UNIT I

OVERVIEW OF OPTICAL FIBER COMMUNICATION: INTRODUCTION

Introduction

Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information.[1] Fiber is preferred over electrical cabling when high bandwidth, long distance, or immunity to electromagnetic interference are required. This type of communication can transmit voice, video, and telemetry through local area networks, computer networks, or across long distances.

Optical fiber is used by many telecommunications companies to transmit telephone signals, Internet communication, and cable television signals. Researchers at Bell Labs have reached internet speeds of over 100 peta bit ×kilometer per second using fiber-optic communication.

The process of communicating using fiber-optics involves the following basic steps:

1. creating the optical signal involving the use of a transmitter, usually from an electrical signal
2. relaying the signal along the fiber, ensuring that the signal does not become too distorted or weak
3. receiving the optical signal
4. converting it into an electrical signal

Historical Development

First developed in the 1970s, fiber-optics have revolutionized the telecommunications industry and have played a major role in the advent of the Information Age. Because of its advantages over electrical transmission, optical fibers have largely replaced copper wire communications in core networks in the developed world.

In 1880 Alexander Graham Bell and his assistant Charles Sumner Tainter created a very early precursor to fiber-optic communications, the Photophone, at Bell's newly established Volta Laboratory in Washington, D.C. Bell considered it his most important invention. The device allowed for the transmission of sound on a beam of light. On June 3, 1880, Bell conducted the world's first wireless telephone transmission between two buildings, some 213 meters apart.[4][5] Due to its use of an atmospheric transmission medium, the Photophone would not prove practical until advances in laser and optical fiber technologies permitted the secure transport of light. The Photophone's first practical use came in military communication systems many decades later.

In 1954 Harold Hopkins and Narinder Singh Kapany showed that rolled fiber glass allowed light to be transmitted. Initially it was considered that the light can traverse in only straight medium. Jun-ichi Nishizawa, a Japanese scientist at Tohoku University, proposed the use of optical fibers for communications in 1963. Nishizawa invented the PIN diode and the static induction transistor, both of which contributed to the development of optical fiber communications.

In 1966 Charles K. Kao and George Hockham at STC Laboratories (STL) showed that the losses of 1,000 dB/km in existing glass (compared to 5–10 dB/km in coaxial cable) were due to contaminants which could potentially be removed.

Optical fiber was successfully developed in 1970 by Corning Glass Works, with attenuation low enough for communication purposes (about 20 dB/km) and at the same time GaAs semiconductor lasers were developed that were compact and therefore suitable for transmitting light through fiber optic cables for long distances.

In 1973, Optelecom, Inc., co-founded by the inventor of the laser, Gordon Gould, received a contract from APA for the first optical communication systems. Developed for Army Missile Command in Huntsville, Alabama, it was a laser on the ground and a spout of optical fiber played out by missile to transmit a modulated signal over five kilometers.

After a period of research starting from 1975, the first commercial fiber-optic communications system was developed which operated at a wavelength around 0.8 µm and used GaAs semiconductor lasers. This first-generation system operated at a bit rate of 45 Mbit/s with repeater spacing of up to 10 km. Soon on 22 April 1977, General Telephone and Electronics sent the first live telephone traffic through fiber optics at a 6 Mbit/s throughput in Long Beach, California.

In October 1973, Corning Glass signed a development contract with CSELT and Pirelli aimed to test fiber optics in an urban environment: in September 1977, the second cable in this test series, named COS-2, was experimentally deployed in two lines (9 km) in Turin, for the first time in a big city, at a speed of 140 Mbit/s.

The second generation of fiber-optic communication was developed for commercial use in the early 1980s, operated at 1.3 µm and used InGaAsP semiconductor lasers. These early systems were initially limited by multi mode fiber dispersion, and in 1981 the single-mode fiber was revealed to greatly improve system performance, however practical connectors capable of working with single mode fiber proved difficult to develop. Canadian service provider SaskTel had completed construction of what was then the world's longest commercial fiber optic network, which covered 3,268 km (2,031 mi) and linked 52 communities.[11] By 1987, these systems were operating at bit rates of up to 1.7 Gb/s with repeater spacing up to 50 km (31 mi).

The first transatlantic telephone cable to use optical fiber was TAT-8, based on Desurvire optimised laser amplification technology. It went into operation in 1988.

Third-generation fiber-optic systems operated at 1.55 µm and had losses of about 0.2 dB/km. This development was spurred by the discovery of Indium gallium arsenide and the development of the Indium Gallium Arsenide photodiode by Pearsall. Engineers overcame earlier difficulties with pulse-spreading at that wavelength using conventional InGaAsP semiconductor lasers. Scientists overcame this difficulty by using dispersion-shifted fibers designed to have minimal dispersion at 1.55 µm or by limiting the laser spectrum to a single longitudinal mode.

These developments eventually allowed third-generation systems to operate commercially at 2.5 Gbit/s with repeater spacing in excess of 100 km (62 mi).

The fourth generation of fiber-optic communication systems used optical amplification to reduce the need for repeaters and wavelength-division multiplexing to increase data capacity. These two improvements caused a revolution that resulted in the doubling of system capacity every six months starting in 1992 until a bit rate of 10 Tb/s was reached by 2001. In 2006 a bit-rate of 14 Tbit/s was reached over a single 160 km (99 mi) line using optical amplifiers.

The focus of development for the fifth generation of fiber-optic communications is on extending the wavelength range over which a WDM system can operate. The conventional wavelength window, known as the C band, covers the wavelength range 1.53–1.57 µm, and *dry fiber* has a low-loss window promising an extension of that range to 1.30–1.65 µm. Other developments include the concept of "optical solutions", pulses that preserve their shape by counteracting the effects of dispersion with the nonlinear effects of the fiber by using pulses of a specific shape.

In the late 1990s through 2000, industry promoters, and research companies such as KMI, and RHK predicted massive increases in demand for communications bandwidth due to increased use of the Internet, and commercialization of various bandwidth-intensive consumer services, such as video on demand. Internet protocol data traffic was increasing exponentially, at a faster rate than integrated circuit complexity had increased under Moore's Law. From the bust of the dot-com bubble through 2006, however, the main trend in the industry has been consolidation of firms and offshoring of manufacturing to reduce costs. Companies such as Verizon and AT&T have taken advantage of fiber-optic communications to deliver a variety of high-throughput data and broadband services to consumers' homes.

Advantages of Fiber Optic Transmission

Optical fibers have largely replaced copper wire communications in core networks in the developed world, because of its advantages over electrical transmission. Here are the main advantages of fiber optic transmission.

Extremely High Bandwidth: No other cable-based data transmission medium offers the bandwidth that fiber does. The volume of data that fiber optic cables transmit per unit time is far great than copper cables.

Longer Distance: in fiber optic transmission, optical cables are capable of providing low power loss, which enables signals can be transmitted to a longer distance than copper cables.

Resistance to Electromagnetic Interference: in practical cable deployment, it’s inevitable to meet environments like power substations, heating, ventilating and other industrial sources of interference. However, fiber has a very low rate of bit error (10 EXP-13), as a result of fiber being so resistant to electromagnetic interference. Fiber optic transmission is virtually noise free.

Low Security Risk: the growth of the fiber optic communication market is mainly driven by increasing awareness about data security concerns and use of the alternative raw material. Data or signals are transmitted via light in fiber optic transmission. Therefore there is no way to detect the data being transmitted by "listening in" to the electromagnetic energy "leaking" through the cable, which ensures the absolute security of information.

Small Size: fiber optic cable has a very small diameter. For instance, the cable diameter of a single OM3 multimode fiber is about 2mm, which is smaller than that of coaxial copper cable. Small size saves more space in fiber optic transmission.

Light Weight: fiber optic cables are made of glass or plastic, and they are thinner than copper cables. These make them lighter and easy to install.

Easy to Accommodate Increasing Bandwidth: with the use of fiber optic cable, new equipment can be added to existing cable infrastructure. Because optical cable can provide vastly expanded capacity over the originally laid cable. And WDM (wavelength division multiplexing) technology, including CWDM and DWDM, enables fiber cables the ability to accommodate more bandwidth.

Disadvantages of Fiber Optic Transmission

Though fiber optic transmission brings lots of convenience, its disadvantages also cannot be ignored. **Fragility:** usually optical fiber cables are made of glass, which lends to they are more fragile than electrical wires. In addition, glass can be affected by various chemicals including hydrogen gas (a problem in underwater cables), making them need more cares when deployed under ground.

Difficult to Install: it's not easy to splice fiber optic cable. And if you bend them too much, they will break. And fiber cable is highly susceptible to becoming cut or damaged during installation or construction activities. All these make it difficult to install.

Attenuation & Dispersion: as transmission distance getting longer, light will be attenuated and dispersed, which requires extra optical components like EDFA to be added.

Cost Is Higher Than Copper Cable: despite the fact that fiber optic installation costs are dropping by as much as 60% a year, installing fiber optic cabling is still relatively higher than copper cables. Because copper cable installation does not need extra care like fiber cables. However, optical fiber is still moving into the local loop, and through technologies such as FTTx (fiber to the home, premises, etc.) and PONs (passive optical networks), enabling subscriber and end user broadband access.

Special Equipment Is Often Required: to ensure the quality of fiber optic transmission, some special equipment is needed. For example, equipment such as OTDR (optical time-domain reflectometry) is required and expensive, specialized optical test equipment such as optical probes and power meter are needed at most fiber endpoints to properly provide testing of optical fiber.

Applications of Optical Fiber Communications

Fiber optic cables find many uses in a wide variety of industries and applications. Some uses of fiber optic cables include:

- **Medical**

  Used as light guides, imaging tools and also as lasers for surgeries

- **Defense/Government**

  Used as hydrophones for seismic waves and SONAR , as wiring in aircraft, submarines and other vehicles and also for field networking
- **Data Storage**

  Used for data transmission
- **Telecommunications**

  Fiber is laid and used for transmitting and receiving purposes
- **Networking**

  Used to connect users and servers in a variety of network settings and help increase the speed and accuracy of data transmission
- **Industrial/Commercial**

  Used for imaging in hard to reach areas, as wiring where EMI is an issue, as sensory devices to make temperature, pressure and other measurements, and as wiring in automobiles and in industrial settings
- **Broadcast/CATV**

  Broadcast/cable companies are using fiber optic cables for wiring CATV, HDTV, internet, video on-demand and other applications

  Fiber optic cables are used for lighting and imaging and as sensors to measure and monitor a vast array of variables. Fiber optic cables are also used in research and development and testing across all the above mentioned industries

The optical fibers have many applications. Some of them are as follows –

- Used in telephone systems
- Used in sub-marine cable networks
- Used in data link for computer networks, CATV Systems
- Used in CCTV surveillance cameras
- Used for connecting fire, police, and other emergency services.
- Used in hospitals, schools, and traffic management systems.
- They have many industrial uses and also used for in heavy duty constructions.

Block Diagram of Optical Fiber Communication System

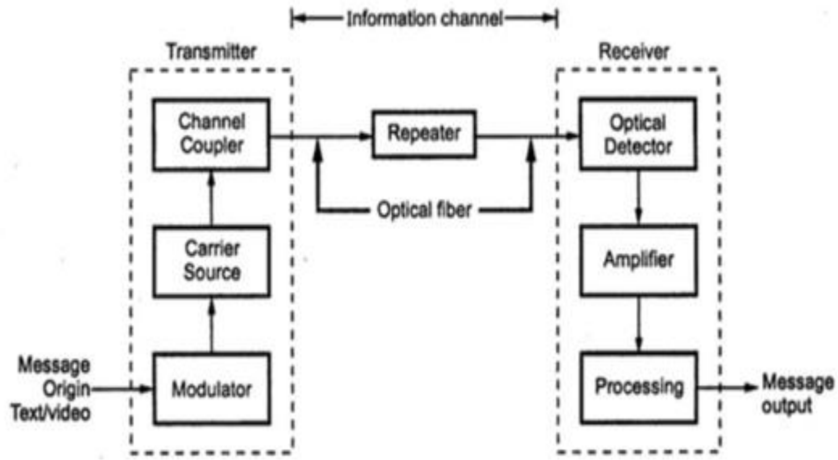

Fig 1: Block Diagram of Optical Fiber Communication System

Message origin:

Generally message origin is from a transducer that converts a non-electrical message into an electrical signal. Common examples include microphones for converting sound waves into currents and video (TV) cameras for converting images into current. For data transfer between computers, the message is already in electrical form.

Modulator:

The modulator has two main functions.

1) It converts the electrical message into proper format.

2) It impresses this signal onto the wave generated by the carrier source.

wo distinct categories of modulation are used i.e. analog modulation and digital modulation.

Carrier source:

. Carrier source generates the wave on which the information is transmitted. This wave is called the carrier. For fiber optic system, a laser diode (LD) or a light emitting diode (LED) is used. They can be called as optic oscillators, they provide stable, single frequency waves with sufficient power for long distance propagation.

Channel coupler:

. Coupler feeds the power into information channel. For an atmospheric optic system, the channel coupler is a lens used for collimating the light emitted by the source and directing this light towards the receiver. The coupler must efficiently transfer the modulated light beam from the source to the optic fiber. The channel coupler design is an important part of fiber system because of possibility of high losses.

Information channel:

. The information channel is the path between the transmitter and receiver. In fiber optic communications, a glass or plastic fiber is the channel. Desirable characteristics of the information channel include low attenuation and large light acceptance cone angle. Optical amplifiers boost the power levels of weak signals. Amplifiers are needed in very long links to provide sufficient power to the receiver. Repeaters can be used only for digital systems. They convert weak and distorted optical signals to electrical ones and then regenerate the original digital pulse trains for further transmission.

. Another important property of the information channel is the propagation time of the waves travelling along it. A signal propagating along a fiber normally contains a range of fiber optic frequencies and divides its power along several ray paths. This results in a distortion of the propagation signal. In a digital system, this distortion appears as a spreading and deforming of the pulses. The spreading is so great that adjacent pulses begin to overlap and become unrecognizable as separate bits of information.

Optical detector:

. The information begin transmitted is detected by detector. In the fiber system the optic wave is converted into an electric current by a photodetector. The current developed by the detector is proportional to the power in the incident optic wave. Detector output current contains the transmitted information. This detector output is then filtered to remove the constant bias and then amplified.

. The important properties of photodetectors are small size, economy, long life, low power consumption, high sensitivity to optic signals and fast response to quick variations in the optic power.

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Message output:

. The electrical form of the message emerging from the signal processor is transformed into a sound wave or visual image. Sometimes these signals are directly usable when computers or other machines are connected through a fiber system.

Electromagnetic Spectrum

The radio waves and light are electromagnetic waves. The rate at which they alternate in
polarity is called their frequency (f) measured in hertz (Hz). The speed of electromagnetic wave (c) in free space is approximately 3 x 108 m/sec. The distance travelled during each cycle is called as wavelength (λ)

In fiber optics, it is more convenient to use the wavelength of light instead of the frequency with light frequencies; wavelength is often stated in microns or nanometers.

1 micron (μ) = 1

Micrometre (1 x 10-6) 1 nano (n) = 10-9 meter

Fiber optics uses visible and infrared light. Infrared light covers a fairly wide range of wavelengths and is generally used for all fiber optic communications. Visible light is normally used for very short range transmission using a plastic fiber.

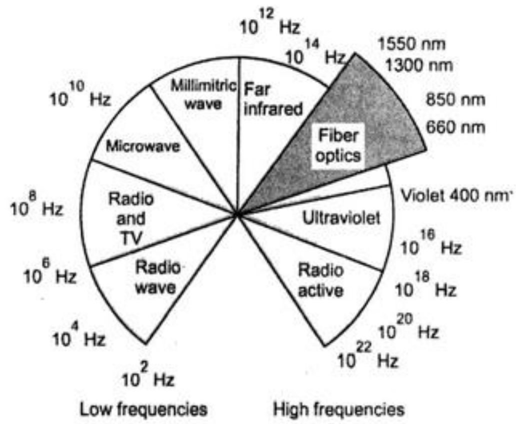
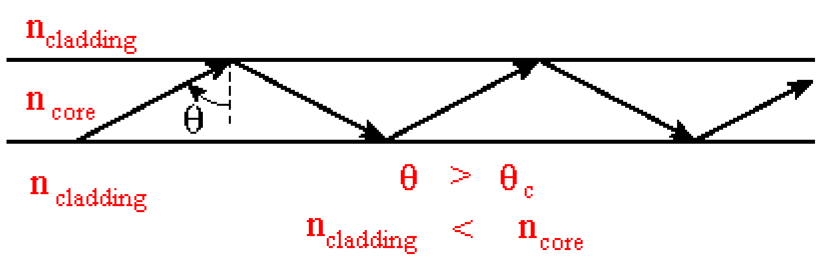


Fig 2: Electromagnetic Spectrum

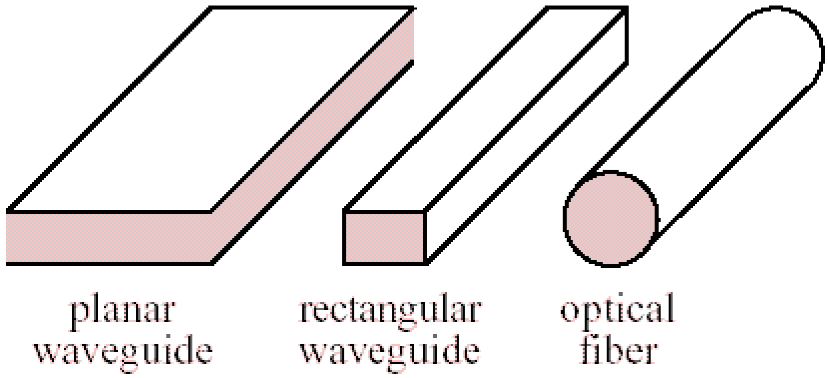
Optical Fiber Waveguides

In free space light ravels as its maximum possible speed i.e. 3 x 108 m/s or 186 x 103 miles/sec. When light travels through a material it exhibits certain behavior explained by laws of reflection, refraction.

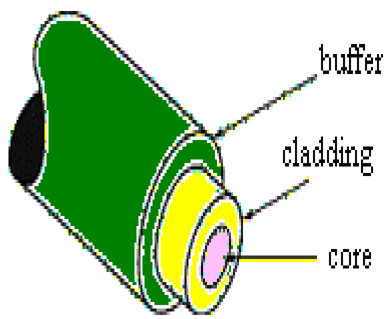
An optical wave guide is a structure that "guides" a light wave by constraining it to travel along a certain desired path. If the transverse dimensions of the guide are much larger than the wavelength of the guided light, then we can explain how the optical waveguide works using geometrical optics and total internal reflection.



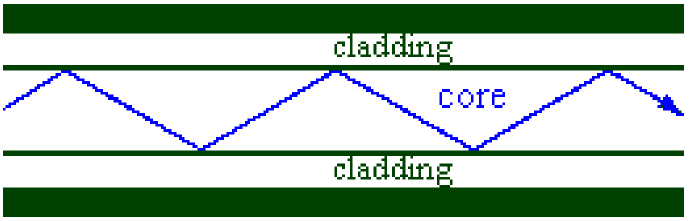
A wave guide traps light by surrounding a guiding region, called the core, made from a material with index of refraction n_{core}, with a material called the cladding, made from a material with index of refraction **$n_{cladding} < n_{core}$.** Light entering is trapped as long as **$\sin\theta > n_{cladding}/n_{ncore}$.**



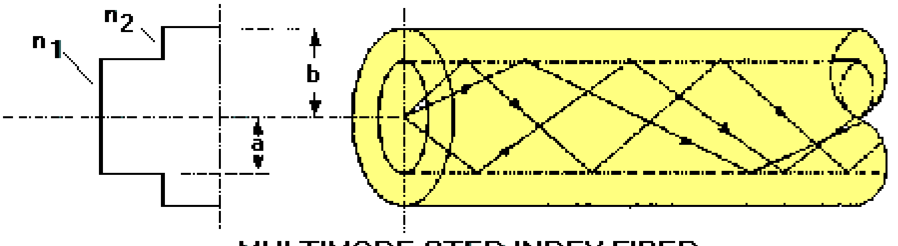
Light can be guided by planar or rectangular wave guides, or by optical fibers.An optical fiber consists of three concentric elements, the core, the cladding and the outer coating, often called the buffer. The core is usually made of glass or plastic. The core is the light-carrying portion of the fiber. The cladding surrounds the core. The cladding is made of a material with a slightly lower index of refraction than the core. This difference in the indices causes total internal reflection to occur at the core-cladding boundary along the length of the fiber. Light is transmitted down the fiber and does not escape through the sides of the fiber.



- Fiber Optic Core:
    - the inner light-carrying member with a high index of refraction.
- Cladding:
    - the middle layer, which serves to confine the light to the core. It has a lower index of refraction.

- Buffer:
    - the outer layer, which serves as a "shock absorber" to protect the core and cladding from damage. The coating usually comprises one or more coats of a plastic material to protect the fiber from the physical environment. Sometimes metallic sheaths are added to the coating for further physical protection.
    - 

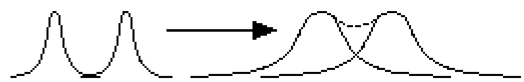
- Light injected into the fiber optic core and striking the core-to-cladding interface at an angle greater than the critical angle is reflected back into the core. Since the angles of incidence and reflection are equal, the light ray continues to zigzag down the length of the fiber. The light is trapped within the core. Light striking the interface at less than the critical angle passes into the cladding and is lost.



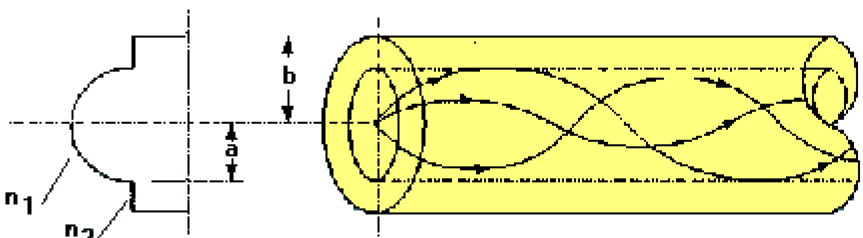
MULTIMODE STEP-INDEX FIBER

- Fibers for which the refractive index of the core is a constant and the index changes abruptly at the core-cladding interface are called step-index fibers. Step-index fibers are available with core diameters of 100 mm to 1000 mm. They are well suited to applications requiring high-power densities, such as delivering laser power for medical and industrial applications.

- Multimode step-index fibers trap light with many different entrance angles, each mode in a step-index multimode fiber is associated with a different entrance angle. Each mode therefore travels along a different path through the fiber. Different propagating modes have different velocities. As an optical pulse travels down a multimode fiber, the pulse begins to spread. Pulses that enter well separated from each other will eventually overlap each other. This limits the distance over which the fiber can transport data. Multimode step-index fibers are not well suited for data transport and communications.

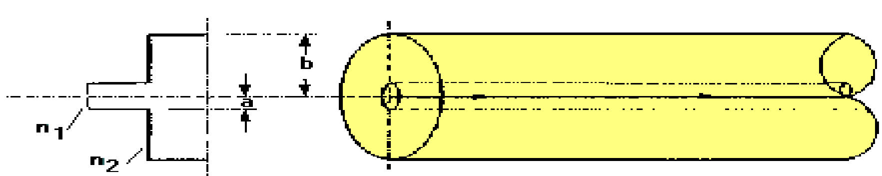


- In a multimode graded-index fiber the core has an index of refraction that decreases as the radial distance from the center of the core increases. As a result, the light travels faster near the edge of the core than near the center. Different modes therefore travel in curved paths with nearly equal travel times. This greatly reduces the spreading of optical pulses.



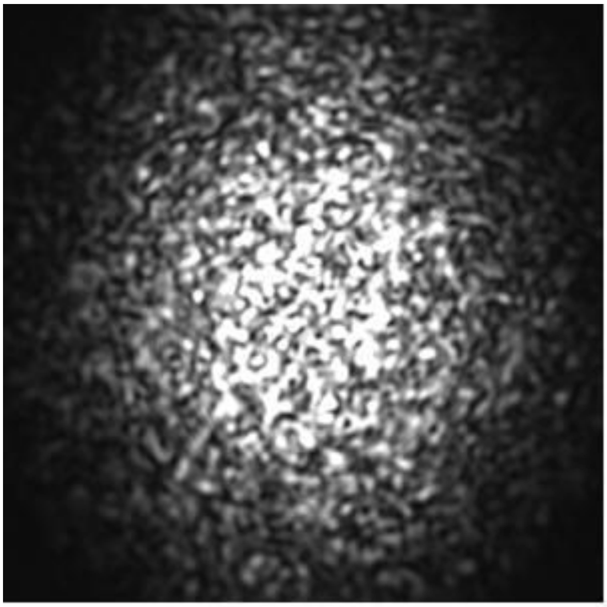
MULTIMODE GRADED-INDEX FIBER

- A **single mode fiber** only allows light to propagate down its center and there are no longer different velocities for different modes. A single mode fiber is much thinner than a multimode fiber and can no longer be analyzed using geometrical optics. Typical core diameters are between 5 mm and 10 mm.

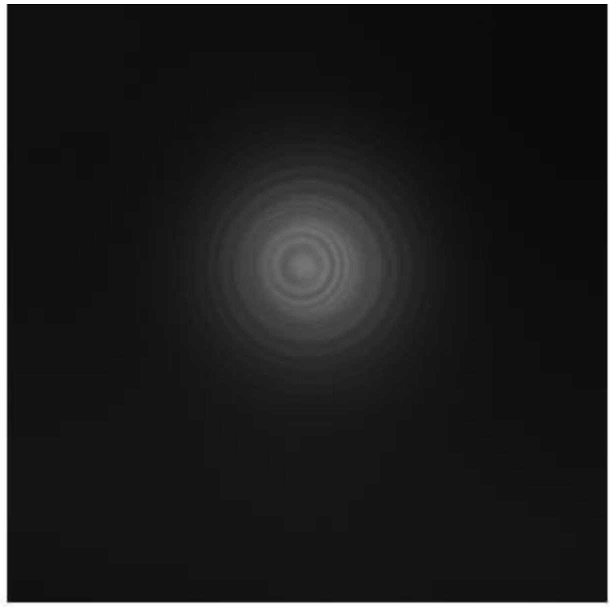


SINGLE MODE STEP-INDEX FIBER

When laser light is coupled into a fiber, the distribution of the light emerging from the other end reveals if the fiber is a multimode or single mode fiber.



Light emerging from a multi-mode fiber

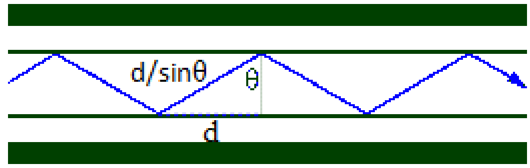


Light emerging from a single-mode fiber

Optical fibers are used widely in the medical field for diagnoses and treatment. Optical fibers can be bundled into flexible strands, which can be inserted into blood vessels, lungs and other parts of the body. An Endoscope is a medical tool carrying two bundles of optic fibers inside one long tube. One bundle directs light at the tissue being tested, while the other bundle carries light reflected from the tissue, producing a detailed image. Endoscopes can be designed to look at regions of the human body, such as the knees, or other joints in the body

Problem:

In a step-index fiber in the ray approximation, the ray propagating along the axis of the fiber has the shortest route, while the ray incident at the critical angle has the longest route. Determine the difference in travel time (in ns/km) for the modes defined by those two rays for a fiber with $n_{core} = 1.5$ and $n_{cladding} = 1.485$.



Solution:

If a ray propagating along the axis of the fiber travels a distance d, then a ray incident at the critical angle θ_c travels a distance $L = d/\sin\theta_c$.

The respective travel times are $t_d = dn_{core}/c$ and $t_L = dn_{core}/(\sin\theta_c\, c)$.

$\sin\theta_c = n_{cladding}/n_{core}$.

$\theta_c = 81.9$ deg.

For d = 1000 m we have $t_d = 5000$ ns and $t_L = 5050.51$ ns.

The difference in travel time is therefore 50.51 ns/km.

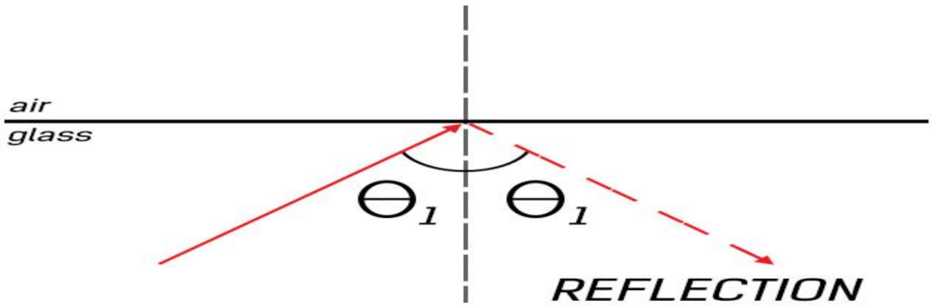
Ray theory

The phenomenon of splitting of white light into its constituents is known as dispersion. The concepts of reflection and refraction of light are based on a theory known as Ray theory or geometric optics, where light waves are considered as waves and represented with simple geometric lines or rays.

The basic laws of ray theory/geometric optics

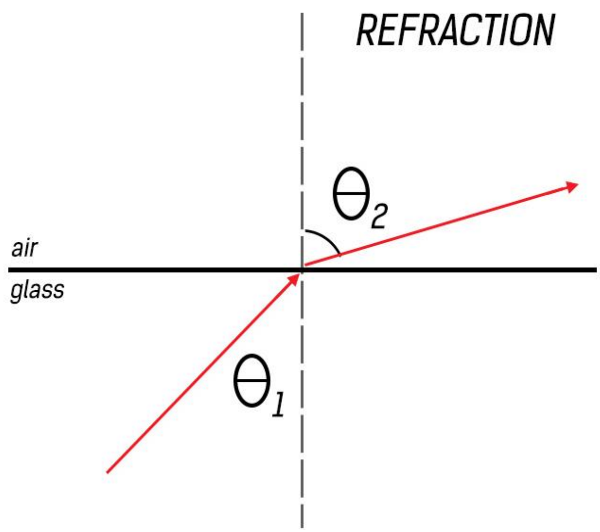
- In a homogeneous medium, light rays are straight lines.
- Light may be absorbed or reflected
- Reflected ray lies in the plane of incidence and angle of incidence will be equal to the angle of reflection.

- At the boundary between two media of different refractive indices, the refracted ray will lie in the plane of incidence. Snell's Law will give the relationship between the angles of incidence and refraction.



Reflection depends on the type of surface on which light is incident. An essential condition for reflection to occur with glossy surfaces is that the angle made by the incident ray of light with the normal at the point of contact should be equal to the angle of reflection with that normal.

The *images* produced from this reflection have different properties according to the shape of the surface. For example, for a flat mirror, the image produced is upright, has the same size as that of the object and is equally distanced from the surface of the mirror as the real object. However, the properties of a parabolic mirror are different and so on.



Refraction is the bending of light in a particular medium due to the speed of light in that medium. The speed of light in any medium can be given by $v = \frac{c}{n}$

$$\text{Refractive index n} = \frac{\text{Speed of light in air}}{\text{Speed of light in medium}} = \frac{c}{v}$$

The refractive index for vacuum and air os 1.0 for water it is 1.3 and for glass refractive index is 1.5. Here n is the **refractive index** of that medium. When a ray of light is incident at the interface of two media with different refractive indices, it will bend either towards or away from the normal depending on the refractive indices of the media.

According to **Snell's law**, refraction can be represented as

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

n_1 = refractive index of first medium

θ_1 = angle of incidence

n_2 = refractive index of second medium

θ_2 = angle of refraction

For $n_1 > n_2$, θ_2 is always greater than θ_1. **Or** to put it in different words, light moving from a medium of high refractive index (glass) to a medium of lower refractive index (air) will move away from the normal.

Total internal reflection

To consider the propagation of light within an optical fiber utilizing the ray theory model it is necessary to take account of the refractive index of the dielectric medium. Optical materials are characterized by their index of refraction, referred to as n.The refractive index of a medium is defined as the ratio of the velocity of light in a vacuum to the velocity of light in the medium.

When a beam of light passes from one material to another with a different index of refraction, the beam is bent (or refracted) at the interface (Figure 2).

$$n_I \sin I = n_R \sin R$$

where n_I and n_R are the indices of refraction of the materials through which the beam is refracted and I and R are the angles of incidence and refraction of the beam. If the angle of incidence is greater than the critical angle for the interface (typically about 82° for optical fibers), the light is reflected back into the incident medium without loss by a process known as total internal reflection (Figure 3).

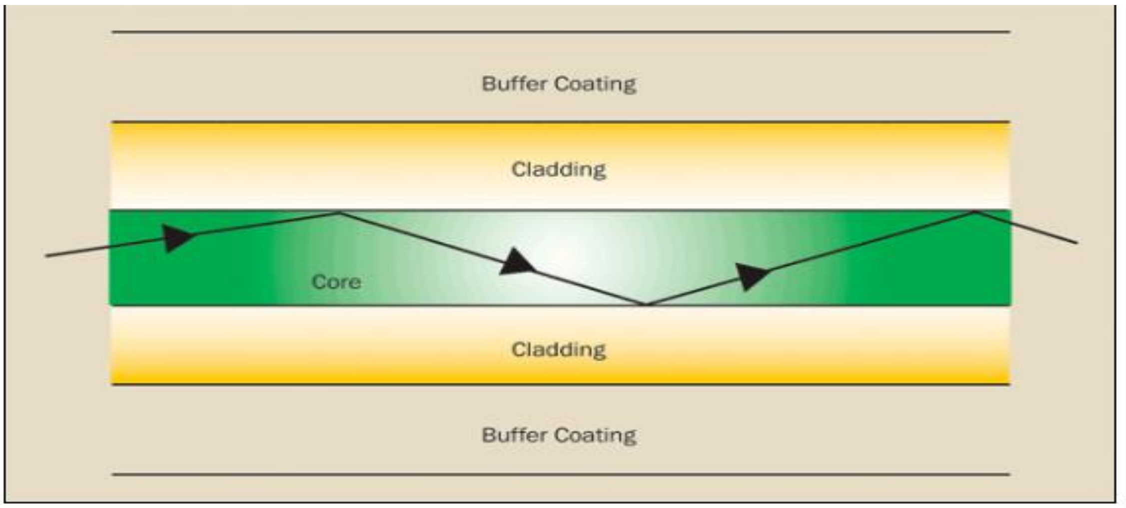


Figure 3. *Total internal reflection allows light to remain inside the core of the fiber.*

Refraction is described by Snell's law:

A ray of light travels more slowly in an optically dense medium than in one that is less dense, and the refractive index gives a measure of this effect. When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass–air), refraction occurs, as illustrated in Figure 1.2(a). It may be observed that the ray approaching the interface is propagating in a dielectric of refractive index n and is at an angle ϕ to the normal at the surface of the interface.

If the dielectric on the other side of the interface has a refractive index *n* which is less than *n*1, then the refraction is such that the ray path in this lower index medium is at an angle to the normal, where is greater than . The angles of incidence and refraction are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction, which states that:

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

Or

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1}$$

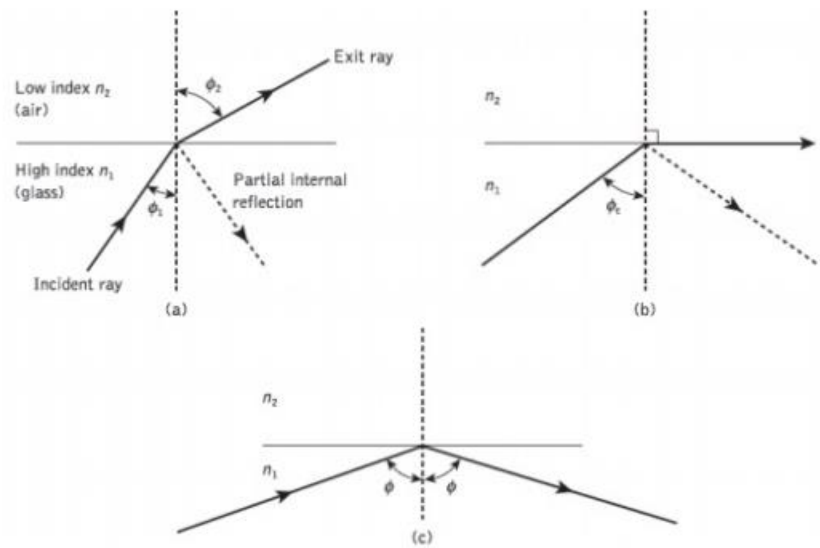


Figure 1.2 Light rays incident on a high to low refractive index interface (e.g. glass air): (a) refraction; (b) the limiting case of refraction showing the critical ray at an angle φ_c (c) total internal reflection where $\varphi > \varphi_c$

It may also be observed in Figure 1.2(a) that a small amount of light is reflected back into the originating dielectric medium (partial internal reflection). As *n* is greater than *n*, the angle of refraction is always greater than the angle of incidence. Thus when the angle of refraction is 90° and the refracted ray emerges parallel to the interface between the dielectrics, the angle of incidence must be less than 90°.

This is the limiting case of refraction and the angle of incidence is now known as the critical angle ϕc, as shown in Figure 1.2(b). From Eq. (1.1) the value of the critical angle is given by

$$\sin \phi_c = \frac{n_2}{n_1}$$

At angles of incidence greater than the critical angle the light is reflected back into the originating dielectric medium (total internal reflection) with high efficiency (around 99.9%). Hence, it may be observed in Figure 1.2(c) that total internal reflection occurs at the inter- face between two dielectrics of differing refractive indices when light is incident on the dielectric of lower index from the dielectric of higher index, and the angle of incidence of the ray exceeds the critical value. This is the mechanism by which light at a sufficiently shallow angle (less than 90° − may be considered to propagate down an optical fiber with low loss.

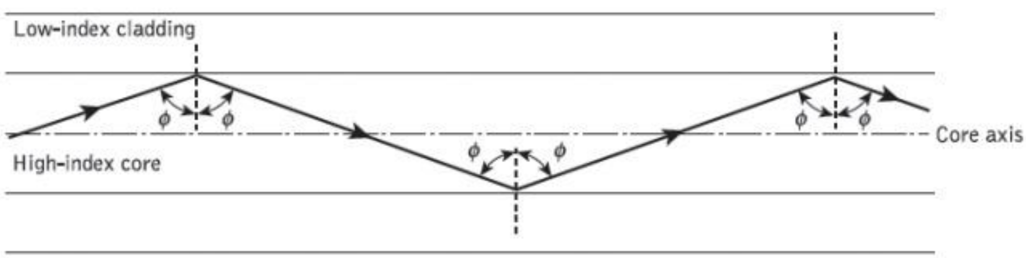


Figure 1.3 The transmission of a light ray in a perfect optical fiber

Figure 1.3 illustrates the transmission of a light ray in an optical fiber via a series of total internal reflections at the interface of the silica core and the slightly lower refractive index silica cladding. The ray has an angle of incidence ϕ at the interface which is greater than the critical angle and is reflected at the same angle to the normal.

The light ray shown in Figure 1.3 is known as a meridional ray as it passes through the axis of the fiber core. This type of ray is the simplest to describe and is generally used when illustrating the fundamental transmission properties of optical fibers. It must also be noted that the light transmission illustrated in Figure 1.3 assumes a perfect fiber, and that any discontinuities or imperfections at the core–cladding interface would probably result in refraction rather than total internal reflection, with the subsequent loss of the light ray into the cladding.

Critical Angle

When the angle of incidence (ϕ_1) is progressively increased, there will be progressive increase of refractive angle (ϕ_2). At some condition (ϕ_1) the refractive angle (ϕ_2) becomes 90^o to the normal. When this happens the refracted light ray travels along the interface. The angle of incidence (ϕ_1) at the point at which the refractive angle (ϕ_1) becomes 90^O is called the critical angle. It is denoted by ϕ_c.

The **critical angle** is defined as the minimum angle of incidence (ϕ_1) at which the ray strikes the interface of two media and causes an angle of refraction (ϕ_2) equal to 90^O. Fig 1.6.5 shows critical angle refraction. When the angle of refraction is 90 degree to the normal the refracted ray is parallel to the interface between the two media.

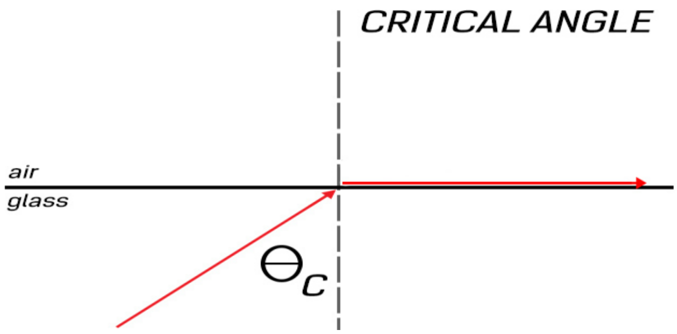
Hence at critical angle $\phi_1 = \phi_c$ and $\phi_2 = 90^O$

Using Snell's law: $n_1 \sin \phi_1 = n_2 \sin \phi_2$

$$\sin \phi_c = \frac{n_2}{n_1} \sin 90^o$$

$$\because \quad \sin 90^o = 1$$

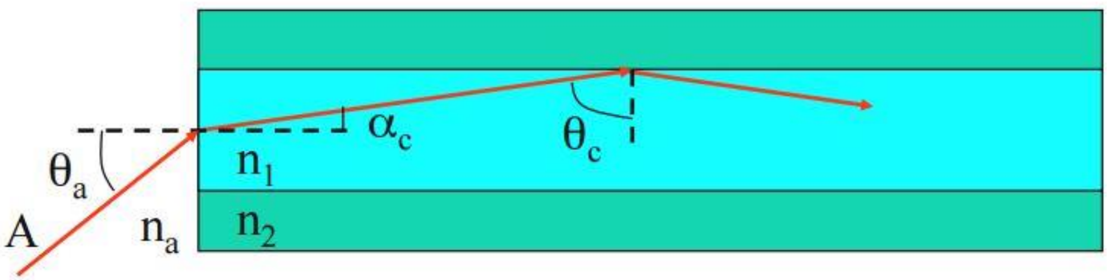
$$\boxed{\text{Critical angle } \phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)}$$



It is important to know about this property because reflection is also possible even if the surfaces are not reflective. If the *angle of incidence is greater than the critical angle* for a given setting, the resulting type of reflection is called **Total Internal Reflection**, and it is the basis of Optical Fiber Communication.

Acceptance angle

In an optical fiber, a light ray undergoes its *first refraction* at the air-core interface. The angle at which this refraction occurs is crucial because this particular angle will dictate whether the subsequent *internal* reflections will follow the principle of Total Internal Reflection. This angle, at which the light ray first encounters the core of an optical fiber is called Acceptance angle.

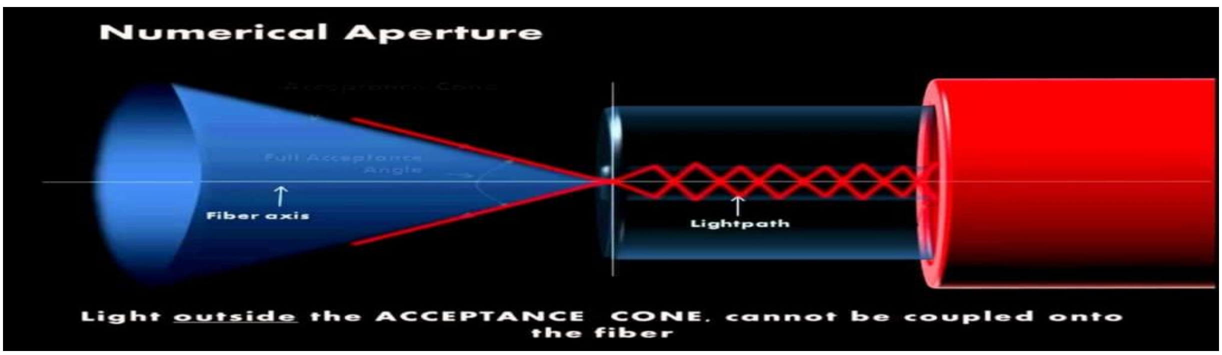


The objective is to have [latex] \theta_{c}[/latex] greater than the critical angle for this particular setting. As you can notice, θ_c depends on the orientation of the refracted ray at the input of the optical fiber. This in turn depends on θ_a, the acceptance angle.

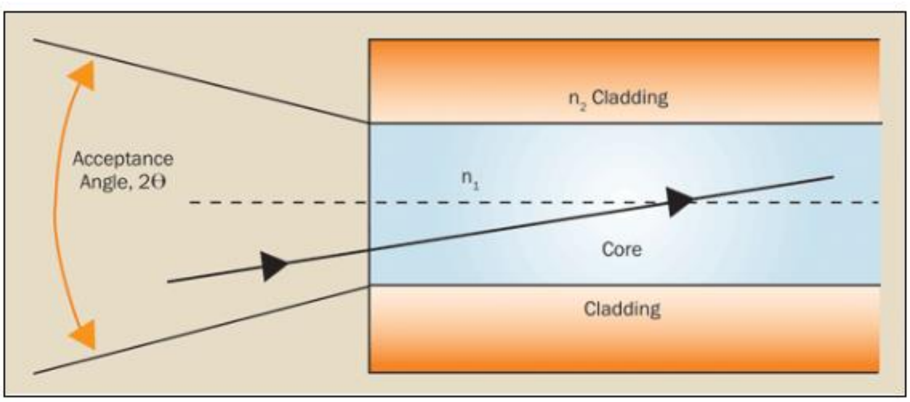
The acceptance angle can be calculated with the help of the formula below.

Numerical Aperture

Numerical Aperture is a characteristic of any optical system. For example, photo-detector, optical fiber, lenses etc. are all optical systems. Numerical aperture is the ability of the optical system to collect all of the light incident on it, in one area.



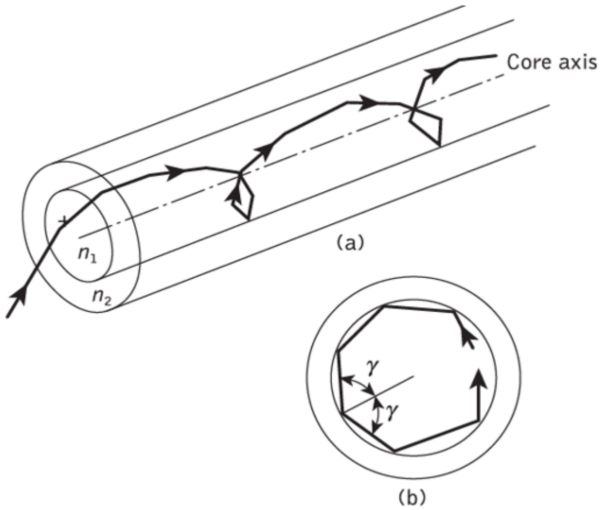
The blue cone is known as the cone of acceptance. As you can see it is dependent on the Acceptance Angle of the optical fiber. Light waves within the acceptance cone can be collected in a small area which can then be sent into the optical fiber (Source)



Numerical aperture (NA), shown in above Figure, is the measure of maximum angle at which light rays will enter and be conducted down the fiber. This is represented by the following equation:

$$NA = \sqrt{(n^2_{core} - n^2_{cladding})} = \sin\theta$$

skew rays: In a multimode optical fiber, a bound ray that travels in a helical path along the fiber and thus (a) is not parallel to the fiber axis, (b) does not lie in a meridional plane, and (c) does not intersect the fiber axis is known as a Skew Ray.



1. Skew rays are rays that travel through an optical fiber without passing through its axis.
2. A possible path of propagation of skew rays is shown in figure. Figure 24, view (a), provides an angled view and view (b) provides a front view.

3. Skew rays are those rays which follow helical path but they are not confined to a single plane. Skew rays are not confined to a particular plane so they cannot be tracked easily. Analyzing the meridional rays is sufficient for the purpose of result, rather than skew rays, because skew rays lead to greater power loss.

4. Skew rays propagate without passing through the center axis of the fiber. The acceptance angle for skew rays is larger than the acceptance angle of meridional rays.

5. Skew rays are often used in the calculation of light acceptance in an optical fiber. The addition of skew rays increases the amount of light capacity of a fiber. In large NA fibers, the increase may be significant.

6. The addition of skew rays also increases the amount of loss in a fiber. Skew rays tend to propagate near the edge of the fiber core. A large portion of the number of skew rays that are trapped in the fiber core are considered to be leaky rays.

7. Leaky rays are predicted to be totally reflected at the core-cladding boundary. However, these rays are partially refracted because of the curved nature of the fiber boundary. Mode theory is also used to describe this type of leaky ray loss.

Cylindrical fiber

1. Modes

When light is guided down a fiber (as microwaves are guided down a waveguide), phase shifts occur at every reflective boundary. There is a finite discrete number of paths down the optical fiber (known as modes) that produce constructive (in phase and therefore additive) phase shifts that reinforce the transmission. Because each mode occurs at a different angle to the fiber axis as the beam travels along the length, each one travels a different length through the fiber from the input to the output. Only one mode, the zero-order mode, travels the length of the fiber without reflections from the sidewalls. This is known as a single-mode fiber. The actual number of modes that can be propagated in a given optical fiber is determined by the wavelength of light and the diameter and index of refraction of the core of the fiber.

The exact solution of Maxwell's equations for a cylindrical homogeneous core dielectric waveguide* involves much algebra and yields a complex result. Although the presentation of this mathematics is beyond the scope of this text, it is useful to consider the resulting modal fields. In common with the planar guide (Section 1.3.2), TE (where $E_z = 0$) and TM (where $H_z = 0$) modes are obtained within the dielectric cylinder. The cylindrical waveguide, however, is bounded in two dimensions rather than one. Thus two integers, l and m, are necessary in order to specify the modes, in contrast to the single integer (m) required for the planar guide.

For the cylindrical waveguide we therefore refer to TE_{lm} and TM_{lm} modes. These modes correspond to meridional rays (see Section 1.2.1) traveling within the fiber. However, hybrid modes where E_z and H_z are nonzero also occur within the cylindrical waveguide.

These modes, which result from skew ray propagation (see Section 1.2.4) within the fiber, are designated HE*lm* and EH*lm* depending upon whether the components of **H** or **E** make the larger contribution to the transverse (to the fiber axis) field. Thus an exact description of the modal fields in a step index fiber proves somewhat complicated.

Fortunately, the analysis may be simplified when considering optical fibers for communication purposes. These fibers satisfy the weakly guiding approximation where the relative index difference Δ1. This corresponds to small grazing angles θ in Eq. (1.34). In fact is usually less than 0.03 (3%) for optical communications fibers. For weakly guiding structures with dominant forward propagation, mode theory gives dominant transverse field components. Hence approximate solutions for the full set of HE, EH, TE and TM modes may be given by two linearly polarized components.

These linearly polarized (LP) modes are not exact modes of the fiber except for the fundamental (lowest order) mode. However, as in weakly guiding fibers is very small, then HE– EH mode pairs occur which have almost identical propagation constants. Such modes are said to be degenerate. The superpositions of these degenerating modes characterized by a common propagation constant correspond to particular LP modes regardless of their HE, EH, TE or TM field configurations. This linear combination of degenerate modes obtained from the exact solution produces a useful simplification in the analysis of weakly guiding fibers.

The relationship between the traditional HE, EH, TE and TM mode designations and the LP*lm* mode designations is shown in Table 1.1. The mode subscripts *l* and *m* are related to the electric field intensity profile for a particular LP mode (see Figure 1.11(d)). There are in general 2*l* field maxima around the circumference of the fiber core and *m* field maxima along a radius vector. Furthermore, it may be observed from Table 1.1 that the notation for labeling the HE and EH modes has changed from that specified for the exact solution in the cylindrical waveguide mentioned previously.

Table 1.1 Correspondence between the lower order in linearly polarized modes and the traditional exact modes from which they are formed

Linearly polarized	*Exact*
LP_{01}	HE_{11}
LP_{11}	HE_{21}, TE_{01}, TM_{01}
LP_{21}	HE_{31}, EH_{11}
LP_{02}	HE_{12}
LP_{31}	HE_{41}, EH_{21}
LP_{12}	HE_{22}, TE_{02}, TM_{02}
LP_{lm}	HE_{2m}, TE_{0m}, TM_{0m}
LP_{lm} ($l \neq 0$ or 1)	$HE_{l+1,m}$, $EH_{l-1,m}$

2. Mode coupling

We have thus far considered the propagation aspects of perfect dielectric waveguides. However, waveguide perturbations such as deviations of the fiber axis from straightness, variations in the core diameter, irregularities at the core–cladding interface and refractive index variations may change the propagation characteristics of the fiber. These will have the effect of coupling energy traveling in one mode to another depending on the specific perturbation. Ray theory aids the understanding of this phenomenon, as shown in Figure 1.13, which illustrates two types of perturbation. It may be observed that in both cases the ray no longer maintains the same angle with the axis. In electromagnetic wave theory this corresponds to a change in the propagating mode for the light. Thus individual modes do not normally propagate throughout the length of the fiber without large energy transfers to adjacent modes, even when the fiber is exceptionally good quality and is not strained or bent by its surroundings. This mode conversion is known as mode coupling or mixing. It is usually analyzed using coupled mode equations which can be obtained directly from Maxwell's equations.

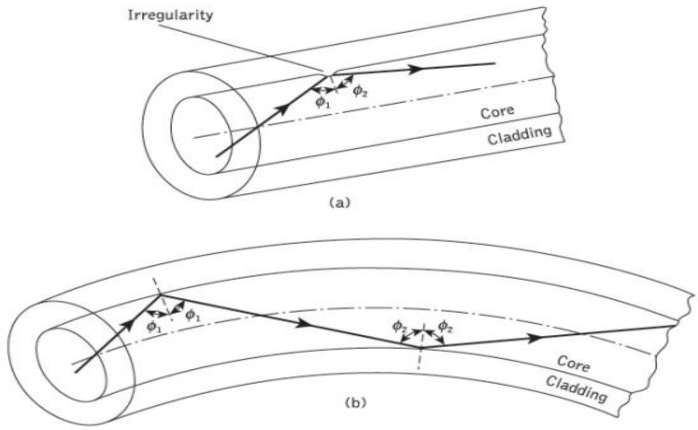


Figure 1.13 *Ray theory illustrations showing two of the possible fiber perturbations which give mode coupling: (a) irregularity at the core–cladding interface; (b) fiber bend*

3. Step index fibers

The optical fiber considered in the preceding sections with a core of constant refractive index *n*1 and a cladding of a slightly lower refractive index *n*2is known as step index fiber. This is because the refractive index profile for this type of fiber makes a step change at the core–cladding interface, as indicated in Figure 1.14, which illustrates the two major types of step index fiber.The refractive index profile may be defined as

$$n(r) = \begin{cases} n_1 & r < a \quad \text{(core)} \\ n_2 & r \geq a \quad \text{(cladding)} \end{cases} \tag{1.48}$$

in both cases.

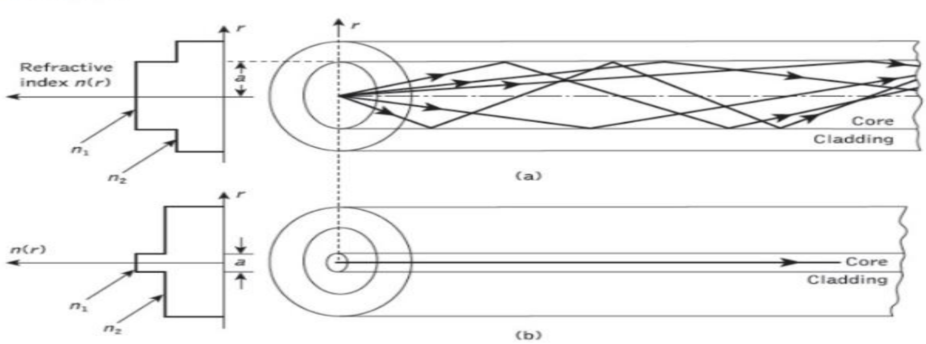


Figure 1.14 The refractive index profile and ray transmission in step index fibers: (a) multimode step index fiber, (b) single-mode step index fiber

Figure 1.14(a) shows a multimode step index fiber with a core diameter of around 50µm or greater, which is large enough to allow the propagation of many modes within the fiber core. This is illustrated in Figure 1.14(a) by the many different possible ray paths through the fiber. Figure 1.14(b) shows a single-mode or monomode step index fiber which allows the propagation of only one transverse electromagnetic mode (typically HE11), and hence the core diameter must be of the order of 2 to 10µm. The propagation of a single mode is illustrated in Figure 1.14(b) as corresponding to a single ray path only (usually shown as the axial ray) through the fiber.

The single-mode step index fiber has the distinct advantage of low intermodal dispersion (broadening of transmitted light pulses), as only one mode is transmitted, whereas with multimode step index fiber considerable dispersion may occur due to the differing group velocities of the propagating modes. This in turn restricts the maximum bandwidth attainable with multimode step index fibers, especially when com- pared with single-mode fibers.

However, for lower bandwidth applications multimode fibers have several advantages over single-mode fibers. These are:

a) The use of spatially incoherent optical sources (e.g. most light-emitting diodes) which cannot be efficiently coupled to single-mode fibers.

b) Larger numerical apertures, as well as core diameters, facilitating easier coupling to optical sources

c) Lower tolerance requirements on fiber connectors

Multimode step index fibers allow the propagation of a finite number of guided modes along the channel. The number of guided modes is dependent upon the physical parameters (i.e. relative refractive index difference, core radius) of the fiber and the wavelengths of the transmitted light which are included in the normalized frequency V for the fiber.

Mode propagation does not entirely cease below cutoff. Modes may propagate as unguided or leaky modes which can travel considerable distances along the fiber. Nevertheless, it is the guided modes which are of paramount importance in optical fiber communications as these are confined to the fiber over its full length. that the total number of guided modes or mode volume *M*s for a step index fiber is related to the *V* value for the

fiber by the approximate expression

Which allows an estimate of the number of guided modes propagating in a particular multimode step index fiber.

4. Graded index fibers

Graded index fibers do not have a constant refractive index in the core* but a decreasing core index $n(r)$ with radial distance from a maximum value of n_1 at the axis to a constant value n_2 beyond the core radius a in the cladding. This index variation may be represented as:

$$n(r) = \begin{cases} n_1(1 - 2\Delta(r/a)^{\alpha})^{\frac{1}{2}} & r < a \quad \text{(core)} \\ n_1(1 - 2\Delta)^{\frac{1}{2}} = n_2 & r \geq a \quad \text{(cladding)} \end{cases} \tag{1.50}$$

where is the relative refractive index difference and α is the profile parameter which gives the characteristic refractive index profile of the fiber core. Equation (1.50) which is a convenient method of expressing the refractive index profile of the fiber core as a variation of α, allows representation of the step index profile when α = ∞, a parabolic profile when α = 2 and a triangular profile when α = 1. This range of refractive index profiles is illustrated in Figure 1.15

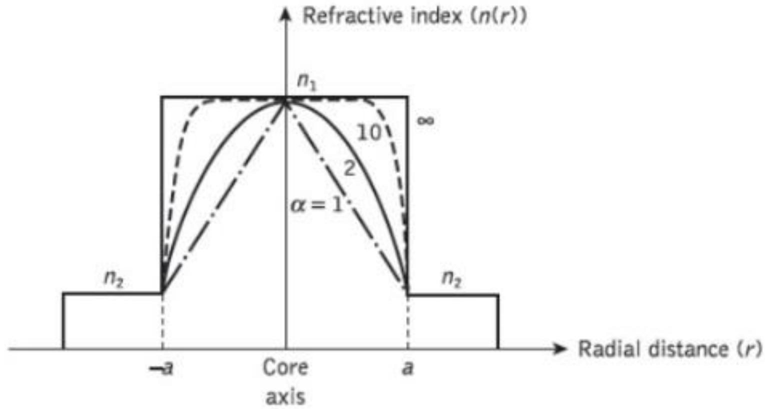


Figure 1.15 Possible fiber refractive index profiles for different values of α (given in Eq. (1.50)

The graded index profiles which at present produce the best results for multimode optical propagation have a near parabolic refractive index profile core with α ~~2. Fibers with such core index profiles are well established and consequently when the term ‘graded index’ is used without qualification it usually refers to a fiber with this profile.

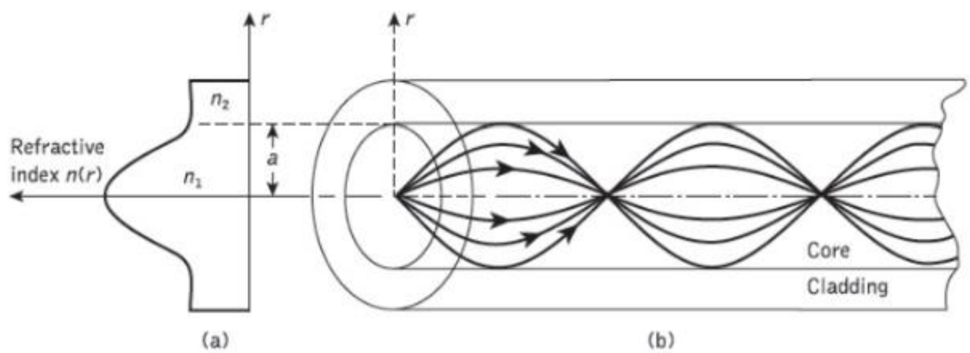


Figure 1.16 The refractive index profile and ray transmission in a multimode graded index fiber

Where r = Radial distance from fiber axis

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

a = Core radius

n_1= Refractive index of core

n_2 = Refractive index of cladding α = Shape of index profile.

Profile parameter α determines the characteristic refractive index profile of fiber core.

For this reason in this section we consider the waveguiding properties of graded index fiber with a parabolic refractive index profile core. A multimode graded index fiber with a parabolic index profile core is illustrated in Figure 1.16. It may be observed that the meridional rays shown appear to follow curved paths through the fiber core. Using the concepts of geometric optics, the gradual decrease in refractive index from the center of the core creates many refractions of the rays as they are effectively incident on a large number or high to low index interfaces. This mechanism is illustrated in Figure 1.17 where a ray is shown to be gradually curved, with an ever- increasing angle of incidence, until the conditions for total internal reflection are met, and the ray travels back towards the core axis, again being continuously refracted.

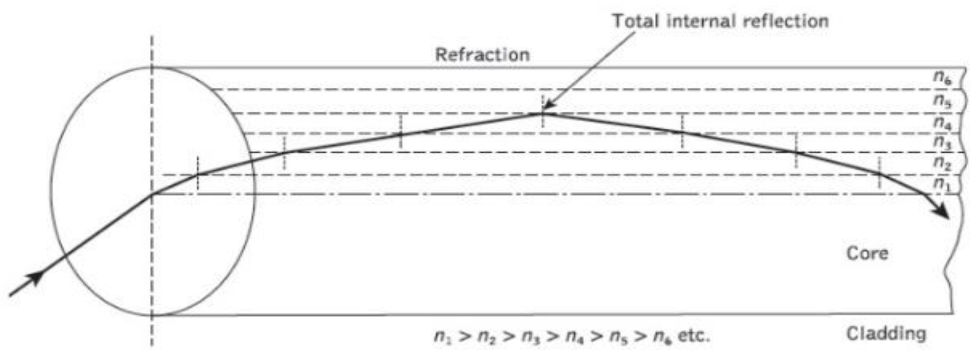


Figure 1.17 An expanded ray diagram showing refraction at the various high to low index interfaces within a graded index fiber, giving an overall curved ray path into the outer regions of the core.

Multimode graded index fibers exhibit far less intermodal dispersion than multimode step index fibers due to their refractive index profile. Although many different modes are excited in the graded index fiber, the different group velocities of the modes tend to be normalized by the index grading. Again considering ray theory, the rays traveling close to the fiber axis have shorter paths when compared with rays which travel

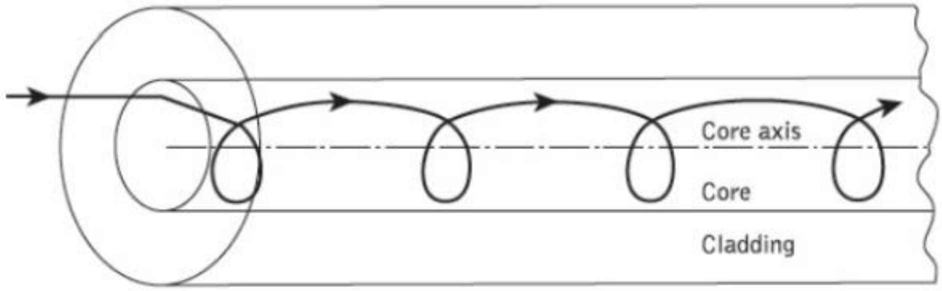


Figure 1.18 A helical skew ray path within a graded index fiber

However, the near axial rays are transmitted through a region of higher refractive index and therefore travel with a lower velocity than the more extreme rays. This compensates for the shorter path lengths and reduces dispersion in the fiber. A similar situation exists for skew rays which follow longer helical paths, as illus- trated in Figure 1.18. These travel for the most part in the lower index region at greater speeds, thus giving the same mechanism of mode transit time equalization. Hence, multi- mode graded index fibers with parabolic or near-parabolic index profile cores have trans- mission bandwidths which may be orders of magnitude greater than multimode step index fiber bandwidths. Consequently, although they are not capable of the bandwidths attain- able with single-mode fibers, such multimode graded index fibers have the advantage of large core diameters (greater than 30 μm) coupled with bandwidths suitable for long- distance communication. The parameters defined for step index fibers (i.e. NA, Δ, V) may be applied to graded index fibers and give a comparison between the two fiber types. However, it must be noted that for graded index fibers the situation is more complicated since the numerical aperture is a function of the radial distance from the fiber axis. Graded index fibers, therefore, accept less light than corresponding step index fibers with the same relative refractive index difference.

Single-mode fiber

The advantage of the propagation of a single mode within an optical fiber is that the signal dispersion caused by the delay differences between different modes in a multimode fiber may be avoided. Multimode step index fibers do not lend themselves to the propagation of a single mode due to the difficulties of maintaining single-mode operation within the fiber when mode conversion (i.e. coupling) to other guided modes takes place at both input mismatches and fiber imperfections.

Hence, for the transmission of a single mode the fiber must be designed to allow propagation of only one mode, while all other modes are attenuated by leakage or absorption. Following the preceding discussion of multimode fibers, this may be achieved through choice of a suitable normalized frequency for the fiber. For single-mode operation, only the fundamental LP01 mode can exist. Hence the limit of single-mode operation depends on the lower limit of guided propagation for the LP11 mode. The cutoff normalized frequency for the LP11 mode in step index fibers occurs at V_c = 2.405. Thus single-mode propagation of the LP01 mode in step index fibers is possible over the range:

$$0 \leq V < 2.405 \tag{1.51}$$

as there is no cutoff for the fundamental mode. It must be noted that there are in fact two modes with orthogonal polarization over this range, and the term single-mode applies to propagation of light of a particular polarization. Also, it is apparent that the normalized frequency for the fiber may be adjusted to within the range given in Eq. (1.51) by reduction of the core radius.

1. Cutoff wavelength

It may be noted that single-mode operation only occurs above a theoretical cutoff wavelength λ_c given by:

$$\lambda_c = \frac{2\pi a n_1}{V_c}(2\Delta)^{\frac{1}{2}} \tag{1.52}$$

where V_c is the cutoff normalized frequency. Hence λ_c is the wavelength above which a particular fiber becomes single-moded.

Dividing Eq. (1.52) by $V = \frac{2\pi}{\lambda} a n_1 (2\Delta)^{\frac{1}{2}}$

$$\frac{\lambda_c}{\lambda} = \frac{V}{V_c} \tag{1.53}$$

Thus for step index fiber where V_c = 2.405, the cutoff wavelength is given by:

$$\lambda_c = \frac{V\lambda}{2.405} \tag{1.54}$$

An effective cutoff wavelength has been defined by the ITU-T which is obtained from a 2 m length of fiber containing a single 14 cm radius loop. This definition was produced because the first higher order LP11 mode is strongly affected by fiber length and curvature near cutoff. Recommended cutoff wavelength values for primary coated fiber range from 1.1 to 1.28 μm for single-mode fiber designed for operation in the 1.3μm wavelength region in order to avoid modal noise and dispersion problems. Moreover, practical transmission systems are generally operated close to the effective cutoff wavelength in order to enhance the fundamental mode confinement, but sufficiently distant from cutoff so that no power is transmitted in the second-order LP11 mode.

2. Mode-field diameter and spot size

Many properties of the fundamental mode are determined by the radial extent of its electromagnetic field including losses at launching and jointing, micro bend losses, waveguide dispersion and the width of the radiation pattern. Therefore, the MFD is an important parameter for characterizing single-mode fiber properties which takes into account the wavelength-dependent field penetration into the fiber cladding. In this context it is a better measure of the functional properties of single-mode fiber than the core diameter. For step index and graded (near parabolic profile) single-mode fibers operating near the cutoff wavelength λc, the field is well approximated by a Gaussian distribution. In this case the MFD is generally taken as the distance between the opposite 1/e = 0.37 field amplitude points and the power 1/e2 = 0.135 points in relation to the corresponding values on the fiber axis.

Another parameter which is directly related to the MFD of a single-mode fiber is the spot size (or mode-field radius) ω0. Hence MFD = 2ω0, where ω0is the nominal half width of the input excitation.

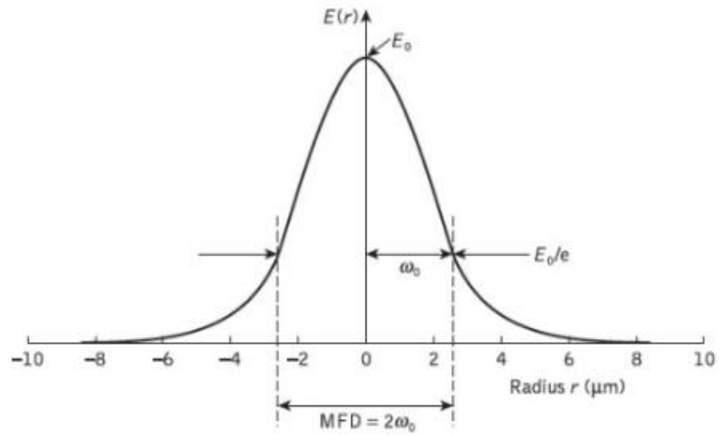


Figure 1.19 Field amplitude distribution $E(r)$ of the fundamental mode in a single-mode fiber illustrating the mode-field diameter (MFD) and spot size (ω□)

The MFD can therefore be regarded as the single- mode analog of the fiber core diameter in multimode fibers. However, for many refractive index profiles and at typical operating wavelengths the MFD is slightly larger than the single-mode fiber core diameter.

Often, for real fibers and those with arbitrary refractive index profiles, the radial field distribution is not strictly Gaussian and hence alternative techniques have been proposed. However, the problem of defining the MFD and spot size for non-Gaussian field dis- tributions is a difficult one and at least eight definitions exist.

3. Effective refractive index

The rate of change of phase of the fundamental LP01 mode propagating along a straight fiber is determined by the phase propagation constant . It is directly related to the wavelength of the LP01 mode λ01 by the factor 2π, since β gives the increase in phase angle per unit length. Hence:

$$\beta\lambda_{01} = 2\pi \quad \text{or} \quad \lambda_{01} = \frac{2\pi}{\beta} \tag{1.55}$$

Moreover, it is convenient to define an effective refractive index for single-mode fiber, sometimes referred to as a phase index or normalized phase change coefficient n_{eff}, by the ratio of the propagation constant of the fundamental mode to that of the vacuum propagation constant:

$$n_{\text{eff}} = \frac{\beta}{k} \tag{1.56}$$

Hence, the wavelength of the fundamental mode λ_{01} is smaller than the vacuum wave-length λ by the factor $1/n_{\text{eff}}$ where:

$$\lambda_{01} = \frac{\lambda}{n_{\text{eff}}} \tag{1.57}$$

It should be noted that the fundamental mode propagates in a medium with a refractive index $n(r)$ which is dependent on the distance r from the fiber axis. The effective refractive index cantherefore be considered as an average over the refractive index of this medium.

Within a normally clad fiber, not depressed-cladded fibers, at long wavelengths (i.e. small V values) the MFD is large compared to the core diameter and hence the electric field extends far into the cladding region. In this case the propagation constant β will be approximately equal to $n2k$ (i.e. the cladding wave number) and the effective index will be similar to the refractive index of the cladding $n2$. Physically, most of the power is transmitted in the cladding material.

At short wavelengths, however, the field is concentrated in the core region and the propagation constant β approximates to the maximum wave number nlk. Following this discussion, and as indicated previously, then the propagation constant in single-mode fiber varies over the interval $n2k < \beta < n1k$. Hence, the effective refractive index will vary over the range $n2 < n\text{eff} < n1$.

4. Group delay and mode delay factor

The transit time or group delay τg for a light pulse propagating along a unit length of fiber is the inverse of the group velocity υg . Hence:

$$\tau_g = \frac{1}{\upsilon_g} = \frac{d\beta}{d\omega} = \frac{1}{c}\frac{d\beta}{dk} \tag{1.61}$$

The group index of a uniform plane wave propagating in a homogeneous medium has been determined as:

$$N_g = \frac{c}{\upsilon_g}$$

However, for a single-mode fiber, it is usual to define an effective group index* N_{ge} By:

$$N_{ge} = \frac{c}{\upsilon_g} \tag{1.62}$$

Where υg is considered to be the group velocity of the fundamental fiber mode. Hence, the specific group delay of the fundamental fiber mode becomes:

$$\tau_g = \frac{N_{ge}}{c} \tag{1.63}$$

Fiber materials

Most of the fibers are made up of glass consisting of either Silica (SiO_2) or .Silicate. High- loss glass fibers are used for short-transmission distances and low-loss glass fibers are used for long distance applications. Plastic fibers are less used because of their higher attenuation than glass fibers. Glass Fibers.

The glass fibers are made from oxides. The most common oxide is silica whose refractive index is 1.458_at 850 nm. To get different index fibers, the dopants such as GeO_2, P_2O_5 are added to silica. GeO_2 and P_2O_3 increase the refractive index whereas fluorine or B_20_3 decreases the refractive index.

Few fiber compositions are given below as follows,

(i) $GeO_2 - SiO_2$ Core: SiO_2 Cladding

(ii) $P_2Q_5 - SiO_2$, Core; SiO_2 Cladding

The principle raw material for silica is sand. The glass composed of pure silica is referred to as silica glass, nitrous silica or fused silica. Some desirable properties of silica are,

(i) Resistance to deformation at temperature as high as 1000°C.

(ii) High resistance to breakage from thermal shock.

(iii) Good chemical durability.

(iv) High transparency in both the visible and infrared regions.

Basic Requirements and Considerations in Fiber Fabrication

(i) Optical fibers should have maximum reproducibility.

(ii) Fibers should be fabricated with good stable transmission characteristics i.e., the fiber should have invariable transmission characteristics in long lengths.

(iii) Different size, refractive index and refractive index profile, operating wavelengths material. Fiber must be available to meet different system applications.

(iv) The fibers must be flexible to convert into practical cables without any degradation of their characteristics.

(v) Fibers must be fabricated in such a way that a joining (splicing) of the fiber should not affect its transmission characteristics and the fibers may be terminated or connected together with less practical difficulties.

Fiber Fabrication in a Two Stage Process

(i) Initially glass is produced and then converted into perform or rod.

Glass fiber is a mixture of selenides, sulfides and metal oxides. It can be classified into,

1. Halide Glass Fibers
2. Active Glass Fibers
3. Chalgenide Glass Fibers.

Glass is made of pure SiO_2 which refractive index 1.458 at 850 nm. The refractive index of SiO_2 can be increased (or) decreased by adding various oxides are known as dopant. The oxides GeO2 or P2O3 increases the refractive index and B_2O_3 decreases the refractive index of SiO_2 .

The various combinations are,

(i) GeO_2 SiO_2 Core; SiO_2 cladding

(ii) P_2O_3 – SiO_2 Core; SiO_2 cladding

(iii) SiO_2 Core; B_2O_3, - SiO_2 cladding

(iv) GeO_2- B_2O_3- SiO_2, Core; B_2O_3 - SiO_2 cladding.

From above, the refractive index of core is maximum compared to the cladding.

(1) Halide Glass Fibers

A halide glass fiber contains fluorine, chlorine, bromine and iodine. The most common Halide glass fiber is heavy "metal fluoride glass". It uses ZrF_4 as a major component. This fluoride glass is known by the name ZBLAN Since it is constituents are ZrF_4, BaF_2, LaF_3 $A1F_3$, and NaF.

The percentages of these elements to form ZBLAN fluoride glass is shown as follows,

Materials	Molecular percentage
ZrF_4	54%
BaF_2	20%
LaF_3	4.5%
$A1F_3$	3.5%
NaF	18%

These materials add up to make the core of a glass fiber. By replacing ZrF_4 by HaF_4, the lower refractive index glass is obtained.

The intrinsic losses of these glasses is 0.01 to 0.001 dB/km

(2) Active Glass Fibers

Active glass fibers are formed by adding erbium and neodymium to the glass fibers. The above material performs amplification and attenuation

(3) Chalgenide Glass Fibers

Chalgenide glass fibers are discovered in order to make use of the nonlinear properties of glass fibers. It contains either "S", "Se" or "Te", because they are highly nonlinear and it also contains one element from “Cl”, "Br”, “Cd”,”Ba” or”Si”.The mostly used chalgenide glass is AS_2-S_3, $AS_{40}S_{58}Se_2$ is used to make the core and AS_2S_3 is used to make the cladding material of the glass fiber. The insertion loss is around 1 dB/m.

Plastic Optical Fibers

Plastic optical fibers are the fibers which are made up of plastic material. The core of this fiber is made up of Polymethylmethacrylate (PMMA) or Perflourmated Polymer (PFP).Plastic optical fibers offer more attenuation than glass fiber and is used for short distance applications.

These fibers are tough and durable due to the presence of plastic **material**. The modulus of this plastic material is two orders **of** magnitude lower than that of silica and even a 1 mm diameter graded index plastic optical fiber can be installed **in** conventional fiber cable routes. The diameter of the core of these fibers is 10-20 times larger than that of glass fiber which reduces the connector losses without sacrificing coupling efficiencies. So we can use inexpensive connectors, splices and transceivers made up of plastic injection-molding technology. Graded index plastic optical fiber is in great demand in customer premises to deliver high-speed services due to its high bandwidth.

UNIT-II

SIGNAL DISTORTION IN OPTICAL FIBERS

Introduction

One of the important property 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. Another important property of optical fiber is distortion mechanism. As the signal pulse travels along the fiber length it becomes more broader. 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.

Attenuation

- Attenuation is a measure of decay of signal strength or loss of light power that occurs as light pulses propagate through the length of the fiber.
- In optical fibers the attenuation is mainly caused by two physical factors absorption and scattering losses. Absorption is because of fiber material and scattering due to structural imperfection within the fiber. Nearly 90 % of total attenuation is caused by Rayleigh scattering only. Microbending of optical fiber also contributes to the attenuation of signal.
- The rate at which light is absorbed is dependent on the wavelength of the light and the characteristics of particular glass. Glass is a silicon compound, by adding different additional chemicals to the basic silicon dioxide the optical properties of the glass can be changed.
- The Rayleigh scattering is wavelength dependent and reduces rapidly as the wavelength of the incident radiation increases.

- The attenuation of fiber is governed by the materials from which it is fabricated, the manufacturing process and the refractive index profile chosen. Attenuation loss is measured in dB/km.

Attenuation Units

As attenuation leads to a loss of power along the fiber, the output power is significantly less than the couples power. Let the couples optical power is p(0) i.e. at origin (z = 0).

Then the power at distance z is given by,

$$P(z) = P(0)e^{-\alpha_p z} \qquad \text{... (2.1.1)}$$

where, α_p is fiber attenuation constant (per km).

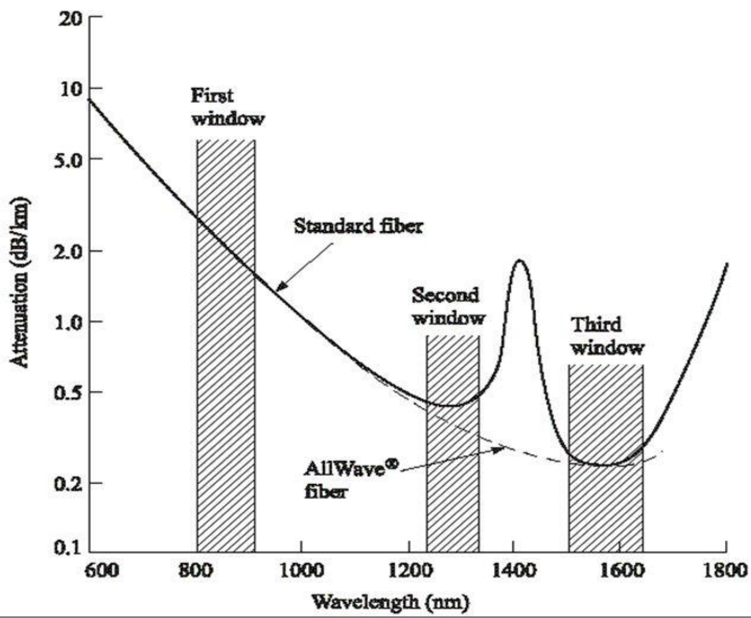
$$\alpha_p = \frac{1}{z} \ln \left[\frac{P(0)}{P(z)}\right]$$

$$\boxed{\alpha_{dB/km} = 10 . \frac{1}{z} \log \left[\frac{P(0)}{P(z)}\right]}$$

$$\alpha_{dB/km} = 4.343 \ \alpha_p \ \text{per km}$$

This parameter is known as fiber loss or fiber attenuation.

- Attenuation is also a function of wavelength. Optical fiber wavelength as a function of wavelength is shown in Fig. 2.1.1.



Optical fiber attenuation as a function of wavelength yields nominal values of 0.5 dB/km at 1310 nm and 0.3 dB/km at 1550 nm for standard single mode fiber. Absorption by the water molecules causes the attenuation peak around 1400nm for standard fiber. The dashed curve is the attenuation for low water peak fiber. Irfan khan

Fig 2.1.1: Optical fiber wavelength as a function of wavelength

Example 2.1.1 : A low loss fiber has average loss of 3 dB/km at 900 nm. Compute the length over which –

a) Power decreases by 50 % b) Power decreases by 75 %.

Solution : $\alpha = 3$ dB/km

$$\Rightarrow \qquad \frac{p(0)}{p(z)} = 50\ \% = 0.5$$

a) Power decreases by 50 %.

□ is given by,

$$\left[\frac{200\ \mu W}{P(z)}\right] = 10^{2.4}$$

$$3 = 10 \cdot \frac{1}{z} \log [0.5]$$

z = **1 km… Ans.**

b) $\frac{P(0)}{P(z)} = 25\ \% = 0.25$ Since power decrease by 75

%.

$$3 = 10 \text{ x } \frac{1}{z} \log[0.25]$$

z = **2 km… Ans.**

Example 2.1.2 : For a 30 km long fiber attenuation 0.8 dB/km at 1300nm. If a 200 µwatt power is launched into the fiber, find the output power.

Solution : z = 30 km

 = 0.8 dB/km

P(0) = 200

µW

Attenuation in optical fiber is given by,

$$0.8 = 10 \text{ x } \frac{1}{30} \log \left[\frac{200\ \mu W}{P(z)}\right]$$

$$2.4 = 10 \text{ x } \log \left[\frac{200\ \mu W}{P(z)}\right]$$

Example 2.1.3 : When mean optical power launched into an 8 km length of fiber is 12 µW, the mean optical power at the fiber output is 3 µW.

Determine –

Overall signal attenuation in dB.

The overall signal attenuation for a 10 km optical link using the same fiber with splices at 1 km intervals, each giving an attenuation of 1 dB.

Solution: Given : $z = 8$ km

$P(0) = 120\ \mu W$

$P(z) = 3\ \mu W$

1) Overall attenuation is given by,

$$\alpha = 10 \,.\log\left[\frac{P(0)}{P(z)}\right]$$

$$\alpha = 10 \,.\log\left[\frac{120}{3}\right]$$

$$\alpha = 16.02 \text{ dB}$$

2) Overall attenuation for 10 km,

Attenuation per km

$\propto_{dB} = \frac{16.02}{z} = \frac{16.02}{8} = 2.00 \text{ dB/km}$ Attenuation in 10 km link = 2.00 x 10 = 20 dB

In 10 km link there will be 9 splices at 1 km interval. Each splice introducing attenuation of 1 dB.

Total attenuation = 20 dB + 9 dB = **29 dB**

Example 2.1.4 : A continuous 12 km long optical fiber link has a loss of 1.5 dB/km.

- What is the minimum optical power level that must be launched into the fiber to maintain as optical power level of 0.3 μW at the receiving end?
- What is the required input power if the fiber has a loss of 2.5 dB/km?

Solution : Given data : z = 12 km

= 1.5 dB/km

P(0) = 0.3 μW

- Attenuation in optical fiber is given by,

$$\alpha = 10 \text{ x } \frac{1}{z} \log\left(\frac{P(0)}{P(z)}\right)$$

$$1.5 = 10 \text{ x } \frac{1}{12} \log\left(\frac{0.3\ \mu W}{P(z)}\right)$$

$$\log\left(\frac{0.3\ \mu W}{P(z)}\right) = \frac{1.5}{0.833}$$

= 1.80

$$\left(\frac{0.3\ \mu W}{P(z)}\right) = 10^{1.8}$$

$$P(z) = \left(\frac{0.3\ \mu W}{10^{1.8}}\right) = \frac{0.3}{63.0}$$

$$P(z) = 4.76 \times 10^{-9} W$$

Optical power output = **4.76×10^{-9} W** **... Ans.**

ii) Input power = ? P(0)

When $\alpha = 2.5$ dB/km

$$\boxed{\alpha = 10 \times \frac{1}{z} \log\left(\frac{P(0)}{P(z)}\right)}$$

$$2.5 = 10 \times \frac{1}{z} \log\left(\frac{P(0)}{4.76 \times 10^{-9}}\right)$$

$$\log\left(\frac{P(0)}{4.76 \times 10^{-9}}\right) = \frac{2.5}{0.833} = 3$$

$$\frac{P(0)}{4.76 \times 10^{-9}} = 10^3 = 1000$$

P(0) = 4.76 µW

Input power= **4.76 µW** **... Ans.**

Example 2.1.5 : Optical power launched into fiber at transmitter end is 150 µW. The power at the end of 10 km length of the link working in first windows is – 38.2 dBm. Another system of same length working in second window is 47.5 µW. Same length system working in third window has 50 % launched power. Calculate fiber attenuation for each case and mention wavelength of operation. **[Jan./Feb.-2009, 4 Marks]**

Solution : Given data:

$P(0) = 150\ \mu W$

$z = 10\ km$

$$P(z) = -38.2\ \text{dBm} \Rightarrow \begin{cases} -38.2 = 10 \log \dfrac{P(z)}{1\ \text{mW}} \\ P(z) = 0.151\ \mu W \end{cases}$$

$z = 10\ km$

$$\boxed{\alpha = 10 \text{ x } \frac{1}{z} \log \left[\frac{P(0)}{P(z)}\right]}$$

Attenuation in 1st window:

$$\alpha_1 = 10 \text{ x } \frac{1}{10} \log \left[\frac{150}{0.151}\right]$$

$$\propto_1 = \mathbf{2.99\ dB/km}$$

Attenuation in 2nd window:

$$\propto_2 = 10\ \text{x}\ \frac{1}{10}\log\left[\frac{150}{47.5}\right]$$

$$\propto_2 = \mathbf{0.49\ dB/km}$$

Attenuation in 3rd window:

$$\propto_3 = 10\ \text{x}\ \frac{1}{10}\log\left[\frac{150}{75}\right]$$

$$\propto_3 = \mathbf{0.30\ dB/km}$$

Wavelength in 1st window is 850 nm.

Wavelength in 2nd window is 1300 nm.

Wavelength in 3rd window is 1550 nm.

Example 2.1.6 : The input power to an optical fiber is 2 mW while the power measured at the output end is 2 µW. If the fiber attenuation is 0.5 dB/km, calculate the length of the fiber.

Solution: Given : P(0) = 2 mwatt = 2 x 10^{-3} watt

P(z) = 2 µwatt = 2 x 10^{-6} watt

α = 0.5 dB/km

$$\boxed{\alpha = 10 \text{ x } \frac{1}{z}\left[\frac{P(0)}{P(z)}\right]}$$

$$z = 60 \text{ km}$$ ... **Ans.**

$$0.5 = 10 \text{ x } \frac{1}{z}\log\left[\frac{2 \text{ x } 10^{-3}}{2 \text{ x } 10^{-6}}\right]$$

$$0.5 = \frac{1}{z} \text{x} \, 3$$

$$z = \frac{3}{0.05}$$

Absorption

- Absorption loss is related to the material composition and fabrication process of fiber. Absorption loss results in dissipation of some optical power as hear in the fiber cable. Although glass fibers are extremely pure, some impurities still remain as residue after purification. The amount of absorption by these impurities depends on their concentration and light wavelength.

Absorption in optical fiber is caused by these three mechanisms.

1. Absorption by atomic defects in the glass composition
2. Extrinsic absorption by impurity atoms in the glass material
3. Intrinsic absorption by the basic constituent atoms of the fiber material.

Absorption by Atomic Defects

Atomic defects are imperfections in the atomic structure of the fiber materials such as missing molecules, high density clusters of atom groups. These absorption losses are negligible compared with intrinsic and extrinsic losses.

- The absorption effect is most significant when fiber is exposed to ionizing radiation in nuclear reactor, medical therapies, space missions etc. The radiation dames the internal structure of fiber. The damages are proportional to the intensity of ionizing particles. This results in increasing attenuation due to atomic defects and absorbing optical energy. The total dose a material receives is expressed in rad (Si), this is the unit for measuring radiation absorbed in bulk silicon.

$$1 \text{ rad (Si)} = 0.01 \text{ J.kg}$$

The higher the radiation intensity more the attenuation as shown in Fig 2.2.1.

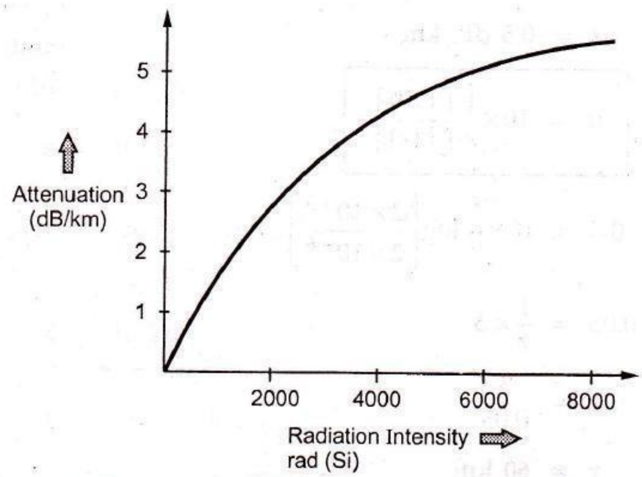


Fig. 2.2.1 Ionizing radiation intensity Vs fiber attenuation

Extrinsic Absorption

Extrinsic absorption occurs due to electronic transitions between the energy level and because of charge transitions from one ion to another. A major source of attenuation is from transition of metal impurity ions such as iron, chromium, cobalt and copper. These losses can be upto 1 to 10 dB/km. The effect of metallic impurities can be reduced by glass refining techniques.

- Another major extrinsic loss is caused by absorption due to **OH (Hydroxil)** ions impurities dissolved in glass. Vibrations occur at wavelengths between 2.7 and 4.2 μm.

  The absorption peaks occurs at 1400, 950 and 750 nm. These are first, second and third overtones respectively.

- Fig. 2.2.2 shows absorption spectrum for OH group in silica. Between these absorption peaks there are regions of low attenuation.

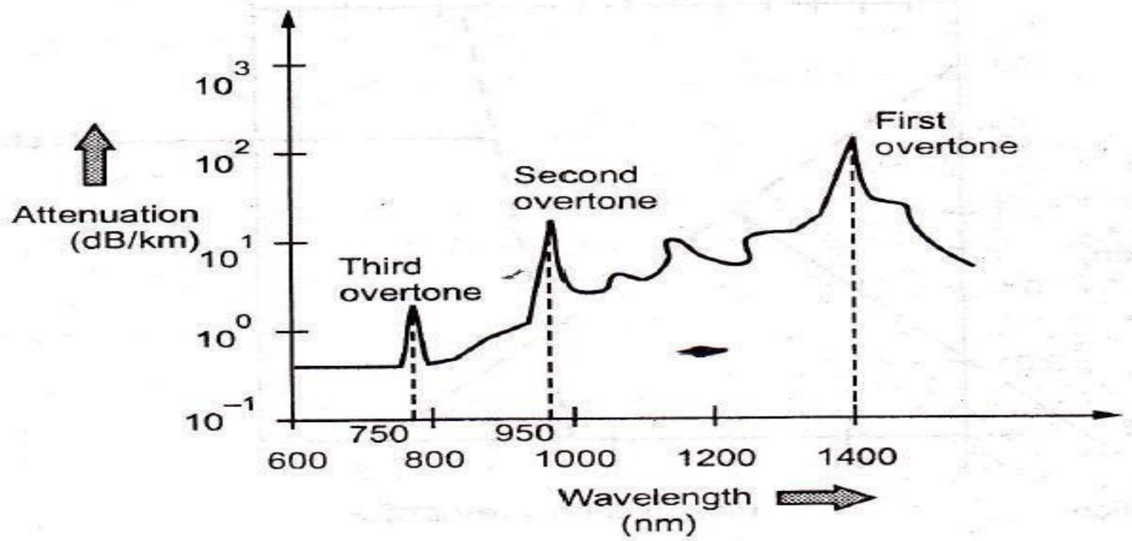


Fig. 2.2.2 Absorption spectra for OH group

Intrinsic Absorption

Intrinsic absorption occurs when material is in absolutely pure state, no density variation and inhomogenities. Thus intrinsic absorption sets the fundamental lower limit on absorption for any particular material.

- Intrinsic absorption results from electronic absorption bands in UV region and from atomic vibration bands in the near infrared region.
- The electronic absorption bands are associated with the band gaps of amorphous glass materials. Absorption occurs when a photon interacts with an electron in the valene band and excites it to a higher energy level. UV absorption decays exponentially with increasing wavelength (λ).

- In the IR (infrared) region above 1.2 µm the optical waveguide loss is determined by presence of the OH ions and inherent IR absorption of the constituent materials. The inherent IR absorption is due to interaction between the vibrating band and the electromagnetic field of optical signal this results in transfer of energy from field to the band, thereby giving rise to absorption, this absorption is strong because of many bonds present in the fiber.

The ultraviolet loss at any wavelength is expressed as,

$$\propto_{uv} = \frac{154.2}{46.6\,x + 60} \times 10^{-2} \times e^{\left(\frac{4.63}{\lambda}\right)} \qquad \text{... (2.2.1)}$$

where, x is mole fraction of GeO_2.

λ is operating wavelength.

α_{uv} is in dB/km.

□□ The loss in infrared (IR) region (above 1.2 µm) is given by expression :

$$\propto_{IR} = 7.81 \times 10^{11} \times e^{\left(\frac{-48.48}{\lambda}\right)} \qquad \text{... (2.2.2)}$$

The expression is derived for GeO_2-SiO_2 glass fiber.

Rayleigh Scattering Losses

Scattering losses exists in optical fibers because of microscopic variations in the material density and composition. As glass is composed by randomly connected network of molecules and several oxides (e.g. SiO_2, GeO_2 and P_2O_5), these are the major cause of compositional structure fluctuation. These two effects results to variation in refractive index and Rayleigh type scattering of light.

Rayleigh scattering of light is due to small localized changes in the refractive index of the core and cladding material.

There are two causes during the manufacturing of fiber.

1. The first is due to slight fluctuation in mixing of ingredients. The random changes because of this are impossible to eliminate completely.

2. The other cause is slight change in density as the silica cools and solidifies. When light ray strikes such zones it gets scattered in all directions. The amount of scatter depends on the size of the discontinuity compared with the wavelength of the light so the shortest wavelength (highest frequency) suffers most scattering.

Fig. 2.3.1 shows graphically the relationship between wavelength and Rayleigh scattering loss.

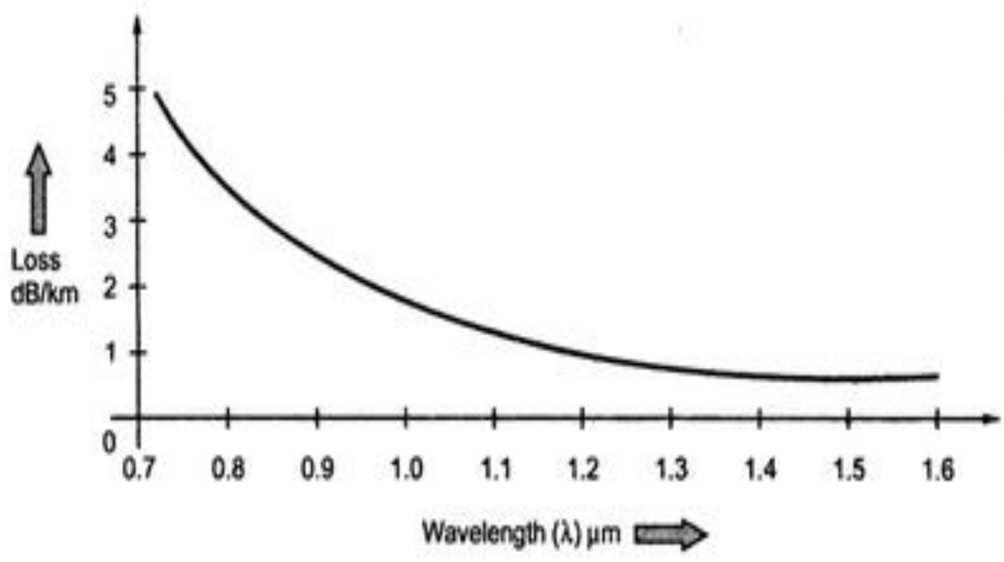


Fig. 1 Scattering loss

Scattering loss for single component glass is given by,

(2.3.1) $$\propto_{scat} = \frac{8\pi^3}{3\lambda^4} (n^2 - 1)^2 k_B T_f \beta_T \text{ nepers}$$

where, n = Refractive index

k_B = Boltzmann's constant

β_T = Isothermal compressibility of material

T_f = Temperature at which density fluctuations are frozen into the glass as it solidifies (fictive temperature)

Another form of equation is

$$\propto_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 k_B T_f \beta_T \text{ neper} \propto_{scat} = \frac{8\pi^3}{3\lambda^4} (\delta_n^2)^2 \delta v$$

... (2.3.2)

where, P = Photoelastic coefficient

where, δ_n^2 = Mean square refractive index fluctuation

δv = Volume of fiber

- Multimode fibers have higher dopant concentrations and greater compositional fluctuations. The overall losses in this fibers are more as compared to single mode fibers.

Mie Scattering :

- Linear scattering also occurs at inhomogenities and these arise from imperfections in the fiber's geometry, irregularities in the refractive index and the presence of bubbles etc. caused during manufacture. Careful control of manufacturing process can reduce Mie scattering to insignificant levels.

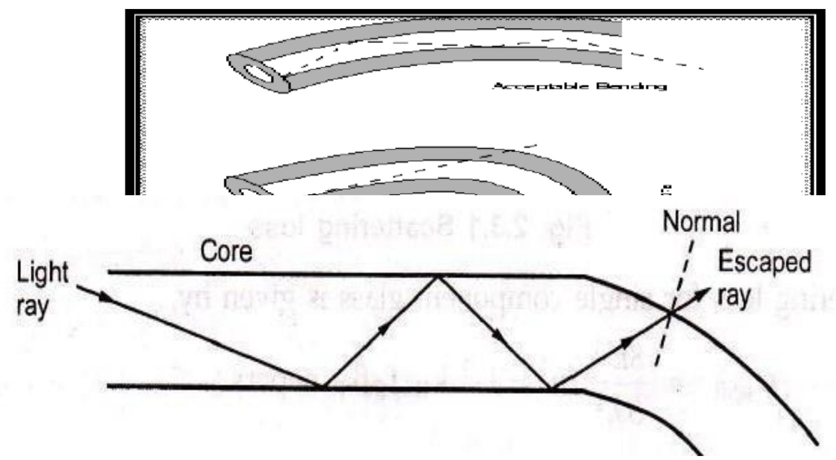
Bending Loss

Radiative losses occur whenever an optical fiber undergoes a bend of finite radius of curvature. Fibers can be subjected to two types of bends: a)Macroscopic bends (having radii that are large as compared with the fiber diameter)

b) Random microscopic bends of fiber axis

Losses due to curvature and losses caused by an abrupt change in radius of curvature are referred to as 'bending losses.'

- The sharp bend of a fiber causes significant radiative losses and there is also possibility of mechanical failure. This is shown in Fig. 2.4.1.



As the core bends the normal will follow it and the ray will now find itself on the wrong side of critical angle and will escape. The sharp bends are therefore avoided.

The radiation loss from a bent fiber depends on –Field strength of certain critical distance x_c from fiber axis where power is lost through radiation.

The radius of curvature R.

The higher order modes are less tightly bound to the fiber core, the higher order modes radiate out of fiber firstly.

For multimode fiber, the effective number of modes that can be guided by curved fiber is where, α is graded index profile.

□ is core – cladding index difference.

n_2 is refractive index of cladding.k is

wave propagation constant $\left(\frac{2\pi}{\lambda}\right)$.

N_∞ is total number of modes in a straight fiber.

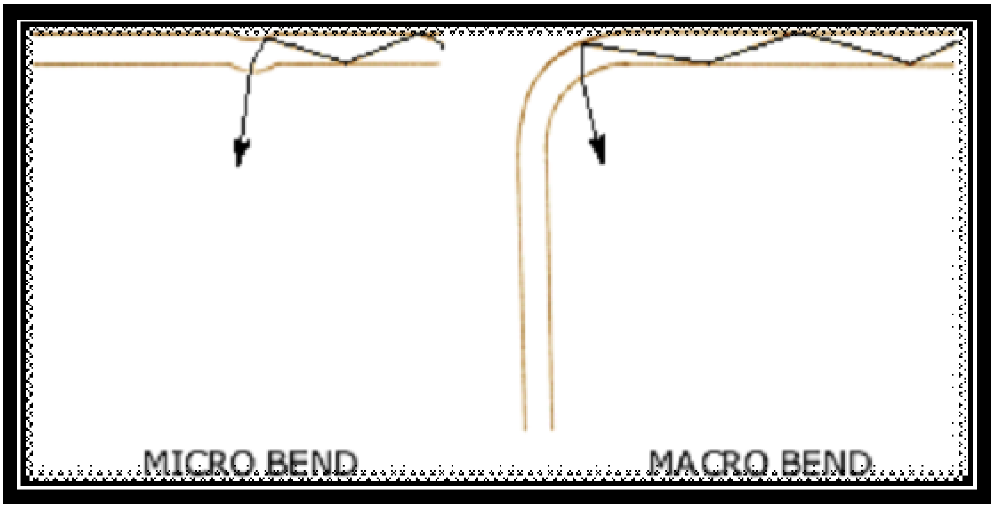
$$N_\infty = \frac{\alpha}{\alpha+2}(n_1\, k\, a)^2 \Delta \qquad \text{... (2.4.2)}$$

Microbending

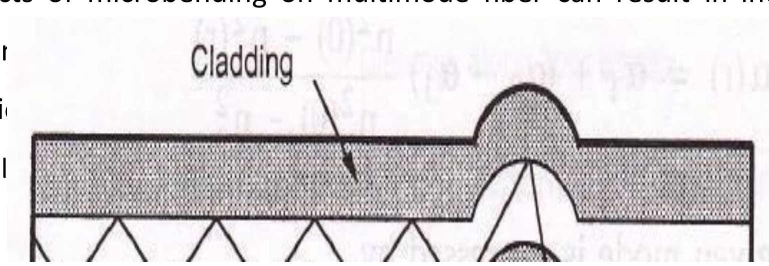
Micro bending Loss

Another form of radiation loss in optical waveguide results from mode coupling caused by random micro bends of the optical fiber. Micro bends are repetitive small scale fluctuations in the radius of curvature of the fiber axis. They are caused either by non uniformities in the manufacturing of the fiber or by non uniform lateral pressures created during the cabling of the fiber. An increase in attenuation results from micro bending because the fiber curvature causes repetitive coupling of energy between the guided modes and the leaky or non guided modes in the fiber.

Micro bending losses can be minimized by placing a compressible jacket over the fiber. When external forces are applied to this configuration, the jacket will be deformed but the fiber will tend to stay relatively straight.



- Microbending is a loss due to small bending or distortions. This small microbending is not visible. The losses due to this are temperature related, tensile related or crush related.
- The effects of microbending on multimode fiber can result in increasing attenuation (dependi ghs on the spectral attenuati llation and testing. Fig.2.4.2 il



Macrobending

For slight bends, the loss is extremely small and is not observed. As the radius of curvature decreases, the loss increases exponentially until at a certain critical radius of curvature loss becomes observable. If the bend radius is made a bit smaller once this threshold point has been reached, the losses suddenly become extremely large. It is known that any bound core mode has an evanescent field tail in the cladding which decays exponentially as a function of distance from the core. Since this field tail moves along with the field in the core, part of the energy of a propagating mode travels in the fiber cladding. When a fiber is bent, the field tail on the far side of the centre of curvature must move faster to keep up with the field in the core, for the lowest order fiber mode. At a certain critical distance $x_{c,}$ from the centre of the fiber; the field tail would have to move faster than the speed of light to keep up with the core field. Since this is not possible the optical energy in the field tail beyond x_c radiates away.
The amount of optical radiation from a bent fiber depends on the field strength at x_c and on the radius of curvature R. Since higher order modes are bound less tightly to the fiber core than lower order modes, the higher order modes will radiate out of the fiber first.

- The change in spectral attenuation caused by macrobending is different to microbending. Usually there are no peaks and troughs because in a macrobending no light is coupled back into the core from the cladding as can happen in the case of microbends.

- The macrobending losses are cause by large scale bending of fiber. The losses are eliminated when the bends are straightened. The losses can be minimized by not exceeding the long term bend radii. Fig. 2.4.3 illustrates macrobending.

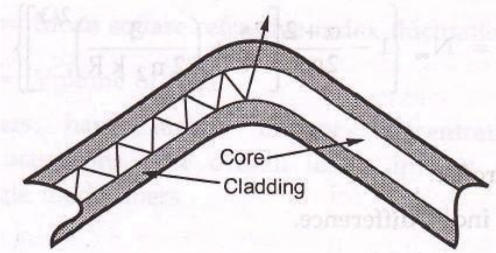
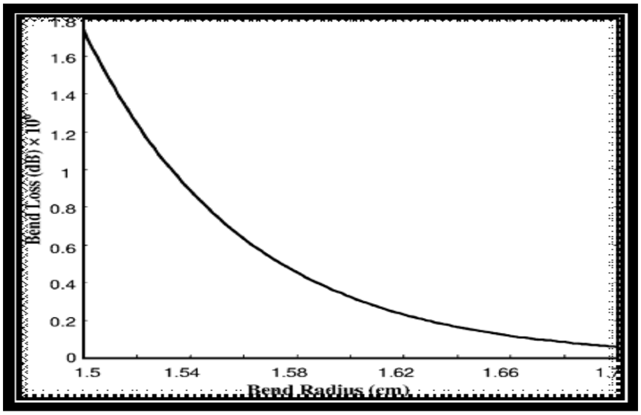


Fig. 2.4.3 Macrobending



Macro bending Loss

Core and Cladding Loss

- Since the core and cladding have different indices of refraction hence they have different attenuation coefficients α_1 and α_2 respectively.

$$\propto(r) = \propto_1 + (\propto_2 - \propto_1)\frac{n^2(0) - n^1(r)}{n^2(0) - n_2^2}$$

- For step index fiber, the loss for a mode order (v, m) is given by,

$$\propto_{vm} = \propto_1 \frac{P_{core}}{P} + \propto_2 \frac{P_{cladding}}{P} \quad \ldots$$

(2.5.1)

For low-order modes, the expression reduced to

$$\propto_{vm} = \propto_1 + (\propto_2 + \propto_1)\frac{P_{cladding}}{P} \quad \ldots$$

(2.5.2)

where, $\frac{P_{core}}{P}$ and $\frac{P_{cladding}}{P}$ are fractional powers.

- For graded index fiber, loss at radial distance is expressed as,

… (2.5.3)

The loss for a given mode is expressed by,

$$\propto_{Graded\ Index} = \frac{\int_0^{\infty} \propto(r)\, P(r)\, r\, dr}{\int_0^{\infty} P(r)\, r\, dr} \quad \ldots$$

(2.5.4)

where, P(r) is power density of that model at radial distance r.

Signal Distortion in Optical Waveguide

- The pulse gets distorted as it travels along the fiber lengths. Pulse spreading in fiber is referred as dispersion. Dispersion is caused by difference in the propagation times of light rays that takes different paths during the propagation. The light pulses travelling down the fiber encounter dispersion effect because of this the pulse spreads out in time domain. Dispersion limits the information bandwidth. The distortion effects can be analyzed by studying the group velocities in guided modes.

Information Capacity Determination

- Dispersion and attenuation of pulse travelling along the fiber is shown in Fig. 2.6.1.

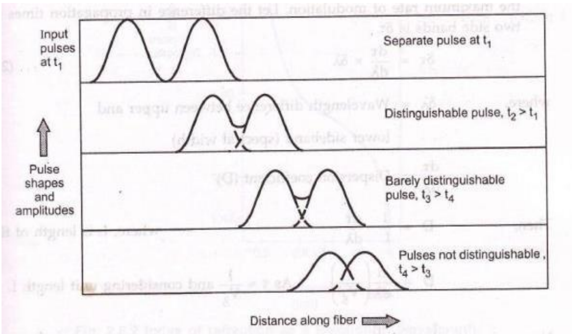


Fig. 2.6.1 Dispersion and attenuation in fiber

- Fig. 2.6.1 shows, after travelling some distance, pulse starts broadening and overlap with the neighbouring pulses. At certain distance the pulses are not even distinguishable and error will occur at receiver. Therefore the information capacity is specified by bandwidth- distance product (MHz . km). For step index bandwidth distance product is 20 MHz . km and for graded index it is 2.5 MHz . km.

Group Delay

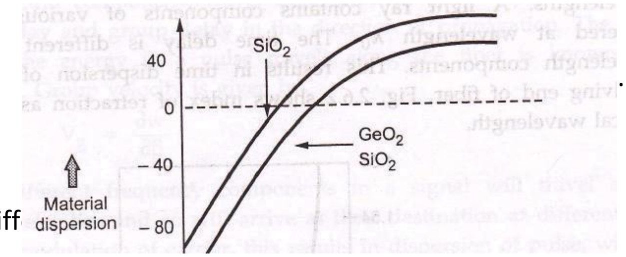
- Consider a fiber cable carrying optical signal equally with various modes and each mode contains all the spectral components in the wavelength band. All the spectral components travel independently and they observe different **time delay** and **group delay** in the direction of propagation. The velocity at which the energy in a pulse travels along the fiber is known as **group velocity**. Group velocity is given by,

$$V_g = \frac{\partial w}{\partial \beta} \quad \text{... (2.6.1)}$$

- Thus different frequency components in a signal will travel at different group velocities and so will arrive at their destination at different times, for digital modulation of carrier, this results in dispersion of pulse, which affects the maximum rate of modulation. Let the difference in propagation times for two side bands is $\delta\tau$.

$$\delta\tau = \frac{d\tau}{d\lambda}\ x\ \delta\lambda$$

(2.6.2)



where, $\delta\tau$ = Wavelength diff

(spectral width) $\frac{d\tau}{d\lambda}$ = Dispersion coefficient (D)

Then, $D = \frac{1}{L}.\frac{d\tau}{d\lambda}$ where, L is length of fiber.

$$D = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right)$$

As $\tau = \frac{1}{V_g}$ and considering unit length L = 1.

Now $\frac{1}{V_g} = \frac{d\beta}{d\omega}$

$$\frac{1}{V_g} = \frac{d\lambda}{d\omega} x \frac{d\beta}{d\lambda}$$

$$\frac{1}{V_g} = \frac{-\lambda^2}{2\pi c} x \frac{d\beta}{d\lambda}$$

$$D = \frac{d}{d\lambda}\left(\frac{-\lambda^2}{2\pi\ c}.\frac{d\beta}{d\lambda}\right)$$

- Dispersion is measured in picoseconds per nanometer per kilometer.

Material Dispersion

Material dispersion is also called as chromatic dispersion. Material dispersion exists due to change in index of refraction for different wavelengths. A light ray contains components of various wavelengths centered at wavelength λ10. The time delay is different for different wavelength components. This results in time dispersion of pulse at the receiving end of fiber. Fig. 2.6.2 shows index of refraction as a function of optical wavelength.

The material dispersion for unit length (L = 1) is given by

$$\boxed{D_{mat} = \frac{-\lambda}{c} x \frac{d^2 n}{d\lambda^2}}$$

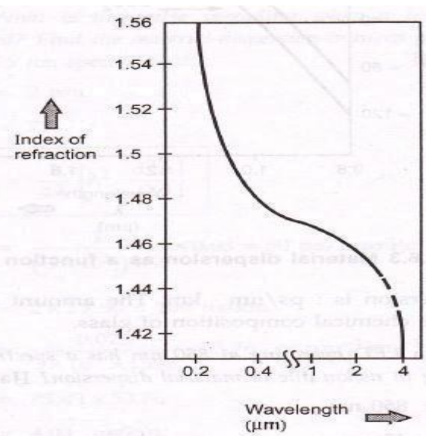


Fig. 2.6.2 Index of refraction as a function of wavelength

... (2.6.4)

where, c = Light velocity

λ = Center wavelength

$\frac{d^2n}{d\lambda^2}$ = Second derivative of index of refraction w.r.t wavelength

Negative sign shows that the upper sideband signal (lowest wavelength) arrives before the lower sideband (highest wavelength).

- The unit of dispersion is : ps/nm . km. The amount of material dispersion depends upon the chemical composition of glass.

Example 2.6.1 : An LED operating at 850 nm has a spectral width of 45 nm. What is the pulse spreading in ns/km due to material dispersion?

Solution : Given : λ = 850 nm

σ = 45 nm

pulse broadening due to material dispersion is given by,

$$\sigma_m = \sigma LM$$

Considering length L = 1 metre

$$\text{Material dispersion constant } D_{mat} = \frac{-\lambda}{c} \cdot \frac{d^2n}{d\lambda^2}$$

For LED source operating at 850 nm, $\left|\lambda^2 \frac{d^2n}{d\lambda^2}\right|$ =0.025

$$M = \frac{1}{c\lambda}\left|\lambda^2 \frac{d^2n}{d\lambda^2}\right| = \frac{1}{(3 \times 10^5)(850)} \times 0.025$$

M = 9.8 ps/nm/km

σ_m = **441 ns/km** ...

Ans.

Waveguide Dispersion

- Waveguide dispersion is caused by the difference in the index of refraction between the core and cladding, resulting in a ‘drag’ effect between the core and cladding portions of the power.
- Waveguide dispersion is significant only in fibers carrying fewer than 5-10 modes. Since multimode optical fibers carry hundreds of modes, they will not have observable waveguide dispersion.
- The group delay (τ_{wg}) arising due to waveguide dispersion.

$$\left(\tau_{wg}\right) = \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d\,(kb)}{dk}\right] \quad \ldots$$

(2.6.5)

Where, b = Normalized propagation constant k = 2π / λ (group velocity)

Normalized frequency V,

$$V = ka(n_1^2 - n_2^2)^{\frac{1}{2}}$$

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d\,(V_b)}{dV}\right]$$

The second term $\frac{d(V_b)}{dV}$ is waveguide dispersion and is mode dependent term..

- As frequency is a function of wavelength, the group velocity of the energy varies with frequency. The produces additional losses (waveguide dispersion). The propagation constant (b) varies with wavelength, the causes of which are independent of material dispersion.

Chromatic Dispersion

- The combination of material dispersion and waveguide dispersion is called chromatic dispersion. These losses primarily concern the spectral width of transmitter and choice of correct wavelength.

- A graph of effective refractive index against wavelength illustrates the effects of material, chromatic and waveguide dispersion.

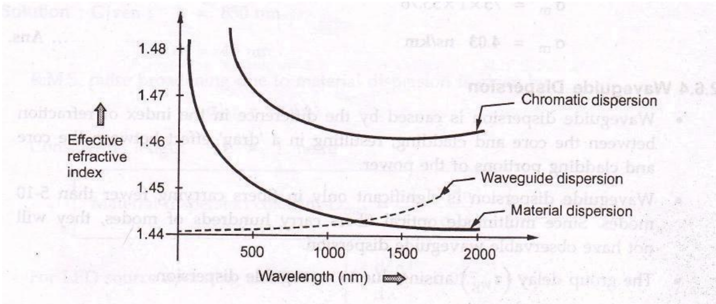


Fig. 2.6.4 Graph of effective refractive index against wavelength showing effects of chromatic, waveguide and material dispersion

Material dispersion and waveguide dispersion effects vary in vary in opposite senses as the wavelength increased, but at an optimum wavelength around 1300 nm, two effects almost cancel each other and chromatic dispersion is at minimum. Attenuation is therefore also at minimum and makes 1300 nm a highly attractive operating wavelength.

Modal Dispersion

As only a certain number of modes can propagate down the fiber, each of these modes carries the modulation signal and each one is incident on the boundary at a different angle, they will each have their own individual propagation times. The net effect is spreading of pulse, this form o dispersion is called modal dispersion.

- Modal dispersion takes place in multimode fibers. It is moderately present in graded index fibers and almost eliminated in single mode step index fibers.

- Modal dispersion is given by,

$$\boxed{\Delta t_{modal} = \frac{n_1 Z}{c}\left(\frac{\Delta}{1-\Delta}\right)}$$

where Δt_{modal} = Dispersion

n_1 = Core refractive index

Z = Total fiber length

c = Velocity of light in air

□ = Fractional refractive index $\left(\frac{n_1 - n_2}{n_1}\right)$

Putting in above equation $\Delta = \frac{(NA^2)Z}{2n_1 c}$

$$\boxed{\Delta t_{modal} = \frac{(NA^2)Z}{2n_1\, c}}$$

$$t_{r\,mod} = 0.44\,(\Delta t_{modal})\pi r^2$$

Example 2.6.3 : For a single mode fiber $n_2 = 1.48$ and = 0.2 % operating at A = 1320 nm, compute the waveguide dispersion if $V.\frac{d^2(Vb)}{dv^2} = 0.26.$

Solution :

$n_2 = 1.48$

0.2

= 1320 nm

Waveguide dispersion is given by,z

$$D_{wg}(\lambda) = \frac{-n_2\Delta}{\ldots}\left[V\frac{d^2(Vb)}{\ldots}\right]$$

$$= \frac{-1.48 \times 0.2}{3 \times 10^5 \times 1320}[0.20]$$

-1.943 picosec/nm .

km.

Higher Order Dispersion

S.

$$S = \frac{dD}{d\lambda}$$

Higher order dispersive effective effects are governed by dispersion slope

where, D is total dispersion

Also,

$S = \left(\frac{2\pi c}{\lambda^2}\right)^2 \beta_3 + \left(\frac{4\pi c}{\lambda^3}\right)\beta_2$ where,

β_2 and β_3 are second and third order dispersion parameters.

- Dispersion slope S plays an important role in designing WDM system

Dispersion Induced Limitations

- The extent of pulse broadening depends on the width and the shape of input pulses. The pulse broadening is studied with the help of wave equation.

Basic Propagation Equation

- The basic propagation equation which governs pulse evolution in a single mode fiber is given by,

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2} . \frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6} \frac{\partial^3 A}{\partial t^3} = 0$$

where,

β_1, β_2 and β_3 are different dispersion parameters.

Chirped Gaussian Pulses

- A pulse is said to b e chirped if its carrier frequency changes with time.
- For a Gaussian spectrum having spectral width σ_ω, the pulse broadening factor is given by,

$$\frac{\sigma^2}{\sigma_0^2} = \left(1 + \frac{C\beta_2 L}{2\sigma_2^2}\right)^2 + (1 + V_\omega^2)\left(\frac{\beta_2 L}{2\sigma_0^2}\right)^2 + (1 + C + V_\omega^2)^2 \left(\frac{\beta_3 L}{4\sqrt{2\sigma_0^3}}\right)\pi r^2$$

where, $V_\omega = 2\sigma_\omega \sigma_0$

Limitations of Bit Rate

- The limiting bit rate is given by,

$$4B\sigma \leq 1$$

- The condition relating bit rate-distance product (BL) and dispersion (D) is given

$$BL\,|S|\sigma_\lambda^2 \le \frac{1}{\sqrt{8}}$$

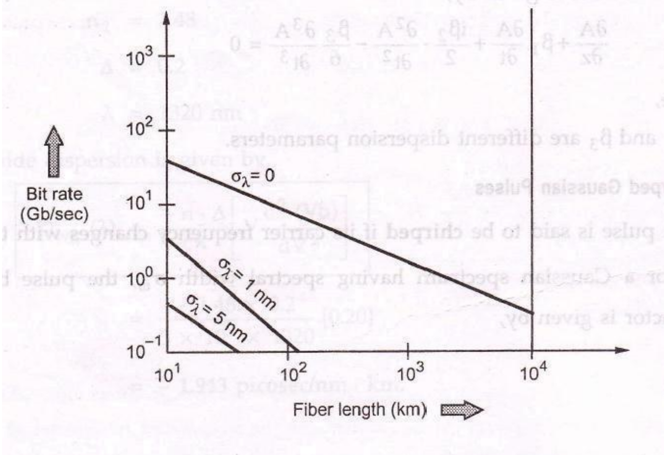


Fig. 2.6.5 Dependence of bit rate on fiber length

where, S is dispersion slope.Limiting bit rate a single mode fibers as a function of fiber length for σλ = 0, a and 5nm is shown in fig. 2.6.5.

Polarization Mode Dispersion (PMD)

- Different frequency component of a pulse acquires different polarization state (such as linear polarization and circular polarization). This results in pulse broadening is kno**w as polarization mode dispersion (PMD).**
- PMD is the limiting factor for optical communication system at high data rates. The effects of PMD must be compensated.

Pulse Broadening in GI Fibers

- The core refractive index varies radially in case of graded index fibers, hence it supports multimode propagation with a low intermodal delay distortion and high data rate over long distance is possible. The higher order modes travelling in outer regions of the core, will travel faster than the lower order modes travelling in high refractive index region. If the index profile is carefully controlled, then the transit times of the individual modes will be identical, so eliminating modal dispersion.
    - The r.m.s pulse broadening is given as:

$$\sigma = \left(\sigma_{\text{intermodal}}^2 + \sigma_{\text{intermodal}}^2\right)^{1/2} \qquad \text{... (2.7.1)}$$

where,

$\sigma_{\text{intermodal}}$ – R.M.S pulse width due to intermodal delay distortion.

$\sigma_{\text{intermodal}}$ – R.M.S pulse width resulting from pulse broadening within each mode.

- The intermodal delay and pulse broadening are related by expression given by Personick.

$$\sigma_{\text{intermodal}} = \left(\langle \tau_g^2 \rangle - \langle \tau_g \rangle^2\right)^{1/2} \qquad \text{... (2.7.2)}$$

Where τ_g is group delay.

From this the expression for intermodal pulse broadening is given as:

$$\propto_{\text{intermodal}} = \frac{LN_1\Delta}{2c} \cdot \frac{\propto}{\propto+1}\left(\frac{\propto+2}{3\propto+2}\right)^{1/2} \text{x}$$

$$\left[c_1^2 + \frac{4c_1c_2(\propto+1)}{2\propto+1} + \frac{16\Delta^2c_2^2(\propto+1)^2}{(5\propto+2)(3\propto+2)}\right]^{1/2}$$

… (2.7.3)

$$c_1 = \frac{\propto-2-E}{\propto+2} \; and \; c_2 = \frac{3\propto-2-2c}{2(\propto+2)}$$

- The intramodal pulse broadening is given as :

$$\sigma_{intramodal}^2 = \left(\frac{\sigma\lambda}{\lambda}\right)^2 \left\langle \left(\lambda\frac{d\tau g}{d\lambda}\right)^2 \right\rangle$$ … (2.[illegible].4)

Where σλ is spectral width of optical source.

Solving the expression gives :

$$\sigma_{intramodal}^2 = \frac{L}{c} \cdot \frac{\sigma\lambda}{\lambda}\left[\left(-\lambda^2\frac{d^2n_1}{d\lambda^2}\right)^2 - N_1c_1\Delta\right.$$

$$\left(2\lambda^2 \frac{d^2 n_1}{d\lambda^2} \cdot \frac{\alpha}{\alpha+1} - N_1 c_1 \Delta \frac{4\alpha^2}{(\alpha+2)(3\alpha+2)}\right)\Bigg]^{1/2}$$

Mode Coupling

After certain initial length, the pulse distortion increases less rapidly because of mode coupling. The energy from one mode is coupled to other modes because of Structural imperfections, Fiber diameter variations, Refractive index variations, Microbends in cable.Due to the mode coupling, average propagation delay become less and intermodal distortion reduces.Suppose certain initial coupling length = L_C, mode coupling length, over L_C = Z. Additional loss associated with mode coupling = h (dB/ km).Therefore the excess attenuation resulting from mode coupling = hZ. The improvement in pulse spreading by mode coupling is given as :

$$hZ\left(\frac{\sigma_c}{\sigma_0}\right) = C$$

where, C is constant independent of all dimensional quantities and refractive indices. σ_C is pulse broadening under mode coupling.σ_0 is pulse broadening in absence of mode coupling. For long fiber length's the effect of mode coupling on pulse distortion is significant. For a graded index fiber, the effect of distance on pulse broading for various coupling losses are shown

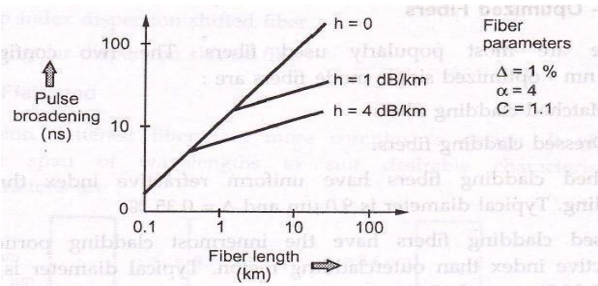


Fig. 2.8.1 Mode coupling effects on pulse broadening

Design Optimization

Features of single mode fibers are : Longer life, Low attenuation ,Signal Transfer quality is good, Modal noise is absent,Largest BW-distance product.

Basic design – optimization includes the following : Dispersion,Mode field,Diameter,bending loss, Refractive index profile,Cut-off wavelength.

Refractive Index Profile

Dispersion of single mode silica fiber is lowest at 1300 nm while its attenuation is minimum at 1550 nm. For archiving maximum transmission distance the dispersion null should be at the wavelength of minimum attenuation. The waveguide dispersion is easier to control than the material dispersion. Therefore a variety of core-cladding refractive.

1300 nm – Optimized Fibers

These are most popularly used fibers. The two configurations of 1300 nm – optimized single mode fibers are

- Matched cladding fibers.
- Dressed cladding fibers.

Matched cladding fibers have uniform refractive index throughout its cladding. Typical diameter is 9.0 µm and $\Delta = 0.35$ %.

Dressed cladding fibers have the innermost cladding portion has low refractive index than outrcladding region. Typical diameter is 8.4 µm and $\Delta_1 = 0.25$ %, $\Delta_2 = 0.12$ %.

Fig 2.9.1 shows both types of fibers.

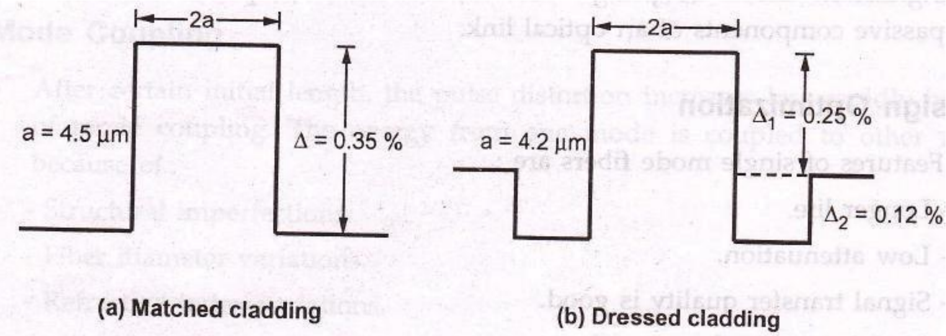


Fig. 2.9.1 1300 nm - optimized refractive index profile

Dispersion Shifted Fibers

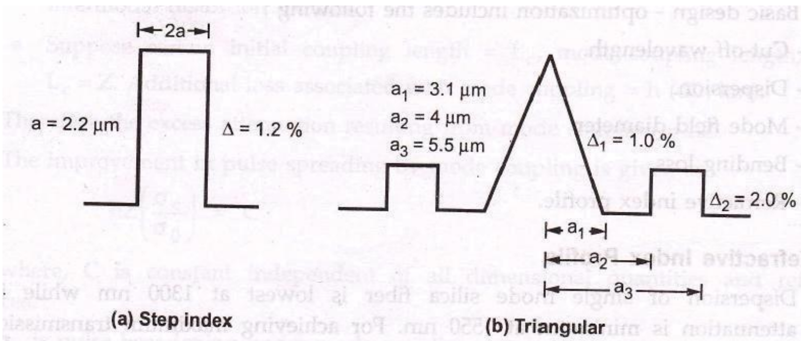


Fig. 2.9.2 Dispersion shifted fibers

2. The addition of wavelength and material dispersion can shift the zero dispersion point of longer wavelength. Two configurations of dispersion shifted fibers are

Dispersion Flattened

Dispersion flattened fibers are more complex to design. It offers much broader span of wavelengths to suit desirable characteristics. Two configurations are :

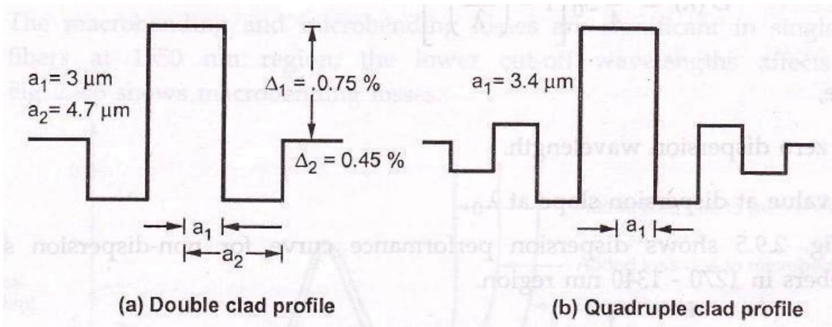


Fig. 2.9.3 Dispersion flattened

- Fig 2.9.4 shows total resultant dispersion.

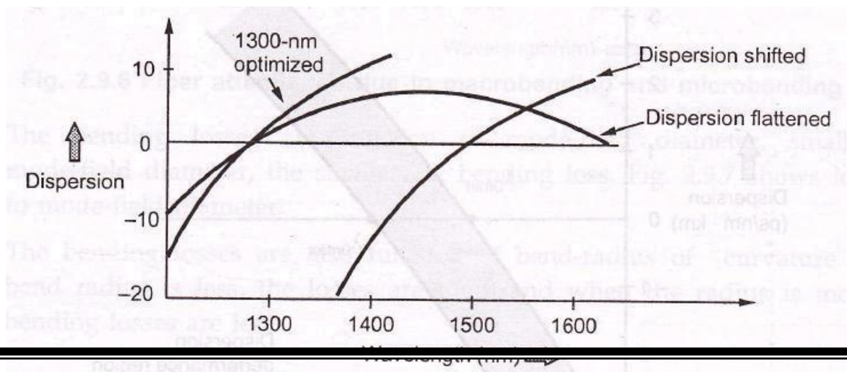


Fig. 2.9.4 Total resultant dispersion

Dispersion Calculations

The total dispersion consists of material and waveguide dispersions. The resultant intermodal dispersion is given as,

$$D(\lambda) = \frac{d\tau}{d\lambda}$$

where, τ is group delay per unit length of fiber.

The broadening σ of an optical pulse is given

$$\sigma = D(\lambda) L\sigma \lambda$$

where, $\sigma\lambda$ is half power spectral width of source.

As the dispersion varies with wavelength and fiber type. Different formulae are used to calculate dispersions for variety of fiber at different wavelength. For a non –

$$D(\lambda) = \frac{\lambda}{4} S_0 \left[1 - \left(\frac{\lambda_0}{\lambda}\right)^4\right]$$

dispersion shifted fiber between 1270 nm to 1340 nm wavelength, the expression for dispersion is given as :

where, λ_0 is zero dispersion wavelength.

S_0 is value at dispersion slop at λ_0.

Fig 2.9.5 shows dispersion performance curve for non-dispersion shifted fibers in 1270 – 1340 nm region.

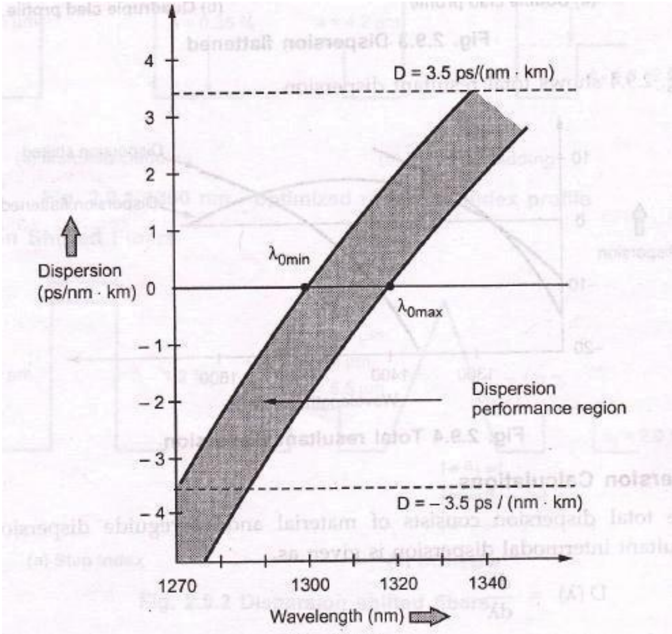


Fig. 2.9.5

Maximum dispersion specified as 3.5 ps/(nm . km) marked as dotted line in Fig. 2.9.5.

The cut-off frequency of an optical fiber

The cut-off frequency of an optical fiber is determined not only by the fiber itself (modal dispersion in case of multimode fibers and waveguide dispersion in case of single mode fibers) but also by the amount of material dispersion caused by the spectral width of transmitter.

Bending Loss Limitations

The macrobending and microbending losses are significant in single mode fibers at 1550 nm region, the lower cut-off wavelengths affects more. Fig. 2.9.6 shows macrobending losses.

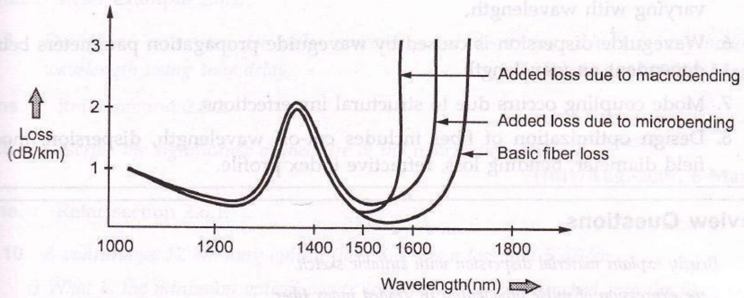


Fig. 2.9.6 Fiber attenuation due to macrobending and microbending

The bending losses are function of mode-filed diameter, smaller the mode-field diameter, the smaller the bending loss. Fig. 2.9.7 shows loss due to mode-field diameter.The bending losses are also function of bend-radius of curvature. If the bend radius is less, the losses are more and when the radius is more, the bending losses are less.

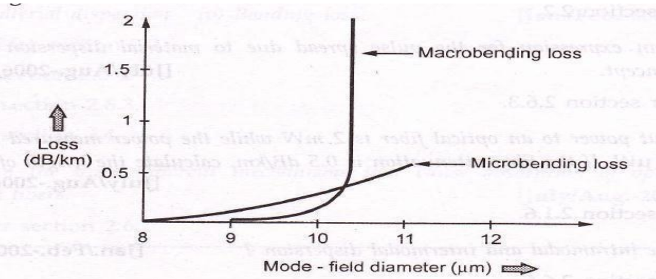


Fig. 2.9.7 Loss due to mode field diameter variation

Optical fiber connectors

An optical fiber connector terminates the end of an optical fiber, and enables quicker connection and disconnection than splicing. The connectors mechanically couple and align the cores of fibers so light can pass. Better connectors lose very little light due to reflection or misalignment of the fibers. In all, about 100 different types of fiber optic connectors have been introduced to the market.

An optical fiber connector is a flexible device that connects fiber cables requiring a quick connection and disconnection. Optical fibers terminate fiber-optic connections to fiber equipment or join two fiber connections without splicing. Hundreds of optical fiber connector types are available, but the key differentiator is defined by the mechanical coupling techniques and dimensions. Optical fiber connectors ensure stable connections, as they ensure the fiber ends are optically smooth and the end-to-end positions are properly aligned.

An optical fiber connector is also known as a fiber optic connector. 1980s. Most fiber connectors are spring loaded.

The main components of an optical fiber connector are a ferrule, sub-assembly body, cable, stress relief boot and connector housing. The ferrule is mostly made of hardened material like stainless steel and tungsten carbide, and it ensures the alignment during connector mating. The connector body holds the ferrule and the coupling device serves the purpose of male-female configuration

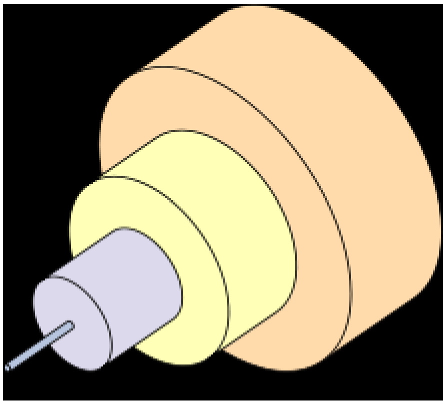
The fiber types for fiber optic connectors are categorized into simplex, duplex and multiple fiber connectors. A simplex connector has one fiber terminated in the connector, whereas duplex has two fibers terminated in the connector. Multiple fiber connectors can have two or more fibers terminated in the connector. Optical fiber connectors are dissimilar to other electronic connectors in that they do not have a jack and plug design. Instead they make use of the fiber mating sleeve for connection purposes.

Common optical fiber connectors include biconic, D4, ESCON, FC, FDDI, LC and SC.

- Biconic connectors use precision tapered ends to have low insertion loss.
- D4 connectors have a keyed body for easy intermateability.
- ESCON connectors are commonly used to connect from a wall outlet to a device.

- FC connector (fixed connection connector) is used for single-mode fibers and high-speed communication links.
- FDDI connector is a duplex connector which makes use of a fixed shroud.
- LC connector (local connection connector) has the benefit of small-form-factor optical transmitter/receiver assemblies and is largely used in private and public networks.
- SC connector (subscriber connector) is used in simplex and multiple applications and is best suited for high-density applications.

In fiber-optic communication, a single-mode optical fiber (SMF) is an optical fiber designed to carry only a single mode of light - the transverse mode. Modes are the possible solutions of the Helmholtz equation for waves, which is obtained by combining Maxwell's equations and the boundary conditions. These modes define the way the wave travels through space, i.e. how the wave is distributed in space. Waves can have the same mode but have different frequencies. This is the case in single-mode fibers, where we can have waves with different frequencies, but of the same mode, which means that they are distributed in space in the same way, and that gives us a single ray of light. Although the ray travels parallel to the length of the fiber, it is often called transverse mode since its electromagnetic oscillations occur perpendicular (transverse) to the length of the fiber. The 2009 Nobel Prize in Physics was awarded to Charles K. Kao for his theoretical work on the single-mode optical fiber.[1] The standard G.652 defines the most widely used form of single-mode optical fiber.[2]



The structure of a typical single-mode fiber.

1. Core 8 -9 µm diameter
2.Cladding 125 µm dia.
3.Buffer 250 µm dia.
4. Jacket 900 µm dia.

Like multi-mode optical fibers, single-mode fibers do exhibit modal dispersion resulting from multiple spatial modes but with narrower modal dispersion.[citation needed] Single-mode fibers are therefore better at retaining the fidelity of each light pulse over longer distances than multi-mode fibers. For these reasons, single-mode fibers can have a higher bandwidth than multi-mode fibers. Equipment for single-mode fiber is more expensive than equipment for multi-mode optical fiber, but the single-mode fiber itself is usually cheaper in bulk.

Cross section of a single-mode optical fiber patch cord end, taken with a Fiberscope. The round circle is the cladding, 125 microns in diameter. Debris is visible as a streak on the cross-section, and glows due to the illumination.

A typical single-mode optical fiber has a core diameter between 8 and 10.5 µm[6] and a cladding diameter of 125 µm. There are a number of special types of single-mode optical fiber which have been chemically or physically altered to give special properties, such as dispersion-shifted fiber and nonzero dispersion-shifted fiber. Data rates are limited by polarization mode dispersion and chromatic dispersion. As of 2005, data rates of up to 10 gigabits per second were possible at distances of over 80 km (50 mi) with commercially available transceivers (Xenpak). By using optical amplifiers and dispersion-compensating devices, state-of-the-art DWDM optical systems can span thousands of kilometers at 10 Gbit/s, and several hundred kilometers at 40 Gbit/s.[citation needed]

The lowest-order bounds mode is ascertained for the wavelength of interest by solving Maxwell's equations for the boundary conditions imposed by the fiber, which are determined by the core diameter and the refractive indices of the core and cladding. The solution of Maxwell's equations for the lowest order bound mode will permit a pair of orthogonally polarized fields in the fiber, and this is the usual case in a communication fiber.

In step-index guides, single-mode operation occurs when the normalized frequency, *V*, is less than or equal to 2.405. For power-law profiles, single-mode operation occurs for a normalized frequency, *V*, less than approximately where *g* is the profile parameter.

,

Cross section of a single-mode optical fiber patch cord end, taken with a Fiberscope. The round circle is the cladding, 125 microns in diameter. Debris is visible as a streak on the cross-section, and glows due to the illumination.

In practice, the orthogonal polarizations may not be associated with degenerate modes.OS1 and OS2 are standard single-mode optical fiber used with wavelengths 1310 nm and 1550 nm (size 9/125 µm) with a maximum attenuation of 1 dB/km (OS1) and 0.4 dB/km (OS2). OS1 is defined in ISO/IEC 11801,[7] and OS2 is defined in ISO/IEC 24702.

Optical fiber connectors

Optical fiber connectors are used to join optical fibers where a connect/disconnect capability is required. The basic connector unit is a connector assembly. A connector assembly consists of an adapter and two connector plugs. Due to the sophisticated polishing and tuning procedures that may be incorporated into optical connector manufacturing, connectors are generally assembled onto optical fiber in a supplier's manufacturing facility. However, the assembly and polishing operations involved can be performed in the field, for example to make cross-connect jumpers to size.

Optical fiber connectors are used in telephone company central offices, at installations on customer premises, and in outside plant applications. Their uses include:

- Making the connection between equipment and the telephone plant in the central office
- Connecting fibers to remote and outside plant electronics such as Optical Network Units (ONUs) and Digital Loop Carrier (DLC) systems
- Optical cross connects in the central office
- Patching panels in the outside plant to provide architectural flexibility and to interconnect fibers belonging to different service providers
- Connecting couplers, splitters, and Wavelength Division Multiplexers (WDMs) to optical fibers
- Connecting optical test equipment to fibers for testing and maintenance.

Outside plant applications may involve locating connectors underground in subsurface enclosures that may be subject to flooding, on outdoor walls, or on utility poles. The closures that enclose them may be hermetic, or may be "free-breathing." Hermetic closures will prevent the connectors within being subjected to temperature swings unless they are breached. Free-breathing enclosures will subject them to temperature and humidity swings, and possibly to condensation and biological action from airborne bacteria, insects, etc. Connectors in the underground plant may be subjected to groundwater immersion if the closures containing them are breached or improperly assembled.

The latest industry requirements for optical fiber connectors are in Telcordia GR-326, *Generic Requirements for Singlemode Optical Connectors and Jumper Assemblies*.A *multi-fiber* optical connector is designed to simultaneously join multiple optical fibers together, with each optical fiber being joined to only one other optical fiber.The last part of the definition is included so as not to confuse multi-fiber connectors with a branching component, such as a coupler. The latter joins one optical fiber to two or more other optical fibers.Multi-fiber optical connectors are designed to be used wherever quick and/or repetitive connects and disconnects of a group of fibers are needed. Applications include telecommunications companies' Central Offices (COs), installations on customer premises, and Outside Plant (OSP) applications.The multi-fiber optical connector can be used in the creation of a low-cost switch for use in fiber optical testing. Another application is in cables delivered to a user with pre-terminated multi-fiber jumpers. This would reduce the need for field splicing, which could greatly reduce the number of hours necessary for placing an optical fiber cable in a telecommunications network. This, in turn, would result in savings for the installer of such cable.

The return loss RL is a measure of the portion of light that is reflected back to the source at the junction. It is expressed in decibel. The higher the RL value in decibels, the lower are the reflections. Typical RL values lie between 35 and 50 dB for PC, 60 to 90 dB for APC and 20 to 40 dB for multimode fibres.

In the early days of fibre-optic plug-in connectors, the abutting endfaces were polished to an angle of 90° to the fibre axis, while current standards require PC (Physical Contact) polishing or APC (Angled Physical Contact) polishing. The term HRL (High Return Loss) is frequently used, but it has the same meaning as APC.

In PC polishing, the ferrule is polished to a convex end to ensure that the fibre cores touch at their highest point. This reduces the occurrence of reflections at the junction.A further improvement in return loss is achieved by using the APC polishing technique. Here, the convex end surfaces of the ferrules are polished to an angle (8°) relative to the fibre axis. SC connectors are also sold with a 9° angle. They possess IL and RL values identical to 8° versions, and for this reason they have not established themselves worldwide.

Return Loss

In optics (particularly in fiberoptics) a loss that takes place at discontinuities of refractive index, especially at an air-glass interface such as a fiber endface. At those interfaces, a fraction of the optical signal is reflected back toward the source. This reflection phenomenon is also called "**Fresnel reflection loss**," or simply "**Fresnel loss**."

Fiber optic transmission systems use lasers to transmit signals over optical fiber, and a high optical return loss (ORL) can cause the laser to stop transmitting correctly. The measurement of ORL is becoming more important in the characterization of optical networks as the use of wavelength-division multiplexing increases. These systems use lasers that have a lower tolerance for ORL, and introduce elements into the network that are located in close proximity to the laser.

Definition of Return Loss

In technical terms, RL is the ratio of the light reflected back from a device under test, P_{out}, to the light launched into that device, P_{in}, usually expressed as a negative number in dB.

$$RL = 10 \log_{10}(P_{out}/P_{in})$$

where is the reflected power and is the incident, or input, power.

Sources of loss include reflections and scattering along the fiber network. A typical RL value for an Angled Physical Contact (APC) connector is about -55dB, while the RL from an open flat polish to air is typically about -14dB. High RL is a large concern in high bitrate digital or analog single mode systems and is also an indication of a potential failure point, or compromise, in any optical network.