1.1 A Brief History of Fiber Optical Communication

The use of light to send messages is not new. Fires were used for signaling in biblical times, smoke signals have been used for thousands of years and flashing lights have been used to communicate between warships at sea since the days of Lord Nelson.

The idea of using glass fiber to carry an optical communications signal originated with Alexander Graham Bell. However this idea had to wait some 80 years for better glasses and low cost electronics for it to become useful in practical situations.

Since its invention in the early 1970s, the use of and demand for optical fiber have grown tremendously. The uses of optical fiber today are quite numerous. With the explosion of information traffic due to the Internet, electronic commerce, computer networks, multimedia, voice, data, and video, the need for a transmission medium with the bandwidth capabilities for handling such vast amounts of information is paramount. Fiber optics, with its comparatively infinite bandwidth, has proven to be the solution.

Among the tens of thousands of developments and inventions that have contributed to this progress four stands out as milestones:

1. The invention of the LASER (in the late 1950's)
2. The development of low loss optical fiber (1970's)
3. The invention of the optical fiber amplifier (1980's)
4. The invention of the in-fiber Bragg grating (1990's)

The continuing development of semiconductor technology is quite fundamental but of course not specifically optical.

The predominant use of optical technology is as very fast "electric wire". Optical fibers replace electric wire in communications systems and nothing much else changes. Perhaps this is not quite fair. The very speed and quality of optical communications systems has itself predicated the development of a new type of electronic communications itself designed to be run on optical connections. ATM and SDH technologies are good examples of the new type of systems.

It is important to realize that optical communications is not like electronic communications. While it seems that light travels in a fiber much like electricity does in a wire this is very misleading. Light is an electromagnetic wave and optical fiber is a waveguide. Everything to do with transport of the signal even to simple things like coupling (joining) two fibers into one is very different from what happens in the electronic world. The two fields (electronics and optics) while closely related employ different principles in different ways.

In 1998 the "happening" area in optical communications is Wavelength Division Multiplexing (WDM). This is the ability to send many (perhaps up to 1000) independent optical channels on a single fiber. The first fully commercial WDM products appeared on the market in 1996.

INTRODUCTION

WDM is a major step toward fully optical networking. Today, a variety of industries including the medical, military, telecommunication, industrial, data storage, networking, and broadcast industries are able to apply and use fiber optic technology in a variety of applications.

After refer the several books and resources here I have included some important invention related to optical communication to reach this level:

Year	Inventor	Invention
1790	French Chappe brothers	**optical semaphore telegraph** It was a system comprised of a series of lights mounted on towers where operators would relay a message from one tower to the next. Over the course of the next century great strides were made in optical science.
1840	physicists Daniel Collodon and Jacques Babinet	Showed that light could be directed along jets of water for fountain displays.
1854	John Tyndall, a British physicist	Demonstrated that light could travel through a curved stream of water thereby proving that a light signal could be bent. He proved this by setting up a tank of water with a pipe that ran out of one side. As water flowed from the pipe, he shone a light into the tank into the stream of water. As the water fell, an arc of light followed the water down.
1880	Alexander Graham Bell	patented an optical telephone system called the photophone His earlier invention, the telephone, proved to be more realistic however. That same year, William Wheeler invented a system of light pipes lined with a highly reflective coating that illuminated homes by using light from an electric arc lamp placed in the basement and directing the light around the home with the pipes.
1888	Doctors Roth and Reuss of Vienna	Used bent glass rods to illuminate body cavities
	French engineer Henry Saint-Rene	Designed a system of bent glass rods for guiding light images seven years later in an early attempt at television
1898	American David Smith	Applied for a patent on a dental illuminator using a curved glass rod.
1920	John Logie Baird	patented the idea of using arrays of transparent rods to transmit images for television and Clarence
	W. Hansell	Patented the idea of using arrays of transparent rods to transmit images for facsimiles.

Year	Inventor	Invention
1930	Heinrich Lamm	The first person to transmit an image through a bundle of optical fibers. It was an image of a light bulb filament. His intent was to look inside inaccessible parts of the body, but the rise of the Nazis forced Lamm, a Jew, to move to America and abandon his dream of becoming a professor of medicine. His effort to file a patent was denied because of Hansell's British patent.
1951	Holger Moeller	Applied for a Danish patent on fiber-optic imaging in which he proposed cladding glass or plastic fibers with a transparent low-index material, but was denied because of Baird and Hansell's patents.
1954	Abraham Van Heel and Harold H. Hopkins	Presented imaging bundles in the British journal Nature at separate times. Van Heel later produced a cladded fiber system that greatly reduced signal interference and crosstalk between fibers.
	Charles Townes and his colleagues at Columbia University	"maser" Maser stands for "microwave amplification by stimulated emission of radiation."
1954	Dutch scientist Abraham Van Heel and British scientist Harold H. Hopkins	Separately wrote papers on imaging bundles. Hopkins reported on imaging bundles of unclad fibers, whereas Van Heel reported on simple bundles of clad fibers. Van Heel covered a bare fiber with a transparent cladding of a lower refractive index. This protected the fiber reflection surface from outside distortion and greatly reduced interference between fibers. Abraham Van Heel is also notable for another contribution. Stimulated by a conversation with the American optical physicist Brian O'Brien, Van Heel made the crucial innovation of cladding fiber-optic cables. All earlier fibers developed were bare and lacked any form of cladding, with total internal reflection occurring at a glass-air interface. Abraham Van Heel covered a bare fiber or glass or plastic with a transparent cladding of lower refractive index. This protected the total reflection surface from contamination and greatly reduced cross talk between fibers
1958	Charles Townes and Arthur Schawlow	The laser was introduced as a efficient source of light. Show that masers could be made to operate in optical and infrared regions. Basically, light is reflected back and forth in an energized medium to generate amplified light as opposed to excited molecules of gas amplified to generate radio waves, as is the case with the maser. Laser stands for "light amplification by stimulated emission of radiation."

Year	Inventor	Invention
1961	Elias Snitzer of American Optical	Published a theoretical description of single mode fibers whose core would be so small it could carry light with only one wave-guide mode. Snitzer was able to demonstrate a laser directed through a thin glass fiber which was sufficient for medical applications, but for communication applications the light loss became too great.
1964	Charles Kao and George Hockham, of Standard Communications Laboratories in England	Demonstrating, theoretically, that light loss in existing glass fibers could be decreased dramatically by removing impurities.
1970	scientists at Corning Glass Works	Goal of making single mode fibers with attenuation less then 20dB/km was reached. This was achieved through doping silica glass with titanium.
	Morton Panish and Izuo Hayashi of Bell Laboratories, along with a group from the Ioffe Physical Institute in Leningrad	Demonstrated a semiconductor diode laser capable of emitting continuous waves at room temperature.
	one team of researchers	began experimenting with fused silica, a material capable of extreme purity with a high melting point and a low refractive index
1973	Bell Laboratories	Developed a modified chemical vapor deposition process that heats chemical vapors and oxygen to form ultra-transparent glass that can be mass-produced into low-loss optical fiber. This process still remains the standard for fiber-optic cable manufacturing.
1986	David Payne of the University of Southampton and Emmanuel Desurvire at Bell Labratories	The erbium-doped fiber amplifier, which reduced the cost of long-distance fiber systems by eliminating the need for optical-electrical-optical repeaters, was invented
1991	Desurvire and Payne	Demonstrated optical amplifiers that were built into the fiber-optic cable itself. The all-optic system could carry 100 times more information than cable with electronic amplifiers.

1.2 Introduction to Fiber Optics

Fiber optics uses light to send information (data). More formally, **fiber optics** is the branch of optical technology concerned with the transmission of radiant power (light energy) through fibers.

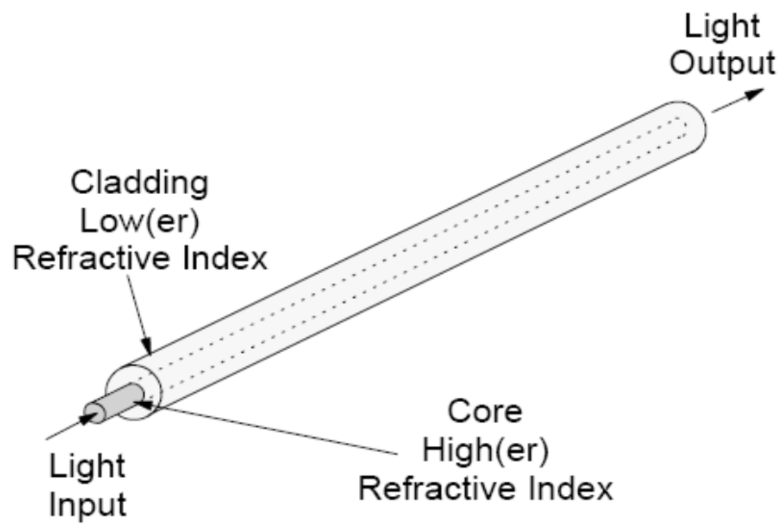


Fig.1.1 Optical fiber construction

An optical fiber is a very thin strand of silica glass in geometry quite like a human hair. In reality it is a very narrow, very long glass cylinder with special characteristics. When light enters one end of the fiber it travels (confined within the fiber) until it leaves the fiber at the other end. Two critical factors stand out:

1. Very little light is lost in its journey along the fiber.
2. Fiber can bend around corners and the light will stay within it and be guided around the corners.

As shown in Figure, an optical fiber consists of two parts: **the core and the cladding.**

The core is a narrow cylindrical strand of glass and the cladding is a tubular jacket surrounding it. **The core has a (slightly) higher refractive index than the cladding.**

This means that the boundary (interface) between the core and the cladding acts as a perfect mirror. Light travelling along the core is confined by the mirror to stay within it - even when the fiber bends around a corner.

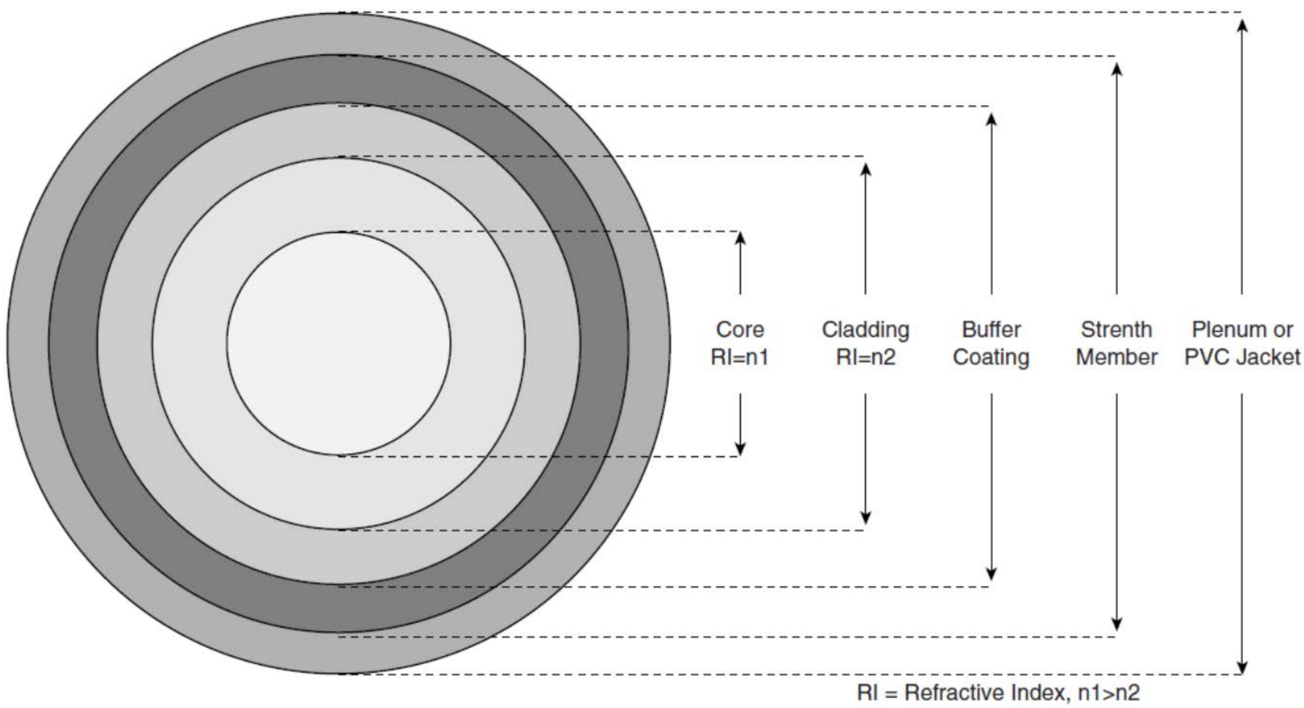


Fig.1.2 Cross Section of a Fiber Optic Cable

When light is transmitted on a fiber, the most important consideration is "what kind of light?"

The electromagnetic radiation that we call light exists at many wavelengths. These wavelengths go from invisible infrared through all the colours of the visible spectrum to invisible ultraviolet. Because of the attenuation characteristics of fiber, we are only interested in infrared "light" for communication applications. This light is usually invisible, since the wavelengths used are usually longer than the visible limit of around 750 nanometers (nm). If a short pulse of light from a source such as a laser or an LED is sent down a narrow fiber, it will be changed (degraded) by its passage down the fiber. It will emerge (depending on the distance) much weaker, lengthened in time ("smeared out"), and distorted in other ways.

From the above discussion we can state; the optical fiber is a cylindrical wave guide operating at optical frequency (Above THz)

1.3 Benefits of Fiber Optics

Optical fiber systems have many advantages over metallic-based communication systems. These advantages include:

Security
Unlike metallic-based systems, the dielectric nature of optical fiber makes it impossible to remotely detect the signal being transmitted within the cable. The only way to do so is by accessing the optical fiber. Accessing the fiber requires intervention that is easily detectable by security surveillance. These circumstances make fiber extremely attractive to governmental bodies, banks, and others with major security concerns.

Long-distance signal transmission
The low attenuation and superior signal integrity found in optical systems allow much longer intervals of signal transmission than metallic-based systems. While single-line, voice-grade copper systems longer than a couple of kilometers (1.2 miles) require in-line signal for satisfactory performance, it is not unusual for optical systems to go over 100 kilometers (km), or about 62 miles, with no active or passive processing.

Large bandwidth, light weight, and small diameter
Today's applications require an ever-increasing amount of bandwidth. Consequently, it is important to consider the space constraints of many end users. It is commonplace to install new cabling within existing duct systems or conduit. The relatively small diameter and light weight of optical cable make such installations easy and practical, saving valuable conduit space in these environments.

Non-conductivity
Another advantage of optical fibers is their dielectric nature. Since optical fiber has no metallic components, it can be installed in areas with electromagnetic interference (EMI), including radio frequency interference (RFI). Areas with high EMI include utility lines, power-carrying lines, and railroad tracks. All-dielectric cables are also ideal for areas of high lightning-strike incidence.

No Electromagnetic Interference
Because the connection is not electrical, you can neither pick up nor create electrical interference (the major source of noise). This is one reason that optical communication has so few errors. There are very few sources of things that can distort or interfere with the signal. In a building this means that fiber cables can be placed almost anywhere electrical cables would have problems, (for example near a lift motor or in a cable duct with heavy power cables). In an industrial plant such as a steel mill, this gives much greater flexibility in cabling than previously available. In the wide area networking environment there is much greater flexibility in route selection. Cables may be located near water or power lines without risk to people or equipment.

Material Cost
Fiber cable costs significantly less than copper cable for the same transmission capacity.

Information Capacity
The data rate of systems in use in 1998 is generally 150 or 620 Mbps on a single (unidirectional) fiber. This is because these systems were installed in past years. The usual rate for new systems is 2.4 Gbps or even 10 Gbps. This is very high in digital transmission terms.

In telephone transmission terms the very best coaxial cable systems give about 2,000 analog voice circuits. A 150 Mbps fiber connection gives just over 2,000 digital telephone (64 Kbps) connections. But the 150 Mbps fiber is at a very early stage in the development of fiber optical systems. The coaxial cable system with which it is being compared is much more costly and has been developed to its fullest extent. Fiber technology is still in its infancy. Using just a single channel per fiber, researchers have trial systems in operation that communicate at speeds of 100 Gbps. By sending many ("wavelength division multiplexed") channels on a single fiber, we can increase this capacity a hundred and perhaps a thousand times.

Distances between Regenerators
As a signal travels along a communication line it loses strength (is attenuated) and picks up noise. The traditional way to regenerate the signal, restoring its power and removing the noise, is to use a either a repeater or an amplifier (Indeed it is the use of repeaters to remove noise that gives digital transmission its high quality). In long-line optical transmission cables now in use by the telephone companies, the repeater spacing is typically 40 kilometers. This compares with 12 km for the previous coaxial cable electrical technology. The number of required repeaters and their spacing is a major factor in system cost. Some recently installed systems (1997) have spacing of up to 120 kilometers.

No Electrical Connection
This is an obvious point but nevertheless a very important one. Electrical connections have problems. In electrical systems there is always the possibility of "ground loops" causing a serious problem, especially in the LAN or computer channel environment. When you communicate electrically you often have to connect the grounds to one another or at least go to a lot of trouble to avoid making this connection. One little known problem is that there is often a voltage potential difference between "ground" at different locations.

With shielded cable there can be a problem if you earth the shields at both ends of the connection. Optical connection is very safe. Electrical connections always have to be protected from high voltages because of the danger to people touching the wire. In some tropical regions of the world, lightning poses a severe hazard even to buried telephone cables! Of course, optical fiber isn't subject to lightning problems but it must be remembered that sometimes optical cables carry wires within them for strengthening or to power repeaters. These wires can be a target for lightning.

Open Ended Capacity
The maximum theoretical capacity of installed fiber is very great (almost infinite). This means that additional capacity can be had on existing fibers as new technology becomes available. All that must be done is change the equipment at either end and change or upgrade the regenerators.

Designed for future applications needs
Fiber optics is affordable today, as electronics prices fall and optical cable pricing remains low. In many cases, fiber solutions are less costly than copper. As bandwidth demands increase rapidly with technological advances, fiber will continue to play a vital role in the long-term success of telecommunication.

Key Points:

Aspects	Advantages
System Performance	• Greatly increased bandwidth and capacity • Lower signal attenuation (Loss)
Immunity to Electrical Noise	• Immune to noise (Electromagnetic Interference [EMI] and radio frequency interference [RFI] • No Crosstalk • Lower bit error rates
Signal Security	• Difficult to tap • Nonconductive (Does not radiate signals)
Electrical Isolation	• No common ground required • Freedom from short circuit and sparks
Size and Weight	• Reduced size and weight cables
Environmental Protection	• Resistant to radiation and corrosion • Resistant to temperature variations • Improved ruggedness and flexibility • Less restrictive in harsh environments
Overall System Economy	• Low per – channel cost • Lower installation cost • Silica is the principle, abundant and inexpensive material (source is sand)

1.4 Limitations of Fiber Optics

Joining Cables
The best way of joining cables is to use “fusion splicing”. This is where fiber ends are fused to one another by melting the glass. Making such splices in a way that will ensure minimal loss of signal is a skilled task that requires precision equipment. It is particularly difficult to do outdoors in very low temperatures, such as in the North American or European winter. In the early days of fiber optical systems (the early 1980s) connectors which allowed cables to be plugged and unplugged were unreliable and caused a large amount of signal loss (as much as 3 dB per connector). Of course, the larger the core diameter of the fiber, the easier it is to make a low-loss connector.

Bending Cables
As light travels along the fiber, it is reflected from the interface between the core and cladding whenever it strays from the path straight down the center. When the fiber is bent, the light only stays in the fiber because of this reflection. But the reflection only works if the angle of incidence is relatively low. If you bend the fiber too much the light escapes. The amount of allowable bending is specific to particular cables because it depends on the difference in refractive index, between core and cladding. The bigger the difference in refractive index, the tighter the allowable bend radius. There is a tradeoff here because there are many other reasons that we would like to keep this difference as small as possible.

Slow Standards Development
This is nobody's fault. Development is happening so quickly, and getting worldwide agreement to a standard is necessarily so slow that standards setting just can't keep up. Things are improving considerably and very quickly, however. Cable sizes and types are converging toward a few choices, although the way they are used is still changing almost daily.

Optics for Transmission Only
Until very recently there was no available optical amplifier. The signal had to be converted to electrical form and put through a complex repeater in order to boost its strength. Recently, optical amplifiers have emerged and look set to solve this. However, optical logic processing and/or switching systems seem to be a few years off yet.

Gamma Radiation
Gamma radiation comes from space and is always present. It can be thought of as a high-energy X-ray. Gamma radiation can cause some types of glass to emit light (causing interference) and also gamma radiation can cause glass to discolor and hence attenuate the signal. In normal situations these effects are minimal. However, fibers are probably not the transmission medium of choice inside a nuclear reactor or on a long-distance space probe.
(A glass beaker placed inside a nuclear reactor for even a few hours comes out black in color and quite opaque.)

Electrical Fields

Very high-voltage electrical fields also affect some glasses in the same way as gamma rays. One proposed route for fiber communication cables is wrapped around high-voltage electrical cables on transmission towers. This actually works quite well where the electrical cables are only of 30000 volts or below. Above that (most major transmission systems are many times above that), the glass tends to emit light and discolor. Nevertheless, this is a field of current research - to produce a glass that will be unaffected by such fields. It is a reasonable expectation that this will be achieved within a very few years. Some electricity companies are carrying fibers with their high voltage distribution systems by placing the fiber inside the earth wire (typically a 1 inch thick aluminum cable with steel casing). This works well, but long-distance high-voltage distribution systems usually don't have earth wires.

Sharks Eat the Cable

In the 1980s there was an incident where a new undersea fiber cable was broken on the ocean floor. Publicity surrounding the event suggested that the cable was attacked and eaten by sharks. It wasn't just the press; this was a serious claim. It was claimed that there was something in the chemical composition of the cable sheathing that was attractive to sharks! Another explanation was that the cable contained an unbalanced electrical supply conductor. It was theorized that the radiated electromagnetic field caused the sharks to be attracted. Other people have dismissed this claim as a joke and suggest that the cable was badly laid and rubbed against rocks. Nevertheless, the story has passed into the folklore of fiber optical communication and some people genuinely believe that sharks eat optical fiber cable.

Gophers (and Termites) Really Do Eat the Cable

Gophers are a real problem for fiber cables in the United States. There is actually a standardized test (conducted by a nature and wildlife organization) which involves placing a cable in a gopher enclosure for a fixed, specified length of time. In other countries termites have been known to attack and eat the plastic sheathing. Most people evaluate the advantages as overwhelming the disadvantages for most environments. But advantages and disadvantages need to be considered in the context of the environment in which the system is to be used. The types of fiber systems appropriate for the LAN environment are quite different from those that are optimal in the wide area world.

1.5 Basic Fiber Optic Communication System

Fiber optics is a medium for carrying information from one point to another in the form of light. Unlike the copper form of transmission, fiber optics is not electrical in nature. A basic fiber optic system consists of a transmitting device that converts an electrical signal into a light signal, an optical fiber cable that carries the light, and a receiver that accepts the light signal and converts it back into an electrical signal. The complexity of a fiber optic system can range from very simple (i.e., local area network) to extremely sophisticated and expensive (i.e., long distance telephone or cable television trunking).

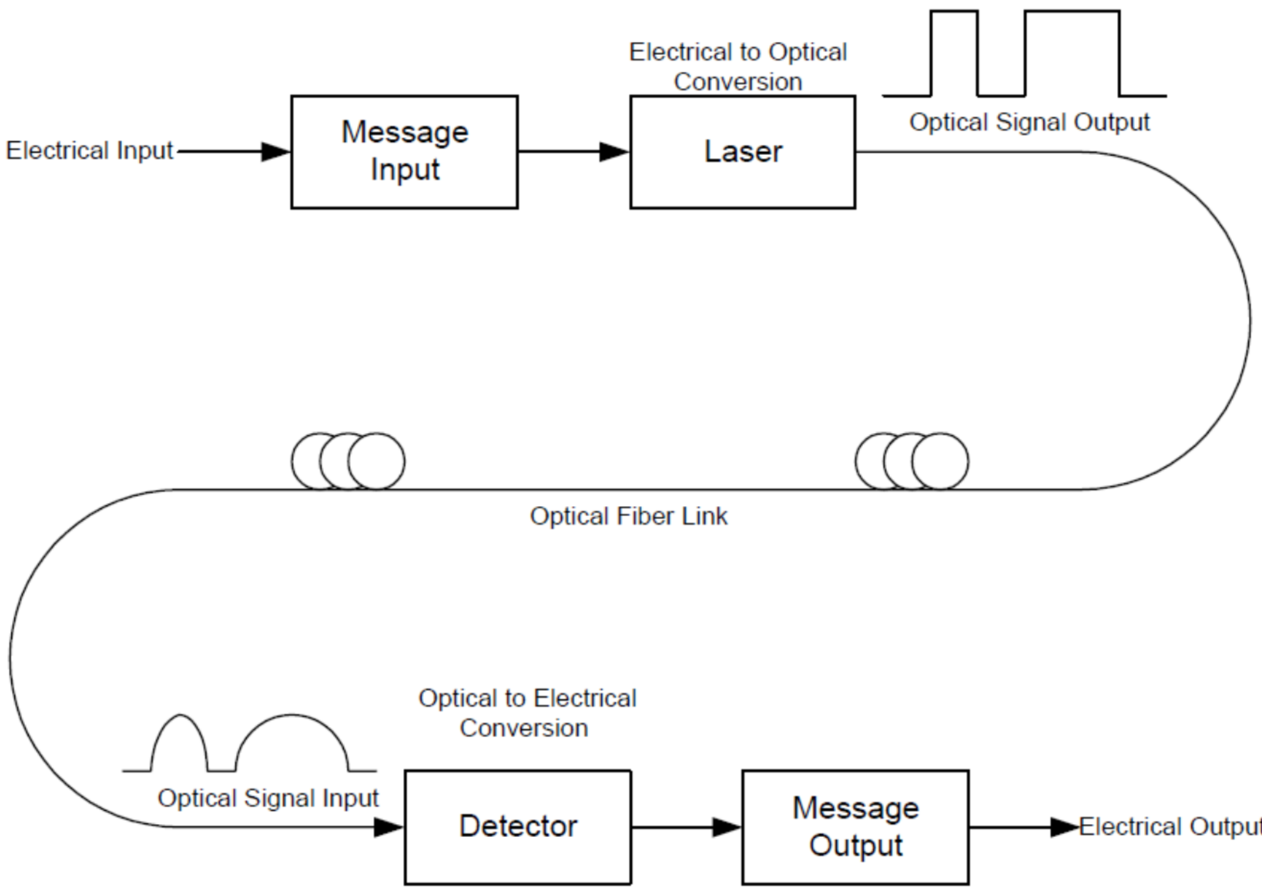


Fig 1.3 Basic fiber optic communication system

For example, the system shown in Figure could be built very inexpensively using a visible LED, plastic fiber, a silicon photodetector, and some simple electronic circuitry. The overall cost could be less than $20.

On the other hand, a typical system used for long-distance, high-bandwidth telecommunication that employs wavelength-division multiplexing, erbium-doped fiber amplifiers, external modulation using DFB lasers with temperature compensation, fiber Bragg gratings, and high-speed infrared photo detectors could cost tens or even hundreds of thousands of dollars.

1.6 Elements of an Optical Fiber Transmission Link

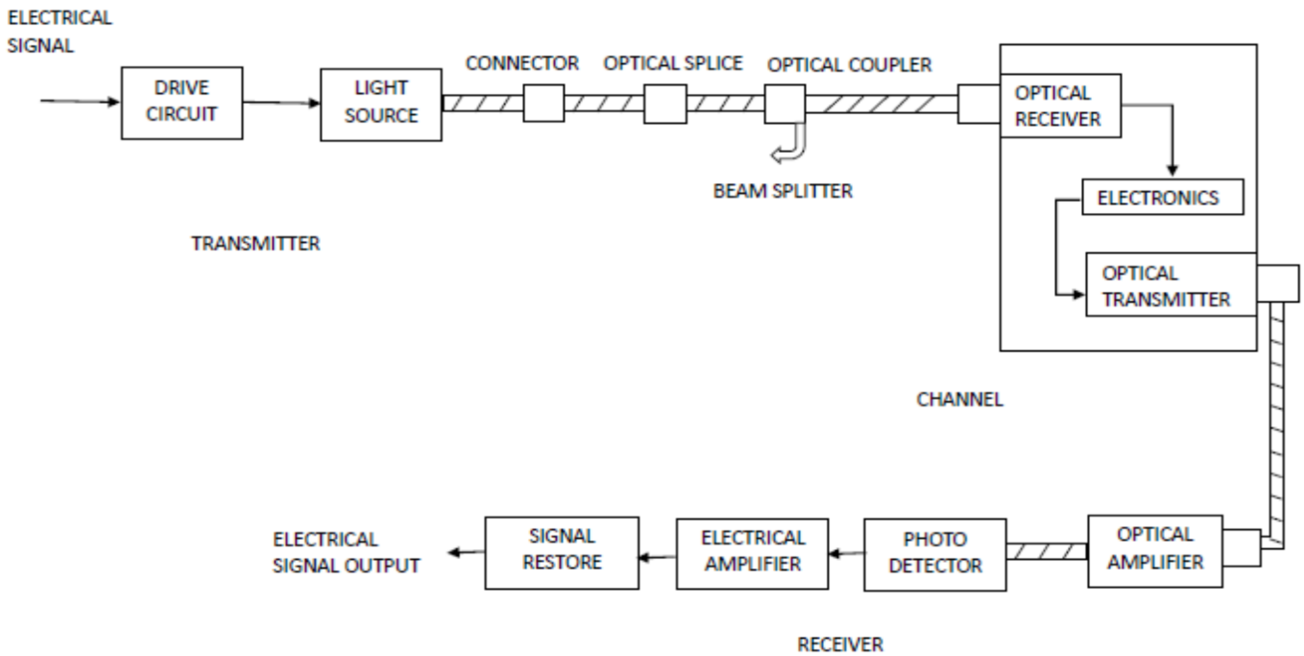


Fig 1.4 Basic Elements of an Optical Fiber Transmission Link

Consist of Three Parts: Transmitter, Channel, Receiver

Transmitter:

Input Signal	-	Electrical Signal
The Driver Circuit	-	Convert Electrical into Optical Signal
Light Source	-	LED or LASER

Channel:

Optical Fiber	-	Act as a Channel Types: Single Mode Fiber & Multimode Fiber Classification: Single Mode Step Index Fiber Multimode Step Index Fiber Multimode Graded Index Fiber
Connectors	-	Used to connect temporary connection between two fibers
Optical Splice	-	Used to connect Permanent connection between two fibers
Beam Splitter & Coupler	-	Used to split or combine the light paths
Repeater	-	Used to regenerate the original signal

Receiver:

Photo Detectors	-	Convert light signal into electrical signal
Amplifiers	-	Used to amplify the signal Example: RAMAN Amplifier EDFA – Erbium Doped Fiber Amplifier

1.7 Fiber Transmission Windows (Bands)

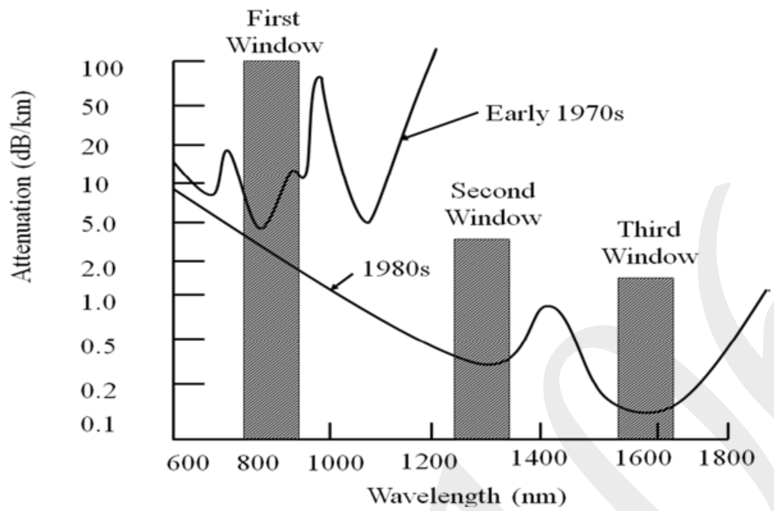


Fig 1.5 Transmission Windows

The upper curve shows the absorption characteristics of Fiber in the 1970s. The lower one is for modern Fiber. In the early days of optical Fiber communication, Fiber attenuation was best represented by the upper curve in Figure (a large difference from today). Partly for historic reasons, there are considered to be three "windows" or bands in the transmission spectrum of optical Fiber. The wavelength band used by a system is an extremely important defining characteristic of that optical system.

Fiber optic systems usually use the 850, 1310 and 1550 nm wavelengths for transmission because losses are lower at these wavelengths due to properties inherent to the glass.

Transmission capacity of the fiber is calculated by BL. Here B is the transmitted bit and L is repeater spacing. In every generation, *BL* increases initially but then begins to saturate as the technology matures. Each new generation brings a fundamental change that helps to improve the system performance further.

Short Wavelength Band (First Window) – First Generation

This is the band around 800-900 nm. This was the first band used for optical Fiber communication in the 1970s and early 1980s. It was attractive because of a local dip in the attenuation profile (of Fiber at the time) but also (mainly) because you can use low cost optical sources and detectors in this band.

Semiconductor used	-	GaAs
Wavelength	-	850 nm
Bit Rate (B)	-	45 Mb/s
Repeater Spacing	-	10 km

The larger repeater spacing compared with 1-km spacing of coaxial systems was an important motivation for system designers because it decreased the installation and maintenance costs associated with each repeater.

Medium Wavelength Band (Second Window) -– Second Generation
It was clear during the 1970s that the repeater spacing could be increased considerably by operating the light wave system in the wavelength region near 1.3 μm, where fiber loss is below 1 dB/km. Furthermore, optical fibers exhibit minimum dispersion in this wavelength region.

This is the band around 1310 nm which came into use in the mid-1980s. This band is attractive today because there is zero Fiber dispersion here (on single-mode Fiber). While sources and detectors for this band are more costly than for the short wave band the Fiber attenuation is only about 0.4 dB/km. This is the band in which the majority of long distance communications systems operate today.

Semiconductor used	-	InGaAsP
Wavelength	-	1310 nm
Bit Rate (B)	-	100 Mb/s to 1.7 Gb/s
Repeater Spacing	-	50 km

Long Wavelength Band (Third Window) - Third Generation
The band between about 1510 nm and 1600 nm has the lowest attenuation available on current optical Fiber (about 0.26 dB/km). In addition optical amplifiers are available which operate in this band. However, it is difficult (expensive) to make optical sources and detectors that operate here. Also, standard Fiber disperses signal in this band. In the late 1990s this band is where almost all new communications systems operate.

Semiconductor used	-	InGaAsP
Wavelength	-	1550 nm
Bit Rate (B)	-	10 Gb/s
Repeater Spacing	-	100 km

The Fourth Generation
The fourth generation of light wave systems makes use of *optical amplification* for increasing the repeater spacing and of *wavelength-division multiplexing* (WDM) for increasing the bit rate. In most WDM systems, fiber losses are compensated periodically using erbium-doped fiber amplifiers spaced 60–80 km apart. Such amplifiers were developed after 1985 and became available commercially by 1990.

Technology used	-	WDM
Wavelength	-	1450 to 1570 nm
Bit Rate (B)	-	10 Tb/s
Repeater Spacing	-	above 10000 km

The current emphasis of WDM light wave systems is on increasing the system capacity by transmitting more and more channels through the WDM technique. With increasing WDM signal bandwidth, it is often not possible to amplify all channels using a single amplifier. As a result, new kinds of amplification schemes are being explored for covering the spectral region extending from 1.45 to 1.62 μm.

The Fifth Generation

The fifth generation of fiber-optic communication systems is concerned with extending the wavelength range over which a WDM system can operate simultaneously. The conventional wavelength window, known as the C band, covers the wavelength range 1.53–1.57μm. It is being extended on both the long- and short-wavelength sides, resulting in the L and S bands, respectively. The Raman amplification technique can be used for signals in all three wavelength bands. Moreover, a new kind of fiber, known as the *dry fiber* has been developed with the property that fiber losses are small over the entire wavelength region extending from 1.30 to 1.65 μm. Availability of such fibers and new amplification schemes may lead to lightwave systems with thousands of WDM channels.

Technology used	-	WDM with RAMAN Amplifier & Optical Soliton
Wavelength	-	1530 to 1570 nm
Bit Rate (B)	-	40 to 160 Gb/s
Repeater Spacing	-	25000 to 35000 km

The fifth-generation systems also attempt to increase the bit rate of each channel within the WDM signal. Starting in 2000, many experiments used channels operating at 40 Gb/s; migration toward 160 Gb/s is also likely in the future. Such systems require an extremely careful management of fiber dispersion. An interesting approach is based on the concept of *optical solitons*—pulses that preserve their shape during propagation in a lossless fiber by counteracting the effect of dispersion through the fiber nonlinearity.

Even though the fiber-optic communication technology is barely 25 years old, it has progressed rapidly and has reached a certain stage of maturity. This is also apparent from the publication of a large number of books on optical communications and WDM networks since 1995.

Spectrum	Frequency	Wavelength
Radio Waves	100 KHz to 1 THz	3 km to 300 μm
Infra Red Light	1 THz to 100 THz	300 to μm
Optical Communication	176 THz to 375 THz	1.7 to 0.8 μm
1550 nm Window	193.5 THz	1.550 μm
1310 nm Window	230 THz	1.310 μm
850 nm Window	353 THz	0.85 μm
Visible Light	428 THz to 750 THz	0.7 to 0.4 μm
UV, X & γ rays	750 THz to 10^7 THz	0.4 to $3*10^{-6}$ μm

Fiber optic systems usually use the 850, 1300, and 1550 nm wavelengths for transmission. Because losses are lower at these wavelengths due to properties inherent to the glass.

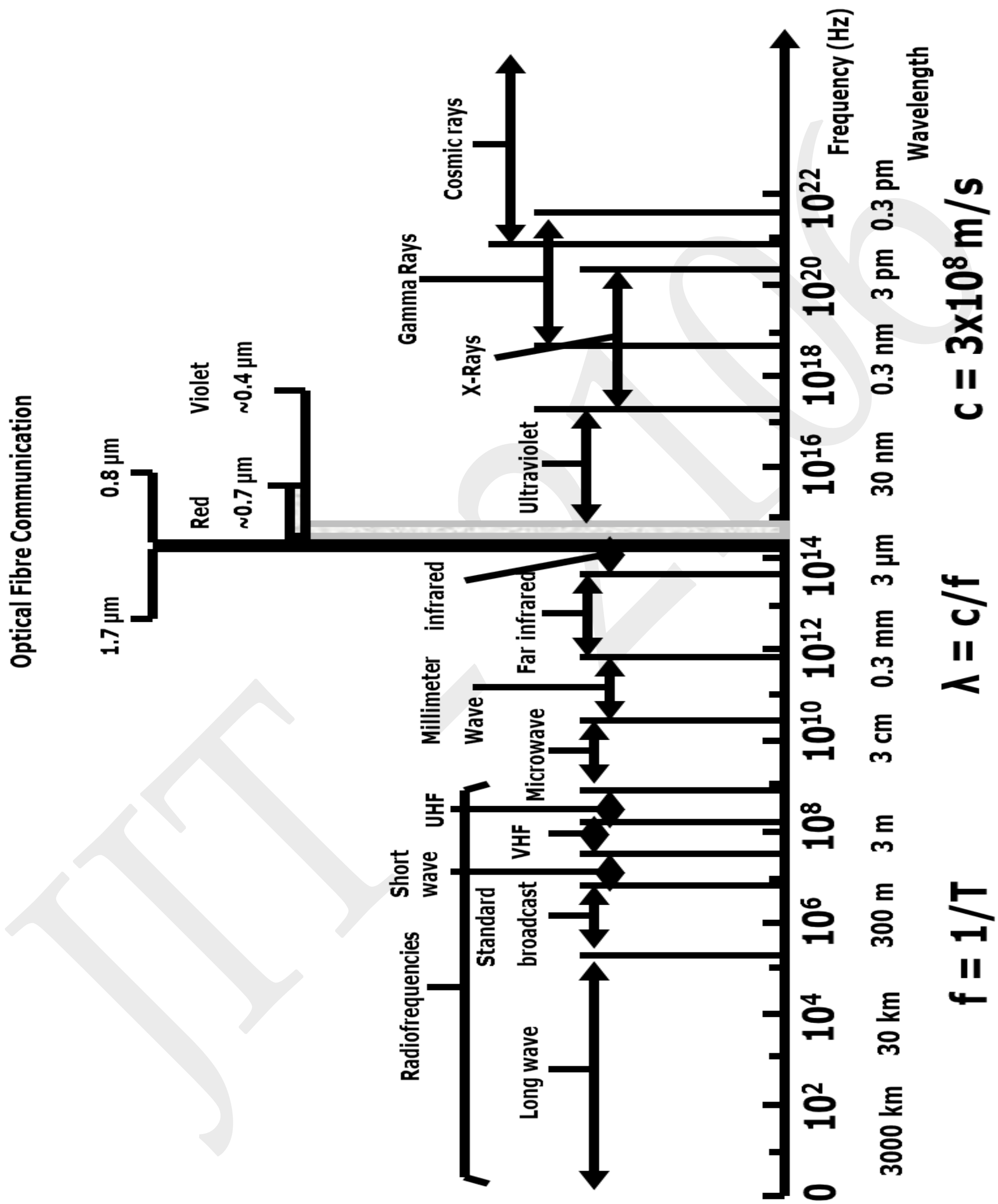


Fig 1.6 Wavelength Range of Electromagnetic Transmission

1.8 Light Transmission in a Fiber

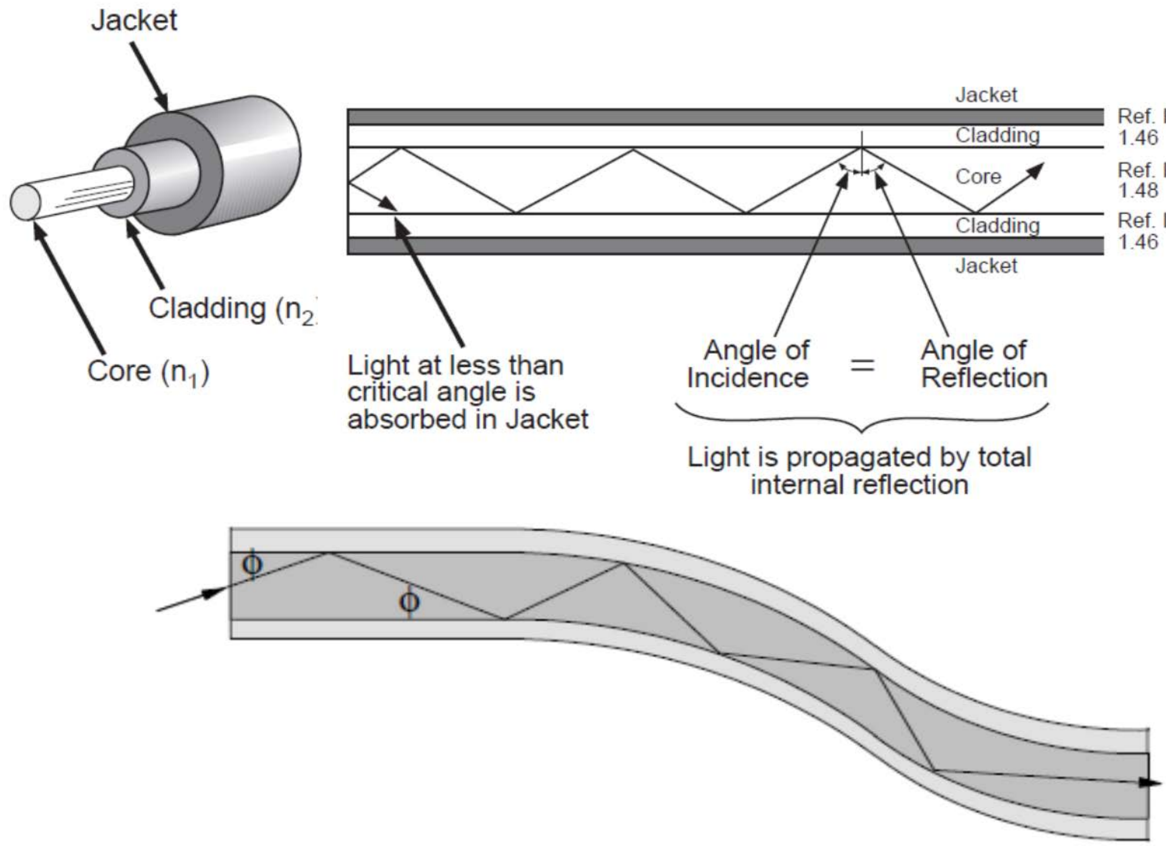


Fig 1.7 Light Travel in a Fiber

The key feature of light propagation in a fiber is that the fiber may bend around corners. Provided the bend radius is not too tight (2 cm is about the minimum for most multimode fibers) the light will follow the fiber and will propagate without loss due to the bends. This phenomenon is called **"Total Internal Reflection".**

A ray of light entering the fiber is guided along the fiber because it bounces off the interface between the core and the (lower refractive index) cladding. Light is said to be "bound" within the fiber.

Reflection

The amount of light reflected away from the surface.

Two types of Reflections:

Diffuse Reflection: The reflection from rough surface.
Specular Reflection: The reflection from smooth surface. A good mirror is specular reflection source.

According to law of reflection, "The angle of incidence is equal to the angle of reflection." This means that $\Theta_1 = \Theta_2$.

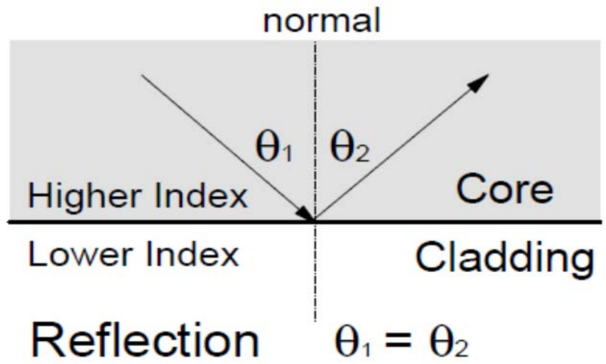


Fig 1.8 Reflection Principal

Refraction

As electromagnetic wave changes direction at the interface of two mediums, if the angle of incidence is not 90 then the index of refraction of light is the sine of angle of incidence to the sine of angle of refraction. The refractive index is the function or wavelength.

The Snells law is $n1/n2 = \sin\beta / \sin\alpha$

When light moves from rare medium to denser medium it refracts towards normal and vice versa.

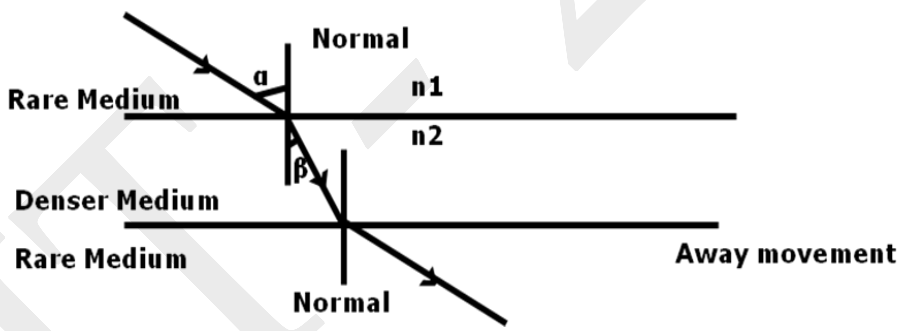


Fig 1.9 Refraction Principal

Refractive Index:

The refractive index (symbolized as *n*) of a material is defined as the ratio of the speed of light in a vacuum to the speed of light in the material.

Light is bent as it passes through a surface where the refractive index changes, for example, as it passes from air to glass. This **"Bending"** of light is called refraction. The amount of bending depends on the refractive indexes of the two materials and the angle at which the light strikes the surface between them.

The ratio of speed of light travelling at free space to speed of light travelling in medium.

$$Refractive\ Index = \frac{c}{v}$$

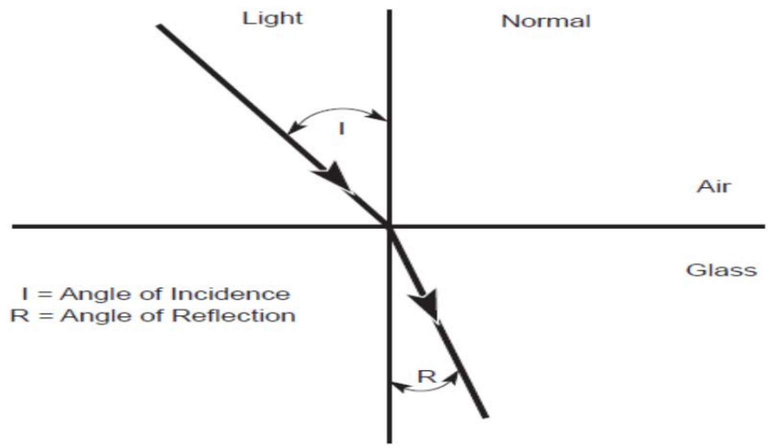


Fig 1.10 Refractive Index

C = vλ. Light travel in free space depends upon velocity and wavelength. Where C= $3 * 10^8$ (Speed of Light)

Wavelength
The distance between crests of electromagnetic waveform measured in nm.

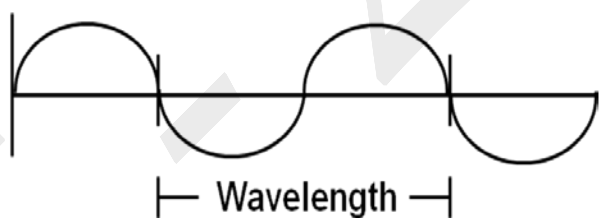


Fig. 1.11 Wavelength

Material	Refractive Index	Speed of Light
Air	1.00028	299,706 Km/s
Ice	1.310	228,847 Km/s
Water	1.333	224,900 Km/s
Perspex	1.495	200,528 Km/s
Typical Fiber Core	**1.487**	**201,607 Km/s**
Crown Glass	1.52	197,230 Km/s
Flint Glass	1.62	185,055 Km/s
Diamond	2.42	123,880 Km/s

Refractive Index versus Wavelength

Wavelength λ (nm)	Refractive Index n
600	1.4580
700	1.4553
800	1.4533
900	1.4518
1000	1.4504
1100	1.4492
1200	1.4481
1300	1.4469
1400	1.4458
1500	1.4466
1600	1.4434
1700	1.4422
1800	1.4409

Refraction and Snell's Law

When a ray is incident on the interface between two media of differing refractive indices, refraction takes place

Snell's law defines the relationship between refractive indices and the light ray angles

$$n_1 \sin \Theta_1 = n_2 \sin \Theta_2$$

Where n denotes the refractive index of the material.

The refractive index of the core, n1, is always greater than the index of the cladding, n2. Light is guided through the core, and the fiber acts as an optical waveguide.

If we know the refractive indices of both materials then the critical angle can be derived quite easily from Snell's law. At the critical angle we know that Θ_2 equals 90° and sin 90° = 1 and so:

$$n_1 \sin \Theta_1 = n_2$$

Therefore

$$\sin \Theta_1 = \frac{n_2}{n_1}$$

Consider an example with a light ray travelling from one medium to another

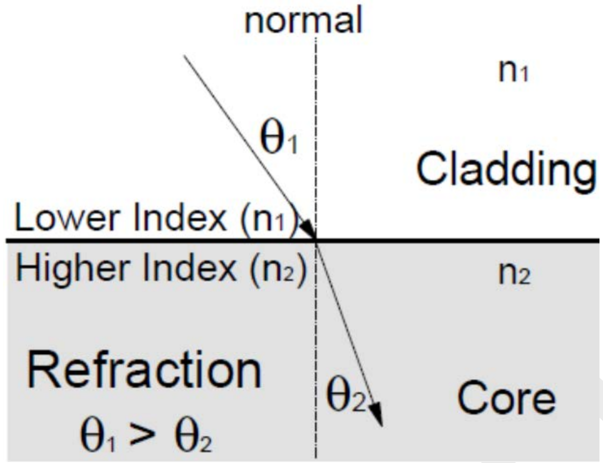


Fig 1.12 Refraction Principal

Notice here that:

1. The angle ө is the angle between incident ray and an imaginary line normal to the plane of the core-cladding boundary. This is counter to intuition but the accepted convention.
2. When light passes from material of higher refractive index to a material of lower index the (refracted) angle ө gets larger.
3. When light passes from material of lower refractive index to a material of higher index the (refracted) angle ө becomes smaller.

The principle of Total Internal Reflection (TIR)

If the light rays enter from optically denser medium to optically rare medium, it will move away from the normal. If the angle of incidence is increased so that the angle of refraction becomes 90^0.

The phenomena known as total internal reflection will occur, if angle of incidence is further increased. The light instead of refracting will reflect internally. The phenomenon used in optical fiber communication/ propagation

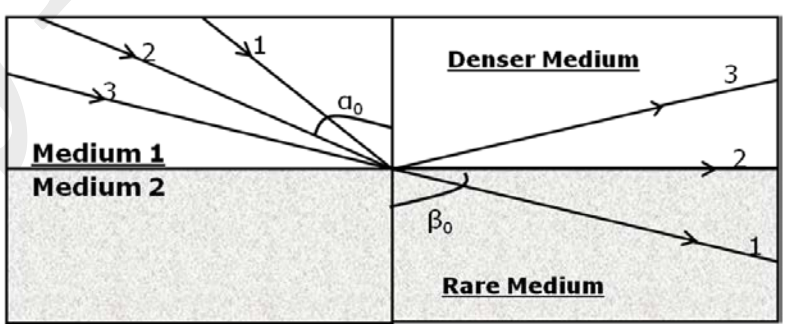


Fig 1.13 Total Internal Reflection

Physics of Total Internal Reflection

Consider a ray of light passing between two media of different refractive indexes n1 and n2 as shown in figure. If n1 > n2 the light ray as it passes from one media to the next will bend away from an imaginary line (the normal) perpendicular to the media's mating surface. Conversely if n1 < n2 then the ray will bend towards the normal.

Total internal reflection occurs when n1 > n2 and the incident ray of light makes an angle, Θc, such that it does not enter the adjacent medium but travels along the interface. At angles greater than Θc the ray will be reflected back into medium A.

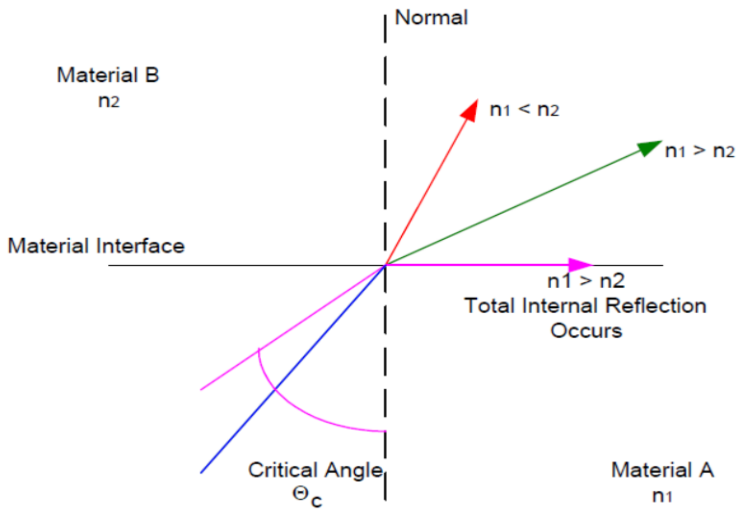


Fig 1.14 Total Internal Reflection

Ray Theory

Light is confined within the core of the optical fiber through total internal reflection. To understand the phenomenon of total internal reflection and how it is responsible for the confinement of light in an optical fiber consider a ray of light incident on the fiber core as shown in figure.

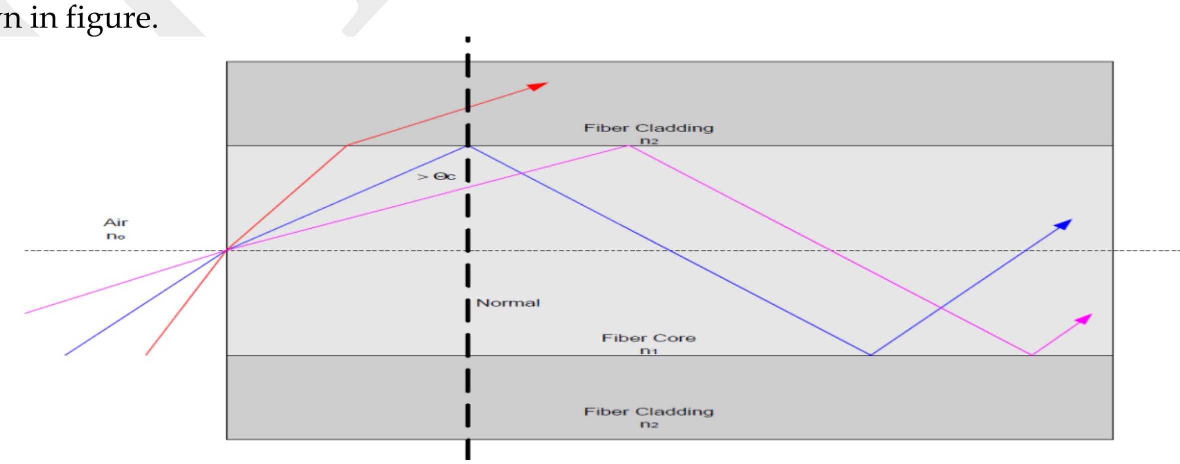


Fig 1.15 Light Propagates through a Fiber due to Total Internal Reflection

Light enters the core of the optical fiber and strikes the core/cladding interface at an angle ϴ. If this angle is greater than the critical angle (i.e. ϴ ≥ ϴc where ϴc =arcsin (n2/n1)) then the ray will reflect back into the core thus experiencing total internal reflection. This ray of light will continue to experience total internal reflection as it encounters core/cladding interfaces while propagating down the fiber.

Conditions for Propagation

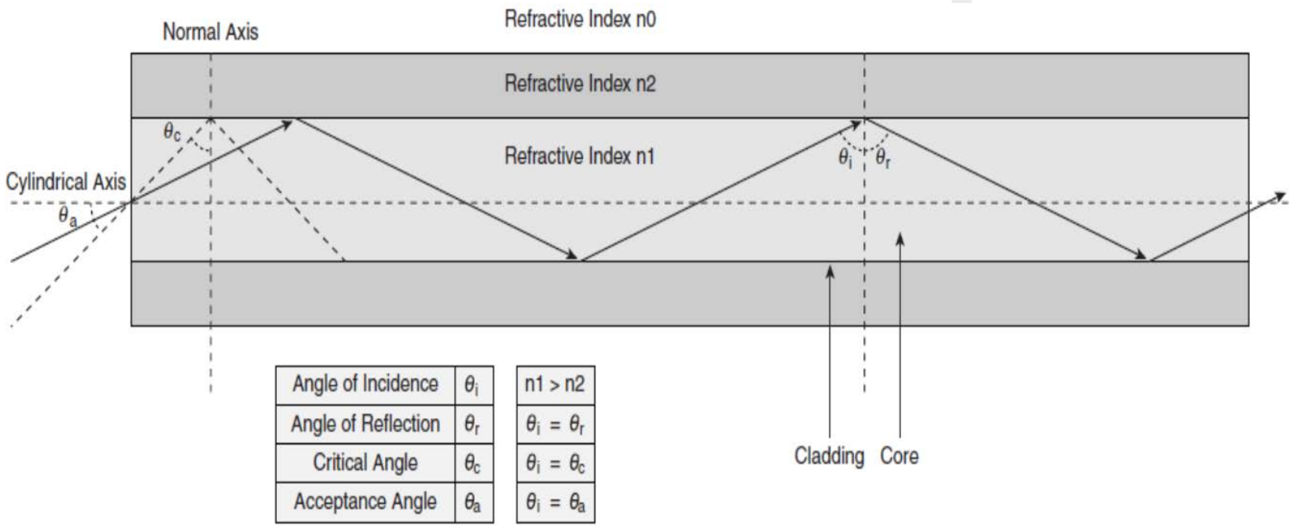


Fig 1.16 Total Internal Reflection in an Optical Fiber

Figure shows the propagation of light down the fiber-optic cable using the principle of total internal reflection. As illustrated, a light ray is injected into the fiber-optic cable on the left. If the light ray is injected and strikes the core-to-cladding interface at an angle greater than the critical angle with respect to the normal axis, it is reflected back into the core. Because the angle of incidence is always equal to the angle of reflection, the reflected light continues to be reflected. The light ray then continues bouncing down the length of the fiber-optic cable.

If the angle of incidence at the core-to-cladding interface is less than the critical angle, both reflection and refraction take place. Because of refraction at each incidence on the interface, the light beam attenuates and dies off over a certain distance.

The **critical angle** is fixed by the indices of refraction of the core and cladding and is computed using the following formula:

$$\theta_c = sin^{-1}\left(\frac{n_2}{n_1}\right)$$

The critical angle can be measured from the normal or cylindrical axis of the core. If n_1=1.557 and n_2 = 1.343, for example, the critical angle is 30.39 degrees.

Figure shows a light ray entering the core from the outside air to the left of the cable. Light must enter the core from the air at an angle less than an entity known as the **acceptance angle** (θa):

$$\theta_a = sin^{-1}\left[\left(\frac{n_1}{n_0}\right) sin(\theta_c)\right]$$

Or

$$\theta_a = sin^{-1}\,(NA)$$

In the formula, n0 is the refractive index of air and is equal to one. This angle is measured from the cylindrical axis of the core. In the preceding example, the acceptance angle is 51.96 degrees.

The optical fiber also has a numerical aperture (NA). The NA is given by the following formula:

Numerical Aperture = Sin θa

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

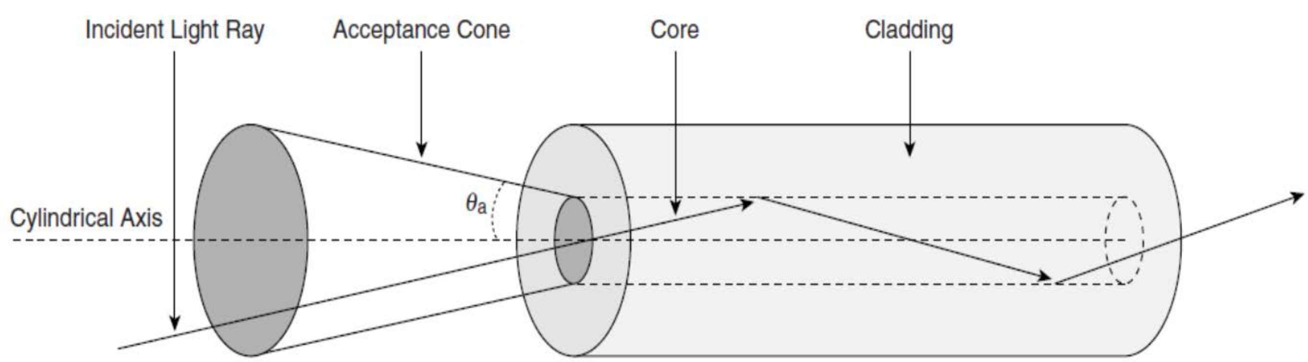


Fig 1.17 Acceptance Cone

From a three-dimensional perspective, to ensure that the signals reflect and travel correctly through the core, the light must enter the core through an acceptance cone derived by rotating the acceptance angle about the cylindrical fiber axis. As illustrated in Figure, the size of the acceptance cone is a function of the refractive index difference between the core and the cladding. There is a maximum angle from the fiber axis at which light can enter the fiber so that it will propagate, or travel, in the core of the fiber. The sine of this maximum angle is the NA of the fiber. The NA in the preceding example is 0.787. Fiber with a larger NA requires less precision to splice and work with than fiber with a smaller NA. Single-mode fiber has a smaller NA than MMF.

This last value is the maximum value that Incident Angle can take on if TIR is to take place; it is therefore called the **fiber acceptance angle**.

Acceptance Angle & Numerical Analysis

Numerical aperture (NA) is defined as the sine of the acceptance angle for a fiber. Thus the NA can be written as:

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

The Numerical Aperture (NA) of a fiber is the maximum angle that light can be accepted into the fiber. The acceptance angle will vary depending on the refractive indexes of the core and the cladding.

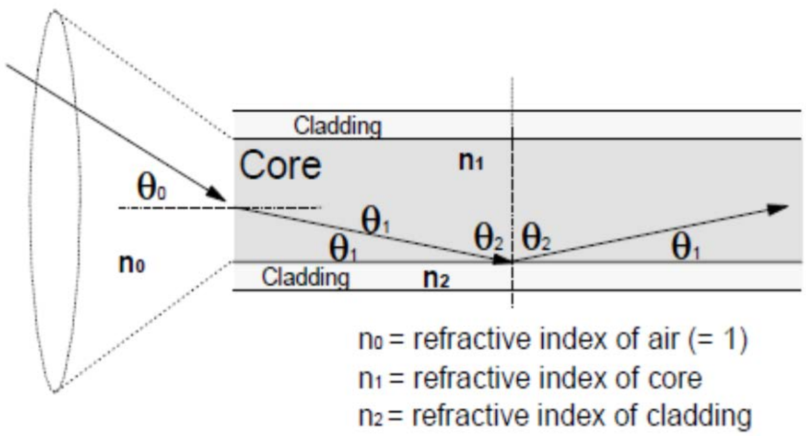


Fig 1.18 Acceptance Angle Analyze

Typical NA For single-mode fiber is 0.1.
For multimode, NA is between 0.2 and 0.3 (usually closer to 0.2).

NA is related to a number of important fiber characteristics.

1. It is a measure of the ability of the fiber to gather light at the input end.

2. Because it is a measure of the contrast in RI between the core and the cladding it is a good measure of the light guiding properties of the fiber. The higher the NA the tighter (smaller radius) we can have bends in the fiber before loss of light becomes a problem.

3. The higher the NA the more modes we have Rays can bounce at greater angles and therefore there are more of them. This means that the higher the NA the greater will be the dispersion of this fiber (in the case of MM fiber)

4. In SM fiber a high RI contrast usually implies a high level of dopant in the cladding. Since a significant proportion of optical power in SM travels in the cladding we get a significantly increased amount of attenuation due to the higher level of dopant. Thus (as a rule of thumb) the higher the NA of SM fiber the higher will be the attenuation of the fiber.

The problem is to find an expression for NA

We know that $\sin\theta_2 = \frac{n_2}{n_1}$ because Θ_2 is the critical angle

And $n_0 \sin\theta_0 = n_1 \sin\theta_1$ from snell's Law

Now, $\cos\theta_1 = \sin\theta_2 = \frac{n_2}{n_1}$

We know that $\sin x = \sqrt{1 - \cos^2 x}$ (Mathematical Rule)

Therefore $\sin\theta_1 = \sqrt{1 - \frac{n_2^2}{n_1^2}}$

Since $n_0 = 1$ then $\sin\theta_0 = n_1\sqrt{1 - \frac{n_2^2}{n_1^2}}$

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

Where n_1 – Refractive Index of the Core

n_2 – Refractive Index of the Cladding

Fibers having a large N.A. enter the fiber at a steeper angle, which results in light taking more time to propagate down the fiber. This decreases the bandwidth and increases the attenuation. Fibers having a small N.A. enter the fiber at less of an angle, which results in light taking less time to propagate down the fiber. This increases the bandwidth and decreases the attenuation.

1.9 Meridional ray & Skew Ray Propagation

Meridional Rays in Fiber

Meridional rays are the rays following Zig Zag path when they travel through fiber and for every reflection it will cross the fiber axis.

Example: Singlemode Step Index Fiber, Multimode Step Index Fiber

Skew Rays in Fiber

Skew rays are the rays following the helical path around the fiber axis when they travel through the fiber and they would not cross the fiber axis at any time.

Example: Multimode Gradded Index Fiber

Skew ray propagation is difficult to visualize, but looking at the fiber end on we see a 2d projection of the rays. Seen in this way reflection takes place with an angle γ to the radius

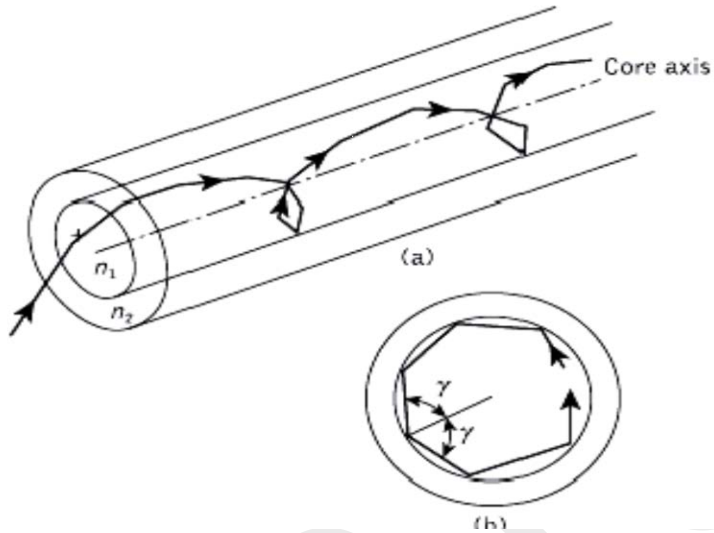


Fig 1.19 a) Meridional Rays b) Skew Ray

With Meridional rays at the fiber output the angle depends on the input angle. For skew rays this is not so, instead the output angle depends on the number of reflections undergone. Thus skew rays tend to make the light output from a fiber more uniform.

Ray direction defined in two planes as shown.

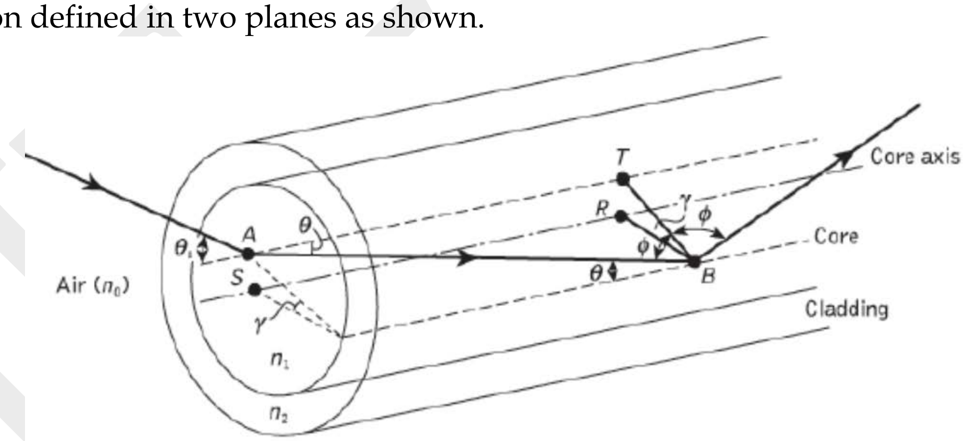


Fig 1.20 Skew Ray Directions

In point B:

$$\cos\gamma \sin\theta = \cos\Phi$$

Using trigonometrically relationship, it becomes

$$\cos\gamma \sin\theta = \cos\Phi = (1 - sin^2\Phi)^{\frac{1}{2}}$$

If the limiting case for total internal reflection is considered

$$\cos\gamma \sin\theta \leq \cos\Phi_c = \left(1 - \frac{n_2^2}{n_1^2}\right)^{\frac{1}{2}}$$

The Snell's law at point A:

$$n_0 \sin\theta_a = n_1 \sin\theta$$

Therefore, we get the maximum acceptance angle for skew rays

$$\sin\theta_{as} = \frac{n_1}{n_0}\frac{\cos\emptyset_c}{\cos\gamma} = \frac{n_1}{n_0\cos\gamma}\left(1 - \frac{n_2^2}{n_1^2}\right)^{\frac{1}{2}}$$

The acceptance conditions for skew rays are:

$$n_0 \sin\theta_{as}\cos\gamma = (n_1^2 - n_2^2)^{\frac{1}{2}} = NA$$

$$\textbf{Acceptance Angle for Skew Rays} = \sin^{-1}\left[\frac{\sqrt{n_1^2 - n_2^2}}{\cos\gamma}\right]$$

In the case of the fiber in air:

$$\sin\theta_{as}\cos\gamma = NA$$

γ is the angle of reflection for skew rays within the fiber, defined previously. Since cos γ is < 1, acceptance angle is higher for skew rays.

1.10 Optical Fiber Modes and Configuration

The modes of the fiber refer to the number of paths for the light rays within the cable. According to modes optic fibers can be classified into two types

- Single Mode Fiber - Single path for Light rays with in the cable (Only one Light can travel)
- Multimode Fiber - Multipath for the light rays with in the cable (Many Bundles of fiber)

Optical Fiber Configuration:

Depending on the refractive index profile of fiber and modes of the fiber, there exists three types of optical fiber configuration.

- ❖ Single Mode Step Index Fiber
- ❖ Multimode Step Index Fiber
- ❖ Multimode Gradded Index Fiber

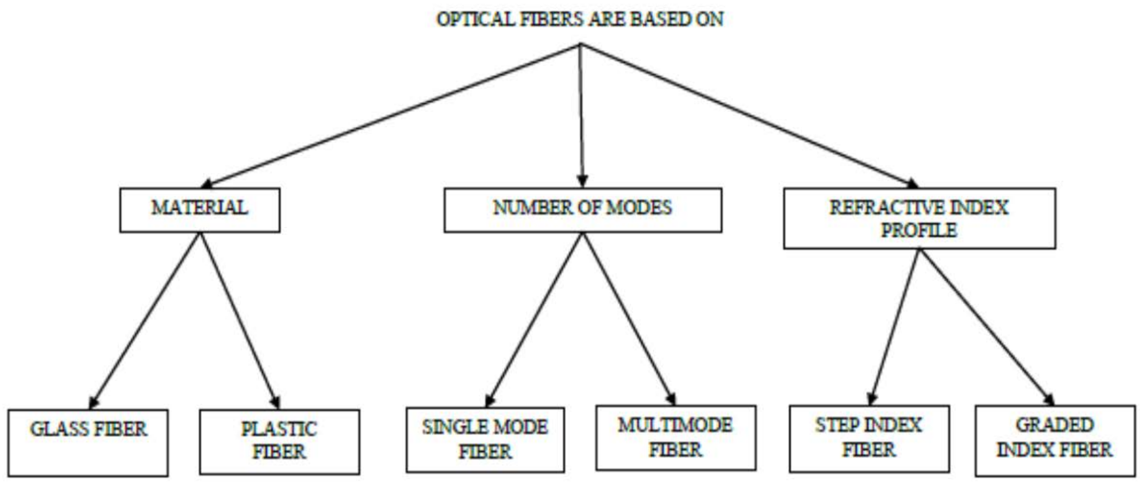


Fig 1.21 Types of Optical Fiber

Operational Principles

The difference between them is in the way light travels along the Fiber. The top section of the following figure shows the operation of "multimode" Fiber. There are two different parts to the Fiber.

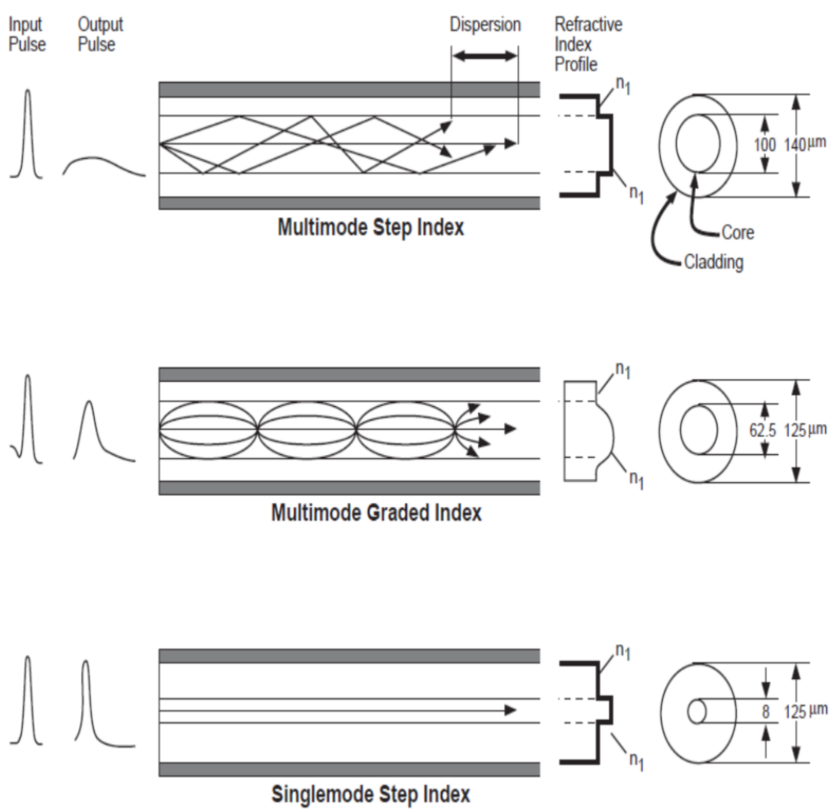


Fig 1.22 Illustrates the three different kinds of optical fiber.

In the figure, there is a core of 50 microns (µm) in diameter and a cladding of 125 µm in diameter. (Fiber size is normally quoted as the core diameter followed by the cladding diameter. Thus the Fiber in the figure is identified as 50/125.) The cladding surrounds the core. The cladding glass has a different (lower) refractive index than that of the core, and the boundary forms a mirror.

Single-Mode Fiber:

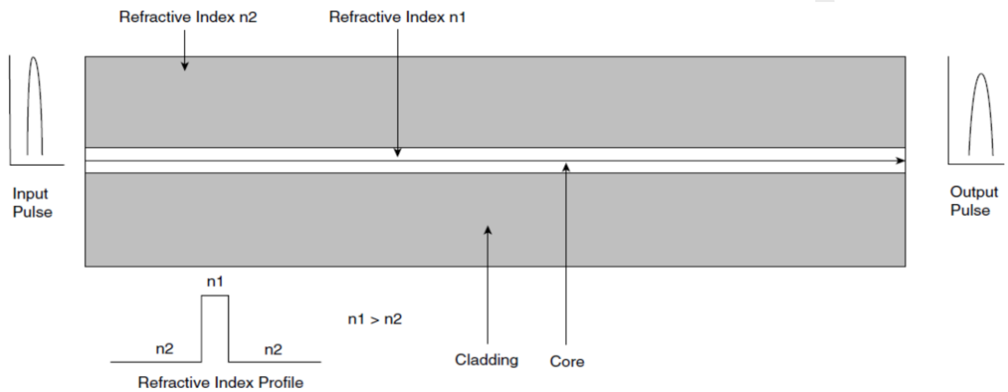


Fig 1.23 Single-Mode Fiber

The **core diameter is typically between 8 and 9 microns** while the diameter of **the cladding is 125 microns.** If the fiber core is very narrow compared to the wavelength of the light in use then the light cannot travel in different modes and thus the fiber is called "**single-mode" or "monomode".**

There is no longer any reflection from the core-cladding boundary but rather the electromagnetic wave is tightly held to travel down the axis of the fiber. It seems obvious that the longer the wavelength of light in use, the larger the diameter of fiber we can use and still have light travel in a single-mode. The core diameter used in a typical single-mode fiber is nine microns. It is not quite as simple as this in practice. A significant proportion (up to 20%) of the light in a single-mode fiber actually travels in the cladding. For this reason the "apparent diameter" of the core (the region in which most of the light travels) is somewhat wider than the core itself.

The region in which light travels in a single-mode fiber is often called the "mode field" and the mode field diameter is quoted instead of the core diameter. The mode field varies in diameter depending on the relative refractive indices of core and cladding, Core diameter is a compromise. We can't make the core too narrow because of losses at bends in the fiber. As the core diameter decreases compared to the wavelength (the core gets narrower or the wavelength gets longer), the minimum radius that we can bend the fiber without loss increases. If a bend is too sharp, the light just comes out of the core into the outer parts of the cladding and is lost.

You can make fiber single-mode by:

1. Making the core thin enough
2. Making the refractive index difference between core and cladding small enough
3. Using a longer wavelength

Single-mode fiber usually has significantly lower attenuation than multimode (about half). This has nothing to do with fiber geometry or manufacture. Single-mode fibers have a significantly smaller difference in refractive index between core and cladding. This means that less dopant is needed to modify the refractive index as dopant is a major source of attenuation. It's not strictly correct to talk about "single-mode fiber" and "multimode fiber" without qualifying it - although we do this all the time.

Single-mode step-index fiber allows for only one path, or mode, for light to travel within the fiber. In a multimode step-index fiber, the number of modes M_n propagating can be approximated by

$$M_n = \frac{V^2}{2}$$

Here V is known as the normalized frequency, or the ***V*-number**, which relates the fiber size, the refractive index, and the wavelength. The V-number is given by Equation

$$V = \left[\frac{2\pi a}{\lambda}\right] * NA$$

or by Equation

$$V = \left[\frac{2\pi a}{\lambda}\right] * n_1 * (2\Delta)^{\frac{1}{2}}$$

In either equation,

a is the fiber core radius
λ is the operating wavelength
N.A. is the numerical aperture
$n1$ is the core index and
Δ is the relative refractive index difference between core and cladding.

The analysis of how the V-number is derived is beyond the scope of this module, but it can be shown that by reducing the diameter of the fiber to a point at which the V-number is less than 2.405, higher order modes are effectively extinguished and single-mode operation is possible. The core diameter for a typical single-mode fiber is between 5 μm and 10 μm with a 125-μm cladding. Single-mode fibers are used in applications in which low signal loss and high data rates are required, such as in long spans where repeater/amplifier spacing must be maximized.

Because single-mode fiber allows only one mode or ray to propagate (the lowest-order mode), it does not suffer from modal dispersion like multimode fiber and therefore can be used for higher bandwidth applications. However, even though single-mode fiber is not affected by modal dispersion, at higher data rates chromatic dispersion can limit the performance.

This problem can be overcome by several methods. One can transmit at a wavelength in which glass has a fairly constant index of refraction (~1300 nm), use an optical source such as a distributed feedback laser (DFB laser) that has a very narrow output spectrum, use special dispersion compensating fiber, or use a combination of all these methods. In a nutshell, single-mode fiber is used in high-bandwidth, long-distance applications such as long-distance telephone trunk lines, cable TV head-ends, and high-speed local and wide area network (LAN and WAN) backbones.

The major drawback of single-mode fiber is that it is relatively difficult to work with (i.e., splicing and termination) because of its small core size. Also, single-mode fiber is typically used only with laser sources because of the high coupling losses associated with LEDs.

Multimode Step-Index Fiber

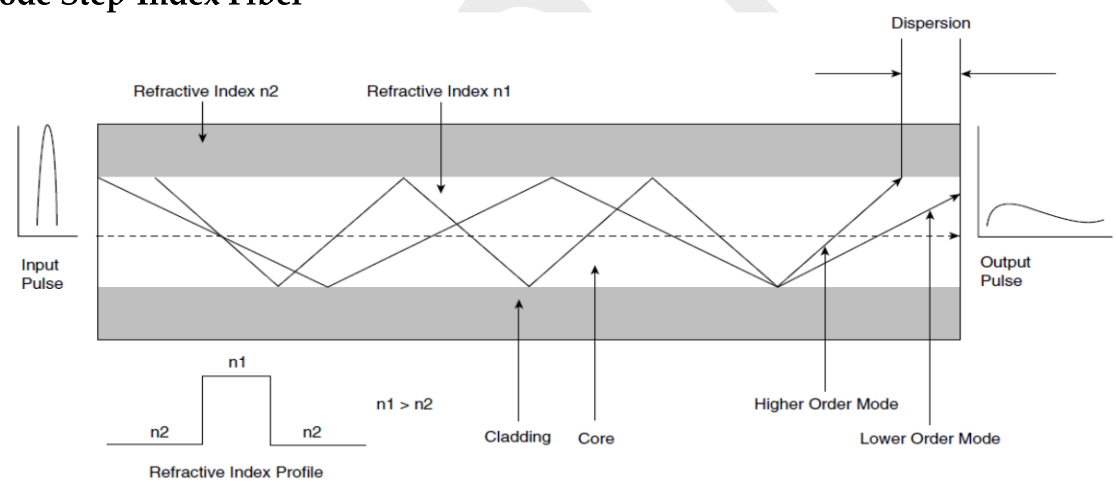


Fig 1.24 Multimode Step Index Fiber

The expectation of many people is that if you shine a light down a Fiber, then the light will enter the Fiber at an infinitely large number of angles and propagate by internal reflection over an infinite number of possible paths. This is not true.

What happens is that there are only a finite number of possible paths for the light to take. These paths are called "modes" and identify the general characteristic of the light transmission system being used. Fiber that has a core diameter large enough for the light used to find multiple paths is called "multimode" Fiber.

Step-index multimode fiber has an index of refraction profile that "steps" from low to high to low as measured from cladding to core to cladding. Relatively large core diameter and numerical aperture characterize this fiber.

The **core/cladding diameter** of a typical multimode fiber used for telecommunication is **62.5/125 µm** (about the size of a human hair). The term “multimode” refers to the fact that multiple *modes* or *paths* through the fiber are possible. Step index multimode fiber is used in applications that require high bandwidth (< 1 GHz) over relatively short distances (< 3 km) such as a local area network or a campus network backbone.

For a Fiber with a core diameter of 62.5 microns using light of wavelength 1300 nm, the number of modes is around 400 depending on the difference in refractive index between the core and the cladding. The problem with multimode operation is that some of the paths taken by particular modes are longer than other paths. This means that light will arrive at different times according to the path taken. Therefore the pulse tends to disperse (spread out) as it travels through the Fiber. This effect is one cause of “intersymbol interference”. This restricts the distance that a pulse can be usefully sent over multimode Fiber.

Multimode Graded Index Fiber

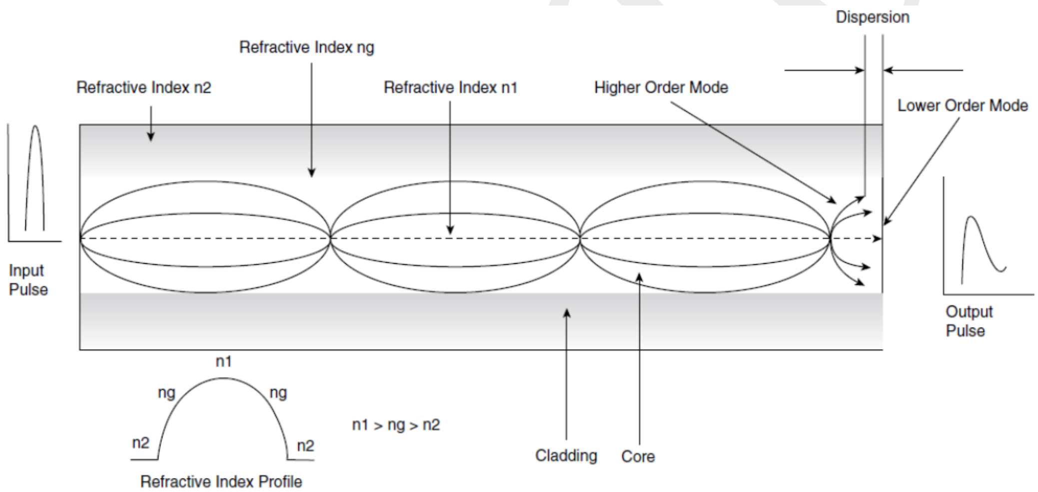


Fig 1.25 Multimode Graded index Fiber

One way around the problem of (modal) dispersion in multimode Fiber is to do something to the glass such that the refractive index of the core changes gradually from the center to the edge. Light travelling down the center of the Fiber experiences a higher refractive index than light that travels further out towards the cladding. Thus light on the physically shorter paths (modes) travels more slowly than light on physically longer paths. The light follows a curved trajectory within the Fiber as illustrated in the figure.

The aim of this is to keep the speed of propagation of light on each path the same with respect to the axis of the Fiber. Thus a pulse of light composed of many modes stays together as it travels through the Fiber. This allows transmission for longer distances than does regular multimode transmission. This type of Fiber is called “Graded Index” Fiber. Within a GI Fiber light typically travels in around 400 modes (at a wavelength of 1300 nm) or 800 modes (in the 800 nm band).

Graded-index fiber is a compromise between the large core diameter and N.A. of multimode fiber and the higher bandwidth of single-mode fiber. With creation of a core whose index of refraction decreases parabolically from the core center toward the cladding, light traveling through the center of the fiber experiences a higher index than light traveling in the higher modes. This means that the higher-order modes travel faster than the lower-order modes, which allows them to "catch up" to the lower-order modes, thus decreasing the amount of modal dispersion, which increases the bandwidth of the fiber

Note that only the refractive index of the core is graded. There is still a cladding of lower refractive index than the outer part of the core.

The major benefits of multimode fiber are:

1. It is relatively easy to work with
2. Because of its larger core size, light is easily coupled to and from it
3. It can be used with both lasers and LEDs as sources; and
4. Coupling losses are less than those of the single-mode fiber.

The drawback is that because many modes are allowed to propagate (a function of core diameter, wavelength, and numerical aperture) it suffers from modal dispersion. The result of modal dispersion is bandwidth limitation, which translates into lower data rates.

A fiber is single-mode or multi-mode at a particular wavelength. If we use very long wave light (say 10.6 nm from a CO^2 laser) then even most MM fiber would be single-mode for that wavelength. If we use 600 nm light on standard single-mode fiber then we do have a greater number of modes than just one (although typically only about 3 to 5). There is a single-mode fiber characteristic called the "cutoff wavelength". This is typically around 1100 nm for single-mode fiber with a core diameter of 9 microns. The cutoff wavelength is the shortest wavelength at which the fiber remains single-mode. At wavelengths shorter than the cutoff the fiber is multimode. When light is introduced to the end of a fiber there is a critical angle of acceptance. Light entering at a greater angle passes into the cladding and is lost. At a smaller angle the light travels down the fiber. If this is considered in three dimensions, a cone is formed around the end of the fiber within which all rays are contained. The sine of this angle is called the "numerical aperture" and is one of the important characteristics of a given fiber.

Single-mode fiber has a core diameter of 4 to 10 µm (8 µm is typical). Multimode fiber can have many core diameters but in the last few years the core diameter of 62.5 µm in the US and 50 µm outside the US has become predominant. However, the use of 62.5 µm fiber outside the US is gaining popularity - mainly due to the availability of equipment (designed for the US) that uses this type of fiber.

Comparison of Various Fibers

Single Mode Fiber	Multimode Fiber
In single mode fiber only one mode (LP_{01} mode or HE_{11} mode) can propagate through the fiber	Multimode fiber allows a large number of paths or modes for the light rays travelling through it
The single mode fiber has smaller core diameter (10µm) and the difference between the refractive indices of the core and cladding is very small	Generally in multimode fiber core diameter and the relative refractive index difference are larger than the single mode fiber
In practice there is no dispersion (i.e. no degradation of signal during travelling through the fiber)	Even though there is self focussing effect there is signal degradation due to multimode dispersion and material dispersion
Since the information transmission capacity in optical fiber is inversely proportional to dispersion, the single mode fibers are more suitable for long distance communication.	Due to large dispersion and attenuation of the signal the multimode fibers are less suitable for communication. Anyhow these fibers are generally used in the local area networks
Launching of light into single mode fibers and jointing of two fibers are very difficult	Launching of light into fiber and jointing of two fibers are easy in these fibers
Fabrication is very difficult and so the fiber is so costly	Fabrication is less difficult and so the fiber is not costly
The condition for the single mode operation is given by the V number of the fiber which is defined as $V = \frac{2\Pi a}{\lambda} n_1 a \sqrt{2\Delta}$ Such that $V \leq 2.405$ Here a = radius of the core of the fiber n_1= refractive index of the core λ= wavelength of light propagating through the fiber Δ=relative refractive index difference $\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \approx \frac{n_1 - n_2}{n_1}$ Where n_2= refractive index of cladding. When V = 2.405, then the wavelength of the fiber, which is the minimum wavelength that can be transmitted through the fiber.	Here the V-number is greater than 2.405. Total number of modes 'N' propagating through a given multimode step index fiber is given by $N = \frac{V^2}{2} = 4.9 \left(\frac{dn_1\sqrt{2\Delta}}{\lambda}\right)^2$ Where d is the diameter of the core of the fiber. For multimode graded index fiber having parabolic refractive index profile core, $N = \frac{V^2}{4}$ Which is half the number supported by a multimode step index fiber. Taking into account of the two possible polarizations, the maximum number of propagating modes is doubled such that $N_{step\ index} = V^2$ $N_{graded\ Index} = \frac{V^2}{2}$

Step Index Fiber	Graded Index Fiber
The refractive index of the core is uniform throughout and undergoes an abrupt (or) step change at the cladding boundary	The refractive index of the core is made to vary in the parabolic manner such that the maximum refractive index is present at the center of the core
The diameter of the core is about 50-200 µm in the case of multimode fiber and 10 µm in the case of single mode fiber	The diameter of the core is about 50µm in the case of multimode fiber
The light rays propagating through it are in the form of Meridional rays which will cross the fiber axis during every reflection at the core-cladding boundary and are propagating in a zig-zag manner.	The light rays propagating through it are in the form of skew rays (or) helical rays which will not cross the fiber axis at any time and are propagating around the fiber axis in a helical (or) spiral manner.
Attenuation is more for multimode step index fibers but for single mode step index fiber, it is very less.	Attenuation is less
Bandwidth is about 50 MHz-km for multimode step index fibers. But for single mode step index fibers, the bandwidth is more than 1 GHz-km	Bandwidth is from 200 MHz-km to 600 MHz-km
Numerical Aperture is more for multimode step index fibers but for single mode step index fiber, it is very less	Numerical Aperture is less
Signal distortion is more in multimode step index fiber since the rays reflected at high angles or the higher order modes travel a greater distance than the rays reflected at low angles or the lower order modes, to reach the exit end of the fiber. So high angle rays arrive later than the low angle rays. Hence the signal pulses are broadened out (dispersion) and distortion takes place. But this distortion does not take place in single mode step index fiber.	Signal distortion is very low because of self focussing effect. Here the light rays travel at different speeds in different paths of the fiber because the refractive index varies throughout the fiber. As a result rays near the outer edge travel faster than the light rays near the center of the core. In effect, light rays are continuously refocused as they travel down the fiber and almost all the rays reach the exit end of the fiber at the same time due to the helical path of the light propagation

Key Points

Description	MM.SI	MMGI	SMSI
Core Refractive Index	Constant	gradually varies	Constant
Signal	Delayed	no delay	no delay
Diameter of the Core	Large core diameter 50/125 µm or 62.5/125 µm.		Small core diameter 8/125 µm or 10/125 µm.
Application	Used for short haul distance Used heavily in LANS originally.		Used for long haul distance Deployed in carrier, local loop, and LANs.
Power launching	Easy		Difficult
Source	LED can be used		Laser
Splicing	Easy		Difficult
wavelength	850/1300 nm		1300 nm or 1550 nm
Cost	Originally the least expensive fiber produced.		Currently costs less than multimode.
Bandwidth	Limited bandwidth per kilometer 600 MHz for 1 km		Unlimited bandwidth. Single mode is specified by dispersion instead of bandwidth. Single mode's upper limits on bandwidth is in the THz.
Distance	850 nm wavelengths can travel approximately 3 miles before regeneration. 1300 nm Wavelength can travel approximately 8 miles.		1300 nm wavelength can travel approximately 25 miles before regeneration. 1550 nm wavelength can travel approximately 50 miles.

As you can see, single mode has advantages over multimode in cost, bandwidth, and the distance the signal can be transmitted without adding repeaters.

So why are multimode systems desirable in the LAN?

Multimode fibers usually incorporate LEDs instead of LASERs because of the short distance the signal needs to travel, which results in a large cost savings. When splicing fiber or installing connectors it is much easier to align the multimode fiber than single mode fiber because the core of the glass is much larger. The amount of training and expertise on multimode fiber is less critical.

	Step Index Fiber	Graded Index Fiber
Refractive Index Profile	$n_1\,;r \leq a$ $n_2\,;r > a$	$n_1\sqrt{1-2\Delta(r/a)^\alpha}\,;r \leq a$ $n_2\,;r > a$
Numerical Aperture	$\sqrt{n_1^2 - n_2^2}$	$\sqrt{n(r)^2 - n_2^2}\,;r \leq a$
Normalized Frequency (V)	$\frac{2\pi a}{\lambda}(NA)$	$\frac{2\pi a}{\lambda}(NA)$
Cut-off Value of the normalized frequency	2.405	$2.405\sqrt{1+2/\alpha}$
Number of Modes (M)	$V^2/2$	$\frac{V^2\alpha}{2(\alpha+2)}$
Modal Dispersion $\Delta T_{mod}/L$	$\frac{n_1^2\Delta}{cn_2}$	$\frac{n_1\Delta^2}{8c}$ (when $\alpha = 2(1-\Delta)$)

n_1	Core refractive index
n_2	Cladding refractive index ($n_1 > n_2$)
a	Core radius
r	Varying radius
α	Profile parameter
NA	Numerical Aperture
L	Total length of the optical fiber (typically in km)
Δ	$\frac{n_1^2 - n_2^2}{2n_1^2} \approx 1 - \frac{n_2}{n_1}$

1.11 Fiber Refractive Index Profiles

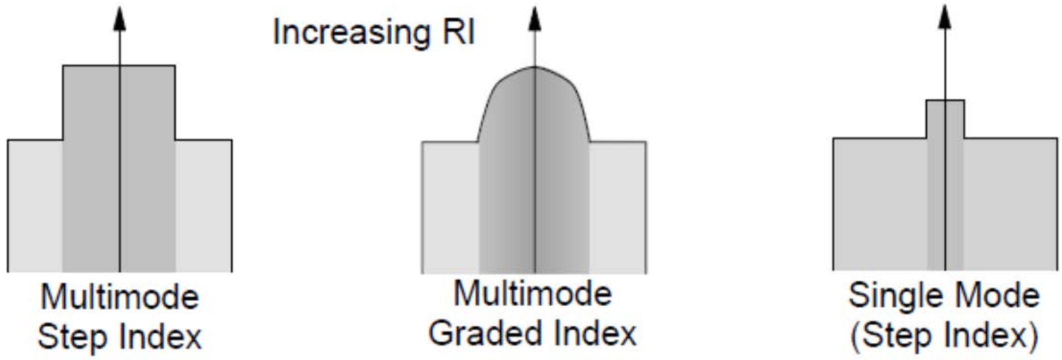


Fig 1.26 Fiber Refractive Index Profiles

Figure shows the refractive index profiles of some different types of fiber.

RI Profile of Multimode Step-Index Fiber

Today's standard MMSI fiber has a core diameter of either 62.5 or 50 microns with an overall cladding diameter in either case of 125 microns. Thus it is referred to as 50/125 or 62.5/125 micron fiber. Usually the core is SiO^2 doped with about 4% of GeO^2. The cladding is usually just pure silica. There is an abrupt change in refractive index between core and cladding. The bandwidth distance product for standard step index multimode fiber varies between about 15 MHz/km and 50 MHz/km depending on the wavelength in use, the core diameter and the RI contrast between core and cladding.

RI Profile of Multimode Graded Index Fiber

Graded index fiber has the same dimensions as step index fiber. The refractive index of the core changes slowly between the fiber axis and the cladding. This is achieved by using a varying level of dopant across the diameter of the core. Note the gradations are not linear - they follow a “parabolic” index profile. It is important to realize that GI fiber is relatively difficult to make and is therefore significantly more expensive than step index fiber (either MM or SM).

The usual bandwidth Distance product for 62.5 micron GI MM fiber is 500 MHz/km at 1300 nm. In the 800 nm band the bandwidth. Distance product is typically much less at 160 MHz/km. For MMGI fiber with a core diameter of 50 microns the bandwidth. Distance product is 700 MHz/km (again at 1300 nm). Recently (1997) MM GI fiber with significantly improved characteristics has become available. A bandwidth, Distance product figure for 62.5 micron fiber is advertised as 1000 MHz/km and for 50 micron fiber of 1,200 MHz/km. This is a result of improved fiber manufacturing techniques and better process control. Of course these fibers are considered “premium” fibers and are priced accordingly.

RI Profile of Single-Mode Fiber

Single-mode fiber is characterized by its narrow core size. This is done to ensure that only one mode (well, actually two if you count the two orthogonal polarizations as separate modes) can propagate. The key parameter of SM fiber is not the core size but rather the "Mode Field Diameter".

Core size is usually between 8 and 10 microns although special purpose SM fibers are often used with core sizes of as low as 4 microns. The RI difference between core and cladding is typically very small (around .01). This is done to help minimize attenuation. You can achieve the index difference either by doping the core to raise its RI (say with GeO^2) or by doping the cladding (say with fluoride) to lower its RI. Dopants in both core and cladding affect attenuation and therefore it's not a simple thing to decide. There are many different core and cladding compositions in use. Bandwidth, Distance product is not a relevant concept for single-mode fiber as there is no modal dispersion (although there is chromatic dispersion). The refractive index of fibers is changed and manipulated by adding various "dopants" to the basic SiO^2 glass.

These can have various effects:

- Some dopants increase the refractive index and others decrease it. This is the primary reason we use dopants.
- All dopants increase attenuation of the fiber. Thus dopants are to be avoided (or at least minimized) if attenuation is important for the fiber's application. It is almost always very important.

We might expect that since the light travels in the core that dopant levels in the cladding may not make too much difference. Wrong! In single-mode fiber a quite large proportion of the optical power (electromagnetic field) travels in the cladding. In single-mode fiber attenuation and speed of propagation are strongly influenced by the characteristics of the cladding glass. In multimode graded index fiber the core is doped anyway (albeit at different levels) so (for multimode) it is an issue even in the core. In multimode step-index fiber there is an "evanescent field" set up in the cladding every time a ray is reflected. This is an electromagnetic field and is affected by the attenuation characteristics of the cladding. If we use a dopant at too high a level not only does it change the refractive index of the glass but it also changes the coefficient of expansion. This means that in operational conditions if we use too much dopant the cladding may crack away from the core.

Mode Theory for Circular Waveguide (Key Model Concept)

By solving Maxwell's equation for hollow metallic waveguide we get transverse electric mode and transverse magnetic mode. It is not satisfied core-cladding boundary conditions.

In optical fiber 3 – modes satisfy this boundary conditions. That are

- Guided Modes
- Leaky Modes
- Radiation Modes

Guided mode used for signal transmission instead of TE and TM mode. We are using hybrid mode (3 different materials are used)

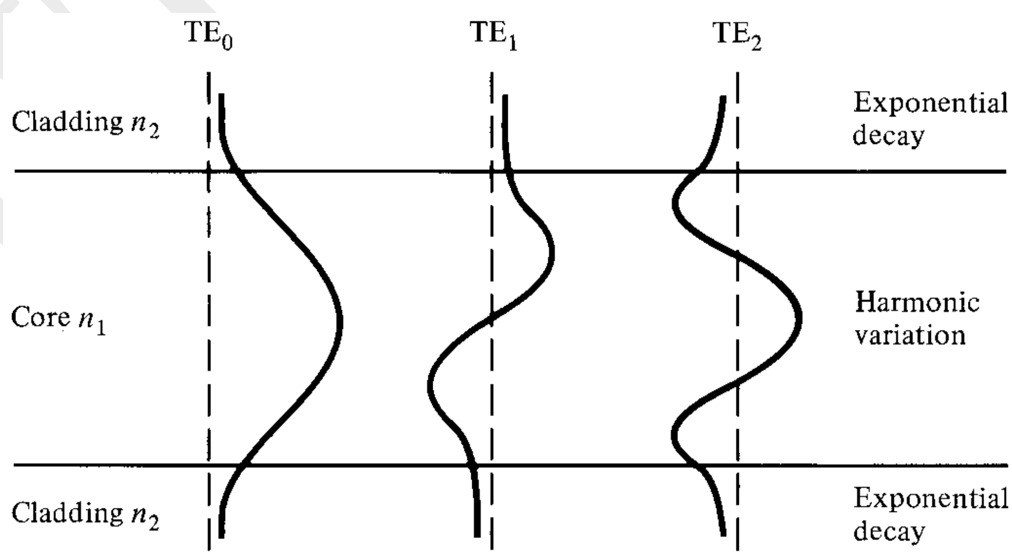
HE	-	Transfer Electric Field
EH	-	Transfer Magnetic Field

The core cladding difference is very low for guided wave. i.e., n_1-n_2 << 1

So we are going for the Linearly Polarized Mode.

It is denoted by $LP_{j, m.}$ Where j & m are integers

LP_{om}	-	HE_{1m} Mode
LP_{1m}	-	TE_{0m}, TM_{om}, HE_{0m} Mode
LP_{01}	-	HE_{11} Mode



Consider dielectric slab of refractive index $n_1 < n_2$. In figure the field pattern of several of the lower order transverse electric modes. The order of the mode is equal to the number of field 0's across the guide.

The mode is also related to the angle is stepper the angle means we get the higher order modes. The waves are reach to the cladding means loss occurs. The mode depend on the incident angle (here mode means number of zero occurs). Leaky Modes are used to get confined output.

In guided modes we didn't get the proper confined output. In Leaky modes we get the Confined output in core regions. The boundary between truly guided modes and Leaky is defined by the Cutoff Conditions

$$\beta = n_2 k$$

Where k – propagation constant

$$k = \frac{2\pi}{\lambda}$$

The important parameter connected with the cutoff condition is the V-Number defined by

$$V_{number} = \frac{2\pi a}{\lambda}\left({n_1}^2 - {n_2}^2\right)^{\frac{1}{2}}$$

This is a dimension less number that determines how many modes a fiber can support

$$Number\ of\ Modes\ (m) = \frac{V^2}{2}$$

$$Number\ of\ Modes\ (m) = \frac{2\pi^2 a^2}{\lambda^2}\,(N.A)^2$$

$$m = \frac{1}{2}\left(\frac{2\pi a}{\lambda}\right)^2 * \left({n_1}^2 - {n_2}^2\right)$$

The V-number can also be used to express the number of modes 'm' in a multimode fiber

The lower order HE11 mode does not satisfy this conditions

V ≤ 2.405

The average optical power resisting in the cladding can be estimated by

$$\frac{P_{cladd}}{P} = \frac{4}{3\sqrt{m}}$$

Where p – Total optical power in the fiber

If m increase power at cladding will be decreased

Therefore, m is proportional to V^2

If V increases the number of modes in the fiber which is not desirable for a high band capability.

Linearly Polarized Modes

The difference between the core and cladding refractive index is very small means, then that the mode called as Linearly Polarized Modes.

$$\Delta = \frac{n_1 - n_2}{n_1}$$

This modes will be analyzed with the help of weakly guiding fiber approximation. Generally linearly polarized modes are regenerated modes. This is different modes are designed by changing some of parameters such as j, m, v.

LP_{om}	-	HE_{1m} Mode
LP_{1m}	-	TE_{0m}, TM_{om}, HE_{0m} Mode
LP_{01}	-	HE_{11} Mode

Inner Regions:
Electric field tends to be zero in cladding. We are using power distribution guided modes.

Outer Region:
Electric field tends to infinite in cladding or we are using refracting mode or linear mode.

Merits of Linearly Polarized Mode:

1. It provides the ability to visualize a mode quickly and easily
2. The concept of linearly polarized mode is very useful in understanding as well as in analyzing the transmission characteristics of optical fiber
3. In a complete set of modes only one electric filed and one magnetic component are significant
4. There are equivalent solutions with field polarity reserved

Demerits of Linearly Polarized Mode:

1. Linearly polarized mod concept is valid only under the weakly guiding approximation (Δ<<1)
2. When this approximation does not hold degenerating modes separate from each other and LPm the designation has no sense.
3. Polarization is nothing but the direction in which the electric field is distributed or propagated.
4. LPm is degenerative mode or derived mode

Fiber Manufacturing

Manufacturing of fiber cables, suitable for installation in an actual light wave system, involves sophisticated technology with attention to many practical details.

2.1.1 Design Issues

In its simplest form, a step-index fiber consists of a cylindrical core surrounded by a cladding layer whose index is slightly lower than the core. Both core and cladding use silica as the base material; the difference in the refractive indices is realized by doping the core, or the cladding, or both. Dopants such as GeO_2 and P_2O_5 increase the refractive index of silica and are suitable for the core. On the other hand, dopants such as B_2O_3 and fluorine decrease the refractive index of silica and are suitable for the cladding.

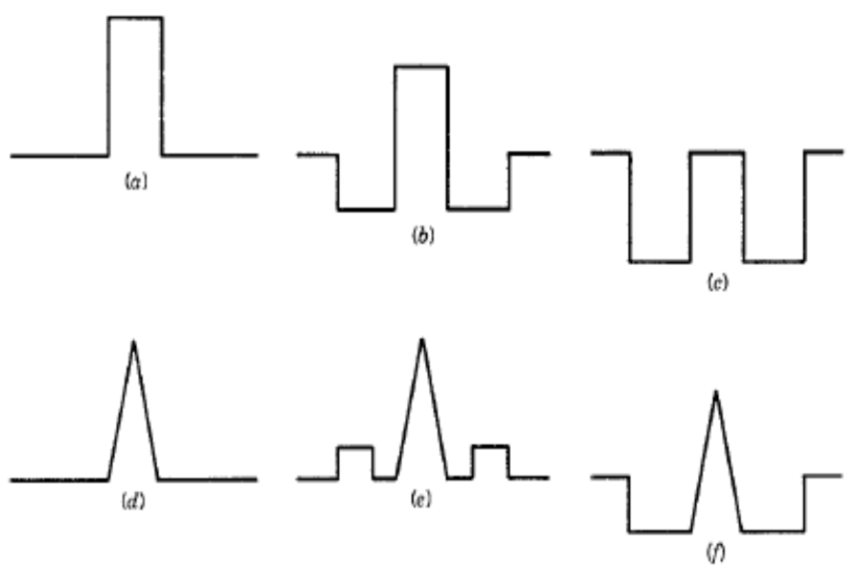


Fig 2.1 Several index profiles used in the design of single-mode fibers. Upper and lower rows correspond to standard and dispersion-shifted fibers, respectively.

The major design issues are related to the refractive-index profile, the amount of dopants, and the core and cladding dimensions. The diameter of the outermost cladding layer has the standard value of 125 μm for all communication grade fibers.

Figure 2.1 shows typical index profiles that have been used for different kinds of fibers. The top row corresponds to standard fibers which are designed to have minimum dispersion near 1.3 μm with a cutoff wavelength in the range 1.1–1.2 μm.

The simplest design [Fig.2.1 (a)] consists of a pure-silica cladding and a core doped with GeO_2 to obtain $\Delta \approx 3\times10^{-3}$. A commonly used variation [Fig.2.1 (b)] lowers the cladding index over a region adjacent to the core by doping it with fluorine. It is also possible to have an undoped core by using a design shown in Fig.2.1 (c). The fibers of this kind are referred to as doubly clad or depressed-cladding fibers. They are also called W fibers, reflecting the shape of the index profile.

The bottom row in Fig. 2.1 shows three index profiles used for dispersion-shifted fibers for which the zero-dispersion wavelength is chosen in the range 1.45–1.60 μm. A triangular index profile with a depressed or raised cladding is often used for this purpose. The refractive indices and the thickness of different layers are optimized to design a fiber with desirable dispersion characteristics. Sometimes as many as four cladding layers are used for dispersion-flattened fibers.

2.2 Fabrication Methods

Fabrication of telecommunication-grade silica fibers involves two stages. In the first stage a vapor-deposition method is used to make a cylindrical preform with the desired refractive-index profile. The preform is typically 1 m long and 2 cm in diameter and contains core and cladding layers with correct relative dimensions. In the second stage, the preform is drawn into a fiber by using a precision-feed mechanism that feeds the preform into a furnace at the proper speed.

Several methods can be used to make the preform. The three commonly used methods are

- Modified Chemical Vapor Deposition (MCVD),
- Outside Vapor Deposition (OVD),
- Vapor Axial Deposition (VAD).

2.2.1 Modified Chemical Vapor Deposition (MCVD)

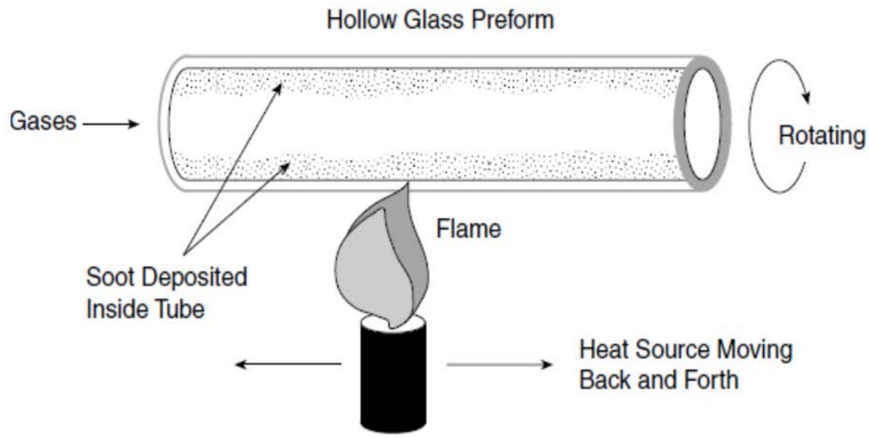


Fig.2.2 Modified Chemical Vapor Deposition (MCVD)

In MCVD a hollow glass tube, approximately 3 feet long and 1 inch in diameter (1 m long by 2.5 cm diameter), is placed in a horizontal or vertical lathe and spun rapidly. A computer-controlled mixture of gases is passed through the inside of the tube. On the outside of the tube, a heat source (oxygen/hydrogen torch) passes up and down as illustrated in Figure 2.2.

Each pass of the heat source fuses a small amount of the precipitated gas mixture to the surface of the tube. Most of the gas is vaporized silicon dioxide (glass), but there are carefully controlled remounts of impurities (dopants) that cause changes in the index of refraction of the glass. As the torch moves and the preform spins, a layer of glass is formed inside the hollow preform. The dopant (mixture of gases) can be changed for each layer so that the index may be varied across the diameter. After sufficient layers are built up, the tube is collapsed into a solid glass rod referred to as a preform. It is now a scale model of the desired fiber, but much shorter and thicker. The preform is then taken to the drawing tower, where it is pulled into a length of fiber up to 10 kilometers long.

Example:

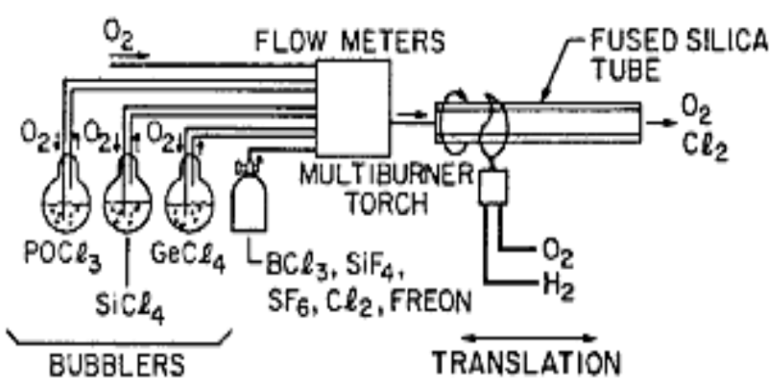


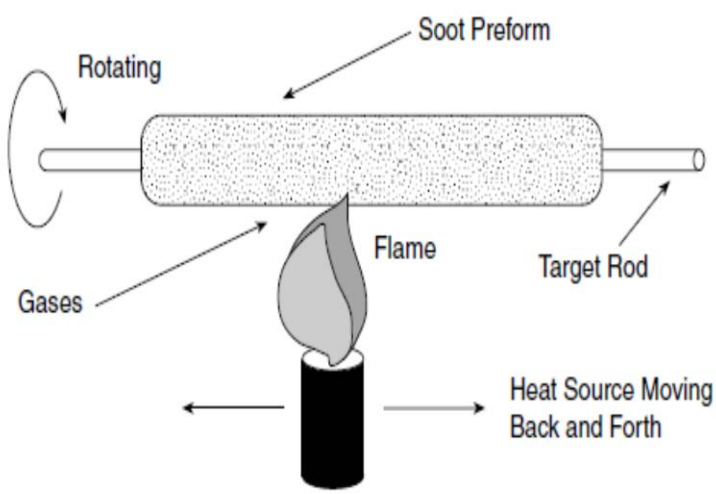
Fig.2.3 MCVD process commonly used for fiber fabrication.

Figure 2.3 shows a schematic diagram of the MCVD process. In this process, successive layers of SiO_2 are deposited on the inside of a fused silica tube by mixing the vapors of $SiCl_4$ and O_2 at a temperature of about 1800°C. To ensure uniformity, a multiburner torch is moved back and forth across the tube length using an automatic translation stage. The refractive index of the cladding layers is controlled by adding fluorine to the tube. When a sufficient cladding thickness has been deposited, the core is formed by adding the vapors of $GeCl_4$ or $POCl_3$. These vapors react with oxygen to form the dopants GeO_2 and P_2O_5:

$$GeCl_4 + O_2 \rightarrow GeO_2 + 2Cl_2,$$
$$4POCl_3 + 3O_2 \rightarrow 2P_2O_5 + 6Cl_2.$$

The flow rate of $GeCl_4$ or $POCl_3$ determines the amount of dopant and the corresponding increase in the refractive index of the core. A triangular-index core can be fabricated simply by varying the flow rate from layer to layer. When all layers forming the core have been deposited, the torch temperature is raised to collapse the tube into a solid rod of preform. The MCVD process is also known as the **inner-vapor-deposition method**, as the core and cladding layers are deposited inside a silica tube.

2.2.2 Outside Vapor Deposition (OVD)



2.4 Outside Vapor Deposition (OVD)

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

2.2.3 Vapor Axial Deposition (VAD)

The VAD process utilizes a very short glass target rod suspended by one end. A computer-controlled mixture of gases is applied between the end of the rod and the heat source as shown in Figure 2.5. The heat source is slowly backed off as the preform lengthens due to tile soot buildup caused by gases reacting to the heat and fusing to the end of the rod. After sufficient length is formed, the target rod is removed from the end, leaving the soot preform. The preform is then taken to the drawing tower to be heated and pulled into the required fiber length.

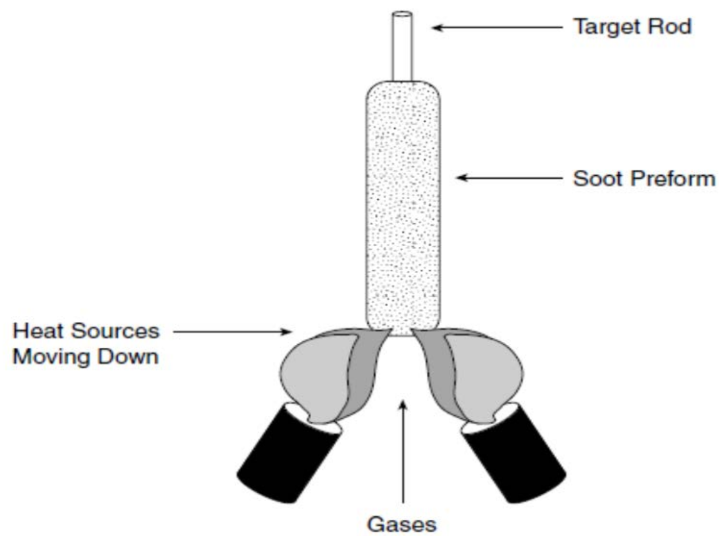


Fig 2.5 Vapor Axial Deposition (VAD).

2.3 COATING THE FIBER FOR PROTECTION

2.3.1 COATING

During manufacture fiber is usually coated with a very thin layer of plastic bonded closely to the cladding. This is often referred to as the "jacket". It is applied as a continuous process as the fiber is drawn. There are two main reasons for this:

1. To prevent water from diffusing into the fiber. Water can cause micro-cracking of the surface. In addition the -OH group is a major source of attenuation due to absorption.
2. If a plastic with a higher refractive index than the cladding glass is used this helps to guide unwanted "cladding modes" out of the fiber.

Secondary functions of the coating are that it is usually coloured so that individual fibers can be identified. In loose-tube or gel-filled cables multiple fibers are often packed close together in a common sheath and there is a need to identify which is which. In addition it makes the fiber thicker, easier to handle and less susceptible to damage in handling.

Standard coated fiber has a diameter of 250 microns and thus the coating is 62.5 microns thick. Of course the individual fibre is usually further enclosed in a plastic sheath before integration with other fibres and components into a cable.

These coatings are typically strippable by mechanical means and must be removed before fibers can be spliced or connectorized as shown in Fig 2.6

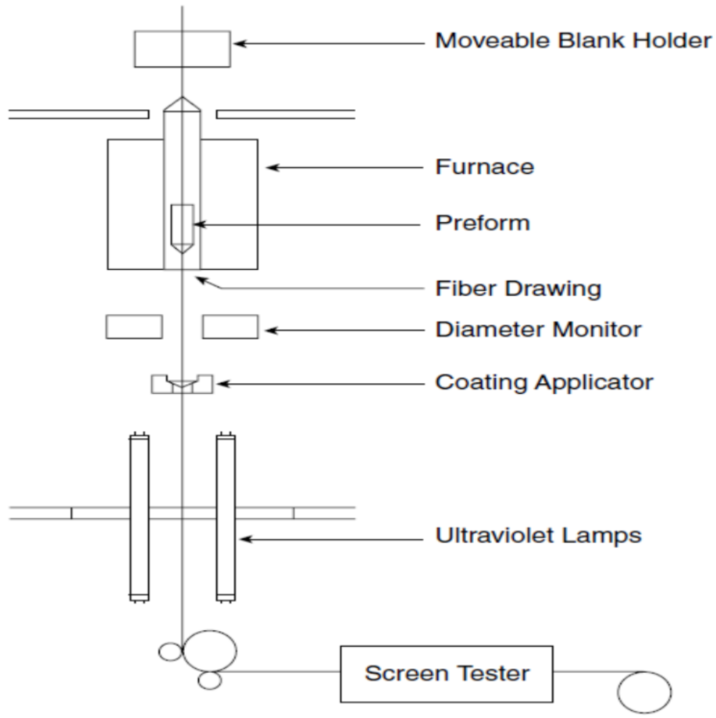


Fig.2.6 Drawing the fiber from the preform and coating the fiber.

Fiber is made by vertically drawing a cylindrical preform made of ultrapure $Si0_2$ in which dopants (e.g., $Ge0_2$) have been added in a controlled manner. The various dopants, which are homogeneously distributed in tubular fashion, determine the refractive index profile of the fiber. The base of the preform is heated at 2000°C (where silica starts melting and becomes viscous) in a high-frequency doughnut shaped furnace. As the fiber is drawn, its diameter is continuously monitored, and minute adjustments remade (via an automatic control mechanism) to ensure that the fiber is produced with tight diameter tolerance.

Fiber Performance

Purity of the medium is very important for best transmission of an optical signal inside the fiber. Perfect vacuum is the purest medium we can have in which to transmit light. Since all optical fibers are made of solid, not hollow, cores, we have to settle for second best in terms of purity. Technology makes it possible for us to make glass very pure, however. Impurities are the unwanted things that can get into the fiber and become a part of its structure. Dirt and impurities are two different things. Dirt comes to the fiber from dirty hands and a dirty work environment. This can be cleaned off with alcohol wipes. Impurities, on the other hand, are built into the fiber at the time of manufacture; they cannot be cleaned off. These impurities will cause parts of optical signal to be lost due to scattering or absorption causing attenuation of the signal. If we have too many impurities in the fiber, too much of the optical signal will be lost and what is left over at the output of the fiber will not be enough for reliable communications.

Much of the early research and development of optical fiber centered on methods to make the fiber purity higher to reduce optical losses. Today's fibers are so pure that as a point of comparison, if water in the ocean was as pure, we would be able to see the bottom on a sunny day. Optical glass fiber has another layer (or two) that surrounds the cladding, known as the buffer. The buffer is a plastic coating(s) that provides scratch protection for the glass below. It also adds to the mechanical strength of the fiber and protects it from moisture damage. On straight pulling (tension), glass optical fiber is five times stronger than some steel. But when it comes to twisting and bending, glass must not be stressed beyond its limits or it will fracture.

How Is the Preform Made?

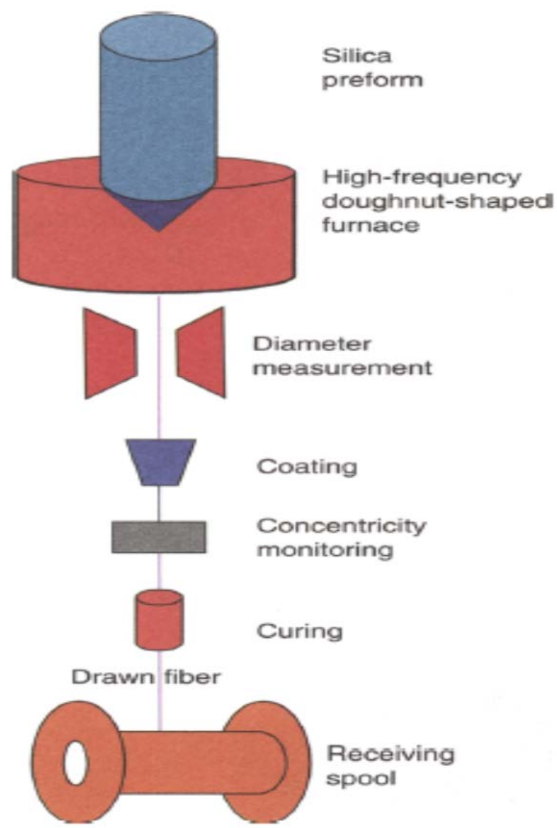


Fig.2.7 Making a fiber.

The cylindrical preform is made by one of several methods, such as vapor phase axial deposition (VAD), outer vapor deposition (OVD), or modified chemical vapor deposition (MCVD), invented in 1970 by scientists at Bell Laboratories. **In** the MCVD method, oxides and oxygen enter a rotating, highly pure silica tube in a specified sequence. The tube is maintained at a very high temperature so that chemical interaction with silica and dopant elements (Ge, B, etc.) takes place in a controlled manner. The products of reaction are deposited in the interior walls of the preform evenly. As deposition takes place, the opening of the tube closes in (Figure 2.7). The even and radial deposition of the elements in the preform determines the profile of index of refraction of the fiber, when it is drawn. The highly pure silica tube is manufactured using a typically proprietary method.

2.4 OPTICAL FIBER CABLE CONSTRUCTION

The core is the highly refractive central region of an optical fiber through which light is transmitted. The standard telecommunications core diameter in use with SMF is between 8 μm and 10 μm, whereas the standard core diameter in use with MMF is between 50 μm and 62.5 μm.

Figure 2.8 shows the core diameter for SMF and MMF cable. The diameter of the cladding surrounding each of these cores is 125 μm. Core sizes of 85 μm and 100 μm were used in early applications, but are not typically used today. The core and cladding are manufactured together as a single solid component of glass with slightly different compositions and refractive indices.

The third section of an optical fiber is the outer protective coating known as the *coating*. The coating is typically an ultraviolet (UV) light-cured acrylate applied during the manufacturing process to provide physical and environmental protection for the fiber. The buffer coating could also be constructed out of one or more layers of polymer, nonporous hard elastomers or high performance PVC materials. The coating does not have any optical properties that might affect the propagation of light within the fiber-optic cable. During the installation process, this coating is stripped away from the cladding to allow proper termination to an optical transmission system. The coating size can vary, but the standard sizes are 250 μm and 900 μm. The 250-μm coating takes less space in larger outdoor cables. The 900- μm coating is larger and more suitable for smaller indoor cables.

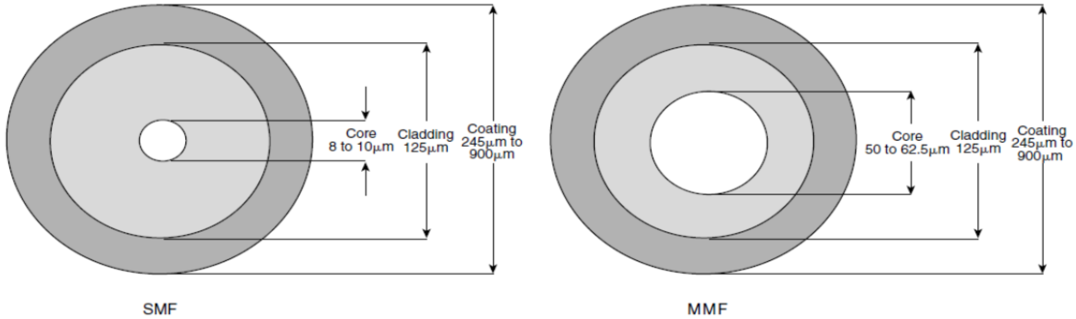


Fig 2.8 Core Diameter of SMF and MMF Cable

Fiber-optic cable sizes are usually expressed by first giving the core size followed by the cladding size. Consequently, 50/125 indicates a core diameter of 50 microns and a cladding diameter of 125 microns, and 8/125 indicates a core diameter of 8 microns and a cladding diameter of 125 microns. The larger the core, the more light can be coupled into it from the external acceptance angle cone. However, larger-diameter cores can actually allow in too much light, which can cause receiver saturation problems. The 8/125 cable is often used when a fiber-optic data link operates with single-mode propagation, whereas the 62.5/125 cable is often used in a fiber-optic data link that operates with multimode propagation.

Three types of material make up fiber-optic cables:

- Glass
- Plastic
- Plastic-clad silica (PCS)

These three cable types differ with respect to attenuation. Attenuation is principally caused by two physical effects: Absorption and Scattering.

Absorption removes signal energy in the interaction between the propagating light (photons) and molecules in the core. Scattering redirects light out of the core to the cladding. When attenuation for a fiber-optic cable is dealt with quantitatively, it is referenced for operation at a particular optical wavelength, a window, where it is minimized. The most common peak wavelengths are 780 nm, 850 nm, 1310 nm, 1550 nm, and 1625 nm.

The 850-nm region is referred to as the *first window* (as it was used initially because it supported the original LED and detector technology). The 1310-nm region is referred to as the *second window*, and the 1550-nm region is referred to as the *third window*.

Glass Fiber-Optic Cable

Glass fiber-optic cable has the lowest attenuation. A pure-glass, fiber-optic cable has a glass core and a glass cladding. This cable type has, by far, the most widespread use. It has been the most popular with link installers, and it is the type of cable with which installers have the most experience. The glass used in a fiber-optic cable is ultra-pure, ultra-transparent, silicon dioxide, or fused quartz. During the glass fiber-optic cable fabrication process, impurities are purposely added to the pure glass to obtain the desired indices of refraction needed to guide light. Germanium, titanium, or phosphorous is added to increase the index of refraction. Boron or fluorine is added to decrease the index of refraction. Other impurities might somehow remain in the glass cable after fabrication. These residual impurities can increase the attenuation by either scattering or absorbing light.

Plastic Fiber-Optic Cable

Plastic fiber-optic cable has the highest attenuation among the three types of cable. Plastic fiber-optic cable has a plastic core and cladding. This fiber-optic cable is quite thick. Typical dimensions are 480/500, 735/750, and 980/1000. The core generally consists of polymethylmethacrylate (PMMA) coated with a fluropolymer. Plastic fiber-optic cable was pioneered principally for use in the automotive industry. The higher attenuation relative to glass might not be a serious obstacle with the short cable runs often required in premise data networks. The cost advantage of plastic fiber-optic cable is of interest to network architects when they are faced with budget decisions. Plastic fiber-optic cable does have a problem with flammability. Because of this, it might not be appropriate for certain environments and care has to be taken when it is run through a plenum. Otherwise, plastic fiber is considered extremely rugged with a tight bend radius and the capability to withstand abuse.

Plastic-Clad Silica (PCS) Fiber-Optic Cable

The attenuation of PCS fiber-optic cable falls between that of glass and plastic. PCS fiber-optic cable has a glass core, which is often vitreous silica, and the cladding is plastic, usually a silicone elastomer with a lower refractive index. PCS fabricated with a silicone elastomer cladding suffers from three major defects. First, it has considerable plasticity, which makes connector application difficult. Second, adhesive bonding is not possible. And third, it is practically insoluble in organic solvents. These three factors keep this type of fiber-optic cable from being particularly popular with link installers. However, some improvements have been made in recent years.

Indoor Cables

- *Simplex cable*—contains a single fiber for one-way communication
- *Duplex cable*—contains two fibers for two-way communication
- *Multifiber cable*—contains more than two fibers. Fibers are usually in pairs for duplex operation. A ten-fiber cable permits five duplex circuits.
- *Breakout cable*—typically has several individual simplex cables inside an outer jacket. The outer jacket includes a zipcord to allow easy access
- *Heavy-, light-, and plenum-duty and riser cable*
  - Heavy-duty cables have thicker jackets than light-duty cable, for rougher handling.
  - Plenum cables are jacketed with low-smoke and fire-retardant materials.
  - Riser cables run vertically between floors and must be engineered to prevent fires from spreading between floors.

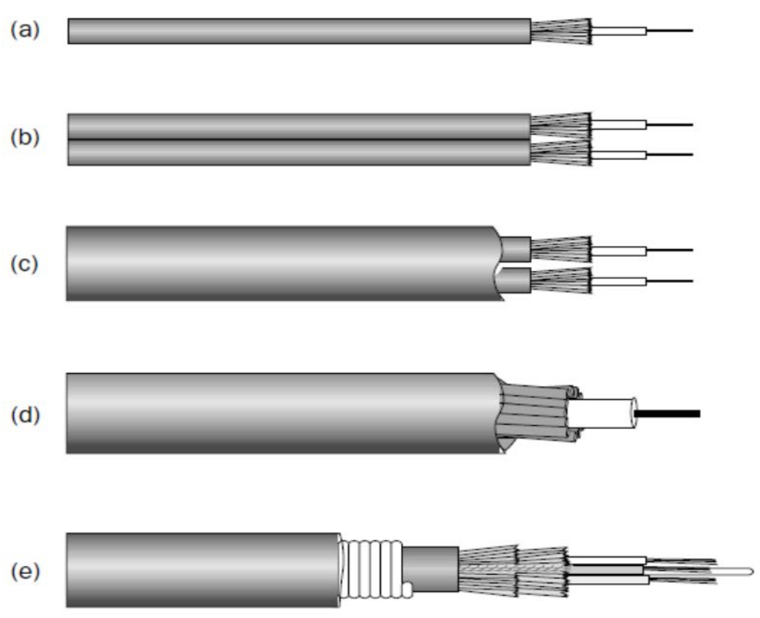
Outdoor Cables

Outdoor cables must withstand harsher environmental conditions than indoor cables. Outdoor cables are used in applications such as:

- *Overhead*—cables strung from telephone lines
- *Direct burial*—cables placed directly in trenches

- *Indirect burial*—cables placed in conduits
- *Submarine*—underwater cables, including transoceanic applications

Sketches of indoor and outdoor cables are shown in Figure



(a) Simplex cable. (b) Zipcord cable. (c) Tightpack cable. (d) Breakout cable. (e) Armored loose-tube cable.

Core/ Cladding Diameter	Application	Typical Parameters
50/125 Graded Index	Standard telecoms multimode fiber also video applications	3 dB/km 600 MHz-km (850 nm) 1 dB/km and 1000 MHz-km (1300 nm)
62.5/125 Graded Index	Standard Fiber for FDDI Backbones	3 dB/km 300 MHz-km (850 nm) 1 dB/km and 800 MHz-km (1300 nm)
100/140 Graded Index	Older Local Area Network Fiber	4 dB/km 160 MHz-km (850 nm) 2 dB/km and 300 MHz-km (1300 nm)
200/230 Step Index PCS	Industrial Control Applications	8 dB/km and 20 MHz-km (850 nm)
8/125 Single Mode	Long Distance High Bit Rate Telecoms Applications	0.3 dB/km (1550 nm)

DERIVATIONS

1. Starting from Maxwell's equation, derive an expression for wave equation of an electromagnetic wave propagating through optical fiber.

Maxwell's equation provides the basis for study of electromagnetic wave propagation.

Consider Maxwell's equations,

$$\nabla \times E = -\frac{\partial B}{\partial t}$$
$$\nabla \times H = \frac{\partial D}{\partial t} \quad \text{----------- I}$$

Where, E is the Electric field
B is the magnetic flux density
H is the Magnetic field
D is the electric flux density

Consider divergence condition,

$$\nabla . D = 0$$
$$\nabla . B = 0 \quad \text{----------- II}$$

(no free charges and no free poles respectively)

Where, ∇ is the vector operator

The four field vectors are related by,

$$D = \xi E$$
$$B = \mu H \quad \text{----------- III}$$

Where, ξ is the dielectric permittivity
μ is the magnetic permeability of the medium.

Substituting III in I,

$$\nabla \times E = -\frac{\mu \partial H}{\partial t}$$
$$\nabla \times H = \frac{\xi \partial E}{\partial t} \quad \text{----------- IV}$$

Taking curl for equation IV,

$$\nabla \times (\nabla \times E) = \nabla \times (-\mu \frac{\partial H}{\partial t}) = -\mu \frac{\partial (\nabla \times H)}{\partial t}$$

$$= -\mu \frac{\partial}{\partial t}(\xi \frac{\partial E}{\partial t})$$

$$\therefore \nabla \times (\nabla \times E) = -\mu\xi \frac{\partial^2 E}{\partial t^2} \text{ ---------- V}$$

Similarly,

$$\nabla \times (\nabla \times H) = \nabla \times (\xi \frac{\partial E}{\partial t}) = \xi \frac{\partial (\nabla \times E)}{\partial t} = \xi \frac{\partial}{\partial t}(-\mu \frac{\partial H}{\partial t})$$

$$\therefore \nabla \times (\nabla \times H) = -\mu\xi \frac{\partial^2 H}{\partial t^2} \text{ ----------- VI}$$

Vector identity equation is,

$$\nabla \times (\nabla \times E) = \nabla(\nabla . E) - \nabla^2 (E)$$

From equation III,

$$E = \frac{D}{E}$$

$$\therefore \nabla \times (\nabla \times E) = \nabla(\nabla . \frac{D}{E}) - \nabla^2 (E) = 0 - \nabla^2 (E)$$

$$(\because \nabla . D = 0)$$

$$\therefore \nabla \times (\nabla \times E) = -\nabla^2 (E) \text{ ------------- VII}$$

Equating V and VII, we get,

$$-\mu\xi \frac{\partial^2 E}{\partial t^2} = -\nabla^2 (E)$$

$$\therefore \nabla^2 (E) = \mu\xi \frac{\partial^2 E}{\partial t^2} \text{ --------------- VIII}$$

Similarly,

$$\nabla^2 H = \mu\xi \frac{\partial^2 H}{\partial t^2} \text{ ---------------- IX}$$

Equations VIII and IX are called as general wave equations for dielectric wave guide.

Let field ψ be E or H, then

Equation VIII can be replaced by phase velocity as

$$V_p = \frac{1}{\sqrt{\mu\xi}}$$

$$\therefore \nabla^2 \psi = \frac{1}{V_p^2} \frac{\partial^2 \psi}{\partial t^2} \text{ ------------- X}$$

General wave equation is,

$$\psi = \psi_0 e^{j(\omega_t - \beta_z)}$$

Where, ψ_0 is amplitude of electric field

EM wave travels with frequency ω, propagation constant β and along Z-direction.

Laplacian operation of planar waveguides described by rectangular Cartesian co-ordinates (x, y, z) is

$$\nabla^2\psi = \frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} + \frac{\partial^2\psi}{\partial z^2} \text{ ------------ XI}$$

Laplacian operation of circular fibers described by cylindrical polar co-ordinates (r, ϕ, z) is

$$\nabla^2\psi = \frac{\partial^2\psi}{\partial r^2} + \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\psi}{\partial\phi^2} + \frac{\partial^2\psi}{\partial z^2} \text{ -------------- XII}$$

Equating X and XII,

$$\frac{1}{V_p^2}\frac{\partial^2\psi}{\partial t^2} = \frac{\partial^2\psi}{\partial r^2} + \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\psi}{\partial\phi^2} + \frac{\partial^2\psi}{\partial z^2} \text{ ------------- XII*}$$

But $\psi = \psi_0 e^{j(\varpi_t - \beta_z)}$ --------------- XIII

Where, ψ_0 is the amplitude of electric field

Differentiating above equation w.r.t. z,

$$\frac{\partial\omega}{\partial z} = \psi_0 e^{j(\omega t - \beta z)}.(-j\beta)$$

$$\frac{\partial^2\psi}{\partial z^2} = \psi_0 e^{j(\omega t - \beta z)}(-j\beta)(-j\beta)$$

$$= -\psi_0 e^{j(\omega t - \beta z)}.\beta^2$$

$$\frac{\partial^2\psi}{\partial z^2} = -\beta^2\psi \text{ ------------- XIV}$$

$$(\because \psi_0 e^{j(\omega t - \beta z)} = \psi)$$

Differentiating equation XIII w.r.t 't',

$$\frac{\partial\psi}{\partial t} = \psi_0 e^{j(\omega t - \beta z)}.j\omega$$

$$\frac{\partial^2\psi}{\partial t^2} = \psi_0 (j\omega)^2 e^{j(\omega t - \beta z)}$$

$$\frac{\partial^2 \psi}{\partial t^2} = -\omega^2 \psi \text{ ------------- XV}$$

Substituting equation XIV and XV in XII*, we get

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \psi}{\partial \phi^2} + (-\beta^2 \psi) = \frac{1}{V_p^2}(-\omega^2 \psi)$$

Refractive index is given by

$$n = \frac{c}{V_p}$$

(Since, core refractive index is n_1)

$$V_p = \frac{c}{n_1}$$

$$\therefore \frac{1}{V_p^2}(-\omega^2 \psi) = \frac{1}{(c/n_1)^2}(-\omega^2 \psi) = \frac{-n_1^2 (2\pi f)^2 \psi}{c^2} = \frac{-n_1^2 (2\pi \frac{c}{\lambda})^2}{c^2}$$

$$= -n_1^2 (\frac{2\pi}{\lambda})^2 . \psi$$

$$\frac{1}{V_p^2}(-\omega^2 \psi) = -n_1^2 k^2 \psi \text{ ------------ XVI} \quad (\because \text{ propagation constant } k = \frac{2\pi}{\lambda})$$

Rewriting equation X11, $\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \psi}{\partial \phi^2} - \beta^2 \psi = -n_1^2 k^2 \psi$

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \psi}{\partial \phi^2} + \psi[n_1^2 k^2 - \beta^2] = 0 \text{ ------------- XVII}$$

Equation XVII is the scalar wave equation for cylindrical optical fiber.

2. **Derive an expression for linearly polarized modes in optical fibers and obtain the equation for V- number.**

(or)

Mode theory of circular waveguide or cylindrical fibers.

Wave equation for cylindrical waveguide is

$$\frac{\partial^2\psi}{\partial r^2}+\frac{1}{r}\frac{\partial\psi}{\partial r}+\frac{1}{r^2}\frac{\partial^2\psi}{\partial\phi^2}+\psi(n_1^2k^2-\beta^2)=0 \text{ --------------- I}$$

Where, k is the propagation constant

a. In the core region, the electromagnetic field ψ is real, that is,

$$n_1^2k^2 \geq \beta^2$$
$$\therefore \beta \leq n_1 k \text{ --------------- II}$$

b. In cladding region,

$$n_1^2k^2-\beta^2 \geq n_2^2k^2-\beta^2$$
$$(\because n_1 > n_2)$$

ψ should fall rapidly with distance

$$\therefore n_1^2k^2-\beta^2=0$$
$$n_2^2k^2 \leq \beta^2$$
$$\therefore n_2k \leq \beta$$

$\therefore \beta$ lies between n_2k and n_1k (i.e.), $n_2k < \beta < n_1k$ ------------- III

If equation III is satisfied, then the mode is said to be **bounded or guided or trapped mode**

If equation III is not satisfied, then the mode is said to be **unbounded or radiation mode.**

According to separation of variable solution for equation I

$$\psi = E(r)F_1(\phi)F_2(\omega)F_3(z) \text{ -------------- IV}$$

Let time and z dependent factors be

$$F_1(\phi)=e^{jl\phi} \text{ --------------- V}$$

$$F_2(\omega)F_3(z)=e^{j(\omega t-\beta z)} \text{ --------------VI}$$

Substituting V and VI in IV, we get

$$\psi = E(r)e^{jl\phi}e^{j(\omega t-\beta z)} \text{ ---------------- VII}$$

Differentiating equation VII w.r.t. 'r', we get,

$$\frac{\partial\psi}{\partial r}=\frac{\partial E(r)}{\partial r}e^{jl\phi}e^{j(\omega t-\beta z)} \text{ --------------- VIII}$$

$$\frac{\partial^2\psi}{\partial r^2}=\frac{\partial^2 E(r)}{\partial r^2}e^{jl\phi}e^{j(\omega t-\beta z)} \text{ --------------- IX}$$

Differentiating equation VII w.r.t 'ϕ', we get

$$\frac{\partial \psi}{\partial \phi} = E(r)e^{jl\phi}(jl)e^{j(\omega t - \beta z)} \text{ --------------- X}$$

$$\frac{\partial^2 \psi}{\partial \phi^2} = E(r)e^{jl\phi}(jl)^2 e^{j(\omega t - \beta z)}$$

$$\frac{\partial^2 \psi}{\partial \phi^2} = -l^2 E(r)e^{jl\phi} e^{j(\omega t - \beta z)} \text{ --------------- XI}$$

Substituting equation VIII, IX and XI in equation I,

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r}\frac{\partial \omega}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \psi}{\partial \phi^2} + \psi(n_1^2 k^2 - \beta^2) = 0$$

$$\frac{\partial^2 E(r)}{\partial r^2} e^{jl\phi} e^{j(\omega t - \beta z)} + \frac{1}{r}[\frac{\partial E(r)}{\partial r} e^{jl\phi} e^{j(\omega t - \beta z)}] + \frac{1}{r^2}[-l^2 E(r)e^{jl\phi} e^{j(\omega t - \beta z)} + \psi(n_1^2 k^2 - \beta^2) = 0$$

Substituting expression for ψ from equation VII in the above equation,

$$\frac{\partial^2 E}{\partial r^2}.e^{jl\phi} e^{j(\omega t - \beta z)} + \frac{1}{r}[\frac{\partial E(r)}{\partial r} e^{jl\phi} e^{j(\omega t - \beta z)}] - \frac{l^2}{r^2} E(r)e^{jl\phi} e^{j(\omega t - \beta z)} + E(r)e^{jl\phi} e^{j(\omega t - \beta z)}(n_1^2 k^2 - \beta^2) = 0$$

$$e^{jl\phi} e^{j(\omega t - \beta z)}[\frac{\partial^2 E(r)}{\partial r^2} + \frac{1}{r}\frac{\partial E(r)}{\partial r} + (n_1^2 k^2 - \beta^2 - \frac{l^2}{r^2})E(r)] = 0 \text{ ------------- XII}$$

Bessel's differential equation is arrived as follows,

$$\frac{\partial^2 E}{\partial r^2} + \frac{1}{r}\frac{\partial E}{\partial r} + (n_1^2 k^2 - \beta^2 - \frac{l^2}{r^2})E] = 0$$

Solution of Bessel differential equation is called Bessel function. Bessel differential equation has two solutions

- **a.** Bessel's function of **first kind** $J_l(U_r)$: In core region: 'E' must be finite.
- **b.** Bessel's function of **second kind** $k_l(w_r)$**:** in cladding region, 'E' must decay from 'r' tends to infinity.

$$E_r = \{GJ_l(UR), R < 1, (core)$$

$$GJ_l(U)\frac{k_r(WR)}{k_l(W)}, R > 1, (cladding)\}$$

U and W are Eigen values
R is the normalized radius
G is the amplitude constant

$R = \frac{r}{a}$, Where, 'a' is the radius of the core

U and W are defined as

$$U = a\sqrt{(n_1^2k^2 - \beta^2)}$$
$$W = a\sqrt{(\beta^2 - n_2^2k^2)}$$
$$U^2 + W^2 = a^2(n_1^2 - n_2^2)k^2$$
$$\sqrt{U^2 + W^2} = ka\sqrt{n_1^2 - n_2^2}$$
$$= kaNA$$
$$\sqrt{U^2 + W^2} = V$$

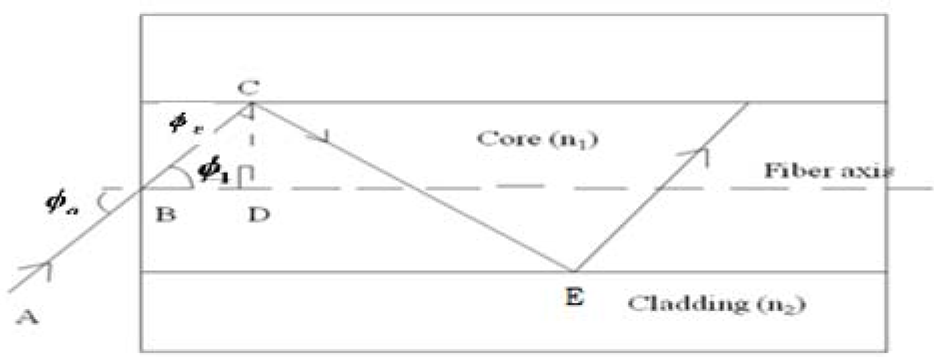
Where 'k' is the free space propagation constant and $k = \frac{2\pi}{\lambda}$

$$V = \frac{2\pi a}{\lambda} NA \text{ --------------- XIII}$$

Where, NA is the Numerical Aperture

Equation XIII is the expression for V-number.

3. **Deduce an expression for NA and acceptance angle of a fiber:**



Numerical aperture is a figure of merit which determines light gathering capability of the fiber. Its value ranges between 0 and 1. Larger the NA, greater is the amount of light occupied by fiber.

In the above figure,

AB is incident light ray

BC is Refracted light ray

CE is Reflected light ray

1. **Consider the interface between a glass slab with n_1 = 1.48 and air for which n_2 = 1.00. What is the critical angle for light traveling in the glass?**

$$\varphi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1} 0.676 = 42.5^\circ$$

2. **Consider a multimode silica fiber that has a core refractive index n_1 = 1.480 and a cladding index n_2 = 1.460. Find (a) the critical angle, (b) the numerical aperture, and (c) the acceptance angle.**

   Critical angle

$$\varphi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1.460}{1.480} = 80.5^\circ$$

   Numerical aperture

$$\mathrm{NA} = \left(n_1^2 - n_2^2\right)^{1/2} = 0.242$$

   Acceptance angle in air (n = 1.00)

$$\theta_A = \sin^{-1}\mathrm{NA} = \sin^{-1} 0.242 = 14^\circ$$

3. **Consider a multimode fiber that has a core refractive index of 1.480 and a core-cladding index difference 2.0 percent (Δ = 0.020). Find the (a) numerical aperture, (b) the acceptance angle, and (c) the critical angle.**

   Cladding index

$$n_2 = n_1(1-\Delta) = 1.480(0.980) = 1.450.$$

   Numerical aperture

$$\mathrm{NA} = n_1\sqrt{2\Delta} = 1.480(0.04)^{1/2} = 0.296$$

   Acceptance angle in air (n = 1.00)

$$\theta_A = \sin^{-1}\mathrm{NA} = \sin^{-1} 0.296 = 17.2^\circ$$

   Critical angle at the core cladding interface is

$$\varphi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1} 0.980 = 78.5^\circ$$

4. **A step-index fiber has a normalized frequency V = 26.6 at a 1300-nm wavelength. If the core radius is 25 mm, what is the numerical aperture?**

$$V = \frac{2\pi a}{\lambda}\left(n_1^2 - n_2^2\right)^{1/2} = \frac{2\pi a}{\lambda}\mathrm{NA}$$

$$NA = V\frac{\lambda}{2\pi a} = 26.6\frac{1.30\,\mu\mathrm{m}}{2\pi \times 25\,\mu\mathrm{m}} = 0.22$$

5. **Consider a multimode step-index fiber with a 62.5-mm core diameter and a core-cladding index difference of 1.5 percent. If the core refractive index is 1.480, estimate the normalized frequency of the fiber and the total number of modes supported in the fiber at a wavelength of 850 nm.**

Normalized frequency is

$$V \approx \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta} = \frac{2\pi \times 31.25\,\mu\mathrm{m} \times 1.48}{0.85\,\mu\mathrm{m}}\sqrt{2 \times 0.015}$$

$$= 59.2$$

The total number of modes is

$$M \approx \frac{\mathrm{V}^2}{2} = 1752$$

6. **Suppose we have a multimode stepindex optical fiber that has a core radius of 25 mm, a core index of 1.48, and an index difference Δ = 0.01. What are the number of modes in the fiber at wavelengths 860, 1310, and 1550 nm?**

$$V \approx \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta} = \frac{2\pi \times 25\,\mu\mathrm{m} \times 1.48}{0.86\,\mu\mathrm{m}}\sqrt{2 \times 0.01}$$

$$= 38.2$$

$$M \approx \frac{\mathrm{V}^2}{2} = 729$$

Similarly, at 1310 nm we have $V = 25.1$ and $M = 315$.

Finally at 1550 nm we have $V = 21.2$ and $M = 224$.

7. **Suppose we have three multimode step-index optical fibers each of which has a core index of 1.48 and an index difference Δ = 0.01. Assume the three fibers have core diameters of 50, 62.5, and 100 mm. What are the number of modes in these fibers at a wavelength of 1550 nm?**

$$V \approx \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta} = \frac{2\pi \times 25\,\mu\text{m} \times 1.48}{1.55\,\mu\text{m}} \sqrt{2 \times 0.01}$$
$$= 21.2$$

$$M \approx \frac{V^2}{2} = 224$$

Similarly, at 62.5-μm we have $V = 26.5$ and $M = 351$.
Finally at 100-μm we have $V = 42.4$ and $M = 898$.

8. **Consider a multimode step-index optical fiber that has a core radius of 25 mm, a core index of 1.48, and an index difference Δ = 0.01. Find the percentage of optical power that propagates in the cladding at 840 nm.**

$$V \approx \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta} = \frac{2\pi \times 25\,\mu\text{m} \times 1.48}{0.84\,\mu\text{m}} \sqrt{2 \times 0.01}$$
$$= 39$$

$$M \approx \frac{V^2}{2} = 760$$

$$\frac{P_{\text{clad}}}{P} \approx \frac{4}{3\sqrt{M}} = 0.05$$

Thus approximately 5 percent of the optical power propagates in the cladding. If Δ is decreased to 0.03 in order to lower the signal dispersion, then there are 242 modes in the fiber and about 9 percent of the power propagates in the cladding.

9. **A manufacturing engineer wants to make an optical fiber that has a core index of 1.480 and a cladding index of 1.478. What should the core size be for single-mode operation at 1550 nm?**

Using the condition that V = 2.405 must be satisfied for single-mode operation

$$a = \frac{V\lambda}{2\pi}\frac{1}{\sqrt{n_1^2 - n_2^2}}$$

$$\leq \frac{2.405 \times 1.55\mu\text{m}}{2\pi}\frac{1}{\sqrt{(1.480)^2 - (1.48\ )^2}} = 7.7\mu\text{m}$$

10.An applications engineer has an optical fiber that has a 3.0-mm core radius and a numerical aperture of 0.1. Will this fiber exhibit single-mode operation at 800 nm?

$$V \approx \frac{2\pi a}{\lambda} NA = \frac{2\pi \times 3\mu\text{m}}{0.80\mu\text{m}} 0.10 = 2.356$$

Since V < 2.405, this fiber will exhibit single-mode operation at 800 nm.

11. A single mode optical fiber has a beat length of 8 cm at 1300 nm. What is the birefringence?

$$\text{B}_f = n_y - n_x = \frac{\lambda}{L_p} = \frac{1.3 \times 10^{-6}\text{m}}{8 \times 10^{-2}\text{ m}} = 1.63 \times 10^{-5}$$

$$\beta = \frac{2\pi}{L_p} = \frac{2\pi}{0.08\text{ m}} = 78.5\text{ m}^{-1}$$

This indicates an intermediate-type fiber because birefringence can vary from Bf = 1* 10^{-3} (a typical high-birefringence fiber) to Bf = = 1 * 10^{-8} (a typical low birefringence fiber).

12.Suppose we have a 50-mm diameter graded-index fiber that has a parabolic refractive index profile (a = 2). If the fiber has a numerical aperture NA = 0.22, what is the total number of guided modes at a wavelength of 1310 nm?

$$V = \frac{2\pi a}{\lambda} NA = \frac{2\pi \times 25\mu\text{m}}{1.31\mu\text{m}} \times 0.22 = 26.4$$

The total number of modes for a = 2 is

$$M \approx \frac{a}{a+2}\frac{V^2}{2} = \frac{V^2}{4} = 174$$

13.A step – index multimode fiber with a numerical aperture of 0.20 supports approximately 1000 nodes at an 850nm wave length?

a) What is the diameter of its core?

b) How many modes does the fiber support at 1320nm?

c) How many modes does the fiber support at 1550nm?

a) To find the diameter of the core.

The total number of modes supported in a fiber is

$$M = \frac{V^2}{2}$$

$$V^2 = 2M$$

$$V = \sqrt{2M}$$

$$V = \sqrt{2 \times 1000}$$

$$V = 44.72$$

To find the core diameter we have $V = \frac{2\pi 9}{\lambda} NA$

$$a = \frac{V\lambda}{(NA)2\pi}$$

$$a = \frac{44.72 \times 850 \times 10^{-9}}{0.20 \times 2 \times 3.14}$$

$$a = 1.19 \times 10^{-3} m$$

since a is radius of the core

$\therefore$ diameter = 2a

$=1.19 \times 10^{-3} \times 2$

$=2.38 \times 10^{-3} m$

d=2.88mm

b) How many modes does the fiber support at 1320 nm?

$$V = \frac{2\pi a}{\lambda} NA$$

$$= \frac{2 \times 3.14 \times 2.38 \times 10^{-3}}{1320 \times 10^{-9}} \times 0.2$$

$$V = 2264$$

Total No. of modes supported in a fiber is

$$M = \frac{V^2}{2}$$

$$M = 2562848 \text{ Modes}$$

C) How many modes does the fiber support at 1550nm

$$\lambda = \frac{2\pi a}{\lambda} NA$$

$$= \frac{2 \times 3.14 \times 2.38 \times 10^{-3} \times 0.2}{1550 \times 10^{-9}}$$

$$V = 1928$$

$$\text{No.of modes } M = \frac{v^2}{2}$$

$$M = \frac{(1928)^2}{2}$$

$$\boxed{M = 1858592}$$

14.

a) Determine the normalized frequency at 820nm for a step – index fiber having a 25 μm core radius, n_1=1.48 and n_2=1.46.

b) How many modes propagate in this fiber at 1550nm?

c) What percent of the optical power flows in the cladding?

a) Normalized frequency at 820nm

$$\lambda = \frac{2\pi a}{\lambda} \left(n_1^2 - n_2^2\right)^{1/2}$$

$$= \frac{2 \times 3.14 \times 25 \times 10^{-6}}{820 \times 10^{-9}} \times \sqrt{(1.48)^2 - (1.46)^2}$$

$$(\ )\times^{\times 0.2424}$$

$$\boxed{V = 46.41}$$

b) No. of modes propagating in the fiber at 1550nm.

$$M=\frac{v^2}{2}$$

$$M=\frac{(46.41)^2}{2}$$

$$\boxed{M=1076}$$

(c) Percentage of optical power flows in the cladding is given by

$$\%\left(p_{clad}\right)=\frac{4}{3\sqrt{M}}$$

$$=\frac{4}{3\sqrt{1076}}$$

$$\%\left(P_{clad}\right)=4\%$$

15. A step index multimode fiber with a numerical aperture of 0.2 support approx. 1000 modes at an 850nm wavelength. What is the diameter of its core?

$$N = 4.9\left[\frac{d\ NA}{\lambda}\right]^2$$

N=60.7μm