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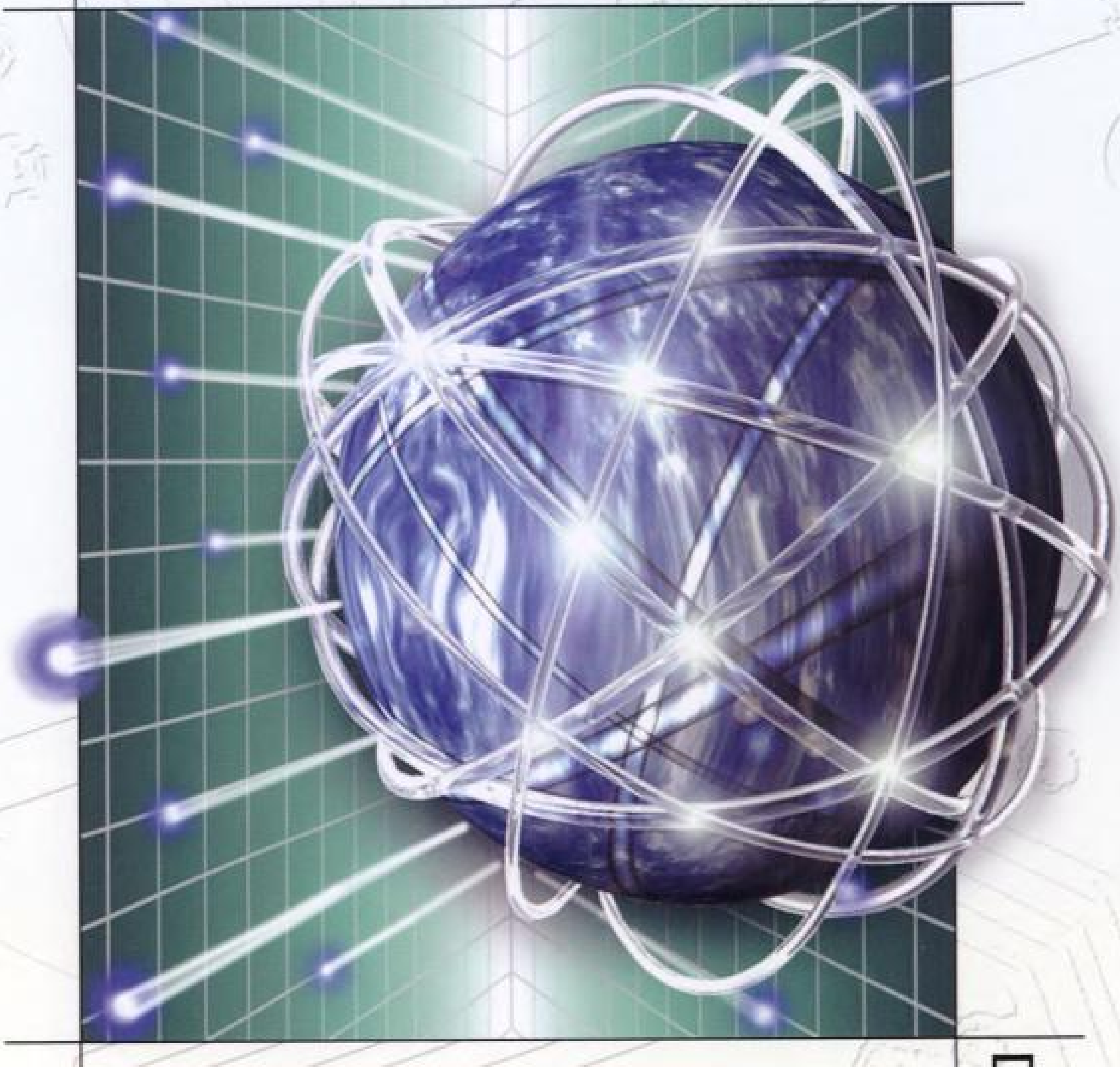
Fiber Optic Communications



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THOMSON
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Fiber-Optic Communications
James N. Downing

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CONTENTS

junction diode are presented followed by a close look at the light-emitting diode (LED). After a discussion of LED operation and physical structure, the laser diode is introduced. Laser operation is described in considerable detail and the types of lasers used in communications are reviewed. The transmitter is then discussed, including the internal components and the packaging necessary to launch light into a fiber efficiently.

Chapter 6

At the opposite end of the fiber is an optical detector. Chapter 6 describes the characteristics and the operation of optical detectors and receivers. The photodetection process is defined and the process described, followed by a look at various types of receiver photodiodes. Optical absorption, quantum efficiency, and responsivity are among the parameters investigated. The importance of understanding noise in detection circuits is presented, and noise factors such as thermal, shot, and dark current noises and signal-to-noise ratio are defined. Amplifiers are then discussed, followed by other receiver components such as signal recovery and electronic control circuits. The chapter concludes with sections on receiver performance and the transceiver.

Chapter 7

Chapter 7 covers all fiber-optic devices not discussed elsewhere in the text. Optical amplifiers are explained and the relationship between amplification, reshaping, and retiming is established. Different types of couplers are introduced, along with the equations for coupler loss and an explanation of how they are used in wavelength multiplexers. Direct and indirect modulators are compared and wavelength demultiplexers are discussed in detail. After an explanation of the different filters used in wavelength demultiplexing, the optical add-drop multiplexer is introduced. Switches and optical cross-connects are then investigated with a focus on opaque and transparent definitions and switch implementation using microelectromechanical systems (MEMS) switches. The chapter concludes with a section on integrated optical devices and their advantages in improving system performance.

Chapter 8

In Chapter 8, the text begins the examination of fiber-optic systems by first looking at the nature of the input optical signal. The electrical-to-optical conversion process is reviewed and data modulation and multiplexing formats are examined. Wavelength division multiplexing formats and implementations are introduced including the ITU-T DWDM and CWDM

About the Author

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convergence of voice, video, and data over the same channel by the early twenty-first century.

The importance of the milestones presented cannot be overstated, as our intent here is to provide only an overview of the evolution of telecommunications. Those wishing to gain a more thorough understanding of these important historical developments should consult the references noted.

Regulation and Standards

The regulation and standardization of any large technical enterprise is essential to ensure consistency and integrity of service, compatibility between service providers and device vendors, and connectivity and interoperability of all systems components. International and national regulatory and standards organizations attempt to provide this necessary framework for the telecommunications industry.

Regulation and Deregulation

Attempts at regulation of the telecommunications industry did not occur in the United States until the early 1900s when the dominance and monopolistic practices of the American Telephone and Telegraph (AT&T) Company attracted the attention of legislators. The Interstate Commerce Commission (ICC) eventually became the watchdog of the fledgling telecommunications industry, and in 1934 the Communications Act established the Federal Communications Commission (FCC) as the regulatory institution for telephone and radio broadcasting networks. Antitrust claims against AT&T continued, by 1968 private mobile radio systems were allowed to connect to the PSTN, and in 1976, long-distance service could be provided by companies other than AT&T. This deregulation trend continued, and in 1984 AT&T was ordered to divest itself of the subsidiary Bell Operating Companies (BOCs). These original regional BOCs or RBOCs were Ameritech, Bell Atlantic, Bell South, NYNEX, Southwestern Bell, Pacific Telesis, and US West. By 2002 this number was reduced to four because of buyouts and mergers: Verizon, SBC, Bell South, and Qwest.

The Telecommunications Act of 1996 was intended to continue the trend toward deregulation and to enhance industry competition. Many previous restrictions were lifted and the late 1990s saw tremendous growth in all areas of the telecommunications industry, probably due at least in part to this ruling. Today the FCC plays an important role in the implementation of all types of communications including fiber-optic, cable TV, and wireless networks. The regulation of radio, microwave, and extended regions of the electromagnetic spectrum has always been the domain of the FCC, and modifications opening up new spectral regions are still common. In another example, a 2003 FCC ruling provided economic incentive for service providers to implement fiber-to-the-home communications.

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(b) $V_{out} = T_{sys}V_{in} = (1.68)(0.08\ \text{V})$

$$\boxed{V_{out} = 0.1344\ \text{V}}$$

The decibel (dB) is often used to describe a voltage or power ratio as in a communication transfer function. The transfer function expressed in decibels is

$$T_{dB} = 20\log\left(\frac{V_{out}}{V_{in}}\right) = 20\log(T) \quad \text{for voltage ratio} \tag{1–4}$$

or

$$T_{dB} = 10\log\left(\frac{P_{out}}{P_{in}}\right) = 10\log(T) \quad \text{for power ratio}$$

For any fiber-optic system, we can describe the fraction of light transmitted through the system by

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

In decibels, the fractional transmittance becomes

$$T_{dB} = 10\log T = 10\log\left(\frac{P_{out}}{P_{in}}\right)$$

If the result is positive, it describes the gain in decibels; if it is negative, it describes a loss. To return to fractional transmittance from decibel notation use

$$T = 10^{\frac{T_{dB}}{20}} \quad \text{for voltage}$$

or

$$T = 10^{\frac{T_{dB}}{10}} \quad \text{for power}$$

EXAMPLE 1.3

A fiber-optic communications system has an output power of 2 mW for an input of 3 mW. Find the loss in dB.

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300 Hz to 3300 Hz (or a bandwidth of 3 kHz) are transported over the local loop to the CO where switching takes place. Today, even most voice signals are converted to digital with a CODEC or coder/decoder used to convert voice signals into a PCM representation and then transported. Computers with an attached modem (modulator-demodulator) can send and receive data over the PSTN system to other computer networks or to the Internet. Enhanced Internet services such as **ADSL (Asymmetrical Digital Subscriber Line)** allow significantly faster downstream speeds on a dedicated line.

Cable Television

Cable television or CATV has taken up the lion's share of the television broadcasting business, although competition is still provided by satellite systems. Initially designed for downstream traffic only, with frequencies specified from 55.25 MHz to over 700 Mhz, CATV uses both coaxial cable and optical fiber. Cable modems allow the transport of data over the CATV network, thereby allowing Internet access and CATV over one line.

Data Networks

Data networks are at the heart of most telecommunications systems today, as almost all information is transmitted in digital form. Besides ownership and purpose, networks are also classified according to the interconnection topology, spatial extent, switching technology, and the protocol(s) used.

Networks are connected in ways that enhance the efficiency and speed of the network using various topologies. Figure 1–10 illustrates some possible network topologies. In a bus topology, all system components are attached to a single cable or line. This single cable or backbone may serve a specific local network or may be used for long-haul transport from city to city. A star network has a centralized hub to which other components are connected. In a physical star topology, an Ethernet switch is used as a physical bus to which all components are connected. The ring topology connects each device with a bus, but with the ends of the bus connected together. The ring allows traffic to travel in one direction to reach its destination. A second ring can provide redundancy in case of a break in the main ring. In a collapsed ring, the ring is formed inside of a hub to which all devices are connected.

The spatial extent, or area covered by a network, is often included in the network name, such as LAN, MAN, and WAN. The local area network (LAN) consists of networks at businesses, colleges, or office buildings, which allow users to share computer resources (storage, printer, in-house email), and may also have a router or Ethernet switch for connection to the MAN or WAN. LANS can be interconnected with bridges and switches and often have a bus backbone connecting the individual LANs to the MAN or

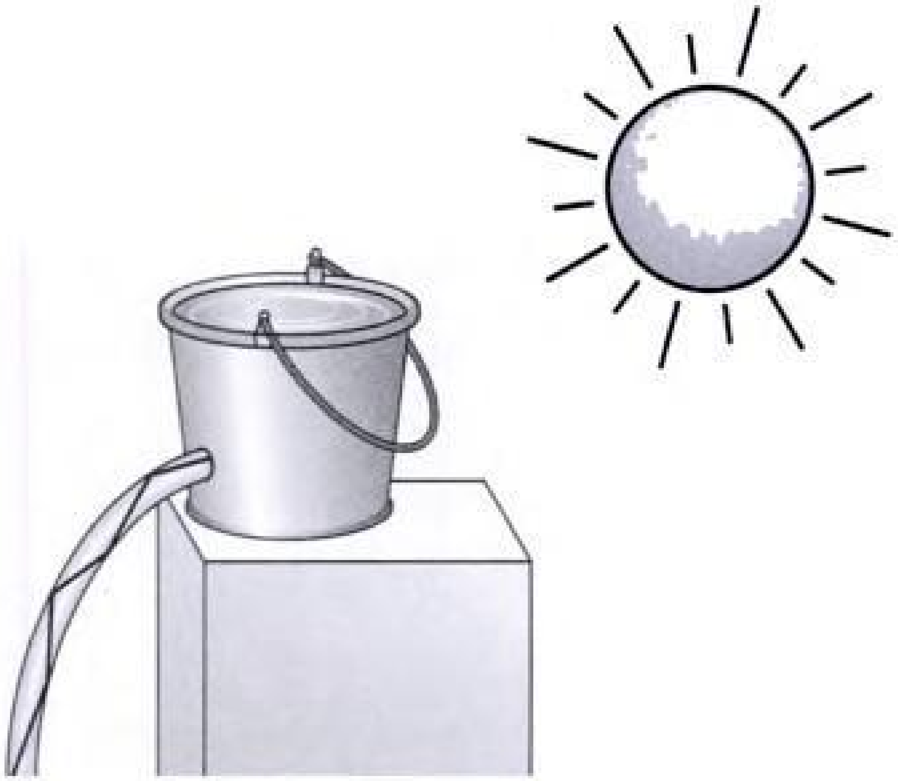
Convergence

The delivery of separate voice, video, and data services over different channels and media continues to drive developers toward a single multi-service device. This integration of all services in one transport mechanism is called convergence. The successful integration of some data types has already been achieved, as in data and voice over the PSTN, cell phones that take pictures, and Internet access and voice over a CATV line. Other combinations, such as voice over IP (VoIP), are now available and are rapidly catching on. Concurrent with convergence efforts is the evolution of an all-optical network (AON). While the use of wireless continues to flourish and much of the worldwide installed copper base will be around for some time, the AON should help provide the necessary bandwidth and switching fabric to support such a variety of formats simultaneously.

1.4 The Evolution of Fiber-Optic Communications

The idea of communications using light and the understanding of fiber-optic principles are not recent developments. The Greeks of the eighth century BC used fire signals for alarms and for notification of special events, while in ancient Egypt, Heron of Alexandria demonstrated how sunlight travels down a stream of water flowing out of a hole in a bucket (see Figure 1–13). Later, Paul Revere saw only one light in the steeple of the Old North Church, signaling that the British were coming by land, and

FIGURE 1–13 Heron of Alexandria demonstrates fiber optics.



exceeding 1 Gbps over 50-km fiber lengths were achieved. Dispersion-shifted fiber also enhanced fiber performance during this period. Over six million miles of fiber for telephone service had been installed by 1990.

Optical amplification and practical wavelength division multiplexing (WDM) allowed for the full use of the 1550-nm optical fiber region in the mid 1990s. The time wasted in optical-to-electrical-to-optical conversions at repeaters was eliminated and WDM increased the system bit rate significantly. By the turn of the century, optical routers and switches and tunable lasers had been introduced, global networks could carry an aggregate 2.56 Tbps (64 WDM channels, 4 fiber pairs) and over 75 million miles of optical fiber had been installed around the world.

Attenuation was less than 0.16 dB/km by 2001, and although the telecommunications industry went through a downturn in the first years of the new millenium, the demand for more bandwidth and more efficient systems continued to drive the photonics market toward the conversion of electro-optical to optical components and the proliferation of the all-optical network of the near future.

1.5 Why Fiber Optics?

Fiber-optics communications systems hold some distinct advantages over other systems. These advantages include a greater information-carrying capacity, lower loss, lower cost per bit, electrical isolation, small size and weight, and environmental ruggedness.

The larger information-carrying capacity is by far the greatest advantage of fiber optics for communications. A fiber-optic system bandwidth is limited mostly by the bandwidth of transmitters and receivers and not by the fiber itself. Adding additional wavelength carriers can increase capacity, something not as easily implemented in electrical systems. The bandwidth increase is hundreds of times that of conventional electrical systems, and an equivalent THz of information-carrying capability is possible, using a 10 Gb/s per channel DWDM system.

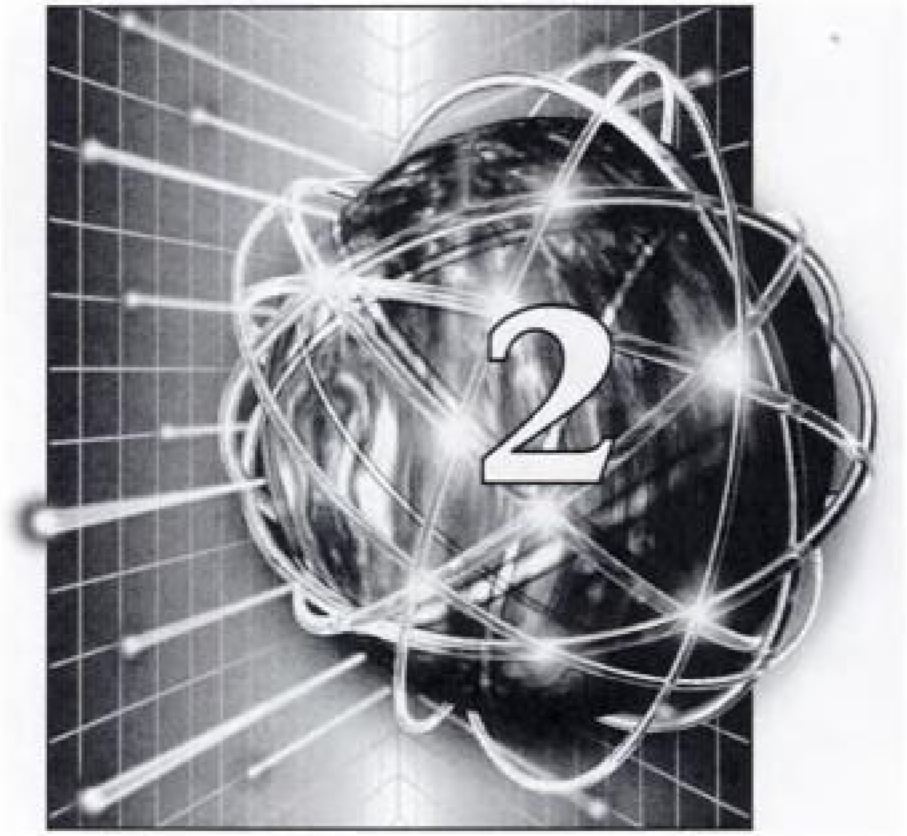
The low loss modern optical fibers allow for signals to be transmitted over great distances without having to be amplified. Instead of placing amplifiers every kilometer or so, as is done with conventional systems, amplification is only needed for about every 200 km of optical fiber. Current ITU attenuation standards allow maximums of 0.5 dB/km in the 1310-nm region and 0.4 dB/km in the 1500-nm region. Combining the wider bandwidth with the lower attenuation results in a much lower cost per bit.

Electrical isolation makes the use of fiber attractive for several reasons. First, the fiber is immune to disturbances caused by lightning and electromagnetic interference (EMI). Much of the noise in electrical systems is

3 dB. If the input is 4 mW, what power reaches the receiver?

6. Light is launched into a fiber that has a loss of 1 dB for each km of length. After what length of fiber will the signal drop to one-half of the input signal?
7. Fiber loss is wavelength-dependent, and the loss of Problem 6 was actually at 850 nm. The same fiber has a loss of 0.7 dB/km at 1310 nm and 0.4 dB/km at 1550 nm. Repeat Problem 6 for the remaining two wavelengths.
8. A DS-2 signal consists of four DS-1 signals and some overhead for timing and synchronization. Use Table 1-1 and your calculator to determine how many extra bits are needed for overhead.
9. An analog voice signal that varies over the range from 0 to 50 mA is converted to a 4-bit digital signal using an A-D converter. The 4 bits allow room for 2^4-1 steps over 50 mA or 3.125 mA per step. This means that 0 is 0000, 3.125 is 0001, 6.25 is 0010, and so forth. Make a table to determine the digital output versus the analog current input.
10. According to Nyquist, what is the sampling rate necessary for the PSTN to ensure that no information is lost?

Principles of Optics



Objectives Upon completion of this chapter, the student should be able to:

- Describe how refraction and reflection take place
- Define index of refraction and phase velocity
- Define Snell's law
- Understand polarization and coherence
- Describe and calculate the different types of interference
- Understand the principles of diffraction
- Identify the condition for Rayleigh scattering
- Identify and describe nonlinear fiber processes
- Understand radiometric and photometric units
- Calculate input and output optical power parameters
- Use decibels (dB) and dBm in optical power calculations

Outline

2.1 Geometrical Optics
2.2 Wave Optics
2.3 Quantum Optics
2.4 Nonlinear Optics
2.5 Optical Power

Key Terms

absorption
Bohr model
Bragg grating
coherence
constructive interference
critical angle
destructive interference
diffraction

diffraction grating
dispersion
electromagnetic spectrum
electromagnetic waves
emission
excited state
four-wave mixing
Fresnel reflection
geometrical optics
ground state
index of refraction
interference
linewidth
Mie scattering
optical path length
phase
phase modulation
phase velocity
photon
Planck's radiation law
polarization
Rayleigh scattering
reflection
refraction
scattering
Snell's law
spatial coherence
spontaneous emission
stimulated emission
temporal coherence
wavenumber

Introduction

Our understanding of just what light is has evolved significantly over the last 300 years. Efforts to discover the exact nature of light have led to breakthroughs in related fields as well as in the understanding that light is but a small part of the much larger electromagnetic spectrum. A clear, physical description of light, however, continues to remain elusive.

Isaac Newton assumed that light was a particle since it seemed to travel in a straight line. During his famous work with prisms and the breaking up of white light into its component colors, he came to understand that light was a stream of particles moving from the object to the eye. At about the same time (1678), Dutch physicist Christian Huygens found that light behaved more like a wave, spreading out from its source. According to the *Huygen's Principle,* as the light spreads, each point on the wave acts as a new source. Both theories worked well in explaining many of the properties of light, but each fell short as the definitive description for light.

The Scottish mathematician and physicist James Clerk Maxwell arrived at a more unified theory of light during his research from 1864 to 1873. Maxwell studied the work that Michael Faraday had done on lines of force and the curious relationship between electricity and magnetism. He concluded that electricity and magnetism were inseparable and that velocity of the wave generated is the ratio of magnetic to electric units, which just happened to be the speed of light! He further explained that light is but a small part of the vast electromagnetic spectrum which stretches out beyond 10^{25} Hz. The electromagnetic spectrum also includes many other common phenomena such as X-rays, ultraviolet, microwave, radio, and millimeter waves.

In the early 1900s, the application of quantum theory helped explain the behavior of light even more clearly. First Max Planck, a German physicist, determined that the light "particles" had a certain energy associated with them; therefore, only certain light energies or "quanta" were allowed. Einstein used the generation of a current in a material produced by light striking the surface as a practical example of quantum theory, and Niels Bohr applied quantum theory to atomic structure. Controversial at the time (1926), Heisenberg's uncertainty principle served as the foundation for modern quantum optics and has led to a more widely accepted description of light. The dual nature of position and momentum (if you know one exactly, you can't know the other) proposed by Heisenberg parallels the wave/particle duality of light. Also, the apparent statistical and probabilistic nature of light is in agreement with the wave/particle nature of light. In general terms, while a quantum description of light is possible, it is evident that light is beyond what we are able to clearly comprehend or describe accurately in words. We can, however, use these different models of light to understand the energy associated with it, how it travels, and what happens when it strikes a medium.

In this chapter we will begin our study of optics with a discussion of geometrical optics, including refraction, Snell's law, and reflection, and then we will look at the wave model of light. The wave model will enable us to understand such phenomena as polarization, coherence, interference, diffraction, and scattering. Quantum optics will cover atomic interactions, which result in absorption and emission as stated in Planck's law. We will also explore nonlinear phenomena such as four-wave mixing, phase modulation, and Brillouin and Raman scattering, and conclude with a look at optical power.

Why investigate the principles of optics in such detail you might ask? Fiber-optic technicians are no longer just being asked to polish, connectorize, and install fiber. Newer systems contain complex multiple wavelength systems, with common components operating as interference filters, optical isolators, nonlinear optical amplifiers, and polarization maintaining devices. You may not have to completely understand all the topics discussed, but familiarization with these basic principles will go a long way in understanding and then troubleshooting fiber-optic communications systems.

2.1 Geometrical Optics

Geometrical optics is a model by which the ray nature of light is used to explain refraction, reflection, and the propagation of light through optical systems. Using lens equations, ray-tracing, and matrix formulations of optical elements, complex optical systems can be modeled with great accuracy. While the rigor necessary for lens design is beyond our needs here, we will study the principles required to understand light propagation in optical fibers. As light passes from one medium into another, we can determine the magnitude and the direction of both the rays passing into the second medium and the rays reflecting back into the first.

Refraction

Refraction is the bending of light rays as they pass through a medium, which is accompanied by a change in velocity. The ratio of the speed of light in a vacuum (c) to the speed of light in that medium (v) is called the **index of refraction** and is given by

$$n = \frac{c}{v} \tag{2–1}$$

where c is the vacuum speed of light or 3.0×10^8 m/s. The speed of light in a medium is also referred to as the **phase velocity**. Note that the **optical path length** (S), or the apparent length of the optical element can be determined from

$$S = Ln \tag{2–2}$$

where L is the actual length of the element. One complication with respect to the refractive index is that it is wavelength dependent. This is called dispersion, and it is critical in understanding the performance of fiber-optic systems, as we shall see in Section 3.2. The refractive indices of some common media are given in Table 2–1.

•—EXAMPLE 2.1

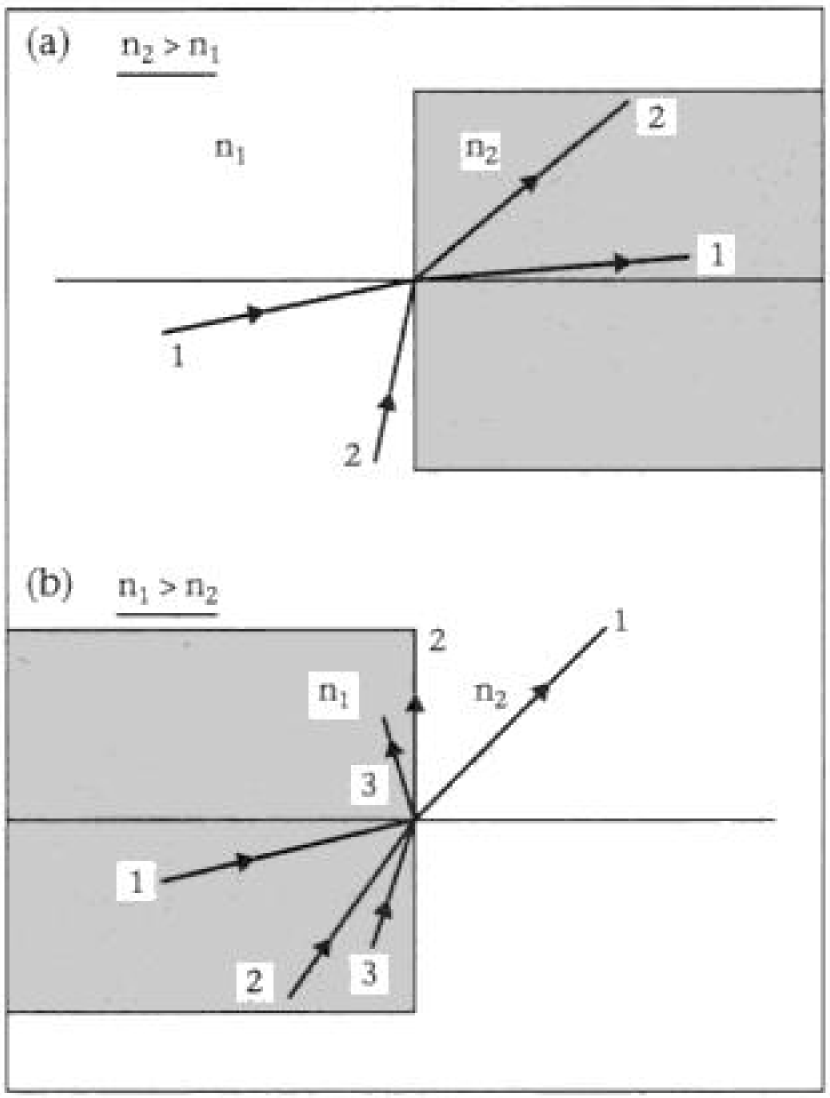
What is the velocity of light in water?

•–SOLUTION

$$n = \frac{c}{v} \rightarrow v = \frac{c}{n} = \frac{3.0 \times 10^8 \frac{m}{s}}{1.33}$$

$$\boxed{v = 2.3 \times 10^8 \frac{m}{s}}$$

FIGURE 2–2 Refraction at an interface.
(a) $n_2 > n_1$,
(b) $n_1 > n_2$.



For light traveling in the other direction as in Figure 2–2b on page 38, the critical angle occurs when the refracted angle is 90° and

$$n_1 \sin \theta_1 = n_2$$

$$\boxed{\theta_1 = \sin^{-1} \frac{n_2}{n_1} = 41.14°}$$

Reflection

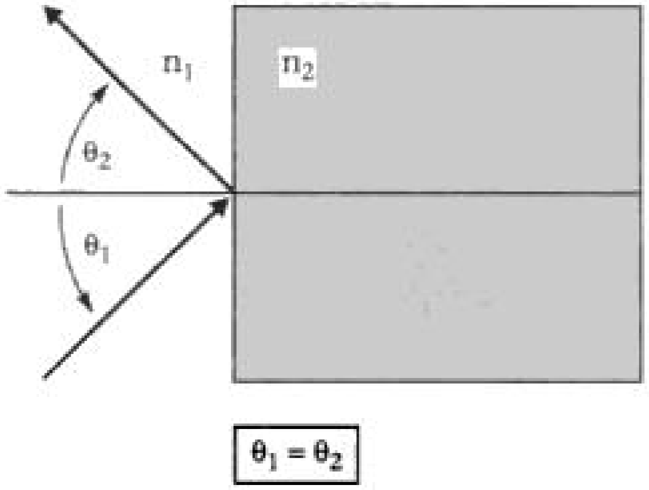
The **reflection** of light is the bouncing off of rays from a material interface and is the result of the smoothness of the interface and the refractive indices of the media. While wave theory and Maxwell's equations lead to a mathematical description of reflection and refraction at an interface (including phase information), we will only apply relevant results here.

Assuming a smooth interface, the reflected angle is equal to the incident angle by

$$\theta_1 = \theta_2 \tag{2–4}$$

This Law of Reflection is illustrated in Figure 2–3.

FIGURE 2–3 Reflection of light at an interface.



Although a detailed discussion of reflection theory is beyond the scope of this text, an understanding of Fresnel reflection principles will aid greatly in our study of fiber-optic interfaces. In the early 1700s Fresnel developed his laws of reflection, which determined the fraction of light reflected as a function of incident angle. Graphical results, for both parallel and perpendicular polarizations (polarization will be discussed shortly) are shown in Figures 2–4 ($n_2 > n_1$) and 2–5 ($n_1 > n_2$), respectively. For both polarizations at normal incidence, Fresnel reflection reduces to

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2 \tag{2–5}$$

Reflection also tells us the fraction of incident light transmitted or refracted into the second medium. For example, if 20% of the light is reflected, then 80% is refracted or transmitted (T) into the medium. The relationship between the fraction of light transmitted and reflected is

$$T = 1 - R \tag{2–6}$$

Note that for a specific angle with $n_2 > n_1$, 0% of the light is reflected (or 100% transmitted). This is known as Brewster's angle and is used often in laser cavities to allow the appropriate wavelength of light to be transmitted. Also apparent from the graphical data for $n_1 > n_2$ is the total internal reflection, which occurs after the critical angle is reached.

•–SOLUTION

(a) $$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2 = \left(\frac{1.45 - 1}{1.45 + 1}\right)^2$$

$$\boxed{R = 0.0337 \text{ or } 3.37\%}$$

(96.63% transmitted)

(b) $$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2 = \left(\frac{1.51 - 1}{1.51 + 1}\right)^2$$

$$\boxed{R = 0.0413 \text{ or } 4.13\%}$$

(95.87% transmitted)

2.2 Wave Optics

Wave or physical optics refers to the modeling of light using electromagnetic waves. These waves help explain the behavior of light as it appears to turn after passing an edge or propagating through an aperture. The waves combine and generate light and dark patterns on a screen or can be polarized to oscillate in only one direction. Electromagnetic waves may change direction abruptly when encountering other particles. While the mathematical analysis of electromagnetic waves is quite complex, we will use only the results that aid in our understanding of fiber-optic principles.

Electromagnetic Waves

Electromagnetic waves are the result of the dual properties of electricity and magnetism whereby one field induces the other. Derived from Maxwell's equations, some approximations, and boundary conditions, these electric and magnetic field oscillations are perpendicular to each other and trace out a sinusoidal wave pattern in time and space. This three-dimensional wave model used to describe the electrical and magnetic field properties is shown in Figure 2-6. Note again that these waves are functions of both space and time, and usually one variable is held constant for analysis purposes. While wave equations are seldom used for troubleshooting systems, they are useful in understanding the relationships between and magnitude of wave parameters.

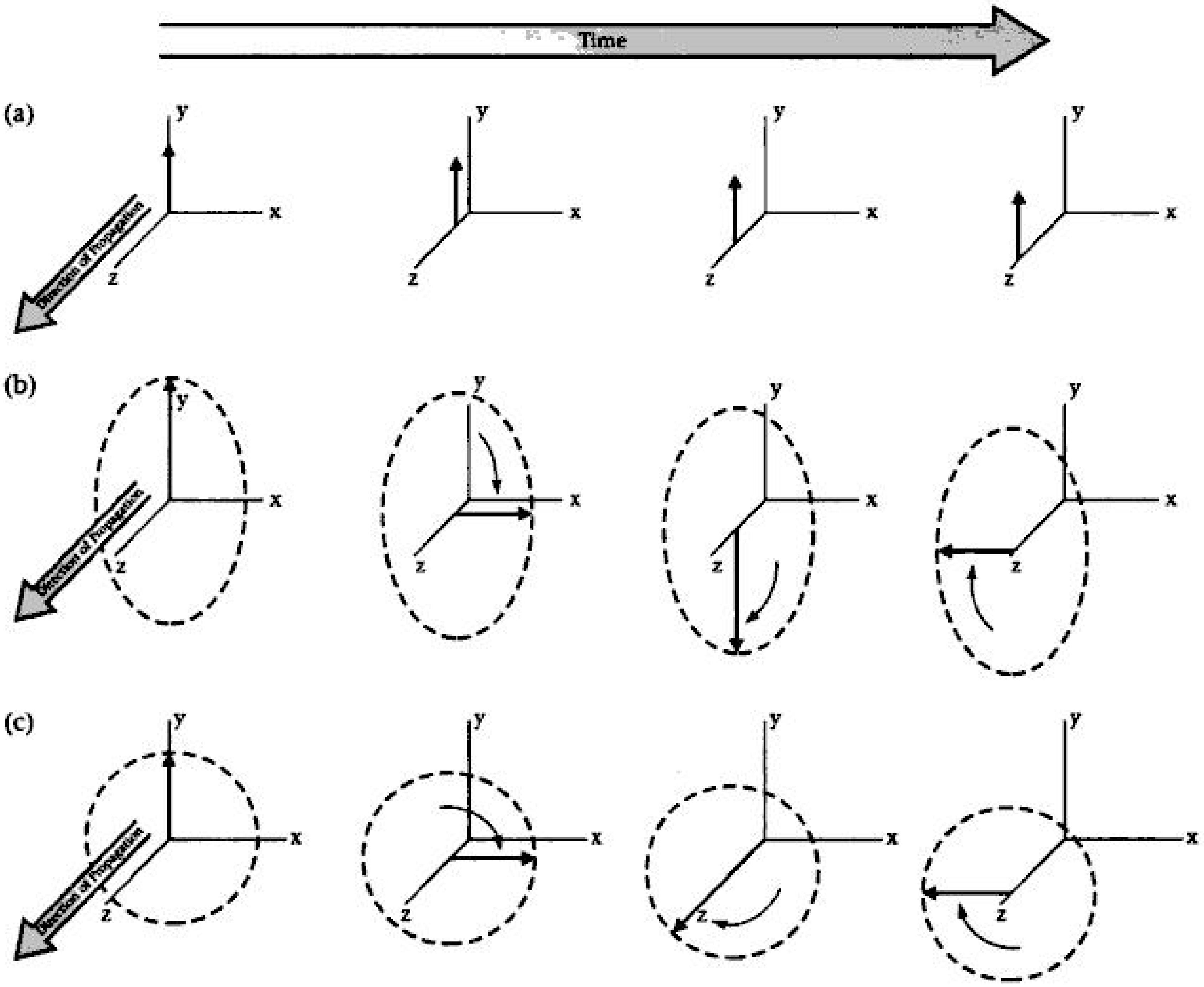


FIGURE 2–8 Polarization states: (a) linear polarization, (b) elliptical polarization, and (c) circular polarization.

Coherence

If we have more than one electromagnetic wave, we can express the **phase** difference (ϕ) between the waves, or displacement of one wave from another by

$$E_1(z,t) - E_{01}\sin(\omega t - kz)$$

and

$$E_2(z,t) - E_{02}\sin(\omega t - kz + \phi)$$

(assuming ω and k are the same for each wave)

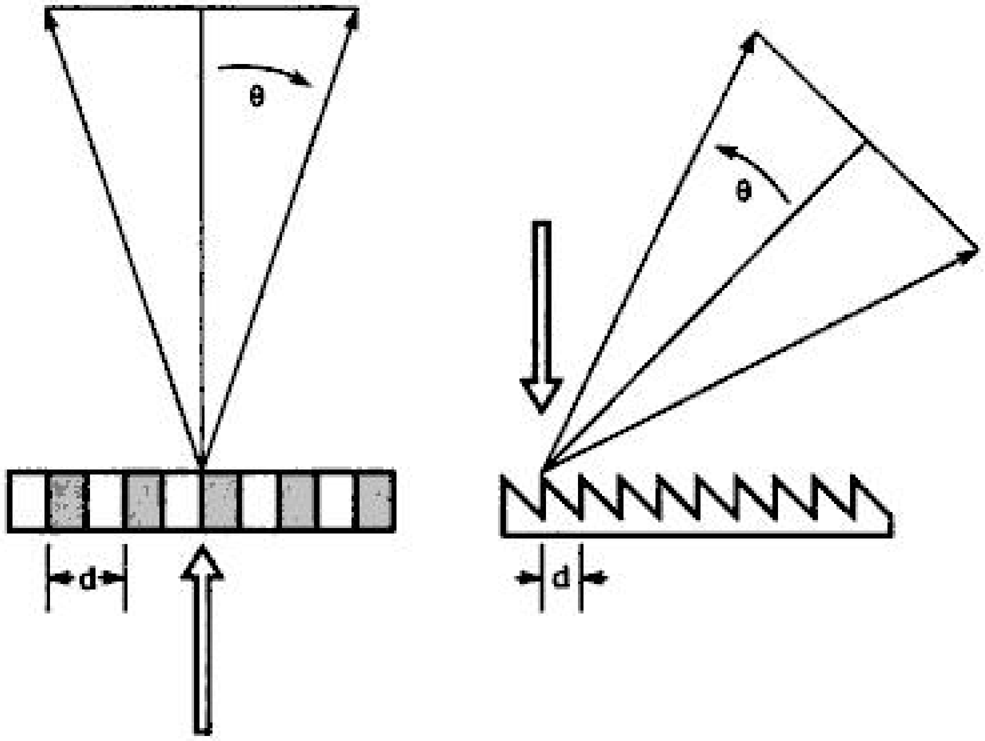


FIGURE 2–12
Transmission and reflection gratings.

interference play a large role in establishing fiber modes, as we shall see in Chapter 3.

EXAMPLE 2.7

A Fabry-Perot cavity inside a glass substrate (n = 1.52) is adjustable between about 100 μm and 100.1 μm. What length will be needed for optimization of 1550 nm?

SOLUTION

$$L = \frac{m\lambda}{2n} \approx 100\ \mu m >> m = \frac{2nL}{\lambda} = \frac{2(1.52)(100\ \mu m)}{1550\ nm} \approx 197$$

$$L = \frac{m\lambda}{2n} = \frac{197(1550\ nm)}{2(1.52)}$$

$$\boxed{L = 100.44\ nm}$$

EXAMPLE 2.8

A transmission grating is made from evenly spaced dark lines (1,000 lines per millimeter) on a glass plate. At what angle will the first three orders of red light (650 nm) be diffracted?

•–SOLUTION

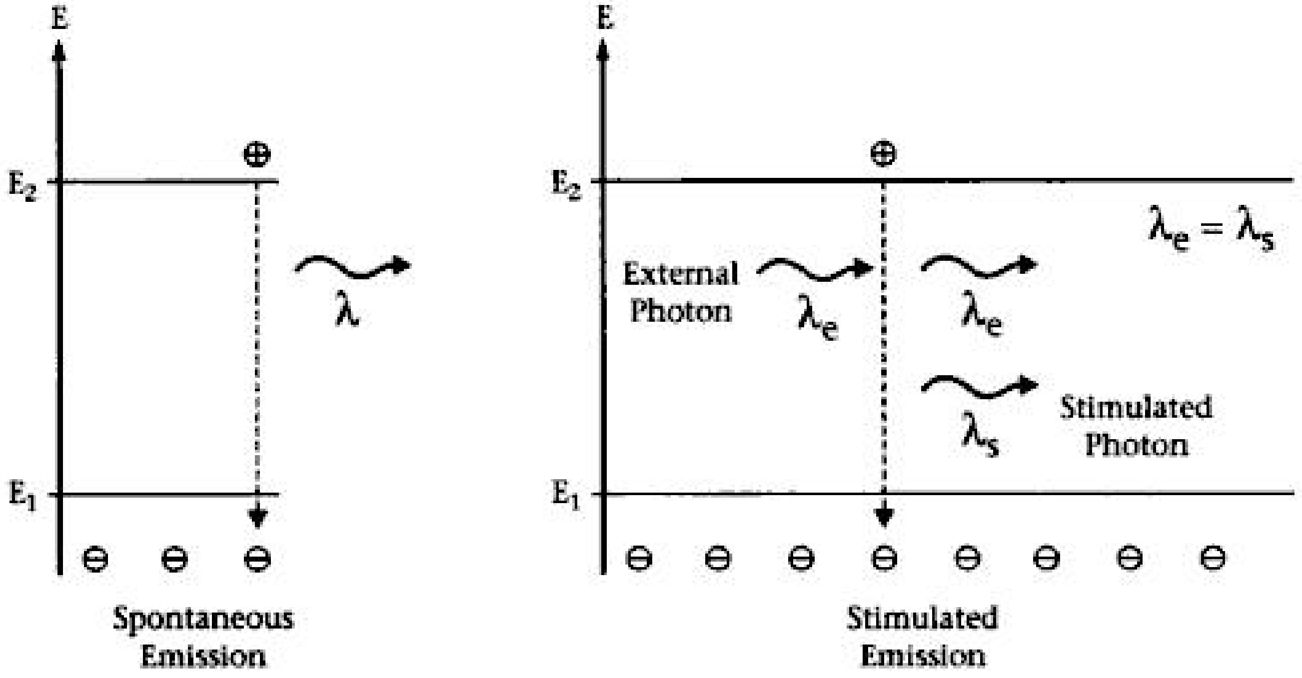
$$P_{out} = P_{in}\, e^{-\alpha x} = (2\text{ mW})\, e^{\frac{-0.2}{\text{cm}}(2\text{ cm})}$$

$$\boxed{P_{out} = 1.34\text{ mW}}$$

Emission

If an atom begins with an electron in the excited state and then it returns to its ground state, often energy is released in the form of a photon and light energy is produced. This process is called **emission**. This emission process can be spontaneous or stimulated. **Spontaneous emission** is the process just described wherein an excited electron returns to its initial state and releases a photon. In **stimulated emission**, an electron excited by an external photon has excess energy and in turn is stimulated by an additional external photon. The second external photon causes the excited electron to drop to the ground state, which adds a second photon of the same wavelength. Lasers require stimulated emission as we shall see in Chapter 5. Spontaneous and stimulated emission are illustrated in Figure 2–16.

FIGURE 2–16
Spontaneous and stimulated emission.



Usually emission involves sublevels and the probabilistic nature of quantum energies, so the wavelength of light emitted stretches over a finite width known as the **linewidth** ($\Delta\lambda$). In terms of frequency, the corresponding width is found from Equation 2–8 by

$$\Delta v \approx \frac{c\,\Delta\lambda}{\lambda^2} \qquad \text{(2–16)}$$

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and the output can be determined directly by

$$P_{out\text{-}dBm} = P_{in\text{-}dBm} + T_{dB} \tag{2–25}$$

EXAMPLE 2.12

For a system with a gain of 10, find the output for an input of 20 mW using both Watts and dBms.

SOLUTION

$$T = \frac{P_{out}}{P_{in}} \rightarrow P_{out} = TP_{in} = (10)(20\text{ mW})\; P_{out} \text{ in mW} = 200 \text{ mW}$$

$$P_{in\text{-}dBm} = 10\log\left(\frac{P \text{ in mW}}{1\text{ mW}}\right) = 10\log\left(\frac{20\text{ mW}}{1\text{ mW}}\right) = 13\text{ dBm}$$

$$T_{dB} = 10\ \log T = 10\ \log(10) = 10\text{ dB}$$

$$P_{out\text{-}dBm} = P_{in\text{-}dBm} + T_{dB} = 13\text{ dBm} + 10\text{ dB}$$

$$\boxed{P_{out\text{-}dBm} = 23\text{ dBm}}$$

also

$$P_{out} \text{ in mW} = 10^{\frac{P_{out\text{-}dBm}}{10}} = 10^{\frac{23}{10}}$$

$$\boxed{P_{out} \text{ in mW} = 200\text{ mW}}$$

Irradiance is based on power per unit area (W/m^2), and radiance is based on power per unit area per steradian (W/m^{2}sr) or irradiance per projected angle. Steradian is a measure of solid angle, or a ratio of the area of part of the surface of a sphere to the whole surface area of the sphere, or the area subtended by the solid angle divided by the radius squared. For a total sphere, the solid angle is $4\pi r^2/r^2 = 4\pi$ steradians.

Summary

The physics of light is an essential element in any study of fiber optics. From early studies by Newton and Huygens to Maxwell's electromagnetic equations, we have developed an adequate understanding of the somewhat contradictory properties of light. While light may behave like a particle or a wave and our definition of what light is has changed significantly over

fiber modes
graded-index fiber
leaky modes
material dispersion
modal dispersion
mode coupling
mode distribution
mode scrambler
mode-field diameter
multimode fiber
numerical aperture
photonic crystal fiber
polarization maintaining fiber
polarization mode dispersion
single-mode fiber
steady state
step-index fiber
V-number
waveguide dispersion

Introduction

Optical fiber is the key component in any fiber-optic communications system, serving as the media by which information can be transported at aggregate rates of over 1 Tbps. By examining the characteristics of the fiber, the dynamics of light propagation, and the limitations of fiber transport, we can then see how the control of various fiber parameters can lead to the optimization of fiber systems and the design of special fibers for specific communications applications.

In this chapter we will examine light propagation in optical fibers, limitations of fiber as a major communications medium, and how fiber design can optimize communications speed and bandwidth to overcome application limitations. Beginning with a look at how light propagation is governed by the numerical aperture (NA) and modal structure of the fiber, we will see how propagation is limited by dispersion and fiber losses. While NA and modal structure determine the shape of the input and output beams and the angles at which light waves will propagate, the control of both pulse spreading and loss of power with length is essential in establishing efficient fiber communication links. The modal structure and wavelength dependence of numerical aperture dominates dispersion while inherent fiber losses or attenuation is a result of material absorption and scattering. A study of various fiber types will serve to underline the major differences in physical structure responsible for fiber performance. After a comparison of the performance and applications of fiber types, we will investigate special fibers designed for specific communications applications and learn how to minimize the effect of fiber dispersion or loss mechanisms. Example problems and brief application notes will reinforce the concepts presented and clarify the process by which information is transported by fiber-optic means.

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The number of modes propagating in a common type of step-index fiber is approximated by:

$$N = \frac{V^2}{2} \tag{3–4}$$

For a special type called graded-index fiber, the V-number is approximated as 3.4. Step- and graded-index fibers will be explained in more detail in the Section 3.4.

•—EXAMPLE 3.2

Determine the number of propagating modes in a step-index fiber with a numerical aperture of .18 and a core radius of 50 μm at 1300 nm.

•—SOLUTION

$$V = \frac{2\pi a\,\mathrm{NA}}{\lambda} = \frac{2\pi(50 \times 10^{-6})(.18)}{1300 \times 10^{-9}} = 43.5$$

$$N = \frac{V^2}{2} = \frac{41.25^2}{2}$$

$$\boxed{N = 946}$$

•—EXAMPLE 3.3

Find the radius required for single-mode operation at 1300 nm of a fiber with a numerical aperture of .12.

•—SOLUTION

$$V = \frac{2\pi a\,\mathrm{NA}}{\lambda} < 2.405$$

$$a < \frac{2.405\lambda}{2\pi \mathrm{NA}} \quad \text{or} \quad a < \frac{2.405(1300 \times 10^{-9})}{2\pi(.12)}$$

$$\boxed{a < 4.15\ \mu\mathrm{m}}$$

Modal Properties

Ideally, all available modes (or angles) within the fiber carry equal amounts of energy and are confined to their own paths within the core. This is not generally the case, as the actual mode distribution is a result of launch

$$z_t = \frac{z}{\sin \phi}$$

where z_t is the longest length traveled, z is the shortest length and the actual length of the fiber, and ϕ is the angle of incidence as measured from the normal to the core/clad interface. The difference between the minimum (z) and maximum (z_t) pathlengths traveled along with the velocity can lead to an expression for the modal dispersion per unit length. Saving the derivation for a student exercise, the result shows

$$D_{mod} = \frac{1000n_1}{c}\left(\frac{n_1}{n_2} - 1\right) \text{ in } \left[\frac{s}{km}\right] \tag{3-7}$$

where the D_{mod} is the modal dispersion parameter and c is the speed of light in a vacuum. The modal dispersion for a given length is then

$$\Delta t_{mod} = D_{mod} z \tag{3-8}$$

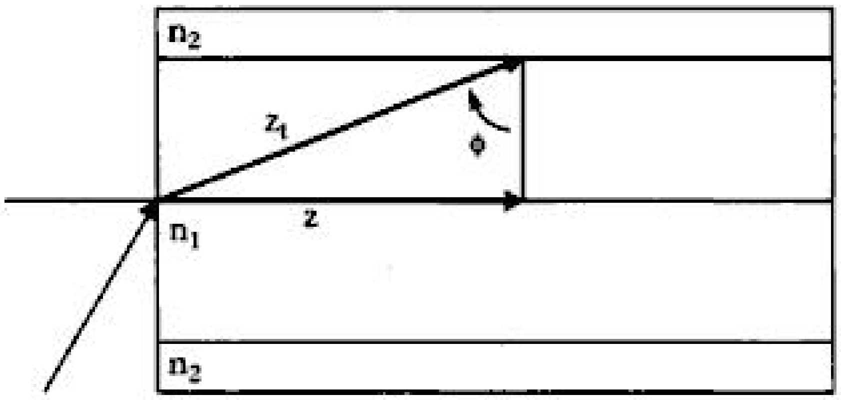


FIGURE 3–4 Modal dispersion.

•—EXAMPLE 3.5

For a 5-km fiber with core index of 1.51 and a clad index of 1.49, find the total modal dispersion.

•—SOLUTION

$$D_{mod} = \frac{1000n_1}{c}\left(\frac{n_1}{n_2} - 1\right) = \frac{1000(1.51)}{3 \times 10^8}\left(\frac{1.51}{1.49} - 1\right) = 67.6\frac{ns}{km}$$

$$\Delta t_{mod} = D_{mod} z = \left(67.6\frac{ns}{km}\right)(5\ km)$$

$$\boxed{\Delta t_{mod} = 338\ ns}$$

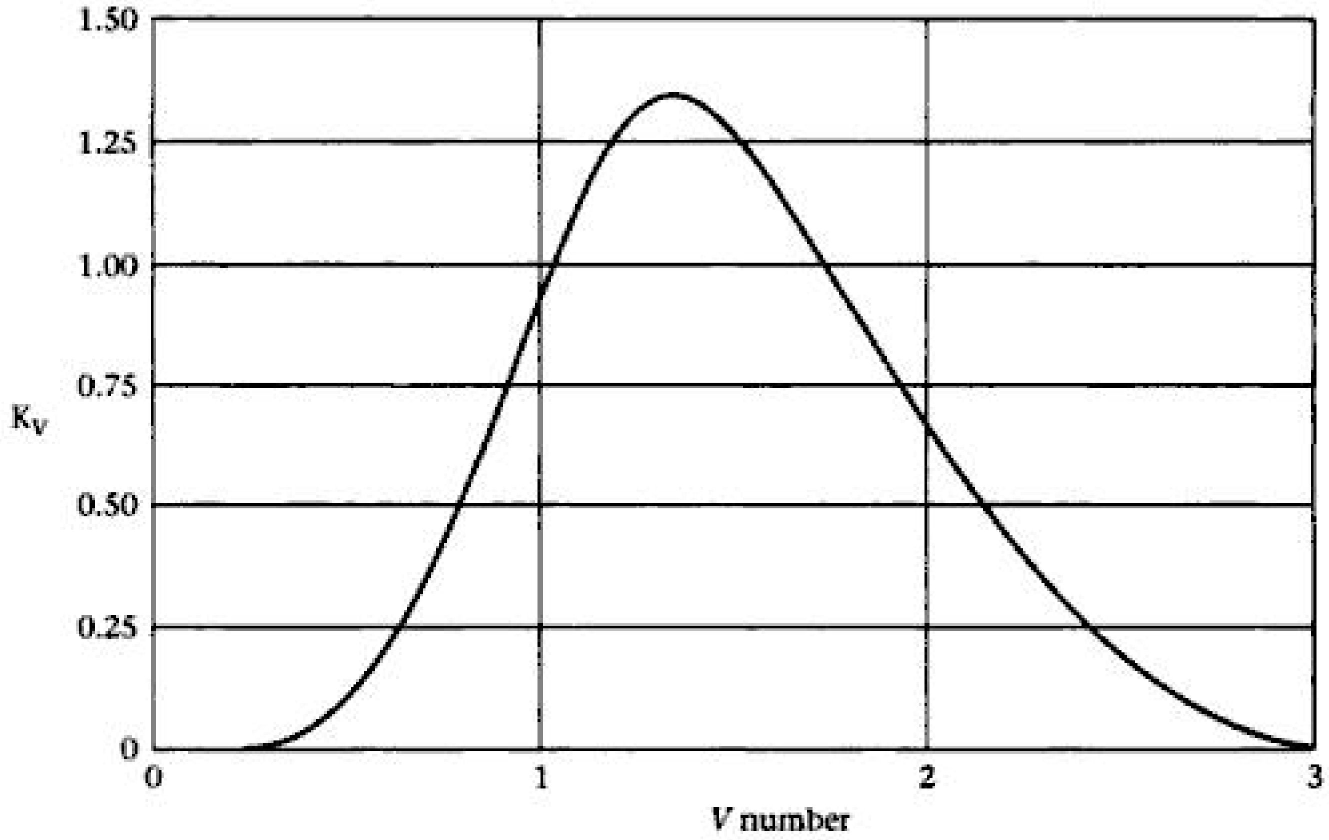


FIGURE 3–9 Graphical representation of waveguide dispersion parameter.

constant (K_V) as a function of the V-number about the single-mode fiber condition V-number (V = 2.405). The waveguide dispersion factor is then determined by

$$D_{wg} = \left(\frac{n_2}{c\lambda}\right)\left(\frac{n_1 - n_2}{n_1}\right)K_V \quad \text{in} \quad \left[\frac{s}{nm \cdot km}\right] \tag{3–10}$$

where c is in km (3×10^5 km) and λ is in nm. Finally, the total waveguide dispersion is

$$\Delta_{t_{wg}} = D_{wg} z \Delta\lambda \tag{3–11}$$

•—EXAMPLE 3.7

For a single-mode silica fiber with a core index of 1.480 and a clad index of 1.475, find the total waveguide dispersion for a length of 3 km. The fiber has a V-number of 2.25, and the source has a wavelength of 1310 nm and a linewidth of 40 nm. Use Figure 3–9 to find the waveguide dispersion coefficient.

•–SOLUTION

From the figure, $K_V = 0.40$. Then

$$\Delta t_{pol} = D_{pol}\sqrt{z} = +85\left[\frac{s}{\sqrt{km}}\right]\sqrt{5.0\ km} = 425\ ps$$

$$\Delta t_{total} = \sqrt{\Delta t^{2}_{chrom} + \Delta t^{2}_{pol}} = \sqrt{2.4^{2} + 0.425^{2}}$$

$$\boxed{\Delta t_{total} = 2.44\ ns}$$

$$D_{tot}\ z\Delta\lambda = -35.4\left[\frac{ps}{nm \cdot km}\right] \times 3\ km \times 40\ nm = 4.25\ ns$$

$$t_{out} = t_{in} + \Delta_{t\text{-}total} = 20\ ns + 2.44\ ns$$

$$\boxed{t_{out} = 22.4\ ns}$$

$$B = \frac{1}{t_{out}} = \frac{1}{t_{in} + \Delta_{t\text{-}total}} + \frac{1}{22.4\ ns}$$

$$\boxed{B = 44.6\ Mbps}$$

3.3 Fiber Losses

Fiber losses are certainly the most critical of fiber characteristics, and they can be divided into several categories. While some losses are more significant than others, an understanding of absorption, scattering, and bending losses is essential to the comprehension of optical fiber performance. All internal losses are wavelength dependent and can be combined into one attenuation coefficient, which describes the total loss induced in the fiber at a specific wavelength per unit length. Other losses, which are initiated from the physical structure of the cable or layout of the installation, can be determined from measurement and should be kept to a minimum.

Absorption

As detailed in Chapter 2, absorption occurs when a photon is absorbed by an atom or molecule, changing the energy of the system. The primary absorption processes in silica fiber are due to small traces of metal impurities in the glass and from OH bonds formed from oxygen in the glass. The presence of OH absorption peaks at 0.95 μm, 1.24 μm, and 1.38 μm had eliminated these bands for communications uses until the 1990s, when vast improvements in fiber manufacturing processes virtually eliminated losses due to OH absorption. Fiber losses below about 1.55 μm are now primarily governed by scattering, as we shall see in the next section. At wavelengths greater than 1.55 μm, infrared vibration absorption becomes dominant.

•—EXAMPLE 3.10

Find the output power in milliwatts for Example 3.9 if the input power is 30 mW.

•–SOLUTION

$$P_{dBm\text{-}in} = 10\log\left(\frac{P_{in}}{1\ \text{mW}}\right) = 10\log\left(\frac{30}{1}\right) = 14.8\ \text{dBm}$$

$$P_{dBm\text{-}out} = P_{dBm\text{-}in} - 2\ \text{dB} = 12.8\ \text{dBm}$$

$$P_{out} = 10^{\frac{P_{dBm\text{-}out}}{10}} = 10^{\frac{12.8\ \text{dBm}}{10}}$$

$$\boxed{P_{out} = 19.05\ \text{mW}}$$

Bending Losses

Bending losses occur when the total internal reflection is compromised by the physical condition of the installation. Microbends are the result of physical or thermal stress at the core/clad interface, which cause small cracks or bumps and change the effective critical angle. Macrobends are caused by the addition of sharp corners or sags in the fiber cable upon installation. In both cases some light is lost, which can have a cumulative effect over long distances.

3.4 Types of Fiber

Optical fiber can be manufactured to optimize performance for different communications applications. The major types are categorized by their diameter and refractive index profile, where the index profile is the refractive index as a function of fiber radius. Equations 3–2 and 3–3 define multimode and single-mode fibers according to their core radii. Step-index and graded-index fibers have special refractive index profiles, as do some other fiber types as shown in Figure 3–14.

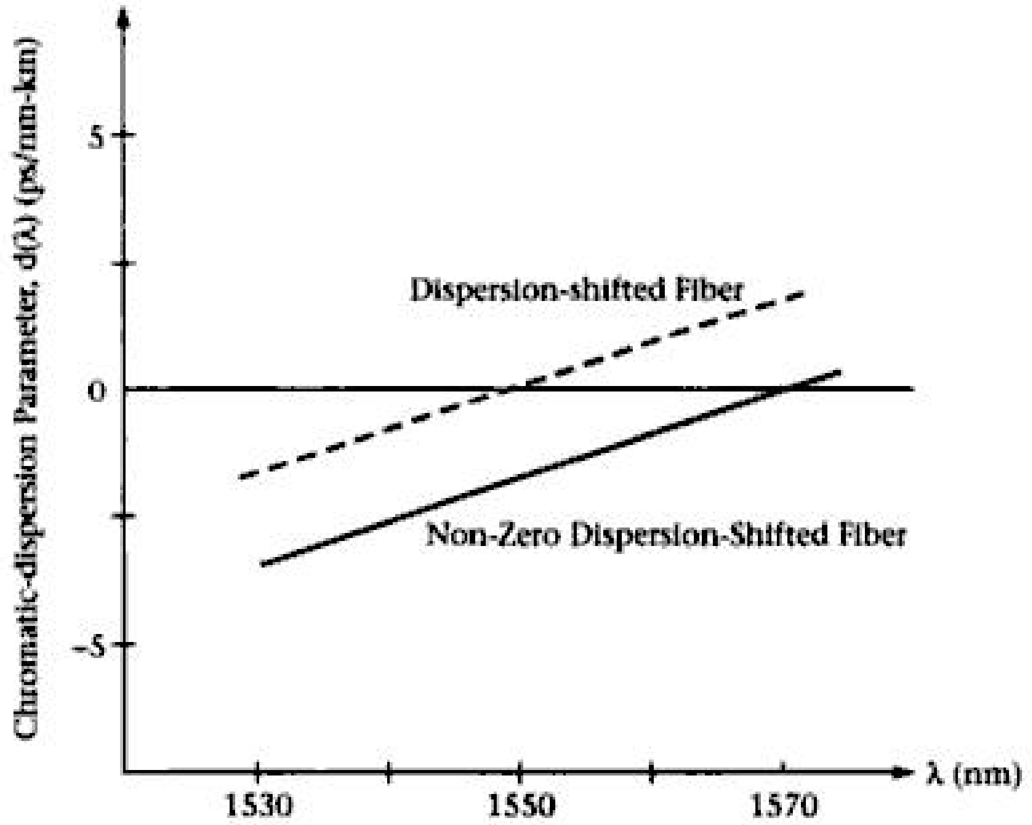
Multimode Fiber

Multimode (MM) fiber allows for the transmission of more than just a single mode. MM fiber is relatively inexpensive and easy to couple with LED sources and detectors. The addition of a large bandwidth (< 200 MHz-Km)

Dispersion-Shifted Fiber

Dispersion-shifted fiber (DSF) adjusts for pulse spreading caused by material and waveguide dispersion. Compensating fiber can also be used to adjust for dispersion in existing fiber systems. Since waveguide dispersion offsets material dispersion at 1.31 μm in step-index single-mode fiber, it makes sense that appropriate adjustments to various forms of dispersion could eliminate dispersion at the region of interest. For instance, zero dispersion-shifted fibers can be made with increased waveguide dispersion to achieve zero total dispersion near 1.55 μm where fiber absorption is minimum. Non-zero dispersion-shifted fibers move the total dispersion slope outside of the erbium-fiber band to avoid fourwave mixing. A graphical view of dispersion-shifted fiber is shown in Figure 3–16. Note that low (but not zero) dispersion can be achieved with layered core structures.

TFIGURE 3–16 Dispersion-shifted fibers.



For existing systems, alternating lengths of positive and negative dispersion-shifted fibers allow for the upgrade of existing single-mode fiber systems to 10 Gb/s and higher over the entire fiber window region. In this general approach, finite local dispersion is used to generate near zero total system dispersion. Look for other special fibers for dispersion management as the demand for more bandwidth continues.

Polarization Maintaining Fiber

Polarization maintaining fiber (PMF) is used in lithium niobate modulators, Raman amplifiers, and other polarization sensitive systems to

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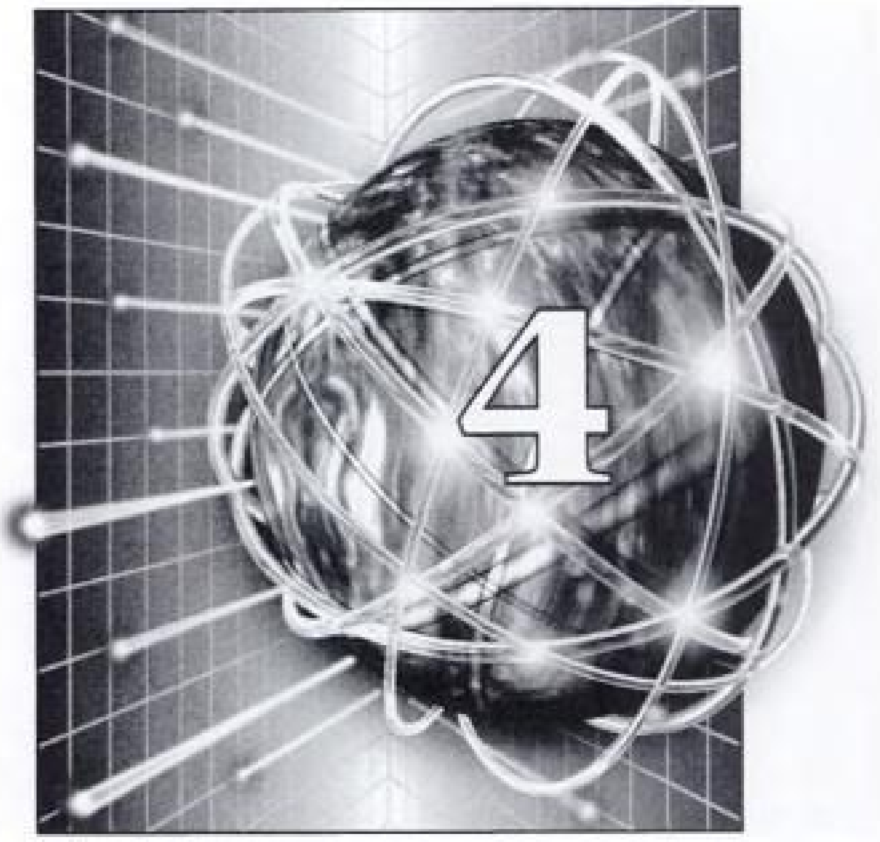
Questions

SECTION 3.1

1. The incident angular cone of light, which is transmitted down an optical fiber, is called
   - **A.** minimum angle.
   - **B.** numerical aperture.
   - **C.** critical angle.
   - **D.** acceptance angle.
2. The sine of the half-angle of the acceptance angle is known as the
   - **A.** numerical aperture.
   - **B.** acceptance cone.
   - **C.** critical angle.
   - **D.** refractive index.
3. At the core/clad interface, the critical angle occurs when the refracted angle is at what angle?
   - **A.** 45°
   - **B.** 90°
   - **C.** 0°
   - **D.** 180°
4. Under what conditions is numerical aperture evaluated?
   - **A.** short lengths of fiber
   - **B.** high frequencies
   - **C.** high power
   - **D.** steady state
5. What factor does not contribute to the cutoff wavelength of a fiber and the mode-field diameter at the output?
   - **A.** core diameter
   - **B.** wavelength
   - **C.** numerical aperture
   - **D.** input power
6. What happens to the highest order modes at bends in a fiber?
   - **A.** nothing
   - **B.** light escapes
   - **C.** light enters the clad and cannot escape
   - **D.** propagation is enhanced
7. The transfer of energy between modes is called
   - **A.** transfer function.
   - **B.** crosstalk.
   - **C.** dispersion.
   - **D.** attenuation.
8. What is used to reach a steady state of energy on shorter fiber lengths?
   - **A.** cleaver
   - **B.** leaky modes
   - **C.** mode scrambler
   - **D.** dispersion
9. What modes should be avoided on longer runs of fiber?
   - **A.** leaky modes
   - **B.** dispersion
   - **C.** cutoff
   - **D.** mode distribution
10. The mode field diameter is what diameter of a multimode fiber?
    - **A.** numerical aperture
    - **B.** core diameter
    - **C.** Gaussian-shaped spot
    - **D.** modal dispersion
11. A Gaussian-shaped spot is generated at the output of a single-mode fiber that is ________ than the core size.
    - **A.** smaller
    - **B.** larger
    - **C.** the same
    - **D.** none of the above

Fiber and Cable Fabrication



Objectives Upon completion of this chapter, the student should be able to:

- Become familiar with fiber fabrication processes
- Describe the fiber draw process
- Identify the parts of a fiber cable
- Define tensile strength and bend radius
- Identify the common types of fiber connectors
- Understand the principles of fiber and connector losses
- Describe intrinsic and extrinsic connector losses
- Calculate intrinsic diameter and NA mismatch losses
- Define insertion loss and return loss
- Understand the procedures involved with cleaving, polishing, connectorization, and splicing

Outline
4.1 Optical Fiber Fabrication
4.2 Fiber Cable
4.3 Connectors
4.4 Connector Losses
4.5 Splices

Key Terms
APC finish
axial vapor deposition
double crucible method
duplex
extrinsic losses
flat finish
fusion splicer
insertion loss
inside vapor deposition
intrinsic losses
jacket
loose buffer

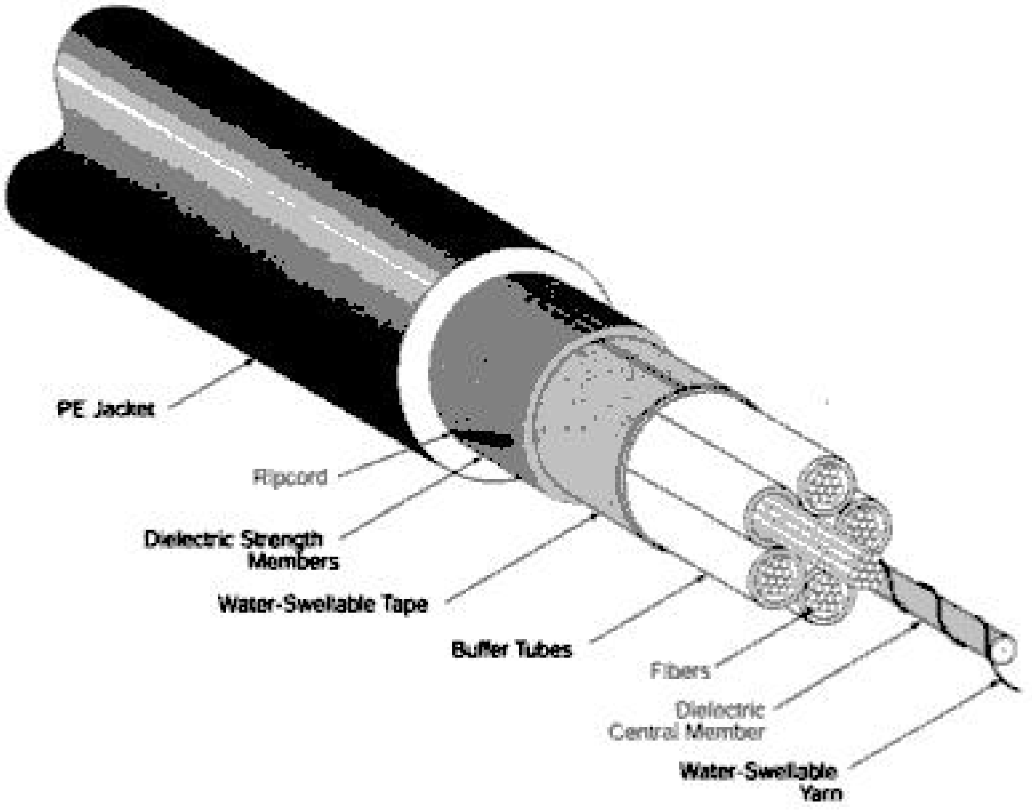


FIGURE 4–9 *(continued)*

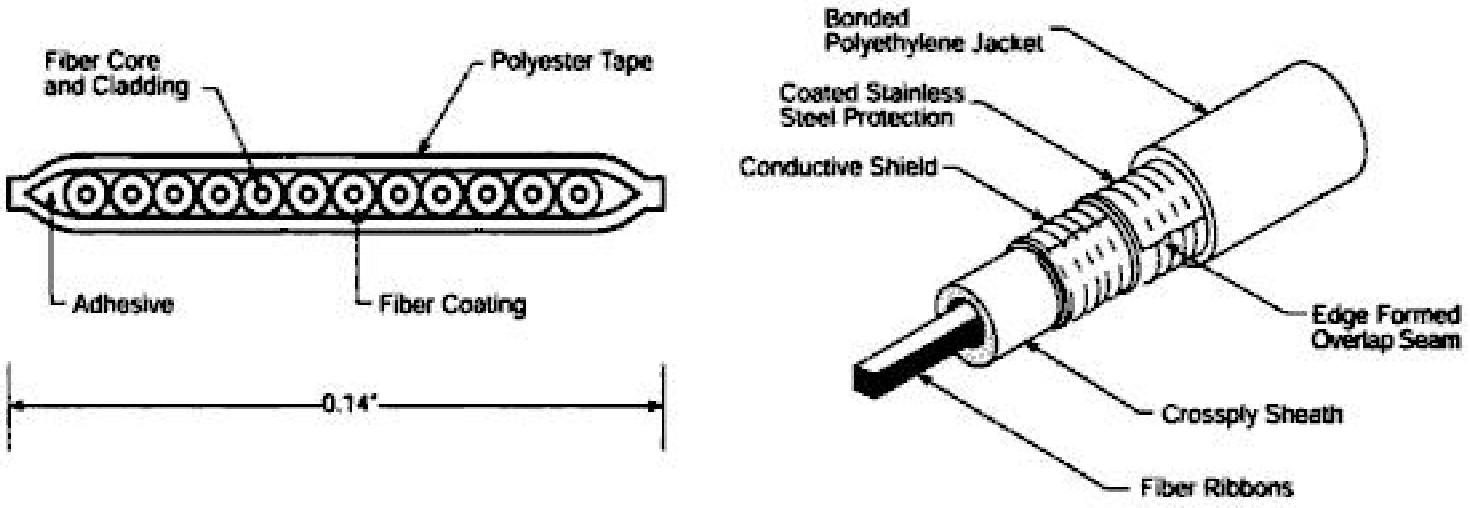


FIGURE 4–10 Ribbon cables.

Cables can also be classified according to their applications. The four basic applications are light duty, heavy duty, between walls (plenum), and between floors (riser). Indoor cables are of many types and structures and are usually pulled through walls, floors, and ceilings. Outdoor cables must be able to withstand the environment and are used in telephone pole, trench, buried duct, or underwater installations. Obviously, outdoor cables must be provided with sufficient protection against the elements.

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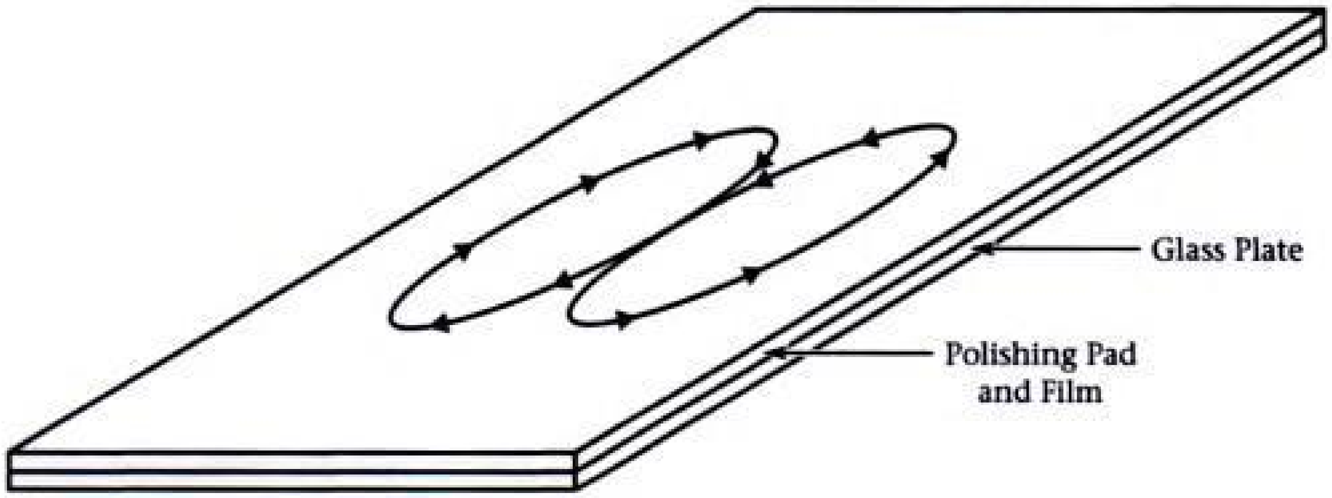
FIGURE 4–15
Polishing machine.

FIGURE 4–16 Hand polishing motion.



cleaned with isopropanol, and then the procedure is repeated using 1-µm and 0.3-µm polishing films. This technique should leave a smooth, clean fiber-end face, ready for connection. The ends should be inspected, using a fiber inspection scope or a fiber video viewer (Figure 4–18). If the end face is not clean and smooth, the polishing procedure should be repeated. Some good and bad end-face polishes are shown in Figure 4–19 on page 115.

RJ-45 type connector with a push-to-release latch. Volition connectors continue the trend of smaller and easier to use connectors. The VF-45 consists of a fiber holder, hinged door, and V-groove body for alignment. When the connection is made, pressure forces the fibers closer together.

4.4 Connector Losses

Many factors contribute to attenuation when two fibers are connected together. In general, connector losses can be divided into those losses caused by the fiber (intrinsic losses), and those caused by the connector (extrinsic losses). Most devices inserted inline (including connectors and splices) are also described by a total or insertion loss. Note that the length of the fiber plays an important part in loss as described in Section 3.3. Here, short fiber lengths are to be expected, and higher order modes will propagate producing higher numerical aperture and spot size and sometimes greater loss. Steady-state conditions may not exist in all connector circumstances, so the measurement lengths should always be considered when evaluating connector loss.

Intrinsic Losses

Intrinsic losses occur because no two fibers are exactly identical. Losses can occur from numerical aperture mismatch, core diameter mismatch, and core area mismatch. Figure 4–24 shows the geometries for these losses. Numerical aperture mismatch causes light to be wasted when the NA of the first fiber is larger than that of the second. Note that no loss occurs and a gain is often falsely indicated when light travels in the other direction. But for $NA_1 > NA_2$, we have the transmitted light in decibels as

$$T_{dB} = 10 \log T = 10 \log \left(\frac{NA_2}{NA_1} \right)^2 \tag{4–1}$$

$$T_{dB} = 20 \log \left(\frac{NA_2}{NA_1} \right)$$

Of course T_{dB} will be negative, indicating a loss.

When core diameters are not identical we have (for $d_1 > d_2$)

$$T_{dB} = 10 \log T = 10 \log \left(\frac{d_2}{d_1} \right)^2 \tag{4–2}$$

$$T_{dB} = 20 \log \left(\frac{d_2}{d_1} \right)$$

- **C.** weighed.
- **D.** covered.

12. The fiber end is polished using a _______ motion.
- **A.** circular
- **B.** back-and-forth
- **C.** figure-eight
- **D.** up-and-down

13. The domed finish, allowing core centers to come in contact, is called
- **A.** PC.
- **B.** face-to-face.
- **C.** index matching gel.
- **D.** core-centered.

14. The type of end finish that involves an angled polish and yields the least connector losses is the
- **A.** PC.
- **B.** face-to-face.
- **C.** APC.
- **D.** side-on.

15. SFF connectors all have a
- **A.** single fiber form.
- **B.** small fiber finish.
- **C.** small form factor.
- **D.** swimming for fun.

16. Standard connectors are all based on a
- **A.** small form factor.
- **B.** snap-in plug.
- **C.** push-pull connector.
- **D.** 2.5-mm ceramic ferrule.

17. MT type connectors hold
- **A.** 12 fibers.
- **B.** fiber cables.
- **C.** single fiber.
- **D.** stacked connectors.

18. The LC connector has _______ as many fibers as standard connectors but in the same area.
- **A.** only
- **B.** twice
- **C.** half
- **D.** three times

SECTION 4.4

19. Intrinsic fiber connector losses are caused by differences in the
- **A.** connectors.
- **B.** fiber.
- **C.** system.
- **D.** transmitter.

20. Extrinsic fiber connector losses are caused by differences in the
- **A.** connectors.
- **B.** system.
- **C.** receiver.
- **D.** fiber.

21. Return loss is the result of fiber
- **A.** lateral displacement.
- **B.** angular displacement.
- **C.** NA mismatch.
- **D.** end separation.

22. When a component or fiber is installed inline in a system, the loss incurred is called the _______ loss.
- **A.** insertion
- **B.** reflection
- **C.** return
- **D.** intrinsic

23. Losses resulting from end separation can be minimized using
- **A.** UV curable epoxy.
- **B.** standard ST connectors.
- **C.** index matching gel.
- **D.** larger core sizes.

24. For light proceeding through a connector from fiber 1 to fiber 2, considerable loss (> 1 dB) occurs when
- **A.** $d_2 > d_1$.
- **B.** $NA_1 > NA_2$.

We begin this chapter with an explanation of source considerations and electronic principles necessary to understand conductors and semiconductors. Then, after a look at conduction at the atomic level and a review of the optoelectronic processes presented in Chapter 2, the operation, physical structure, and performance of both LEDs and laser diodes will be detailed. A discussion of source-to-fiber launch conditions, modulation techniques, and source drive circuitry will be followed by a physical description and the optical integration of practical transmitters.

5.1 Source Considerations

The optical source chosen must fit the application in terms of the fiber used and the type of data to be transmitted. The source must be matched to the fiber in terms of power, size, modal characteristics, numerical aperture, linewidth, and fiber-window wavelength range. The data type will dictate the bandwidth (and response time) and source modulation requirements. Then the source should provide the power necessary to launch a significant signal into the specific fiber diameter and numerical aperture without initiating nonlinear properties. The source wavelength and linewidth must be matched to the appropriate fiber window since bandwidth and modulation can be compromised by modal and chromatic dispersive effects.

5.2 Electronic Considerations

Optical sources used for fiber-optic communications are best understood when presented in conjunction with some basic electronic principles. Since materials used for both LEDs and laser diodes are semiconductors, it makes sense to gain an understanding of conduction before talking about the characteristics of semiconductors. The basic form of both devices is the *pn* junction diode, which will be detailed here.

Conduction

Conduction is the flow of electrons. The Bohr model of the atom is used again here, this time to illustrate how conduction arises. If a small voltage is placed across a **conductor** (such as copper), the electrons in the outermost shell of the conductor atom move from the valence band (their normal place) up into the conduction band as shown in Figure 5–1a on page 136. Here the negatively-charged electrons (–) are drawn toward the

11. If the semiconductor gives up rotational or vibrational energies in a transition, the bandgap is
    - **A.** indirect.
    - **B.** large.
    - **C.** lossy.
    - **D.** covered.
12. LEDs and laser diodes are generally fabricated from column ______ elements in the Periodic Table.
    - **A.** II-VI
    - **B.** III-V
    - **C.** I-VII
    - **D.** IV-VIII
13. When a semiconductor source *p*- and *n*-regions are fabricated from the same base material, the junction is called a
    - **A.** biased junction.
    - **B.** homojunction.
    - **C.** heterojunction.
    - **D.** active junction.
14. The transfer function of an LED is called the
    - **A.** responsivity.
    - **B.** quantum efficiency.
    - **C.** external power.
    - **D.** output.
15. LEDs have wavelengths that cover the entire fiber window and linewidths of
    - **A.** 4 nm to 6 nm.
    - **B.** 100 nm to 120 nm.
    - **C.** 20 pm to 30 pm.
    - **D.** 15 nm to 60 nm.
16. LEDs that have light emitted through the p-region are called ______ LEDs.
    - **A.** edge-emitting
    - **B.** *p*-type
    - **C.** positive-emitting
    - **D.** surface-emiting
17. LEDs are capable of coupling ______ of power into a fiber.
    - **A.** 1 mW to 10 mW
    - **B.** 0.01 μW to 0.1 μW
    - **C.** 10 μW to 100 μW
    - **D.** 1 μW to 10 μW

SECTION 5.4

18. The process of ________ ________ occurs when an external photon hits an excited-state electron, forcing a second photon to be emitted at the same wavelength.
    - **A.** stimulated emission
    - **B.** optical absorptionr
    - **C.** spontaneous emission
    - **D.** emission spectra
19. In ________ ________, more electrons are in the excited state than in the ground state.
    - **A.** stimulated emission
    - **B.** population inversion
    - **C.** positive feedback
    - **D.** spontaneous emission
20. In ________ ________, a Fabry-Perot resonator is produced by placing two mirrors at opposite ends of the active laser region.
    - **A.** stimulated emission
    - **B.** population inversion
    - **C.** positive feedback
    - **D.** spontaneous emission
21. The laser spectral output profile with secondary mode structures is produced as a result of both the stimulated emission process and the
    - **A.** material.
    - **B.** input.
    - **C.** current.
    - **D.** cavity.

generated. If an electric field is applied (see Figure 6–1), or in the case of a *pn* junction a potential is generated, electrons and holes are attracted to positive and negative charges, respectively, resulting in a current flow. As shown in Figure 6–2, the device detects incoming photons over a certain wavelength range by converting the photon energy greater than the bandgap energy into electron-hole pairs. Characteristics of some common semiconductor materials used in photodetectors are shown in Table 6–1. Note that materials can often be tuned to provide a particular wavelength response by adjusting the composition.

FIGURE 6–1 Photodetection in a semiconductor.

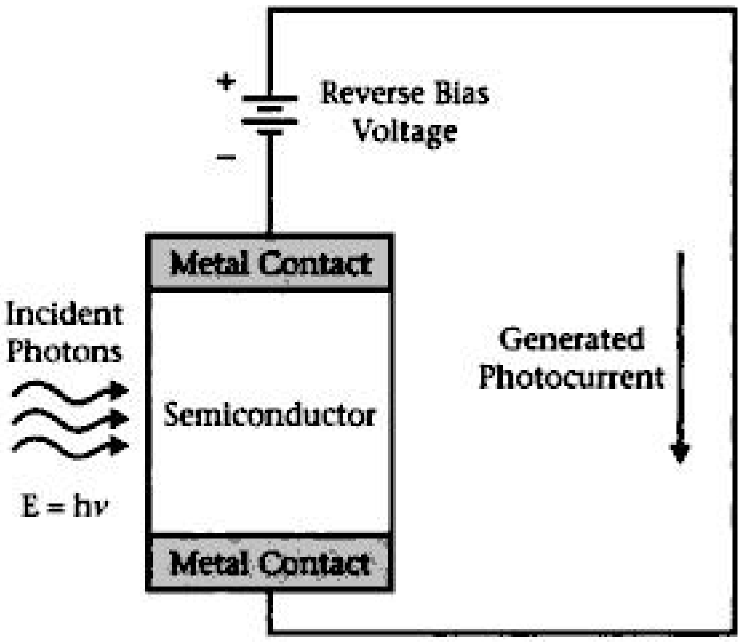
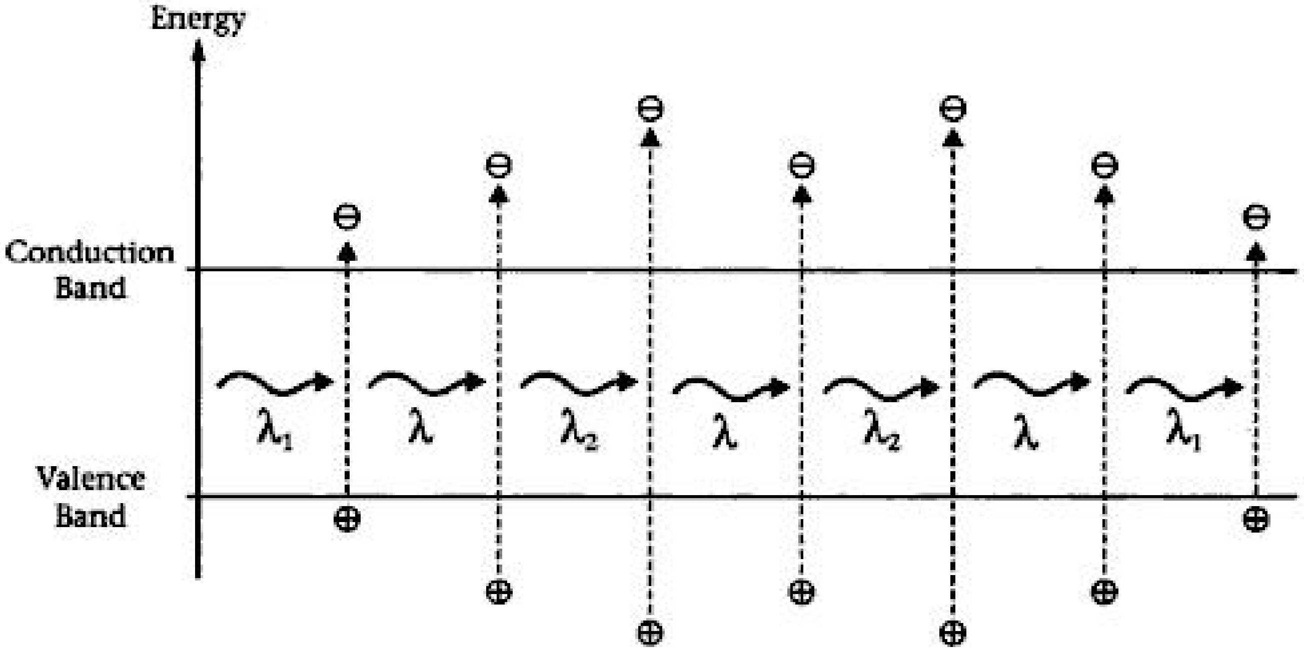


FIGURE 6–2 The photodetection process.



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difference at the receiver end is that, for most systems, the efficiency is higher. Still, reflections can be fed back through the fiber and hinder system performance, and the loss of even a small quantity of optical power out of the fiber can be critical for low-light levels. While the photodiode and amplifier stages were described in previous sections, we will detail several other receiver functions here.

Signal Recovery

The **signal recovery circuit** ensures that the correct information is received. Most fiber-optic communications systems use intensity modulation with direct detection, so no elaborate demodulation is required. For an analog signal, the information is already present from direct detection. Digital signal recovery requires further signal processing. This is accomplished by the decision and clock recovery circuits, which interpret the incoming data and generate a new synchronized data stream.

The **decision circuit** compares the incoming signal level to a threshold voltage, which determines if that bit is a one or a zero. The time at which the signal is sampled is determined by the recovered clock signal. The **clock recovery circuit** measures the bit slot and generates a new clock pulse for the decision circuit. This then helps the decision circuit to recover the original signal. The receiver must be designed such that the SNR is as high as possible and waveform distortion is minimized by the time the signal reaches the signal recovery stage. In this fashion, errors can be kept to a minimum. Error rates have yielded as few as one error in every 10^9 bits with the design techniques described above. Often an eye diagram (detailed in Chapters 9 and 10) is used to monitor receiver error performance.

Receiver Performance

Receivers are characterized by the efficiency with which they transform the optical signal into meaningful data. Dynamic range, sensitivity, SNR, and bit error rate are the major parameters considered when evaluating a receiver.

Dynamic range is the range of detectable signal levels with a linear response. The response of photodiodes and receivers can become nonlinear at higher powers, so this parameter serves as a guide to avoiding these anomalies. Common dynamic ranges are 30 to 40 dB.

Sensitivity, usually expressed in dBm, is the minimum input optical power level that can be detected by the receiver. Put another way, sensitivity is the minimum input power required to obtain the SNR needed for a specific quality of service. Quality of service (QoS) describes the reliability of a network or communications system under certain conditions. The SNR is a function of photodiode quantum efficiency, receiver noise statistics, demodulation losses or errors, and efficiency of error correction. As we found in the Section 6.3, noise is inescapable and difficult to quantify. The signal recovery process may reveal a time jitter or offset in the digital waveform, and error correction can also enhance SNR indirectly by improving the bit error rate. In the end, the bit error rate is probably the most important parameter for digital communications receivers as it most directly ties to communications system performance.

The **bit error rate (BER)** is the average probability of incorrect bit identification. While sometimes stated in bits per second, the more useful definition (bit rate independent) is the number of errors per number of bits, or one error in BER^{-1} bits. If we have one error for every 10^9 bits, the BER is 10^{-9}. In fact, most communications systems require a BER of 10^{-9}. For a typical receiver, a BER of 10^{-9} corresponds to a sensitivity of of –25 to –30 dBm. Figure 6–15 shows the relationship between receiver input power and BER for a typical *pin* receiver. Since the relationship between BER, SNR, and the sensitivity is based on noise statistics, error probabilities, and other variables, often a noise margin or power margin is added to the sensitivity to account for uncertainties in sensitivity estimation.

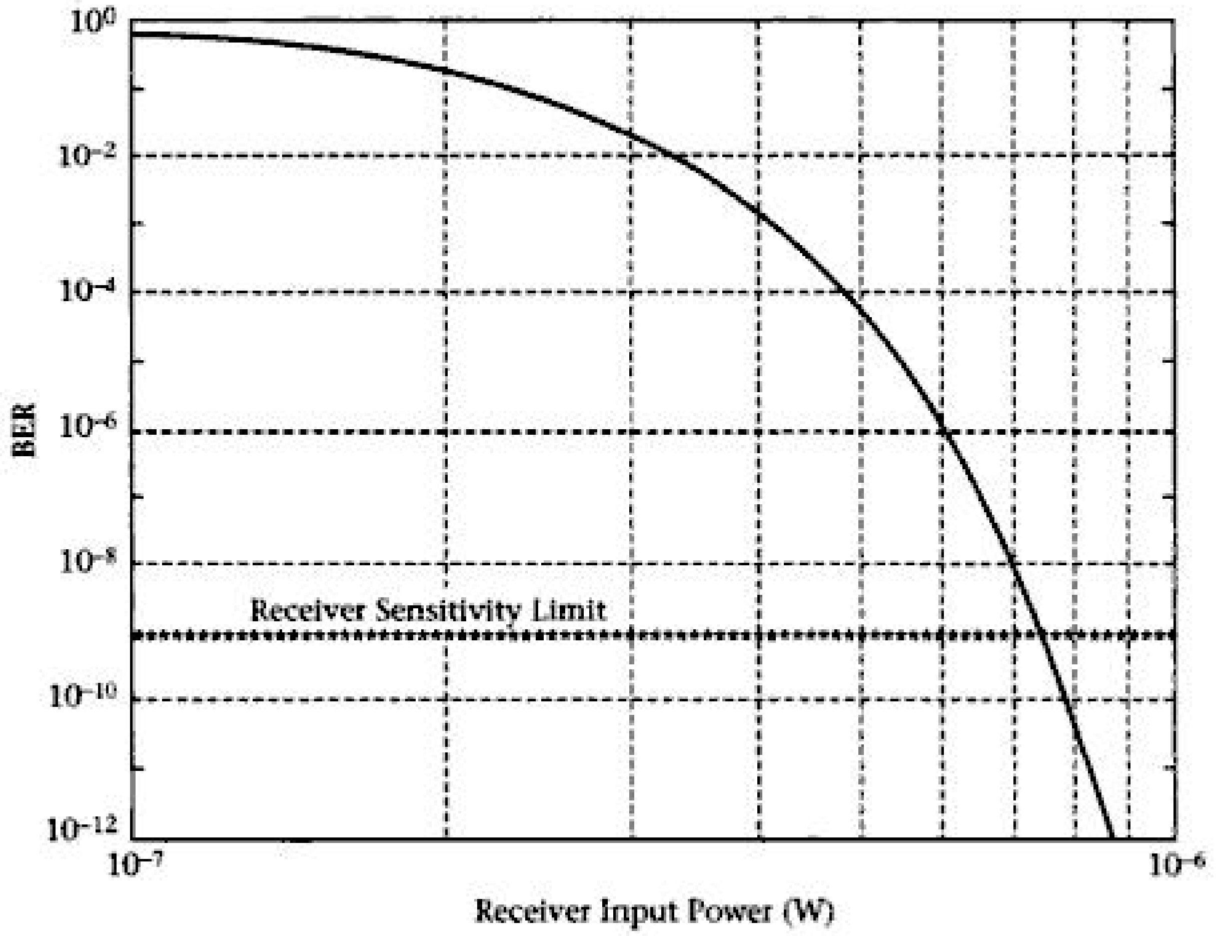

FIGURE 6–15 Bit error rate versus input power for a typical receiver system.

Receiver Packaging

Receiver packaging is important for the same reason that transmitter packaging is. Fiber end, photodiode, amplifiers, and signal recovery circuitry must all be protected from the installation environment. Also (even more detectivity, and noise equivalent power. The analysis and minimization of receiver noise is a critical part of any receiver design.

Amplifiers are used to make the small generated photocurrents larger before much noise has been added to the received signal without compromising the bandwidth. The two most common types are low-impedance and transimpedance. Either amplifier is usually followed by a main amplifier, which includes automatic gain control and a low-pass filter. By spreading the gain out over two amplifiers, more bandwidth can be preserved. Sometimes other functions, such as pulse shaping, are performed in this section in preparation for signal recovery.

Design and analysis of the receiver subsystems has led to advanced devices capable of wide bandwidth detection and information recovery. By optimizing the fiber input with direct- or lens-coupling and using the most efficient photodiode and preamplifier for the specific application, the front end can then send the signal through the main amplifier for further gain. The signal recovery section then extracts the original information from the signal. In the analog case, the signal is already present due to the direct detection of the photodetector. For digital signals, decision and clock recovery signals are used to regenerate the original digital information. Receiver performance is quantified using such parameters as sensitivity, dynamic range, and bit error rate, which describe the lowest detectable power level, the range of detectable powers, and the number of transmitted bits without error. Detector performance is significantly enhanced through integrated manufacturing and packaging.

Questions

SECTION 6.1

1. The fundamental process of photodetection begins with
   - **A.** conduction.
   - **B.** noise.
   - **C.** resistance.
   - **D.** absorption.
2. The transfer function of the photodetector is called the
   - **A.** bandwidth.
   - **B.** responsivity.
   - **C.** conductivity.
   - **D.** quantum efficiency.
3. Which of the following detector parameters is NOT necessary for fiber optic communications?
   - **A.** small linewidth
   - **B.** high speed
   - **C.** low noise
   - **D.** wide bandwidth
4. The distance at which the initial transmitted power level falls to 1/e of its original value is called the
   - **A.** absorption length.
   - **B.** depletion width.
   - **C.** penetration depth.
   - **D.** all of the above.

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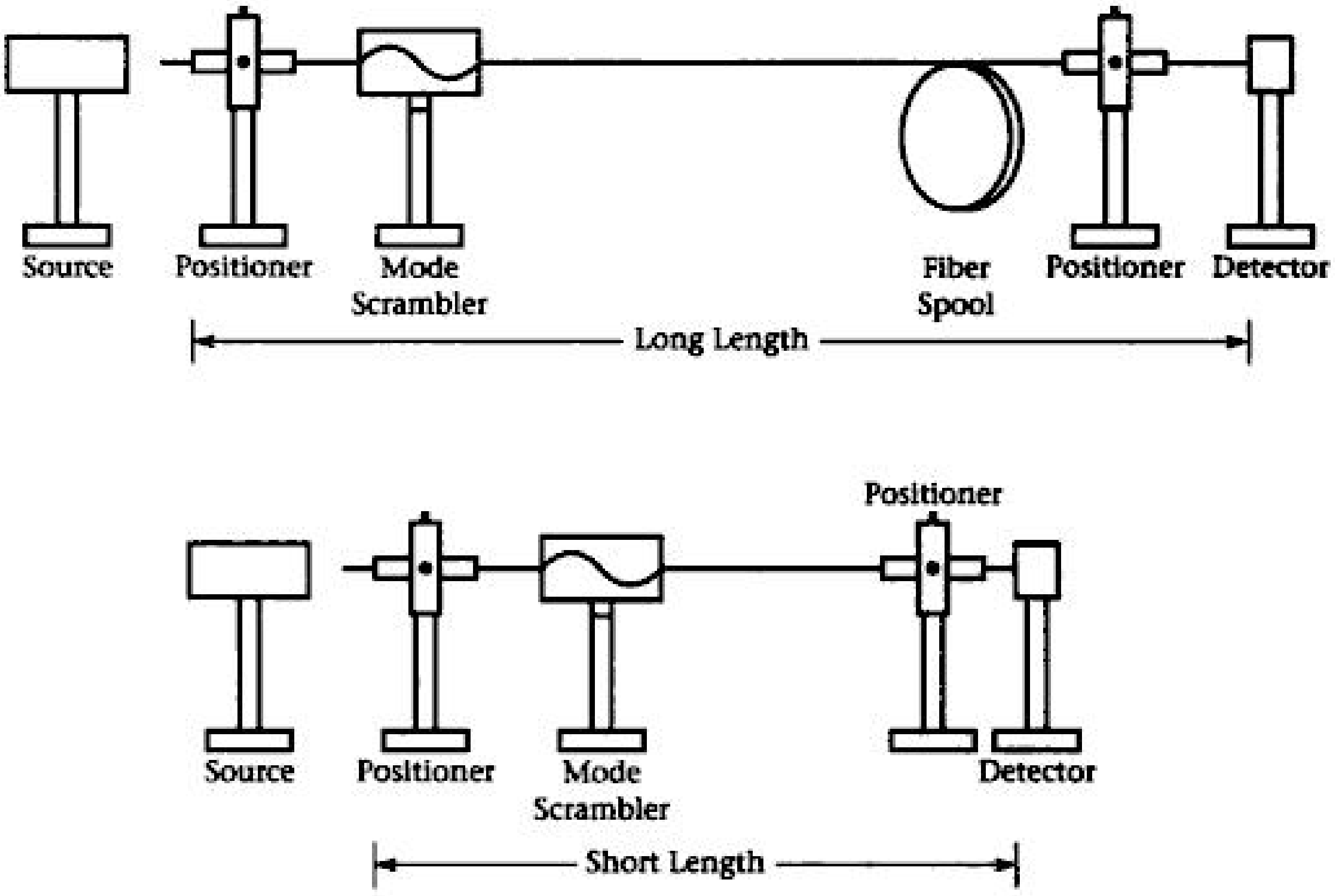
FIGURE 10–2 Fiber attenuation measurement: Cutback method.



beam should have a larger effective NA than the fiber, and the core should be overfilled and have a good cleave. The mode scrambler will take care of any unneeded modes. A detector is placed at the other end of the fiber (L_2) and a power measurement (P_2) is taken. Then, without moving the input in any way, the fiber is cut back to a length of 4 or 5 meters (L_1). The cut end (cleaved, of course) is placed at the detector, and the power is measured again (P_1). The attenuation coefficient (α) is then determined by

$$\alpha = \frac{P_{loss}}{L} = \frac{-10 \log\left(\frac{P_2}{P_1}\right)}{L_2 - L_1} \qquad \textbf{(10–1)}$$

where $L_2 - L_1$ is the actual length (L) of the fiber measured. Note that the only difference between the two measurements is the length of fiber, as the inputs are identical and the outputs are easily duplicated.

EXAMPLE 10.1

Determine the attenuation coefficient (dB/km) found using the cutback method on a 1-km length of fiber. The long length measured power was 475 μW and the short length (20 m) power was 625 μW.

•–SOLUTION

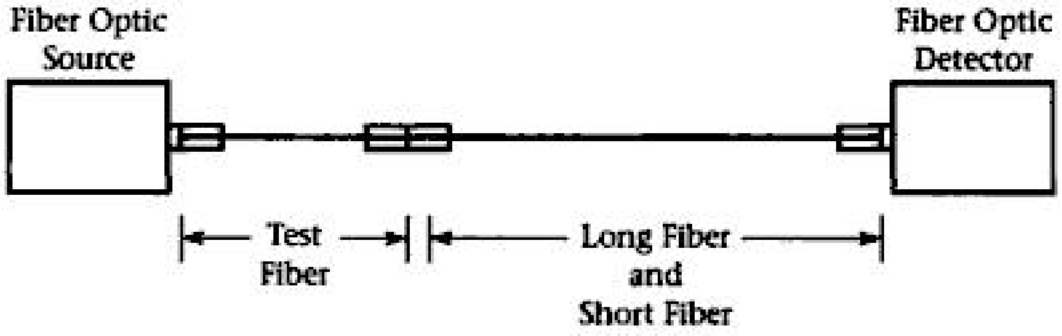
$$\alpha = \frac{P_{loss}}{L} = \frac{-10\log\left(\frac{P_2}{P_1}\right)}{L_2 - L_1} = \frac{-10\log\left(\frac{475\ \mu W}{625\ \mu W}\right)}{1\ km - 0.02\ km}$$

$$\boxed{\alpha = 1.22\ dB/km}$$

Power measurements at the manufacturing location are performed on other fiber-optic components as well, usually to adhere to specific insertion-loss requirements and other power-related parameters.

Power measurements are performed in the field to expand, troubleshoot, and repair or just confirm proper operation of existing networks and systems. To measure fiber cable attenuation, an Optical Time-Domain Reflectometer (OTDR) can be used or the **substitution method** can be used as a replacement for the cutback method. The slope of the fiber trace on the OTDR yields the attenuation coefficient in dB/km directly. The substitution method is illustrated in Figure 10–3. By this method, the power through a long cable is first measured (P_2) followed by the power through a short cable (P_1). The same input test cable is used in both cases in an effort to keep input powers consistent. The attenuation coefficient is then determined as with the cutback method. Note that the substitution method is less accurate since the input conditions are not identical.

FIGURE 10–3 Fiber attenuation measurement: Substitution method.



In many cases the technician must only determine if any power is getting through a fiber, component, or system. This is called a **continuity test** and is often performed visually as described in the next section. The loss in a particular cable, connector, or splice should be within manufacturer's specifications.

Power Measurement Instrumentation

Several instruments have been developed to measure optical power levels, most of which contain some type of photodetector to perform the optical-to-electrical conversion necessary for displaying results. Some instruments are designed specifically for laboratory use to characterize components in research or quality assurance. Other instruments are battery-powered, compact units for use in the field. Power measurement instruments usually consist of an optical source at the wavelength of interest that provides the necessary input power levels. The calibrated detection system then records and displays the resulting power level in Watts or dBm. Some instruments used to measure power in the fiber-optic industry are the power meter, the loss set, the talk set, and the optical time-domain reflectometer (OTDR).

A fiber-optic **power meter** (Figure 10–4) is the basic instrument for power measurement. It usually includes adjustable ranges, input adapters for various fiber cable connectors, and often visual readouts in both Watts and dBms. Sometimes built with other functions included, power meters are very portable (often battery-powered) and durable (field models). Sometimes, a power meter and optical source are coupled together to make a **loss set** (see Figure 10–5). This instrument pair allows the technician to measure the loss of cables, insertion loss of a coupler or other component, or the loss in a small system with the original source disabled. Probably the simplest "loss set" is your eye and a red LED fiber-optic flashlight, such as the one shown in Figure 10–6. This works just fine as an optical continuity tester (less than 1 mile) or when all that is required is to find out if an optical connection is working or not. Just a reminder: *Never* look into one end of a fiber with the transmitter at the other end on.

A **fiber-optic talk set** is sometimes used when technicians need to be at different positions along the same link. The talk set includes a transmitter and receiver that can be attached directly to nearby fiber cables. The devices can be used to talk, to send a test signal (2 kHz) as an aid in fiber

FIGURE 10–4 Fiber-optic power meter.

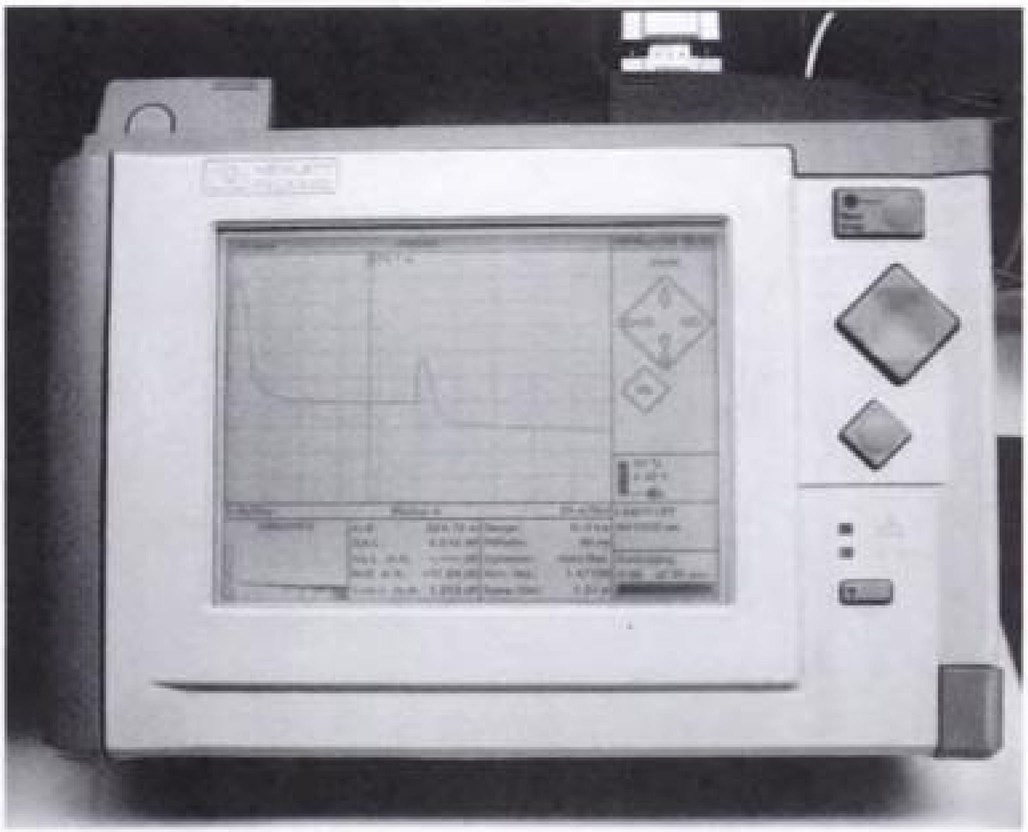


FIGURE 10–7 Optical time-domain reflectometer (OTDR).

decays with fiber attenuation and initiates a reflection wherever splices, connectors, or other losses are present. By measuring the time of each occurrence, the instrument can locate the position of each abrupt change in power throughput. Results are shown graphically on a screen, which displays optical power as a function of path length. The OTDR is a powerful instrument that has proven its value consistently in the field, with multiple sources and multiple measurement capability options available. Often OTDR traces are kept as baseline data on existing fiber plants for use in system expansion and troubleshooting. Some limitations should also be noted however, as the OTDR results are not as precise as measurements performed with power meters. Precision is lost at distances less than 1 km, and using an OTDR for longer distances requires measurements from both ends (systems longer than 40 km). The advantages far outweigh this loss in precision as OTDRs remain one of the most popular and versatile instruments used by fiber-optic technicians. A typical OTDR trace is shown in Figure 10–8.

10.2 Optical Wavelength Measurements

Wavelength measurements for fiber-optic systems usually imply obtaining information about the spectral content of the signal or the **spectral response**. Accurate measurement systems are calibrated to some standard source wavelength and provide both peak wavelength and linewidth

Chapter 6

1. $P_i = 5\,\text{mW}, \quad \alpha = 2\times10^3\text{cm}^{-1}, \quad x = 2\,\mu\text{m} = 2\times10^{-4}\text{cm}$

$$R = \left(\frac{n_2-n_1}{n_2+n_1}\right)^2 = \left(\frac{3.50-1}{3.50+1}\right)^2 = 0.31 \text{ or } 31\%$$

$$P = P_i(1-R)(1-e^{-\alpha x}) = (5\,\text{mW})(1-0.31)\left(1-e^{-(2\times10^3)(2\times10^{-4})}\right)$$

$$\boxed{P = 1.14\,\text{mW}} \qquad x = \frac{1}{\alpha} = \frac{1}{2\times10^3} \rightarrow \boxed{x = 5\times10^{-4}\text{cm} = 5\,\mu\text{m}}$$

3. $P_i = 300\,\mu\text{W}, \quad \alpha = 1\times10^4\text{cm}^{-1}, \quad x = 1\,\mu\text{m} = 1\times10^{-4}\text{cm}$

$$R = \left(\frac{n_2-n_1}{n_2+n_1}\right)^2 = \left(\frac{3.76-1}{3.76+1}\right)^2 = 0.336 \textit{ or } 3.36\%$$

$$P = P_i(1-R)(1-e^{-\alpha x}) = (300\,\mu\text{W})(1-0.336)\left(1-e^{-(1\times10^4)(1\times10^{-4})}\right)$$

$$\boxed{P = 126\,\mu\text{W}} \qquad x = \frac{1}{\alpha} = \frac{1}{1\times10^4\text{cm}^{-1}} \rightarrow \boxed{x = 1\,\mu\text{m}}$$

5. $R = \frac{I_P}{P_i}M = \frac{200\,\mu\text{A}}{300\,\mu\text{W}}(53) \rightarrow \boxed{R = 35.35\frac{\text{A}}{\text{W}}}$

7. $x = 5\,\mu\text{m}, \quad D = 40\frac{\text{cm}^2}{\text{s}}$

$$t_D = \frac{x^2}{D} = \frac{(5\times10^{-4}\text{cm})^2}{40\frac{\text{cm}^2}{\text{s}}} \rightarrow \boxed{t_D = 625\,\text{ns}}$$

$$f_c = \frac{2.88}{2\pi t_D} = \frac{2.88}{2\pi\, 625\,\text{ns}} \rightarrow \boxed{f_c = 713\,\text{kHz}}$$

9. $I_p = 20\,\mu\text{A}, \quad P_i = 30\,\mu\text{W}, \quad \lambda = 1150\,\text{nm}$

$$\eta = \frac{I_p h\nu}{P_i q} = \frac{I_p hc}{P_i q\lambda} = \frac{(20\,\mu\text{A})(6.626\times10^{-34})(3\times10^8)}{(30\,\mu\text{W})(1.602\times10^{-19})(1150\,\text{nm})}$$

$$\boxed{\eta = 0.719}$$

$$R = \frac{I_P}{P_i} = \frac{20\,\mu\text{A}}{30\,\mu\text{W}} \rightarrow \boxed{R = 0.67\frac{\text{A}}{\text{W}}}$$

5. $P_{in} = 2\text{ dBm},\ P_{out} = -20\text{ dBm}$

$$T_{1\text{-dB}} = \alpha L = \left(\frac{0.6\text{ dB}}{\text{km}}\right)(12\text{ km}) = -7.2\text{ dB}$$

$$T_{2\text{-dB}} = (2\text{ dB})N, \quad \text{where } N = \text{number of OADMs}$$

$$P_{out} = T_{dB} + P_{in} \quad \rightarrow \quad -20\text{ dBm} = -7.2\text{ dB} - 2\text{ dB N} + 2\text{ dBm}$$

$$2\text{ dB N} = 14.8\text{ dB} \quad \rightarrow \quad N = 5.9 \quad \rightarrow \quad \boxed{\text{Only 5 OADMs can be used}}$$

7. $L_1 = 8\text{ km},\ \alpha = 0.6\text{ dB/km},\ L_2 = 1\text{ km},\ P_{out} = -40\text{ dBm}$

$$T_{1\text{-dB}} = -\alpha L = \left(-0.6\frac{\text{dB}}{\text{km}}\right)(9\text{ km}) = -5.4\text{ dB}$$

$$T_{2\text{-dB}} = -9.33\text{ dB} \quad \rightarrow \quad T_{dB} = T_{1\text{-dB}} + T_{2\text{-dB}} = -14.73\text{ dB}$$

$$T_{dB} = P_{out\text{-dBm}} - P_{in\text{-dBm}}$$

$$P_{in\text{-dBm}} = P_{out\text{-dBm}} - T_{dB} = -40\text{ dBm} - (-14.73\text{ dBm})$$

$$P_{in\text{-dBm}} = -25.27\text{ dBm} \quad \rightarrow \quad P_{in} = 10^{\frac{-25.27}{10}} \quad \rightarrow \quad \boxed{P_{in\text{-min}} = 3.0\ \mu\text{W}}$$

Chapter 8

1. $\Delta v = 50\text{ GHz},\ \lambda_1 = 1562.33\text{ nm}.$
From Equation 2–15:

$$\Delta v = \frac{c\,\Delta\lambda}{\lambda^2} \quad \rightarrow \quad \Delta\lambda = \frac{c\,\Delta v}{v^2}$$

$$v_1 = \frac{c}{\lambda_1} = \frac{3\times10^8\text{m/s}}{1562.33\text{ nm}} = 192.02\text{ THz}$$

$$\Delta\lambda = \frac{c\,\Delta v}{v_1^2} = \frac{(3\times10^8\text{m/s})(50\text{ GHz})}{(192.02\text{ THz})} \quad \rightarrow \quad \boxed{\Delta\lambda = 0.410\text{ nm}}$$

$$\lambda_2 = \lambda_1 + \Delta\lambda, \quad \lambda_3 = \lambda_1 + 2\Delta\lambda \quad \rightarrow \quad \boxed{\lambda_2 = 1562.74\text{ nm}, \quad \lambda_3 = 1563.15\text{ nm}}$$

3. Approximate available ranges are 1270 nm to 1330 nm (90 nm) and 1450 nm to 1610 nm (160 nm). The unusable OH band is approximately from 1360 nm to 1450 nm. If we put 3 channels in the first range and 5 in the second range, the spacing is 45 nm and 40 nm, respectively (or 40 nm in each to be consistent).

The channel wavelengths are then:

1270	1315	1360			
1450	1490	1520	1560	1600	or
1270	1310	1350			
1450	1490	1520	1560	1600	

Note that other configurations are possible.

5. If we subtract 1 OC-3 and 1 OC-12, we get:

$$\boxed{BW_{aggregate} = 22{,}550.04\text{ Mbps}}$$

$$\boxed{\text{SONET rate} = 10\text{ OC}-48 = 24{,}883.2\text{ Mbps}}$$

7. ESCON channel = 196 Mbps.

$$\boxed{\frac{STS-12}{ESCON} = \frac{2{,}488.32}{196\text{ Mbps}} \approx 12\text{ ESCON channels}}$$

Chapter 9

1. $G_{EDFA} = 22\text{ dB},\ P_{out} = -28\text{ dB},\ L = 350\text{ km},\ P_{in} = 2\text{ dBm},$
$Loss_{actual} = 140\text{ dB}$

$$Loss_{acceptable} = P_{in-dBm} - P_{out-dBm} = 2\text{ dBm} - (-28\text{ dBm}) = 30\text{ dB}$$

$$N = \frac{Loss_{actual} - Loss_{acceptable}}{G_{EDFA}} = \frac{140\text{ dB} - 30\text{ dB}}{22}$$

$$\boxed{N = 5} \rightarrow L_{EDFA} = \frac{L}{N+1} = \frac{350\text{ km}}{5+1} \rightarrow \boxed{L_{EDFA} = 58.33\text{ km}}$$

3. $\Delta\lambda = 40\text{ nm},\ t_{r-tran} = 4\text{ ns},\ t_{r-rec} = 0.8\text{ ns},\ D_{mod} = 1.0\text{ ns/km},$
$D_{mat} = -3\text{ps/nm}\cdot\text{km}$

$$\Delta t_{mod} = D_{mod}L = \left(\frac{1.0\text{ ns}}{\text{km}}\right)(2\text{km}) = 2\text{ ns}$$

$$\Delta t_{mat} = D_{mat}L\,\Delta\lambda = \left(\frac{-3\text{ ps}}{\text{nm}\cdot\text{km}}\right)(2\text{ km})(40\text{ nm}) = 240\text{ ps}$$

$$\Delta t_{fiber} = \sqrt{\Delta t_{mod}^2 + \Delta t_{mat}^2} = 2\text{ ns}$$

$$t_{r-total} = \sqrt{t_{r-tran}^2 + \Delta t_{fiber}^2 + t_{r-rec}^2} = \sqrt{4^2 + 2^2 + 0.8^2}$$

$$\boxed{t_{r-total} = 4.54\text{ ns}} \rightarrow B = \frac{.7}{t_{r-total}} \rightarrow \boxed{B = 154.2\text{ Mbps}}$$

3. $\alpha_{1300} = 1\ \text{dB/km},\ \ \alpha_{1550} = 0.5\ \text{dB/km},\ L = 4\ \text{km}.$

$$T_{\text{dB-1300nm}} = -\alpha_{1300}L + G_{1300} = -\frac{1\ \text{dB}}{\text{km}}(4\ \text{km}) + G_{1300} = -4\ \text{dB} + G_{1300}$$

$$T_{\text{dB-1550nm}} = -\alpha_{1550}L + G_{1550} = -\frac{0.5\ \text{dB}}{\text{km}}(4\ \text{km}) + G_{1550} = -2\ \text{dB} + G_{1550}$$

$$T_{\text{dB-1300nm}} = T_{\text{dB-1550nm}}$$

$$-4\ \text{dB} + G_{1300} = -2\ \text{dB} + G_{1550} \quad \rightarrow \quad \boxed{G_{1300} = G_{1550} + 2\ \text{dB}}$$

5. From Figure 10–13:

$$f_{\text{sig}} = \frac{1}{T} = \frac{1}{10\ \mu\text{s}} \quad \rightarrow \quad \boxed{f_{\text{sig}} = 100\ \text{kHz}}$$

$$f_{\text{noise}} = \frac{1}{T} = \frac{1}{0.5\ \mu\text{s}} \quad \rightarrow \quad \boxed{f_{\text{noise}} = 2\ \text{MHz}}$$

$$V_{\text{sig}} \approx 2V_{\text{noise}} \quad \rightarrow \quad \boxed{\text{SNR} = 2}$$

Fiber Optic Communications

James Downing

Part of Thomson Delmar Learning's, *National Center for Telecommunications Technologies* series, this new book offers a complete, concise and practical introduction to fiber optic communications. Coverage begins with a brief history, advantages of fiber optics, and a description of basic telecommunication systems. Increased coverage of basic optics and communications provide the background for understanding modern fiber optic devices. Full of detailed descriptions of actual systems applications, the book concludes with practical instruction on the installation and troubleshooting of fiber optic communications networks and systems.

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