) that creates a critical angle close enough to 90° such that the beam propagates in a straight line. In this mode, light can propagate only in a straight line, without bouncing.
- In this case, propagation of different beams is almost identical and delays are negligible. The beams arrive at destination together and can be recombined with little distortion to the signal.

Single Mode Fiber (SMF)

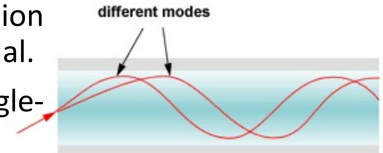
- In single mode, there is almost no dispersion of light in the single-mode fiber. No degradation of the signal when the light is traveling through the fiber.
- Single mode fibers are more expensive and are widely used for long distance communication.
- These types of fibers can transmit data at 50 Gbps for 100 kilometers without amplification.
- It makes use of a laser light source. In this, light pulses are generated by the injection laser diodes (ILD) due to small size of core.

Multimode Fiber (MMF)

- In MMF, multiple beams travel in the core in different paths.
- In MMF, the diameter of the small core is 50 – 60 μm, and the diameter of cladding is 60 – 90 μm.
- The relative refractive index difference in multi-mode fiber is more significant than the single-mode fiber.
- MMF is not suitable for the long-distance communication because of large dispersion and attenuation of the signal.
- It can support less bandwidth as comparative to single-mode fiber. In this, the data rate is up to 1 Gbps.
- MMFs are further categorized into Step index fibers and Graded index fibers.

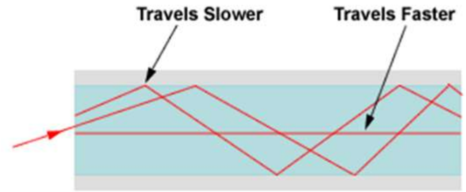


Step-Index Multimode Fiber



Graded-Index Multimode Fiber

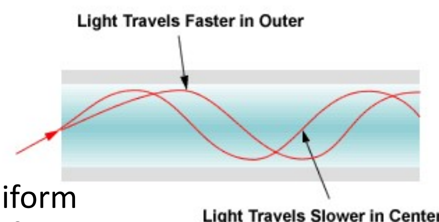
Step Index Optical Fiber



Step-Index Multimode Fiber

- Density and therefore the refractive index of core remains constant from the center to the edges.
- A beam of light moves in a straight line in this medium until it reaches the interface of core and the cladding. At this interface, the angle of ray is changed due to the change in density.
- In this fiber, a ray with smaller angle of incidence requires more bounces thus will take more time to reach the destination whereas the ray with high angle of incidence will require less number of bounces and will reach the destination in lesser time.
- In this, the light rays propagate in the zigzag manner.

Graded Index Optical Fiber

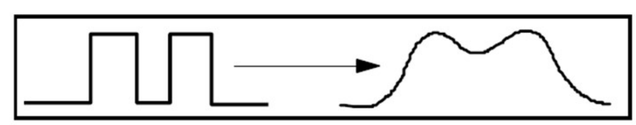


Graded-Index Multimode Fiber

- In graded-index fiber, the core has non-uniform refractive index and the cladding has uniform refractive index. The refractive index of the core decreases gradually from the center of the core to the core-cladding interface.
- Because of this difference in refractive index, different beams refract at different angles into a curve.
- Only the horizontal beams move in a straight line due to constant density at the center.
- In this, the light rays propagate in the form of skew rays or in helical manner.

Dispersion in Optical Fibres

- In an optical medium, such as fiber, there are three types of dispersion,
  - Chromatic (Intramodal)
  - Modal (Intermodal)
  - Material.

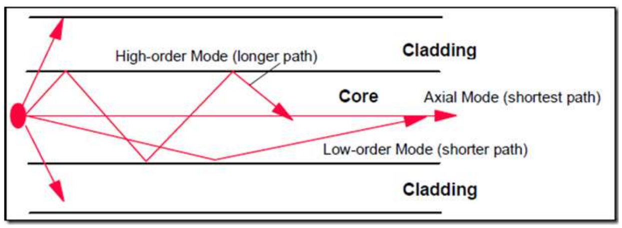


Chromatic Dispersion

- Chromatic dispersion results from the **spectral width of the emitter**.
- The spectral width determines the number of different wavelengths that are emitted from the LED or laser. The smaller the spectral width, the fewer the number of wavelengths that are emitted.
- Because longer wavelengths travel faster than shorter wavelengths (higher frequencies) these longer wavelengths will arrive at the end of the fiber ahead of the shorter ones, **spreading out the signal**.
- One way to decrease **chromatic dispersion** is to narrow the spectral width of the transmitter. **Lasers**, for example, have a more narrow spectral width than **LEDs**.
- A monochromatic laser emits only one wavelength and therefore, does not contribute to chromatic dispersion.

Modal Dispersion

- **Modal dispersion** deals with the path (mode) of each light ray.
- Most transmitters emit many different modes. Some of these light rays will travel straight through the center of the fiber (axial mode) while others will repeatedly bounce off the cladding/core boundary to zigzag their way along the waveguide, as illustrated below.



Modal Dispersion

- The modes that enter at sharp angles are called high-order modes.
- These modes take much longer to travel through the fiber than the low-order modes and therefore contribute to **modal dispersion**.
- One way to reduce modal dispersion is to use graded-index fiber.
- Unlike the two distinct materials in a step-index fiber, the **graded-index fiber's** cladding is doped so that the refractive index gradually decreases over many layers.
- The corresponding cross-sections of the graded-index fiber types are shown in next slide.

Graded Index Optical Fiber

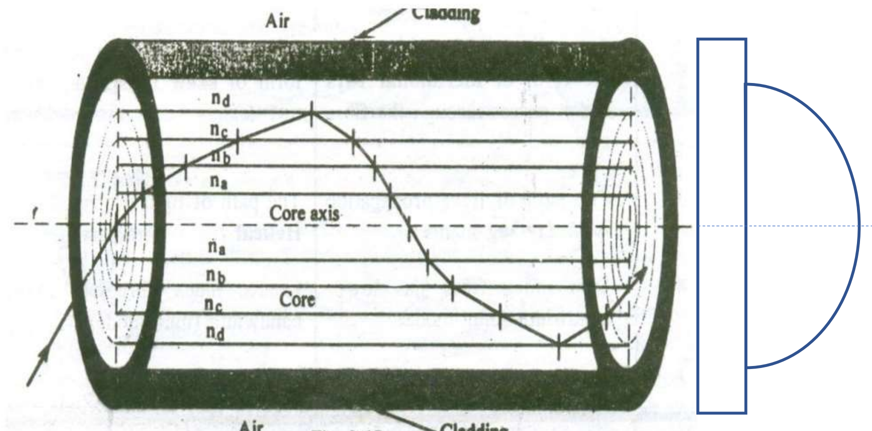
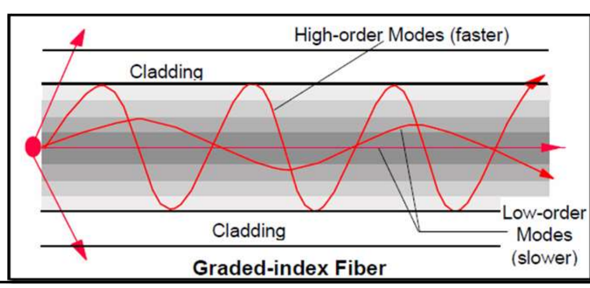


Fig. 3.15

Modal Dispersion

- With a **graded-index fiber**, the light follows a more curved path.
- The high-order modes spend most of the time traveling in the lower-index cladding layers near the outside of the fiber. These lower-index core layers allow the light to travel faster than in the higher-index center layers. Therefore, their higher velocity compensates for the longer paths of these high-order modes. A good waveguide design appreciably reduces modal dispersion.



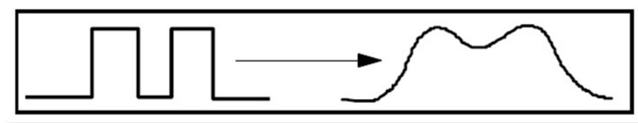
Modal Dispersion

- Modal dispersion can be completely eliminated by using a **single-mode fiber**. As its name implies, single mode fiber transmits only one mode of light so there is no spreading of the signal due to modal dispersion.
- A monochromatic **laser** with single-mode fiber completely eliminates dispersion in an optical waveguide but is usually used in very long distance applications because of its complexity and expense.

Material Dispersion

- **Material dispersion** is caused by the wavelength dependence of the refractive index on the fiber core material, while the **waveguide dispersion** occurs due to dependence of the mode propagation constant on the fiber parameters (core radius, and difference between refractive indexes in fiber core and fiber cladding) and signal wavelength.

Dispersion



- Dispersion in fiber optics results from the fact that in multimode propagation, the signal travels faster in some modes than it would in others.
- Single-mode fibers are relatively free from dispersion except for *chromatic dispersion*
- Graded-index fibers reduce *modal dispersion* by taking advantage of higher-order modes.
- One form of dispersion is called *material dispersion* because it depends upon the material of the core.
- Dispersion increases with the bandwidth of the light source.

Transmission Characteristics of Optical Fibers

- One of the important properties of optical fiber is signal attenuation. It is also known as **fiber loss** or signal loss.
- The signal attenuation of fiber determines the **maximum distance** between transmitter and receiver.
- The attenuation also determines the number of **repeaters** required, maintaining repeater is a costly affair.

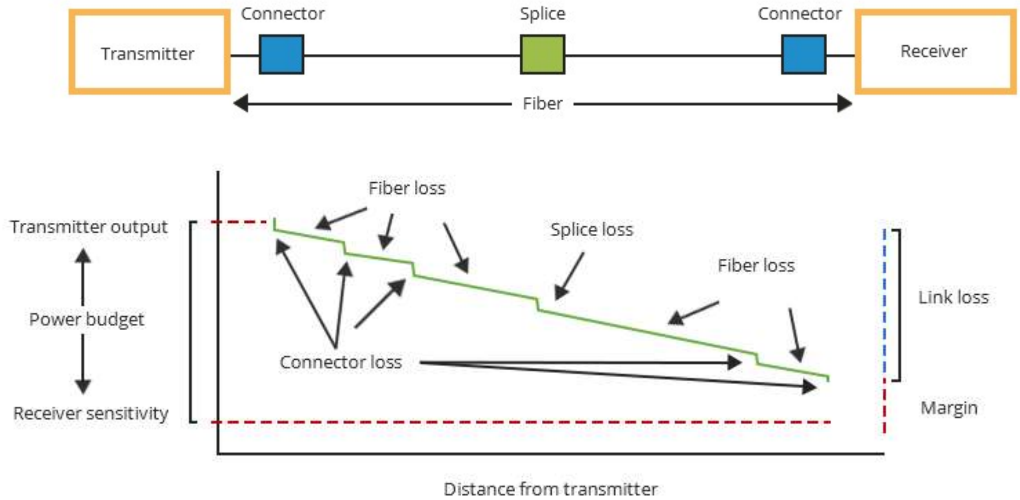
Transmission Characteristics of Optical Fibers

- Another important property of optical fiber is distortion mechanism. As the signal pulse travels along the fiber length it becomes broader. Which is known as **pulse broadening**.
- After sufficient length the broad pulses starts **overlapping** with adjacent pulses.
- This creates error in the receiver. Hence the distortion limits the information carrying capacity of fiber.

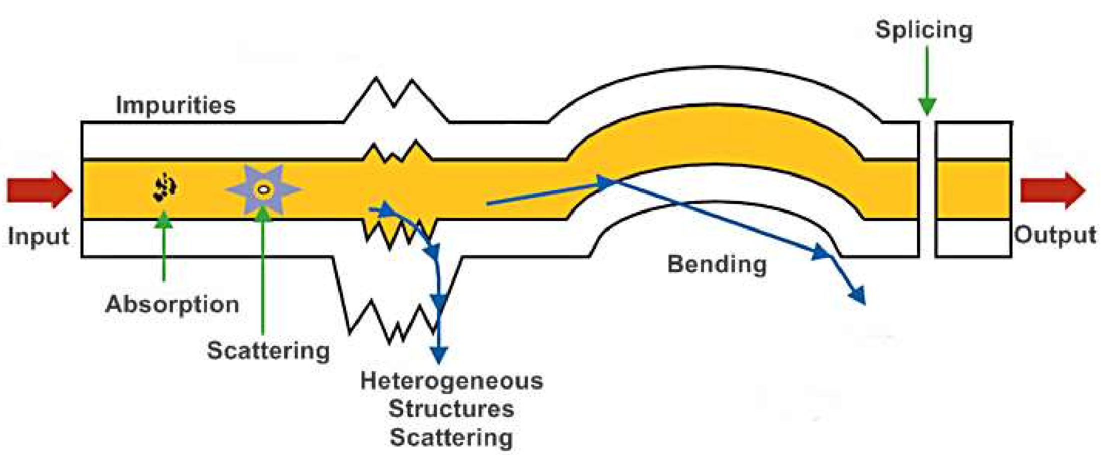
Fiber Loss

- Fiber loss can be also called *attenuation loss*, which measures the amount of light loss between input and output.
- Factors causing fiber loss are various, such as intrinsic material absorption, bending, connector loss, etc.
- Losses in the optical fiber can be categorified into intrinsic optical fiber losses and extrinsic optical fiber loss depending on whether the loss is caused by intrinsic fiber characteristics or operating conditions.
- Intrinsic Optical Fiber Losses comprise of absorption loss, dispersion loss and scattering loss caused by the structural defects.
- Extrinsic Optical Fiber Losses contains splicing loss, connector loss, and bending loss.

Fiber Loss

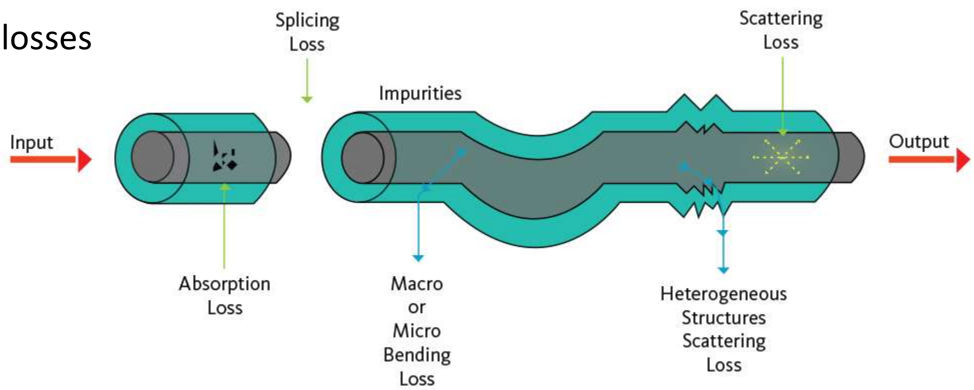


Different Types of Losses in Optical Fiber



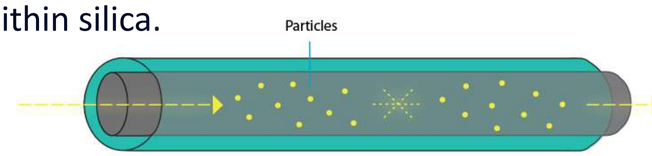
Intrinsic Optical Fiber Losses

- Absorption losses
- Dispersion losses
- Scattering losses



Intrinsic Optical Fiber Losses

- Absorption losses in optical fiber are the major cause of optical fiber losses during the transmission.
- When the photon interacts with the components of the glass, an electron or metal ions, the light power is absorbed and transferred into other forms of energy like heat, due to molecular resonance.
- They are of two types; Intrinsic absorption & Extrinsic absorption.
- Intrinsic absorption losses correspond to absorption by fused silica (material used to make fibers) whereas extrinsic absorption is related to losses caused by impurities within silica.

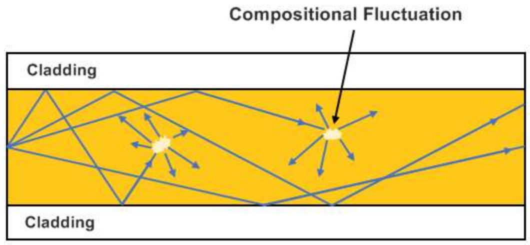


Intrinsic Optical Fiber Losses

- Dispersion losses are the results of the distortion of optical signal when traveling along the fiber.
- Dispersion losses in optical fiber can be *modal* (intermodal) or *chromatic* (intramodal).
- Modal dispersion is the pulse broadening due to the propagation delay differences between modes in multimode fiber.
- Chromatic dispersion is the pulse spreading in single mode fiber, because the refractive index varies with wavelength.

Intrinsic Optical Fiber Losses

- Scattering losses in optical fiber are due to microscopic variations in the material density, compositional fluctuations, structural inhomogeneities and manufacturing defects.
- Basically, scattering losses are caused by the interaction of light with density fluctuations within a fiber. Density changes are produced when optical fibers are manufactured. They may be of two types;
  - Linear Scattering Losses
    - Mie scattering
    - Rayleigh scattering.
  - Non-Linear Scattering Losses
    - Stimulated Raman Scattering
    - Stimulated Brillouin Scattering.



Rayleigh Scattering

- most common form of scattering.
- caused by microscopic non-uniformities making light rays partially scatter.
- nearly 90% of total attenuation is attributed to Rayleigh Scattering.
- becomes important when wavelengths are short - comparable to size of the structures in the glass: long wavelengths are less affected than short wavelengths.
- Rayleigh scattering causes the sky to be blue, since only the short (blue) wavelengths are significantly scattered by the air molecules.
- The loss (dB/km) can be approximated by the formula below with λ in μm;

$$\alpha = 1.7\left(\frac{0.85}{\lambda}\right)^4$$

Mie Scattering

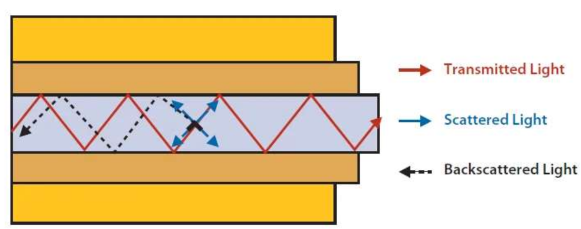
- caused in inhomogeneities which are comparable in size to the guided wavelength.
- These result from the non-perfect cylindrical structure of the waveguide and may be caused by fiber imperfections such as;
  - irregularities in the core-cladding interface,
  - core-cladding refractive index differences along the fiber length,
  - diameter fluctuations,
  - strains and bubbles.

Stimulated Raman Scattering (SRS)

- Raman scattering occurs when the incident light interacts with a material and causes the molecules in the material to vibrate, resulting in a change in the frequency and phase of the scattered light.
- This change is known as the Raman shift and is characteristic of the material being penetrated.
- In optical fibers, Raman scattering can cause the scattered light to be shifted to longer or shorter wavelengths, depending on the vibrational modes of the material in the fiber.

Stimulated Brillouin Scattering (SBS)

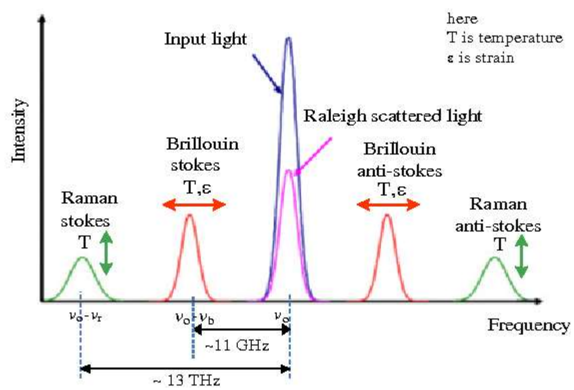
- Brillouin scattering occurs when the incident light interacts with the acoustic waves in a material and causes a shift in the frequency and phase of the scattered light.
- This shift is known as the Brillouin shift and is proportional to the velocity of the acoustic waves in the material.



Backscattering effects of light transmission

SBS Vs SRS

- In Raman scattering, photons are scattered by the effect of vibrational and rotational transitions in the bonds between first-order neighboring atoms, while Brillouin scattering results from the scattering of photons caused by large scale, low-frequency phonons.
- The optical phonons participate in SRS while SBS is through acoustic phonons.



Extrinsic Optical Fiber Losses

- Splicing losses
- Connector losses
- Bending losses

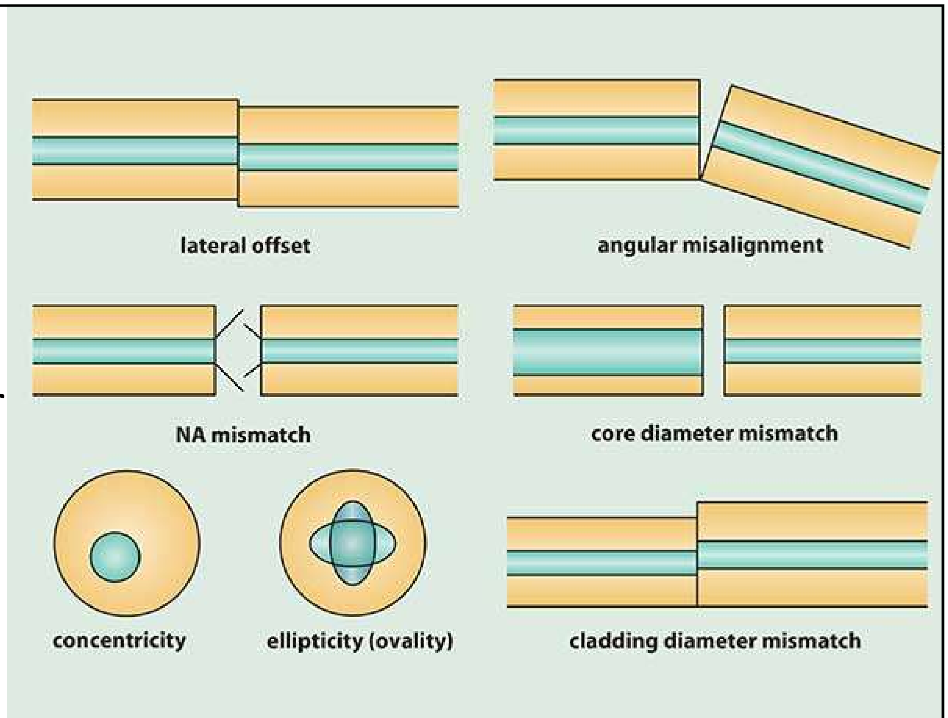
Extrinsic Optical Fiber Losses

- By joining two optical fibers end-to-end, splicing aims to ensure that the light passing through it is almost as strong as the virgin fiber itself.
- But no matter how good the splicing is, the splicing loss is inevitable.
- Fusion splicing losses of multimode fiber are 0.1 - 0.5 dB, 0.3 dB being a good average value.
- For single mode fiber, the fusion splicing loss typically can be less than 0.05 dB.

Extrinsic Optical Fiber Losses

- Connector losses or insertion losses in optical fiber, are the losses of light power resulting from the insertion of a device in a transmission line or optical fiber.
- Multimode connectors will have losses of 0.2-0.5 dB (0.3 typical). **Factory made** single mode connectors will have losses of 0.1-0.2 dB and **Field terminated** single mode connectors may have losses as high as 0.5-1.0 dB (average 0.75 dB).

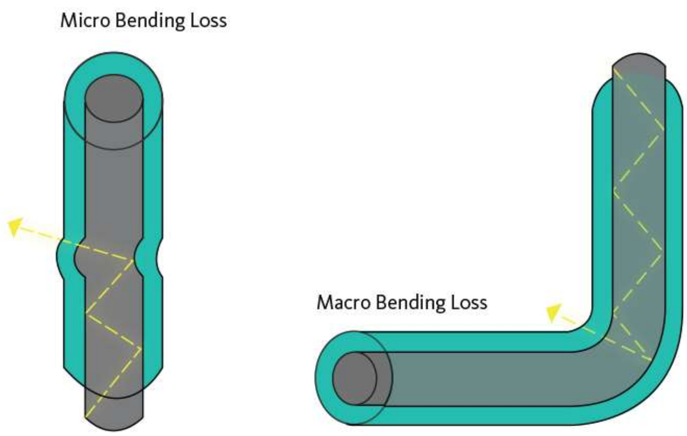
Splicing and Connector Losses



Extrinsic Optical Fiber Losses

- Bending is the common problem that can cause optical fiber losses generated by improper fiber optic handling.
- There are two basic types; Micro bending and Macro bending.
- Micro-bending losses are caused due to non-uniformities or micro bends inside the fiber. This micro bends in fiber appears due to non uniform pressures created during the cabling of the fiber or even during the manufacturing itself. This lead to loss of light by leakage through the fiber.
- If the radius of the core is large compared to fiber diameter, it may cause large-curvature at the position where the fiber cable turns at the corner. At these corners the light will not satisfy the condition for TIR and hence it escapes out from the fiber. This is called as macro bending losses. Also note that this loss is negligible for small bends.

Bending Losses



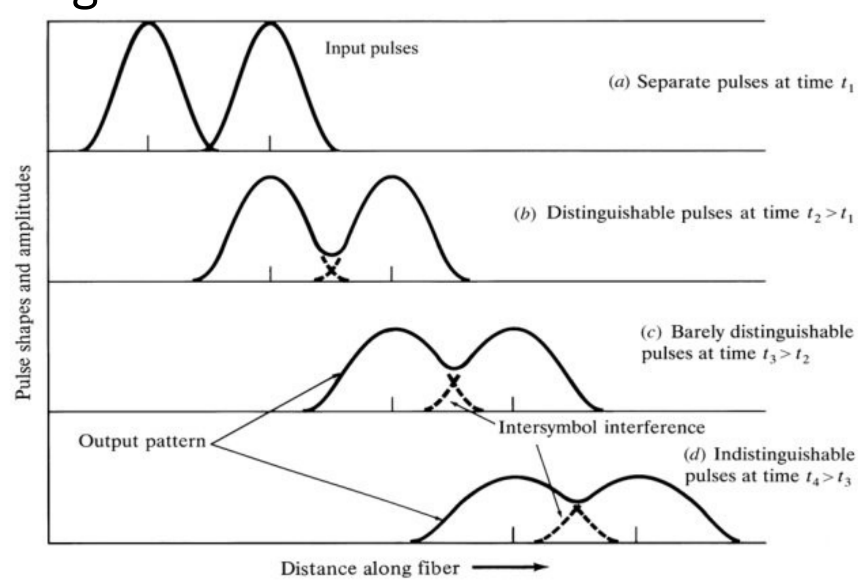
Pulse Broadening

- Pulse broadening is defined as the spreading of the light pulses as they travel down the fiber. Because of dispersion and thus the spreading effect, pulses tend to overlap making them unreadable by the receiver which limits the maximum possible bandwidth.

Pulse Broadening

- Ideally, an optical pulse transmitted at one end of an optical fiber should arrive at the far end of that fiber with its shape unchanged.
- However the optical pulse not only loses its power but the pulse broadens as it propagates.
- The phenomenon of broadening of a pulse during its propagation through the optical fiber is known as **dispersion**.
- The widened pulse may overlap into its neighboring pulses and causes transmission errors.

Pulse Broadening



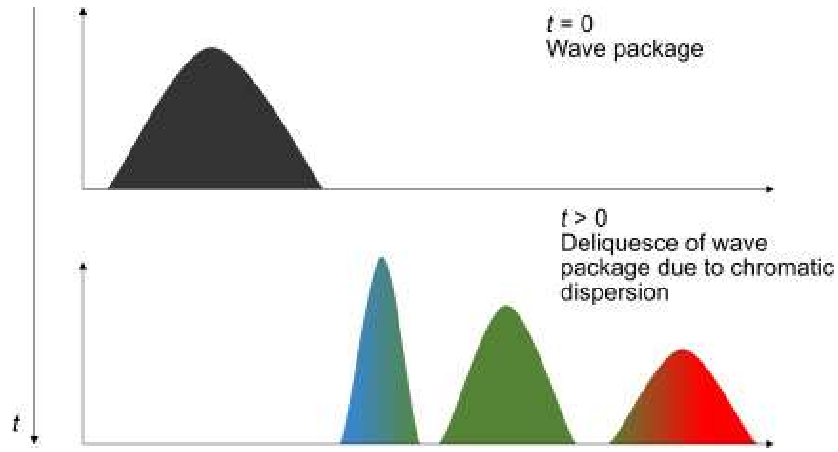
Pulse Broadening

- Due to overlapping, the propagating pulses eventually may become indistinguishable at the receiver which results in Inter Symbol Interference (ISI).
- Thus, the transmission errors encountered on the optical receiver increases as the ISI becomes more distinct.
- These pulses can be made distinguished by spacing them out at the transmitter, which means reducing the transmission bit rate.
- Hence, fiber transmission distance is limited due to both of the fiber loss and dispersion.

Pulse Broadening

- In multimode fiber, the incident light can take many different paths or modes as it propagates through the fiber. Each mode in multimode fiber traverses a unique path along the fiber to reach terminal and therefore arrives at a different interval resulting in pulse spreading.
- This type of dispersion is called modal dispersion, which is applicable only to multimode fibers.
- Single mode fiber is used to avoid modal dispersion. Only the fundamental mode propagates in SMF hence no modal dispersion is experienced by the propagating signal.
- However in SMF, chromatic dispersion is the dominant.

Pulse Broadening

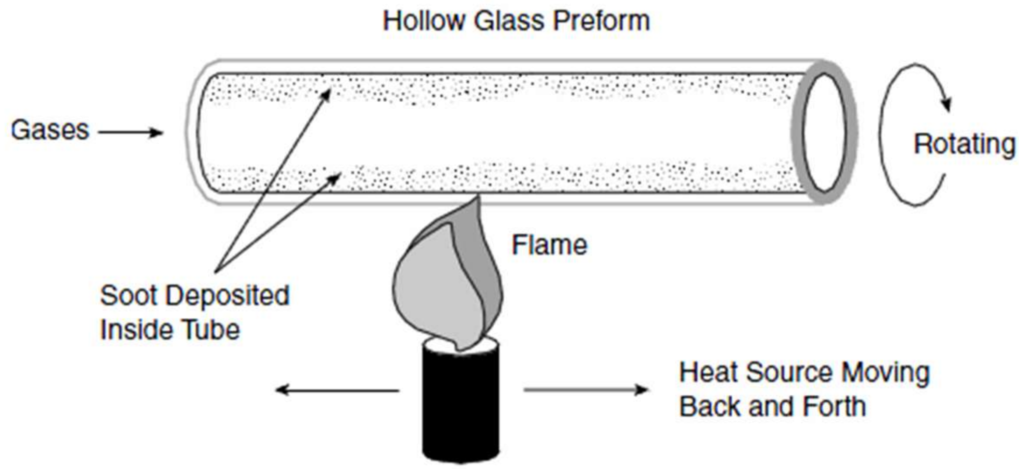


Optical Fiber Fabrication Techniques

Three methods are used today to fabricate moderate-to-low loss waveguide fibers:

- **M**odified **C**hemical **V**apor **D**eposition (MCVD),
- **O**utside **V**apor **D**eposition(OVD), and
- **V**apor **A**xial **D**eposition (VAD).

Modified Chemical Vapor Deposition (MCVD)



Modified chemical vapor deposition (MCVD)

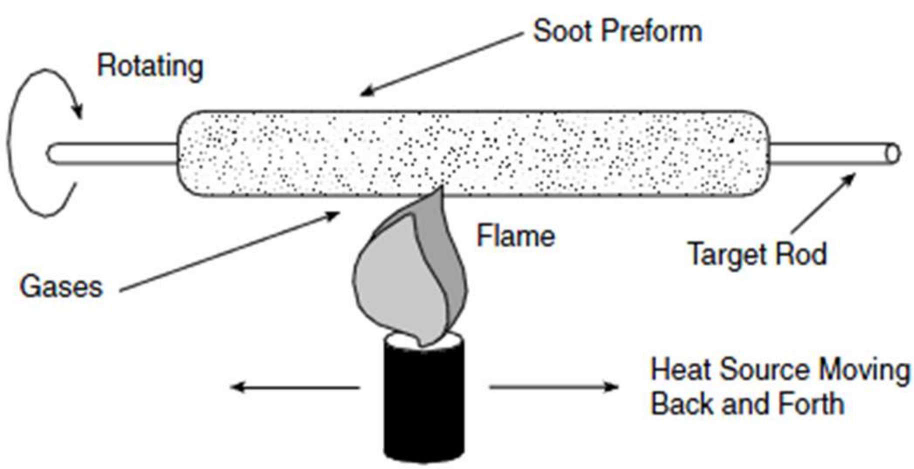
Modified Chemical Vapor Deposition (MCVD)

- In MCVD a hollow glass tube, approximately 1 m long and 2.5 cm in diameter, is placed in a horizontal or vertical lathe and spun rapidly.
- A computer-controlled mixture of gases is passed through the inside of the tube.
- On the outside of the tube, a heat source (oxygen/hydrogen torch) passes up and down
- Each pass of the heat source fuses a small amount of the precipitated gas mixture to the surface of the tube.
- Most of the gas is vaporized silicon dioxide (glass), but there are carefully controlled remounts of impurities (dopants) that cause changes in the index of refraction of the glass.

Modified Chemical Vapor Deposition (MCVD)

- As the torch moves and the preform spins, a layer of glass is formed inside the hollow preform.
- The dopant (mixture of gases) can be changed for each layer so that the index may be varied across the diameter.
- After sufficient layers are built up, the tube is collapsed into a solid glass rod referred to as a **preform**.
- It is now a scale model of the desired fiber, but much shorter and thicker. The preform is then taken to the **drawing tower**, where it is pulled into a length of fiber up to 10 kilometers long.

Outside Vapor Deposition(OVD)

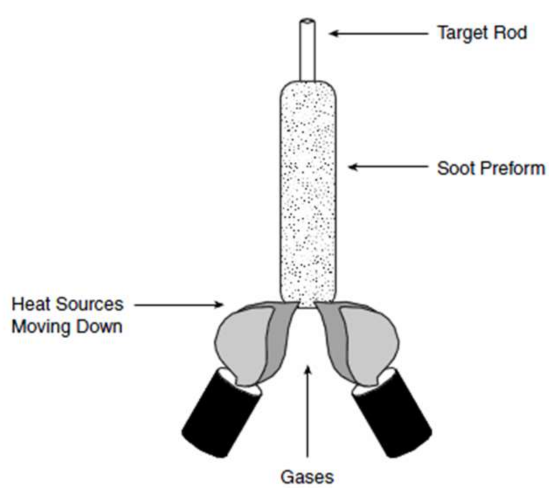


Outside vapor deposition (OVD).

Outside Vapor Deposition(OVD)

- The OVD method utilizes a glass target rod that is placed in a chamber and spun rapidly on a lathe.
- A computer-controlled mixture of gases is then passed between the target rod and the heat source.
- On each pass of the heat source, a small amount of the gas reacts and fuses to the outer surface of the rod.
- After enough layers are built up, the target rod is removed and the remaining soot preform is collapsed into a solid rod.
- The preform is then taken to the tower and pulled into fiber.

Vapor Axial Deposition(VAD)



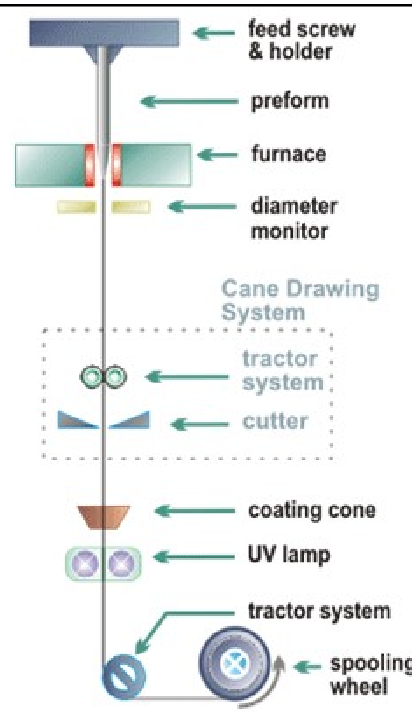
Vapor axial deposition (VAD).

Vapor Axial Deposition(VAD)

- The VAD process utilizes a very short glass target rod suspended by one end. A computer-controlled mixture of gases is applied between the end of the rod and the heat source.
- The heat source is slowly backed off as the preform lengthens due to tile soot buildup caused by gases reacting to the heat and fusing to the end of the rod.
- After sufficient length is formed, the target rod is removed from the end, leaving the soot preform.
- The preform is then taken to the drawing tower to be heated and pulled into the required fiber length.

Drawing Tower

- After the solid glass preform is prepared, it is transferred to a vertical drawing system. In this system, the preform is first heated.
- As it does so, a ‘gob’ of molten glass forms at its end and then falls away, allowing the single optical fiber inside to be drawn out.
- The fiber then proceeds through the machine, where its diameter is checked, a protective coating is applied, and it is cured by heat. Finally, it is wound on a spool.



Drawing Optical Fiber

- The preform first passes through a furnace, where it is heated to about 2000 ^{o}C
- Next, a drop of molten glass called a 'gob' forms at the end of the preform.
- The gob then falls away, and the single optical fiber inside is drawn out of the preform.
- As the optical fiber is pulled from the preform, the material in the original substrate rod forms the **cladding**, and the silicon dioxide deposited as soot forms the **core** of the optical fiber.

END

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