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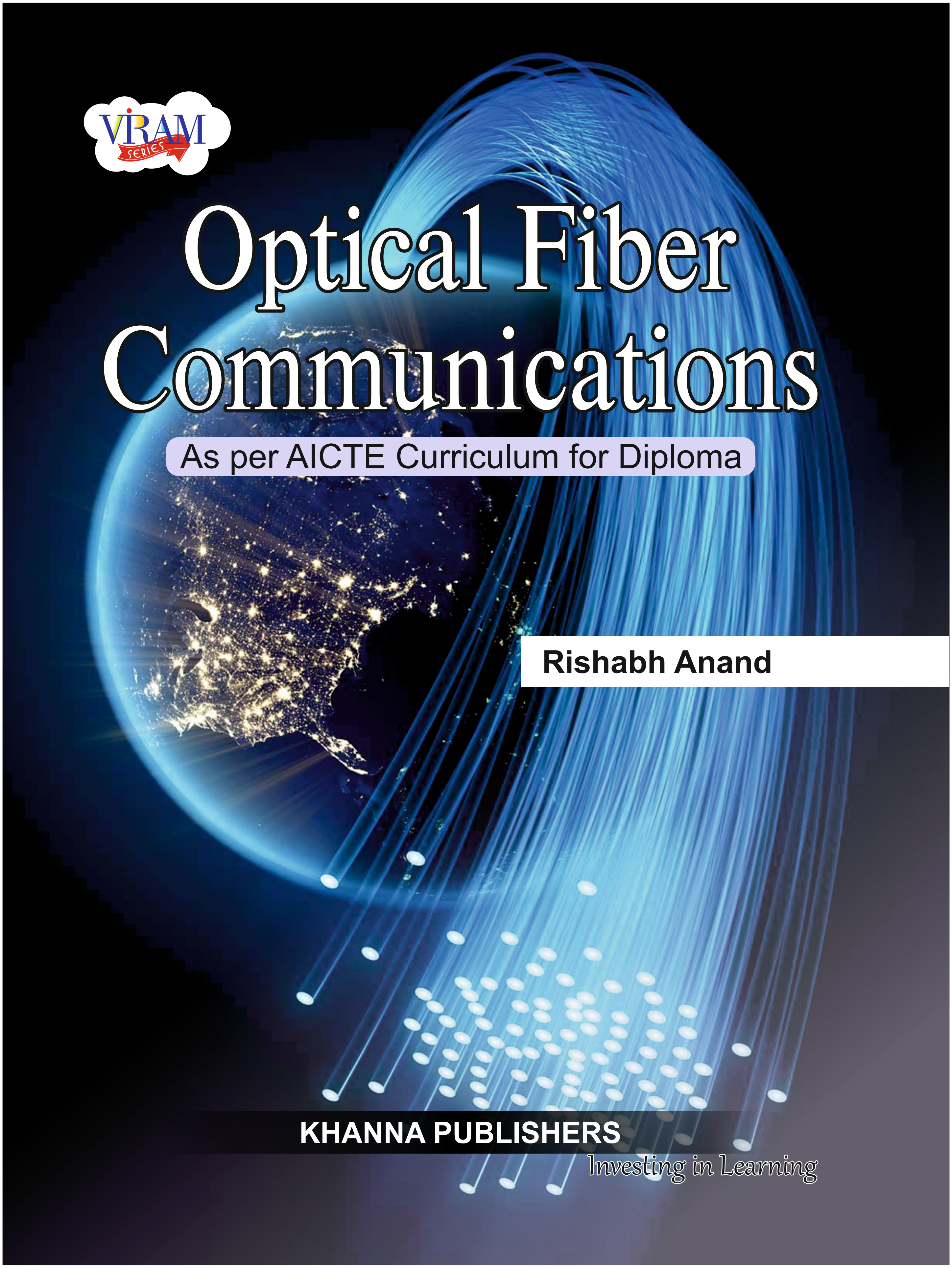
# Optical Fiber Communications

As per AICTE Curriculum for Diploma

**Rishabh Anand**



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# *Optical Fiber Communications*


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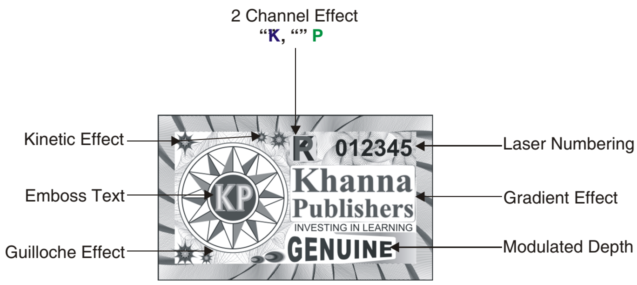


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# *Preface*

At home, the quadruple play: digital television, radio, high speed Internet, landline and cell phones ... At work, multiple and diverse computer applications combining voice, data and images ... We conduct our business as if it is completely natural to exchange and receive all this information, but how does this transmission of information happen? This is what, author of this book, skillfully and clearly explains, and reminds us of all the levels of creativity, mathematical calculations and technical magic that had to happen in order for a simple fiber glass cable, the optical fiber to be able to transport digital information at speeds that today exceed a dozen terabits per second or 10,000 billion bits per second on a single fiber!

What more is there to say to you, dear reader, except maybe to insist on the triple application of fiber-optic telecommunications: at home, at work and in social relations. Currently at home there are over 25 million subscribers worldwide using fiber optics providing them with 100 Mbit/s and already in Japan, several thousand users can use throughputs of 1 Gbit/s enabling them to simultaneously receive several high definition television channels while having access to hyper-realistic online video. At work, high throughput digital data, combined with video telephony, ensure rapid circulation of large volumes of data, their storage and their query in relational database management systems simultaneously. As for the social aspect, much interest is based on the development of e-government, e-training, e-medicine and other type relations. Another significant advantage of these social evolutions resulting from fiber-optic telecommunications involves environmental protection by greatly decreasing the movement of people.

The dramatic reduction in transmission loss of optical fibers coupled with equally important developments in the area of light sources and detectors have brought about a phenomenal growth of the fiber optic industry during the past two decades. Indeed, the birth of optical fiber communications coincided with the fabrication of low-loss optical fibers and operation of room temperature semiconductor lasers in 1970. Since then, the scientific and technological progress in the field has been so phenomenal that optical fiber communication systems find themselves already in the fifth generation within a span of about 25 years. Broadband optical fiber amplifiers coupled with wavelength division multiplexing techniques and soliton communication systems are some of the very important developments that have taken place in the past few years, which are already revolutionizing the field of fiber optics. Although the major application of optical fibers has been in the area of telecommunications, many new related areas such as fiber optic sensors, fiber optic devices and components, and integrated optics have witnessed considerable growth. In addition, optical fibers allow us to perform many interesting and simple experiments permitting us to understand basic physical principles. Indeed, although optical fiber communications could now, nearly two decades after that period finished, be defined as mature, this statement fails to signal the continuing rapid and extensive developments that have subsequently taken place. Furthermore the pace of innovation and deployment fueled, in particular, by the Internet is set to continue with developments in the next decade likely to match or even exceed those which have occurred in the last decade.

Major advances which have occurred while the second edition has been in print include: those associated with low-water-peak and high-performance single-mode fibers; the development of photonic crystal fibers; a new generation of multimode graded index plastic optical fibers; quantum-dot fabrication for optical sources and detectors; improvements in optical amplifier technology and, in particular, all-optical regeneration; the realization of photonic integrated circuits to provide ultrafast optical signal processing together with silicon photonics; developments in digital signal processing to mitigate fiber transmission impairments and the application of forward error correction strategies. In addition, there have been substantial enhancements in transmission and multiplexing techniques such as the use of duobinary-encoded transmission, orthogonal frequency division multiplexing and coarse/dense wavelength division multiplexing, while, more recently, there has been a resurgence of activity concerned with coherent and, especially, phase-modulated transmission. Finally, optical networking techniques and optical networks have become established employing both specific reference models for the optical transport network together with developments originating from local area networks based on Ethernet to provide for the future optical Internet (i.e. 100 Gigabit Ethernet for carrier-class transport networks). Moreover, driven by similar broadband considerations, activity has significantly increased in relation to optical fiber solutions for the telecommunication access network.

Optical Fiber Communications is fast extending the boundaries of research laboratories and attaining the threshold of real-life applicability. Beginning with an overview of historical development, the electromagnetic spectrum, and optical power basics, this book offers an in-depth discussion of optic receivers, optical transmitters and amplifiers. The text discusses attenuation, transmission losses, optical sources such as semiconductor light emitting diodes, and lasers, providing several dispersion-management schemes that restore the amplified signal to its original state. Topics are discussed in a structured manner, with definitions, explanations, examples, illustrations, and informative facts.

The book can serve as a text for undergraduate or graduate courses and various scenarios are possible depending on the background preparation of the class and the curriculum of the institution.

New Delhi

Rishabh Anand

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CHAPTER

# Introduction to Optical Fiber Communications

## 1.1 INTRODUCTION

The communication usually means the transfer of signal from one point to other. This is achieved by using an electromagnetic wave as a carrier on which the information to be transferred is superimposed or modulated. At the receiving end carrier is removed by the process of demodulation and the original information retrieved. Carrier can be generated by using radio, microwave and millimeter wave frequencies. More recently, the communications have also been achieved by using optical range of frequencies as a carrier. The frequencies and wavelengths corresponding to radio, microwave and optical regions of the electromagnetic spectrum are given in Fig. 1.1.

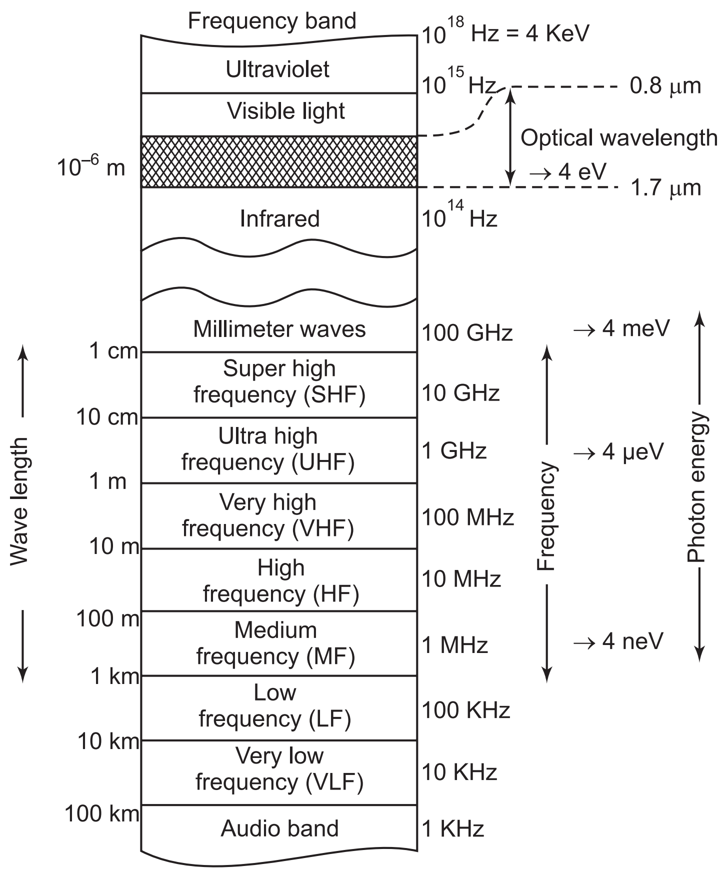


**Fig. 1.1:** Electromagnetic spectrum.

Fiber optics are being used extensively in place of copper wires as an effective means of communication. They are in use spanning long distances between local phone systems as well as providing viable set up for many network systems. They have found extensive use in cable Television services, university campuses, office buildings, industrial plants and electrical utility.

At one end of the system is a transmitter which accepts the coded electronic pulse information. These are then processed and translated into equivalently coded light pulses. These are then coupled into the fiber optic medium and transmitted down the line. Light pulses move down the fiber optic line by the process of total internal reflection, where the angle of incidence exceeds the critical value, thereby transmitting information down the fiber lines in the form of light pulses. Fiber optic cable functions as a light guide, guiding the light introduced at one end of the cable through to the other end. The light source is pulsed on and off, and a light sensitive receiver at the other end of the cable converts the pulse back into the digital ones and zeros of the original signal.

## 1.2. HISTORICAL BACKGROUND

The use of light for communication purposes dates back to antiquity if we interpret optical communications in a broad sense. Most civilizations have used mirrors, fire beacons, or smoke signals to convey a single piece of information (such as victory in a war).

Communication using light in not a new science. Greeks used smoke and reflected sunlight during the day and fire at night to convey message over long distances. Old Romans used polished metal plates as mirrors to reflect sunlight for long range signaling. The navies of the world have been using for centuries blinking lights to send messages from one ship to another. This process is practised even today. In 1880, Alexandra Graham Bell experimented with his photophone that used sunlight reflected off a vibrating mirror and a selenium photocell to send telephone like signals. Fig. 1.2 shows the photophone experiment, where sunlight is deflected by a mirror and directed onto another mirror. This mirror is mounted on the diaphragm of a microphone. The beam after reflection from the diaphragm falls on a selenium photocell. Diaphragm varies in accordance with the speech acoustic signal which results in the intensity modulation of the reflected beam.

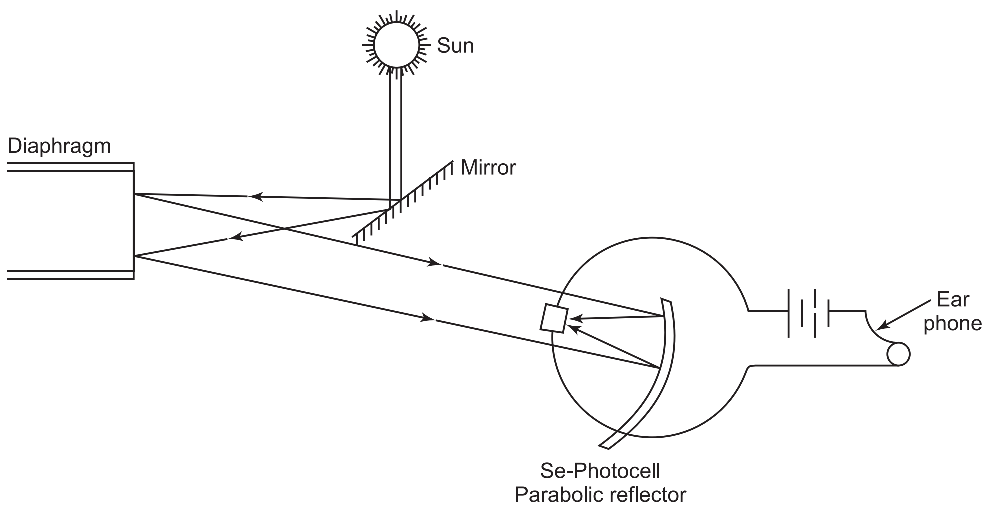


**Fig. 1.2:** Photophone experiment.

This idea however took around 80 years to have better glasses and low cost electronics for use in practical applications. Table 1.1 indicates the chronology of the Research and Development to achieve the fiber optical transmission as it exists today. In any communication system, signal from end is transmitted via a transmitter and received at other end by a matched receivers through a low loss medium. The transmitter and the receiver operates at low frequency of $10^3$ Hz, medium frequency of $10^6$ Hz and higher frequency of $10^{14}$ Hz depending upon the requirement of communication at narrow band, medium band or broad band frequencies and according, transmitters and receivers are used at different frequencies. Similarly, different media are used for communication of audio, video, data, and text messages, which are sent over short and long distances.

Telephone signals are transmitted through copper wire at frequencises upto 10 kHz. Higher frequency signals are transmitted over coaxible cables upto 100 MHz. The radio and microwave frequencies are transmitted through atmosphere from ground to satellite and then back to ground. Broadband communication at super high frequencies ($10^{14}$ Hz) is done over optical fiber cables which are satisfactorily working at 1300 nm, 1550 nm and in future it will go to higher wavelengths around 2550 nm.

**Table 1.1**

| Year | Light Sources | Transmission Medium |
|---|---|---|
| 1879 | | Theoretical study of waveguide (Rayleigh) |
| 1910 | | Theoretical study of dielectric waveguide (Hondros and Debye) |
| 1920 | | Experimental study of dielectric waveguide (Schriever) |
| 1951 | | Development of glass fiber for medical use |
| 1960 | Invention of ruby laser | |
| 1961 | He-Ne laser oscillation (Bell laborateries) | Mode Theory of dielectric wave guide (Snitzer) |
| 1962 | GaAs Semiconductor laser (General Electric, IBM, MIT) | Study of lens array waveguide (Goubou et al.) |
| 1964 | | Experiment of the above (Bell labs). Suggestion of graded index fiber (Nishi zawa and Sasaki, Tohoku University) |
| 1965 | $CO_2$ laser oscillation (Bell labs) | Study of thin film optical waveguide (Karbowiak) |
| 1966 | | Dielectric fiber surface waveguides for optical frequencies (Kao and Hockharm) |
| 1969 | | Trially made graded index fiber (Uchida and Kitano) Graded index rod (Bell labs) |
| 1970 | GaAl As laser continuous oscillation (Bell labs, USSR, NEC) | Development of low loss silica fiber (20 dB/km) (Corning glass works) concept of weakly guiding fiber (Gloge) |

| | | |
|---|---|---|
| 1972 | GaAl As Sb laser oscillation (NTT) | Development of 4 dB/km fiber (corning glass works) |
| 1973 | | Development of MCVD process (Bell labs) |
| 1974 | | Installation and splicing of optical fiber cable on site (Furukawa) |
| 1976 | Ga In ASP laser continuous oscillations (MIT, KDD, NTT, Tokyo institute of Technology) | Development of 0.5 dB/km fiber (1.2 μm) (NTT, Fujikura) |
| 1977 | Estimated life of GaAl AS (1,000, 000 hr) | Invention of VAD process (NTT) |
| 1978 | | Development of ultra-low loss fiber (0.2 dB/km 1.55 μm) (NTT) |
| 1980 | | Invention of the optical fiber amplifier |

Out of these inventions and developments, the four inventions have basically contributed to the progress of the optical communication system. These are ;

(*a*) The inventions of laser during 1960's

(*b*) Fabrication of low loss optical fiber in 1970's

(*c*) Optical fiber amplifier development in 1980's

(*d*) In-fiber Bragg grating invention in 1990's.

During the last thirty years great strides have been made in electro-optics. Light beam communication devices are now extensively used in many common appliances, like telephone equipment and computer systems. The invention of laser in 1960 as a coherent, monochromatic and very intense source of optical frequency, helped in the rapid development of optical communication technology. Initially these lasers had a poor lifetime, but today we have lasers which have a lifetime of around 10 years at room temperature and above. This optical frequency was used as a carrier for telecommunication. This gave an enormous increase in bandwidth. Infact at optical frequencies there is an increase in the usable bandwidth by a factor of $10^4$ over high frequency microwave transmission. A semi-conductor laser that emits a narrow wavelength of light if modulated at a modest 10 GHz rate, could transmit in one second : 900 high density floppy discs, 6,50,000 pages of text, 1000 novels, two 30-volume encyclopedias, 200 minute of high quality music or 10,000 T.V. Pictures. The use of high carrier frequencies allows the communication systems to concentrate available power within the transmitted electromagnetic wave, thus improving the system performance. Another unique feature of the optical communication is that it is usually guided through a fiber and the signalling rates are very high. It was felt during this period that the type of glass fiber used in endoscopes might be used for telecommunications. Thus the concept of the use of fiber for communications was evolved.

The fiber is made of a central glass core surrounded by a cladding of slightly lower refractive index. The fiber is thus like a dielectric waveguide. Originally the fiber with the best glass then available gave a minimum attenuation of 1000. db/km at visible wavelength which initially discouraged its use. But, by eliminating the absorbing impurities from the fiber glass at a convenient wavelength in visible or near infrared, it was possible to develop a practical communication system.

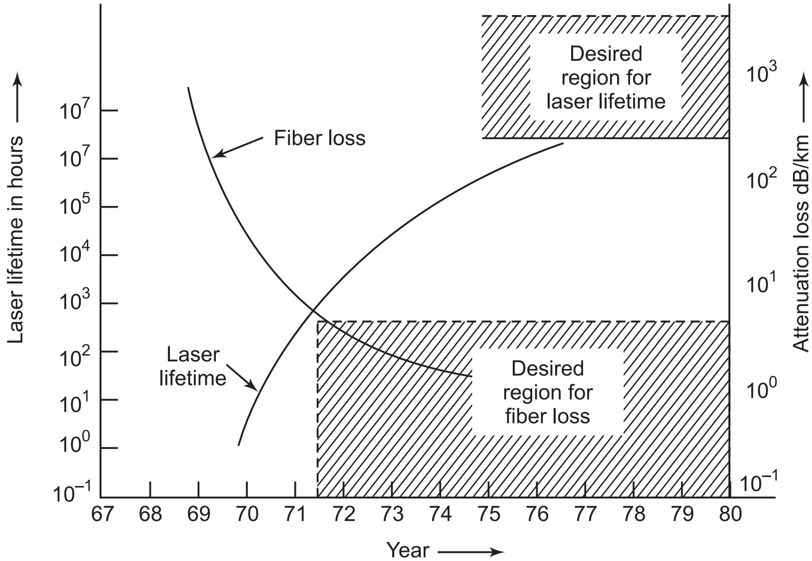


**Fig. 1.3:** Shows the progress that has been made in optical loss in the fibers and semi-conductor laser lifetime.

Fig. 1.3 shows the reduction in the optical loss of fibers and in the increase of the mean time of failure of the semiconductor lasers. The levels that should be obtained for viable optical communication system are also indicated. Fiber losses of less than few decibels per kilometer are necessary to obtain repeaterless communication for a few kilometers or more. At the same time the mean time failure for lasers should be of the order of atleast $10^6$ hours.

Glass manufacturers led by corning in USA and Japanese workers succeeded in eliminating impurities in fiber and attained the attenuation levels as low as 0.2 db/km involving wavelengths (1.3 and 1.55 μm) and 0.15 dB/km at 1.6 μm using silica glass. This was made possible by eliminating transition elements and Hydroxyl ions ($OH^-$) from the fiber. Low attenuation is not the only requirement that the fiber must have, it should also have low dispersion so that the light pulse is not broadened where it becomes unrecognisable in a short transmission distance. Such broadening, which limits the bandwidth of the transmission medium has been controlled by careful radial distribution of the refractive index, which was achieved by corning and Japenese workers. The optical fibers that we use are generally robust and can be manufactured into multifiber cables. A single optical fiber could carry the equivalent information that would require tens of thousands of copper wires. The fiber can also carry information over much longer distances than the copper cables.

There are two types of fibers, multimode and the monomode. The multimode fiber has a core diameter in the range of 50-200 μm whereas for monomode fiber, core diameter is less than 10 μm. The cladding diameter has a value fixed at 125 μm except those with core diameter of 100 μm or more. The three optical wavelengths usually are at 0.85, 1.3 and 1.55 μm.

The first generation system made use of multimode fiber with a core diameter of 50 μm and a laser source radiating at 850 μm. However as the time passed, they became obsolete for long haul applications. Therefore we had to take recourse to the second-generation system where monomode fibers with longer wavelength sources of 1300 nm or 1550 nm were used, thereby giving higher capacity and the longer repeater spacings. The monomode optical fiber systems are thus used extensively for both the overland and the undersea telecommunications. One such example is the establishment of optical fiber transatlantic submarine cable TAT-8 in 1988. During 1998, the major area that emerged in optical communication was the Wavelength Division Multiplexing. This, helped to send as many as 1000 independent optical channels on a single fiber. In 1996, the first commercial WDM system appeared in the market. This was a major step towards fully optical networking.

## 1.3. ADVANTAGES OF OPTICAL COMMUNICATION SYSTEMS

The growth and application of optical fiber system resulted from the development of semiconductor technology, that provided necessary light sources, photodiodes and optical waveguide technology. The optical fiber transmission lines have certain advantages over conventional copper system and these are :

**1. Low Transmission Loss and Wide Bandwidth:** Optical fibers have low transmission losses and wider bandwidths as compared with the copper wires. Typical losses on fiber line are 0.2 dB/km whereas on a copper based facility one can usually expect a loss of atleast 5 dB/km. This means that more data can be sent over long distance in optical fiber system. The number of wire and repeaters needed for transmission are also reduced. The system cost is thus reduced because of reduction in the equipment and the components involved. It is possible to have low attenuation and low dispersion over the fiber links and one can have the repeater spacing as high as > 100 km, with the highest bit rates > 1 Gb/s.

**2. Small Size and Weight:** Fibers have a small size (Hair sized dimension) and low weight. This is an advantage over the heavy, bulky copper wire cables. A 7.6 cm bundle of 900 twisted copper pairs, can carry about 21,000 channels of traffic and weigh about 11250 kg/km whereas a 1.2 cm fiber with 12 fiber strands can carry about 3,00,000 channels and weigh about 90 kg/km. In addition less duct space is required to make the cable within the building. The small light weight cables are found to be advantages in aircraft, satellites, ships and in tactical military applications.

**3. Immunity to Interference:** We know that optical fibers form a dielectric waveguide. Because of this dielectric nature, it provides immunity to electromagnetic interference (EMI). This is so because the connection is not electrical with the result there can neither be a pick up nor creation of electrical interference. It also shows immunity to lightening. It also has immunity from electromagnetic pulse effect (BMP). This shows that optical fiber communication system is unaffected when transmission takes place through an electrically noisy environment. The fiber cable thus requires no shielding from EMI. This means that fiber cables can be placed almost anywhere in comparison to the electrical cables which create problems if placed near a lift, motor or in a cable duct with heavy power cables. Fiber cables also show great flexibility in route selection in wide area networks. Fiber cables can be layed near water or power lines without any risk to the people or equipment. This is of particular interest in military applications.

**4. Electric Isolation:** Ground loops in an electrical system cause serious problems particularly in the LAN or computer channel systems. This is so because connections are to be made with the ground which results in the voltage difference between the ground at various locations. A voltage difference of 1 to 2 volts is usual over a distance of around 1 km. Even if cables are shielded, they have to be connected to the earth at both ends of the connection. There is thus no electric isolation in the copper system. We know that optical fibers are constructed of glass and glass being an insulator, there won't be any ground loops and interface problems. The fiber-to-fiber cross talk is also low. The use of fibers is also attractive in electrically hazardous environment, because there is no arcing or sparking.

**5. Signal Security:** Optical fibers provide a high degree of data security because the optical signal is well contained within the wave-guide and signal cannot be obtained from the fiber without drawing the optical power. To draw optical power, a tap has to be inserted and once an intruder does that, there is an interruption of the service and the operational staff is alerted. Further there are very few access points where an intruder can insert a tap. In case the intruder uses an active tap, it is very difficult to actually insert a signal. In addition there is an opaque jacket surrounding the fiber which can absorb any emanations. Thus fiber finds use in applications where security is of prime concern like banking, computer network and military applications.

**6. Resistance to High Temperature:** The melting point of silica is about 1900°C, far above that of copper or plastics. Therefore cables made with silica are resistant to high temperatures.

**7. Abundant Raw Material:** Since the silica is the principal material for making the optical fibers, it is available in abundance and is inexpensive, as it is found in the ordinary sand. However, the cost of making actual fiber will depend on the process involving making of ultrapure glass from the raw material.

**8. Open Ended Capacity:** The capacity of the installed fiber is very great and theoretically is infinite. This means that with the availability of new technology, additional capacity can be added to the existing fibers. This can be done by changing the equipment at either end or upgrade the regeneration.

### 1.3.1. Limitation of Optical Fibers

**1. Branching of Optical Fibers:** Optical fibers cannot be branched easily. Optical fibers are thin, and it is difficult to branch them directly, where branching is required, it is done after converting that particular section into an electric system.

**2. Joining Fibers:** Fibers are usually joined by the use of fusion splicing which in itself is a difficult task as it requires precision equipment. The task is still more difficult if the splicing is done under extremely low temperature climates.

**3. Effect of Gamma Radiation:** Gamma radiation coming from space is always present. It can be considered as a high energy X-ray. Gamma radiation cause glass to emit light causing interference and also cause glass to discolour thereby attenuating the signal. Therefore fibers are not used as transmission medium inside a nuclear reactor or on a long distance space probe.

**4. Effect of Electric Fields:** It has been observed that very high electric fields also affect some glasses like the gamma rays. Although fiber communication cables are wrapped around high-voltage electric cables on transmission towers, the system works very well where voltage is around 30,000 volts or below.

Above that voltage, the glass tends to emit light and discolour producing losses. Nevertheless recent research effort have helped to produce glasses that will be unaffected by such high fields.

**5. Effect of Sharks and Termites:** During 1980's a new undersea fiber cable was found to be broken on the ocean floor and it was thought that the cable was attacked and eaten by sharks. It was suggested that the chemical composition of the cable sheathing was attractive to sharks. Another explanation indicated that the radiated electromagnetic field caused the sharks to be attracted. Although some people thought that the cable was badly laid and rubbed against rocks, others generally believe that sharks eat optical fiber cables.

Termites have also been known to attack and eat the plastic sheathing of an optical cable.

## 1.4. THE BASIC OPTICAL COMMUNICATION SYSTEM AND ITS ARCHITECTURE

The block diagram of a generalised optical communication system is given in Fig. 1.4. The system consists of an optical source, which is modulated with the signal to be transmitted. The transmission medium is usually made of optical fiber. This is followed by a photo detector, which converts the received optical power back into electric waveforms. Finally we use electronic amplification and signal processing to retrieve the signal and present it in a suitable form. The system can be used for both the analog and digital communication systems. Since optical fibers are used as transmission medium, sources used are only semiconductor light emitting diodes and lasers. At the receiver end semiconductor junction photodiode detectors are used. The advantage of semiconductor sources is that their output power can be modulated directly and with ease by controlling the flow of electric current. The optical signal is usually intensity modulated. The intensity modulation is also referred to as amplitude shift keying (ASK) and on-off keying (OOK). This is the simplest method for modulating the carrier generated by an optical source. The resulting modulated optical carrier is given by :

$$E_s(t) = E_0 m(t) \cos (2\pi f_s t)$$

where $m(t)$ is the modulating signal and the information assumes only the values of '0' and '1'. $f_s$ is the optical carrier frequency.

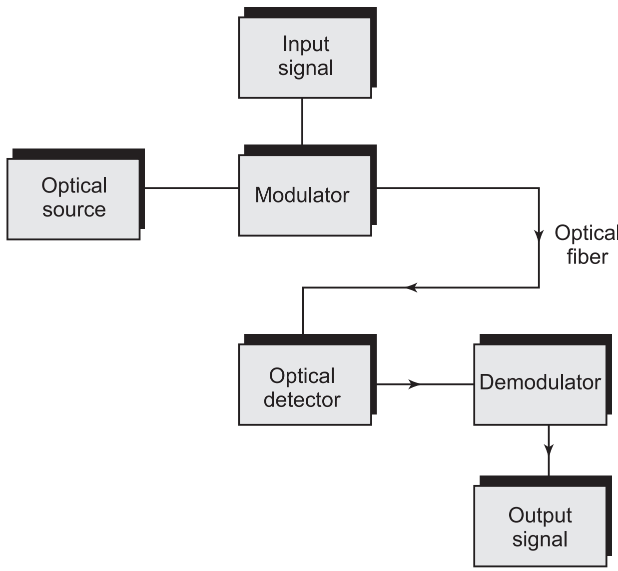


**Fig. 1.4:** Basic optical communication system.

The demodulation function in the receiver will be just to observe the presence or absence of energy during a bit time interval.

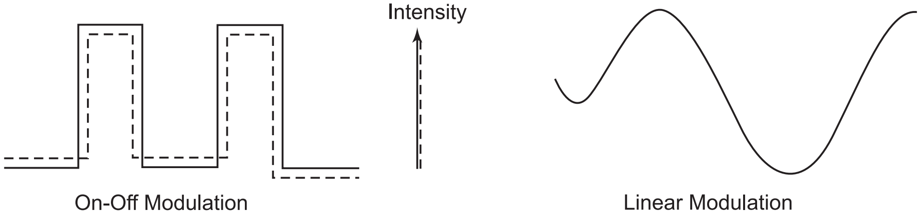


**Fig. 1.5:** Basic optical modulation methods.

The basic optical transmitter usually converts electric input signals into modulated light for transmission over an optical fiber. The modulated light may be turned on and off or may be linearly varied in intensity between two predetermined levels Fig. 1.5 shows a graphic representation of these two basic schemes.

Light emitting diodes (LEDs) and laser diodes (LDs) operate in the infrared portion of the electromagnetic spectrum. Their ligit output is therefore usually invisible to the human eye The wavelengths are so chosen that they have the lowest transmission loss wavelengths of glass fibers and highest sensitivity ranges of the photodiodes. The common wavelengths in use today are 850 nm : 1300 nm and 1550 nm. Both LED's and LDs are available in all three wavelengths. They can be modulated in one of the two ways either on and off or linearly. .

Fig. 1.6 shows the simplified circuitry for modulating LED's or laser diodes. Fig. 1.6(a) shows a transistor being used to switch the LED or LD on and off in step with an input digital signal.

Any digital format can be converted by appropriate circuitry to drive the base of the transistor. Fig. 1.6(*b*) shows an operational amplifier circuit for linear modulation of an LED or LD. The inverting input supplies the modulating drive to the LED or LD, whereas the non-inverting pulse is used to supply a D.C. bias reference. Digital on/off modulation of an LED or LD can take a number of forms. The simplest will be the light on for logic " 1" and light off for logic "0". The two other common forms are pulse width modulation and pulse rate modulation. In the pulse width modulation, a constant stream of pulses is produced with one width signifying a logic "1" and another width, a logic "0". In the pulse rate modulation, pulses are all of the same width but the pulse rate changes to differentiate between logic "1" and logic "0". Analog modulation can also take number of forms. The simplest is intensity modulation where the brightness of an LED is varied in direct step with the variations of the transmitted signal.

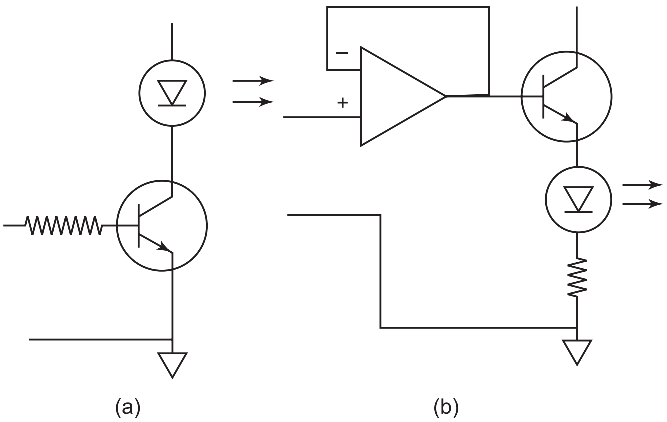


**Fig. 1.6:** Methods of modulating LED's or laser diodes.

There are other methods of modulation where an RF carrier is first frequency modulated with other signal or, in some eases, several RF carries are separately modulated with separate signals and these are then all combined and transmitted as one complex waveform. Fig. 1.7 shows various modulation methods as a function of light output.

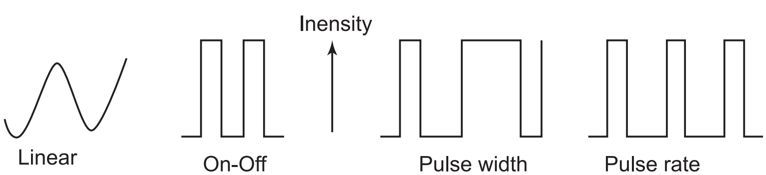


**Fig. 1.7:** Various methods to optically transmit analog information.

It is possible to have many combinations of the source and the detector. However, the source must be of high intensity and this can be provided by a laser. We also need an external means of modulating the light source. It has been observed that the transmission path is often variable leading to attenuation, which results in the fluctuating level of received power. At the receiver either a photodector or a photomultiplier can be used but the choice of detectors will depend upon the wavelengths to be used and the physical size of the systems involved.

## 1.5. CAPACITY OF A TELECOMMUNICATION CHANNEL FOR MEASUREMENT OF INFORMATION

The combination of transmitter, transmission medium and a receiver constitutes a communication link. How effectively this link can operate will depend on various factors.

The link performance will depend on the choice of the transmissions medium. Every transmission medium has constraints on its operation. As the signal propagates down a transmission medium to the receiver its amplitude decreases and gets weaker and weaker. The input data is said to suffer attenuation. Fig. 1.8 shows the signal attenuation as it propagates down the transmission medium.

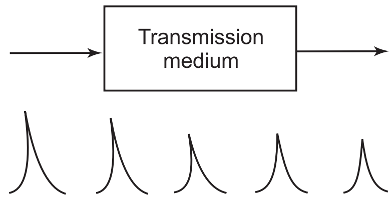


**Fig. 1.8:** Input data signal attenuating as it propagates down a transmission medium.

Thus we find that the attenuation increases with distance through the transmission medium and is measured in dB/km. As the propagation continues, signal is attenuated until it can just be sensed by the receiver in the presence of whatever interference is expected. The distance at which the signal reaches this minimal level is quite significant, because the transmission medium must be able to deliver this minimum detectable signal to the receiver, otherwise the communication cannot take place. In such a situation, even if the minimal signal does not reach the receiver after attenuation, it can be regenerated by the use of a repeater and the signal will propagate on its way to the receiver. This is shown in Fig. 1.9.

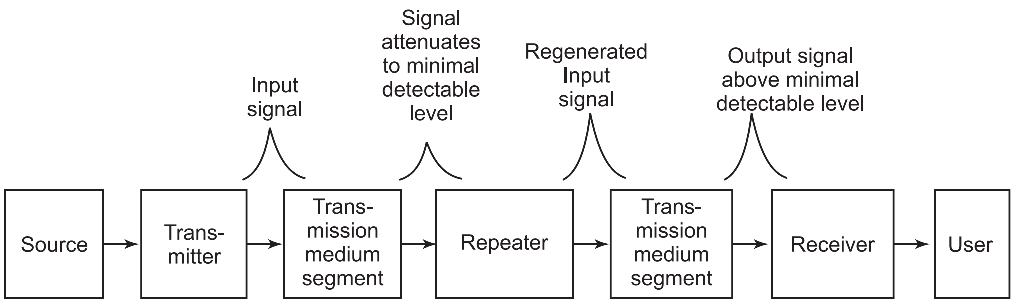


**Fig. 1.9:** Regenerating and repeating an attenuated signal in order to reach the user.

It has been observed that as the signal propagates down the transmission medium, it will encounter noise or interference. The noise is nothing but some extraneous signal that is usually generated outside the transmission medium and somehow gets into the medium and usually adds itself to the propagation signal. The effect of noise interference can be best known through bit error rate. Therefore, for any transmission medium to be effective, it must be capable of delivering the required BER in the presence of noise/interference.

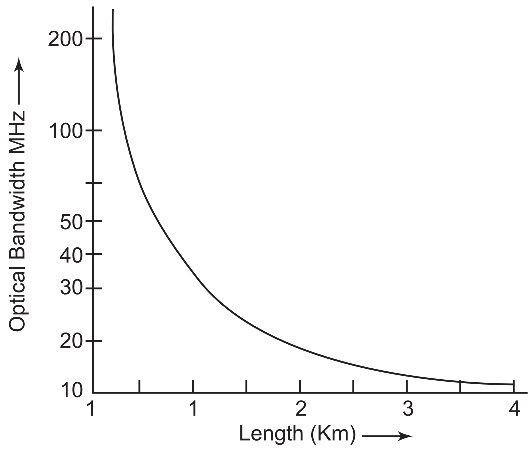


**Fig. 1.10:** Bandwidth of fiber optic cable vs length.

# Optical Fiber Communications

## About the Book

Optical Fiber Communications provides students with the most up-to-date, comprehensive coverage of modern optical fiber communications and applications, striking a fine balance between theory and practice that avoids excessive mathematics and derivations. Unlike other textbooks currently available, this book covers all of the important recent technologies and developments in the field, including electro-optic modulators, coherent optical systems, and silicon integrated photonic circuits. Filled with practical, relevant worked examples and exercise problems, the book presents complete coverage of the topics that optical and communications engineering students need to be successful. Extensive pedagogical features, such as numerical problems, and review questions, are also provided. Mathematical derivations and geometrical representations are included where necessary.

This book is primarily intended as a text for undergraduate students of Electrical Engineering, Electronics and Communication Engineering and Telecommunication Engineering. The book would also prove to be of immense benefit to postgraduate students of Physics and those preparing for AMIE and AMIETE exams.

## About the Author

Rishabh Anand is an eminent academician; plays versatile roles and responsibilities juggling between industry, research, publications and consultancy. He has completed his PostDoc (AI & ML) from Sao Paulo State University, Brazil, Ph.D.(Computer Science) from University of Bristol, United Kingdom, Degree of Master of Business Administration as MBA Management from International MBA Institute, Switzerland and Program Diploma in Innovation Management from International Business Management Institute, Germany. Also, he is the Reviewer/Editor for IJTESSS, IJISP, IJCAC, IJECME, IJICTE, JITR, IJMPA, IJTHI, IRJET, IJCRT and IJSDR. He is a prolific author with 34 Text and Reference books to his credit. He is also associated with various professional bodies like IEEE, LMCEGR, IAENG, Internet Society, IAOP, and IAOIP. He is currently working in ITES MNC industry as a Global Service Delivery Manager with overall 15 years of experience. He is CDPT™, PMP®, PRINCE2®, DevOps-PM™, ITIL4®, CSM® & Kanban-ASC™ Certified Professional.

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