CHAPTER 1

INTRODUCTION

1.1 Background

A communication system transmits information from one place to another, whether separated by a few kilometers or by transoceanic distances. Information is often carried by an electromagnetic carrier wave whose frequency can vary from a few megahertz to several hundred terahertzes. Optical communication systems use high carrier frequencies (~100 THz) in the visible or near-infrared region of the electromagnetic spectrum. They are sometimes called lightwave systems to distinguish them from microwave systems, whose carrier frequency is typically smaller by five orders of magnitude (~1GHz). Fiber-optic communication systems are lightwave systems that employ optical fibers for information transmission. Such systems have been deployed worldwide since 1980 and have revolutionized the field of telecommunications. Indeed, lightwave technology, together with microelectronics, led to the advent of the "information age" during the 1990s. This chapter provides a concise introduction and background of optical communication systems

1.2 Historical Perspective

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). Essentially the same idea was used up to the end of the eighteenth century through signaling lamps, flags, and other semaphore devices. The idea was extended further, following a suggestion by *Claude Chappe* in 1792, to transmit mechanically coded messages over long distances (~ 100 km) by the use of intermediate relay stations, acting as regenerators or repeaters in the modern-day language.

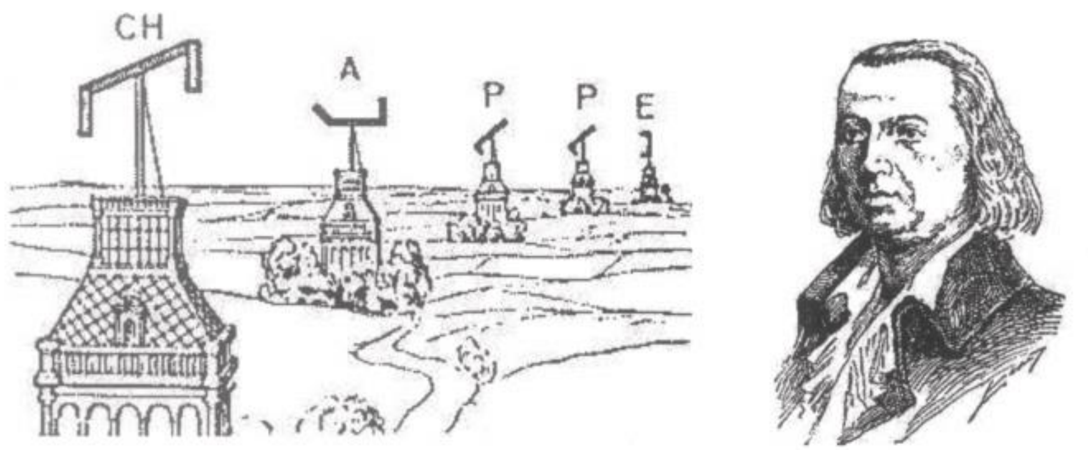

Figure 1.1: Schematic illustration of the optical telegraph and its inventor Claude Chappe.

Figure 1.1 shows the basic idea schematically. The first such "optical telegraph" was put in service between Paris and Lille (two French cities about 200 km apart) in July 1794. By 1830, the network had expanded throughout Europe. The role of light in such systems was simply to make the coded signals visible so that they could be intercepted by the relay stations. The opto-mechanical communication systems of the nineteenth century were inherently slow. In modern-day terminology, the effective bit rate of such systems was less than 1 bit per second ($B < 1$ b/s).

1.3 Need for Fiber-Optic Communications

The advent of telegraphy in the 1830s replaced the use of light by electricity and began the era of electrical communications. The bit rate B could be increased to ~ 10 b/s by the use of new coding techniques, such as the Morse code. The use of intermediate relay stations allowed communication over long distances (~1000 km). Indeed, the first successful transatlantic telegraph cable went into operation in 1866. Telegraphy used essentially a digital scheme through two electrical pulses of different durations (dots and dashes of the Morse code). The invention of the telephone in 1876 brought a major change inasmuch as electric signals were transmitted in analog form through a continuously varying electric current. Analog electrical techniques were to dominate communication systems for a century or so.

The development of worldwide telephone networks during the twentieth century led to many advances in the design of electrical communication systems. The use of coaxial cables in place of wire pairs increased system capacity considerably. The first coaxial-cable system, put into service in 1940, was a 3 MHz system capable of transmitting 300 voice channels or a single television channel. The bandwidth of such systems is limited by the frequency-dependent cable losses, which increase rapidly for frequencies beyond 10 MHz. This limitation led to the development of microwave communication systems in which an electromagnetic carrier wave with frequencies in the range of 1-10 GHz is used to transmit the signal by using suitable modulation techniques.

The first microwave system operation at the carrier frequency of 4 GHz was put into service in 1948. Since then, both coaxial and microwave systems have evolved considerably and are able to operate at bit rates ~ 100 Mb/s. The most advanced coaxial system was put into service in 1975 and operated at a bit rate of 274 Mb/s. A severe drawback of such high-speed coaxial systems is their small repeater spacing (~ 1 km), which makes the system relatively expensive to operate. Microwave communication systems generally allow for larger repeater spacing, but their bit rate is also limited by the carrier frequency of such waves. A commonly used figure of merit for communication systems is the ***bit rate-distance*** product, **BL**, where **B** is the ***bit rate*** and **L** is the ***repeater spacing***. Figure 1.2 shows how the **BL** product has increased through technological advances during the last century and a half. Communication systems with BL about 100 (Mb/s)-km were available by 1970 and were limited to such values because of fundamental limitations.

It was realized during the second half of the twentieth century that an increase of several orders of magnitude in the **BL** product would be possible if optical waves were used as the carrier. However, neither a **coherent optical source** nor a **suitable transmission medium** was available during the 1950s. The **invention of the laser** and its demonstration in 1960 solved the **first problem**. Attention was then focused on finding ways for using laser light for optical communications

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It was suggested **in 1966 that optical fibers might be the best choice, as they are capable of guiding the light in a manner similar to the guiding of electrons in copper wires.** The **main problem** was the ***high losses of optical fibers***. The fibers that available during the 1960s had losses in excess of **1000 dB/km**. A breakthrough occurred in 1970 when fiber losses could be reduced to **< 20 dB/km** in the wavelength region **near 1 μm**. At the same time, **GaAs** semiconductor lasers, operating **continuously at room temperature**, were demonstrated. **The simultaneous availability of compact optical sources and low-loss optical fibers led to a worldwide effort to develop fiber-optic communication systems**.

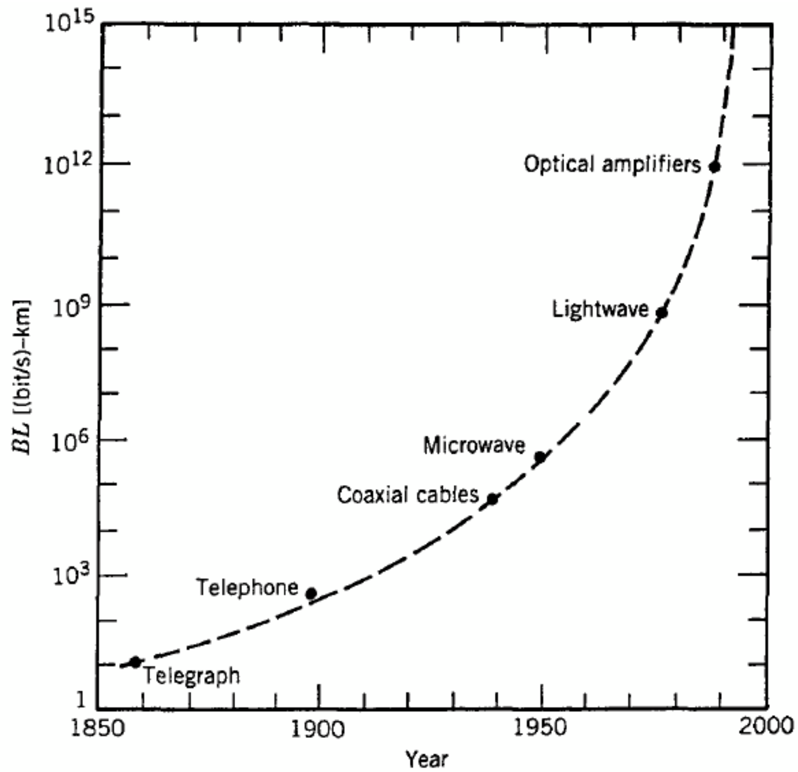

Figure 1.2: Increase in bit rate-distance product BL during the period 1850-2000. The emergence of a new technology is marked by a solid circle.

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1.4 Historical Development of Lightwave Systems

The research phase of fiber-optic communication systems started around 1975. The enormous progress realized over the 25-year period extending from 1975 to 2000 can be grouped into several distinct generations. Figure 1.3 shows the increase in the BL product over this time period as quantified through various laboratory experiments. The straight line corresponds to a doubling of the BL product every year. In every generation, **BL** increases initially, but then begins to saturate as the technology matures. Each new generation brings a fundamental change that helps to improve the system performance further.

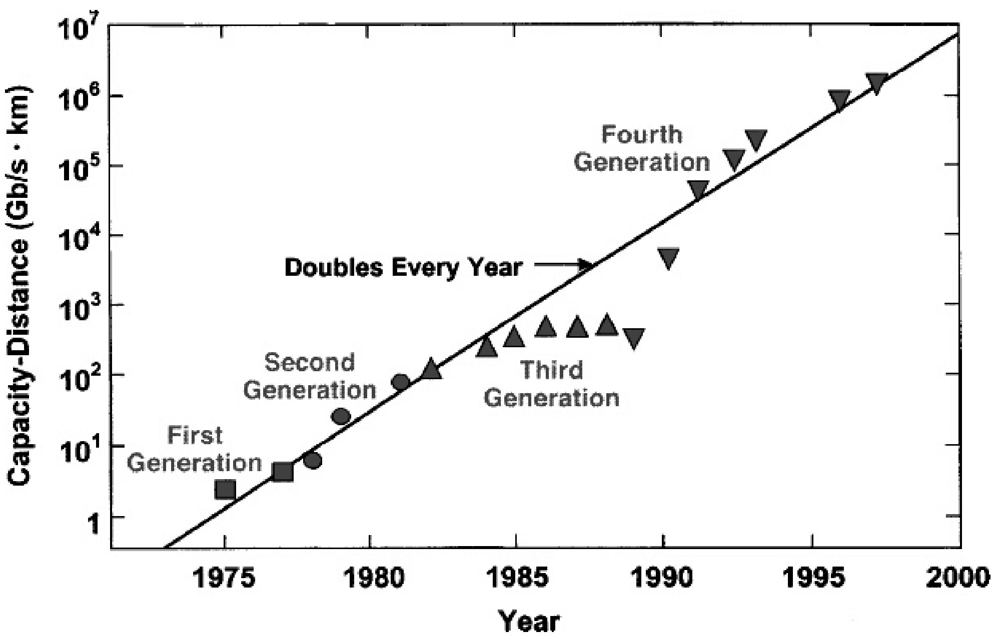

Figure 1.3: Increase in the BL product over the period 1975 to 1980 through several generations of lightwave systems. Different symbols are used for successive generations.

The ***first generation*** of lightwave systems operated near 800 nm and used GaAs semiconductor lasers. After several field trials during the period 1977-79, such systems became available commercially in 1980. They operated at a bit rate of 45 Mb/s and allowed repeater spacing of up to 10 km. The larger repeater spacing compared with 1-km spacing of coaxial systems was an ***important motivation*** for system designers because it decreased the installation and maintenance costs associated with each repeater.

It was clear during the 1970s that the repeater spacing could be increased considerably by operating the lightwave system in the wavelength region near 1300 nm, where fiber loss is below 1 dB/km. Furthermore, optical fibers exhibit minimum dispersion in this wavelength region. This realization led to a worldwide effort for the development of ***InGaAsP*** semiconductor lasers and detectors operating near 1300 nm.

The ***second generation*** of fiber-optic communication systems became available in the early 1980s, but the bit rate of early systems was limited to below 100 Mb/s because of dispersion in multimode fibers. This limitation was overcome by the use of single mode fibers (SMF). A laboratory experiment in 1981 demonstrated transmission at 2 Gb/s over 44 km of SMF. The introduction of commercial systems soon followed. By 1987, second-generation lightwave systems, operating at bit rates of up to 1.7 Gb/s with a repeater spacing of about 50 km, were commercially available. The repeater spacing of the second-generation lightwave systems was limited by the fiber losses at the operating wavelength of 1300 nm typically about 0.5 dB/km. Losses of silica fibers become minimum near 1550 nm. Indeed, a 0.2 dB/km loss was realized in 1979 in this spectral region. However, the introduction of ***third generation*** lightwave systems operating at 1550 nm was considerably delayed by large fiber dispersion near 1550 nm. Conventional InGaAsP semiconductor lasers could not be used because of pulse spreading has occurred as a result of simultaneous oscillation of several longitudinal modes. The dispersion problem can be overcome either by using dispersion shifted fibers designed to have minimum dispersion near 1550 nm or by limiting the laser spectrum to a single longitudinal mode. Both approaches were followed during the 1980s. By 1985, laboratory experiments indicated the possibility of transmitting information at bit rates of up to 4 Gb/s over distances in excess of 100 km. Third generation lightwave systems operating at 2.5 Gb/s became available commercially in 1990. Such systems are capable of operating at a bit rate of up to 10 Gb/s. The best performance is achieved using dispersion shifted fibers in combination with lasers oscillating in a single longitudinal mode.

A drawback of third generation 1550 nm systems is that the signal is regenerated periodically by using electronic repeaters spaced apart typically by 60-70 km. The repeater spacing can be increased by making use of a homodyne or heterodyne detection scheme because its use improves receiver sensitivity. Such systems are referred to as coherent lightwave systems. Coherent systems were under development worldwide during the 1980s, and their potential benefits were demonstrated in many system experiments. However, commercial introduction of such systems was postponed with the advent of fiber amplifiers in 1989.

The ***fourth generation*** of lightwave systems makes use of optical amplification for increasing the repeater spacing and of wavelength division multiplexing (WDM) for increasing the bit rate. As seen from Figure 1.3, the advent of the WDM technique around 1992 started a revolution that resulted in doubling of the system capacity every 6 months or so and led to lightwave systems operating at a bit rate of 10 Tb/s by 2001. In most WDM systems, fiber losses are compensated periodically using erbium doped fiber amplifiers (EDFA) spaced 60-80 km apart. Such amplifiers were developed after 1985 and became available commercially by 1990. In 1991 the experiment showed the possibility of data transmission over 21,000 km at 2.5 Gb/s, and over 14,300 km at 5 Gb/s, using a recirculating loop configuration. This performance indicated that an amplifier based, all-optical, submarine transmission system was feasible for intercontinental communication. By 1996, not only transmission over 11,300 km at a bit rate of 5 Gb/s had been demonstrated by using actual submarine cables, but commercial transatlantic and transpacific cable systems also became available. Since then, a large number of submarine lightwave systems have been deployed worldwide.

1.5 The General Communication System

An optical fiber communication system is similar in basic concept to any type of communication system. A block schematic of a general communication system is shown in Figure 1.4. The communication system, therefore, consists of a ***transmitter*** or ***modulator*** linked to the ***information source***, the ***transmission medium***, and a ***receiver*** or ***demodulator*** at the ***destination point***.

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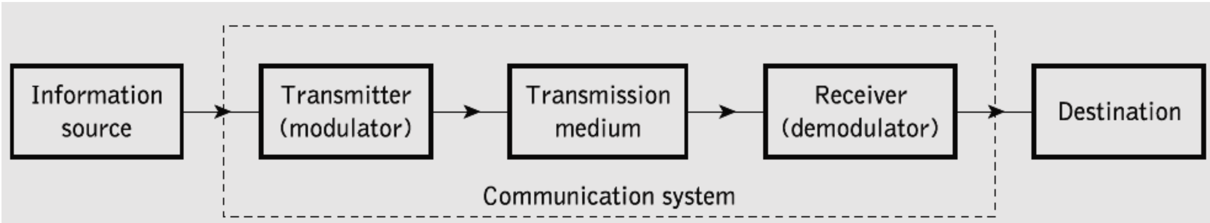

Figure 1.4: General communication system.

In electrical communications the information source provides an electrical signal, usually derived from a message signal which is not electrical (e.g. sound), to a transmitter comprising electrical and electronic components which converts the signal into a suitable form for propagation over the transmission medium.

This is often achieved by modulating a carrier, which, as mentioned previously, may be an electromagnetic wave. The transmission medium can consist of a pair of wires, a coaxial cable or a radio link through free space down, which the signal is transmitted to the receiver, where it is transformed into the original electrical information signal (demodulated) before being passed to the destination. However, it must be noted that in any transmission medium the signal is attenuated, or suffers loss, and is subject to degradations due to contamination by random signals and noise, as well as possible distortions imposed by mechanisms within the medium itself. Therefore, in any communication system, there is a maximum permitted distance between the transmitter and the receiver beyond which the system effectively ceases to give intelligible communication. For long-haul applications, these factors necessitate the installation of repeaters or line amplifiers at intervals, both to remove signal distortion and to increase signal level before transmission is continued down the link.

For optical fiber communications the system shown in Figure 1.5 may be considered in slightly greater detail, as given in Figure 1.4. In this case the information source provides an electrical signal to a transmitter comprising an electrical stage which drives, an optical source to give modulation of the lightwave carrier. The optical source which provides the electrical–optical conversion may be either a semiconductor laser which known also by laser diode (LD) or light–emitting diode (LED).

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The transmission medium consists of an optical fiber cable and the receiver consists of an optical detector which drives a further electrical stage and hence provides demodulation of the optical carrier. Photodiodes in some instances, phototransistors and photoconductors are utilized for the detection of the optical signal and the optical–electrical conversion. Thus, there is a requirement for electrical interfacing at either end of the optical link and at present the signal processing is usually performed electrically.

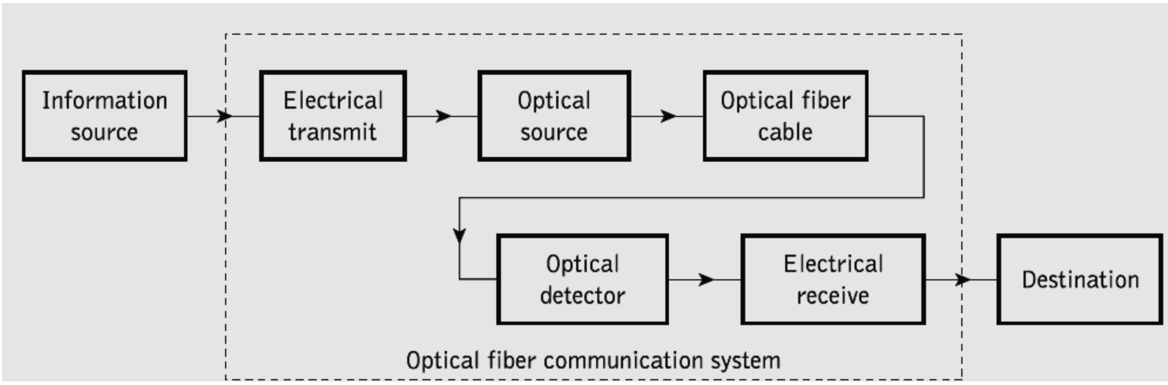

Figure 1.5: Optical fiber communication system.

The optical carrier may be modulated using either analog or digital information signal. The analog modulation involves the variation of the light emitted from the optical source in a continuous manner. With digital modulation, however, discrete changes in the light intensity are obtained (i.e. on–off pulses). Although often simpler to implement, analog modulation with an optical fiber communication system *is less efficient*, *requiring a far higher signal-to-noise ratio at the receiver than digital modulation*. For these reasons, analog optical fiber communication links are generally limited to shorter distances and lower bandwidth operation than digital links.

1.6 Advantages of Optical Fiber Communication

Communication using an optical carrier wave guided along a glass fiber has a number of attractive features, several of which were apparent when the technique was originally conceived. Furthermore, the advances in the technology to date have surpassed even the most optimistic predictions, creating additional advantages. Hence it is useful to consider the merits and special features offered by optical fiber communications over more conventional electrical communications.

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In this context, we commence with the originally foreseen advantages and then consider additional features which have become apparent as the technology has been developed.

1. Extremely high data rate and wide bandwidth.
2. Small size and weight: Optical fibers have very small diameters which are often no greater than the diameter of a human hair.
3. Electrical isolation: Optical fibers which are fabricated from glass, or sometimes a plastic polymer, are electrical insulators and therefore, unlike their metallic counterparts, they do not exhibit interface problems.
4. Signal security: The light from optical fibers does not radiate significantly and therefore they provide a high degree of signal security.
5. Low transmission loss: The development of optical fibers over the last 20 years has resulted in the production of optical fiber cables which exhibit very low attenuation losses about (0.15 dB/km).
6. Longer life expectancy than coaxial cable
7. Longer distance without repeaters, as compared with coaxial
8. copper.
9. System reliability and ease of maintenance.

Low cost: The glass which generally provides the optical fiber transmission medium is made from sand not a scarce resource. So, in comparison with copper conductors, optical fibers offer the potential for low-cost line communication.

1.7 Optical Communications Bands

The optical spectrum ranges from about 5 nm (ultraviolet) to 1 mm (far infrared), the visible region being the 400 to 700 nm band. Optical fiber communications use the spectral band ranging from 800 to 1675 nm. The International Telecommunications Union (ITU) has designated six spectral bands for use in intermediate-range and long-distance optical fiber communications within the 1260 to 1675 nm region. These regions are known by the letters O, E, S, C, L, and U, which are defined as follows:

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1. Original band (O-band): 1260 to 1360 nm.
2. Extended band (E-band): 1360 to 1460 nm.
3. Short band (S-band): 1460 to 1530 nm.
4. Conventional band (C-band): 1530 to 1565nm.
5. Long band (L-band): 1565 to 1625 nm.
6. Ultralong band (U-band): 1625 to 1675 nm.

1.8 Problems

1. Multiple choice questions (MCQ):

1.1 The loss in signal power as light travels down a fiber is called
a. Dispersion
b. Scattering
c. Absorption
d. Attenuation

1.2 Fiber optic cables operate at frequencies near.
a. 20 MHz
b. 200 MHz
c. 2G Hz
d. 800 THz

1.3 When a beam of light enters one medium from another, which quantity will not change?
a. Direction
b. Speed
c. Frequency
d. Wavelength

1.4 Optic fiber is normally made from:
a. Coherent glass and xenon.
b. Copper.
c. Water.
d. Silica glass or plastic.

1.5 The following are the advantages of optical fiber system except
a. Greater capacity.
b. Crosstalk immunity.
c. Safer to handle.
d. Lower initial cost of installation.

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1.6 The basic optical fiber communications system consists of the following except
a. Optical source.
b. Photodetector.
d. Transmission medium.

1.7 In free space, light travels at approximately
a. 186000 m/sec
b. 0.3m/nsec
c. 300 m/sec
d. 3 x 10^9 m/sec

1.8 Which of the following is used as an optical transmitter for the Fiber Optical Communications?
a. Avalanche photodiode (APD).
b. Laser diode (LD) & Light emitting diode (LED).
c. PIN diode.
d. CO_2 laser.

1.9 Which color has the shortest wavelength of light?
a. Red
b. Yellow
c. Blue
d. Green

1.10 What is the light source typically used in single mode optical fiber?
a. Phototransistor
b. Laser
c. Photoresistor
d. LED

1.11 One of the advantages of fiber optics which is referred to the volume of capacity of signals it can carry.
a. Security
b. Weight
c. Bandwidth
d. Physical size

1.12 (1) micron is equal to _____ meters.
a. 10^{-6}
b. 10^{-12}
c. 10^{-15}
d. 10^{-18}

1.13 Where can one find a fiber to detector connector?

a. Transmitter
b. Receiver
c. LED circuit block
d. Analog transmitter block

2. Consider the following signal power levels: 50 μW, 1 mW and 100 mW. Calculate these power levels in dBm.

3. Calculate the carrier frequency and energy in eV for optical communication systems operating at λ= 1, 2, 3 = 800 nm, 1300 nm, and 1550 nm.