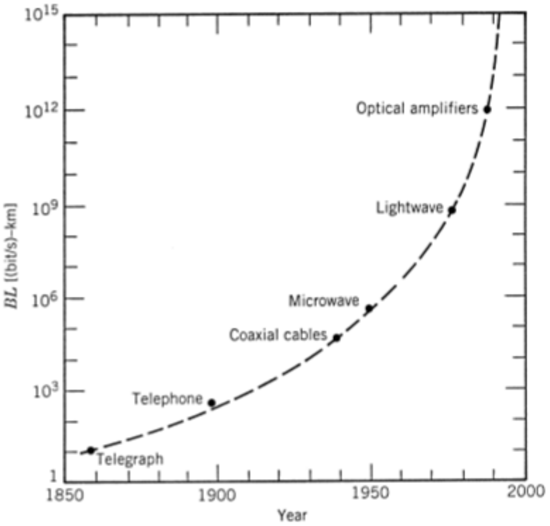
OPTICAL FIBER AND COMMUNICATION

Introduction

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 terahertz. 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 (~1 GHz). Fiber-optic communication systems are light wave systems that employ optical fibers for information transmission.

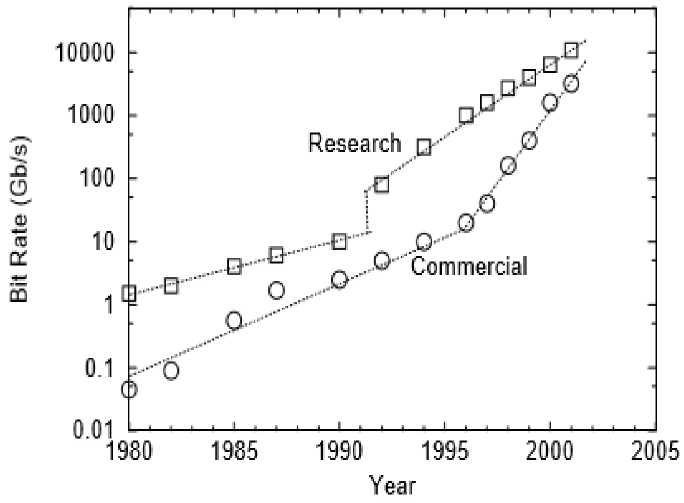
Need for Fiber-Optic Communications

The advent of telegraphy in the 1830s replaced the use of light by electricity and began the era of electrical communications [3]. 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 [4]. Analog electrical techniques were to dominate communication systems for a



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

The first microwave system operating 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 a 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∼100 (Mb/s)-km were available by 1970 and were limited to such values because of fundamental limitations.



Increase in the capacity of light wave systems realized after 1980. Commercial systems (circles) follow research demonstrations (squares) with a few-year lag. The change in the slope after 1992 is due to the advent of WDM technology.

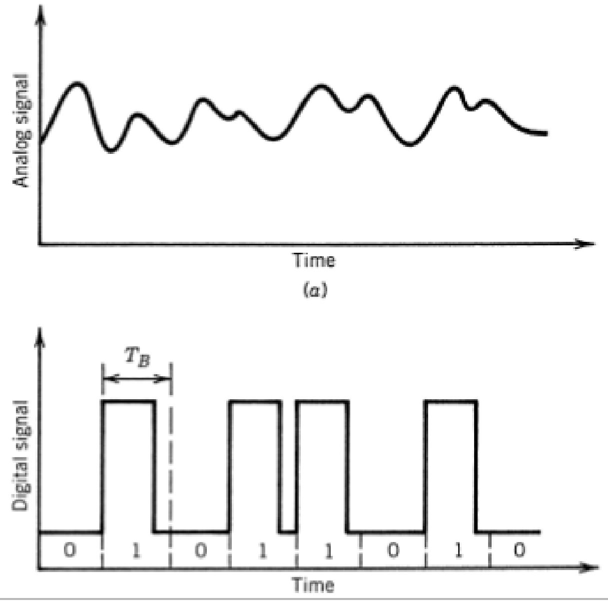
It was realized during the second half of the twentieth century that an increase of several orders of magnitude in the BL product would be possible if optical waves were used as the carrier. However, neither a coherent optical source nor a suitable transmission medium was available during the 1950s.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

Basic Concepts

This section introduces a few basic concepts common to all communication systems. We begin with a description of analog and digital signals and describe how an analog signal can be converted into digital form. We then consider time- and frequencydivision multiplexing of input signals, and conclude with a discussion of various modulation formats.

Analog and Digital Signals

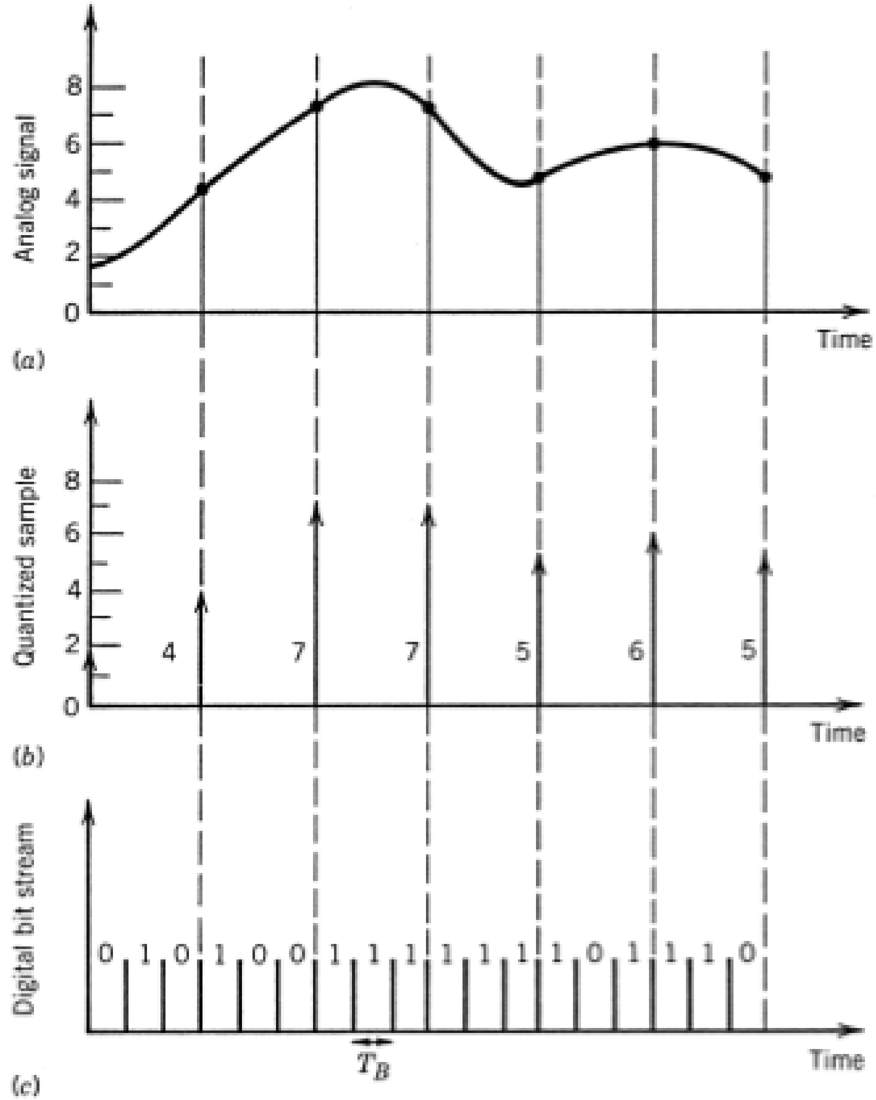
In any communication system, information to be transmitted is generally available as an electrical signal that may take analog or digital form [56]. In the analog case, the signal (e.g., electric current) varies continuously with time, as shown schematically in Fig. 1.6(a). Familiar examples include audio and video signals resulting when a microphone converts voice or a video camera converts an image into an electrical signal. By contrast, the digital signal takes only a few discrete values. In the binary representation of a digital signal only two values are possible. The simplest case of a binary digital signal is one in which the electric current is either on or off, as shown in Fig. 1.6(b). These two possibilities are called "bit 1" and "bit 0" (bit is a contracted form of binary digit). Each bit lasts for a certain period of time TB, known as the bit period or bit slot. Since one bit of information is conveyed in a time interval TB, the bit rate B, denned as the number of bits per second, is simply B=T −1 B . A well-known example of digital signals is provided by computer data. Each letter of the alphabet together with



Representation of (a) an analog signal and (b) a digital signal.

Sampling, Quantization and Coding

$$SNR = 20log10(Amax/AN)$$

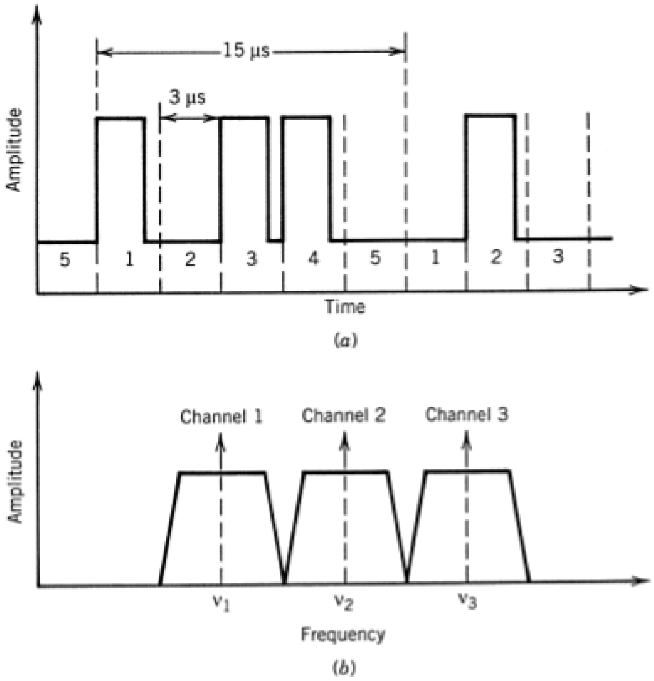


Three steps of (a) sampling, (b) quantization, and (c) coding required for converting an analog signal into a binary digital signal.

where SNR is expressed in decibel (dB) units. Any ratio R can be converted into decibels by using the general definition 10log10 R (see Appendix A). Equation (1.2.1) contains a factor of 20 in place of 10 simply because the SNR for electrical signals is defined with respect to the electrical power, whereas A is related to the electric current (or voltage).

Channel Multiplexing

As seen in the preceding discussion, a digital voice channel operates at 64 kb/s. Most fiber-optic communication systems are capable of transmitting at a rate of more than 1 Gb/s. To utilize the system capacity fully, it is necessary to transmit many channels simultaneously through multiplexing. This can be accomplished through time-division multiplexing (TDM) or frequency-division multiplexing (FDM). In the case of TDM, bits associated with different channels are interleaved in the time domain to form a composite bit stream. For example, the bit slot is about 15 μ s for a single voice channel operating at 64 kb/s. Five such channels can be multiplexed through TDM if the bit streams of successive channels are delayed by 3 micro second



Time-division multiplexing of five digital voice channels operating at 64 kb/s; (b) frequency-division multiplexing of three analog signals

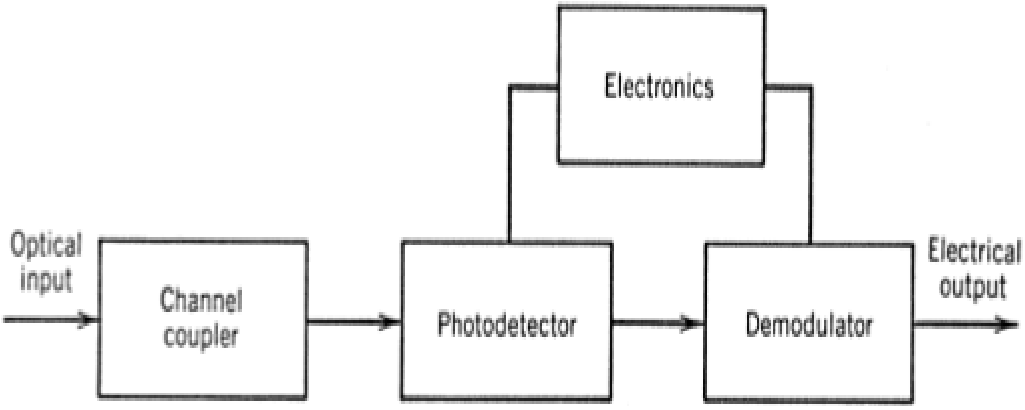
OPTICAL COMMUNICATION SYSTEMS

: Generic optical communication system.

phase-shift keying (PSK), depending on whether the amplitude, frequency, or phase of the carrier wave is shifted between the two levels of a binary digital signal. The simplest technique consists of simply changing the signal power between two levels, one of which is set to zero, and is often called on–off keying (OOK) to reflect the on–off nature of the resulting optical signal. Most digital light wave systems employ OOK in combination with PCM.

The application of optical fiber communications is in general possible in any area that requires transfer of information from one place to another. However, fiber-optic communication systems have been developed mostly for telecommunications applications. This is understandable in view of the existing worldwide telephone networks which are used to transmit not only voice signals but also computer data and fax messages. The telecommunication applications can be broadly classified into two categories, long-haul and short-haul, depending on whether the optical signal is transmitted over relatively long or short distances compared with typical intercity distances (∼100 km).

Optical Transmitters



Components of an optical receiver

The role of an optical transmitter is to convert the electrical signal into optical form and to launch the resulting optical signal into the optical fiber. Figure 1.11 shows the block diagram of an optical transmitter. It consists of an optical source, a modulator, and a channel coupler. Semiconductor lasers or light-emitting diodes are used as optical sources because of their compatibility with the optical-fiber communication channel; both are discussed in detail in Chapter 3. The optical signal is generated by modulating the optical carrier wave. Although an external modulator is sometimes used, it can be dispensed with in some cases, since the output of a semiconductor optical source can be modulated directly by varying the injection current. Such a scheme simplifies the transmitter design and is generally cost-effective

The launched power is an important design parameter. One can increase the amplifier (or repeater) spacing by increasing it, but the onset of various nonlinear effects limits how much the input power can be increased. The launched power is often expressed in “dBm” units with 1 mW as the reference level. The general definition is (see Appendix A) power(dBm)=10log10power 1 mW. (1.4.1) Thus, 1 mW is 0 dBm, but 1 μ W corresponds to −30 dBm. The launched power is rather low (<−10 dBm) for light-emitting diodes but semiconductor lasers can launch powers∼10 dBm. As light-emitting diodes are also limited in their modulation capabilities, most light wave systems use semiconductor lasers as optical sources. The bit rate of optical transmitters is often limited by electronics 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. Chapter 3 is devoted to a complete description of optical transmitters.

Optical Receivers

An optical receiver converts the optical signal received at the output end of the optical fiber back into the original electrical signal. Figure 1.12 shows the block diagram of an optical receiver. It consists of a coupler, a photo detector, and a demodulator. The coupler focuses the received optical signal onto the photo detector. Semiconductor photodiodes are used as photo detectors because of their compatibility with the whole system

Optical Fibers and Cables

Step-Index Fibers Consider the geometry of Fig. 2.2, where a ray making an angle

θ_i with the fiber axis is incident at the core center. Because of refraction at the fiber–air interface, the ray bends toward the normal. The angle θ_r of the refractedray is given by [22]

$n_0\sin$

$\theta_i = n_1\sin$

θ_r, (2.1.1)

wheren_1 andn_0 are the refractive index of the fiber coriander, respectively. The refracted ray hits the core–cladding interface and is refracted again. However, refraction is possible only for an angle of incidence φ such that $\sin\varphi < n_2/n_1$. For angles larger than a critical angle φ_c, define by [22]

$\sin$

$\varphi_c = n_2/n_1$, (2.1.2)

where n_2 is the cladding index, the ray experiences total internal reflection at the core– cladding interface. Since such reflections occur throughout the fiber length, all rays with $\varphi > \varphi_c$ remainconfinedtothefibercore. This is the basic mechanism behind light confinementin optical fibers

Graded-Index Fibers

The refractive index of the core in graded-index fibers is not constant but decreases gradually from its maximum value n1 at the core center to its minimum value n2 at the core–cladding interface. Most graded-index fibers are designed to have a nearly quadratic decrease and are analyzed by using α -profile, given by

. It is easy to understand qualitatively why intermodal or multipath dispersion is reduced for graded-index fibers. shows schematically paths for three different rays. Similar to the case of step-index fibers, the path is longer for more oblique rays. However, the ray velocity changes along the path because of variations in the refractive index. More specifically,the ray propagating along the fiber axis takes the shortest path but travels most slowly as the index is largest along this path. Oblique rays have a large part of their path in a medium of lower refractive index, where they travel faster. It is therefore possible for all rays to arrive together at the fiber output by a suitable choice of the refractive-index profile.

Wave Propagation

In this section we consider propagation of light in step-index fibers by using Maxwell's equations for electromagnetic waves. These equations are introduced in Section 2.2.1. The concept of fiber modes is discussed in Section 2.2.2, where the fiber is shown to support a finite number of guided modes. Section 2.2.3 focuses on how a step-index fiber can be designed to support only a single mode and discusses the properties of single-mode fibers.

Fiber Modes

The concept of the mode is a general concept in optics occurring also, for example, in the theory of lasers. An optical mode refers to a specific solution of the wave equation

Single-Mode Fibers Single-mode fibers support only the HE11 mode, also known as the fundamental mode of the fiber. The fiber is designed such that all higher-order modes are cut off at the operating wavelength. As seen in Fig. 2.5, the V parameter determines the number of modes supported by a fiber. The cutoff condition of various modes is also determined by V. The fundamental mode has no cutoff and is always supported by a fiber.

Fiber Bandwidth

The concept of fiber bandwidth originates from the general theory of time-invariant linear systems [59]. If the optical fiber can be treated as a linear system, its input and output powers should be related by a general relation

Fiber Losses

fiber dispersion limits the performance of optical communication systems by broadening optical pulses as they propagate inside the fiber. Fiber losses represent another limiting factor because they reduce the signal power reaching the receiver. As optical receivers need a certain minimum amount of power for recovering the signal accurately, the transmission distance is inherently limited by fiber losses. Infact, the use of silica fibers for optical communications became practical only when losses were reduced to an acceptable level during the 1970s. With the advent of optical amplifiers in the 1990s, transmission distances can exceed several thousand kilometers by compensating accumulated losses periodically. However, low-loss fibers are still required since spacing among amplifiers is set by fiber losses

Rayleigh Scattering

Rayleigh scattering is a fundamental loss mechanism arising from local microscopic fluctuations in density. Silica molecules move randomly in the molten state and freeze in place during fiber fabrication. Density fluctuations lead to random fluctuations of the refractive index on a scale smaller than the optical wavelength λ . Light scattering in such a medium is known as Rayleigh scattering [22]. The scattering cross section varies as $\lambda -4$. As a result, the intrinsic loss of silica fibers from Rayleigh scattering can be written as

$$\alpha R = C/ \lambda 4,$$

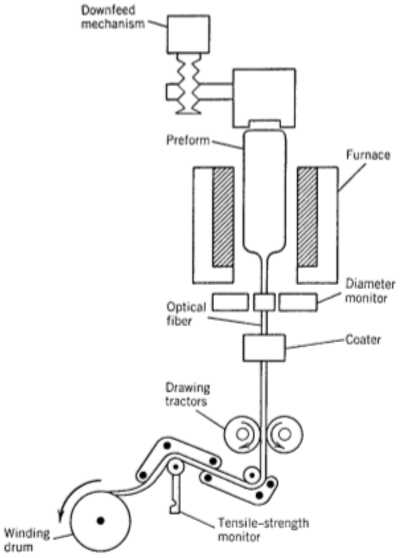
Nonlinear Optical Effects

The response of any dielectric to light becomes nonlinear for intense electromagnetic fields, and optical fibers are no exception. Even though silica is intrinsically not a highly nonlinear material, the waveguide geometry that confines light to a small cross section overlong fiber lengths makes nonlinear effects quite important in the design of modern light wave systems . We discuss in this section the nonlinear phenomena that are most relevant for fiber-optic communications.

Fiber Manufacturing

The final section is devoted to the engineering aspects of optical fibers. Manufacturing of fiber cables, suitable for installation in an actual light wave system, involves sophisticated technology with attention to many practical details. Since such details are available in several texts [12]–[17], the discussion here is intentionally brief

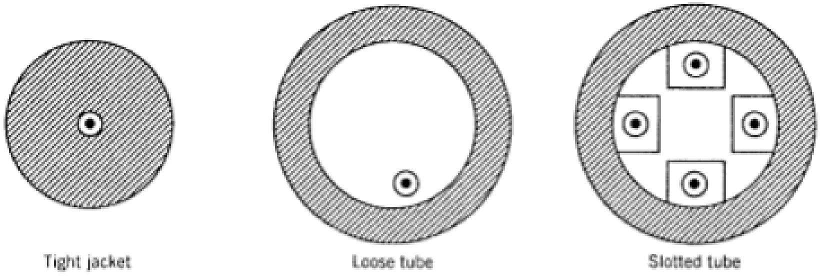
The fiber drawing step is essentially the same irrespective of the process used to make the perform [91]. Figure 2.22 shows the drawing apparatus schematically. The performs fed into a furnace in a controlled manner where it is heated to a temperature of about 2000◦C. The melted perform is drawn into a fiber by using a precision-feed mechanism. The fiber diameter is monitored optically by diffracting light emitted by a laser from the fiber. A change in the diameter changes the diffraction pattern



Apparatus used for fiber drawing.

Cables and Connectors

Cabling of fibers is necessary to protect them from deterioration during transportation and installation [92]. Cable design depends on the type of application. For some



Typical designs for light-duty fiber cables.

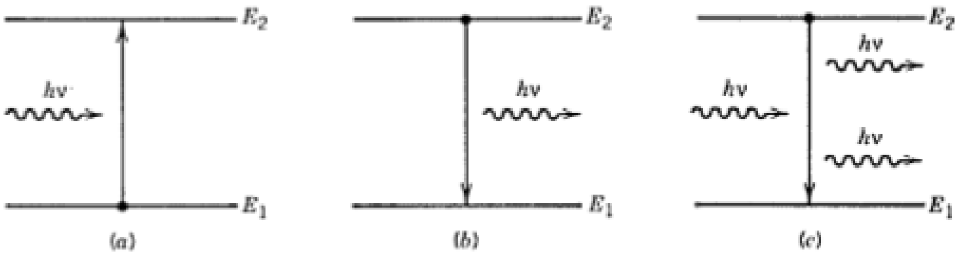
applications it may be enough to buffer the fiber by placing it inside a plastic jacket. Forothersthecablemustbemademechanicallystrongbyusingstrengtheningelements such as steel rods. A light-dutycable is made by surroundingthe fiber by a buffer jacket of hard plastic. Figure 2.23 shows three simple cable designs. A tight jacket can be provided by applying a buffer plastic coating of 0.5–1 mm thickness on top of the primary coating applied during the drawing process. In an alternative approach the fiber lies loosely inside a plastic tube. Micro bending losses are nearly eliminated in this loose-tube construction, since the fiber can adjust itself within the tube. This construction can also be used to make multi fiber cables by using a slotted tube with a different slot for each fiber.

Optical Transmitters

The role of the optical transmitter is to convert an electrical input signal into the corresponding optical signal and then launch it into the optical fiber serving as a communication channel. The major component of optical transmitters is an optical source. Fiber-optic communication systems often use semiconductor optical sources such as light-emitting diodes (LEDs) and semiconductor lasers because of several inherent advantages offered by them. Some of these advantages are compact size, high efficiency, good reliability, right wavelength range, small emissive area compatible with fiber core dimensions, and possibility of direct modulation at relatively high frequencies. Although the operation of semiconductor lasers was demonstrated as early as 1962, their use became practical only after 1970, when semiconductor lasers operating continuously at room temperature became available

Basic Concepts

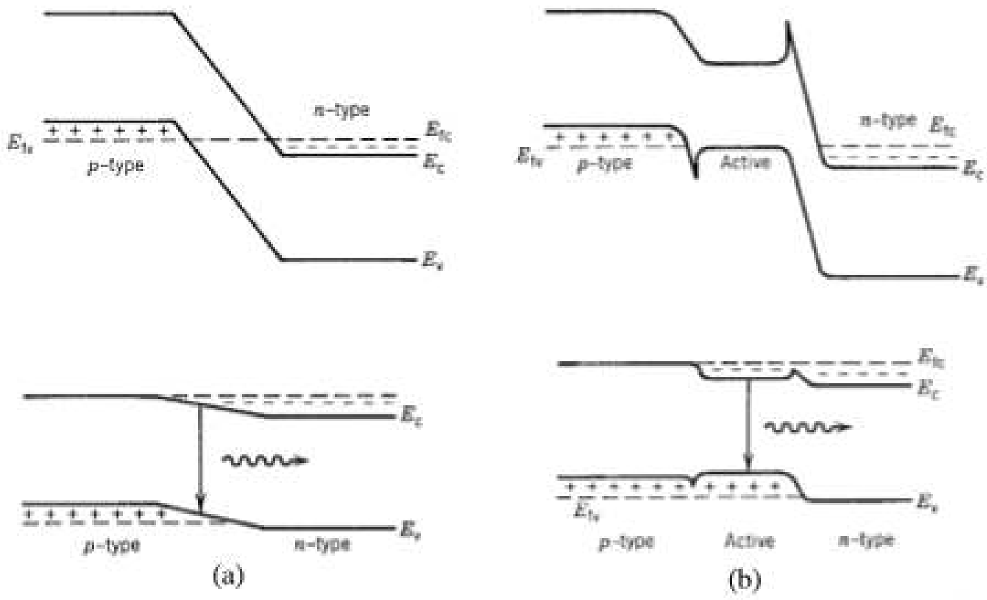
Under normal conditions, all materials absorb light rather than emit it. The absorption process can be understood by referring to Fig. 3.1, where the energy levels E1 and E2 correspondto the ground state and the excited state of atoms of the absorbingmedium. If the photon energy h ν of the incident light of frequency ν is about the same as the energy differenceEg =E2−E1, the photon is absorbed by the atom, which ends up in the excited state. Incident light is attenuated as a result of many such absorption events occurring inside the medium.



The excited atoms eventually return to their normal "ground" state and emit light in the process. Light emission can occur through two fundamental processes known as spontaneous emission and stimulated emission. Both are shown schematically in fig . 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.

p–n Junctions

At the heart of a semiconductor optical our is the p–n junction ,formed by bring in ga p-type and an n-type semiconductor into contact. Recall that a semiconductor is made n-type or p-type by doping it with impurities whose atoms have an excess valence electron are one less electron compared with the semiconductor atoms. In the case of n type semiconductor, the excess electrons occupy the conduction-band states, normally empty in undoped (intrinsic) semiconductors. The Fermi level, lying in the middle of the band gap for intrinsic semiconductors, moves toward the conduction band as the dopant concentration increases. In a heavily doped n-type semiconductor, the Fermi level EFC lies inside the conduction band; such semiconductors are said to be degenerate. Similarly, the Fermi level EFV moves toward the valence band for p-type semiconductors and lies inside it under heavy doping. In thermal equilibrium, the Fermi level must be continuous across the p–n junction. This is achieved through diffusion of electrons and holes across the junction. The charged impurities left behind set up an electric field strong enough to prevent further diffusion of electron sand holds under equilibrium conditions. This field is referred to as the built-in electric field. Figure 3.3(a) shows the energy-band diagram of a p–n junction in thermal equilibrium and under forward bias.



(a) (b)

Light-Emitting Diodes

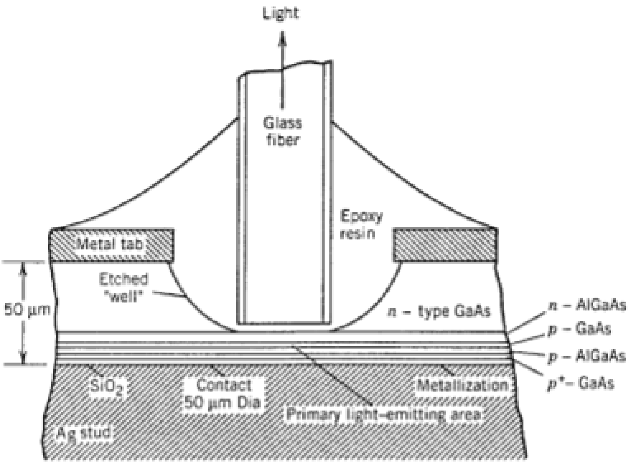
A forward-biased p–n junction emits light through spontaneous emission, a phenomenon referred to as electroluminescence. In its simplest form, an LED is a forward biased p–n homo junction. Radiativere combination of electron–holepairsinthe depletion region generates light; some of it escapes from the device and can be coupled into an optical fiber. The emitted light is incoherent with a relatively wide spectral width (30–60 nm) and a relatively large angular spread. In this section we discuss the characteristics and the design of LEDs from the standpoint of their application in optical communication systems

Power–Current Characteristics

It is easy to estimate the internal power generated by spontaneous emission. At a given current I the carrier-injection rate is I/q. In the steady state, the rate of electron–hole pairs recombining through radioactive and non radiative processes is equal to the carrier injection rate I/q. Since the internal quantum efficiency η int determines the fraction of electron–hole pairs that recombine through spontaneous emission, the rate of photon generations simply η intI/q.

LED Structures

The LED structures can be classified as surface-emitting or edge-emitting, depending on whether the LED emits light from a surface that is parallel to the junction plane or from the edge of the junction region.



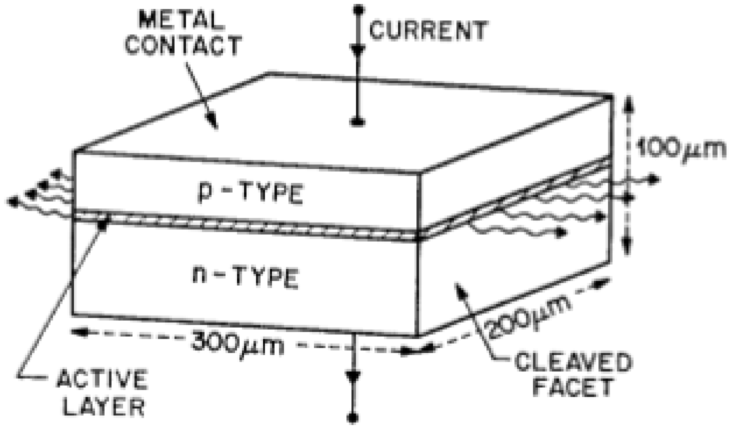
Schematic of a surface-emitting LED with a double-hetero structure geometry

Both types can be made using either a p–n homo junction or a hetero structure design in which the active region is surrounded by p- and n-type cladding layers. The hetero structure design leads to superior performance, as it provides a control over the emissive area and eliminates internal absorption because of the transparent cladding layers.

The edge-emitting LEDs employ a design commonly used for stripe-geometry semiconductor lasers . In fact, a semiconductor laser is converted into an LED by depositing an anti reflection coating on its output face to suppress lasing action. Beam divergence of edge-emitting LEDs differs from surface-emitting LEDs because of wave guiding in the plane perpendicular to the junction. Surface-emitting LEDs operate as a Lambert an source with angular distribution Se(θ)=S0cos θ in both directions. There luring beam divergence has a FWHM of120◦ in each direction. In contrast, edge-emitting LEDs have a divergence of only about 30◦ in the direction perpendicular to the junction plane. Considerable light can be coupled into a fiber of even low numerical aperture (< 0.3) because of reduced divergence and high radiance at the emitting facet The modulation bandwidth of edge-emitting LEDs is generally larger (~200 MHz) than that of surface-emitting LEDs because of a reduced carrier lifetime at the same applied current The choice between the two designs is dictated, in practice, by a compromise between cost and performance.

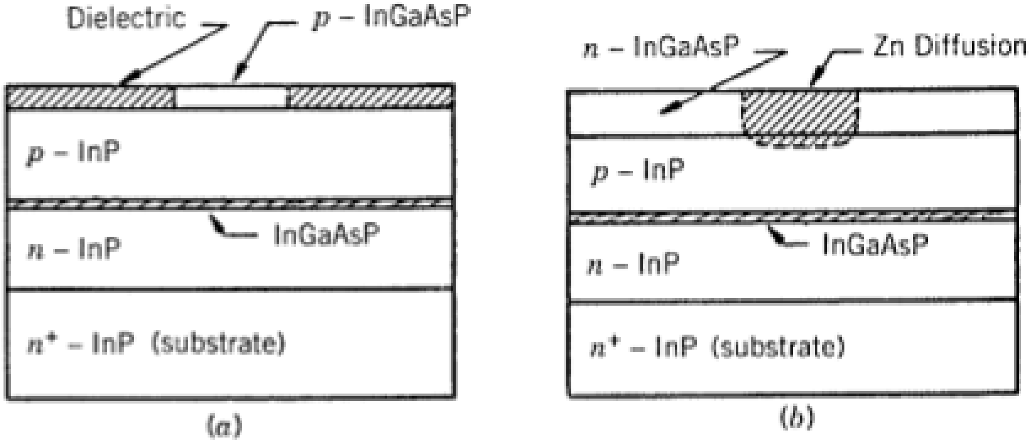
Semiconductor Lasers

Semiconductor lasers emit light through stimulated emission. As a result of the fundamental differences between spontaneous and stimulated emission, they are not only capable of emitting high powers (~100 mW), but also have other advantages related to the coherent nature of emitted light. A relatively narrow angular spread of the output beam compared with LEDs permits high coupling efficiency (~50%) into single-mode



A broad -area semiconductor laser. The active layer (hatched region) is sandwiched between p-type and n-type cladding layers of a higher-band gap material.

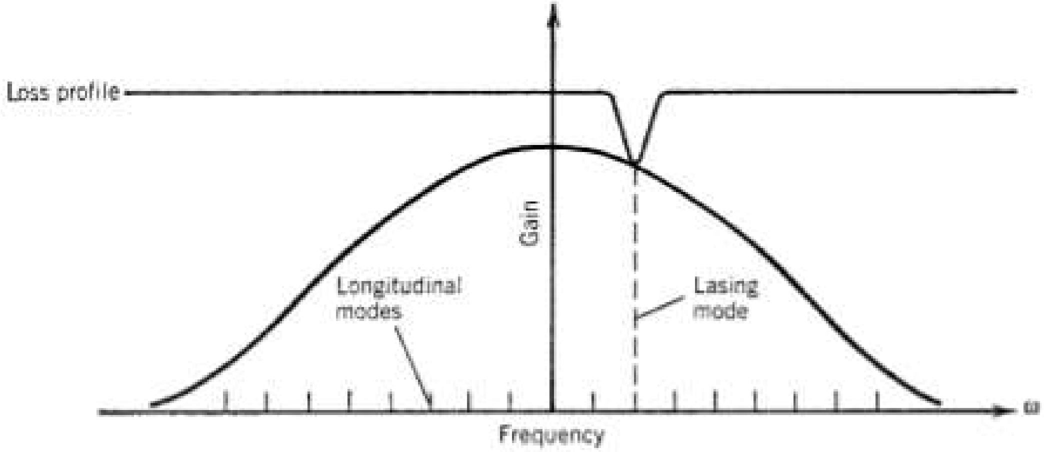
semi conductor lasers are classified into two broad categories Gain-guided semiconductor lasers solve the light-confinement problem by limiting current injection over a narrow stripe. Such lasers are also called stripe-geometry semiconductor lasers. Figure 3.13 shows two laser structures schematically.



Cross section of two stripe-geometry laser structures used to design gain-guided semiconductor lasers and referred to as (a) oxide stripe and (b) junction stripe.

Control of Longitudinal Modes

We have seen that BH semiconductor lasers can be designed to emit light into a single spatial mode by controlling the width and the thickness of the active layer. However, as discussed in such lasers oscillate in several longitudinal modes simultaneously because of a relatively small gain difference (~0.1 cm−1) between neighboring modes of the FP cavity. The resulting spectral width (2–4 nm) is acceptable for light wave systems operating near 1.3 μ m at bit rates of up to 1 Gb/s. However, such multimode lasers cannot be used for systems designed to operate near 1.55 μ m at high bit rates. The only solution is to design semiconductor lasers such that they emit light predominantly in a single longitudinal mode (SLM).



Gain and loss profiles for semiconductor lasers oscillating predominantly in a single longitudinal mode.