# 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.

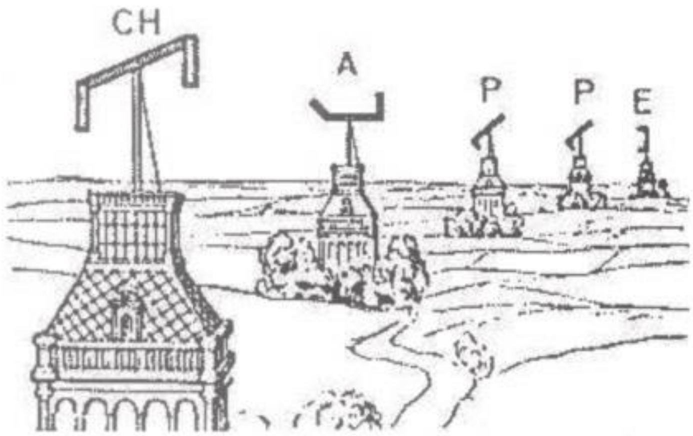


Figure 1.1: Schematic illustration of the optical telegraph and its inventor Claude Chappe.

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

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**.

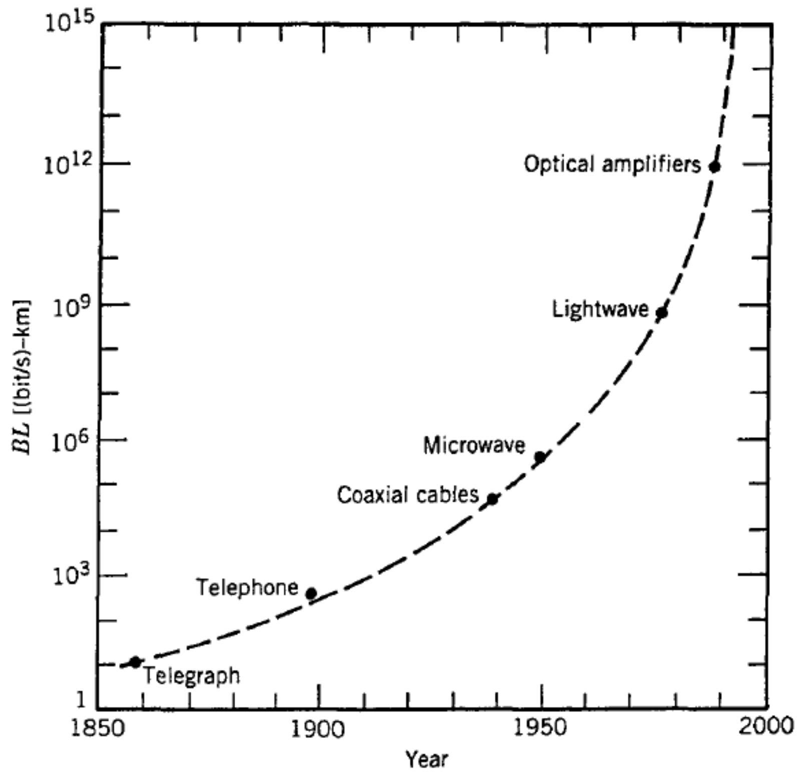


Figure 1.2: Increase in bit rate-distance product BL during the period 1850-2000. The emergence of a new technology is marked by a solid circle.



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**Dr. Abdulla K. Abass**

### 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.

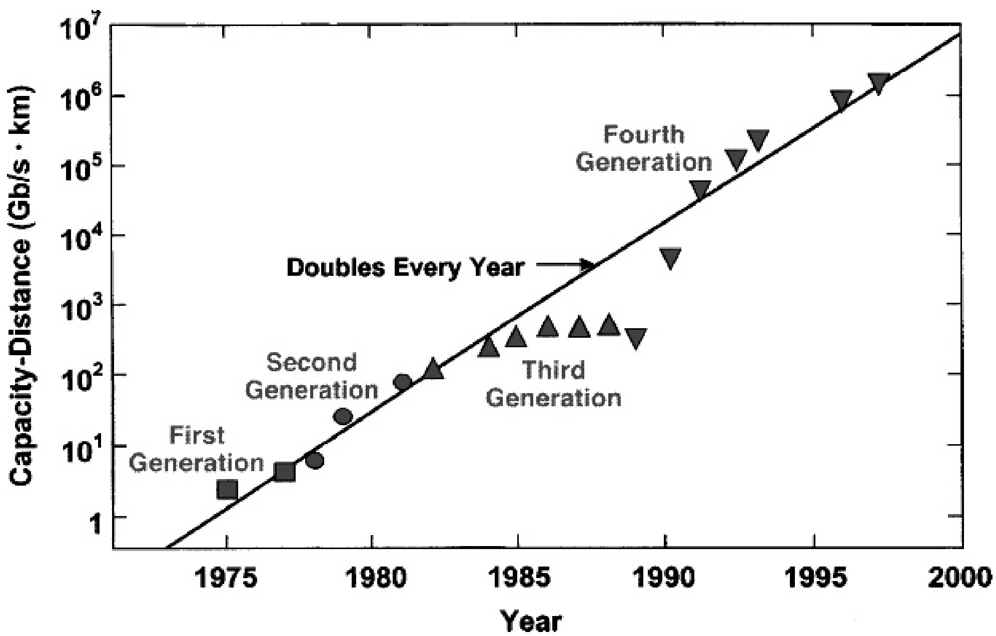


Figure 1.3: Increase in the BL product over the period 1975 to 1980 through several generations of lightwave systems. Different symbols are used for successive generations.

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.



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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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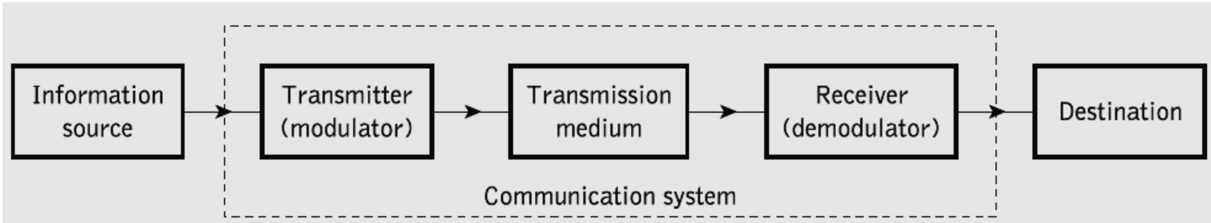


Figure 1.4: General communication system.

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.

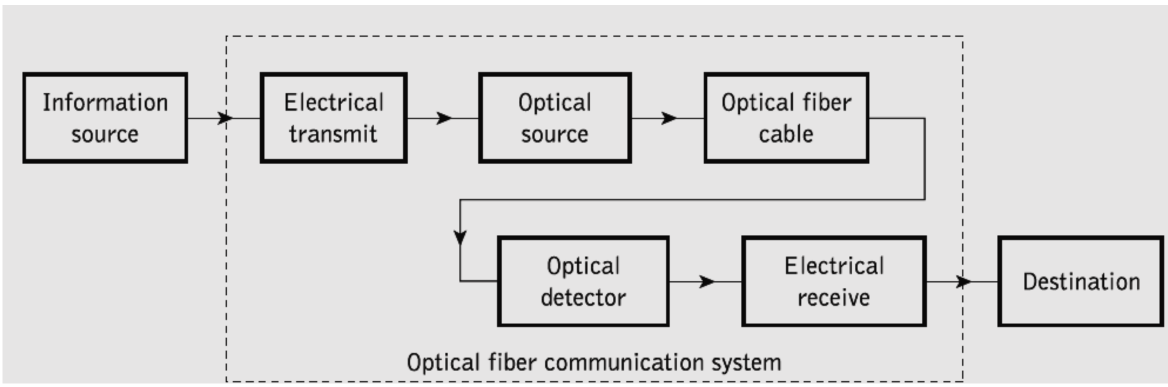


Figure 1.5: Optical fiber communication system.

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.

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 copper.
8. System reliability and ease of maintenance.
9. 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:

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?



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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 $\lambda$= 1, 2, 3 = 800 nm, 1300 nm, and 1550 nm.



**Assistant Prof.**
**Dr. Abdulla K. Abass**

# CHAPTER 2

# OPTICAL FIBERS

## 2.1 Introduction

The availability of low-loss fibers led to a revolution in the field of lightwave technology and started the era of fiber-optic communications. This chapter focuses on the role of optical fibers as a communication channel in lightwave systems.

## 2.2 Ray Transmission Theory

### 2.2.1 Total Internal Reflection

To consider the propagation of light within an optical fiber utilizing the ray theory model it is necessary to take account the ***refractive index*** of the dielectric medium. The refractive index of a medium is defined as ***the ratio of the velocity of light in a vacuum to the velocity of light in the medium***. A ray of light travels more slowly in an optically dense medium than in one that is less dense, and the refractive index gives a measure of this effect. When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass–air), refraction occurs, as illustrated in Figure 2.1 (a). It may be observed that the ray approaching the interface is propagating in a dielectric of refractive index $n_1$ and is at an angle $\varphi_1$ to the normal on the surface of the interface. If the dielectric on the other side of the interface has a refractive index $n_2$ which is less than $n_1$, then the refraction is such that the ray path in this lower index medium is at an angle $\varphi_2$ to the normal, where $\varphi_2$ is greater than $\varphi_1$. The angles of incidence $\varphi_1$ and refraction $\varphi_2$ are related to each other and to the refractive indices of the dielectrics by *Snell's* law of refraction, which states that:

$$n_1 \sin \varnothing_1 = n_2 \sin \varnothing_2 \qquad \text{(Equation 2.1)}$$

Or:

$$\frac{\sin \varnothing_1}{\sin \varnothing_2} = \frac{n_2}{n_1} \qquad \text{(Equation 2.2)}$$

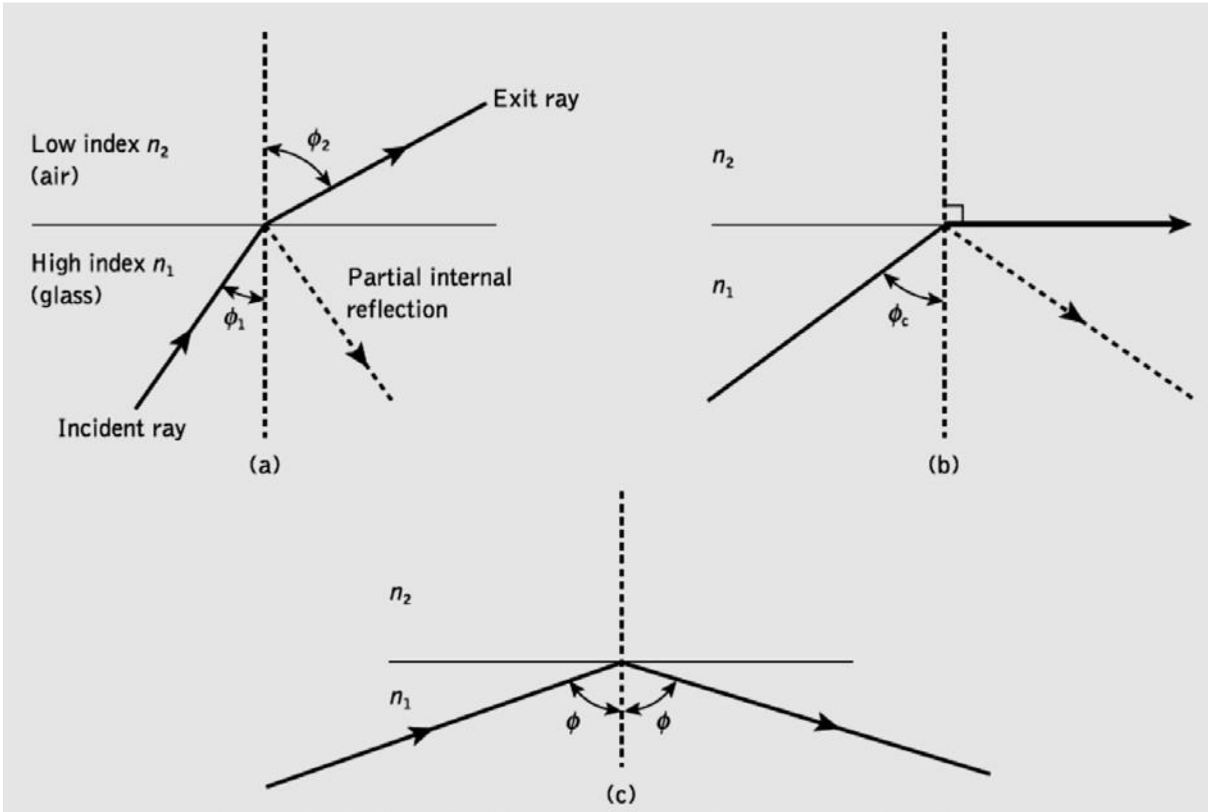


Figure 2.1: Light rays incident on a high to low refractive index interface (e.g. glass–air): (a) Refraction; (b) The limiting case of refraction showing the critical ray at an angle $\varphi_c$; (c) total internal reflection where $\varphi > \varphi_c$

It may also be observed in Figure 2.1 (a) that a small amount of light is reflected back into the originating dielectric medium (partial internal reflection). As $n_1$ is greater than $n_2$, the angle of refraction is always greater than the angle of incidence. Thus, when the angle of refraction is 90° and the refracted ray emerges parallel to the interface between the dielectrics, the angle of incidence must be less than 90°. This is the limiting case of refraction and the angle of incidence is now known as the **critical angle** $\varphi_c$, as shown in Figure 2.1 (b). The critical angle is defined as the angle of incidence *above* which total internal reflection occurs. From Equation (2.2) the value of the critical angle is given by:

$$\sin \phi_c = \frac{n_2}{n_1} \qquad \text{(Equation 2.3)}$$

At angles of incidence greater than the critical angle the light is reflected back into the originating dielectric medium (total internal reflection) with high efficiency (around 99.9%).

Hence, it may be observed in Figure 2.1 (c) that total internal reflection occurs at the interface between two dielectrics of differing refractive indices when light is incident on the dielectric of lower index from the dielectric of higher index, and the angle of incidence ray exceeds the critical value. This is the mechanism by which light at a sufficient shallow angle (less than 90° − φc) may be considered to propagate down an optical fiber with low loss.

Figure 2.2 illustrates the transmission of a light ray in an optical fiber via a series of total internal reflections at the interface of the silica core and the slightly lower refractive index silica cladding. The ray has an angle of incidence φ at the interface which is greater than the critical angle and is reflected at the same angle to the normal. The light ray is known as a **meridional ray** as it passes through the axis of the fiber core.

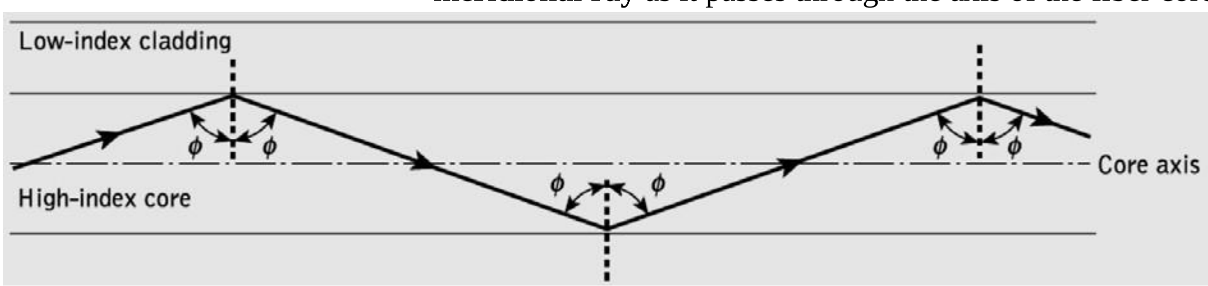


Figure 2.2: The transmission of a light ray in a perfect optical fiber

### 2.2.2 Acceptance Angle

The geometry concerned with launching a light ray into an optical fiber is shown in Figure 2.3, which illustrates a meridional ray $A$ at the critical angle $\varphi_c$ within the fiber at the core–cladding interface. It may be observed that this ray enters the fiber core at an angle θa to the fiber axis and is refracted at the air–core interface before transmission to the core–cladding interface at the critical angle.

Hence, any rays which are incident into the fiber core at an angle greater than $\theta_a$ will be transmitted to the core–cladding interface at an angle less than $\varphi_c$, and will not be totally internally reflected. This situation is also illustrated in Figure 2.3, where the incident ray $B$ at an angle greater than $\theta_a$ is refracted into the cladding and eventually lost by radiation.



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Thus, for rays to be transmitted by total internal reflection within the fiber core they must be incident on the fiber core within an acceptance cone defined by the conical half angle $\theta_a$. Hence θa **is the maximum angle to the axis at which light may enter the fiber in order to be propagated, and is often referred as the acceptance angle for the fiber.**

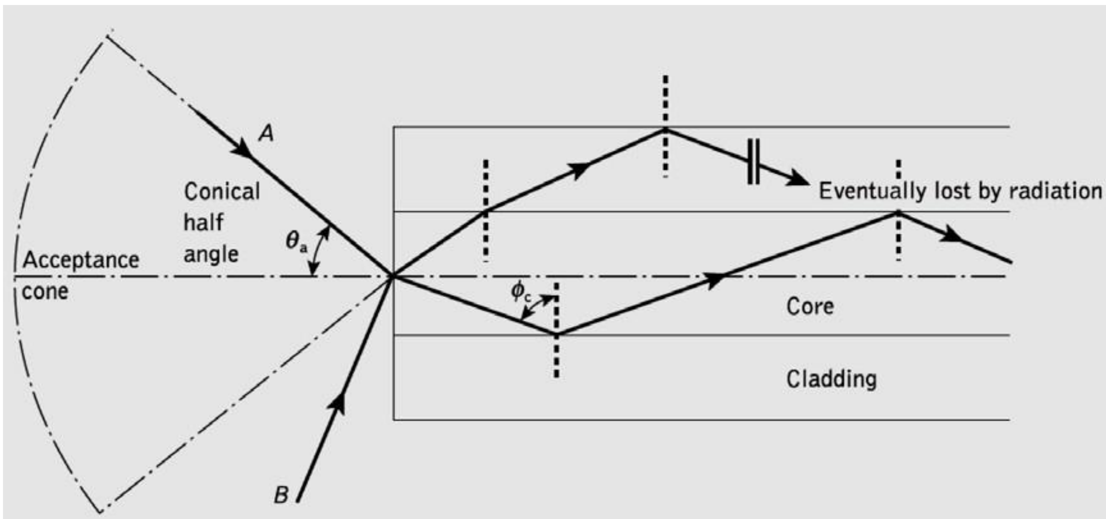


Figure 2.3: The acceptance angle $\theta_a$ when launching light into an optical fiber

### 2.2.3 Numerical Aperture

The numerical aperture (NA) of a fiber is defined **as the sine of the largest angle an incident ray can have for total internal reflectance in the core.** Rays launched outside the angle specified by a fiber's NA will excite radiation modes of the fiber. A higher core index, with respect to the cladding, means larger NA. However, increasing NA causes higher scattering loss from greater concentrations of dopant. A fiber's NA can be determined by measuring the divergence angle of the light cone it emits when all its modes are excited.

Figure 2.4 shows a light ray incident on the fiber core at an angle $\theta_1$ to the fiberaxis, whichh is less than the **acceptance angle** for the fiber $\theta_a$. The ray enters the fiber from a medium (air) of refractive index $n_0$, and the fiber core has a refractive index $n_1$, which is slightly greater than the cladding refractive index $n_2$.

Assuming the entrance face at the fiber core to be normal to the axis, then considering the refraction at the air–core interface and using *Snell's* law given by Equation (2.1):

$$n_0 \sin\theta_1 = n_1 \sin\theta_2 \qquad \text{(Equation 2.4)}$$

Considering the right–angled triangle ABC indicated in Figure 2.4, then:

$$\phi = \frac{\pi}{2} - \theta_2 \qquad \text{(Equation 2.5)}$$

where $\phi$ is greater than the critical angle at the core–cladding interface. Hence Equation (2.4) becomes:

$$n_0 \sin\theta_1 = n_1 \cos\phi \qquad \text{(Equation 2.6)}$$

Using the trigonometrical relationship $\sin^2\phi + \cos^2\phi = 1$, Equation (2.6) may be written in the form:

$$n_0 \sin\theta_1 = n_1 (1 - \sin^2\phi)^{\frac{1}{2}} \qquad \text{(Equation 2.7)}$$

When the limiting case for total internal reflection is considered, $\phi$ becomes equal to the critical angle for the core–cladding interface and is given by Equation (2.3). Also in this limiting case $\boldsymbol{\theta_1}$ becomes the acceptance angle for the fiber $\boldsymbol{\theta_a}$. Combining these limiting cases into Equation (2.7) gives:

$$n_0 \sin\theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \qquad \text{(Equation 2.8)}$$

Equation (2.8), apart from relating the acceptance angle to the refractive indices, serves as the basis for the definition of the important optical fiber parameter, the **numerical aperture (NA)**.

Hence the ***NA*** is defined as:

$$NA = n_0 \sin\theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \qquad \text{(Equation 2.9)}$$

Since the *NA* is often used with the fiber in the air where $\boldsymbol{n_0}$ is unity, it is simply equal to ($\sin\theta_a$). It may also be noted that incident meridional rays over the range $0 \le \theta_1 \le \theta_a$ will be propagated within the fiber. The *NA* may also be given in terms of the relative refractive index difference (Δ) between the core and the cladding which is defined as:

$$NA = n_1 (2\Delta)^{\frac{1}{2}} \qquad \text{(Equation 2.10)}$$

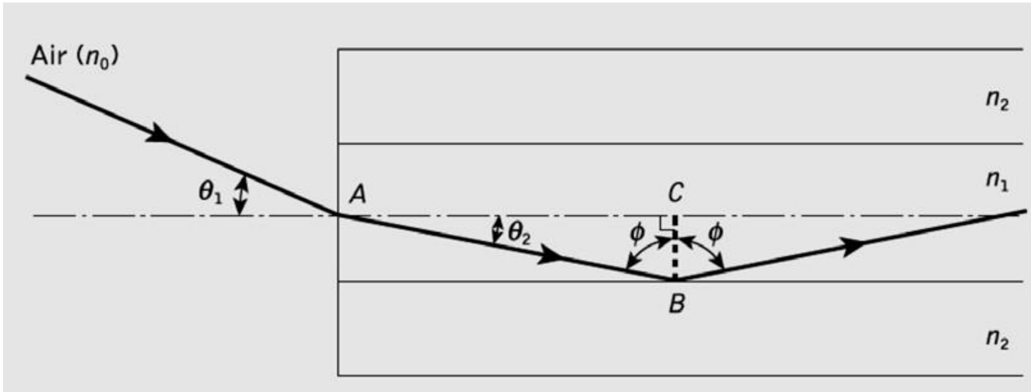


Figure 2.4: The ray path for a meridional ray launched into an optical fiber in air at an input angle less than the acceptance angle for the fiber

**Example 2.1**

A silica optical fiber with a core diameter large enough to be considered by the ray theory has a core refractive index of 1.5 and a cladding refractive index of 1.47, determine:

(a) The critical angle at the core–cladding interface.

(b) The NA of the fiber.

(c) The acceptance angle in air to the fiber.

**Solution:**

(a) The critical angle $\varphi_c$ at the core–cladding interface is given by Equation (2.3) where:

$$\sin\phi_c = \frac{n_2}{n_1} = \frac{1.47}{1.5}, \quad \phi_c = \sin^{-1}\frac{1.47}{1.5}$$

$$= 78.5^o$$

(b) From Equation (2.9) the *NA* is:

$$NA = (n_1^2 - n_2^2)^{\frac{1}{2}} = (1.5^2 - 1.47^2)^{\frac{1}{2}}$$

$$= (2.25 - 2.16)^{\frac{1}{2}} = 0.3$$

(c) Considering Equation (2.9) the acceptance angle in air θa is given by:

$$\theta_a = \sin^{-1} NA = \sin^{-1}(0.3)$$

$$= 17.4^o$$



**Assistant Prof.**
**Dr. Abdulla K. Abass**

### 2.2.4 Optical Rays Types

We have seen that rays approaching from within the cone of acceptance are successfully propagated along the fiber. The position and the angle at which the ray strikes the core will determine the exact path taken by the ray. There are three possibilities, called the **meridional**, the **axial** and the **skew** ray as shown in **Figure 2.5**.

- The **meridional** ray **enters the core and passes through its center**.
- The **axial** ray is a particular ray that just happens to travel straight through the center of the core.
- The **skew ray never passes through the center of the core.** Instead, it reflects off the core/cladding interface and bounces around the outside of the core. It moves forward in a shape reminiscent of a spiral staircase built from straight sections.

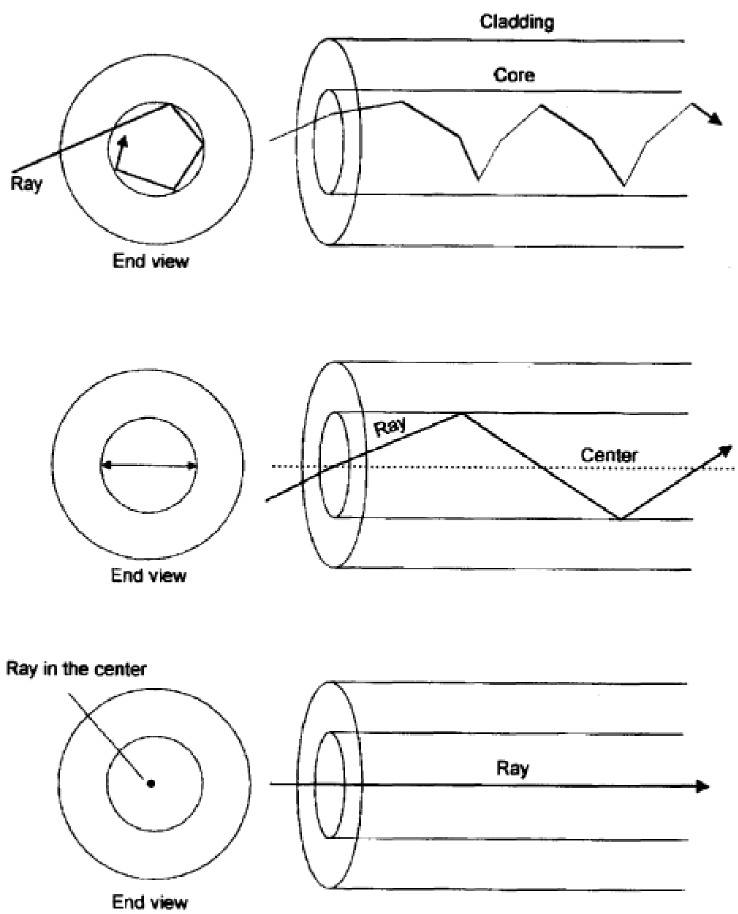


Figure 2.5: The skew ray does not pass through the center (top); the meridional ray passes through the center (middle); the axial ray stays in the center all the time (bottom).



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***Note***: The ***NA*** for the skew rays is given by the equation below:

$$NA = \sin \theta_{as} \cos \gamma \qquad \text{(Equation 2.11)}$$

Where:

$\sin \theta_{as}$ Is the acceptance angle of the skew rays.

$\cos \gamma$ is the angle between the projection of the ray in two dimensions and the radius of the fiber core at the point of reflection. The helical path traced through the fiber gives a change in direction of 2γ at each reflection as shown as in **Figure 2.6**.

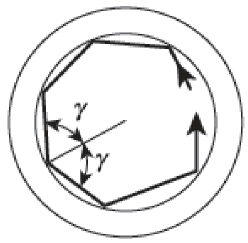


Figure 2.6: Cross-sectional view of the fiber with skew rays.

**Example 2.2**

An optical fiber in the air has an NA of 0.4. Compare the acceptance angle for meridional rays with that for skew rays which change direction by 100° at each reflection.

**Solution:**

The acceptance angle of meridional rays is given by (Equation 2.9) with $n_o$ = 1as:

$$\theta_a = \sin^{-1} NA = \sin^{-1} 0.4 = 23.6^0$$

The skew rays change direction by 100° at each reflection, therefore $\gamma = 50^0$. Hence, using (Equation 2.11) the acceptance angle of skew rays is:

$$\theta_{as} = \sin^{-1}\left(\frac{NA}{\cos\gamma}\right) = \sin^{-1}\left(\frac{0.4}{\cos 50^0}\right) = 38.5^0$$

In this example, the acceptance angle of the skew rays is about 15° greater than the corresponding angle for meridional rays. However, it must be noted that we have only compared the acceptance angle of one particular skew ray path. When the light input to the fiber is at an angle to the fiber axis, it is possible that γ will vary from zero for meridional rays to 90° for rays which enter the fiber at the core–cladding interface giving acceptance of skew rays over a conical half angle of π/2 radians.

## 2.3 Modes Theory for Optical Fiber

The electromagnetic theory shows that the waveguide light propagation is not that simple, as multiple reflections in the core-cladding interfaces will induce constructive interference in the form of transverse standing waves only for a discrete number of incident angles below the maximum acceptance angle given by *NA*. Each of them is called a **propagation mode**, and both the light density transverse distribution and the polarization of each of them remain stable throughout the waveguide.

A mode, in this sense, **is a spatial distribution of optical energy in one or more dimensions that remains constant in time.** For a given mode, a change in wavelength can prevent the mode from propagating along the fiber.

- Maxwell's equations describe electromagnetic waves or modes as having two .components
- .The two components are the electric field, E(x, y, z), and the magnetic field, H(x, y, z) .The electric field, E, and the magnetic field, H, are at right angles to each other
- Modes traveling in an optical fiber are said to be transverse. The transverse modes propagate along the axis of the fiber. In **TE** modes, **the electric field is perpendicular .to the direction of propagation**
- .In **TM** modes, **the magnetic field is perpendicular to the direction of propagation** .The electric field is in the direction of propagation

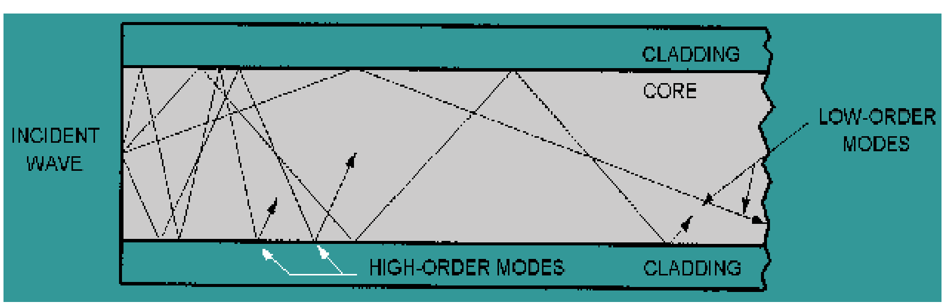


Figure 2.7: Modes in optical fiber.

### 2.3.1 Normalized Frequency (V number)

The **normalized frequency** is a dimensionless parameter and hence is also sometimes simply called the ***V*** **number** or value of the fiber. It combines in a very useful manner, the information about three important design variables for the fiber: namely, the **core radius *a***, the **relative refractive index difference *Δ*** and the **operating wavelength *λ*.**

$$V = \frac{2\pi}{\lambda} N \text{[illegible]} \quad \text{(Equation 2.12)}$$

$$V = \frac{2\pi}{\lambda} \text{[illegible]}_1 (2\Delta)^{\frac{1}{2}} \quad \text{(Equation 2.13)}$$

The analysis of how the V-number is derived is beyond the scope of undergraduate, but it can be shown that by reducing the diameter of the fiber to a point at which the V-number is less than **2.405**, higher-order modes are effectively extinguished and single-mode operation is possible.

### 2.3.2 Number of Modes (M)

**The number of modes can decrease with increasing the wavelength of the light.** However, this alone cannot result in reducing the number of **modes to 1**. Changing from the **850** nm window to the **1550** nm window will only reduce the number of modes by a factor of **3 or 4** which is not enough on its own.

Similarly, a change in the numerical aperture can help but it only makes a **marginal improvement**. We are left with the core diameter. **The smaller the core, the less the modes.** When the **core is reduced sufficiently** the **number of modes can be reduced to just one**.

$$M = \frac{\text{[illegible]}}{2} \quad \text{(Equation 2.14)}$$

### 2.3.3 Cutoff Wavelength $\lambda_{\lambda}$

The cutoff wavelength for any mode is defined as **the maximum wavelength at which that mode propagates.**

$$\lambda_c = \frac{2\pi}{V_c} \text{[illegible]}(N\text{[illegible]}) \quad \text{(Equation 2.15)}$$

$$\lambda_c = \frac{2\pi}{V_c} \text{[illegible]}_1 (2\Delta)^{\frac{1}{2}} \quad \text{(Equation 2.16)}$$

For a fiber to operate single mode, the operating wavelength must be longer than the cutoff wavelength.



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**Example 2.3**

What is the maximum core diameter of a fiber if it is to operate in single mode at a wavelength of 1550 nm if the $NA$ is 0.12.

**:Solution**

From (Equation 2.12)

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

Solving for $\boldsymbol{a}$ yield $a = V\lambda/(2\pi)(NA)$

For single-mode operation, $V$ must be 2.405 or less. The maximum core diameter occurs when $V$ = 2.405. So, plugging into the equation, we get

$$a_{mam} = \frac{(2.405)(1550 \times 10^{-9})}{(2\pi)(0.12)} = 9.9 \mu\mu$$

$$d_{mam} = 2 \times a = 19.7 \mu\mu$$

**Example 2.4**

Determine the cutoff wavelength for a step-index fiber to exhibit single-mode operation when the core refractive index is 1.46 and the core radius is 4.5 μm, with the relative index difference of 0.25 %.

**Solution:**

From (Equation 2.16)

$$\lambda_c = \frac{2\pi}{V_c} a n_1 (2\Delta)^{\frac{1}{2}} = 1214\ n\mu$$

Hence, the fiber is single-mode for λ> 1214 nm.

**Example 2.5**

A multimode step-index fiber with a core diameter of 80 μm and a relative index difference of 1.5 % is operating at a wavelength of 0.85 μm. If the core refractive index is 1.48, estimate (a) the normalized frequency for the fiber; (b) the number of guided modes.

**Solution:**

(a) $V = \frac{2\pi}{\lambda} a n_1 (2\Delta)^{\frac{1}{2}} = 75.8$

(b) M ≈$V^2$/ 2 = 2873 (i.e. nearly 3000 guided modes!)

## 2.4 Optical Fiber Types

.Optical fibers are the actual media that guide the light. They can be made of glass or plastic The plastic fibers exhibit **much losses and tend to have low bandwidths so glass fibers are** eht si eroc ehT .tekcaj a dna gniddalc ،eroc a fo pu edam si rebif lacipyt A .**usually preferred** to5 center or the actual fiber where the light propagates. It has dimensions on the order of eht fo taht naht rewol noitcarfer fo xedni na sah dna eroc eht sdnuorrus gniddalc ehT .mµ 600 .core, in this way the light will propagate through the core by means of internal reflection Surrounding the cladding is the jacket, the outer part of the fiber. The jacket serves to protect .the entire optical fiber

When it comes to the **refractive index profiles**, optical fibers classify in ***step index*** (one homogeneous index in the core and cladding) and ***graded index*** (where the core index value decreases gradually from the fiber axis to the cladding). When it comes to the supported ***propagation modes*** they can be ***single mode*** or ***multimode***.

### 2.4.1 Step Index Fibers

The optical fiber with a core of constant refractive index $n_1$ and a cladding of a slightly lower refractive index $n_2$ is known as **step index fiber**. This is because the refractive index profile for this type of fiber makes a step change at the core–cladding interface, as indicated in **Figure 2.8**, which illustrates the two major types of step index fiber. The refractive index profile may be defined as:

$$n(r) = \begin{cases} n_1, & r < a \ (\text{core}) \\ n_2, & r \geq a \ (\text{cladding}) \end{cases} \qquad \text{(Equation 2.17)}$$

**Figure 2.8** (a) shows a multimode step index fiber (**MMF-step index**) with a core diameter of around **50 µm** or greater, which is large enough to allow the propagation of many modes within the fiber core. This is illustrated in **Figure 2.8** (a) by the many different possible ray paths through the fiber. **Figure 2.8** (b) shows a single-mode or monomode step index fiber (**SMF**) which allows the propagation of only one transverse electromagnetic mode, and hence the core diameter must be of the order of **2 to 10 µm**. The propagation of a SMF is illustrated in **Figure 2.8** (b) as corresponding to a single ray path only (usually shown as the axial ray) through the fiber.

The SMF has the distinct advantage of low **intermodal dispersion (broadening of transmitted light pulses)**, as only one mode is transmitted, whereas with multimode step index fiber considerable dispersion may occur due to the differing group velocities of the propagating modes. This in turn restricts the maximum bandwidth attainable with MMF-step index, especially when compared with SMF. However, for lower bandwidth applications MMF have several advantages over single-mode fibers. These are:

**(a) The use of spatially incoherent optical sources (e.g. most light-emitting diodes) which cannot be efficiently coupled to SMF;**

**(b) Larger numerical apertures, as well as core diameters, facilitating easier coupling to optical sources;**

**(c) Lower tolerance requirements on fiber connectors.**

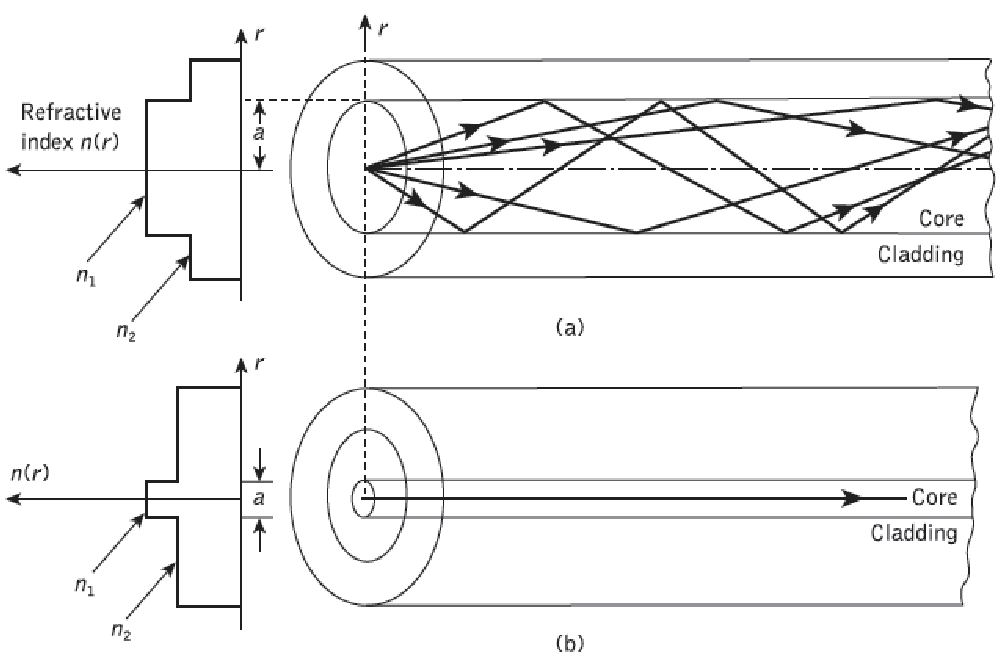


Figure 2.8: The refractive index profile and ray transmission in step index fibers: (a) Multimode step index fiber; (b) single-mode step index fiber

### 2.4.2 Graded Index Fibers

Graded index fibers do not have a constant refractive index in the core but a decreasing core index *n(r)* with radial distance from a maximum value of $n_1$ at the axis to a constant value $n_2$ beyond the core radius a in the cladding.

$$n(r) = \begin{cases} n_1\left(1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right)^{\frac{1}{2}} & r < a \quad (core) \\ n_1(1-2\Delta)^{\frac{1}{2}} = n_2 & r \geq a \quad (cladding) \end{cases} \qquad \text{(Equation 2.18)}$$

Where Δ is the relative refractive index difference and α is the profile parameter which gives the characteristic refractive index profile of the fiber core. Equation (2.75) which is a convenient method of expressing the refractive index profile of the fiber core as a variation of α, allows representation of the step index profile when α = ∞, a parabolic profile when α = 2 and a triangular profile when α = 1.

This range of refractive index profiles is illustrated in **Figure 2.9**. The graded index profiles, which at present produce the best results for multimode optical propagation have a near parabolic refractive index profile core with α ≈2.

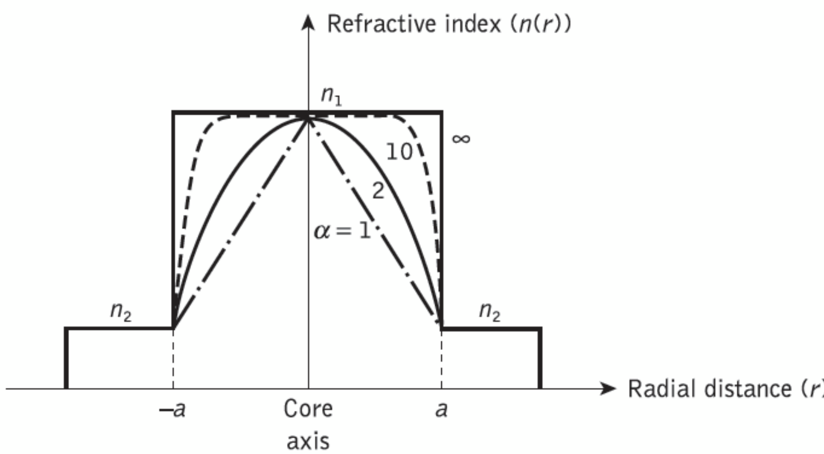


Figure 2.9: Possible fiber refractive index profiles for different values of α (given in (Equation 2.18)).

A multimode graded index fiber with a parabolic index profile core is illustrated in **Figure 2.10**. It may be observed that the meridional rays shown appear to follow curved paths through the fiber core. Using the concepts of geometric optics, the gradual decrease in refractive index from the center of the core creates many refractions of the rays as they are effectively incident on a large number or high to low index interfaces. This mechanism is illustrated in **Figure 2.11** where a ray is shown to be gradually curved, with an ever increasing angle of incidence, until the conditions for total internal reflection are met, and the ray travels back towards the core axis, again being continuously refracted.

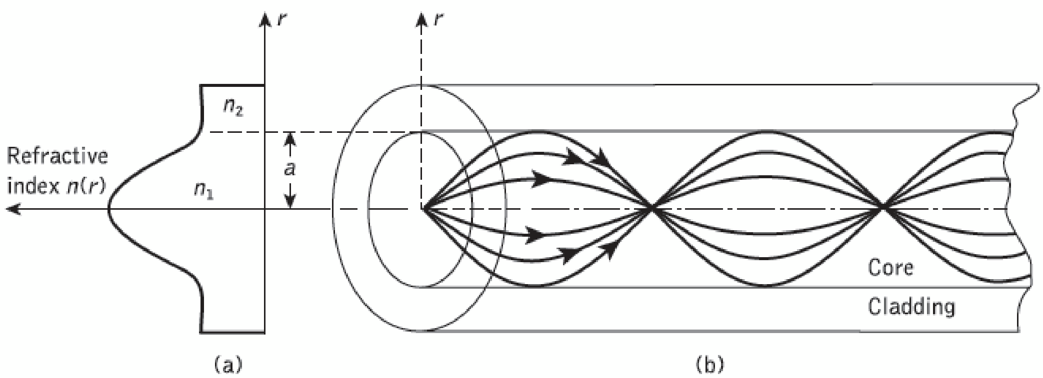


Figure 2.10: The refractive index profile and ray transmission in a multimode graded.

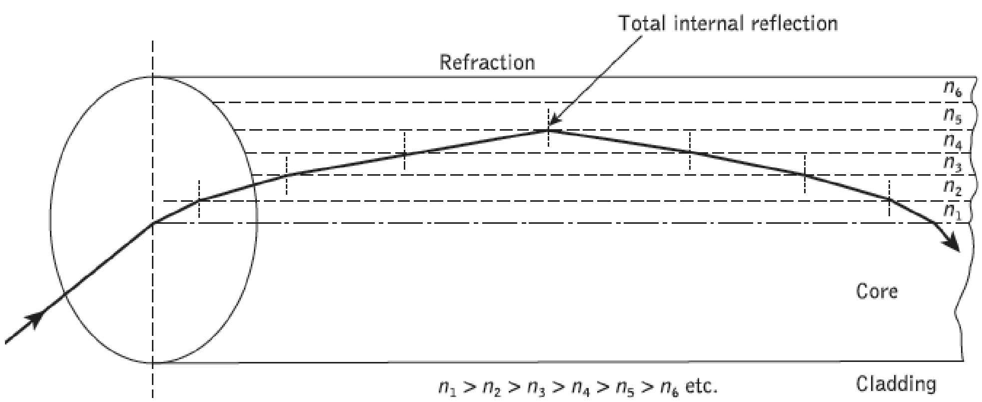


Figure 2.11: An expanded ray diagram showing refraction at the various high to low index interfaces within a graded index fiber, giving an overall curved ray path.



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**Example 2.6**

A graded index fiber has a core with a parabolic refractive index profile which has a diameter of 50 μm. The fiber has a numerical aperture of 0.2. Estimate the total number of guided modes propagating in the fiber when it is operating at a wavelength of 1 μm.

**Solution:** Using (Equation 2.12), the normalized frequency for the fiber is:

$$V = \frac{2\pi}{\lambda} a (NA) = \frac{2\pi \times 25 \times 10^{-6} \times 0.2}{1 \times 10^{-6}} = 31.4$$

$$M_g = \frac{V^2}{4} = \frac{986}{4} = 247$$

Hence the fiber supports approximately 247 guided modes.

### 2.4.3 Single Mode Fibers

The advantage of the propagation of a single mode within an optical fiber is that the signal dispersion caused by the delay differences between different modes in a multimode fiber may be avoided. Multimode step index fibers do not lend themselves to the propagation of a single mode due to the difficulties of maintaining single-mode operation within the fiber when mode conversion (i.e. coupling) to other guided modes takes place at both input mismatches and fiber imperfections. Hence, for the transmission of a single mode the fiber must be designed to allow propagation of only one mode, while all other modes are attenuated by leakage or absorption. Following the emergence of SMF as a viable communication medium in 1983, they quickly became the dominant and the most widely used fiber types within telecommunications. Major reasons for this situation are as follows:

1. They exhibit the greatest transmission bandwidths and the lowest losses of the fiber transmission media.
2. They offer a substantial upgrade capability (i.e. future proofing) for future wide-bandwidth services using either faster optical transmitters and receivers or advanced transmission techniques (e.g. coherent technology).
3. They are compatible with the developing integrated optics technology.
4. The above reasons 1 to 3 provide confidence that the installation of single-mode fiber will provide a transmission medium which will have adequate performance, such that it will not require replacement over its anticipated lifetime of more than 20 years.

## 2.5 Problems

**1. In each case, choose the best option.**

**1.1 The speed of light in a transparent material:**

(a) is always the same regardless of the material chosen.
(b) is never greater than the speed of light in free space.
(c) increases if the light enters a material with a higher refractive index.
(d) is slowed down by a factor of a million within the first 60 meters.

**1.2 A ray of light in a transparent material of refractive index 1.5 is approaching a material with a refractive index of 1.48. At the boundary, the critical angle is:**

(a) 90°.
(b) 9.4°.
(c) 75.2°.
(d) 80.6°.

**1.3 If a ray of light approaches a material with a greater refractive index:**

(a) The angle of incidence will be greater than the angle of refraction.
(b) TIR will always occur.
(c) The speed of the light will increase immediately as it crosses the boundary.
(d) The angle of refraction will be greater than the angle of incidence.

**If a light ray crosses the boundary between two materials with different refractive 1.4 :indices**

.0° saw ecnedicni fo elgna eht fi ecalp ekat dluow noitcarfer on (a)
.rucco syawla lliw noitcarfer (b)
.lamron eht gnola gnilevart si yar tnedicni eht fi egnahc ton lliw thgil eht fo deeps eht (c)
.segnahc reven thgil fo deeps eht (d)

**1.5 As the meridional ray is propagated along the optical fiber it:**

(a) Travels in a sort of spiral shape.
(b) Stays in the center of the fiber.
(c) Passes repeatedly through the center of the core.
(d) Is reflected off the inside surface of the primary buffer. This is called TIR.

**1.6 No material could have a refractive index of:**

(a) 1.5
(b) 1.3
(c) 1.1
(d) 0.9



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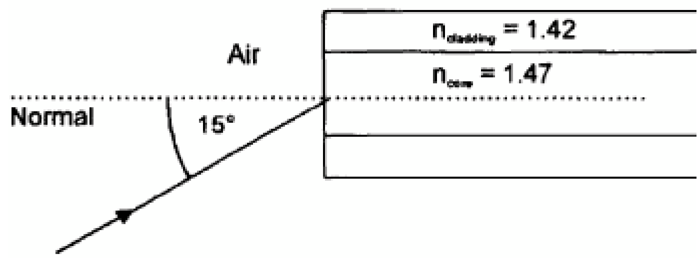
**1.7 The ray enters the optic fiber at an angle of incidence of 15° as shown in the figure below. The angle of refraction in the core would be:**

(a) 8.3°
(b) 14.71°
(c) 75°
(d) 15.54°




**1.8 If the refractive index of the core of an optical fiber was 1.47 and that of the cladding was 1.44, the cone of acceptance would have an angle of approximately:**

(a) 17.19°
(b) 72.82°
(c) 78.4°
(d) 34.36°

**2. Using simple ray theory, describe the mechanism for the transmission of light within an optical fiber.**

**3. Briefly discuss with the aid of a suitable diagram what is meant by the acceptance angle for an optical fiber.**

**4. Derive an expression for the numerical aperture NA.**

**5. An optical fiber has a numerical aperture of 0.2 and a cladding refractive index of 1.59. Determine:**

(a) The acceptance angle of the fiber in **water** which has a refractive index of 1.33.

(b) The critical angle at the core–cladding interface.

**Ans. (a) $8.6^0$, (b) $83.6^0$**



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**Dr. Abdulla K. Abass**

# CHAPTER 3

# TRANSMISSION CHARACTERISTICS OF OPTICAL FIBERS

## 3.1 Introduction

The basic transmission mechanisms of the various types of optical fiber waveguide have been discussed in Chapter 2. However, the factors which affect the performance of optical fibers as a transmission medium were not dealt with in detail. These transmission characteristics are of utmost importance when the suitability of optical fibers for communication purposes is investigated. The transmission characteristics of most interest are those of attenuation (or loss) and bandwidth. The importance of reducing the attenuation has been indicated in Section 1.4. The other characteristic of primary importance is the bandwidth of the fiber. This is limited by the signal dispersion within the fiber, which determines the number of bits of information transmitted in a given time period. Therefore, once the attenuation was reduced to acceptable levels, attention was directed towards the dispersive properties of fibers. Again, this has led to substantial improvements, giving wideband fiber bandwidths of many tens of gigahertz over a number of kilometers.

**_ When designing an optical link one of the most interesting questions is the maximum distance between the emitter and detector for a certain bit rate. Two different analyses have to be done:**

1. An analysis of the attenuation budget: Which is the maximum distance before the signal is too small and the photodiode cannot detect it? (attenuation limited link)
2. An analysis of the dispersion budget: which is the maximum distance before the optical pulse broadens beyond the value when they overlap? (dispersion limited link)

## 3.2 Attenuation

The attenuation of a light signal as it propagates along a fiber is an important consideration in the design of an optical communication system, since it plays a major role in determining the maximum transmission distance prior to signal restoration. The basic attenuation mechanisms in a fiber are **absorption**, **scattering** and **radiative** losses of the optical energy. Absorption is related to the fiber material, whereas scattering is associated both with the fiber material and with structural imperfections in the optical waveguide. Attenuation owing to radiative effects originates from perturbations (both microscopic and macroscopic) of the fiber geometry. The attenuation or transmission losses of optical fibers has proved to be one of the most important factors in bringing about their wide acceptance in telecommunications. As channel attenuation largely determines the maximum transmission distance prior to signal restoration, optical fiber communications became especially attractive when the transmission losses of fibers were reduced below those of the competing metallic conductors (less than 5 dB km$^{-1}$).

Signal attenuation within optical fibers, as with metallic conductors, is usually expressed in the logarithmic unit of the *decibel*. The *decibel*, which is used for comparing two power levels, may be defined for a particular optical wavelength as the ratio of the input (transmitted) optical power $P_i$ into a fiber to the output (received) optical power $P_o$ from the fiber as:

$$\alpha_{dB} = \frac{10}{L}\log_{10}\frac{P_i}{P_o} \qquad \textbf{(Equation 3.1)}$$

In optical fiber communications the attenuation is usually expressed in decibels per unit length (i.e. dB km$^{-1}$). where $\alpha_{dB}$ is the signal attenuation per unit length in decibels, which is also referred to as the fiber loss parameter and $L$ is the fiber length. However, addition and subtraction require a conversion of numerical values which may be obtained using the relationship:

$$\frac{P_i}{P_o} = 10^{(dB/10)} \qquad \textbf{(Equation 3.2)}$$

The attenuation is a function of wavelength, as is shown by the general attenuation curve in Figure 3.1.

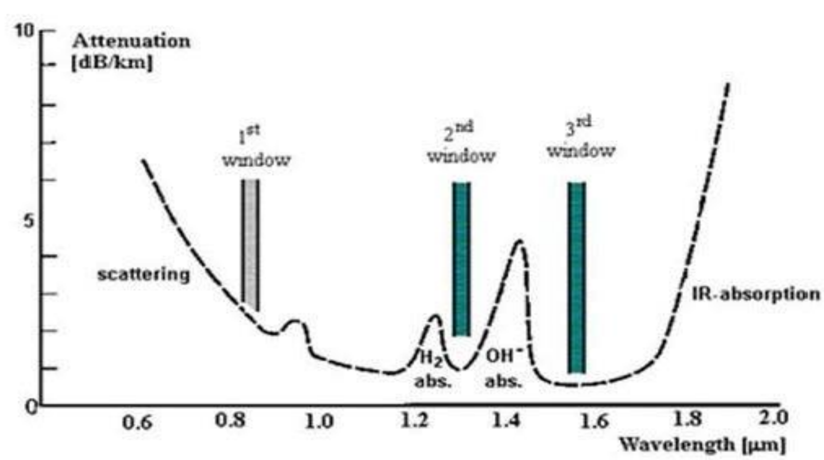


**Figure 3.1: Attenuation versus wavelength**



**Assistant Prof.**
**Dr. Abdulla K. Abass**

**Example 3.1**

When the mean optical power launched into an 8 km of fiber is $120\mu\mu$ and the mean optical power at the fiber output is $3\mu$. Determine:

a. The overall signal attenuation or loss in decibels through the fiber assuming there are no connectors or splice losses.

b. The signal attenuation per kilometer of the fiber.

c. The overall signal attenuation for a 10 km optical link using the same fiber with splices at 0.5 km intervals, each giving an attenuation of 1 dB.

d. The numerical input/output power ratio in (c).

**Solution:**

a. Using Equation (3.1), the overall signal attenuation in decibels through the fiber is:

$$\text{Signal Attenuation} = 10 \log_{10} \frac{P_i}{P_o} = 10 \log_{10} \frac{120 \times 10^{-6}}{3 \times 10^{-6}}$$

$$= 10 \log_{10} 40 = 16\ dB$$

b. The signal attenuation per kilometer for the fiber may be simply obtained by dividing the result in (a) by the fiber length which corresponds to it using **Error! Reference source not found.**) where:

$$\alpha_{dB} L = 16\ dB$$

Hence:

$$\alpha_{dB} = 2\ dB\,km^{-1}$$

c. As $\alpha_{dB} = 2\ \mathrm{dBkm}^{-1}$, the loss incurred along 10 km of the fiber is given by: $\alpha_{dB} = 2 \times 10 = 20\ \mathrm{dB}$. However, the link also has nine splices (at 1 km intervals) each with an attenuation of 1 dB. Therefore, the loss due to the splices is 9 dB. Hence, the overall signal attenuation for the link is:

$$\text{Signal Attenuation} = 20 + 9 = 29\ \mathrm{dB}$$

d. To obtain a numerical value for the input/output power ratio, Equation (3.3) may be used where:

$$\frac{P_i}{P_o} = 10^{(dB/10)} = 10^{(29/10)} = 794.3$$

### 3.2.1 Absorption Losse in Silica Glass Fibers

Absorption is a loss mechanism related to the material composition and the fabrication process for the fiber, which results in the dissipation of some of the transmitted optical power as heat in the waveguide. The absorption of the light can be divided into:

1. Absorption by atomic defects in the glass composition.
2. **Intrinsic** (caused by the interaction with one or more of the major components of the glass).
3. **Extrinsic** (caused by impurities within the glass).

### 3.2.2 Linear Scattering Losses

Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly (proportional to the mode power) into a different mode. This process tends to result in attenuation of the transmitted light as the transfer may be in a leaky or radiation mode, which does not continue to propagate within the fiber core, but is radiated from the fiber. *It must be noted that as with all linear processes, there is no change of frequency on scattering (elastic scattering).*

Linear scattering may be categorized into two major types: *Rayleigh* and *Mie* scattering. Both result *from the non-ideal physical properties of the manufactured fiber, which* are difficult and, in certain cases, impossible to eradicate at present.

#### 3.2.2.1 Rayleigh scattering

Rayleigh scattering is the dominant intrinsic loss mechanism in the low-absorption window between the ultraviolet and infrared absorption tails. It results from inhomogeneities of a random nature occurring on a small scale compared with the wavelength of the light. These inhomogeneities manifest themselves as refractive index fluctuations and arise from density and compositional variations which are frozen into the glass lattice on cooling. The compositional variations may be reduced by improved fabrication, but the index fluctuations caused by the freezing are fundamental and cannot be avoided. The subsequent scattering due to the density fluctuations, which is in almost all directions, produces attenuation proportional to $1/\lambda^4$ following the Rayleigh scattering formula. For a single-component glass this is given by:

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F$$ (**Equation 3.3**)

where $\gamma_R$ is the Rayleigh scattering coefficient, $\lambda$ is the optical wavelength, $n$ is the refractive index of the medium, $p$ is the average photo-elastic coefficient, $\beta_c$ is the isothermal compressibility at a fictive temperature $T_F$, and $K$ is *Boltzmann's* constant. The afictive temperature is defined as the temperature at which the glass can reach a state of thermal equilibrium and is closely related to the anneal temperature.

Furthermore, the Rayleigh scattering coefficient is related to the transmission loss factor (transmissivity) of the fiber $\chi$ following the relation:

$$\chi = \exp(-\gamma_R L)$$ (**Equation 3.4**)

where $L$ is the length of the fiber. It is apparent from Equation (3.4) that the fundamental component of Rayleigh scattering is strongly reduced by operating at the longest possible wavelength.

**Example 3.2**

Silica has an estimated affective temperature of 1400 K with an isothermal compressibility of $7 \times 10^{-11}$ m$^2$ N$^{-1}$. The refractive index and the photo-elastic coefficient for silica are 1.46 and 0.286 respectively. Determine the theoretical attenuation in decibels per kilometer due to the fundamental Rayleigh scattering in silica at optical wavelengths of **630, 1000 and 1300** nm. Boltzmann's constant is $1.381 \times 10^{-21}$ J K$^{-1}$.

**Solution:**

The Rayleigh scattering coefficient may be obtained from Equation (3.4) for each wavelength. However, the only variable in each case is the wavelength, and therefore the constant of proportionality of (**Equation 3.3**) applies in all cases. Hence:

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F = \frac{248.15 \times 20.65 \times 0.082 \times 7 \times 10^{-11} \times 1.381 \times 10^{-23} \times 1400}{3\lambda^4}$$

$$= \frac{1.895 \times 10^{-28}}{\lambda^4} \text{ m}^{-1}$$

At a wavelength of 630 nm:

$$\gamma_R = \frac{1.895 \times 10^{-28}}{0.158 \times 10^{-24}} = 1.199 \times 10^{-3}\ m^{-1}$$

The transmission loss factor for 1 kilometer of fiber may be obtained using (**Equation 3.4**):

$$\chi = \exp(-\gamma_R L) = \exp(-1.199 \times 10^{-3} \times 10^{3}) = 0.301$$

The attenuation due to Rayleigh scattering in decibels per kilometer may be obtained from (**Equation 3.1**) where:

$$attenuation = 10 \log \left(\frac{1}{\chi}\right) = 10 \log(3.322) = 5.2\ dB\ km^{-1}$$

#### 3.2.2.2 Mie scattering

Linear scattering may also occur at inhomogeneities which are comparable in size with the guided wavelength. These results from the non perfect cylindrical structure of the waveguide and may be caused by fiber imperfections such as irregularities in the core–cladding interface, core–cladding refractive index differences along the fiber length, diameter fluctuations, strains and bubbles. When the scattering inhomogeneity size is greater than λ/10, the scattered intensity which has an angular dependence can be very large. The scattering created by such inhomogeneities is mainly in the forward direction and is called Mie scattering. Depending upon the fiber material, design and manufacture, Mie scattering can cause significant losses.

The inhomogeneities may be reduced by:

(a) Removing imperfections due to the glass manufacturing process;

(b) Carefully controlled extrusion and coating of the fiber;

(c) Increasing the fiber guidance by increasing the relative refractive index difference.

By these means it is possible to reduce Mie scattering to insignificant levels.

### 3.2.3 Nonlinear Scattering Losses

Optical waveguides do not always behave as completely linear channels whose increase in output optical power is directly proportional to the input optical power. Several nonlinear effects occur, which in the case of scattering cause disproportionate attenuation, usually at high optical power levels. This nonlinear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes, at a different frequency. It depends critically upon the optical power density within the fiber and hence only becomes significantly above threshold power levels. The most important types of nonlinear scattering within optical fibers are stimulated Brillouin and Raman scattering, both of which are usually only observed at high optical power densities in long single-mode fibers.

These scattering mechanisms in fact give optical gain but with a shift in frequency, thus contributing to attenuation for light transmission at a specific wavelength. However, it may be noted that such nonlinear phenomena can also be used to give optical amplification in the context of integrated optical techniques.

#### 3.2.3.1 Stimulated Brillouin Scattering

Brillouin scattering was first demonstrated by Léon Brillouin, who theoretically predicted light scattering from thermally excited acoustic waves in 1920 [1]. In 1930 it has been experimental demonstrated by E. Gross using a lamp as the light source [2]. After the invention of lasers, the SBS was observed in optical fiber in 1972 [3], and it has been studied extensively since then because of its implications for optical communication systems. Although the scattering cross section of the Brillouin Stokes wave is quite low, but in a nonlinear medium like the optical fiber, it can propagate to a long distance with insignificant attenuation. At a certain pump power, this nonlinear scattering becomes stimulated and known as SBS which is strongly dependent on the pump power.

**Basic Concept**

The underlying physical mechanism of the Brillouin scattering is the transformed of an incident light into a scattered photons and thermal phonons. The scattered wave is propagating in opposite direction to the incident light and it has a frequency downshift set by the nonlinear medium. It is called a Stokes wave which found by George G. Stokes in 19th century [4].

The most distinct origin of the SBS is a physical phenomenon known as electrostriction [5]. Through this phenomenon, the backscattering Stokes interferes with the input pump wave and creates an acoustic wave. Significantly, the propagating wave generates a moving density grating from which it scatters in the opposite direction. The frequency downshift of the Brillouin Stokes can also be attributed by the Doppler effects. The light scattering mechanism is schematically shown in Figure 3.2. Both amplitude of the acoustic wave and the interference pattern are directly proportional with the intensity of the Stokes wave. The acoustic wave in the forward direction works as a Bragg grating, which scatters even more wave in backward direction.

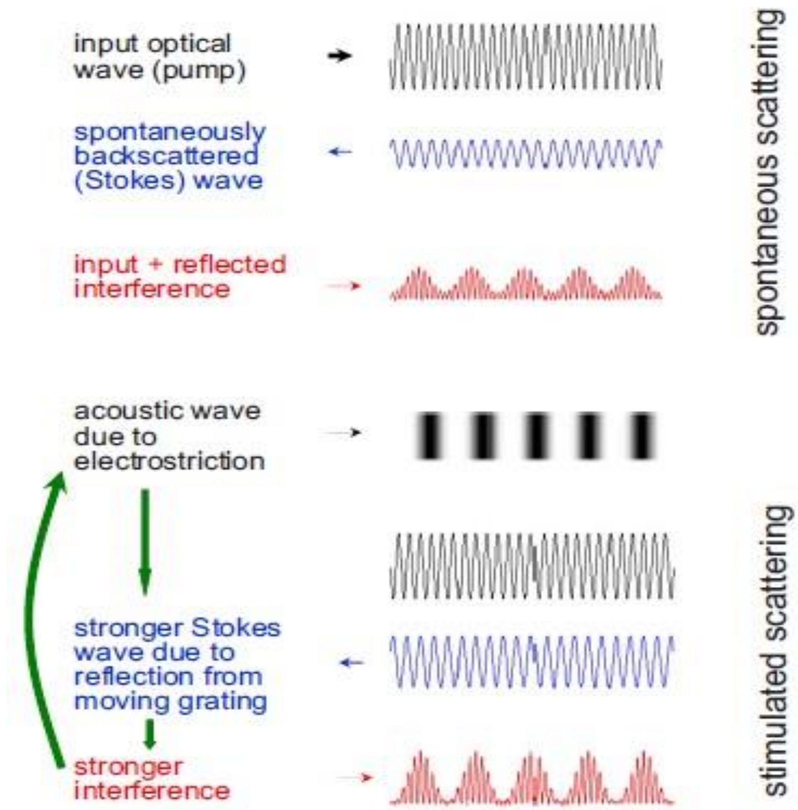


Figure 3.2: SBS light scattering mechanism [4].

The frequency shift is a maximum in the backward direction, reducing to zero in the forward direction, **making SBS a mainly backward process**. Brillouin scattering is only significant above a threshold power density $P_B$ is given by:

$$P_d = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \quad \textbf{(Equation 3.5)}$$

where d and λ are the fiber core diameter and the operating wavelength, respectively, both measured in micrometers, $\alpha_{dB}$ is the fiber attenuation in decibels per kilometer and ν is the source bandwidth (i.e. injection laser) in gigahertz. The expression given in (**Equation 3.5**) allows the determination of the threshold optical power which must be launched into a single-mode optical fiber before SBS occurs.



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### 3.2.3.2 Stimulated Raman Scattering

The transformation of a small fraction power from the incident light to the scattered light is called the spontaneous Raman scattering. This phenomenon was discovered by C. V. Raman in 1928 [6]. In general, the frequencies of the scattering light are different from those of the incident light by an amount defined by the vibrational levels of the medium.

The spontaneous Raman scattering is a weak process to some extent. For example, if the light is propagated through a medium with a volume of 1 $cm^3$ only one part of the million of the incident light will be scattered into the Stokes frequency. However, if an intense laser source is incident on a molecular medium there is a high scattering component can occur and more than 10% of the incident power is transferred to the scattering components [7]. This type of nonlinear scattering was discovered in 1962 and called the SRS phenomenon [8].

**Basic Concept**

The SRS is an important nonlinear phenomenon that can convert the optical fibers into wideband Raman amplifiers and tunable Raman fiber lasers. It can also strongly limit the WDM communication system performance by relocating fraction of power from one wavelength to another [9]. In SRS nonlinear phenomenon, the incident light works as a pump source and called the RPP, and the transmitted power known as the residual Raman pump power (R-RPP). The scattering components which shifted to lower frequencies (red-shift) are known as Stokes waves, and those shifted to higher frequencies (blue-shift) are called anti-Stokes waves [64, 79].

The origin of the Stokes wave generation lies in the energy exchange between the photons and the material molecules. The quantum mechanical energy diagram for Raman scattering is shown in Figure 3.3. In the Stokes generation process, the incident photon of frequency $v_P$ excites a molecule from the ground state to the virtual state. Then, this molecule returns to the vibrational state and releasing a Stokes photon of frequency $v_S$ .

Since, the energy between the virtual state and the vibrational level is smaller than the energy between the ground and the virtual states, as a results the $\nu_S < \nu_P$. On the contrary, in the anti-Stokes process, the excitement molecule will be within the vibrational level. Hence, the frequency of the anti-Stokes signal is higher than the incident photon $\nu_A > \nu_P$.

Furthermore, the intensity of the Stokes waves is many orders of magnitude higher than the intensity of the anti-Stokes waves. This is due to the anti-Stokes process requires the vibrational state to be initially populated with a phonon of right energy and momentum. In what follows the anti-Stokes process was ignored as it plays an insignificant role in Raman amplification.

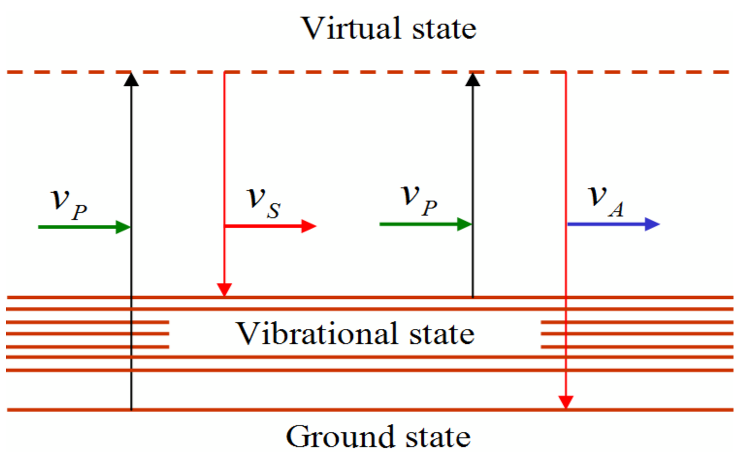


Figure 3.3: Quantum-mechanical energy diagram for Raman scattering.

Using the same criteria as those specified for the Brillouin scattering threshold given in (**Equation 3.5**), it may be shown that the threshold optical power for SRS $P_R$ in a long single-mode fiber is given by:

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} \quad (\text{watts})$$ **(Equation 3.6)**

**Example 3.3**

A long SMF has an attenuation of 0.5 dB km$^{-1}$ when operating at a wavelength of 1.3 μm. The fiber core diameter is 6 μm and the laser source bandwidth is 600 MHz. Compare the threshold optical powers for SBS and SRS within the fiber at the wavelength specified.

**Solution:**

The threshold optical power for SBS is given by (**Equation 3.5**) as:

$$P_d = 4.4 \times 10^{-3}\, d^2 \lambda^2 \alpha_{dB}\, v$$

$$= 4.4 \times 10^{-3}\, 6^2\, 1.3^2\, 0.5 \times 0.6$$

$$= 80.3\ \mu\mu$$

The threshold optical power for SRS may be obtained from (**Equation 3.6**), where:

$$P_R = 5.9 \times 10^{-2}\, d^2 \lambda\, \alpha_{dB}$$

$$= 5.9 \times 10^{-2}\, 6^2\, 1.3\ \ 0.5$$

$$= 1.38\ \mu$$

### 3.2.4 Bending Losses

Bending losses occur whenever an optical fiber undergoes a bend of finite radius of curvature. Fiber can be subject to two types of bends:

a) Macroscopic bends having radii that are large compared to the fiber diameter, for example, such as occur when a fiber cable turns a corner.

b) Microscopic bends of the fiber axis that can arise when the fibers are incorporated into cables.

The minimum bend radius it has a particular importance in the handling of fiber optic cables, which are often used in telecommunications. The minimum bending radius will vary with different cable designs. The manufacturer should specify the minimum radius to which the cable may safely be bent during installation.

The minimum bend radius is in general also a function of tensile stresses, e.g., during installation, while being bent around a sheave while the fiber or cable is under tension. If no minimum bend radius is specified, one is usually safe in assuming a minimum long-term lower-stress radius **not less than 15 times** the cable diameter.

Optical fibers suffer radiation losses at bends or curves on their paths. This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding and hence the guidance mechanism is inhibited, which causes light energy to be radiated from the fiber. An illustration of this situation is shown in **Figure 3.4**. The part of the mode which is on the outside of the bend is required to travel faster than that on the inside so that a wavefront perpendicular to the direction of propagation is maintained. Hence, part of the mode in the cladding needs to travel faster than the velocity of light in that medium. As this is not possible, the energy associated with this part of the mode is lost through radiation. The loss can generally be represented by a radiation attenuation coefficient which has the form:

$$\alpha_r = C_1 \exp(-C_2 R) \qquad \textbf{(Equation 3.7)}$$

where R is the radius of curvature of the fiber bend and $C_1$, $C_2$ are constants which are independent of R. Furthermore, large bending losses tend to occur in multimode fibers at a critical radius of curvature $R_{CMMF}$ which may be estimated from:

$$R_{CMMF} \simeq \frac{3 n_1^2 \lambda}{4\pi (n_1^2 - n_2^2)^{\frac{3}{2}}} \qquad \textbf{(Equation 3.8)}$$

It may be observed from the expression given in (**Equation 3.8**) that potential macrobending losses may be reduced by:

(a) Designing fibers with large relative refractive index differences;

(b) Operating at the shortest wavelength possible.

The above criteria for the reduction of bend losses also apply to SMF, the critical radius of curvature for a SMF $R_{CSMF}$ can be estimated as:

$$R_{CSMF} \simeq \frac{20\lambda}{(n_1 - n_2)^{\frac{3}{2}}} \left(2.748 - 0.996 \frac{\lambda}{\lambda_c}\right)^{-3} \qquad \textbf{(Equation 3.9)}$$

where $\lambda_c$ is the cutoff wavelength for the SMF.

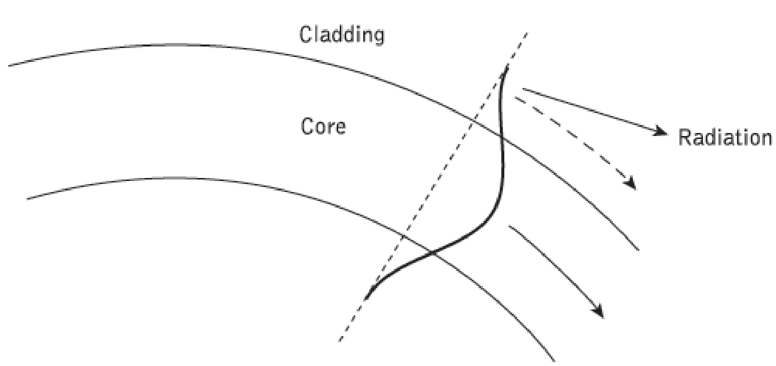



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Figure 3.4: An illustration of the radiation loss at a fiber bend.
The part of the mode in the cladding outside the dashed arrowed line may be required to travel faster than the velocity of light in order to maintain a plane wavefront. Since it cannot do this, the energy contained in this part of the mode is radiated away.

**Example 3.4**

Two step index fibers exhibit the following parameters: **(a)** MMF with a core refractive index of 1.5, a relative refractive index difference of 3% and an operating wavelength of 0.82 μm;

**(b)** an 8 μm core diameter SMF with a core refractive index the same as (a), a relative refractive index difference of 0.3% and an operating wavelength of 1.55 μm. Estimate the critical radius of curvature at which large bending losses occur in both cases.

**Solution**:

(a) The relative refractive index difference is as:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

Hence:

$$n_2^2 = n_1^2 - 2n_1^2\Delta = 2.25 - 2 \times 2.25 \times 0.03 = 2.115$$

Using (**Equation 3.8**) for the multimode fiber critical radius of curvature:

$$R_{CF} = \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{\frac{3}{2}}} = \frac{3 \times 2.25 \times 0.82 \times 10^{-6}}{4\pi \times (0.135)^{\frac{3}{2}}} = 1.2\ \mu m$$

(b) $R_{CS} = 34$ mm

### 3.3 Dispersion

Next to the fiber loss, the capacity of information transmission is an important consideration in designing a fiber-optic communication system. **The dispersion of the fiber essentially determines the maximum bit rate or modulation frequency that can be attained. There are three types of dispersion** [12]:

1. Mode dispersion (MD).
2. Chromatic dispersion (CD).
   a. Material dispersion
   b. Waveguide dispersion
3. Polarization mode dispersion (PMD)

Variation in propagation time among different modes creates **mode dispersion**. If the source were perfectly monochromatic, then mode dispersion would be the only dispersion with which to contend. In reality, all sources, especially when modulated, emit light over a spread of optical frequencies, and the frequency spread of the source leads to other types of dispersion.

The variation in propagation time due to the wavelength dependence of the refractive index creates **material dispersion**. The wavelength dependence of the propagation pattern causes **waveguide dispersion**.

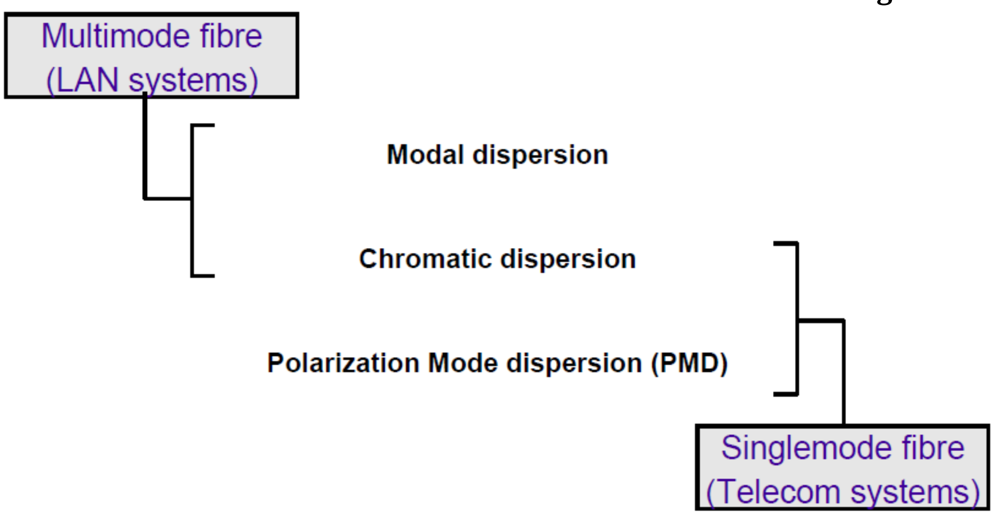


Figure 3.5: Dispersion in an optical fiber.

### 3.3.1 Mode Dispersion (MD)

Using the ray theory model, the fastest and slowest modes propagating in the step index fiber may be represented by the axial ray and the extreme meridional ray (which is incident at the core–cladding interface at the critical angle φc) respectively. The paths taken by these two rays in a perfectly structured step index fiber are shown in Figure 3.8. The delay difference between these two rays when traveling in the fiber core allows estimation of the pulse broadening resulting from intermodal dispersion within the fiber. As both rays are traveling at the same velocity within the constant refractive index fiber core, then the delay difference is directly related to their respective path lengths within the fiber. Hence the time taken for the axial ray to travel along a fiber of length L gives the minimum delay time $T_{Min}$ and: We now derive an approximate measure of the time spread due to intermodal dispersion.



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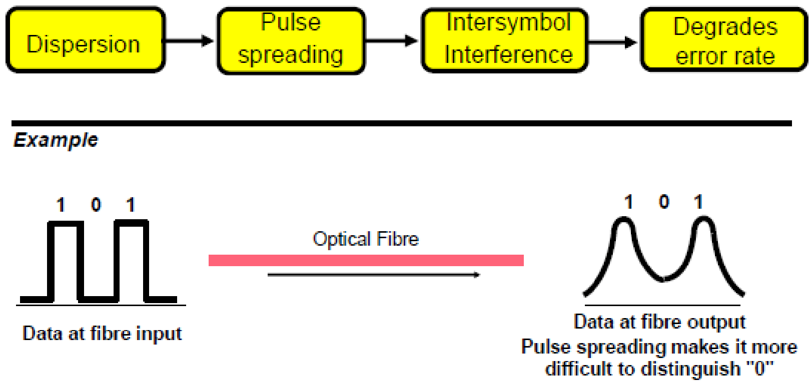


Figure 3.6: Why dispersion is a problem

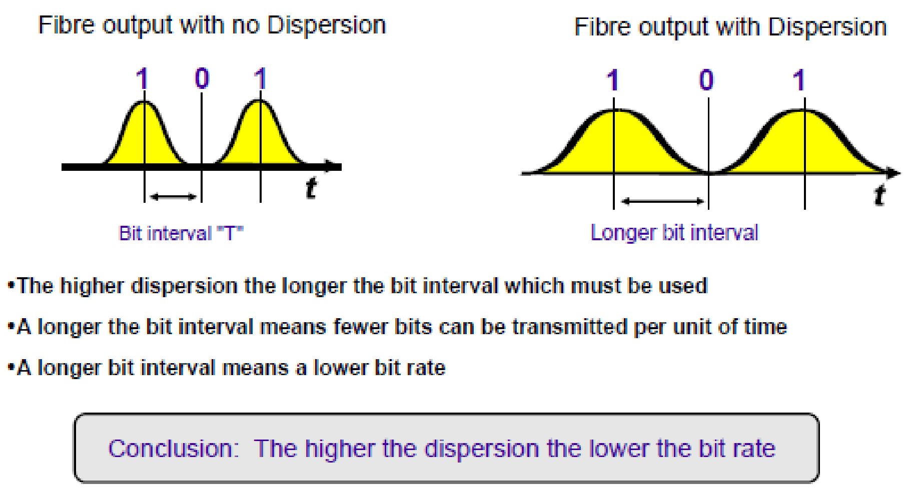


Figure 3.7: Dispersion and Bit Rate.

•Assume:

- Step index fibre
- An impulse-like fibre input pulse
- Energy is equally distributed between rays with paths lying between the axial and the extreme meridional

•What is the *difference in delay* for the two extremes over a linear path length L?

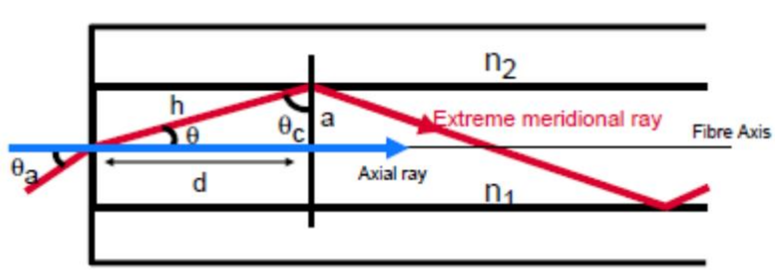




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Figure 3.8: The paths taken by the axial and an extreme meridional ray in a perfect multimode step index fiber.

Transmission distance = L

$T_{max}$ = Transmission time for extreme meridional ray

$T_{min}$ = Transmission time for axial ray

Delay difference $\delta t = T_{max} - T_{min}$

$$T_{min} = \frac{\text{Distance}}{\text{Velocity}} = \frac{L}{(c/n_1)} = \frac{Ln_1}{c}$$

To find $T_{max}$ realise that the ray travels a distance h but only travels a distance d toward the fibre end (d<h). So if the fibre length is L then the actual distance travelled is:

$$\frac{h.L}{d}$$

$$T_{max} = \frac{Ln_1}{c\cos\theta}$$ Using simple trigonometry

Using Snell's law: $\sin\theta_c = \frac{n_2}{n_1} = \cos\theta$

$$T_{max} = \frac{Ln_1^2}{cn_2}$$

Delay difference $\delta t = T_{max} - T_{min} = \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c}$

$$\delta T_s = \frac{Ln_1}{c}\left(\frac{n_1 - n_2}{n_2}\right) \simeq \frac{Ln_1\Delta}{c}$$

How large can δT be before it begins to matter? That depends on the bit rate used. A rough measure of the delay varies $\delta a$ that can be tolerated at a bit rate of B b/s is half the bit period 1/2B s. Thus intermodal dispersion sets the following limit:

$$\delta a = \frac{L\,(N\ \ )^2}{\ \ } < \frac{1}{2d}$$

The capacity of an optical communication system is frequently measured in terms of the bit rate–distance product. If a system is capable of transmitting (x Mb/s over a distance of y km), it is said to have a bit rate-distance product of xy (Mb/s)-km. The intermodal dispersion constrains the bit rate-distance product of an optical communication link to be:

$$BL < \frac{n_2}{n_1^2}\frac{c}{\Delta}$$

For example, if $\Delta$ = 0.01 and $n_1$ = 1.5($\approx n_2$), we get BL < 10 (Mb/s)-km. This limit is plotted in Figure 3.9.

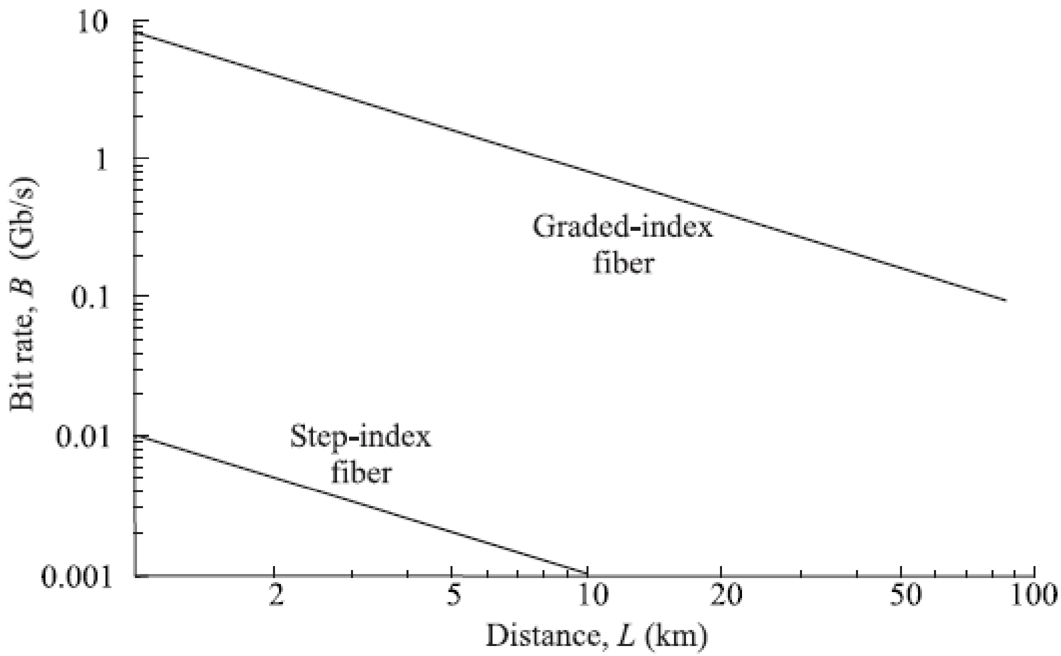



Figure 3.9: Limit on the bit rate–distance product due to intermodal dispersion in a step-index and a graded-index fiber. In both cases, = 0.01 and n1 = 1.5.

- BW get smaller as fibre length L increases
- High NA fibres have lower bandwidths, eg plastic fibre has high NA: Poor bandwidth
- Lowering NA to improve bandwidth makes source coupling more difficult as the acceptance angle decreases

**Example 3.5**

A 6 km optical link consists of multimode step index fiber with a core refractive index of 1.5 and a relative refractive index difference of 1%. Estimate:

(a) The delay difference between the slowest and fastest modes at the fiber output;

(b) The rms pulse broadening due to intermodal dispersion on the link;

(c) The maximum bit rate that may be obtained without substantial errors on the link assuming only intermodal dispersion;

(d) The bandwidth–length product corresponding to (c).

**Solution**:

$$\delta T_s \simeq \frac{Ln_1\Delta}{c} = \frac{6 \times 10^3 \times 1.5 \times 0.01}{2.998 \times 10^8}$$
$$= 300 \text{ ns}$$

$$\sigma_s = \frac{Ln_1\Delta}{2\sqrt{3}c} = \frac{1}{2\sqrt{3}} \frac{6 \times 10^3 \times 1.5 \times 0.01}{2.998 \times 10^8}$$
$$= 86.7 \text{ ns}$$

$$B_T(\max) = \frac{1}{2\tau} = \frac{1}{2\delta T_s} = \frac{1}{600 \times 10^{-9}}$$
$$= 1.7 \text{ Mbit s}^{-1}$$

$$B_T(\max) = \frac{0.2}{\sigma_s} = \frac{0.2}{86.7 \times 10^{-9}}$$
$$= 2.3 \text{ Mbit s}^{-1}$$

$$B_{opt} \times L = 2.3 \text{ MHz} \times 6 \text{ km} = 13.8 \text{ MHz km}$$

### 3.3.2 Chromatic dispersion (CD).

Chromatic or intramodal dispersion may occur in all types of optical fiber and results from the finite spectral linewidth of the optical source. Since optical sources do not emit just a single frequency, but a band of frequencies (in the case of the injection laser corresponding to only a fraction of a percent of the center frequency, whereas for the LED it is likely to be a significant percentage), then there may be propagation delay differences between the different spectral components of the transmitted signal.

This causes broadening of each transmitted mode and hence intramodal dispersion. The delay differences may be caused by the dispersive properties of the waveguide material (material dispersion) and also guidance effects within the fiber structure (waveguide dispersion).

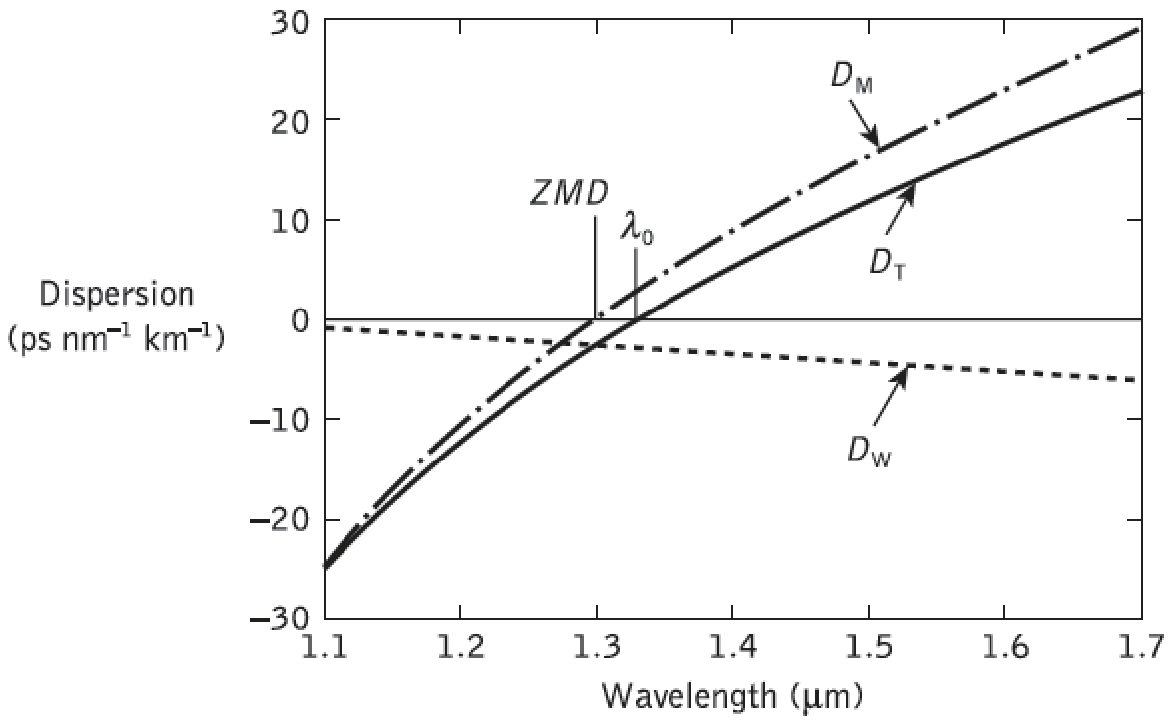
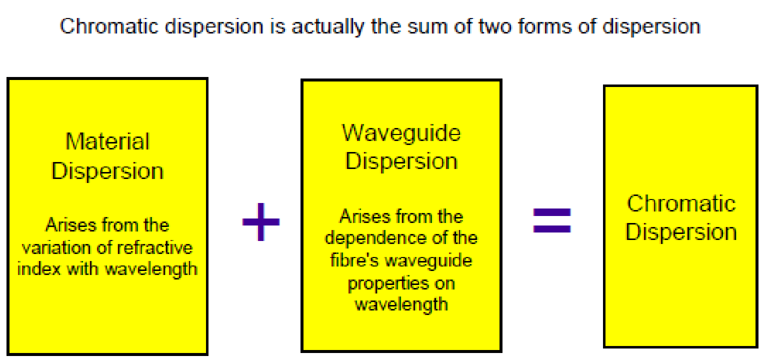



Figure 3.10: The material dispersion parameter ($D_M$), the waveguide dispersion parameter ($D_W$) and the total dispersion parameter ($D_T$) as functions of wavelength for a conventional single-mode fiber




#### 3.3.2.1 Material Dispersion

Pulse broadening due to material dispersion results from the different group velocities of the various spectral components launched into the fiber from the optical source. It occurs when the phase velocity of a plane wave propagating in the dielectric medium varies nonlinearly with wavelength, and a material is said to exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero (i.e. $d^2n/d\lambda^2 \neq 0$).

The rms pulse broadening due to material dispersion is given by:

$$\sigma_m \simeq \frac{\sigma_\lambda L}{c}\left|\lambda \frac{d^2 n_1}{d\lambda^2}\right|$$

However, it may be given in terms of a material dispersion parameter M which is defined as:

$$M = \frac{1}{L}\frac{d\tau_m}{d\lambda} = \frac{\lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right|$$

**Example 3.6**

A glass fiber exhibit material dispersion given by $|\lambda 2(d2n1/d\lambda 2)|$ of 0.025. Determine the material dispersion parameter at a wavelength of 0.85 μm, and estimate the pulse broadening per kilometer for a good LED source with an rms spectral width of 20 nm at this wavelength.

**Solution:**

$$M = \frac{\lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right| = \frac{1}{c\lambda}\left|\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right|$$

$$= \frac{0.025}{2.998 \times 10^5 \times 850} \text{ s nm}^{-1}\text{ km}^{-1}$$

$$= 98.1 \text{ ps nm}^{-1}\text{ km}^{-1}$$

$$\sigma_m \simeq \frac{\sigma_\lambda L}{c}\left|\lambda \frac{d^2 n_1}{d\lambda^2}\right|$$

$$\sigma_m \simeq \sigma_\lambda L M$$

Hence, the rms pulse broadening per kilometer due to material dispersion:

$$\sigma_m(1 \text{ km}) = 20 \times 1 \times 98.1 \times 10^{-12} = 1.96 \text{ ns km}^{-1}$$

### 3.3.2.2 Waveguide Dispersion

The waveguide of the fiber may also create chromatic dispersion. This results from the variation in group velocity with wavelength for a particular mode. Considering the ray theory approach, it is equivalent to the angle between the ray and the fiber axis varying with wavelength which subsequently leads to a variation in the transmission times for the rays, and hence dispersion. For a single mode whose propagation constant is β, the fiber exhibit waveguide dispersion when $d^2\beta/d\lambda^2 \neq 0$. Multimode fibers, where the majority of modes



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propagates far from the cutoff, are almost free of waveguide dispersion and it is generally negligible compared with material dispersion (≈0.1 to 0.2 ns $km^{-1}$). However, with single-mode fibers where the effects of the different dispersion mechanisms are not easy to separate, waveguide dispersion may be significant.

The final expression may be separated into three composite dispersion components in such a way that one of the effects dominates each term [Ref. 46]. The dominating effects are as follows:

1. The material dispersion parameter DM defined by $\lambda/c \mid d^2n/d\lambda^2 \mid$ where $n = n_1$ or $n_2$ for the core or cladding respectively.
2. The waveguide dispersion parameter DW, which may be obtained by:

$$D_W = -\left(\frac{n_1 - n_2}{\lambda c}\right) V \frac{d^2(Vb)}{dV^2}$$

where V is the normalized frequency for the fiber. Since the normalized propagation constant b for a specific fiber is only dependent on V, then the normalized waveguide dispersion coefficient $Vd^2(Vb)/dV^2$ also depends on V. This latter function is another universal parameter which plays a central role in the theory of single mode fibers.

3. A profile dispersion parameter DP which is proportional to $d\Delta/d\lambda$.

**Example 3.7**

A typical single-mode fiber has a zero-dispersion wavelength of 1.31 μm with a dispersion slope of 0.09 ps $nm^{-2}$ $km^{-1}$. Compare the total first-order dispersion for the fiber at the wavelengths of 1.28 μm and 1.55 μm. When the material dispersion and profile dispersion at the latter wavelength are 13.5 ps $nm^{-1}$ $km^{-1}$ and 0.4 ps $nm^{-1}$ $km^{-1}$, respectively, determine the waveguide dispersion at this wavelength.

**Solution:**

The total first-order dispersion for the fiber at the two wavelengths may be obtained from:



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$$D_T(1280\ \text{nm}) = \frac{\lambda S_0}{4}\left[1-\left(\frac{\lambda_0}{\lambda}\right)^4\right]$$
$$= \frac{1280 \times 0.09 \times 10^{-12}}{4}\left[1-\left(\frac{1310}{1280}\right)^4\right]$$
$$= -2.8\ \text{ps nm}^{-1}\ \text{km}^{-1}$$

and:

$$D_T(1550\ \text{nm}) = \frac{1550 \times 0.09 \times 10^{-12}}{4}\left[1-\left(\frac{1310}{1550}\right)^4\right]$$
$$= 17.1\ \text{ps nm}^{-1}\ \text{km}^{-1}$$

The total dispersion at the 1.28 μm wavelength exhibits a negative sign due to the influence of the waveguide dispersion. Furthermore, as anticipated the total dispersion at the longer wavelength (1.55 μm) is considerably greater than that obtained near the zero-dispersion wavelength. The waveguide dispersion for the fiber at a wavelength of 1.55 μm is given by:

$$D_W = D_T - (D_M + D_P)$$
$$= 17.1 - (13.5 + 0.4)$$
$$= 3.2\ \text{ps nm}^{-1}\ \text{km}^{-1}$$

### 3.3.3 Polarization mode dispersion (PMD)

Polarization mode dispersion (PMD) is a form of modal dispersion where two different polarizations of light in a waveguide, which normally travel at the same speed, travel at different speeds due to random imperfections and asymmetries, causing random spreading of optical pulses. Unless it is compensated, which is difficult, this ultimately limits the rate at which data can be transmitted over a fiber.

In practice, fibers are not perfectly circular symmetric, and the two orthogonally polarized modes have slightly different propagation constants; that is, practical fibers are slightly birefringent. Since the light energy of a pulse propagating in a fiber will usually be split between these two modes, this birefringence gives rise to pulse spreading. This phenomenon is called PMD. This is similar, in principle, to pulse spreading in the case of multimode fibers, but the effect is much weaker. PMD is illustrated in Figure 3.11 and Figure 3.12. The assumption here is that the propagation constants of the two polarizations are constant throughout the length of the fiber. If the difference in propagation constants is denoted by



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then the time spread, or differential group delay (DGD) due to PMD after the pulse has propagated through a unit length of fiber is given by

$$\Delta\tau =$$

Δ��/ω

A typical value of the DGD is $\Delta\tau$ = 0.5 ps/km, which suggests that after propagating through 100 km of fiber, the accumulated time spread will be 50 ps comparable to the bit period of 100 ps for a 10 Gb/s system. This would effectively mean that 10 Gb/s transmission would not be feasible over any reasonable distances due to the effects of PMD.

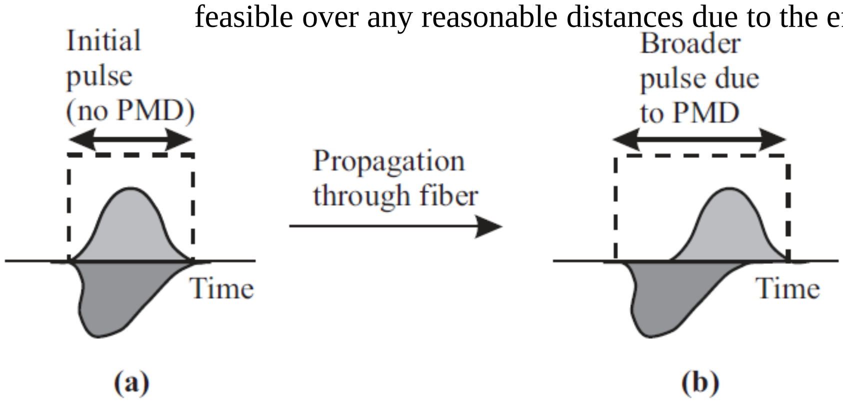


Figure 3.11: Illustration of pulse spreading due to PMD [13].

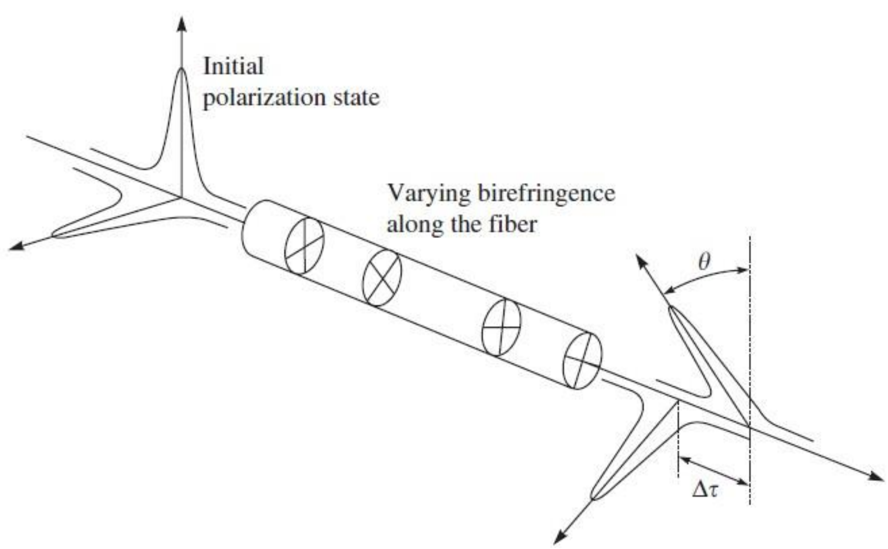


Figure 3.12: Variation in the polarization states of an optical pulse as it passes through a fiber that has varying birefringence along its length [14].

PMD is not a fixed quantity, but fluctuates with time due to factors such as temperature variations and stress changes on the fiber. It varies as the square root of distance and thus is specified as a maximum value in units of ps/$\sqrt{km}$. A typical value $D_{PMD}$ is $= 0.05$ ps/$\sqrt{km}$. Since PMD is a statistically variable parameter, it is more difficult to control than chromatic dispersion, which has a fixed value.

**Total Dispersion Calculation**

If $t_{mod}$, $t_{CD}$, and $t_{PMD}$ are the modal, chromatic, and polarization mode dispersion times, respectively, then the total dispersion $t_T$ can be calculated from the relationship [14]:

$$t_T = \sqrt{(t_{mod})^2 + (t_{CD})^2 + (t_{PMD})^2}$$

**Example 3.8**

Consider a single-mode fiber for which $D_{CD}$ = 2 ps/(km.nm) and $D_{PMD}$ = 0.1 ps/(km.nm). If a transmission link has a length L = 500 km and uses a laser source with a spectral emission width of $\Delta\lambda$ = 0.01 nm, then we have $t_{mod} = 0$, $t_{CD} = D_{CD} \times L \times \Delta\lambda = 10$ ps, and $t_{PMD} = D_{PMD} \times \sqrt{L} = 2.24$ ps. Thus:

$$t_T = \sqrt{(10\,\text{ps})^2 + (2.24\,\text{ps})^2} = 10.2\,\text{ps}$$

If $t_T$ can be no more than 10 percent of a pulse width, then the maximum data rate $R_{max}$ that can be sent over this 500-km link is $R_{max} = 0.1/t_T = 9.8$ Gbps (gigabits per second).

**Example 3.9**

A multimode graded index fiber exhibits total pulse broadening of 0.1 μs over a distance of 15 km. Estimate:

(a) The maximum possible bandwidth on the link assuming no intersymbol interference;
(b) The pulse dispersion per unit length;
(c) The bandwidth–length product for the fiber.

**Solution**:

(a) The maximum possible optical bandwidth which is equivalent to the maximum possible bit rate, assuming no ISI may be obtained, where:

$$B_{opt} = B_T = \frac{1}{2\tau} = \frac{1}{2 \times 0.1 \times 10^{-6}} = 5\ MHz$$

(b) The dispersion per unit length may be acquired simply by dividing the total dispersion by the total length of the fiber:

$$\text{Dispersion} = \frac{0.1 \times 10^{-6}}{15} = 6.67\ ns.km^{-1}$$



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(c) The bandwidth–length product can be obtained by simply multiplying the maximum bandwidth for the fiber link by its length. Hence:

$$����_{oo} \times L = 5 \times 15 = 75\ M$$

$$MMk\mu$$

## 3.4 PROBLEMS

**3.4.1** The mean optical power launched into an optical fiber link is 1.5 mW and the fiber has an attenuation of 0.5 dB km$^{-1}$. Determine the maximum possible link length without repeaters (assuming lossless connectors) when the minimum means optical power level required at the detector is 2 μW. Ans. (57.5 km)

**3.4.2** The numerical input/output mean optical power ratio in a 1 km, length of optical fiber is found to be 2.5. Calculate the received mean optical power when a mean optical power of 1 mW is launched into a 5 km length of the fiber (assuming no joints or connectors). Ans. (10 μW)

**3.4.3** A 15 km optical fiber link uses fiber with a loss of 1.5 dB km$^{-1}$. The fiber is jointed every kilometer with connectors which give an attenuation of 0.8 dB each. Determine the minimum mean optical power which must be launched into the fiber in order to maintain a mean optical power level of 0.3 μW at the detector. Ans. (703 μW)

**3.4.4** Discuss absorption losses in optical fibers, comparing and contrasting the intrinsic and extrinsic absorption mechanisms.

**3.4.5** Briefly describe linear scattering losses in optical fibers with regard to: (a) Rayleigh scattering; (b) Mie scattering.

**3.4.6** The photoelastic coefficient and the refractive index of silica are 0.286 and 1.46 respectively. Silica has an isothermal compressibility of 7 × 10$^{-11}$ m$^2$ N$^{-1}$ and an estimated afictive temperature of 1400 K. Determine the theoretical attenuation in decibels per kilometer due to the fundamental Rayleigh scattering in silica at optical wavelengths of 0.85 and 1.55 μm. Boltzmann's constant is $1.381 \times 10^{-23}$ J $K^{-1}$. Ans. (1.57 dB $km^{-1}$, 0.14 dB $km^{-1}$)

**3.4.7** A $K_2O$–$SiO_2$ glass core optical fiber has an attenuation resulting from Rayleigh scattering of 0.46 dB $km^{-1}$ at a wavelength of 1 μm. The glass has an estimated effective temperature of 758 K, isothermal compressibility of $8.4 \times 10^{-11}$ $m^2$ $N^{-1}$, and a photoelastic coefficient of 0.245. Determine from theoretical considerations the refractive index of the glass. Ans. (1.49)

**3.4.8** Compare stimulated Brillouin and stimulated Raman scattering in optical fibers, and indicate the way in which they may be avoided in optical fiber communications.

**3.4.9** Explain what is meant by the critical bending radius for an optical fiber.

**3.4.10** The threshold optical powers for stimulating Brillouin and Raman scattering in a single-mode fiber with a long 8 μm core diameter are found to be 190 mW and 1.7 W, respectively, when using an injection laser source with a bandwidth of 1 GHz. Calculate the operating wavelength of the laser and the attenuation in decibels per kilometer of the fiber at this wavelength. Ans. (1.5 μm, 0.30 dB $km^{-1}$)

**3.4.11** The threshold optical power for stimulated Brillouin scattering at a wavelength of 0.85 μm in a long single-mode fiber using an injection laser source with a bandwidth of 800 MHz is 127 mW. The fiber has an attenuation of 2 dB $km^{-1}$ at this wavelength. Determine the threshold optical power of stimulated Raman scattering within the fiber at a wavelength of 0.9 μm assuming the fiber attenuation is reduced to 1.8 dB $km^{-1}$ at this wavelength. Ans. (2.4 W)

**3.4.12** A multimode graded index fiber has a refractive index at the core axis of 1.46 with a cladding refractive index of 1.45. The critical radius of curvature which allows large bending losses to occur is 2.56 μm when the fiber is transmitting light of a particular wavelength. Determine the wavelength of the transmitted light. Ans. (0.86 μm)

**3.4.13** A single-mode step index fiber with a core refractive index of 1.49 has a critical bending radius of 10.4 mm when illuminated with light at a wavelength of 1.30 μm. If the cutoff wavelength of the fiber is 1.15 μm calculate its relative refractive index difference. Ans. (0.47%)



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**3.4.14** An 8 km optical fiber link without repeater uses multimode graded index fiber, which has a bandwidth–length product of 400 MHz km. Estimate the total pulse broadening on the link. Ans. (10 ns)

**3.4.15** A step-index multimode glass fiber has a core diameter of 50 μm and cladding refractive index of 1.45. If it is to have a limiting intermodal dispersion and total broadening of a light pulse $\delta T$ of 10 ns, find its acceptance angle for a 1 km fiber length.

Ans: 5.35°



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**Dr. Abdulla K. Abass**

# CHAPTER 4

# FIBER OPTIC AMPLIFIERS

## 4.1 Introduction

Typically, there are two classifications for the optical amplifiers when we come to the gain medium, there are semiconductor and fiber optic amplifier, and when we come to the amplification mechanism there is the linear and nonlinear optical amplifier. This chapter, focuses on the fiber optic amplifier (FOA).

## 4.2 Amplifier Classes

The FOA can be classified into three classes as depicted in:

⇨Booster (power) amplifiers: Boost power into transmission fiber, low NF, high $P_{sat}$.

⇨In-line amplifiers: Periodically amplify signal due to fiber attenuation, high G, high $P_{sat}$.

⇨Receiver pre-amplifiers: Boost power into receiver, low NF, high G.

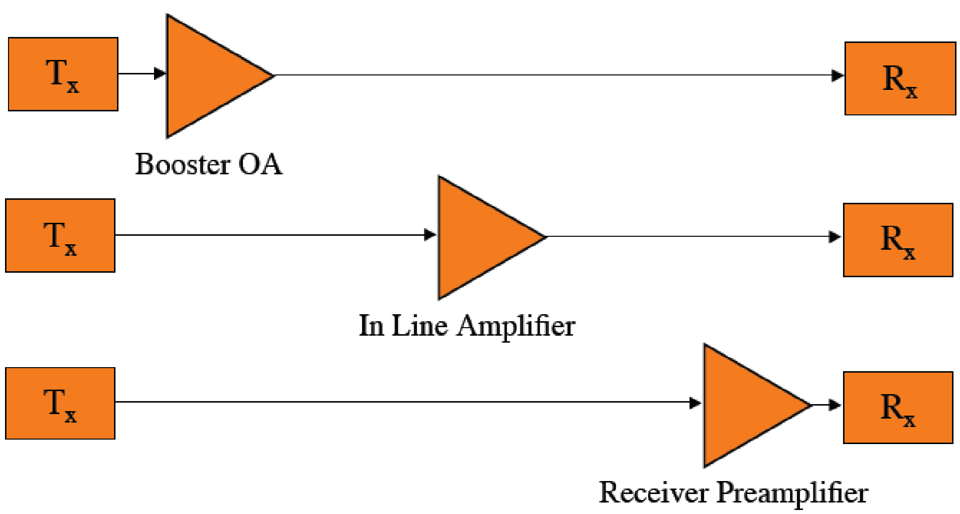


**Figure 4.1: Classes of the FOA.**



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### 4.3 Design Parameters

The FOA design parameters include:

1. Input signal power
2. Input Signal Wavelength
3. Pump Power Level
4. Pump Wavelength

### 4.4 Performance Parameters

The performance parameters for any system can be considered as measures of the efficiency of that system and used to determine the quality of the techniques involved. In this section, the main performance parameters of this type of amplifier are defined.

#### 4.4.1 Amplifier Gain

The amplifier gain or the signal gain can be considered as the one of the most important parameters of optical amplifier which is defined as [119]:

$$G = \frac{P_{out}}{P_{in}}$$

where: G is the amplifier gain, Pin and Pout are the input and output signal powers, respectively. However, several parameters related to amplifier gain are used to evaluate the gain performance, such as; average gain, gain variation, gain bandwidth illustrated in Figure 4.2 and gain saturation demonstrated Figure 4.3. These parameters are explained as follows:

##### 4.4.1.1 Average Gain

The amplifier gain can be expressed in term of average gain through specific bandwidth form ($\lambda_1$ to $\lambda_n$) in which the average gain equal the summation of gain values divided by the number of wavelengths entire the bandwidth as:

$$G_{av} = \frac{G(\lambda_1) + G(\lambda_2) + \ \dots . + G(\lambda_n)}{n}$$

Where: Gav is the average gain of the optical amplifier, $G(\lambda_1)$ is the amplifier gain at specific wavelengths $\lambda_1$ and n is the number of wavelengths entire the bandwidth.

#### 4.4.1.2 Gain Variation

In addition, another parameter based on the gain of optical amplifier is important to describe the gain flatness that is the gain variation which represented through specific gain bandwidth by:

$$G_{var} = G_{max} - G_{min}$$

where: $G_{var}$ is gain variation, $G_{max}$ and $G_{min}$ are the maximum and minimum gain, respectively.

#### 4.4.1.3 Gain Bandwidth

The gain bandwidth or amplification bandwidth is the width of the optical frequency range in which significant gain is available from an amplifier. In addition, the gain bandwidth can be defined as the full width at half–maximum (FWHM) of the logarithmic gain, measured in decibels [46].

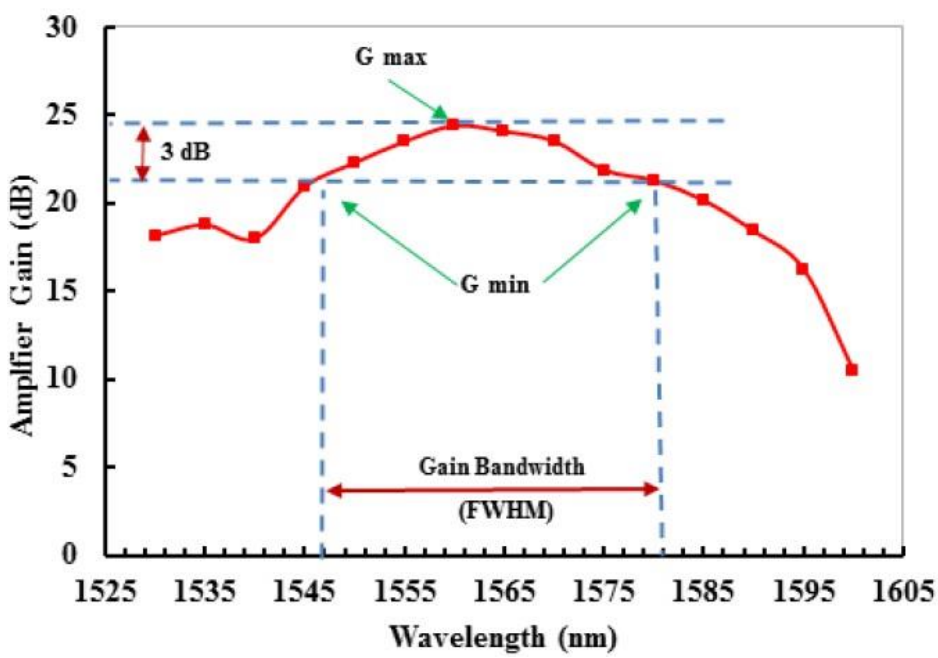


**Figure 4.2: Gain parameters used to evaluate the amplifier gain.**



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#### 4.4.1.4 Gain Saturation

The gain saturation occurs when the signal power increases, the amplifier saturates and cannot produce any more output power, therefore the gain reduces. Saturation is also commonly known as gain compression. The gain saturation is occurring in RFA due to the SBS effect, when the input signal exceeds the SBS threshold, a portion of the input signal is reflected in opposite directions with red shift about 0.08 nm in wavelength. While the gain reduces in EDFA due to the following;

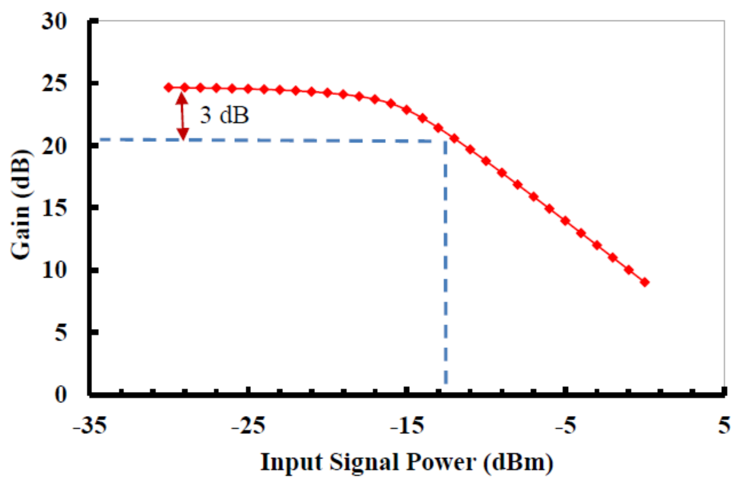


**Figure 4.3: Gain saturation.**

### 4.4.2 Power Conversion Efficiency

Power conversion efficiency (PCE) or sometimes known as pump conversion efficiency describes the relation between pump–to–signal power conversion efficiency. PCE is defined as:

$$PCE = \frac{P_s(L) - P_s(0)}{P_0} \times 100$$

Where: Ps(0), Ps(L) and P0 are the input, output signal power and input pump power, respectively.

### 4.4.3 Noise Figure

The optical noise figure is a parameter used for quantifying the noise penalty added to a signal due to the insertion of an optical amplifier. That is, before the light enters an amplifier the signal to noise ratio is $SNR_{in}$, after amplification it is $SNR_{out}$. Thus, the optical noise figure

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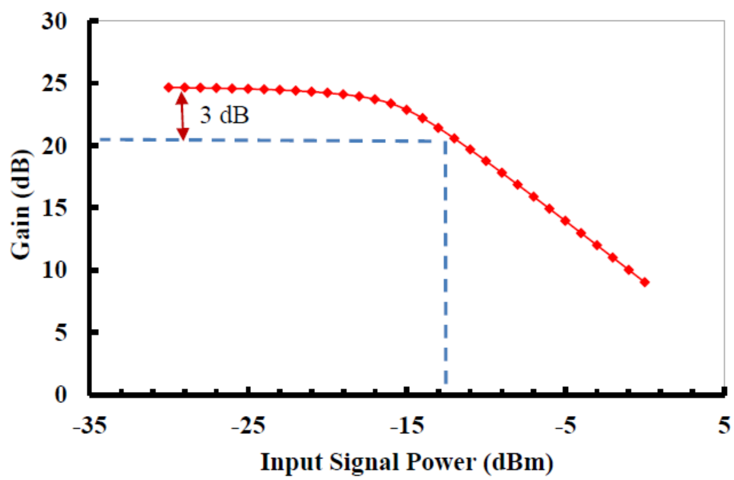


**Figure 4.3: Gain saturation.**

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can be defined as ratio between $SNR_{in}$ to $SNR_{out}$. In other words, the noise figure represents the degradation in signal to noise ratio for the optical amplifier.

## 4.5 Erbium Doped Fiber Amplifier

The EDFA consists of three basic components; erbium doped fiber, the pump laser source, and wavelength selective coupler combine the signal and pump wavelengths, as shown in Figure 4.4. The optimum fiber length used depends upon the pump‟s power, input signal power, amount of erbium doping, and pumping wavelength [49].

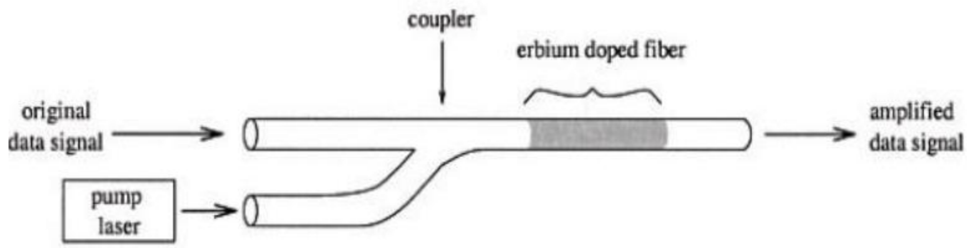


**Figure 4.4: Erbium Doped Fiber Amplifier [43].**

The EDFAs can be extensively used in optical fiber communication systems due to their compatibility with optical fiber. An EDFA has a comparatively wide wavelength range of amplification, rendering it useful as a transmission amplifier in WDM systems. Theoretically, EDFA is capable of amplifying all the wavelengths, ranging from 1500-1600 nm. However, practically, there are two communication windows; the C and L bands. This allows the data signal to stimulate the excited atoms to release photons.

Most EDFAs are pumped by lasers with a wavelength of either 980 nm or 1480 nm [43]. The 980 nm pump wavelength showed gains efficiencies of around 10 dB/mW, while the 1480 nm pump wavelength results in efficiencies of around 5 dB/mW. Typically, the gains are about 25 dB, while the noise figure lies between 4–5 dB with forward pumping, and equivalent figures for backward pumping are 6–7 dB, assuming 1480 nm pumping light was used.



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### 4.5.1 Amplification Mechanism

The basic theories on optical amplification based on EDFs are presented in this section. Incident light was amplified using amplifiers via stimulated emission, which is similar to the mechanism utilized by lasers for the same purpose. In EDFs, optical gain is supplied by excited erbium ions (Er3+) when the amplifier is pumped to prompt population inversion. Based on the energy state of the dopant, the pumping schemes can be classified as a 3–level or 4–level scheme, as shown in Figure 4.5.

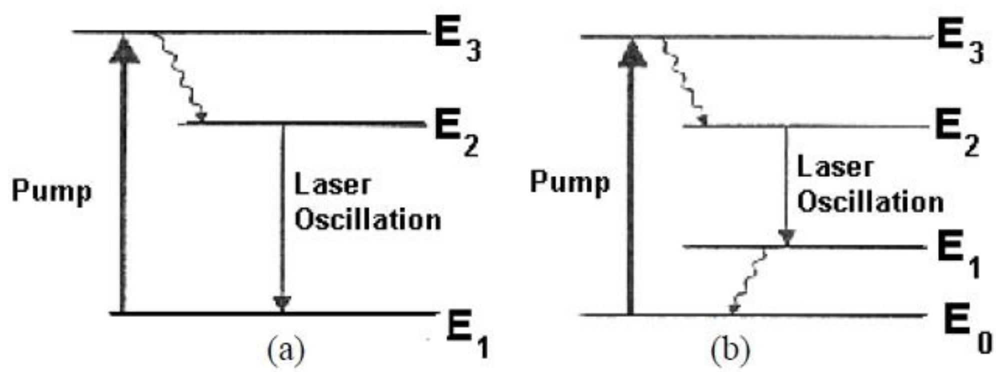


**Figure 4.5: Schematic illustration of (a) Three level pumping scheme (b) Four level pumping scheme [52].**

In the context of both cases, the dopants were excited to a higher energy state by absorbing the pump photons, followed by rapid relaxation to a lower excited state (state 2). This energy amplified a signal beam via stimulated emission; the energy is sent from the pump to the signal. 3–level and 4–level pumping schemes differ based on the energy state occupied by the dopant post-stimulated emission. For the three level scheme, the lower level is the ground state, while in the four level scheme, the ground state is the excited state that comes with a fast relaxation time. This difference makes stronger pumping for the 3–level scheme necessary to realize population inversion [53].

### 4.5.2 Gain Saturation

The gain is achieved in EDFA due to population inversion of the dopant ions. The inversion level of the EDFA is set, primarily, by the power of the pump wavelength and the power at the amplified wavelengths. As the signal power increases, the inversion level will reduce and thereby the gain of the amplifier will be reduced. This effect is known as gain saturation – as the signal level increases, the amplifier saturates and cannot produce any more output power, and therefore the gain reduces. Saturation is also commonly known as gain compression. To achieve optimum noise performance DFAs are operated under a significant amount of gain compression (10 dB typical), since that reduces the rate of spontaneous emission, thereby reducing ASE. Another advantage of operating the DFA in the gain saturation region is that small fluctuations in the input signal power are reduced in the output amplified signal: smaller input signal powers experience larger (less saturated) gain, while larger input powers see less gain. The leading edge of the pulse is amplified, until the saturation energy of the gain medium is reached. In some condition, the width (FWHM) of the pulse is reduced.

## 4.6 Raman Fiber Amplifier

The transformation of a small fraction power from the incident light to the scattered light is called the spontaneous Raman scattering. This phenomenon was discovered by C. V. Raman in 1928 [57]. Generally, the frequency of the scattered light differs from those of the incident light by an amount defined by the vibrational levels of the medium. The spontaneous Raman scattering is regarded as a weak process. For example, if the light is propagated through a medium with a volume of 1 cm3, only one part of the millions of the incident light will be scattered into the Stokes frequency.

However, if an intense laser source is incident on a molecular medium, there might be an occurrence of high scattering component, and more than 10% of the incident power is transferred to the scattering components [58]. This type of nonlinear scattering was discovered in 1962, called the stimulated Raman scattering (SRS) phenomenon [59].



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Biswanath Mukherjee described in [43] the fundamental advantages of a Raman amplifier. First, Raman gain exists in every fiber, which provides a cost–effective means of upgrading the terminal ends. Second, the gain is non-resonant, which is available over the entire transparent region of the fiber. The third advantage of Raman amplifiers is that the gain spectrum can be tailored by adjusting the pump‟s wavelengths. For instance, multiple pump lines can be used to increase the optical bandwidth, and the pump distribution determines the gain‟s flatness. Another advantage is that it is a relatively broadband amplifier, with a bandwidth of > 5 THz, and the gain is reasonably flat over a wide wavelength range.

### 4.6.1 Amplification Mechanism

The SRS process is governed by the following set of two coupled ordinary differential equations [14]:

$$\frac{dP_S}{dz} = g_R P_P P_S - \alpha_S P_S \qquad \textbf{(Equation 4.1)}$$

$$\frac{dP_P}{dz} = -g_R P_P P_S - \alpha_P P_P \qquad \textbf{(Equation 4.2)}$$

Where $g_R$ is the Raman gain coefficient of the fiber normalized with respect to the effective area of the fiber $A_{eff}$, $\alpha_S$ and $\alpha_P$ are the attenuation coefficient at the Stokes and pumps wavelength respectively, $P_S$ and $P_P$ are Stokes and pump intensity.

(**Equation 4.1**) and (**Equation 4.2**) show that the signal receives gain proportional to the pump power with a constant proportion given by the Raman gain efficiency and loss due to the attenuation of optical fiber, while the pump power receives loss due to the energy transfer to the Stokes and the attenuation of optical fiber.

In many practical situations, pump power is so large compared with the signal power that pump depletion can be neglected for the purpose of estimating the Raman gain. The (**Equation 4.2**) is easily solved if the first term on its right side is neglected and the result is:

$$P_P(z) = P_P(0)e^{-\alpha z}$$ (**Equation 4.3**)

Where $P_P(0)$ is the input pump power at z = 0. (**Equation 4.3**) is substituted into (**Equation 4.1**) and the result is [15]:

$$\frac{dP_S}{dz} = g_R P_P(0)\exp(-\alpha_P z)P_S - \alpha_S P_S$$ (**Equation 4.4**)

(**Equation 4.4**) is easily solved by integrating it over the fiber length L, and the Stokes intensity will be as:

$$P_S(L) = P_S(0)\exp(\frac{g_R}{A_{eff}} P_o L_{eff} - \alpha_S L)$$ (Equation 4.5)

The effective fiber length is reduced from $L$ -to- $L_{eff}$, due to fiber losses, and it is given by:

$$L_{eff} = [1 - \exp(-\alpha L)]/\alpha$$ (Equation 4.6)

The unsaturated gain is defined as the ratio of the output signal to the input signal:

$$G(L) = \frac{P_S(L)}{P_S(0)} = \exp(\frac{g_R}{A_{eff}} P_o L_{eff} - \alpha_S L)$$ (Equation 4.7)

The quantity G (L) represents the net signal gain and can be even<1 (net loss) if the Raman gain is not sufficient to overcome fiber losses. It is useful to introduce the concept of the on–off Raman gain using the definition:

$$G_A = \frac{P_s\ (L)\ \text{with pump on}}{P_s\ (L)\ \text{with pump off}} = \exp\left(g_R P_0 L_{\text{eff}}\right)$$ (Equation 4.8)

## 4.7 Examples

Example:1 Amplifier gain = 37 dB

Power in = 0.003 mW

What is the power out ?

$P_{dBm}$ = -25.2 dBm

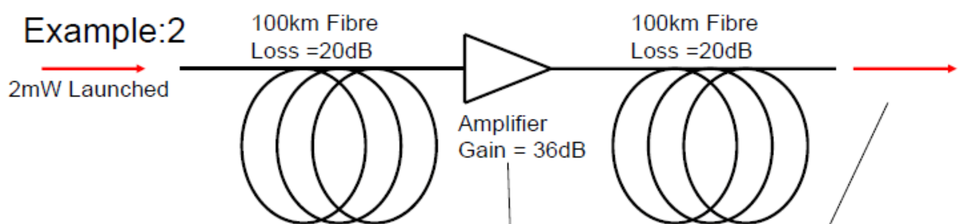
$P_{out} = P_{in} + G_{amp}$

$= -25.2 + 37$

$= 11.8$ dBm

$= 15$ mW

Example:2

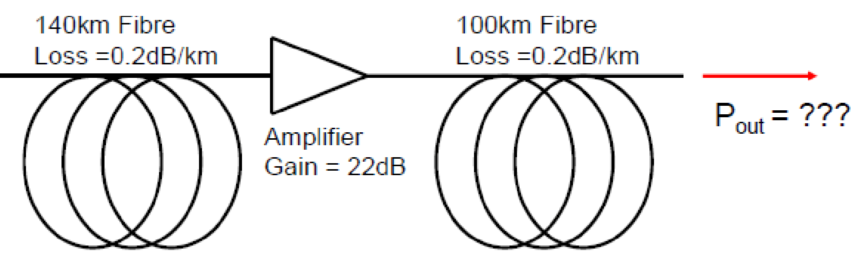



What is $P_{out}$ ?

$P_{in}$= 2mW = 3dBm

$P_{out}$ = 3 – 20 + 36 –20 dBm = -1 dBm = 0.1mW

Example:3




Coupled power = 7dBm

First fibre loss = 140 x –0.2 = -28dB (-21dBm)

Amplifier Gain = +22dB (1dBm)

Second fibre loss = 100 x –0.2 = -20dB (-19dBm)

Output power = -19dBm = 0.012mW



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## 4.8 PROBLEMS

**Q1:** Why the Need for Optical Amplification?

***Answer:***

Semiconductor devices can convert an optical signal into an electrical signal, amplify it and convert the signal back to an optical signal. However, this procedure has several disadvantages:

1. Costly
2. A large number is required over long distances
3. Noise is introduced after each conversion in analog signals
4. Restriction on bandwidth, wavelengths and type of optical signals being used, due to the electronics

By amplifying signal in the optical domain many of these disadvantages would disappear.

**Q2:**

A Raman amplifier is pumped in the backward direction using 1 W of power. Find the output power when a 1 μW signal is injected into the 5 km-long amplifier. Assume losses of 0.2 and 0.25 dB/km at the signal and pump wavelengths, respectively, Aeff = 50 $\mu m^2$, and $g_R = 6\times10^{-14}$ m/W. Neglect gain saturation.

**Answer:2.7** μW

Q3- using the coupled equations to prove that the Raman on-off gain is:

$$G_A = \frac{P_s(L) \text{ with pump on}}{P_s(L) \text{ with pump off}} = \exp(g_R P_0 L_{\text{eff}})$$

# CHAPTER 5

# OPTICAL SOURCES AND FIBER OPTIC TRANSMITTERS

## 5.1 Introduction

A fiber optic transmitter is a hybrid electro-optic device converts electrical signals into optical signals and launches the optical signals into an optical fiber. A fiber optic transmitter consists of an **interface circuit**, a **source drive circuit**, and an **optical source**. The **interface circuit** accepts the incoming electrical signal and processes it to make it compatible with the source drive circuit. The **source drive circuit** intensity modulates the optical source by varying the current through the source. An **optical source converts** electrical energy (current) into optical energy (light). Light emitted by an optical source is launched, or coupled, into an optical fiber for transmission. Fiber optic data link performance depends on the amount of optical power (light) launched into the optical fiber.

Most light sources and detectors are electronic devices built from the same semiconductor materials as are used in transistors and integrated circuits. The design of these devices is a separate study and will not be considered here. Instead, our view will be restricted to the characteristics which are of interest to the user. This chapter attempts to provide an understanding of light-generating mechanisms within the main types of optical sources used in fiber optics.

Figure 5.1 shows the block diagram of an optical transmitter. It consists of an optical source, a modulator, and electronic circuits used to power and operate the two devices. Semiconductor lasers or light-emitting diodes are used as optical sources because of their compact nature and compatibility with optical fibers [15].

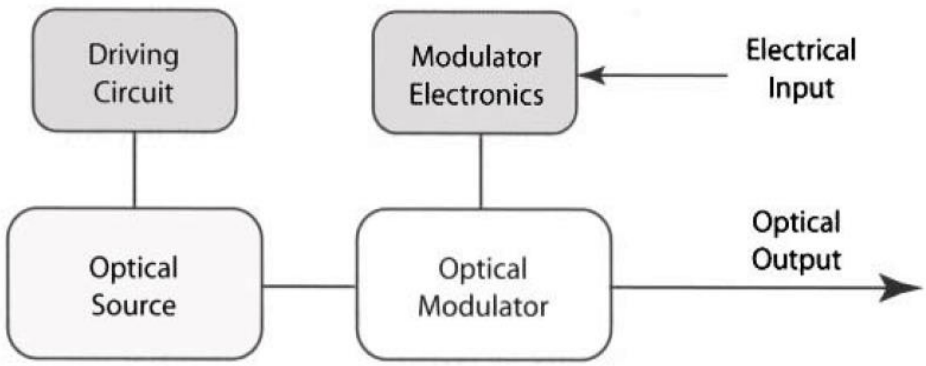


Figure 5.1: Block diagram of an optical transmitter [15].

The modulator uses the data in the form of an electrical signal to modulate the optical carrier. Although an external modulator is often needed at high bit rates, it can be dispensed with at low bit rates using a technique known as **direct modulation**. In this technique, the electrical signal representing information is applied directly to the driving circuit of the semiconductor optical source, resulting in the modulated source output. Such a scheme simplifies the transmitter design and is generally more cost-effective.

An important design parameter is the **average optical power** launched into the communication channel. Clearly, it should be as large as possible to enhance the signal-to-noise ratio (**SNR**) at the receiver end. However, the onset of various nonlinear effects limits how much power can be launched at the transmitter end. The launched power is often expressed in "**dBm**" units with 1 mW acting as the reference level.

$$P(\mathrm{dBm}) = 10\log_{10}\left(\frac{P}{1\ \mathrm{mW}}\right)$$

Thus, 1 mW is 0 dBm, but 1 μW corresponds to -30 dBm. The launched power is rather low (less than -10 dBm) for light-emitting diodes, but semiconductor lasers can launch power levels exceeding 5 dBm. Although light-emitting diodes are useful for some low-end applications related to local-area networking and computer-data transfer, most lightwave systems employ semiconductor lasers as optical sources. The bit rate of optical transmitters is often limited by electronically rather than by the semiconductor laser itself. With proper design, optical transmitters can be made to operate at a bit rate of up to 40 Gb/s.

## 5.2 General Characteristics of Optical Sources

The development of efficient semiconductor optical sources, along with low-loss optical fibers, led to substantial improvements in fiber optic communications. Semiconductor optical sources have the physical characteristics and performance properties necessary for successful implementations of fiber optic systems. Two main types of optical light sources are available, these are:

a. Monochromatic incoherent sources light-emitting diodes (LEDs).
b. Monochromatic coherent sources laser diodes (LDs).

The fundamental requirements for Light Sources (**LED**, **LD**) in fiber optic applications are outlined below:

1. A size and configuration compatible with launching light into an optical fiber. Ideally, the light output should be highly directional.
2. Must accurately track the electrical input signal to minimize distortion and noise. Ideally, the source should be linear.
3. Should emit light at wavelengths where the fiber has low losses, low dispersion and where the detectors are efficient.
4. Must couple sufficient optical power to overcome attenuation in the fiber plus additional connector losses and leave adequate power to drive the detector.
5. Should have a very narrow spectral bandwidth (linewidth) in order to minimize dispersion in the fiber.
6. Must be capable of maintaining a stable optical output which is largely unaffected by changes in ambient conditions (e.g. temperature).

### 5.2.1 Materials

Semiconductor-based light sources are about the size of a grain of salt. This size allows efficient coupling of their light output into the small diameters of fibers. In addition, their **semiconductor structure** and **low-power dissipation** characteristics make them compatible with integrated-circuit electronics. To create a light-emitting device for use in the spectral transmission bands of optical fibers, material engineers fabricate layered structures consisting of different alloy mixtures.

**Table 5-1** lists some **LED** and laser diode material mixtures together with their operating wavelength range and approximate bandgap energies. Alloys consisting of three elements are called ternary compounds, and four-element alloys are known as quaternary compounds. A specific operating wavelength can be selected for AlGaAs, InGaAs, and InGaAsP devices by varying the proportions of the constituent atoms. This devices can be tailored to emit at a selected wavelength in the 780 nm to 850 nm band or in any of the other transmission bands ranging from 1280 to 1675 nm for glass fibers.

Table 5-1: Some LED and LD Material Mixtures and their Characteristics [14].

| Material | Wavelength range nm | Bandgab energies eV |
|---|---|---|
| GaAs | 900 | 1.4 |
| GaAlAs | 800–900 | 1.4–1.55 |
| InGaAs | 1000–1300 | 0.95–1.24 |
| InGaAsP | 900–1700 | 0.73–1.35 |

$h = 4.135 \times 10^{-15}$ $c$

$h = 6.626 \times 10^{-3}$ $s$

.

$s$

### 5.2.2 Light Generating Mechanism

The electrons in semiconductor materials are allowed to reside in only two specific energy bands, as shown in **Figure 5.2**. The two allowed bands are separated by a forbidden region, called an energy gap, in which electrons cannot reside. The energy difference between the top and bottom bands is referred to as the bandgap energy. In the upper band, called the conduction band, electrons are not bound to individual atoms and are free to move around in the material. The lower band is called the valence band. Here holes (which are vacancies in an atom that are not occupied by an electron) are free to move. The mobile electrons and holes set up a current flow when an external electric field is applied.

An electron sitting in the conduction band can drop down into a hole in the valence band, thereby returning an atom to its neutral state. This process is called recombination (**or electron-hole pair recombination**), since an electron recombines with a hole. This recombination process releases energy in the form of a photon and is the basis by which a source emits light.

The energy E emitted during such a recombination is related to a specific wavelength of light $\lambda$ through the relationship $E = 1.240/\lambda$, where $\lambda$ is given in micrometers and E is specified in electron volts. Since each type of material has a unique bandgap energy, electron-hole recombination in different materials results in different wavelengths being emitted.

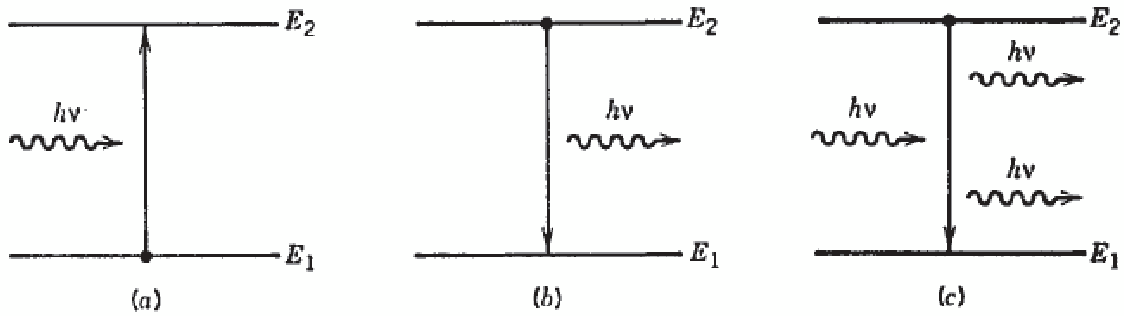


Figure 5.2: Three fundamental processes occurring between the two energy states of an atom: (a) absorption; (b) spontaneous emission; and (c) stimulated emission.

### 5.2.3 Spontaneous and Stimulated Emissions

If an atom is in the excited state, it eventually returns to its normal "ground" state and emits light in the process. The light emission can occur through two fundamental processes known as spontaneous emission and stimulated emission. Both are shown schematically in **Figure 5.2**. In the case of spontaneous emission, photons are emitted in random directions with no phase relationship among them. Stimulated emission, by contrast, is initiated by an existing photon.

The remarkable feature of stimulated emission is that the emitted photon matches the original photon not only in energy (**or in frequency**), but also in its other characteristics, such as the direction of propagation. All lasers, including semiconductor lasers, emit light through the process of stimulated emission and are said to emit coherent light. In contrast, **LEDs** emit light through the incoherent process of spontaneous emission.



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### 5.2.4 Direct and Indirect Bandgap Semiconductors

In order to encourage electroluminescence it is necessary to select an appropriate semiconductor material. The most useful materials for this purpose are direct bandgap semiconductors in which electrons and holes on either side of the forbidden energy gap have the same value of crystal momentum and thus direct recombination is possible. This process is illustrated in Figure 5.3 (a) with an energy–momentum diagram of a direct bandgap semiconductor. It may be observed that the maximum energy of the valence band occurs at the same (**or very nearly the same**) value of electron crystal momentum as the energy minimum of the conduction band. Hence, when electron–hole recombination occurs the momentum of the electron remains virtually constant and the energy released, which corresponds to the bandgap energy, $E_g$, may be emitted as light. This direct transition of an electron across the energy gap provides an efficient mechanism for photon emission and the average time that the minority carrier remains in a free state before recombination (**the minority carrier lifetime**) is short (**$10^{-8}$ to $10^{-10}$ s**). Some commonly used direct bandgap semiconductor materials are shown in **Table 5-2**.

In indirect bandgap semiconductors, however, the maximum and minimum energies occur at different values of crystal momentum Figure 5.3 (b). For electron–hole recombination to take place it is essential that the electron loses momentum such that it has a value of momentum corresponding to the maximum energy of the valence band. The conservation of momentum requires the emission or absorption of a third particle, a phonon.

Table 5-2 Some direct and indirect bandgap semiconductors with calculated recombination coefficients

| *Semiconductor material* | *Energy bandgap (eV)* | *Recombination coefficient $B_r$ ($cm^3\ s^{-1}$)* |
|---|---|---|
| GaAs | Direct: 1.43 | $7.21 \times 10^{-10}$ |
| CaSb | Direct: 0.73 | $2.39 \times 10^{-10}$ |
| InAs | Direct: 0.35 | $8.5 \times 10^{-11}$ |
| InSb | Direct: 0.18 | $4.58 \times 10^{-11}$ |
| Si | Indirect: 1.12 | $1.79 \times 10^{-15}$ |
| Ge | Indirect: 0.67 | $5.25 \times 10^{-14}$ |
| GaP | Indirect: 2.26 | $5.37 \times 10^{-14}$ |

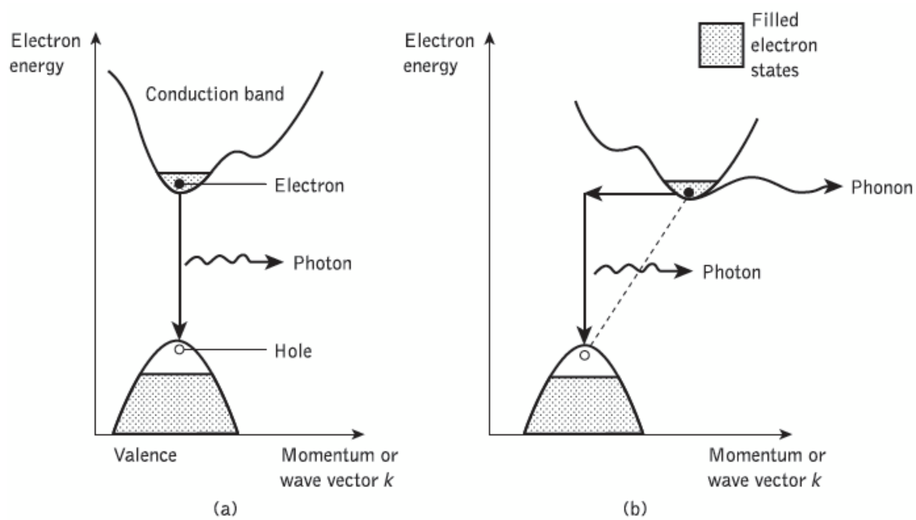


Figure 5.3: Energy–momentum diagrams showing the types of transition:
(a) Direct bandgap semiconductor; (b) indirect bandgap semiconductor

## 5.3 Light Emitting Diodes LEDs

A light-emitting diode (LED) **is a semiconductor device that emits incoherent light, through spontaneous emission, when a current is passed through it**. Typically LEDs for the **850 nm** region are fabricated using **GaAs** and **AlGaAs**. LEDs for the **1300 nm** and **1550 nm** regions are fabricated using an **InGaAsP** and **InP**. The basic LED types used in fiber optic communication systems are:

1. Surface-emitting LED (**SLED**).
2. Edge-emitting LED (**ELED**).

LED performance differences help link designers decide which device is appropriate for the intended application. For short-distance < **3 km**, **low-data-rate** fiber optic systems, **SLED**s and **ELED**s are the preferred optical source. Typically, **SLED**s operate efficiently for bit rates up to **250 Mb/s**. **Because SLEDs emit light over a wide area (wide far-field angle), they are almost exclusively used in multimode systems.** For medium-distance, medium-data-rate systems, ELEDs are preferred. ELEDs may be modulated at rates up to **400 Mb/s** and can be used for both single mode and multimode fiber systems.

### 5.3.1 Surface-Emitting LEDs

In **SLEDs** shown in Figure 5.4, the size of the primary active region is limited to a small circular area of **20 μm** to **50 μm** in diameter. The active region is the portion of the **LED** where photons are emitted. The primary active region is below the surface of the semiconductor substrate perpendicular to the axis of the fiber. A well is etched into the substrate **to make direct coupling between the emitted light and the optical fiber by allowing the optical fiber to come into close contact with the emitting surface.** In addition, the **epoxy resin** that binds the optical fiber to the **SLED reduces** the **refractive index mismatch and increasing coupling efficiency**.

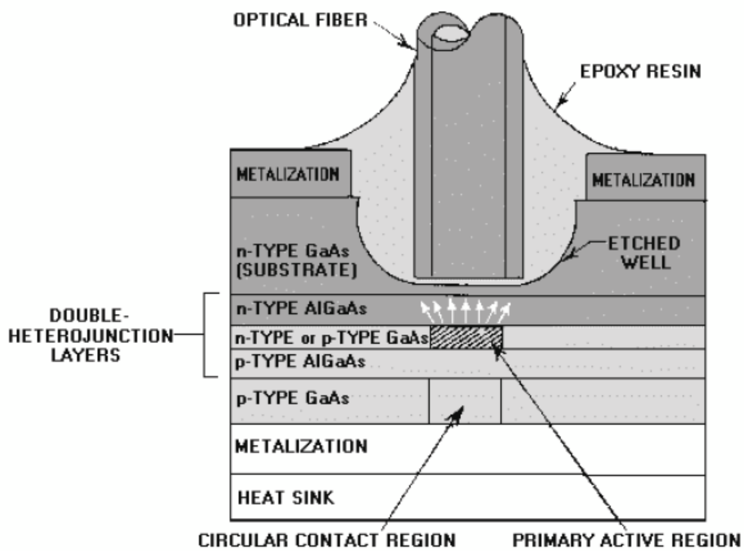


**Figure 5.4:** Schematic of **SLED** structure

### 5.3.2 Edge-Emitting LEDs

The demand for optical sources for **longer distance**, **higher bandwidth** systems operating at **longer wavelengths** led to the development of edge-emitting **LEDs**. Figure 5.5 shows a typical **ELED** structure. It shows the different layers of semiconductor material used in the **ELED**. The primary active region of the **ELED** is a **narrow stripe**, which lies below the surface of the semiconductor substrate. The semiconductor substrate is cut or polished so that the stripe runs between the front and the back of the device. The polished or cut surfaces at each end of the stripe are called facets.

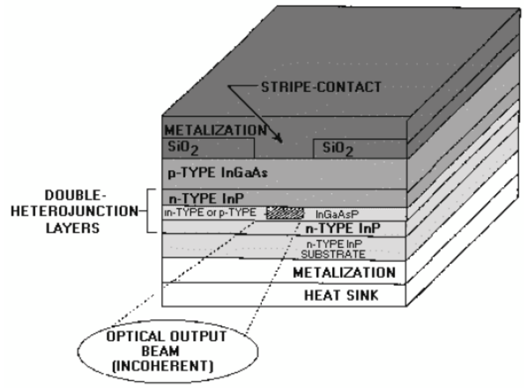


**Figure 5.5** Schematic of **ELED** structure.

In an **ELED** the rear facet is highly reflective and the front facet is antireflection-coated. The rear facet reflects the light propagating toward the rear end-face back toward the front facet. By coating the front facet with antireflection material, the front facet reduces optical feedback and allows light emission. **ELEDs** emit light only through the front facet and emits the light in a narrow emission angle, **allowing for better source-to-fiber coupling**. They couple more power into smaller **NA** fibers than **SLEDs**. **ELEDs** can couple enough power into single mode fibers for some applications and emit power over a narrower spectral range than **SLEDs**. **However, ELEDs typically are more sensitive to temperature fluctuations than SLEDs**.

## 5.4 Laser Diodes

A laser is a device that produces optical radiation by the process of stimulated emission. It is necessary to contain photons produced by stimulated emission within the laser active region. **Figure 5.6** shows an optical cavity formed to contain the emitted photons by placing one reflecting mirror at each end of an amplifying medium. One mirror is made partially reflecting so that some radiation can escape from the cavity for coupling to an optical fiber.

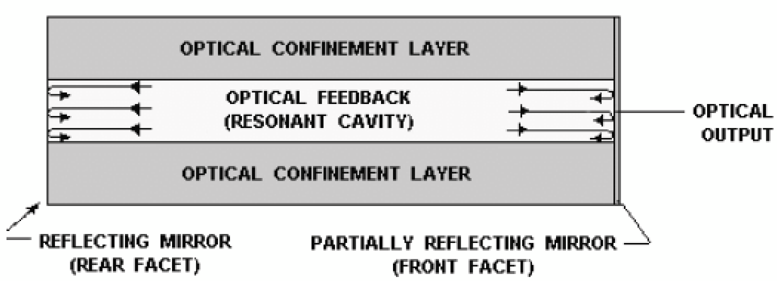


Figure 5.6: Optical cavity for producing lasing.



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Only a portion of the optical radiation is amplified. For a particular laser structure, there are only certain wavelengths that will be amplified by that laser. Amplification occurs when selected wavelengths, also called laser modes, reflect back and forth through the cavity. For lasing to occur, the optical gain of the selected modes must exceed the optical loss during one round-trip through the cavity. This process is referred to as optical feedback. **The lasing threshold is the lowest drive current level at which the output of the laser results primarily from stimulated emission rather than spontaneous emission.**

Figure 5.7 illustrates the transition from spontaneous emission to stimulated emission by plotting the relative optical output power and input drive current of a semiconductor laser diode. The lowest current at which stimulated emission exceeds spontaneous emission is the threshold current. Before the threshold current is reached, the optical output power increases only slightly with small increases in drive current. However, after the threshold current is reached, the optical output power increases significantly with small changes in drive currents.

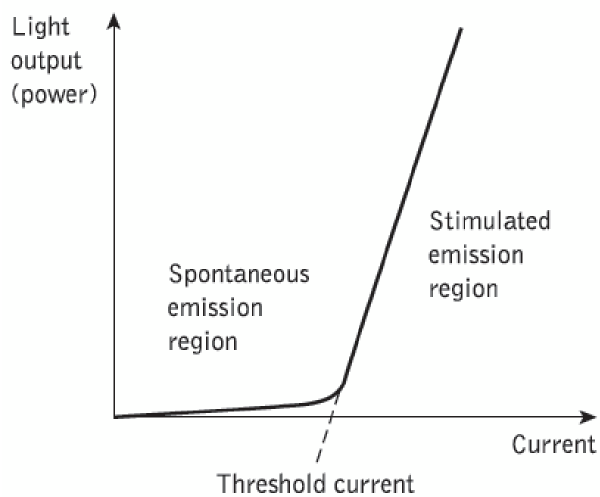


**Figure 5.7:** The optical output power as a function of input drive current of a semiconductor laser diode.

### 5.4.1 Distributed feedback lasers

Distributed feedback (DFB) lasers were developed during the 1980s and are used for WDM lightwave systems. **DFB is laser diode has a grating structure in the cavity that produces multiple reflections throughout the cavity**.

**This leads to narrower linewidth than are produced by Fabry-Perot lasers.** The structure which is employed is the distributed **Bragg diffraction grating** which provides periodic variation in refractive index in the laser heterostructure along the direction of wave propagation so that feedback of optical energy is obtained through Bragg reflection rather than by the usual cleaved mirrors. Hence the corrugated grating structure shown in Figure 5.8 (a) determines the wavelength of the longitudinal mode emission instead of the Fabry–Pérot gain curve shown in Figure 5.8 (b). When the **period of the corrugation (grating space)** is equal to $\mathbf{l\lambda_B/2n_e}$ where **l** is the integer order of the grating, $\boldsymbol{\lambda_B}$ is the Bragg wavelength and $\mathbf{n_e}$ is the effective refractive index of the waveguide, **then only the mode near the Bragg wavelength $\boldsymbol{\lambda_B}$ is reflected constructively** (i.e. Bragg reflection). Therefore, as may be observed in Figure 5.8 (a), this particular mode, will lase while the other modes exhibiting higher losses are suppressed from oscillation.

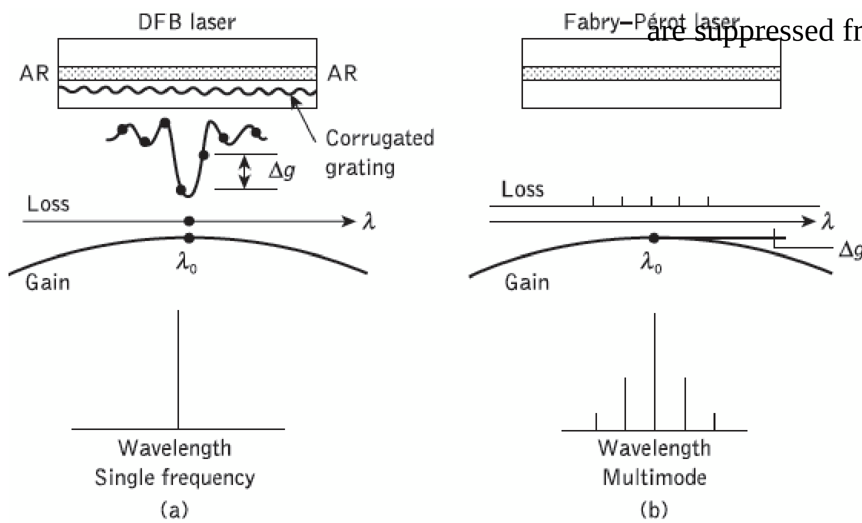


Figure 5.8: Illustrated the single-frequency operation of (a) the distributed feedback (DFB) laser (b) the Fabry–Pérot laser.

### 5.4.2 Vertical cavity surface-emitting laser

The vertical cavity surface-emitting laser (VCSEL, pronounced 'vixel') **emits a coherent optical signal perpendicular to the device substrate**. In comparison with edge-emitting lasers, the VCSEL structure is somewhat different, since a short vertical cavity is formed by the surfaces of epitaxial layers and the optical output is taken from one of the mirror surfaces.



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**Figure 5.9** illustrates the structure of a typical VCSEL where a Fabry–Pérot cavity consisting of multiquantum well (MQW) material is sandwiched between two mirrors each formed by the multilayered distributed Bragg reflector DBR mirror. The top surface DBR mirror comprising p-type material has a low facet reflectivity as compared with the n-type DBR mirror at the bottom of the device. **The number of Bragg gratings determines the amount of facet reflectivity and it generally requires between 10 and 30 Bragg grating periods to develop satisfactory facet reflectivity for the top or bottom DBR mirrors where the particular grating number depends upon the specific semiconductor material composition.**

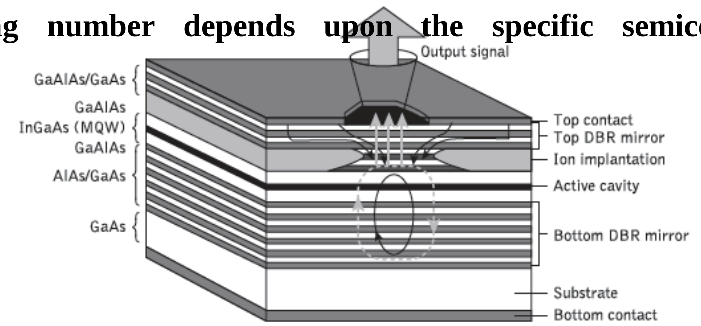


Figure 5.9: Structure of a vertical cavity surface-emitting laser.

## 5.5 Glass fiber lasers

The basic structure of a glass fiber laser is shown in **Figure 5.10**. An optical fiber, the core of which is doped with rare earth ions, is positioned between two mirrors adjacent to its end faces which form the laser cavity. Light from a pumping laser source is launched through one mirror into the fiber core which is a waveguiding resonant structure forming a Fabry–Pérot cavity. The optical output from the device is coupled through the mirror on the other fiber end face. Thus the fiber laser is effectively an optical wavelength converter in which the photons at the pumping wavelength are absorbed to produce the required population inversion and stimulated emission; this provides a lasing output at a wavelength which is characterized by the dopant in the fiber.

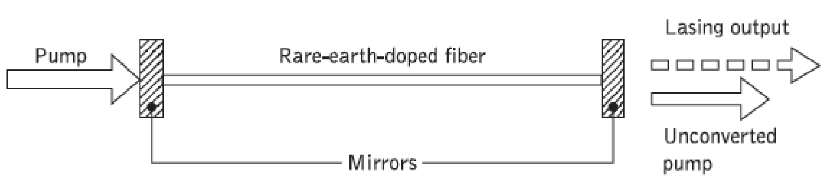


Figure 5.10: Schematic diagram showing the structure of a fiber laser



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In summary, there are two semiconductor sources are used in optical communication, namely, LED and LD. Each source has its own advantages and disadvantages as listed in Table 5-3.

**Table 5-3: The advantages and disadvantages of LED and LD**

| Characteristic | LED | Laser |
|---|---|---|
| Output power | Lower | Higher |
| Spectral width | Wider | Narrower |
| Numerical aperture | Larger | Smaller |
| Speed | Slower | Faster |
| Cost | Less | More |
| Ease of operation | Easier | More difficult |

## 5.6 Source Fiber Coupling

The design objective for any transmitter is to couple as much light as possible into the optical fiber. In practice, the coupling efficiency depends on the type of optical source (LED versus laser) as well as on the type of fiber (multimode versus single mode). The coupling can be very inefficient when light from an LED is coupled into a single-mode fiber. The coupling efficiency for an LED change with the numerical aperture, and can become < 1% in the case of SMF. In contrast, the coupling efficiency for an edge emitting laser is typically 40-50% and can exceed 80% for VCSELs because of their circular spot size. A small piece of fiber (known as a pigtail) is included with the transmitter so that the coupling efficiency can be maximized during packaging; a splice or connector is used to join the pigtail with the fiber cable.

Optical power produced by optical sources can range from microwatts (μW) for LEDs to tens of milliwatts (mW) for semiconductor LDs. However, it is not possible to effectively couple all the available optical power into the optical fiber for transmission. The amount of optical power coupled into the fiber depends on the following factors:

1. The angles over which the light is emitted.
2. The size of the source's light-emitting area relative to the fiber core size.
3. The alignment of the source and fiber.
4. The coupling characteristics of the fiber (such as the NA and the refractive index profile).



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Two approaches have been used for source-fiber coupling. In one approach, known as **direct or butt** coupling, the fiber is **brought close to the source and held in place with epoxy**. In the other, known as **lens coupling**, a lens is used to maximize the coupling efficiency. Each approach has its own merits, and the choice generally depends on the design objectives.

### 5.6.1 Butt Coupling

The coupled power $(P_c)$ into a multimode step index fiber may be estimated from the relationship:

$$P_c = \pi(1 - r) A R_D (NA)^2$$

Where $r$ is the Fresnel reflection coefficient of the fiber surface, $A$ **is the smaller** of the fiber core cross-section **or** the emission area of the source and $R_D$ is the radiance of the source W $sr^{-1}$ $cm^{-2}$ (watt per steradian per square centimeter).

**Example 5.1:**

A surface emitting LED which has an emission area diameter of 50 μm is butt jointed to an 80 μm core step index fiber with a numerical aperture of 0.15. The device has a radiance of 30 W $sr^{-1}$ $cm^{-2}$ at a constant operating drive current. Estimate the optical coupled power into the fiber if it is assumed that the Fresnel reflection coefficient at the index matched fiber surface is 0.01.

**Solution:** The optical power coupled into the fiber $Pc$ is given by:

$$P_c = \pi(1 - r) A R_D (NA)^2$$

In this case $A$ represents the emission area of the source.

Hence:

$$A = \pi(25 \times 10^{-4})^2 = 1.96 \times 10^{-5}\ cm^2$$

Thus:

$$Pc = \pi(1 - 0.01)1.96 \times 10^{-5} \times 30 \times (0.15)^2$$

$$= 41.1\ \mu W$$



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### 5.6.2 Lens Coupling to Fiber

It is apparent that much of the light emitted from **LEDs** is not coupled into the generally narrow acceptance angle of the fiber. Even with the etched well surface emitter, where the low-**NA** fiber is butted directly into the emitting aperture of the device, coupling efficiencies are poor (***of the order of 1 to 2%***). However, it has been found that greater coupling efficiency may be obtained if lenses are used to collimate the emission from the LED, particularly when the fiber core diameter is significantly larger than the width of the emission region. There are several lens coupling configurations which include **spherically polished structures**, **spherical-ended or tapered fiber coupling**, **truncated spherical microlenses**, graded index (**GRIN) rod lenses** and **integral lens structures**.

A GaAs/AlGaAs spherical-ended fiber-coupled **LED** is illustrated in Figure 5.11. It consists of a planar surface-emitting structure with the spherical-ended fiber attached to the cap by epoxy resin. An emitting diameter of **35** μm was fabricated into the device and the light was coupled into fibers with core diameters of **75** and 110 μm. The geometry of the situation is such that it is essential that the active diameter of the device be substantially less (factor of 2) than the fiber core diameter if increased coupling efficiency is to be obtained. In this case good performance was obtained with coupling efficiencies around 6%.

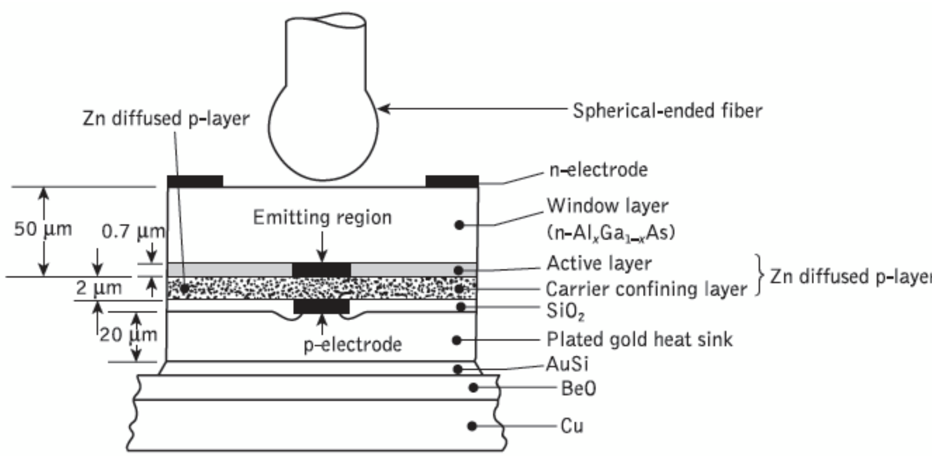


Figure 5.11: Schematic illustration of the structure of a spherical-ended fiber-coupled AlGaAs LED.

Another common lens coupling technique employs a truncated spherical microlens. This configuration is shown in Figure 5.12 for an etched well **InGaAsP/InP** surface emitter operating at a wavelength of 1.3 μm. Again, a requirement for efficient coupling is that the emission region diameter is much smaller than the core diameter of the fiber. In this case the best results were obtained with a 14 μm active diameter and an 85 μm core diameter for a step index fiber with a numerical aperture of 0.16.

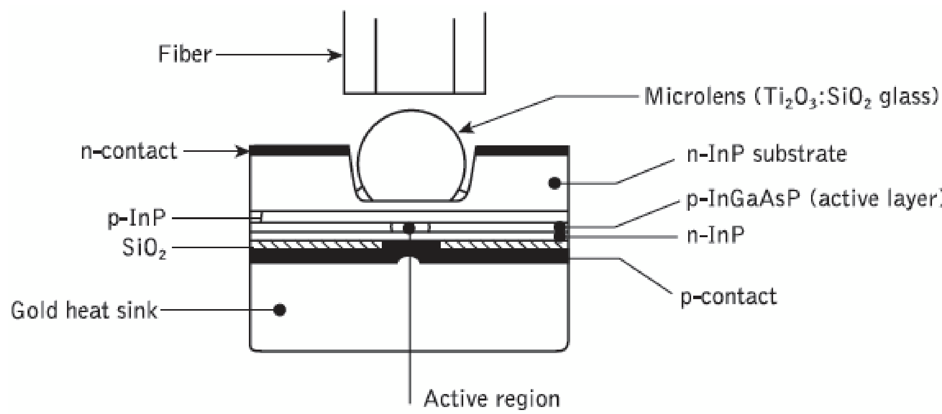


Figure 5.12: The use of a truncated spherical microlens for coupling the emission from an InGaAsP surface-emitting LED to the fiber

An example of the former technique is illustrated in Figure 5.13 (a) in which a hemispherical lens is epoxied onto the fiber end and positioned adjacent to the ELED emission region. The coupling efficiency has been increased by a factor of three to four times using this strategy. Alternatively, a truncated spherical lens glued onto the emitting facet of a superradiant ELED has given a coupling gain of a factor of five or 7 dB.

Tapered fiber lenses have been extensively used to couple power from ELEDs into SMF. Butt coupling of optical power from LEDs into SMF is substantially reduced in comparison with that obtained into multimode fiber. It ranges from between 0.5 and 2 μW for a standard SLED up to around 10 to 12 μW for an ELED. The small core diameter of single-mode fiber does not allow significant lens coupling gain to be achieved with SLEDs. For edge emitters, however, a coupling gain of around 5 dB may be realized using tapered fiber. An alternative strategy to improve the coupling efficiency from an ELED into SMF is depicted in Figure 5.13(b).

In this case a tapered graded index (GRIN) rod lens was positioned between the high-power ELED and the fiber. A coupling efficiency defined as the ratio of the coupled power to the total emitted power of around 15% was obtained. The coupling efficiency can also be improved when microlenses with micrometer dimensions integrate with the specific optical components (i.e. the LED or optical fiber). Using such microlenses the coupling of a SLED to fiber provided increased output power by a factor of 1.6. Moreover, in comparison with a typical flat-end or arc-lensed fiber, the microlensed fiber gave an improvement in coupling efficiency of 40% and 18%, respectively.

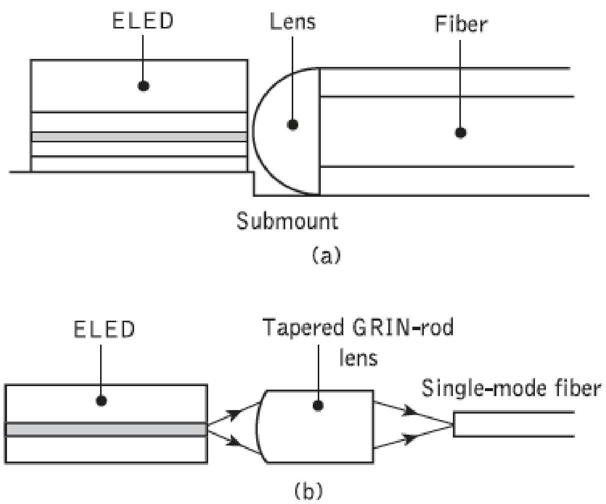


Figure 5.13: Lens coupling with edge-emitting LEDs: (a) lens-ended fiber coupling; (b) tapered (plano-convex) GRIN-rod lens coupling to single-mode fiber

However, the overall power conversion efficiency $\eta_{oc}$ which is defined **as the ratio of the optical power coupled into the fiber $P_c$ to the electric power applied at the terminals of the device P** and is therefore given by:

$$\eta_{oc} = \frac{P_c}{P} \quad \textbf{(Equation 5.1)}$$

**Example 5.2**

A lens-coupled surface-emitting LED launches 190 μW of optical power into a multimode step index fiber when a forward current of 25 mA is flowing through the device. Determine the overall power conversion efficiency when the corresponding forward voltage across the diode is 1.5 V.



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***Solution:*** The overall power conversion efficiency may be obtained from (Equation 5.1) where:

$$\eta_{oc} = \frac{P_c}{P} = \frac{190 \times 10^{-6}}{25 \times 10^{-3} \times 1.5} = 5.1 \times 10^{-3}$$

Hence the overall power conversion efficiency is 0.5%.

## 5.7 Modulation Bandwidth

The modulation bandwidth in optical communications may be defined in either **electrical or optical terms**. However, it is often more useful when considering the associated electrical circuitry in an optical fiber communication system to use the electrical definition **where the electrical signal power has dropped to half its constant value due to the modulated portion of the optical signal**. This **corresponds to the electrical 3 dB point or the frequency at which the output electrical power is reduced by 3 dB with respect to the input electric power**. As optical sources operate down to d.c. level, we only consider the high-frequency 3 dB point, the **modulation bandwidth being the frequency range between zero and this high-frequency 3 dB point.**
Alternatively, if the 3 dB bandwidth of the modulated optical carrier (optical bandwidth) is considered, we obtain an increased value for the modulation bandwidth. The reason for this inflated modulation bandwidth is illustrated in Example 5.3 and Figure 5.14.

### Example 5.3

Compare the electrical and optical bandwidths for an optical fiber communication system and develop a relationship between them.

**Solution**: In order to obtain a simple relationship between the two bandwidths it is necessary to compare the electric current through the system. Current rather than voltage (which is generally used in electrical systems) is compared as both the optical source and optical detector may be considered to have a linear relationship between light and current.

**Electrical bandwidth**: The ratio of the electric output power to the electrical input power in decibels $\mathbf{RE_{dB}}$ is given by:

$$RE_{dB} = 10\log_{10}\frac{\text{Electric power out (at the detector)}}{\text{Electric power in (at the source)}} = 10\log_{10}\frac{I_o^2/R_o}{I_i^2/R_i}$$

$$= 10\log_{10}\left(\frac{I_o}{I_i}\right)^2$$

The electrical 3 dB points occur when the ratio of electric powers shown above is 1/2. Hence it follows that this must occur when:

$$\left(\frac{I_o}{I_i}\right)^2 = \frac{1}{2} \quad \text{or} \quad \frac{I_o}{I_i} = \frac{1}{\sqrt{2}} = 0.707$$

Thus, in the electrical region the bandwidth may be defined by **the frequency when the output current, has dropped to 1/√2 or 0.707 of the input current to the system**.

**Optical bandwidth**: The ratio of the optical output power to the optical input power in decibels $RO_{dB}$ is given by:

$$RO_{dB} = 10\log_{10}\frac{\text{Optical power out (at the detector)}}{\text{Optical power in (at the source)}} = 10\log_{10}\frac{I_o}{I_i}$$

(Due to the linear light/current relationships of the source and detector). Hence the optical 3 dB points occur when the ratio of the currents is equal to 1/2, and:

$$\frac{I_o}{I_i} = \frac{1}{2}$$

Therefore, in the optical regime the bandwidth is defined by **the frequencies at which the output current, has dropped to 1/2 or 0.5 of the input current to the system**.

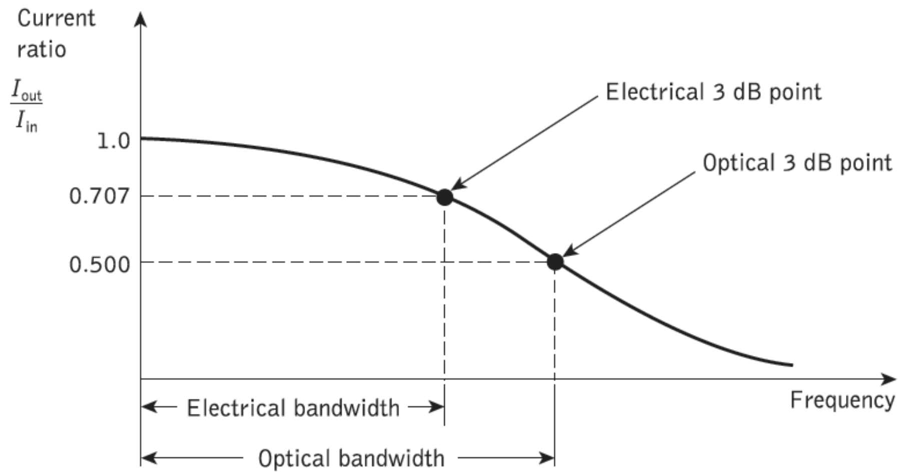


Figure 5.14: The frequency response of an optical fiber system showing the electrical and optical bandwidths.

The comparison between the two bandwidths is illustrated in Figure 7.25 where it may be noted that the optical bandwidth is significantly greater than the electrical bandwidth. The difference between them (in frequency terms) depends on the shape of the frequency response for the system. However, if the system response is assumed to be Gaussian, then the optical bandwidth is a factor of √2 greater than the electrical bandwidth.

The speed at which an LED can be directly current modulated is fundamentally limited by the recombination lifetime of the carriers, where the optical output power Pe(ω) of the device (with constant peak current) and angular modulation frequency ω is given by:

$$\frac{P_e(\omega)}{P_{dc}} = \frac{1}{[1+(\omega\tau_i)^2]^{1/2}}$$

where $\tau_i$ is the injected (minority) carrier lifetime in the recombination region and $P_{dc}$ is the d.c. optical output power for the same drive current.

**Example 5.4**

The minority carrier recombination lifetime for an LED is 5 ns. When a constant d.c. drive current is applied to the device the optical output power is 300 μW. Determine the optical output power when the device is modulated with an rms drive current corresponding to the d.c. drive current at frequencies of (a) 20 MHz; (b) 100 MHz. It may be assumed that parasitic capacitance is negligible. Further, determine the 3 dB optical bandwidth for the device and estimate the 3 dB electrical bandwidth assuming a Gaussian response.

***Solution:*** (a) the optical output power at 20 MHz is:

$$P_e(20\ \text{MHz}) = \frac{P_{dc}}{[1+(\omega\tau_i)^2]^{1/2}}$$

$$= \frac{300\times10^{-6}}{[1+(2\pi\times20\times10^{6}\times5\times10^{-9})^2]^{1/2}} = \frac{300\times10^{-6}}{[1.39]^{1/2}}$$

$$= 254.2\ \mu\text{W}$$

(b) the optical output power at 100 MHz is:

$$P_e(100\ \text{MHz}) = \frac{P_{dc}}{[1+(\omega\tau_i)^2]^{1/2}}$$

$$= \frac{300\times10^{-6}}{[1+(2\pi\times100\times10^{6}\times5\times10^{-9})^2]^{1/2}} = \frac{300\times10^{-6}}{[10.78]^{1/2}}$$

$$= 90.9\ \mu\text{W}$$

To determine the optical 3 dB bandwidth, the high-frequency 3 dB point occurs when $P_e(\omega)/P_{dc} = 1/2$

## 5.8 PROBLEMS

**Q1.** Briefly outline the general requirements for a source in optical fiber communications.

**Q2.** What are the three main parts of a fiber optic transmitter?

**Q3.** The amount of optical power coupled into an optical fiber depends on what four factors?

**Q4.** What are the basic **LED** types used in fiber optic communication systems?

**Q5.** Briefly outlines the advantages and drawbacks of the LED in comparison with the injection laser for use as a source in optical fiber communications.

**Q6.** Describe the relationship between the electrical and optical modulation bandwidths for an optical fiber communication system. Estimate the 3 dB optical bandwidth corresponding to a 3 dB electrical bandwidth of 50 MHz. A Gaussian frequency response may be assumed. Ans. (70.7 MHz)

htiw retemaid eroc mμ50 Estimate the coupling optical power into a step index fiber of **.7Q**
W60 fo ecnaidar a dna mμ75 from a SLED with an emission area diameter of 0.18 an NA of
$^{1-}$sr cm$^{-2}$. The Fresnel reflection at the index-matched semiconductor–fiber interface may be considered negligible.

Ans. (0.26 mW)



**Assistant Prof.**
**Dr. Abdulla K. Abass**