CHAPTER 1

Introduction

Optoelectronic devices are electronic devices that convert an optical signal (light) to an electrical signal (O–E conversion) or an electrical signal to an optical signal (E–O conversion). In the electrical domain, a signal can be processed with the help of electrical technology using electronic components and circuits. The electrically processed signal can be subsequently converted to an optical signal (E–O) with the help of an appropriate optoelectronic device (optical emitter). Similarly, an electrical signal once converted to an optical signal can be processed with the help of several optical (photonic) devices and components. The processed optical signal can be taken back to the electrical domain with the help of a suitable optoelectronic device (optical detector). The frequent conversion of the signal from one domain to the other (E–O and O–E) is an integral part of a conventional optical fiber communication system. However, optoelectronic devices can be deployed in both telecommunication and non-telecommunication applications, these devices are primarily fabricated using semiconductor materials and are mostly available in the form of solid-state devices even though photomultiplier devices are also available in the form of vacuum tubes. The major optoelectronic devices include photodiodes (photodetectors and solar cells), optical sources or emitters (light-emitting diode, injection laser diode), phototransistors, photoconductors, photoresistors, semiconductor laser amplifiers. The present text focuses on optoelectronic devices and other photonic components like optical modulators, switches, attenuators, fiber amplifiers, and electro-optical switches which are key components of optical fiber communication systems. For applications in optical fiber communication systems, optoelectronic devices are designed to operate in the near-infrared (NIR) region of the optical spectrum. Optoelectronic devices for several non-telecommunication applications are also available for operation in the ultraviolet (UV), mid-infrared (MIR), and long wavelength infrared (LWIR) regions of the optical spectrum (Krier, 2004; Ali, 2010). Long-wavelength infrared sources and detectors are also used for free-space optical communication systems.

The purpose of telecommunication or simply communication is to establish a link (wired or wireless) between two distant points to transfer information (or message) from one point to the other (either one way or both ways). This transfer of information from the source to the destination point can be efficiently carried out with the help of electrical technology. The arrangement required for establishing an electrical communication link between two distant points is called a communication system. The fundamental elements of a typical communication system are shown in Fig. 1.1.

In practice, information at the source point may appear in a variety of forms like voice, speech, music, picture (static or video), or data. To make the information available in a non-electrical form suitable for electrical communication we need to convert it into an electrical form with the help of a suitable transducer as shown in Fig. 1.1.

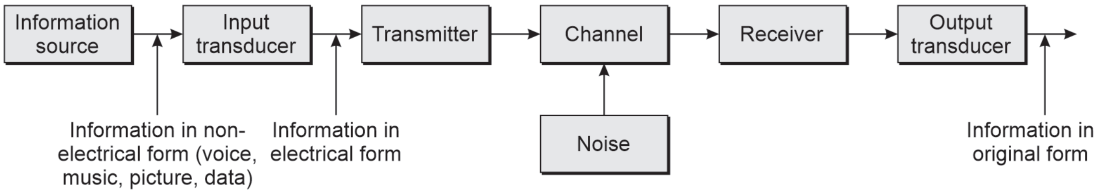

Fig. 1.1 Block diagram of an electrical communication system

The electrical form of the information is subsequently used for transmission. The transfer of information in the electrical form is generally achieved by modulating the information signal with the help of a high-frequency electromagnetic wave which acts as a carrier. This modulation process is done by the transmitter unit. The transmitter then couples the modulated signal onto the transmission channel. Before transmission one needs to ensure that the characteristics of the channel support the modulated information signal and do not cause unacceptable degradation of the signal during propagation of the signal through the channel. The channel is considered as a medium that links the transmitter and the receiver. The channel may be a guided transmission link such as a twin-wire line, coaxial cable, waveguide, or even an unguided atmospheric or space channel. When the transmitted signal travels towards the destination point it is subjected to two major constraints, e.g. noise added in the channel and the attenuation of the signal caused by the absorption of the signal by the channel. While the attenuation can be easily compensated by boosting the signal with the help of signal boosters, the management of noise added by the channel can be quite challenging in some cases (Chakrabarti, 2010; 2018). The transmitted signal to the receiver via the channel then undergoes a reverse process by which the original message signal is extracted from the modulated signal. The process is known as demodulation. The *demodulated* electrical information is finally converted in the original form with the help of a proper transducer.

The information is finally delivered to the message destination. The complexity of this simple arrangement arises from the fact that the transmitted signal gets progressively weakened (attenuated) and mutilated by noise during propagation through the channel. As a result, the receiver has to process a weak and mutilated signal to extract the original message signal. This makes the design of a communication receiver much more complex as compared to the transmitter. Ultra-sophisticated systems have been developed over the past decades for the successful implementation of communication links using electromagnetic waves at radio frequencies, microwave, and millimeter wave frequencies. The successful demonstration of a laser source by Maiman (Maiman, 1960) motivated researchers to use a laser beam as a carrier for the information paving a new avenue for another mode of communication called *optical communication*. In general, optical communication links can be implemented in a variety of forms, for example, it can be in an unguided form (free space optical communication) or a guided form (optical fiber or fiber optic communication). Moreover, light can be used either for intensity modulation by the modulating signal followed by direct detection (IM/DD) or as a coherent carrier in a manner analogous to electrical communication (coherent optical communication). A communication system that uses light as a carrier for the transportation of information from the source to the destination is called an optical communication system.

1.1 GENESIS OF ELECTRICAL AND OPTICAL COMMUNICATION

The era of electrical communication began with the invention of the telegraph by Samuel FB Morse in 1838 (Agrawal, 1995). The first commercial telegraph service could be implemented in 1844. In 1874, Alexander Graham Bell successfully demonstrated the conversion of sound waves into electric current through a small magnet and patented his primitive telephone set in 1876. These two major discoveries paved the way for electrical communication. On the other hand, the feasibility of optical communication could be envisioned nearly after a century with the invention of the LASER (light amplification by stimulated emission of radiation) by Maiman in 1960 (Maiman, 1960). Ironically the earliest mode of communication used by human beings happened to be some form of optical link. In ancient times (the eighth century BC) fire signals were used by the Greeks for sending alarms, distress calls, or making public announcements of events. Later on around 150 BC alphabets were encoded using different optical signals to exchange messages based on some prearranged understanding (protocol). In this mode of optical communication, the human eye was used to work as a receiver. As a result, the speed of this mode of communication was extremely poor and the practical application of this mode was further constrained by the requirement of line-of-sight transmission and the presence of obstacles in the path because of rain, fog, and other atmospheric disturbances. This mode of communication could not be pursued afterward because of technological limitations.

1.1.1 Emergence of Optical Communication

Following the invention of telegraphy in 1838 and the successful implementation of commercial telegraph service in 1844, the first telephone exchange was established in New Haven in 1878. At this time wire cable was the only medium used as the transmission channel. In 1880, Alexander Graham Bell, reported the transmission of speech using a light beam as the carrier and the atmosphere as the transmission medium (Bell, 1876). However, as mentioned earlier, the transmission of light beams through the atmosphere was restricted to line-of-sight paths and affected atmospheric disturbances such as rain, fog, etc. Most importantly, the non-availability of a proper optical source then severely impaired the emergence of optical communication in the early part of the twentieth century (Allard, 1989). James Maxwell theorized a mathematical interpretation of electromagnetic waves in 1864. Later on, in 1884, Heinrich Hertz discovered long-wavelength radiowaves and demonstrated the applicability of Maxwell's theory. Hertz's demonstration revolutionized the concept and scope of electrical communication. In 1895, Marconi G, demonstrated the transmission of radiowaves through free space. In the ensuing years lower frequency (longer wavelength) electromagnetic waves (radio and microwaves) turned out to be suitable carriers for message transmission via the atmospheric channel. Such transmissions are less sensitive to variations in the atmospheric conditions. The era of wireless electrical communication continued to flourish in the ensuing decades. The electromagnetic carrier waves could be transmitted over considerably large distances without having significant attenuation or distortion. However, the information-carrying capacity of these high-frequency electromagnetic waves is directly related to their frequency[1].

In principle, the higher the frequency of the carrier, the larger the transmission efficiency and consequently the higher the information-carrying capacity of the communication system. This fact has been the driving force behind the development of subsequent wireless electrical communication systems that used progressively higher frequencies starting from VHF (very high frequency), and UHF (ultra high frequency) to microwaves and finally to millimeter wave for transmission. The relative frequency and wavelength of various types

[1] The information carrying capacity is directly related to the bandwidth of the modulated carrier which is a fixed fraction of the carrier frequency.

of electromagnetic waves are illustrated in Fig. 1.2. It can be seen that the transmission media used in different ranges of frequency spectrum include metallic wires coaxial cables,

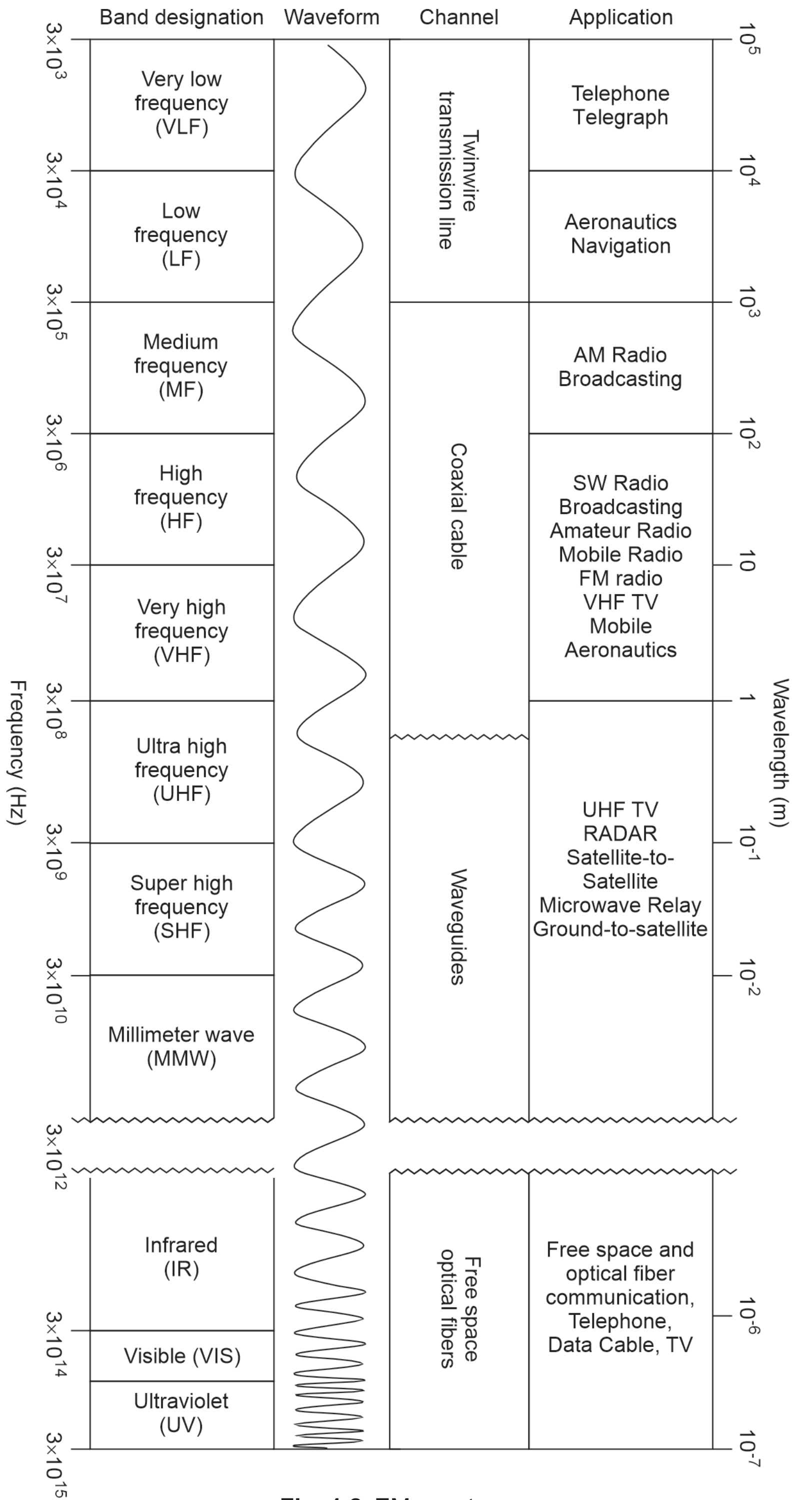

Fig. 1.2 EM spectrum

microwave, and millimeter-wave waveguides, and radiowaves that utilize atmosphere as the channel. The electrical communication systems that utilize various ranges of the electromagnetic spectrum include telephone (landline as well as mobile), AM and FM radio, transmission, radar, satellite-to-satellite links, etc. This frequency range utilized in various commercial applications extends from about 300 Hz in the audio band to 90 GHz in the millimeter wave band.

It is interesting to note here that if the frequency of the electromagnetic carrier is further pushed upwards to encompass the optical region of the electromagnetic spectrum, the bandwidth of the existing microwave transmission can be increased by a factor of 10^4. This would lead to an enormous information-carrying capacity for the new communication system. The system that uses an optical signal as the carrier for transporting the message signal from the source to the destination is called the *optical communication system.* As it stands today this mode of communication has several distinct advantages over conventional electrical communication. For optical communication, it is customary to specify the range of the electromagnetic spectrum in terms of wavelength rather than frequency. However, similar to conventional communication electrical systems, both waveguides and atmospheric channels can be used for the transmission of optical signals in optical communication. The waveguide used in optical communication is generally an optical fiber. Optical communication is thus classified as free space optical communication and optical fiber communication depending on whether a free space channel or a fiber waveguide is used as the transmitting medium.

1.1.2 Evolution of Optical Fiber Communication

This section reviews the most important discoveries that laid the foundation for modern optical communication. The first significant contribution may be traced back to 1917 when Albert Einstein mathematically formulated the conditions for stimulated emission. In 1955 Towns observed stimulated emission leading to microwave amplification. In the subsequent year, Bloembergen demonstrated MASER (microwave amplification by stimulated emission of radiation). The first solid-state MASER was developed by Bell Labs in 1957. Maiman T, demonstrated LASER operation in ruby rods at Hughes research labs in 1960 (Maiman, 1960). By 1962, many of the research labs including IBM and GE succeeded in developing semiconductor laser sources. The invention of the laser source by Maiman in 1960 led to the availability of a coherent optical source operating at a frequency of the order of 5×10^{14} Hz. The invention created interest among researchers in exploring the potential of an optical signal being used as a carrier of message signals in the optical communication system. The early 1960s witnessed several interesting experiments carried out by researchers using the atmosphere as the optical channel (Davis, 1996). It was demonstrated that a coherent optical carrier can be modulated at very high frequencies. Although the low beam divergence of the laser beam extended the free space transmission distance, the high installation cost together with limitations imposed by atmospheric obstructions such as rain, fog, etc. finally made this high-speed system unattractive for practical applications. Today, the application of unguided optical communication (one that uses free space atmosphere as the channel) is restricted to linking a TV camera to a base vehicle, for baseband data linking over a few hundred meters between buildings, and also to long distance earth-to-space and satellite-to-satellite linking (Davis, 1996; De Cusatis *et al* 1998; Fowles, 1975; Gower, 1984; Keiser, 1991; Green, 1993; Hoss, 1993; Senior, 1992; Snyder & Love 1983; Wilson & Hawkes, 1989).

The limitations of free space optical communication using laser as an optical source motivated the researchers to explore the guided transmission of the optical signal via a dielectric waveguide or optical fiber made from glass as a channel. In 1966, Kao[2] and Hockham of proposed dielectric fiber waveguides for the transmission of signals at optical frequencies (Kao *et al* 1966) to avoid the degradation of optical signals by the atmosphere. In principle, this type of guided optical communication should be much more reliable and versatile as compared to free-space optical communication. However, early fibers measured high transmission losses to the tune of 1000 dB/km or so. This extremely high loss associated with the early glass fibers fabricated using traditional glass-making methods was considered impractical for system implementation. Kao and Hockham, attributed this high loss associated with the fiber to impurities present in the glass. It was not until 1970 that Felix Kapron *et al* at Corning Glass Works successfully fabricated a silica fiber having a loss of 20 dB/km at 850 nm. This improvement made the optical fibers look like a viable transmission medium. In subsequent years further improvement in optical fiber fabrication technology reduced the loss from 20 dB/km to 1 dB/km at 1300 nm by 1976. This led to the commercial implementation of the first optical fiber communication link in 1978. By 1982, the fiber loss was brought down to 0.5 dB/km at 1550 nm. Thousands of kilometers of optical fiber lines were installed worldwide by the early 1980s. The other problem associated with guided optical communication in those days included difficulties in satisfactorily jointing the fiber cables. The joint loss used to be significantly high. In the following two decades (1970–1990) extensive research work was carried out worldwide to improve the quality of fiber, reduce the loss, and devise new techniques for jointing fibers. At present, fiber fabrication technology is mature enough to yield silica-based optical fibers that provide an attenuation as low as 0.16 dB/km which is very close to the theoretical limit of 0.14 dB/km.

The growth of optical fiber communication has been sustained by a parallel development in the area of semiconductor devices and technology which provided the necessary light sources, photodetectors, and associated electronic circuits for the optical communication system. Design and development of semiconductor optical sources in the form of semiconductor injection laser diode (ILD), light-emitting diode (LED), and semiconductor photodetectors such as *p-i-n* photodetector, avalanche photodiodes, MSM photodiodes, phototransistors which are compatible in size with the optical fibers (of the order of 100 μm diameter) have been instrumental in successful implementation of practical optical fiber communication link. The semiconductor laser sources of the early 1960s were unsuitable for practical application because of their inability to operate continuously for long hours at room temperature. The early and mid-1970s witnessed dramatic development in the field of semiconductor laser sources and made the fabrication of laser sources with a lifetime of several thousand hours possible. These sources were made of AlGaAs (aluminum-gallium-arsenide), a ternary III-V alloy that emits light in the range of 800–900 nm.

Ever since the successful breakthrough in the development of low-loss optical fibers in 1970, the area of optical fiber communication progressed steadily toward its present maturity. Hundreds of thousands of kilometers of optical fiber cables were installed worldwide in three decades after 1970. Over the past three decades optical communication systems have gone through several different generations of technology which is primarily distinguished based on operating wavelength. The fibers available in the early 1970s

[2] Kao has been awarded 2009, Nobel Prize, along with two others in Physics for his contribution in the area of optical fiber communication.

exhibited low attention loss (~ 5 dB/km) window near 0.8 μm (800 nm). The first generation (1G) optical communication links operated at 800 nm using GaAs-based optical sources and silicon photodetectors. Optical fibers used in this generation were multimode silica fibers. The 1G optical links were used primarily in telephone systems in the United States, parts of Europe, and Japan. The operating bit rate in the 1G system ranged between 30–140 Mbps. The repeater spacing in this generation was nearly 10 km. The availability of good quality optical fibers with extremely low attenuation (~0.5 dB/km) at 1300 nm in the early 1980s motivated the researchers and design engineers to shift the operating wavelength from 800 nm (in the 1G system) to 1300 nm in the second generation (2G) system. This shift resulted in a substantial increase in the repeater spacing thus making optical communication links quite beneficial for long-haul communication, especially telephone trunks. The 2G optical fiber communication system also found applications in intercity links and local area networks (LANs) using multimode silica fiber. The quaternary III-V alloy InGaAsP was available by that time in semiconductor industries to provide laser diodes and light-emitting diodes at this operating wavelength with lifetimes of 25 years and 100 years respectively. As single-mode fibers were found to exhibit lower loss and significantly large bandwidth (because of extremely low dispersion), the 2G system soon switched over from the use of multimode to single-mode fiber particularly in long-haul communication. Bit rates over 500 Mbps and some cases upto 4 Gbps have been reported with a typical repeater spacing of 40 km. The first transatlantic system (TAT-8) operating at 1300 nm was installed in 1988.

Silica-based optical fibers were found to offer the lowest attenuation of 1550 nm. The variation of attenuation of silica-based optical fiber with wavelength is shown in Fig. 1.3, the three windows are shown in the figure as shaded regions.

The fact that silica fiber offers the least attenuation at 1550 nm motivated the design engineers to consider shifting the operating wavelength to 1550 nm. However, a major constraint on optical communication at this wavelength was initially found to be higher signal dispersion in silica fiber as compared to that at 1300 nm. However, this

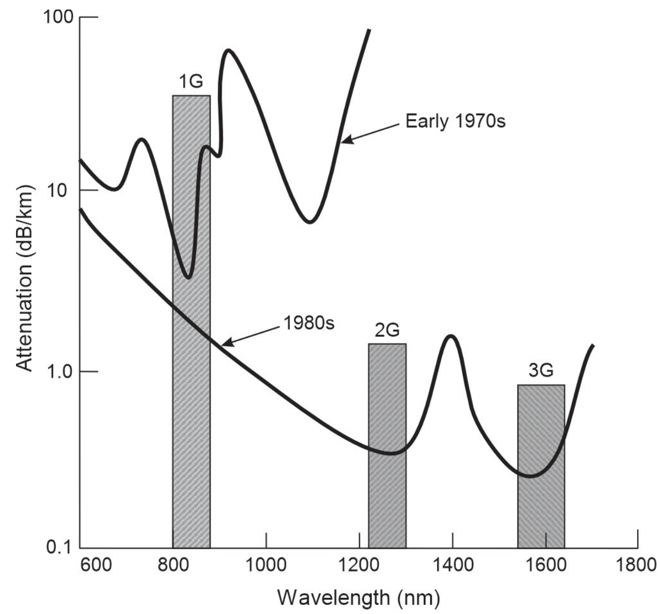

Fig. 1.3 Attenuation of the optical fibers of the 1970s and 1980s

dispersion problem could be tackled easily by making use of artificial techniques for shifting or flattening the minimum dispersion wavelength to the desired value. The third generation (3G) fiber optic system finally adopted 1550 nm as the operating wavelength for high capacity, long-haul, and under-sea optical fiber links. This change of operating wavelength from 1300 nm to 1550 nm in 3G system was possible because of the availability of reliable sources at photodetector based on InP/InGaAs technology. The 3G optical fiber communication system makes use of both an intensity modulation-direct detection (IM/DD) scheme as well as a coherent optical communication scheme. The former scheme involves linear modulation of the intensity of the light source by the input electrical signal (message) at the transmitter and subsequent reconversion of the intensity-modulated signal to the corresponding electrical signal (message) with the help of a photodetector acting as a photon counter at the receiver. In this mode, no attention is paid to the frequency or phase of the optical carrier. This simple mode of optical fiber communication is most popular even though it suffers from limited sensitivity and its inability to take full advantage of the enormous bandwidth of the optical fibers. Coherent optical communication on the other hand involves modulation of amplitude, frequency, phase, or polarization of the optical signal from the light source following the modulating electrical signal (message). At the receiver end the modulated signal is demodulated using a coherent detection technique which is very similar to a conventional electrical communication receiver. A coherent optical fiber communication system offers a significant improvement in the receiver sensitivity over the IM/DD system and enables one to use electrical equalization techniques to compensate for the effect of optical dispersion in fibers. However, there are some practical difficulties with a coherent optical system that has restricted the widespread adoption of this type of optical link in commercial applications.

Theoretically, optical fiber communication systems have unlimited information carrying capacity (~50 THz in practice). However, standard electrical interface schemes such as time division multiplexing (TDM) in the form of synchronous optical network (SONET) or synchronous digital hierarchy (SDH) impose limits on the overall data transmission rate of the optical network. This is due to the limited data-handling capabilities of associated electrical circuits involving amplifiers, multiplexers, demultiplexers, regenerators, etc. The major bottleneck of the present system arises from the frequent conversion of the signal from optical to electrical domain.

The field of optical fiber communication is undergoing dramatic developments even today. There has been a continuous improvement in transmission technology with respect to speed, reliability, and cost. The immense bandwidth potential of optical fibers (~50 THz) has constantly motivated researchers to explore various possibilities for further upgradation of state-of-the-art technology. The information-carrying capacity of optical fibers is doubling almost every two years. It appears that this field of technology would need many more decades to attain the projected goal of information superhighway (optical link). Research carried out in the recent past indicates that there is a possibility of developing systems that would make use of all processing in the optical domain by making use of all-optical switches, couplers, repeaters, etc. This would drastically improve the speed of the existing systems that are constrained by the frequent use of optical-to-electrical (O–E) and electrical-to-optical (E–O) conversions. Further research in the area of soliton transmission opened up a new avenue for improving the information-carrying capacity of optical fibers. A soliton is a special type of non-dispersive pulse that makes judicious use of non-linear effects in the fiber to compensate for the chromatic dispersion of the fiber. It is projected that by making use of dispersion-shifted fiber it would be possible to use soliton pulses to transmit data virtually error-free at 50 Gbps over a distance of 20000 km without any repeater.

1.1.3 Classification of Optical Communication Systems

Optical communication transmission systems can be classified the basis of a variety of criteria such as spectral wavelength range of operation, number of channels (single or multiple), bit rates, type of WDM, channel spacing, nature of application, interface characteristics, etc. From the discussion in the foregoing section, it can be seen that there has been tremendous development in the design and implementation of optical telecommunication links in different countries. Unfortunately, there was a lack of uniformity and compatibility of equipment manufactured by different companies. The International Telecommunication Union–Telecommunication Standardization Sector (ITU-T) plays an important role in achieving interworking among the equipment of different make. Based on the ITU-T recommendations optical communication systems are classified as follows (ITU-T Manual 2009).

In this section, we shall discuss the classification as per ITU-T standard based on operating wavelength bands. It is always desirable to have a large spectral band to achieve a high bit rate. However, the spectral range in each band is constrained by the characteristics of the particular type of fiber, the nature of the source, attenuation, and dispersion in the channel. The prescribed bands and the recommended applications are listed below:

1. The "Original" O-band (1260 nm to 1360 nm)

Historically, this is the first wavelength band used for optical communication because the optical fibers of the 1970s used to exhibit minimum loss in this spectral band. While the lower wavelength (1260 nm) limit is decided by the cut-off wavelength of the fiber cable, the upper limit (1360 nm) is decided by the rising edge of the attenuation peak (occurring at 1383 nm) in glass fiber caused by hydroxyl ions.

2. The "Extended" E-band (1360 nm to 1460 nm)

With the advances in the production of high-quality glass fiber preforms and the invention of dehydrated production of glass fibers, it was possible to achieve fibers exhibiting attenuation less than that exhibited by normal fibers in the "O" band (ITU-T G.652.D). However, the use of the "E" band is very limited because fibers installed before the beginning of this millennium exhibit a high attenuation in this band.

3. The "Conventional" C-band (1530 nm to 1565 nm)

The new-generation fibers exhibit the lowest attenuation in this band. This band is feasible for use in long-haul, submarine, and trans-oceanic optical transmission. This band enables the use of WDM and EDFA (erbium-doped fiber amplifier) technologies.

4. The "Short wavelength" S-band (1460 nm to 1530 nm)

This band is assigned by taking the lower limit to be equal to the upper limit of the E-band and the upper limit to be the lower limit of the C-band. With the availability of EDFAs having wider gain characteristics, the S-band is becoming attractive for future DWDM applications. This band can also be used for pumping fiber amplifiers including the Raman type amplifiers. The S-band is also used for some PON (passive optical network) systems as downstream wavelength.

5. The "Long wavelength" L-band (1565 nm to 1625 nm)

After the C-band, this is the second lowest attenuation wavelength band and is used when the C-band alone is not sufficient for a particular application. This band also supports EDFA and WDM technologies. The combined C plus L band is now suitable for the development of submarine transoceanic transmission using WDM technology.

6. The "Ultra-long wavelength" U-band (1625 nm to 1675 nm)

Unlike the other five bands (O, E, S, C, and L), U- band is not used as a transmission channel in optical communication systems. This band is reserved for testing and maintenance of the optical fiber links after installation. Optical time domain refractometer (OTDR) is used in this band for fault detection and loss testing purposes.

The single-mode spectral bands are listed in Table 1.1.

Table 1.1 Single-mode spectral bands

Band designation	*Full-form*	*Wavelength range (nm)*
O-band	Original	1260 to 1360
E-band	Extended	1360 to 1460
S-band	Short wavelength	1460 to 1530
C-band	Conventional	1530 to 1565
L-band	Long wavelength	1565 to 1625
U-band	Ultra-long wavelength	1625 to 1675

1.2 GENERAL OPTICAL FIBER COMMUNICATION SYSTEM

A generalized optical fiber communication system is shown in Fig. 1.4. The major elements of the system are shown by blocks.

The information source provides an electrical signal usually derived from a message signal which is not generally an electrical signal (e.g. sound, picture). The electrical signal from the information source is fed to a transmitter comprising an electrical stage that drives an optical source to produce modulation of light wave carriers. It is important to note that in the IM/DD system, the modulating signal is used to modulate the intensity of the light source only. It may be emphasized that, unlike conventional electrical modulation schemes where the amplitude, frequency, or phase of the carrier is altered following the modulating signal, the frequency or phase of the optical signal from the optical source remains unaltered. From this viewpoint, the function of the optical source in a way is to provide electrical to-optical (E–O) conversion. This is usually achieved with the help of a light-emitting diode (LED) or a semiconductor laser diode which is generally known as

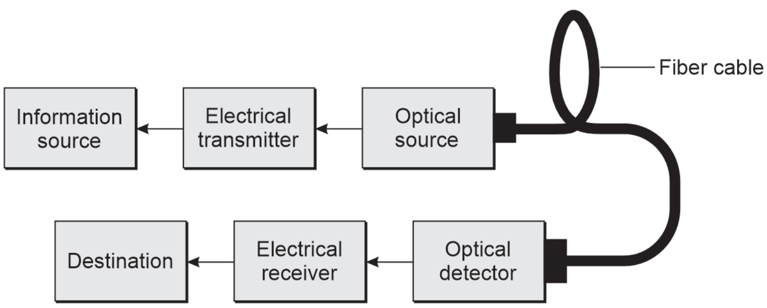

Fig. 1.4 Block diagram of an optical fiber communication system

an injection laser diode (ILD). These optical sources are lightweight, compact, and most importantly compatible in size with the optical fiber which is used as a waveguide for subsequent transmission of the signal. Moreover, both LED and ILD sources consume low electrical power and can generate light waves at different wavelength regions of the optical spectrum where the silica fibers offer less attenuation. The modulated lightwave output from the optical source is coupled to the transmission medium consisting of an optical fiber cable. The fiber cable contains a group of optical fibers which are generally long thin strands (typically of the order of 100 μm diameter) of ultrapure glass that provide low loss at the transmitting wavelength.

An optical fiber consists of two coaxial solid cylinders having slightly different refractive indices. The inner solid cylinder called the core has a higher refractive index as compared to the outer cylinder known as *cladding*. The optical signal propagates through the fiber by total internal reflection. As the optical signal propagates down the fiber length, it gets attenuated due to absorption, scattering, etc. within the fiber and at the same time gets distorted and broadened because of various dispersion mechanisms. The weak distorted optical signal is received by the receiver at the destination. The key component of the receiver is an optical detector which converts the weak and distorted information-bearing optical signal to an electrical signal that is a replica of the modulating signal. The signal is then processed by an electrical receiver and the output is finally sent to the destination.

A practical optical communication system is much more complex than the simple block diagram shown in Fig. 1.4. Like electrical communication, optical communication can be either analog or digital type. A practical digital optical communication link looks more like one shown in Fig. 1.5. The basic components of a practical optical communication link consist of an optical transmitter, optical repeater, optical receiver, optical fiber waveguide, connector, splice, splitter, optical amplifier, etc. The message signal may be in a continuous analog form or the form of digital pulses representing bits 1s and 0s. The message signal is used to modulate the intensity of the optical source with the help of an electrical drive circuit (modulator). The manufacturers generally provide optical sources with a small portion of an optical fiber (1–2 m length) attached to it in an optimum fashion. This is called *fiber pigtail or flylead* which can be easily plugged in for connection with the line fiber by using a demountable connector. The optical signal propagates down the fiber toward the receiver end. While the signal propagates along the fiber it gets attenuated due to the absorption of the optical signal by the fiber material for several reasons to be discussed afterward. In addition to this attenuation, the signal also gets distorted due to the dispersion phenomenon to be discussed afterward. The weak and distorted optical signal is subsequently allowed to travel along the fiber and before the signal gets distorted beyond recognition, it is necessary to have an arrangement to regenerate the signal and retransmit the reconstructed and boosted to travel further over the transmission link. This is achieved with the help of regenerative repeaters. In the present case (Fig. 1.5) only one repeater unit is shown for illustration. The actual number of repeaters needed along a transmission line depends on the transmission characteristics of the channel (optical fiber) and the total distance to be covered.

At the end of the link, the received optical signal which is attenuated and distorted during transmission down the optical fiber is reconverted from optical-to-electrical (O–E) for further electrical processing and extraction of the original electrical message signal. The key element at the receiving end is an optical detector (*p-i-n* or avalanche photodiode) which converts the intensity variation in the recovered optical signal into a corresponding electrical signal. The size of the optical detector should be compatible with

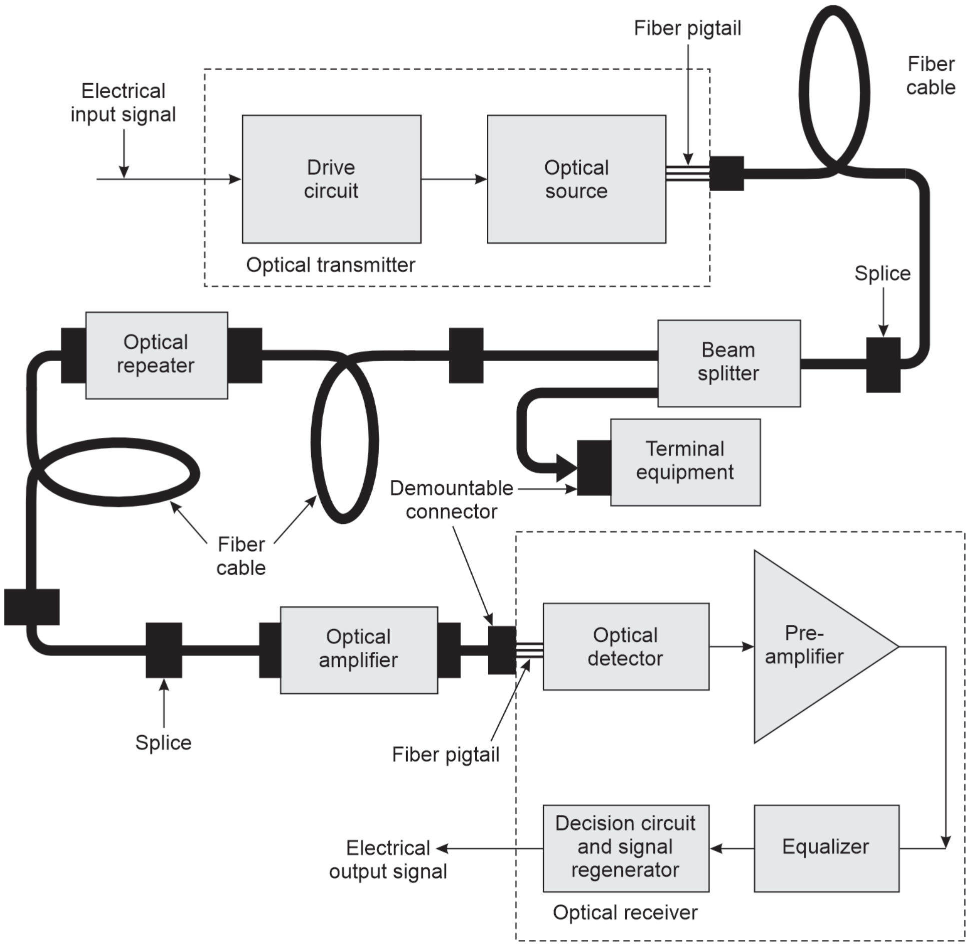

Fig. 1.5 Schematic of an optical communication system

the optical fiber size. The important requirements of photodetector characteristics include linearity, high-speed response, high responsivity, and low-noise behavior. In a practical optical communication system additional components such as optical connectors, splices, couplers, and optical amplifiers are used. The connectors and splices are used for joining two fibers. The connectors are generally demountable while the splices provide permanent joints. The couplers are in-line buses that are used at terminal points to remove a portion of the optical signal from the trunk line at intermediate points or inject additional optical signals onto the trunk. Optical amplifiers provide online amplification to the propagating optical signal. Such amplifiers are useful for compensating for the attenuation caused by the optical fiber during the propagation of the signal. Both semiconductor laser amplifier (SLA) and erbium-doped fiber amplifier (EDFA) are used for providing amplification of the signal in the optical domain.

The generalized optical communication system shown in Fig. 1.5 may be an analog or a digital link, depending on whether the lightwave carrier is modulated using an analog or digital information signal. In an analog system, the modulation involves the variation of the light emitted from the optical source continuously. On the other hand in digital systems, discrete changes in the light intensity (on-off optical pulses) are generally used for transmission of lightwave carriers. In general, analog–optical communication systems are easier to implement but they are less efficient and need a larger signal-to-noise ratio at the receiver end than the digital counterpart. Further, the semiconductor sources do not provide good linearity characteristics (particularly at high modulation frequency) which is essential for the implementation of analog optical links. As a result, digital optical communication is generally preferred for long-haul and high-speed optical links while analog optical links are restricted to use for short distance and low bandwidth operation.

1.3 ADVANTAGES OF OPTICAL FIBER COMMUNICATION

An optical communication system that uses lightwave as the carrier and optical fiber as the waveguide has many attractive features over the conventional electrical communication system that uses copper cable as the waveguide. Some of the features were apparent when the technique was first conceived. The additional features became apparent with the technological development in related areas. Some of the distinct advantages of optical communication include the following.

1. **Large potential bandwidth:** The frequency of lightwave carriers in the infrared region is of the order of 10^{14} Hz (10^5 GHz) which yields a far greater transmission bandwidth as compared to conventional metallic cable systems. For example, coaxial cables provide a bandwidth of the order of 500 MHz. The information carrying capacity of an optical fiber is far superior to the best copper cable system. It may be pointed out that the full potential bandwidth of optical fibers (~50 THz) is not being utilized at present because of technological constraints. With the advent of the wavelength division multiplexing (WDM) technique, it would be possible to enhance bandwidth utilization significantly in the future.
2. **Small size and lightweight:** Optical fibers have a very small diameter (of the order of human hair diameter ~100 μm). The optical fibers coated with protecting layers also turn out to be smaller and lighter as compared to conventional metallic cables. The small size and light weight make them especially attractive for use in aircraft, satellites, and ships.
3. **Electrical isolation:** The optical fibers are made of dielectric materials such as glass or plastic which are electrical insulators. As a result, these waveguides do not exhibit earth loop and interface problems. The optical fiber transmission system is convenient for use in electrical hazardous environments as it does not create sparks. This feature also enables easy interfacing of equipment.
4. **Immunity to interference and cross-talk:** Optical fibers are made of dielectric material and therefore are free from electromagnetic interference (EMI) and radiofrequency interference (RFI). Unlike metal cables, optical fiber cables are free from inductive pick-up from other electrical signal-carrying wires or lightning. In other words, the function of fiber optic communication system remains unaffected even in an electrically noisy environment. The optical inference between individual fibers in an optical fiber cable is also absent and as a result, there is no cross-talk effect which is quite common in conventional electrical communication that uses metal cables.
5. **Signal security:** The optical signals are well confined in optical fiber waveguides and as a result, there is practically no leakage of optical power from the fibers. Emanations, if any get absorbed in opaque jackets surrounding the fibers. This feature provides a high degree of signal security in optical fiber-based communication systems. Unlike the situations with copper cables, signals cannot be tapped from optical fibers during transmission in a non-invasive manner. This feature makes optical communication systems very feasible for military, banking, and other secure data transmission applications.

6. **Low transmission loss:** Optical fibers have much lower loss as compared to conventional copper cables. The development in the field of optical fiber fabrication over the past two decades has resulted in the production of high-quality optical fibers that provide extremely low loss (less than 1 dB/km). Fibers have been fabricated with loss to the tune of 0.2 dB/km. The low-loss fibers have considerably enhanced the repeater spacing and significantly cut down the system cost.
7. **Ruggedness and flexibility:** With proper protecting layers and cabling structures, optical fiber cables remain flexible yet rugged enough to bear stresses during installation. As compared to its metal counterpart, optical fiber cable is superior for transportation, storage, handling, and installation. The optical fiber cables can be used for under-sea installation and other abusive environments without causing any damage.
8. **Reliability and easy maintenance:** The availability of extremely low-loss and low-dispersion single-mode fibers has improved the reliability of long-haul optical links with a lesser number of repeaters as compared to conventional metal cable systems. The average lifetime of the state-of-the-art optical fiber system is nearly 20 years. Moreover, optical communication subsystems require minimum maintenance in the long run.
9. **Potential low cost:** The overall system cost of an optical communication link for long-haul applications is considerably less than its electrical counterpart using metal cables. Extremely low loss and large bandwidth of optical fiber are primarily responsible for low-cost system development using lightwave technology. Although high-quality optical sources (such as ILD), optical fiber connectors, and couplers are still very expensive, the raw material used in making the silica fibers is abundantly available in nature and found in ordinary sand. This significantly reduces the cost of this waveguide used in optical communication systems in comparison to metal cables.

The advantages of optical fiber communication discussed above have made this technology almost indispensable for long-haul optical links and are preferred over conventional electrical communication using electrical transmission lines and even microwave and millimeter wave systems. Initially, optical fiber communication link was intended to be used only in intercity and intercontinental trunk lines. However, with the increasing demand for larger bandwidth and the advent of ISDN (Integrated Service Digital Network) involving transmission of voice, video, facsimile, computer data, etc. optical fibers have finally entered into subscribers loop.

The subject of optical fiber communication has been discussed in several excellent textbooks (Keiser, 1991; Senior, 1992; Gower, 1984).

1.4 SCOPE OF THE BOOK

The primary objective of the book is to provide an understanding of the basic principles of an optical fiber communication system. An attempt has been made throughout the text to focus attention on fundamental concepts underlying various techniques used for the transmission and reception of lightwave carriers through optical fibers. As the field of lightwave technology as a whole is undergoing dramatic changes even today and the older technology is being replaced by newer ones, the intricacies of practical optical fiber communication systems have been deliberately avoided in the text.

The material presented in the subsequent portion of the text has been distributed among 12 chapters including the current chapter to cover the introductory fundamentals and various issues related to the generation, transmission, distribution, and reception of lightwave signals in a variety of optical communication systems. The chapters are organized as follows.

Chapter 2 deals with the concept of optical fiber as a transmission medium. The classifications of optical fibers and their structural variations are also discussed. This is followed by simple analyses based on the principles of geometrical optics. Some important parameters of the fibers are estimated based on simple ray analysis. This chapter also deals with the descriptions of materials used for making fibers, and various techniques for fabrication of optical fibers. The chapter ends with a discussion of issues concerning the strength of optical fibers and different techniques of fiber cabling for strengthening the fibers for field installation. Various issues associated with the installation of optical fiber cables are also dissussed in this chapter.

Ray analysis which is used to explain the propagation of light through an optical fiber discussed in the previous chapter is approximated and is applicable in the case of fibers of large size (such as multimode fibers). An accurate analysis of the propagation of light through an optical fiber can only be done with the help of Maxwell's electromagnetic field theory and by treating optical fibers as a dielectric medium. In Chapter 3, the propagation of light through planar waveguide and also through dielectric waveguide has been analyzed based on electromagnetic wave theory. The chapter begins with a brief discussion of Maxwell's equations and their applications for finding modal equations for the transmission of light as electromagnetic waves through fibers considered cylindrical waveguides of dielectric media. The mathematical treatment is rigorous and may be skipped without affecting the basic understanding of the later part of the book. Nevertheless, the analysis leads to some fundamental formulas related to various propagating modes, cut-off conditions, power flow, etc. which are essential for a thorough understanding of the subject.

Optical signals get progressively degraded and distorted as they propagate down the fiber. The primary reasons for this degradation are attenuation caused by absorption and scattering of the signal by the fiber medium and dispersion of the optical signal. Various mechanisms responsible for the attenuation and distortion of the signal during propagation through optical fibers are discussed in Chapter 4. The methods available for reducing signal degradation in practical fibers are also mentioned in this chapter.

Optical fiber constitutes the transmission medium of an optical fiber communication system. Apart from the transmission medium, the other two major units of an optical communication system are the optical transmitter and the optical receiver. The key component of an optical transmitter is an optical source. A variety of optical sources are commercially available. However, sources that are compatible with the size and transmission characteristics of the optical fibers can only be used for optical fiber communication. Chapter 5 discusses the light sources employed in optical fiber communication. The discussion is primarily confined to semiconductor sources which are predominantly used in optical transmitters because of the stringent requirements stated above. The basic physical principles underlying the operation of semiconductor optical sources (light-emitting diode and injection laser diode) are discussed in this chapter. A thorough understanding of the operation of the sources requires basic concepts of semiconductor devices. It is presumed that the readers have done a basic course on semiconductor devices. A few sections have, however, been devoted to the discussion of basic principles of semiconductor devices which are essential for a proper understanding of the mechanism of operations of semiconductor optical sources and detectors. Further, compound semiconductors and alloys are mostly used for making these optoelectronic devices. Keeping this fact in mind, adequate material about III-V materials which are mostly used for making semiconductor sources and optical detectors has been added in this chapter.

An optical communication system often called an optical link is an interconnection of optical transmitters, receivers, and other optical components along the route for transmission, distribution, and reception of optical signal. The light signal generated by an optical source is generally modulated with the help of a driver circuit. The intensity-modulated light is subsequently launched into the optical fiber for transmission. Chapter 6 deals with various issues related to the launching of power from optical sources to optical fibers. Different techniques used for coupling power from one fiber to the other are also discussed in this chapter. The major factors that affect the coupling efficiency are also discussed in this chapter

At the destination point, the transmitted signal is processed to reproduce the original message/information signal. This is done by an optical receiver. The key component of an optical receiver is an optical detector, also known as a photodetector. It converts the optical signal to an electrical signal (E–O conversion). Chapter 7 is devoted to the study of semiconductor optical detectors and photovoltaic devices. It discusses the principles of photo-detection mechanisms and different non-multiplying and multiplying photodetector structures used in optical communication systems. The noise characteristics of different photodetectors have also been discussed since the noise characteristics of the photodetector play an important role in deciding the sensitivity of an optical receiver. A brief discussion of solar cells is also included at the end of this chapter the solar cells one ophelectric cells that find application as an alternative source of electrical energy by making use solar energy.

After optical detection, the electrical signal undergoes various processing by the subsequent stages of the optical receiver. The theory and design of optical receivers are discussed in Chapter 8. The design of an optical receiver is much more complex than that of an optical transmitter. This is because the signal is generally weak and mutilated at the receiving end. The processing of this weak and distorted signal in the presence of various electrical noise components arising from the processing units is challenging and makes the design of the receiver very complex. A variety of receiver configurations including the state-of-the-art monolithic optoelectronic receiver have been discussed in this chapter.

In optical communication, information, transmission and reception can be either in analog or in digital form. The primary purpose behind digital optical communication is to link telephone exchanges with digital integrated circuits which offer reliable transmission and reception of both voice and data signals at a substantially low cost. In analog optical communication, the message signals are superimposed on radio-frequency (RF) subcarriers. The multiplexed electrical signal is subsequently used to modulate the optical carrier. Chapter 9 deals with various aspects and system requirements of both analog and digital forms of optical communication.

A major bottleneck of a traditional optical communication system lies in the frequent conversion of the signal from the optical to the electrical domain and vice-versa. This conversion drastically affects the speed of the system. The signal after conversion to the electrical domain gets constrained by the limited bandwidth available in the electrical system. On the contrary, if the entire processing can be done in the optical domain the speed of the existing optical communication system can be greatly improved. Because of the above fact, several active optical devices and components have been developed to enable the processing of optical signals without changing them to the electrical domain. Chapter 10 discussed various active optical devices and components that are used in manipulating the signal in the optical domain itself. Optical amplifiers, optical modulators, optical switches, and other elements of integrated optics (IO) such as beam-splitters, directional couplers, etc. are also discussed in this chapter.

Chapter 11 is devoted to the study of the essentials of advanced optical communication systems and optical networks. The enormous bandwidth of optical fibers (particularly single-mode fibers) can be efficiently utilized by making use of Wavelength-Division-Multiplexing (WDM) techniques. This chapter discusses WDM systems and various components used in the design. Traditionally intensity–intensity modulated optical signals are detected by an optical detector which essentially acts as a photon counter and converts the received intensity modulated light to the corresponding electrical signal. In the process, neither the phase nor-polarization of the light comes into the picture. The performance of this type of Intensity Modulation/Direct Detection (IM/DD) optical communication system is limited by the poor sensitivity of the receiver whose sensitivity can never exceed the quantum limit. With the advent of technology, it is possible to add the received light signal with a locally generated optical signal and then detect the resultant signal. This process enables one to achieve an improvement in the sensitivity by –20 dB over the IM/DD system. This is the essence of coherent optical communication. The principles of coherent optical fiber communication have been discussed in this chapter. The Chapter also covers various principles and architectures of optical network which is the backbone of today's communication network. It covers SONET/SDH systems, wavelength-routed, and WDM-based networks. The chapter concludes with the latest development in the area of soliton pulses and soliton-based optical communication systems which is envisaged as the future fourth-generation (4G) optical communication system.

In the concluding chapter (Chapter 12) various standards, tools, and measurement procedures followed in fiber optics are discussed. Special types of measuring equipment are needed to test and characterize optical and optoelectronic components and optical fibers. This chapter discusses all essential measuring equipment and standard practices for making measurements and checking the performances of optical communication systems.

A large number of solved numerical examples are given throughout the text. These examples are intended for a better understanding of the subject and also for having some idea about various parameters and standards of practical systems. Some unsolved problems (qualitative and quantitative) are also included at the end of each chapter to enable the readers to make a self-assessment of their understanding of the subject topics dealt with in various chapters of the book.

At the end of every chapter, a separate list of references has been included. These references would help the readers to find additional materials on relevant topics. Further supplementary study materials can be found in other textbooks listed in the reference sections.

1.5 MAJOR MILESTONES

The breakthrough inventions and developmental work in the field of optoelectronic devices, components, and systems that paved the way for the widespread successful implementation of modern-day optical communication systems and several other non-telecommunication applications are listed below (Hecht, 1999).

1609	Galileo (Italy)	Galilean telescope
1668	Newton (UK)	Reflection telescope
1870	Tyndall (UK)	The light guided in a thin water jet
1873	Maxwell (UK)	Electromagnetic theory
1897	Rayleigh (UK)	Waveguide analysis
1930	Lamb (Germany)	Experiments with silica fibers
1951	Heel, Hopkins, Kapany (UK)	Fiber optic endoscopy

(*Contd.*)

1953	Charles Hard Townes (USA)	Invention of MASER
1954	Bell Lab, USA	First Si solar cell
1958	Goubau (USA)	Experiments with lens guide
1959	Kapany (UK)	Optical fiber with cladding
1960	Maiman (USA) Javan (USA)	First LASER (Ruby) Operation of He-Ne laser
1961	Robert Biard and Gary Pittman for Texas Instruments	First infrared LED
1962	Nick Holonyack (USA)	Visible LED Semiconductor LASER
1966	Kao and Hockham (UK)	Optical fibers for long-distance transmission
1969	Uchida (Japan) Miller at Bell Lab	Graded-index fiber Integrated optics
1970	Kapron and Keck (USA) Delange	Fiber transmission loss <20 dB/km Concept of WDM
1970	Fairchild Optoelectronics	Low-cost LED
1972	Gambling *et al* (UK)	GHz bandwidth over 1 km optical link
1975	Payne and Gambling (UK)	Prediction of zero material dispersion at 1.3 μm
1976	Thomas P Pearsal	High-efficiency and high-radiance LED for fiber optic communication
1977	Kenichi Iga of the Tokyo Institute of Technology, USA	Vertical cavity surface emitting laser
1978	NTT Ibaraki Lab	Commercial optical fiber link Single-mode fiber with record 0.2 dB/km loss at 1.55 μm
1980	Bell Labs	Single-mode 1.3 μm technology for the first transatlantic-fiber-optic cable, TAT-8
1981	Moungi Bawendi of MIT, Louis Brus of Columbia University, and Alexei Ekimov of Nanocrystals Inc.	Semiconductor quantum dots
1982	British Telecom	Single-mode fiber to replace GI fibers
1985	Bell Labs	Single-mode fiber across the USA to carry long-haul telephone signals at 400 Mbps and more
1986	Rome Air Development Centre	Silicon Photonics
1987	Dave Payne, University of Southampton	First erbium-doped fiber amplifier operating at 1.55 μm
	Yablonovitch and John	Photonic crystal (PC)
1987	Ching Wan Tang and Steven van Slyke at Eastman Kodak	First organic light emitting diode (OLED)
1988	Linn Mollenauer	First soliton transmission through 4000 km of single-mode fiber
Dec. 1988	Bell Labs	First transatlantic fiber-optic cable, using 1.3 μm lasers and single-mode fiber
1989	Yablonovitch	Birth of photonic crystals

(*Contd.*)

1993	TAT-8	Transmission of the first soliton signals over 180 million kilometers
1994	Federico Capasso and Alfred Y Cho at Bell Lab, USA	Quantum cascade laser
1996	Ciena Corporation	Commercial deployment of DWDM
	Nakazawa Fujitsu, NTT labs and Bell Labs	Successful transmission of one trillion bits per second through single optical fibers
2012	MetroPCS at Dallas, Texas, USA	Voice over long-term evolution (VoLTE) service began
2015	Sumimoto electric	Multi-core fiberoptic cable

Summary

- The chapter discusses the evolution of today's optical communication and major milestones that paved the way for the incredible expansion of optical fiber communication network all over the globe.
- Major breakthrough works in this area include the successful demonstration of laser by Maiman in 1960 followed by the path breaking work of Kao in 1966 related to the possibility of transmission of light using dielectric waveguide.
- The principle of operation of an IM/DD scheme for realizing a practical optical transmitter and receiver system has been discussed.
- The essence of coherent optical communication and its advantage in terms of increased sensitivity and the disadvantage in terms of increased complexities and practical difficulties with implementation are discussed.
- The major bottleneck of today's optical communication is the speed which is greatly hampered by frequent E–O and O–E conversions.
- The major advantages of an optical communication system include increased bandwidth, reduced size and less weight, security of the signal, ruggedness of the system, low cost, etc.
- The three generations of optical communication centered on 850 nm, 1330 nm, and 1550 nm and the rationale behind the choice of these attenuation windows are discussed in this chapter.
- It outlines the importance of WDM system in terms of enhancing the capacity of existing optical fiber link.
- The scope of the book is outlined in this chapter by highlighting the sequence in which the rest of the chapters have been organized along with a brief discussion of various topics covered.
- The chapter ends with a list of the major milestones that shaped the modern optical communication systems.

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