Types of Rays

- If the rays are launched within core of acceptance can be successfully propagated along the fiber. But the exact path of the ray is determined by the position and angle of ray at which it strikes the core.

There exist three different types of rays.

i) Skew rays

ii) Meridional rays

iii) Axial rays.

**The skew rays** does not pass through the center, as show in Fig. 1.6.11 (a). The skewrays reflects off from the core cladding boundaries and again bounces around the outside of the core. It takes somewhat similar shape of spiral of helical path.

- The **meridional** ray enters the core and passes through its axis. When the core surface is parallel, it will always be reflected to pass through the enter. The meridional ray is shown in fig. 1.6.11 (b).

- The **axial ray** travels along the axis of the fiber and stays at the axis all the time. It is shown in fig. 1.6.11 (c).
Modes of Fiber

- Fiber cables can also be classified as per their mode. Light rays propagate as an electromagnetic wave along the fiber. The two components, the electric field and the magnetic field form patterns across the fiber. These patterns are called modes of transmission. The mode of a fiber refers to the number of paths for the light rays within the cable. According to modes optic fibers can be classified into two types.
  i) Single mode fiber ii) Multimode fiber.

- Multimode fiber was the first fiber type to be manufactured and commercialized. The term multimode simply refers to the fact that numerous modes (light rays) are carried simultaneously through the waveguide. Multimode fiber has a much larger diameter, compared to single mode fiber, this allows large number of modes.

- Single mode fiber allows propagation to light ray by only one path. Single mode fibers are best at retaining the fidelity of each light pulse over longer distance also they do not exhibit dispersion caused by multiple modes.

Thus more information can be transmitted per unit of time.

This gives single mode fiber higher bandwidth compared to multimode fiber.

- Some disadvantages of single mode fiber are smaller core diameter makes coupling light into the core more difficult. Precision required for single mode connectors and splices are more demanding.

Fiber Profiles

- A fiber is characterized by its profile and by its core and cladding diameters.

- One way of classifying the fiber cables is according to the index profile at fiber. The index profile is a graphical representation of value of refractive index across the corediameter.

- There are two basic types of index profiles.

i) Step index fiber. ii) Graded index fiber.

Fig. 1.6.12 shows the index profiles of fibers.
Step Index (SI) Fiber

- The step index (SI) fiber is a cylindrical waveguide core with central or inner core has a uniform refractive index of $n_1$ and the core is surrounded by outer cladding with uniform refractive index of $n_2$. The cladding refractive index ($n_2$) is less than the core refractive index ($n_1$). But there is an abrupt change in the refractive index at the core cladding interface. Refractive index profile of step indexed optical fiber is shown in Fig. 1.6.13. The refractive index is plotted on horizontal axis and radial distance from the core is plotted on vertical axis.

- The propagation of light wave within the core of step index fiber takes the path of meridional ray i.e. ray follows a zig-zag path of straight line segments.
  
The core typically has diameter of 50-80 µm and the cladding has a diameter of 125 µm.
- The refractive index profile is defined as –

$$n(r) = \begin{cases} 
  n_1 & \text{when } r < a \text{ (core)} \\
  n_2 & \text{when } r \geq a \text{ (cladding)}
\end{cases}$$
**Graded Index (GRIN) Fiber**

- The graded index fiber has a core made from many layers of glass.
- In the graded index (GRIN) fiber the refractive index is not uniform within the core, it is highest at the center and decreases smoothly and continuously with distance towards the cladding. The refractive index profile across the core takes the parabolic nature. Fig. 1.6.14 shows refractive index profile of graded index fiber.

![Graded Index Fiber Diagram](image)

- In graded index fiber the light waves are bent by refraction towards the core axis and they follow the curved path down the fiber length. This results because of change in refractive index as moved away from the center of the core.
- A graded index fiber has lower coupling efficiency and higher bandwidth than the step index fiber. It is available in 50/125 and 62.5/125 sizes. The 50/125 fiber has been optimized for long haul applications and has a smaller NA and higher bandwidth. 62.5/125 fiber is optimized for LAN applications which is costing 25% more than the 50/125 fiber cable.
- The refractive index variation in the core is given by relationship

\[
n(r) = \begin{cases} 
    n_1 \left(1 - 2\Delta \left(\frac{r}{a}\right)^a\right) & \text{when } r < a \text{ (core)} \\
    n_1 (1 - 2\Delta)^{\frac{3}{2}} \approx n_2 & \text{when } r \geq a \text{ (cladding)} 
\end{cases}
\]

where,

- \( r \) = Radial distance from fiber axis
- \( a \) = Core radius
- \( n_1 \) = Refractive index of core
n_2 = Refractive index of cladding

\( \alpha = \text{Shape of index profile.} \)

- Profile parameter \( \alpha \) determines the characteristic refractive index profile of fiber core. The range of refractive index as variation of \( \alpha \) is shown in Fig. 1.6.15.

![Fig. 1.6.15 Possible fiber refractive index profiles for different values of \( \alpha \).](image)

Comparison of Step Index and Graded Index Fiber

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Parameter</th>
<th>Step index fiber</th>
<th>Graded index fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Data rate</td>
<td>Slow.</td>
<td>Higher</td>
</tr>
<tr>
<td>2.</td>
<td>Coupling efficiency</td>
<td>Coupling efficiency with fiber is higher.</td>
<td>Lower coupling efficiency.</td>
</tr>
<tr>
<td>3.</td>
<td>Ray path</td>
<td>By total internal reflection.</td>
<td>Light ray travels in oscillatory fashion.</td>
</tr>
<tr>
<td>4.</td>
<td>Index variation</td>
<td>( \Delta = \frac{n_1 - n_2}{n_1} )</td>
<td>( \Delta = \frac{n_1^2 - n_2^2}{2n_1^2} )</td>
</tr>
<tr>
<td>5.</td>
<td>Numerical aperture</td>
<td>NA remains same.</td>
<td>Changes continuously with distance from fiber axis.</td>
</tr>
<tr>
<td>6.</td>
<td>Material used</td>
<td>Normally plastic or glass is preferred.</td>
<td>Only glass is preferred.</td>
</tr>
<tr>
<td>7.</td>
<td>Bandwidth efficiency</td>
<td>10 – 20 MHz/km</td>
<td>1 GHz/km</td>
</tr>
<tr>
<td>8.</td>
<td>Pulse spreading</td>
<td>Pulse spreading by fiber length is more.</td>
<td>Pulse spreading is less</td>
</tr>
<tr>
<td>9.</td>
<td>Attenuation of light</td>
<td>Less typically 0.34 dB/km at 1.3 ( \mu \text{m}. )</td>
<td>More 0.6 to 1 dB/km at 1.3 ( \mu \text{m}. )</td>
</tr>
</tbody>
</table>
10. Typical light source | LED, Lasers.  
11. Applications | Subscriber local network communication. | Local and wide area networks.  

### Optic Fiber Configurations

- Depending on the refractive index profile of fiber and modes of fiber there exist three types of optical fiber configurations. These optic-fiber configurations are -

  i) Single mode step index fiber.
  ii) Multimode step index fiber.
  iii) Multimode graded index fiber.

### Single mode Step index Fiber

- In single mode step index fiber has a central core that is sufficiently small so that there is essentially only one path for light ray through the cable. The light ray is propagated in the fiber through reflection. Typical core sizes are 2 to 15 µm. Single mode fiber is also known as fundamental or monomode fiber.

Fig. 1.6.16 shows single mode fiber.

- Single mode fiber will permit only one mode to propagate and does not suffer from mode delay differences. These are primarily developed for the 1300 nm window but they can be also be used effectively with time division multiplex (TDM) and wavelength division multiplex (WDM) systems operating in 1550 nm wavelength region.

- The core fiber of a single mode fiber is very narrow compared to the wavelength of light being used. Therefore, only a single path exists through the cable core through which light can travel. Usually, 20 percent of the light in a single mode cable actually
travels down the cladding and the effective diameter of the cable is a blend of single mode core and degree to which the cladding carries light. This is referred to as the ‘mode field diameter’, which is larger than physical diameter of the core depending on the refractive indices of the core and cladding.

- The disadvantage of this type of cable is that because of extremely small size interconnection of cables and interfacing with source is difficult. Another disadvantage of single mode fibers is that as the refractive index of glass decreases with optical wavelength, the light velocity will also be wavelength dependent. Thus the light from an optical transmitter will have definite spectral width.

**Multimode step Index Fiber**

- **Multimode step index fiber** is more widely used type. It is easy to manufacture. Its core diameter is 50 to 1000 µm i.e. large aperture and allows more light to enter the cable. The light rays are propagated down the core in zig-zag manner. There are many paths that a light ray may follow during the propagation.

- The light ray is propagated using the principle of total internal reflection (TIR). Since the core index of refraction is higher than the cladding index of refraction, the light enters at less than critical angle is guided along the fiber.

![Fig. 1.6.17 TIR in multimode step index fiber](image)

- Light rays passing through the fiber are continuously reflected off the glass cladding towards the center of the core at different angles and lengths, limiting overall bandwidth.

- The disadvantage of multimode step index fibers is that the different optical lengths caused by various angles at which light is propagated relative to the core, causes the transmission bandwidth to be fairly small. Because of these limitations, multimode step index fiber is typically only used in applications requiring distances of less than 1 km.

**Multimode Graded Index Fiber**

- The core size of **multimode graded index fiber** cable is varying from 50 to 100 µm range. The light ray is propagated through the refraction. The light ray enters the fiber at
many different angles. As the light propagates across the core toward the center it is intersecting a less dense to more dense medium. Therefore the light rays are being constantly being refracted and ray is bending continuously. This cable is mostly used for long distance communication.

Fig 1.6.18 shows multimode graded index fiber.

- The light rays no longer follow straight lines, they follow a serpentine path being gradually bent back towards the center by the continuously declining refractive index. The modes travelling in a straight line are in a higher refractive index so they travel slower than the serpentine modes. This reduces the arrival time disparity because all modes arrive at about the same time.
- Fig 1.6.19 shows the light trajectory in detail. It is seen that light rays running close to the fiber axis with shorter path length, will have a lower velocity because they pass through a region with a high refractive index.
Rays on core edges offers reduced refractive index, hence travel more faster than axial rays and cause the light components to take same amount of time to travel the length of fiber, thus minimizing dispersion losses. Each path at a different angle is termed as ‘transmission mode’ and the NA of graded index fiber is defined as the maximum value of acceptance angle at the fiber axis.

Typical attenuation coefficients of graded index fibers at 850 nm are 2.5 to 3 dB/km, while at 1300 nm they are 1.0 to 1.5 dB/km.

The main advantages of graded index fiber are:
1. Reduced refractive index at the center of core.
2. Comparatively cheap to produce.

### Standard fibers

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Fiber type</th>
<th>Cladding diameter (µm)</th>
<th>Core diameter (µm)</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Single mode (8/125)</td>
<td>125</td>
<td>8</td>
<td>0.1% to 0.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1. Long distance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. High data rate</td>
</tr>
<tr>
<td>2.</td>
<td>Multimode (50/125)</td>
<td>125</td>
<td>50</td>
<td>1% to 2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1. Short distance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Low data rate</td>
</tr>
<tr>
<td>3.</td>
<td>Multimode (62.5/125)</td>
<td>125</td>
<td>62.5</td>
<td>1% to 2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LAN</td>
</tr>
<tr>
<td>4.</td>
<td>Multimode (100/140)</td>
<td>140</td>
<td>100</td>
<td>1% to 2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LAN</td>
</tr>
</tbody>
</table>