Module 3: Types of optical fiber

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Learning Outcome:

1. To get familiar with types of optical fiber
2. To understand criteria based on which they are classified
3. To compare different types of optical fiber
4. To get the insight of application specific optical fiber

1. Introduction:

An optical fiber is a piece of very thin and almost absolutely pure glass. It is thin as human hair. Its outside is made of a cladding of glass which is also another type of glass, with slightly different chemical properties and composition. Hence it has different refractive index compared to inner core material. No single fiber design meets all application requirements mainly due to many economic reasons. However manufacturers have concentrated on three broad categories. This module mainly focuses on the classification of optical fibers and their characteristics.

2. Classification of optical fibers

1. Based on refractive index profile
2. Number of modes transmitted through fiber
3. Tapered fiber

2.1 Based on refractive index profiles

Optical fibers are classified into two types based on the refractive index profile of core and cladding. They are

a. Step index fiber
b. Graded index fiber

In Step index fiber, core has the constant refractive index n2 as shown in Figure 7(a). At the core cladding interface there is sudden decrease in the refractive index from n2 to n1. It remains constant throughout the cladding part of optical fiber.

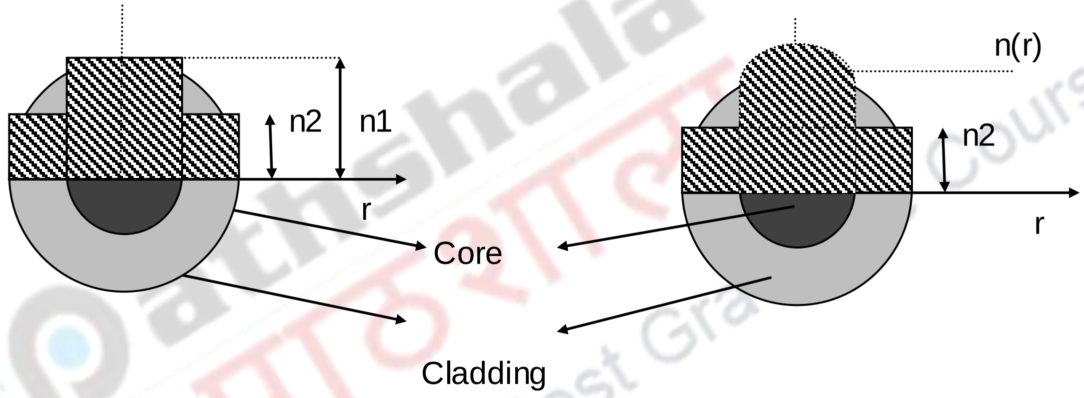
The refractive index profile (n) profile with reference to the radial distance 'r' from the fiber axis is given as

When r=0 n(r) =n1

r < a n(r) = n1

r ≥ a n(r) = n2

where a is core radius of optical fiber.



(a) Step index fiber (b) Graded index fiber

Figure 1: Optical fiber based on refractive index profiles

Figure 1(b) shows another type of optical fiber, graded index fiber, in which the refractive index of core n1 decreases gradually from the centre of core as a function of the radius from the centre of the optical fiber. At the core cladding interface, the refractive index shows decrease from n1 to n2 and it remains constant w.r.t. radial distance r. This type of optical fiber is known as graded index optical fiber. The refractive index (*n*) profile with reference to the radial distance (*r*) from the fiber axis is given as:

when $r = 0$, $n(r) = n1$ --(1)

$$r < a,\quad n(r) = n_1\left[1-\left(2\Delta\left[\frac{r}{a}\right]^2\right)\right]^{\frac{1}{2}} \quad \text{---(2)}$$

$r \geq a, \quad n(r) = n2 = n_1(1-2\Delta)^{\frac{1}{2}}$ --(3)

2.2 Based on the number of modes propagated through optical fiber

Mode is the one which describes the nature of the electromagnetic wave in waveguide. Optical fiber is considered as cylindrical waveguide. It is the allowed direction whose associated angles satisfy the conditions for total internal reflection. Based on the number of modes that propagates through optical fiber, they are classified as

1. Single mode fibers
2. Multimode fibers

2.2.1 Single mode or monomode fibers:

In a fiber, if only one mode is transmitted through it then it is said to be a single mode fiber. A typical single mode fiber may have a core radius of 3 µm and a numerical aperture of 0.1 at a wavelength of 0.8 µm as shown in Figure 1.7. The condition for the single mode operation is given by the V number of the fiber which defined as

$$V = \frac{2\pi na(\sqrt{2\Delta}}{\lambda}$$ --- (4)

For single mode operation, V≤ 2.405. Here n = refractive index of core; a=radius of the core; λ=wavelength of the light propagating through the fiber; Δ=relative refractive indices difference. Single mode fiber has following characteristics:

- Only one path of propagation is available
- V number is less than 2.405
- Core diameter very small
- No dispersion effect
- Higher bandwidth(1000MHz)
- Used for long haul communication
- Fabrication is difficult and costly

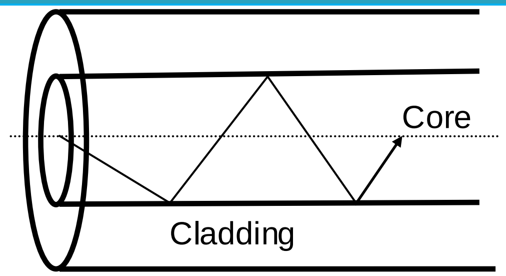


Figure 2 :Single mode fiber

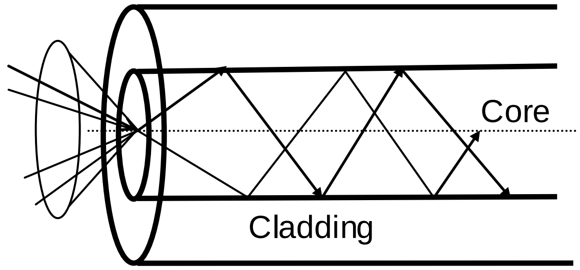


Figure 3: Multimode fibers

2.2.2 Multimode fibers:

If more than one mode is transmitted through optical fiber, then it is said to be multimode fiber as shown in Figure 2.8. The larger core radii of multimode fibers make it easier to launch optical power in to the fiber and facilitate the end to end connection of similar powers. Multimode optical fibers have following characteristics:

- More than one path is available
- V number is greater than 2.405
- Core diameter is higher
- Higher dispersion
- Lower bandwidth(50MHz)
- Used for short distance communication
- Fabrication is less difficult and not costly

Depending upon the refractive index profile and the number of modes propagated through the optical fiber, they are further classified as

- Step index single mode fibers
- Step index multimode fiber
- Graded index single mode fibers
- Graded index multimode fibers

2.2.3 Step Index Single mode optical fibers

The core diameter of this type of fiber is very small i.e. of the order of wavelength of light to be propagated through the fiber. The refractive index profile has step change in the refractive index from core to cladding as shown in Figure 4.

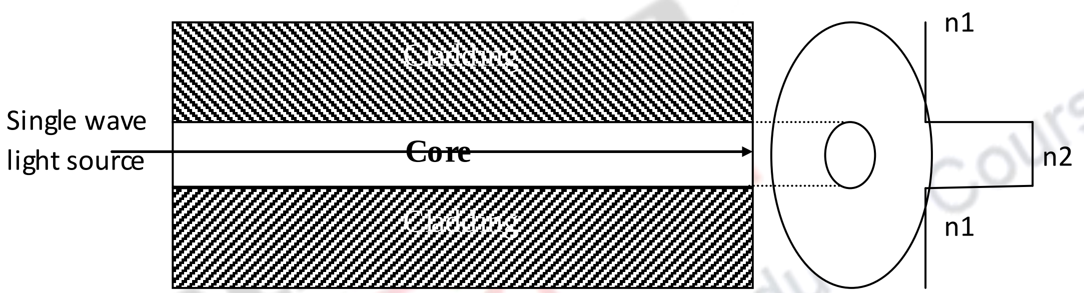


Figure 4 :Step index single mode optical fibers

The main characteristics of step index single mode optical fibers are as follows:

1. Very small core diameter
2. Low numerical aperture
3. Low attenuation
4. Very high bandwidth

In order to get single mode, with all other modes cut off, the diameter of the core must satisfy the relation

$$d < \frac{0.766\lambda}{NA}$$

Where λ is wavelength of light propagating through optical fiber

NA is numerical aperture of the optical fiber

Hence if the operating wavelength is 1.3 μm then the core diameters are of the order of 6 to 10μm. The term "mode field diameter" (2Fd) is another important parameter for single mode fiber. Figure 5 shows the light guiding property of the fiber by indicating the boundary where the electric field of the optical wave falls to 1/eth (i.e. 36.8%) of that at the core centre. In single mode fiber significant amount of the power resides outside the fiber core.

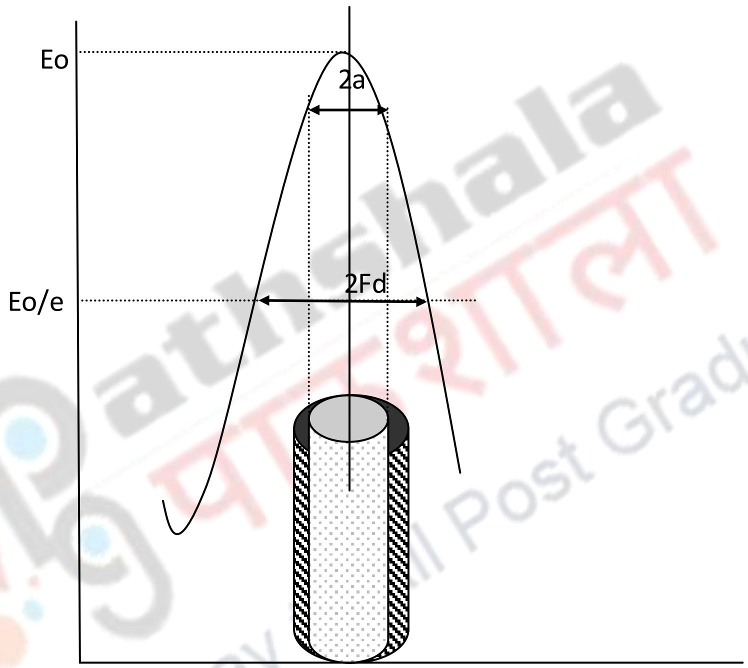


Figure 5: Optical fiber power distribution across the cone of the step index single mode fiber.

The distribution of the optical electric field with the radial position across the core is as shown in Figure 5. It is described approximately by a Gaussian expression near the cut off wavelength as follows:

$$E(x) = E_0 e^{-(\frac{x}{fd})^2}$$

where $F_d = \frac{1}{2} \times$ mode field diameter

Greater the ratio (Fd/a) the larger the amount of light that propagates in the cladding . In the structure of step index single mode fiber the cladding is kept very thick so that residual field at the cladding outer diameter is very insignificant; any optical field ,which is present at the outer boundary of the cladding is radiated. The theoretical value of 2Fd is given by

$$2F_d = 2a[0.65 + 0.434(\lambda/\lambda_c)^{3/2} + 0.0149(\lambda/\lambda_c)^6]$$

Where λ = operating wavelength

λc = cut off wavelength

2a= core diameter

Thus for a particular cut off wavelength the Fd increases with operating wavelength

Disadvantage:

Due to very thin cores creates mechanical difficult in manufacture, handling and splicing of the fibers. It is very expensive

2.2.4 Step index multimode optical fiber

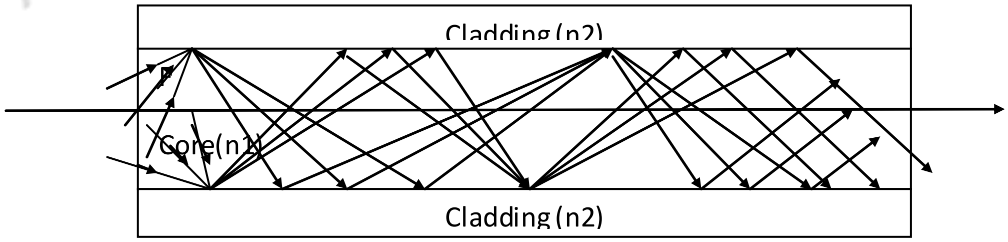


Figure 6 :Step index multimode optical fiber propagation (n1>n2)

Practically, light emanating from any point source will have several paths with different angles of incidence at boundary layer. It may also contain different colours with different frequencies. It is called as step index multimode propagation as shown in Figure 6. Any other light wave which is meeting the core cladding interface at and above the critical value of θc will also be totally reflected and hence will propagate along the core. However any light wave meeting the core cladding interface at an angle less than θc will pass into and be absorbed by the cladding.

Thus the various light waves travelling along the core will have different propagation paths of different path lengths. Hence they will meet at the other end of the fiber at different time instants. This causes dispersion of signal called as transit time dispersion. This dispersion sets an upper limit on the rate at which the light can be modulated by analog or digital electrical signal. As a result of this distortion the variations of successive pulses may overlap into each other and causes distortion of the information being carried. However this defect can be minimized by making the core diameter of the same order as the wavelength of the light wave to be propagated. The resultant propagation is a single light wave, explained earlier in single mode step index optical fiber. This type of fiber has very high capacity and large bandwidth.

2.2.5 Graded index single mode optical fiber

Graded index optical fiber has a property of gradual variation in refractive index(increasing from the outside of the fiber core to the centre of it). The propagation of light through single mode graded index fiber is similar to that for step index fiber. The light wave travels along the centre of the optical fiber.

2.2.6 Graded index multimode optical fiber

Figure 7 shows the refractive index profile and propagation of waves in graded index multimode fiber

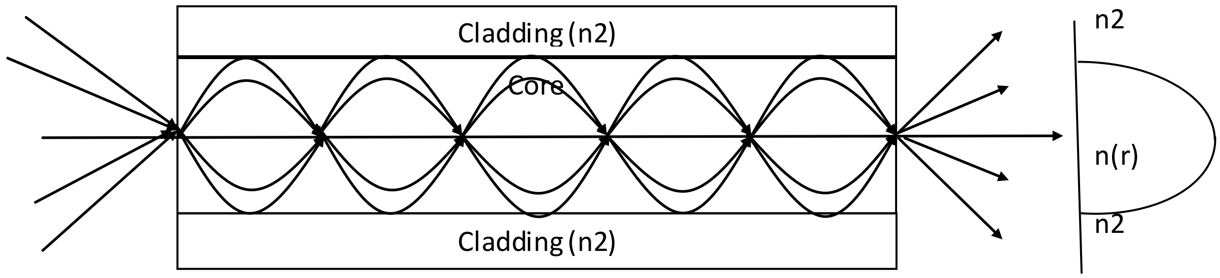


Figure 7 :Graded index multimode fiber with refractive index profile.

From the figure it is quite clear that light waves or rays with large angle of incidence travel more path lengths than those with smaller angles. But we know that the decrease of refractive index allow a higher velocity of light energy propagation. Thus all waves will reach a given point along the fiber at virtually same time. As a result the transit time dispersion is reduced. This type of light propagation is referred as graded index multimode propagation through optical fiber.

The variation of refractive index of the core of graded index fiber with radius ‘r’ measured from the centre of core is given by

$$n(r) = n1[1 - 2\Delta(\frac{r}{a})^{p}]^{2}$$

Where n1 is refractive index at the centre of the core

P is index profile

It is noteworthy that as the light velocity decreases with increasing refractive index for modes near the core centre the light velocity is less than that near the core boundary. For approximately parabolic index profile, for various modes the propagation time is nearly equalized. Thus the multimode distortion is reduced. P has typical value of 2.0 for 850nm applications.

In graded index fiber the number of modes is expressed by the formula given by

$$N = \left(\frac{p}{p+2}\right)\frac{2\pi^2 a^2 (NA)^2}{\lambda^2}$$

This formula is valid for the number of modes >50

One important thing to mention here is that in all three types of fibers((i.e. step index multimode, step index single mode and graded index multimode) the thickness of cladding material around the fiber core should be at least be several wavelengths. This arrangement will prevent light energy losses due to absorption and scattering.

2.3 Other types of optical fibers

1. Plastic fibers

   Plastic fibers are manufactured from a polymer perform drawing into a fiber. The losses associated with this type of fiber are about 100s of dB. The operate at low temperature i.e. upto 125 degree celcius while glass fibers can be used upto 1000 degree celcius.

   These are used in sensors, process control and short distance communication

   Features

   1. High light gathering capacity
   2. Large core area
   3. Low cost components
   4. Uses visible LEDs
   5. Easy to connect or couple

Table below shows various plastic fibers with specification commercially available.

Type	Bandwidth	NA	Operating temperature range in degree celcius
SK or SH	50 MHz(50 m length)	0.50	-40 to +75
EK or EH	120MHz(50 m length)	0.47	-40 to 85
DK or DH	50MHz(50 m length)	0.54	-40 to 115
FH	100MHz(20 m length)	0.75	-40 to 125

Plastic fibers are not available for use at long wavelength, because fibers of that type are very difficult to fabricate and also very expensive.

A fiber with glass core and plastic cladding is called as “plastic clad silica” or PCS fiber. They have following characteristics

1. High NA
2. Large core diameter
3. High attenuation
4. Low bandwidth

Advantage of large core is the greater power coupling. The high value of NA permits use of less expensive surface emitting LED’s.

Along with high attenuation and low bandwidth plastic fibers have poor mechanical strength and low maximum operating temperature.

2.4 Special optical fibers

No single fiber design meets all application requirements due to economic reasons. Therefore some special types of fibers are manufactured for specialized uses. These are special optical fibers.These are explained in brief here

1. High Purity Silica Fiber(HPSUV)

This type of fiber is suitable for transmission of light in the range of 180 to 800 nm. It is good and cheap. It is coated with aluminum which gives very high mechanical strength and extra power handling capacity as aluminum dissipates heat more quickly. These fibers operate at temperatures upto 400 degree celcius and vacuum.

Characteristics

1. Fiber type: Step index multimode
2. Core material: High purity synthetic silica
3. Cladding material: Doped silica
4. Primary coating: Aluminum or polymer
5. Secondary coating: Polymer
6. NA: 0.24
7. Tensile strength: 7 G Pa
8. Minimum bend radius: 40 times fiber radius
9. Temperature range: -169 to 400 degree celcius
10. Humidity:100%
11. Attenuation values: 1. 248 nm (KrF laser)<1.2dB/m
    2. 308 nm (XeCl laser) <0.26dB/m
12. Radiation resistance: Good
13. Maximum intensity of the transmitted power: 1. CW upto 100KW/cm^2
    2. Pulse upto 500 KW/cm^2

2. High Purity Silica (HPSIR)

It is similar to HPSUV fiber with slightly different dopants to give it a longer wavelength capability in the near IR from 500 nm to 2600 nm.

3. Chalcogenide Fiber

This type of fiber is used for transmission of light from 1 to 0.6 µm. They have extremely low losses. There are two types of chalcogenide fibers i.e. A and B. The loss in A type is down to 0.1dB/m. Hence they are particularly suitable for medical applications. The characteristics are

1. Fiber type: Step index multimode
2. Core material: As_2S_3
3. Cladding material: As_xS_{1-x}
4. Primary coating: PTFE
5. Secondary coating: PTFE or PVC
6. NA: 0.3 to 0.5
7. Minimum bend radius: < 10 nm
8. Temperature range: < 200 < T < 100 degree celcius
9. Attenuation values: 1. A type minimum 0.1dB/m
   2. B type minimum 0.6dB/m
10. Radiation resistance: Good
11. Maximum intensity of the transmitted power: 10W(CO laser)
12. Core diameter: 1. CHAL 100: 100µm
    2. CHAL 200:200µm
    3. CHAL 300:300µm

4. Halide fibers:

These fibers are extended to 15 µm region. The most common application is for use with the CO_2 laser in medicine to replace bulk optics delivery systems or in industry. Silver halide fibers are used for transmission of light from 3 to 15 µm. They have low losses and are currently the only known optical fibers for transmission of light from high power, long wavelength lasers like the CO_2 laser. They are very flexible and much more convenient than normal mechanical delivery systems for these long wavelengths.

The fibers comprise a core polycrystalline silver halide surrounded by an opaque tube. Because of high refractive index (2.2) of the material the total internal reflection takes place at the boundary with air. The tube is necessary to prevent UV light from reaching the core which causes premature failure. The normal life time of these fibers is 6 to 12 months depending upon how they are used.

Characteristics

1. Numerical Aperture: < 0.7
2. Outer diameter with protective covering: 0.36 to 1.5 mm
3. Core diameter: 0.1 to 1.2 mm
4. Attenuation at 10.6µm i.e. CO_2 laser: 0.5 to 1.5 dB/m
5. Attenuation at 5 to 6µm i.e. CO_2 laser:< 2dB
6. Usable wavelength range: 3-15mm
7. Maximum length available: < 15m
8. Yield strength: 150-170MPa
9. Radius of elastic bending: >0.4 cm
10. Operating maximum temperature: > 100 degree celcius

5. Tapered optical fibers

Tapered fibers are useful for getting maximum amount of power from a poor quality laser spot into a fiber. The use of tapered optical fiber is an efficient low cost method of transforming a poor quality laser beam into a uniform output spot.

The concept of conversion of brightness states that the spatial and angular parameters of light anywhere within or at either end of the taper are mutually connected by the formula

$A_i n_i^2 \sin^2\theta_i = A_o n_o^2 \sin^2\theta_o$

Where n's and θ's represent refractive indices and angles respectively. Subscripts 'I' and 'o' refer to input and output.

$\frac{A_i}{A_o} = R^2$ Where R is taper diameter ration and it follows that $\frac{(NA)_i}{(NA)_o} = R$

It should be noted that if the product of the input NA and the taper diameter ratio R exceeds the NA of the taper's pigtail, the light will escape into the cladding and will be lost. In that case the above relation is no longer true. To avoid light losses the NA of the light beam at the taper's input should be less than the practical value. Figure 8 shows structure of tapered optical fiber.

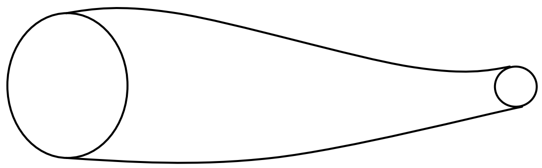


Figure 8 :Tapered optical fiber

Characteristics

1. Input to output ratios: upto 5:1
2. Input core diameter:100µm to 4.0 mm
3. Output core diameter: 50 µm to 1.5 mm
4. Taper length: 1-3m
5. Total length: 3-10m
6. Core material: Pure synthetic silica
7. Primary coating: Aluminum or acrylic
8. Optional secondary coating: Epoxy acrylate, flouropolymers
9. Operating temperature: 196-400 degree celcius (Al coated)
10. Humidity:100%
11. Radiation resistance: good
12. Power transmission:
    1. CW upto 100KW/cm^2
    2. Pulsed 145 , 500KW/cm^2
13. NA:0.24

Applications of optical fibers (Wavelength wise)

Table shows use of different types of optical fibers according to operating wavelength

Type	Range of operating wavelength
HPSUV	180nm to 800nm
HPSIR	500 nm to 2.6 µm
Taper	180nm to 2.6 µm
Chalcogenide	1 µm to 6 µm
Silver halide	3.0 µm to 15 µm

2.5 Some other types of fibers

1. High Bi refringence fiber (type HB): These are also called polarization preserving fibers. These fibers are used in applications where it is important to transmit a polarization state which is rapidly lost in conventional single mode fibers. It is used in variety of optical fiber sensors.

Specifications of such fibers are as shown in table

Type	Operating wavelength	Core diameter in µm	Cut off wavelength	Beat length	Attenuation	Coating
HB 800	0.85 µm	80 -125	0.75-0.81	< 4mm	4dB/km	Epoxy
HB 1250	1.3 µm	80 -125	1.0 -1.25	< 6mm	1.5 dB/km	epoxy

2. Rare earth doped optical fiber:
   Erbium doped optical fibers are now being used extensively in optical amplifier applications. Oxford erbium doped filters are available with a wide choice of doping concentrations and a choice of co-dopants. Sm and Tu doped fibers are also available. Erbium doped fibers are called ED type fibers

Specifications of such fibers are as shown in table

Type	Efficiency dB/km	Cut off wavelength	Erbium concentration	Co-dopant	Cladding diameter
ED 44	5	950 nm	200PPM	GeO_2/Al_2O_3	125µm
ED 29	5	1000nm	50PPM	GeO_2	125µm

Mechanism of refractive index variation:

We know that there is a refractive index difference between the core material and the cladding material. Now to get the index difference between the core and the cladding required for light guiding, impurities are added to silica. Dopants such as fluorine (F) and boron oxide (B2O3) decrease the refractive index of silica whereas dopants like phosphorus oxide (P2O5) and germanium oxide (GeO2) increase the refractive index of the silica. The lowest loss single mode fiber has been attained with a pure silica core and a fluorine doped cladding. Low loss, high bandwidth fiber is made by the process of vapour deposition.

3. Comparison of optical fibers

1. Bandwidth: A good quality step index fiber may have a bandwidth of 50MHz km where as equivalent GRIN fiber can have 200,400 or 600 MHz km bandwidth. Theoretically, the correction gradation in the GRIN fiber will produce nearly an infinite bandwidth
2. Attenuation: GRIN fiber tends to be generally lower attenuation than the step index fiber. There is no fundamental reason why a step index fiber should have higher attenuation than the GRIN fiber. At least theoretically they are made of the exact same kind of glass, with same amount of energy absorption. But as a practical matter, in step index fiber there may be some irregularities at the interface between the core and the cladding which in turn will contribute to mode conversion and some reflection-loss. But in GRIN fiber there is no such interface. Hence the GRIN fiber has no real counterpart for this loss mechanism in the step index fiber. Certain amount of loss from microscopic bubbles and actual attenuation due to dielectric hysteresis etc are present in both the fibers. Attenuation may also be caused by impurity absorption. But the prime culprit is the interface dissipation of the step index fiber.

3. Mode Dispersion: There is an inherent advantage in mode dispersion for the graded index fiber compared to the step index fiber. For if a wavefront had originally crossed the fiber axis with smaller inclinations it would have spent more time wading through glass with higher index and would have travelled more slowly. The rays having wide swinging actually travel farther but they spend more of their time travelling at a faster rate.
4. Numerical aperture: It has been observed that for a given fiber diameter the numerical aperture of GRIN fiber is generally smaller than the one on a step index fiber. For a GRIN fiber with an attenuation between 5 and 10dB/km the NA will tend to run between 0.16 and 0.2 whereas a step index fiber of about the same physical size with a loss of the order of 12dB/km will tend to have NA if the order of 0.2 to 0.35.

Table below shows comparison of single mode and multimode fibers

Single mode fiber	Multimode fiber
1. Only a single mode propagates through fiber	1. Many modes propagate through fiber
2. Diameter is much less than multimode fiber < 10 µm	2. Diameter much larger than single mode fiber
3. Largest transmission bandwidth	3. Transmission bandwidth is small compared to single mode fiber
4. Exhibits low loss	4. Comparitively more lossy
5. Superior transmission quality due to absence of modal noise	5. Lesser transmission quality than single mode fiber

Comparison of step index and graded index optical fibers

Step index optical fiber	Graded index optical fiber
1. Bandwidth: 50MHz	1. Bandwidth: 200,600 MHz
2. Modal dispersion is more	2. Modal dispersion is lower
3. NA: 0.2 to 0.5 (for 12dB/km loss)	3. NA: 0.16 to 0.2(for 5 to 12dB/km loss)

4. Applications:

1. Undersea cable system: Single mode fibers
2. Intra city trunks between telephone central offices: Graded index multimode fibers
3. Data links: Step index fibers

5. Summary

Optical fibers are classified based on the refractive index profile of core and cladding as well as the number of modes traveling through the fiber. Step index fiber and graded index fibers are the types based on the refractive index profile while single mode fiber and multimode fibers are the types based on the number of modes transmitted or propagated through the fiber. There are other types of optical fiber as well depending upon applications in which they are used. E.g. tapered end fibers are used to increase the intensity of dispersed input light. Usefulness of these fibers are compared based on the structure, refractive index profile, immunity to noise, dispersion etc. Lastly applications are discussed for military, datalinks or telephone connections.

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