THEORY & APPLICATION OF OPTICAL FIBER COMMUNICATION

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Abstract:

The visible optical carrier waves or light has been commonly used for communication purpose for many years. Alexander Graham Bell transmitted speech information using a light beam for the first time in 1880. Just after four years of the invention of the telephone Bell proposed his photophone which was capable of providing a speech transmission over a distance of 200m. In the year 1910 Hondros and Debye carried out a theoretical study and in 1920 Schriever reported an experimental work. Although in the early part of twentieth century optical communication was going through some research work but it was being used only in the low capacity communication links due to severe effect of disturbances in the atmosphere and lack of suitable optical sources. However, low frequency (longer wavelength) electromagnetic waves like radio and microwaves proved to be much more useful for information transfer in atmosphere, being far less affected by the atmospheric disturbances. The relative frequencies and their corresponding wavelengths can be known from the electromagnetic spectrum and it is understandable that optical frequencies offer an increase in the potential usable bandwidth by a factor of around 10000 over high frequency microwave transmission. With the LASER coming into the picture the research interest of optical communication got a stimulation. A powerful coherent light beam together with the possibility of modulation at high frequencies was the key feature of LASER. Kao and Hockham proposed the transmission of information via Dielectric waveguides or optical fiber cables fabricated from glass almost simultaneously in 1966. In the earlier stage optical fibers exhibited very high attenuation (almost 1000 dB/km) which was incomparable with coaxial cables having attenuation of around 5 to 10dB/km. Nevertheless, within ten years optical fiber losses were reduced to below 5dB/km and suitable low loss jointing techniques were perfected as well. Parallely with the development of the optical fibers other essential optical components like semiconductor optical sources (i.e. injection LASERs and LEDs) and detectors (i.e. photodiodes and phototransistors) were also going through rigorous research process. Primarily the semiconductor LASERs exhibited very short lifetime of at most a few hours but by 1973 and 1977 lifetimes greater than 1000 hr and 7000 hr respectively were obtained through advanced device structure.

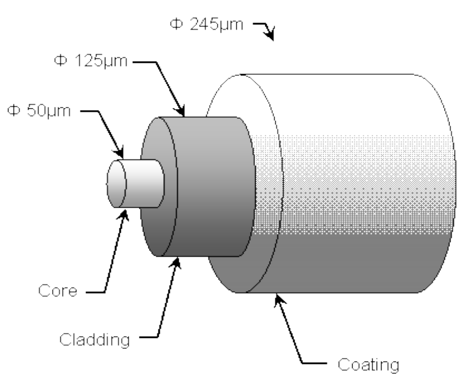
Introduction

The first generation optical fiber links operated at around 850 nm range. Existing GaAs based optical sources, silicon photo detectors, and multimode fibers were used in these links and quiet understandably they suffered from intermodal dispersion and fiber losses. With the advent of optical sources and photo detectors capable of operating at 1300 nm, a shift in transmission wavelength from 850nm to 1300nm was possible which inturn resulted in a substantial increase in the repeaterless transmission distance for long haul telephone trunks. Systems operating at 1550nm provided lowest attenuation and these links routinely carry traffic at around 2.5Gb/s over 90 km repeaterless distance. The introduction of optical amplifiers like Erbium-doped fiber amplifiers (EDFA) and Praseodymium-doped fiber amplifiers (PDFA) had a major thrust to fiber transmission capacity. The use of Wavelength Division Multiplexing along with EDFA proved to be a real boost in fiber capacity. Hence developments in fiber technology have been carried out rapidly over recent years. Glass material for even longer wavelength operation in the mid-infrared (2000 to 5000nm) and far-infrared (8000 to 12000nm) regions have been developed. Furthermore, the implementation of active optoelectronic devices and associated fiber components (i.e. splices, connectors, couplers etc.) has also accelerated ahead with such speed that optical fiber communication technology would seem to have reached a stage of maturity within its developmental path.

A to Z of OPTICAL FIBERS:

Optical fiber is a dielectric waveguide or medium in which information (voice, data or video) is transmitted through a glass or plastic fiber, in the form of light. The basic structure of an optical fiber is shown in figure 1. It consists of a transparent core with a refractive index n1 surrounded by a transparent cladding of a slightly less refractive index n2. The refractive index of cladding is less than 1%, lower than that of core. Typical values for example are a core refractive index of 1.47 and a cladding index of 1.46. The cladding supports the waveguide structure, protects the core from absorbing surface contaminants and when adequately thick, substantially reduces the radiation loss to the surrounding air. Glass core fibers tend to have low loss in comparison with plastic core fibers. Additionally, most of the fibers are encapsulated in an elastic, abrasion-resistant plastic material which mechanically isolates the fibers from small geometrical irregularities and distortions. A set of guided electromagnetic waves, also called the modes of the waveguide, can describe the propagation of light along the waveguide. Only a certain number of modes are capable of propagating through the waveguide.

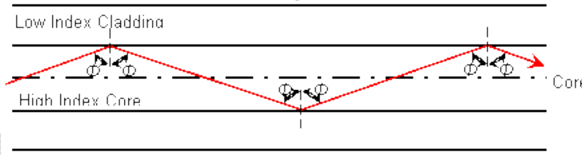
Figure 1.



Principle of ray propagation:

This is the most interesting thing about optical fiber cables. Such an indispensable part of modern day communication system works on an extremely simple property of light ray i.e. **Total Internal Reflection**. As we all know that when light ray is passing from denser (refractive index is higher) dielectric medium to a rarer (refractive index is lower) dielectric medium then from the point of incidence at the interface it bends away from the normal. When the incidence angle is sufficiently high such that the angle of refraction is 90º then it is called critical angle. Now if light ray falls at the interface of the two mediums at an angle greater than the critical angle then the light ray gets reflected back to the originating medium with high efficiency (around 99.9%) i.e. total internal reflection occurs. With the help of innumerable total internal reflections light waves are propagated along the fiber with low loss as shown in figure2. In this context, two parameters are very crucial namely **Acceptance Angle** and **Numerical Aperture**.

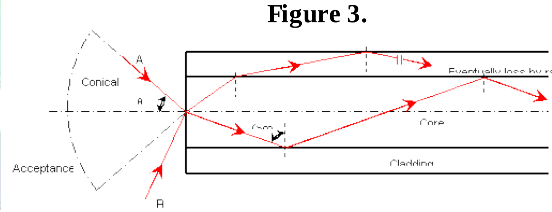
Figure 2.



Acceptance angle is the maximum angle at which light may enter the fiber in order to be propagated and is denoted by θa in figure3. The relationship between the acceptance angle and the refractive indices of the three media involved-core, cladding and air, leads to the definition of Numerical Aperture which is given by – $NA = (n_1^2 - n_2^2)^{1/2} = n_0 \sin \theta_a$ where n_0 is the refractive index of air.

The light ray shown in figure3 is known as a meridional ray as it passes through the axis of the fiber. However, another category of ray exists which is transmitted without passing through the fiber axis and follows a helical path through the fiber.

Figure 3.



Modes in optical fibers :

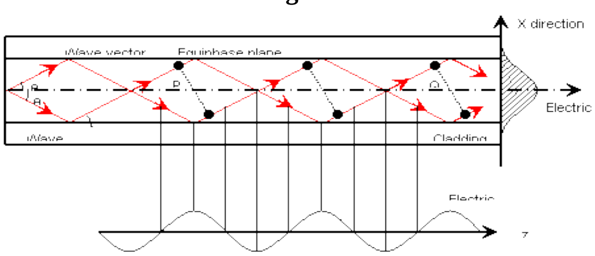
The electromagnetic wave theory must be taken into account for getting an improved model for propagation of light through optical fibers. The optical waveguide can be considered to be either a planer guide or a cylindrical guide. Electromagnetic field comprises of a periodically varying electric field E and magnetic field M which are oriented at right angle to each other. When the electric field is perpendicular to the direction of propagation and hence Ez=0, but a corresponding magnetic field component is in the direction of propagation, that mode is known as **Transverse Electric (TE)** mode. But when the reverse thing happens then it is termed as **Transverse Magnetic (TM)** mode. Now when total field lies in the transverseplane, **Transverse electromagnetic**

(TEM) waves exist where both Ez and Hz are zero. The formation of modes in a planer dielectric guide and the interference of plane waves are shown in figure4. Here the stable field distribution in the x direction with only a periodic z dependence due to sinusoidally varying electric field in z direction is known as a mode. In a cylindrical fiber transverse electric (TE) and transverse magnetic (TM) modes are obtained which is bounded in two dimensions. Thus two integers (l & m) are necessary to specify the modes. Hybrid modes may also occur in the cylindrical fibers. These modes result from skew ray propagation and are designated by HElm when H makes a larger contribution to the transverse field and EHlm when E makes larger contribution to the transverse field.

Transmission Characteristics of Optical Fiber Cables:

The transmission characteristics of optical fiber cables play a major role in determining the performance of the entire communication system. **Attenuation** and **bandwidth** are the two most important transmission characteristics when the suitability of optical fiber for communication is analysed. The various attenuation mechanisms are **linear scattering, non linear scattering, material absorption** and **fiber bends** etc. The bandwidth determines the number of bits of information transmitted in a given time period and is largely limited by signal dispersion within the fiber.

Figure 4.



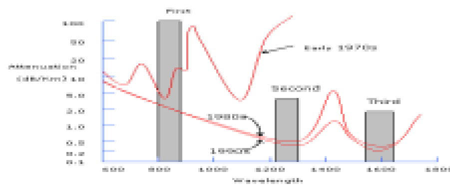
Attenuation in Optical Fibers:

Attenuation is defined as the loss of optical power over a set distance, a fiber with a lower attenuation, will allow more power to reach to the receiver than a fiber with higher attenuation. Signal attenuation within optical fiber is usually expressed in decibel per unit length (i.e. dB/km).

Loss in decibel (dB) = $10 \log_{10}(Pi/Po)$

where Pi and Po are the transmitted and output optical power respectively. Figure5 shows optical fiber attenuation as a function of wavelength.

Figure 5.



Linear scattering losses:

Through this mechanism a portion/total optical power within one propagating mode is transferred to another. Now when the transfer takes place to a leaky or radiation mode then the result is attenuation. It can be divided into two major categories namely **Mie scattering** and **Rayleigh scattering**.

Mie Scattering:

Non perfect cylindrical structure of the fiber and imperfections like irregularities in the core-cladding interface, diameter fluctuations, strains and bubbles may create linear scattering which is termed as Mie scattering.

Rayleigh scattering:

The dominant reason behind Rayleigh scattering is refractive index fluctuations due to density and compositional variation in the core. It is the major intrinsic loss mechanism in the low impedance window. Rayleigh scattering can be reduced to a large extent by using longest possible wavelength.

Nonlinear scattering losses

Especially at high optical power levels scattering causes disproportionate attenuation, due to nonlinearbehavior. Because of this nonlinear scattering the optical power from one mode is transferred in either the forward or backward direction to the same, or other modes, at different frequencies. The two dominant types of nonlinear scattering are :

a) Stimulated Brillouin Scattering and

b) Stimulated Raman Scattering.

Material Absorption losses:

When there happens to be some defect in the material composition and the fabrication process of optical fiber, there is dissipation of optical power in the form of heat in the waveguide. Here also there are two types of absorption losses in the fiber such as **intrinsic absorption** and **extrinsic absorption.** When the absorption is caused by interaction with one or more components of glass it is termed as intrinsic absorption whereas if it is due to impurities within the glass like transition metal or water then it is called the extrinsic one.

Dispersion

It is defined as the spreading of the light pulses as they travel down the fiber. Because of the spreading effect, pulse tend to overlap, making them unreadable by the receiver which is a critical problem to deal with. It creates distortion for both digital and analog transmission. Dispersion limits the maximum possible bandwidth attainable within a particular fiber. Pulse broadening is a very common problem created by dispersion in digital transmission. To avoid it, the digital bit rate must be less than the reciprocal of the broadened pulse duration.

Intermodal Dispersion:

The propagation delay difference between different modes within multimode fibers is responsible for intermodal dispersion and hence pulse broadening. In fact, the different group velocities with which the modes travel through the fiber creates the main problem. Multimode step index fibers exhibit a large amount of intermodal dispersion whereas in a pure single mode fiber there is no intermodal dispersion. By adopting an optimum refractive index profile (parabolic profile in most graded index fibers), we can drastically reduce intermodal dispersion.

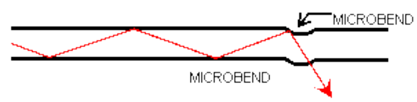
Intramodal Dispersion :

This type of dispersion takes place due to the fact that optical sources do not emit a single frequency but a band of frequencies and there happens to be propagation delay differences between these spectral components. This kind of pulse broadening occurs in almost every type of optical fibers. When the dispersive characteristics of the waveguide material are responsible for the delay differences then it's known as **material dispersion**. On the other hand if imperfect guidance effect is behind the pulse broadening then it's termed as **waveguide dispersion**. There is almost zero waveguide dispersion in multimode fibers.

Fiber bending losses :

Light energy gets radiated at the bends on their path through the fiber and eventually is lost. This is the mechanism known as fiber bend losses. There are two types bending causing this loss namely micro bending and macro bending. If the fiber is sharply bent so that the light traveling down the fiber can not make the turn and gets lost then it's macro bending as shown in figure 6(a). When small bends in the fiber created by crushing, contraction etc causes the loss then it is called micro bending as shown in figure 6(b). These bends are not usually visible with naked eye.

Figure 6 a



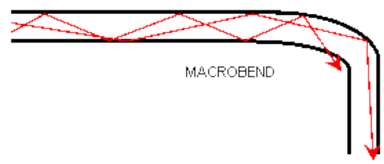


Figure 6b

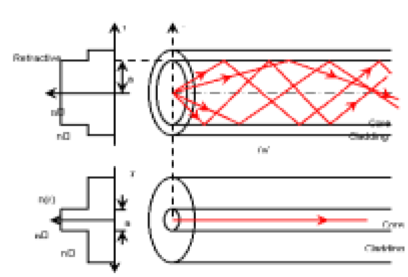
Types of Optical Fibers :

According to the refractive index profile optical fibers can be divided into two categories namely **Step index fibers** and **Graded index fibers** which are described below.

Step index fibers:

If the refractive index profile of a fiber makes a step change at the core cladding interface then it is known as step index fiber. A multimode step index fiber is shown in figure 7(a), the core diameter of which is around 50µm. Some physical parameters like relative refractive index, index difference, core radius etc determines the maximum number of guided modes possible in a multimode fiber. A single mode fiber has a core diameter of the order of 2 to 10µm and the propagation of light wave is shown in figure 7(b). It has the distinct advantage of low intermodal dispersion over multimode step index fiber. On the other hand multimode step index fibers allow the use of spatially incoherent optical sources and low tolerance requirements on fiber connectors.

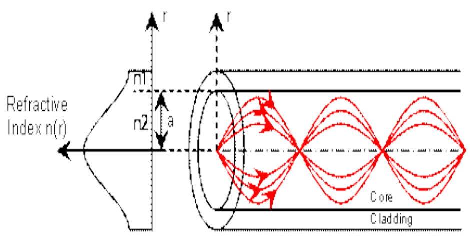
Figure7.



Graded index fibers:

The graded index fibers have decreasing core index n(r) with radial distance from a maximum value of n1 at the axis to a constant value n2 beyond the core radius a in the cladding as shown in figure8. The graded index fiber gives best results for multimode optical propagation for parabolic refractive index profile. Due to this special kind of refractive index profile multimode graded index fibers exhibit less intermodal dispersion than its counterpart i.e. multimode step index fibers.

Figure 8.



GENERAL OVERVIEW OF OPTICAL FIBER COMMUNICATION SYSTEM:

Like all other communication system, the primary objective of optical fiber communication system also is to transfer the signal containing information (voice, data, video) from the source to the destination. The general block diagram of optical fiber communication system is shown in the figure9.

The source provides information in the form of electrical signal to the transmitter. The electrical stage of the transmitter drives an optical source to produce modulated light wave carrier. Semiconductor LASERs or LEDs are usually used as optical source here. The information carrying light wave then passes through the transmission medium i.e. optical fiber cables in this system. Now it reaches to the receiver stage where the optical detector demodulates the optical carrier and gives an electrical output signal to the electrical stage. The common types of optical detectors used are photodiodes (p-i-n, avalanche), phototransistors, photoconductors etc. Finally the electrical stage gets the real information back and gives it to the concerned destination.

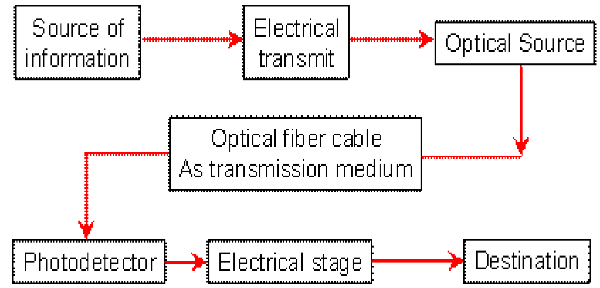


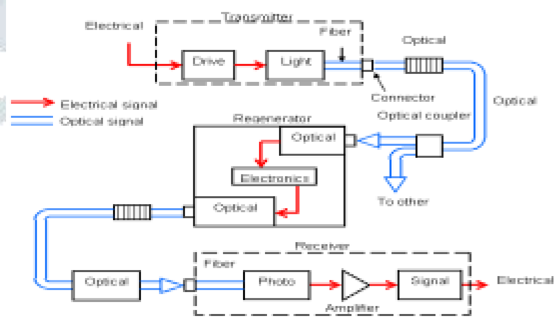
FIGURE 9.

It is notable that the optical carrier may be modulated by either analog or digital information signal. In digital optical fiber communication system the information is suitably encoded prior to the drive circuit stage of optical source. Similarly at the receiver end a decoder is used after amplifier and equalizer stage.

PRIMARY ELEMENTS OF OPTICAL FIBER COMMUNICATION SYSTEM :

Figure10 shows the major elements used in an optical fiber communication system. As we can see the transmitter stage consists of a light source and associated drive circuitry. Again, the receiver section includes photo detector, signal amplifier and signal restorer. Additional components like optical amplifier, connectors, splices and couplers are also there. The regenerator section is a key part of the system as it amplifies and reshapes the distorted signals for long distance links.

Figure 10.



Transmitter section :

The main parts of the transmitter section are a source (either a **LED** or a **LASER**), efficient coupling means to couple the output power to the fiber, a modulation circuit and a level controller for LASERs. In present days, for longer repeater spacing, the use of single mode fibers and LASERs are seeming to be essential whereas the earlier transmitters operated within 0.8µm to 0.9µm wavelength range, used double hetero structure LASER or LED as optical sources. High coupling losses result from direct coupling of the source to optical fibers. For LASERs, there are two types of lenses being used for this purpose namely **discrete lenses** and **integral lenses**.

LED vs LASER as optical source :

A larger fraction of the output power can be coupled into the optical fibers in case of LASERs as they emit more directional light beam than LEDs. That is why LASERs are more suitable for high bit rate systems. Fenlightens how light output power depends on input drive current in case of LASERs and LEDs. From that it is obvious that LASER is more temperature dependent than LED. LASERs have narrow spectral width as well as faster response time. Consequently, LASER based systems are capable of operating at much higher modulation frequencies than LED based systems. Typical LEDs have lifetimes in excess of 10^7 hours, whereas LASERs have only 10^5 hours of lifetime. Another thing is that LEDs can start working at much lower input currents which is not possible for LASERs. So, according to the situation and requirements either LED or LASER can be utilized as an optical source.

Now there are a number of factors that pose some limitations in transmitter design such as electrical power requirement, speed of response, linearity, thermal behavior, spectral width etc.

Drive circuitry :

These are the circuits used in the transmitters to switch a current in the range of ten to several hundred miliamperes required for proper functioning of optical source. For LEDs there are drive circuits like common emitter saturating switch, low impedance, emitter coupled, transconductance drive circuits etc. On the other hand for LASERs, shunt drive circuits, bias control drive circuits, ECL compatible LASER drive etc are noticeable.

Receiver section:

Figure12 enlightens the general structure of a receiver section. It is clear that it includes Photodetector, low noise front end amplifier, voltage amplifier and a decision making circuit to get the exact information signal back. High impedance amplifier and Trans impedance amplifier are the two popular configurations of front end amplifier, the design of which is very critical for sensible performance of the receiver. The two most common photodetectors are **p-i-n diodes** and**avalanche photodiodes**. Quantum efficiency , responsivity and speed of response are the key parameters behind the decision of photodetectors. The most important requirements of an optical receiver are **sensitivity**, **bit rate transparency**, **bit pattern independence**, **dynamic range**,**acquisition time** etc. As the noise contributed by receiver is higher than other elements in the system so, we must put a keen check on it.

BENEFITS OF OPTICAL FIBER COMMUNICATION SYSTEM :

Some of the innumerable benefits of optical fiber communication system are:

- Immense bandwidth to utilize
- Total electrical isolation in the transmission medium
  - Very low transmission loss,
  - Small size and light weight,
  - High signal security,
  - Immunity to interference and crosstalk,
  - Very low power consumption and wide scope of system expansion etc.

These are the main advantages that have made optical fiber communication system such an indispensable part of modern life.

FIELD OF APPLICATION:

Due to its variety of advantages optical fiber communication system has a wide range of application in different fields namely :

a. **Public network field** which includes trunk networks, junction networks, local access networks, submerged systems, synchronous systems etc.

b. **Field of military applications** ,

c. **Civil, consumer and industrial applications,**

d. **Field of computers** which is the center of research right now.

FUTURE OF COMMUNICATION.

Wireless through optical fiber. Getting the most out of limited bandwidth will be more and more essential as wireless demands increase in the near future. One optical networking group at the Institute of Technology in Atlanta is showing how to get the most of wireless capacity and bandwidth by splitting wireless signals into separate components and then using optical fiber to carry wireless signals to their destination where they are re-integrated. The long-range linkages are provided by optical fiber, but the last few tens of meters are provided by wireless. The result: users can communicate wirelessly at a much higher bandwidth over a longer distance than is possible without using a fiber. Optical Fiber: The New Era of High Speed Communication… 23 ii. Ratchting up data rates. IBM has developed a transceiver capable of boosting chip-to-chip bandwidth on printed circuit boards to 300 Gigabits per second (Gb/s) – the fastest rate to date and a development that ultimately will enable even faster speeds for data transmission in homes and businesses. The device, assembled from relatively low-cost components that might someday be easily mass-manufactured, allows for a bi-directional data rate nearly twice that of an earlier generation IBM transceiver. This increased bandwidth is the result of two specific advances. First, the new transceiver includes 24 channels for sending and receiving data compared to 16 such channels in the previous device. Second, the modulation rate of each of the transceiver's vertical cavity surface emitting lasers (VCSELs) has been increased by 25 percent to 12.5 billion bits per second. In an effort to speed commercialization efforts, IBM has incorporated lasers and detectors that operate at the industry-standard wavelength of 850 nanometers (nm) instead of the proprietary 985-nn technology used in the earlier transceiver. iii. Alternative routes on the information superhighway Data transmission capacity has grown enormously in recent years, but so has the demand for this capacity. Although the band currently used for optical communication (1.5 micron wavelength) is sufficient for the moment, the enormous increase of traffic expected in the future demands that scientists and engineers begin exploring new bands now. iv. A new view of the Electromagnetic Spectrum The terahertz band is relatively unexplored and unexploited because its range of frequencies is too high for conventional electronics and too small for semiconductor lasers and detectors, but new research to be presented at OFC/NFOEC reflects what scientists have always known - the terahertz band has great potential. One of a faculty of Institute in Berlin will explore the use of the terahertz band for applications in security, medicine, and materials science and the role telecommunications technologies play in its developments. Terahertz radiation, unlike other scanning technologies, can penetrate materials like paper, clothing and plastics and remain harmless to humans. So, terahertz spectra can indicate explosives or analyze complex pharmaceutical substances where today's technologies, such as X-rays, cannot.

CONCLUSION:

Though there are some negatives of optical fiber communication system in terms of fragility, splicing, coupling, set up expense etc. but it is an un avoidable fact that optical fiber has revolutionized the field of communication. As soon as computers will be capable of processing optical signals, the total arena of communication will be opticalized immediately.

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