Chapter 14

MODERN TOPICS

The future has several names. For the weak, it is the impossible. For the faith-hearted, it is the unknown. For the thoughtful and valiant, it is ideal.

—VICTOR HUGO

14.1 INTRODUCTION

Besides wave propagation, transmission lines, waveguides, and antennas, there are several other areas of applications of EM. These include microwaves, electromagnetic interference and compatibility, fiber optics, satellite communication, bioelectromagnetics, electric machines, radar meteorology, and remote sensing. Due to space limitation, we shall cover the first three areas in this chapter: microwaves, electromagnetic interference and compatibility, and fiber optics. Since these topics are advanced, only an introductory treatment of each topic will be provided. Our discussion will involve applying the circuit concepts learned in earlier courses and the EM concepts learned in earlier chapters.

14.2 MICROWAVES

At the moment, there are three means for carrying thousands of channels over long distances: (a) microwave links, (b) coaxial cables, and (c) fiber optic, a relatively new technology, to be covered later.

Microwaves are EM waves whose frequencies range from approximately 300 MHz to 1000 GHz.

For comparison, the signal from an AM radio station is about 1 MHz, while that from an FM station is about 100 MHz. The higher frequency edge of microwaves borders on the optical spectrum. This accounts for why microwaves behave more like rays of light than ordinary radio waves. You may be familiar with microwave appliances such as the microwave oven, which operates at 2.4 GHz, the satellite television, which operates at about 4 GHz, and the police radar, which works at about 22 GHz.

Features that make microwaves attractive for communications include wide available bandwidths (capacities to carry information) and directive properties of short wavelengths. Since the amount of information that can be transmitted is limited by the available bandwidth, the microwave spectrum provides more communication channels than the radio and TV bands. With the ever increasing demand for channel allocation, microwave communications has become more common.

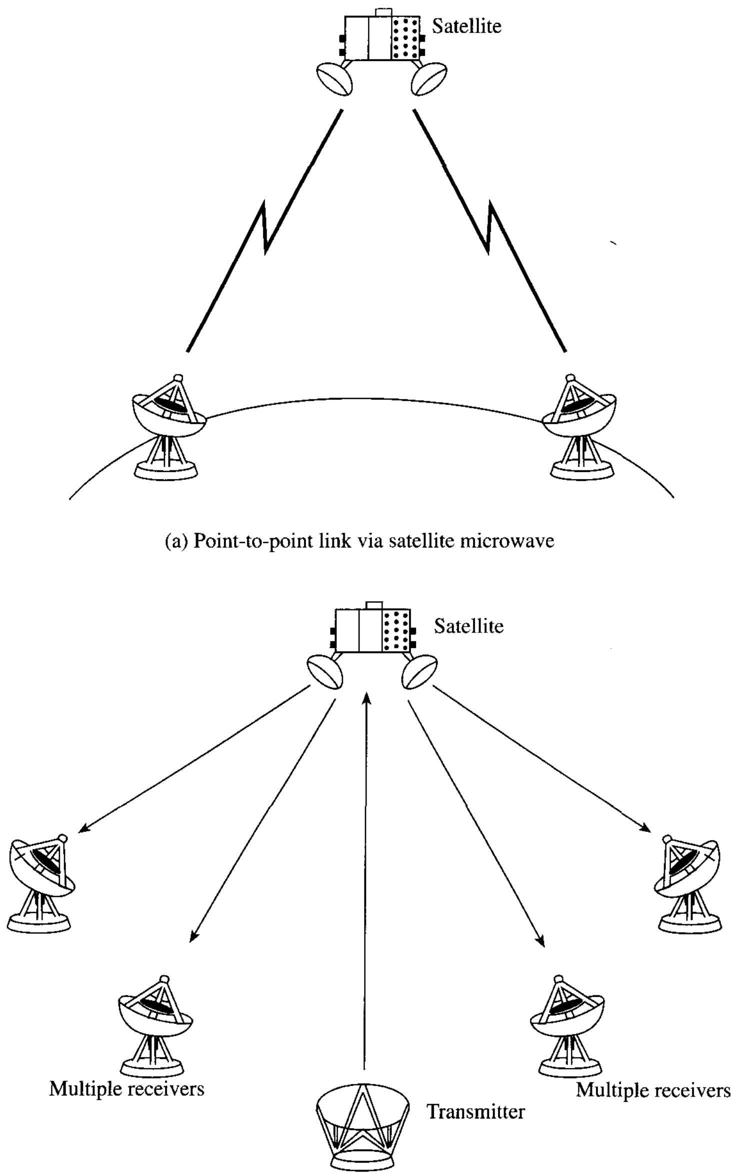
A microwave system[1] normally consists of a transmitter (including a microwave oscillator, waveguides, and a transmitting antenna) and a receiver subsystem (including a receiving antenna, transmission line or waveguide, microwave amplifiers, and a receiver). A microwave network is usually an interconnection of various microwave components and devices. There are several microwave components and variations of these components. Common microwave components include:

- Coaxial cables, which are transmission lines for interconnecting microwave components
- Resonantors, which are usually cavities in which EM waves are stored
- Waveguide sections, which may be straight, curved or twisted
- Antennas, which transmit or receive EM waves efficiently
- Terminators, which are designed to absorb the input power and therefore act as one-ports
- Attenuators, which are designed to absorb some of the EM power passing through it and thereby decrease the power level of the microwave signal
- Directional couplers, which consist of two waveguides and a mechanism for coupling signals between them
- Isolators, which allow energy flow only in one direction
- Circulators, which are designed to establish various entry/exit points where power can either be fed or extracted
- Filters, which suppress unwanted signals and/or separate signals of different frequencies.

The use of microwaves has greatly expanded. Examples include telecommunications, radio astronomy, land surveying, radar, meteorology, UHF television, terrestrial microwave links, solid-state devices, heating, medicine, and identification systems. We will consider only four of these.

1. Telecommunications: (the transmission of analog or digital information from one point to another) is the largest application of microwave frequencies. Microwaves propagate along a straight line like a light ray and are not bent by the ionosphere as are lower frequency signals. This makes communication satellites possible. In essence, a communication satellite is a microwave relay station that is used to link two or more ground-based transmitters and receivers. The satellite receives signals at one frequency, repeats or amplifies it, and transmits it at another frequency. Two common modes of operation for satellite communication are portrayed in Figure 14.1. The satellite provides a point-to-point

[1]For a comprehensive treatment of microwaves, see D. M. Pozar, *Microwave Engineering,* New York, John Wiley, 2nd., 1998.



(a) Point-to-point link via satellite microwave

(b) Broadcast link via satellite microwave

Figure 14.1 Satellite communications configurations. *Source:* W. Stallings, *Data and Computer Communications,* 5th ed. Upper Saddle River, NJ: Prentice Hall, 1977, p. 90.

link in Figure 14.1(a), while it is being used to provide multiple links between one ground-based transmitter and several ground-based receivers in Figure 14.1(b).

2. Radar Systems: Radar systems provided the major incentive for the development of microwave technology because one obtains better resolution for radar instruments at higher frequencies. Only the microwave region of the spectrum could provide the required resolution with antennas of reasonable size. The ability to focus a radiated wave sharply is what makes microwaves so useful in radar applications. Radar is used to detect aircraft, guide supersonic missiles, observe and track weather patterns, and control flight traffic at airports. It is also used in burglar alarms, garage-door openers, and police speed detectors.

3. Heating: Microwave energy is more easily directed, controlled, and concentrated than low-frequency EM waves. Also, various atomic and molecular resonances occur at microwave frequencies, creating diverse application areas in basic science, remote sensing, and heating methods. The heating properties of microwave power are useful in a wide variety of commercial and industrial applications. The microwave oven, shown in Figure 14.2, is a typical example. When the magnetron oscillates, microwave energy is extracted from the resonant cavities. The reflections from the stationary walls and the motion of the stirring fan cause the microwave energy to be well distributed. Thus the microwave enables the cooking process to be fast and even. Besides cooking, microwave heating properties are used in physical diathermy and in drying potato chips, paper, cloth, etc.

A microwave circuit consists of microwave components such as sources, transmission lines, waveguides, attenuators, resonators, circulators, and filters. One way of analyzing such as a circuit is to relate the input and output variables of each component. Several sets of parameters can be used for relating input and output variables but at high frequencies such as microwave frequencies where voltage and current are not well defined, S-parameters are often used to analyze microwave circuits. The *scattering* or S-*parameters* are defined in terms of wave variables which are more easily measured at microwave frequencies than voltage and current.

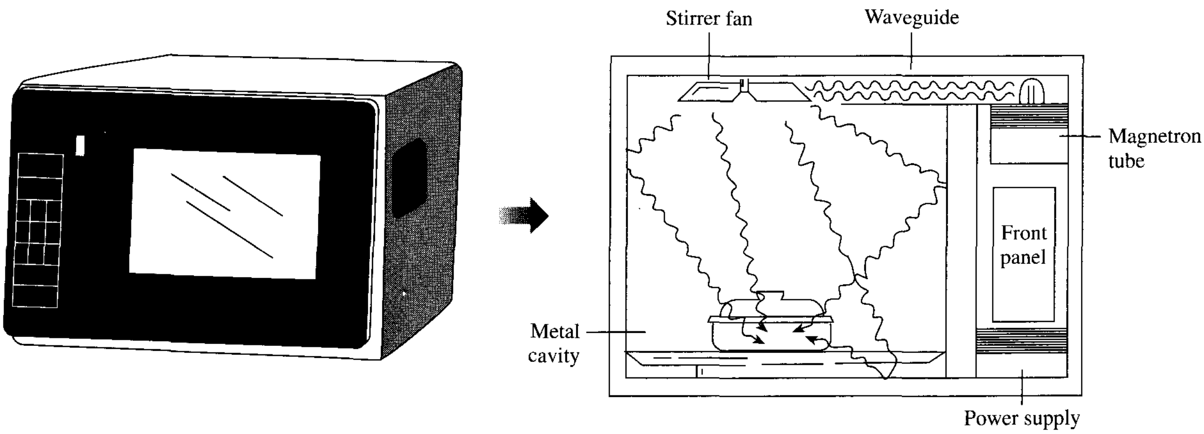


Figure 14.2 Microwave oven. *Source:* N. Schlager (ed.), *How Products are Made.* Detroit, MI: Gale Research Inc., 1994, p. 289.

Consider the two-port network shown in Figure 14.3. The traveling waves are related to the scattering parameters according to

$$b_1 = S_{11}a_1 + S_{12}a_2$$
$$b_2 = S_{21}a_1 + S_{22}a_2 \tag{14.1}$$

or in matrix form

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{14.2}$$

where a_1 and a_2 represent the incident waves at ports 1 and 2 respectively; while b_1 and b_2 represent the reflected waves, as shown in Figure 14.3. For the S matrix, the off-diagonal terms represent voltage wave transmission coefficients, while the diagonal terms represent reflection coefficients. If the network is *reciprocal,* it will have the same transmission characteristics in either direction, i.e.,

$$S_{12} = S_{21} \tag{14.3}$$

If the network is *symmetrical,* then

$$S_{11} = S_{22} \tag{14.4}$$

For a matched two-port, the reflection coefficients are zero and

$$S_{11} = S_{22} = 0 \tag{14.5}$$

The input reflection coefficient can be expressed in terms of the S-parameters and the load Z_L as

$$\Gamma_i = \frac{b_1}{a_1} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} \tag{14.6}$$

where

$$\Gamma_L = \frac{Z_L - Z_o}{Z_L + Z_o} \tag{14.7}$$

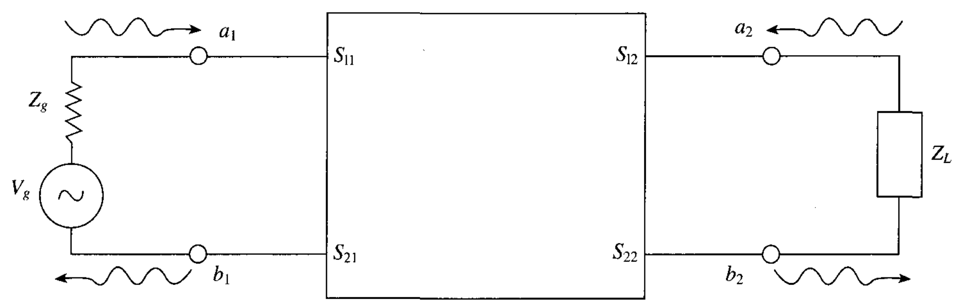


Figure 14.3 A two-port network.

Similarly, the output reflection coefficient (with $V_g = 0$) can be expressed in terms of the generator impedance Z_g and the S-parameters as

$$\Gamma_o = \frac{b_2}{a_2}\bigg|_{V_g=0} = S_{22} + \frac{S_{12}S_{21}\Gamma_g}{1 - S_{11}\Gamma_g} \tag{14.8}$$

where

$$\Gamma_g = \frac{Z_g - Z_o}{Z_g + Z_o} \tag{14.9}$$

EXAMPLE 14.1

The following S-parameters are obtained for a microwave transistor operating at 2.5 GHz: $S_{11} = 0.85\underline{/-30^\circ}$, $S_{12} = 0.07\underline{/56^\circ}$, $S_{21} = 1.68\underline{/120^\circ}$, $S_{11} = 0.85\underline{/-40^\circ}$. Determine the input reflection coefficient when $Z_L = Z_o = 75\ \Omega$.

Solution:

From Eq. (14.7),

$$\Gamma_L = \frac{Z_L - Z_o}{Z_L + Z_o} = 0$$

Hence, using Eq. (14.6) leads to

$$\Gamma_i = S_{11} = 0.85\underline{/-30^\circ}$$

PRACTICE EXERCISE 14.1

For an hybrid coupler, the VSWRs for the input and output ports are respectively given as

$$s_i = \frac{1 + |S_{11}|}{1 - |S_{11}|}$$

$$s_o = \frac{1 + |S_{11}|}{1 - |S_{11}|}$$

Calculate s_i and s_o for the following scattering matrix:

$$S = \begin{bmatrix} 0.4 & j0.6 \\ j0.6 & 0.2 \end{bmatrix}$$

Answer: 2.333, 1.5

14.3 ELECTROMAGNETIC INTERFERENCE AND COMPATIBILITY

Every electronic device is a source of radiated electromagnetic fields called *radiated emissions.* These are often an accidental by-product of the design.

Electromagnetic interference (EMI) is the degradation in the performance of a device due to the fields making up the electromagnetic environment.

The electromagnetic environment consists of various apparatuses such as radio and TV broadcast stations, radar, and navigational aids that radiate EM energy as they operate. Every electronic device is susceptible to EMI. Its influence can be seen all around us. The results include "ghosts" in TV picture reception, taxicab radio interference with police radio systems, power line transient interference with personal computers, and self-oscillation of a radio receiver or transmitter circuit.

Electromagnetic compatibility (EMC) is achieved when a device functions satisfactorily without introducing intolerable disturbances to the electromagnetic environment or to other devices in its neighborhood.

EMC[2] is achieved when electronic devices coexist in harmony, such that each device functions according to its intended purpose in the presence of, and in spite of, the others. EMI is the problem that occurs when unwanted voltages or currents are present to influence the performance of a device, while EMC is the solution to the problem. The goal of EMC is to ensure system or subsystem compatibility and this is achieved by applying proven design techniques, the use of which ensures a system relatively free of EMI problems.

EMC is a growing field because of the ever-increasing density of electronic circuits in modern systems for computation, communication, control, etc. It is not only a concern to electrical and computer engineers, but to automotive engineers as well. The increasing application of automotive electronic systems to improve fuel economy, reduce exhaust emissions, ensure vehicle safety, and provide assistance to the driver has resulted in a growing need to ensure compatibility during normal operation. We will consider the sources and characteristics of EMI. Later, we will examine EMI control techniques.

A. Source and Characteristics of EMI

First, let us classify EMI in terms of its causes and sources. The classification will facilitate recognition of sources and assist in determining means of control. As mentioned earlier, any electronic device may be the source of EMI, although this is not the intention of the designer. The cause of the EMI problem may be either within the system, in which case it is termed an *intrasystem problem,* or from the outside, in which case it is called an *intersys-*

[2] For an in-depth treatment of EMC, see C. R. Paul, *Introduction to Electromagnetic Compatibility,* New York: John Wiley, 1992.

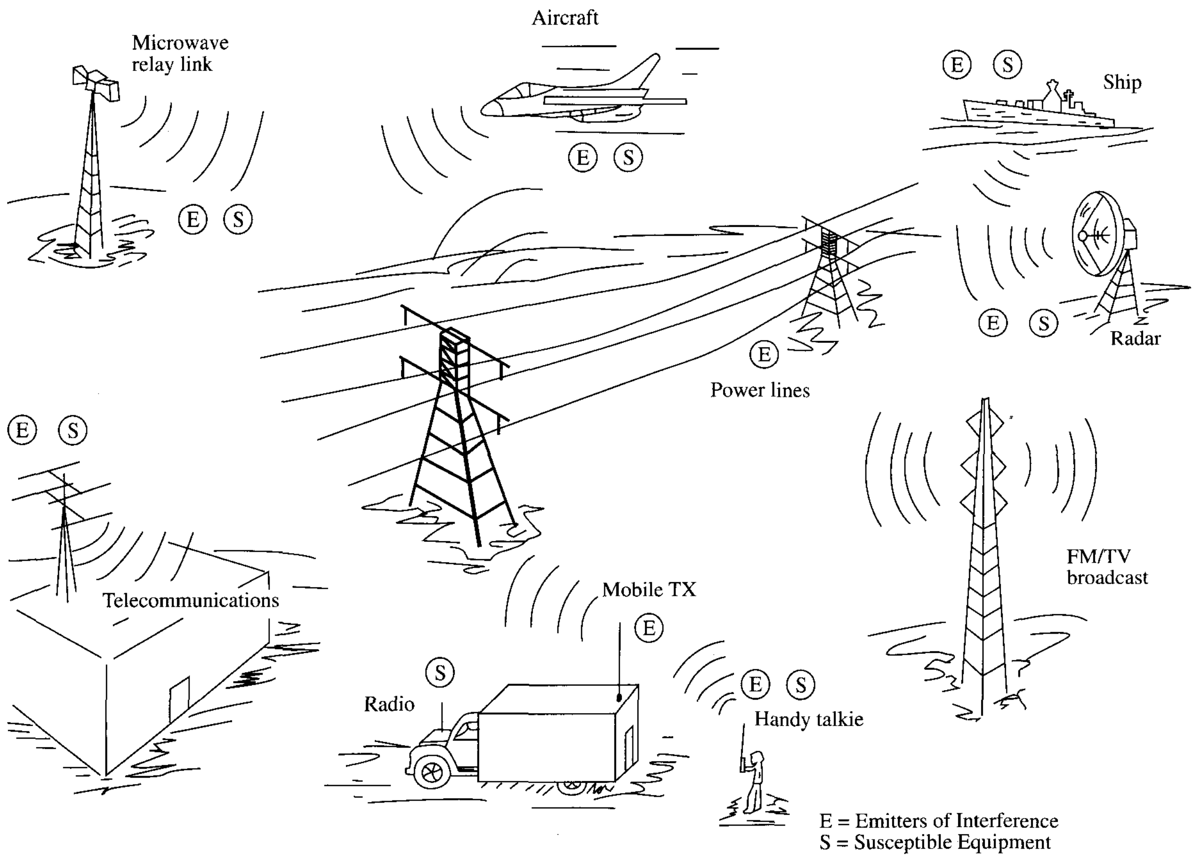


Figure 14.4 Typical examples of intersystem EMI problems. *Source:* J.I.N. Violette et al., *Electromagnetic Compatibility Handbook.* New York: Van Nostrand Reinhold, 1987, p. 4.

tem problem. Figure 14.4 shows intersystem EMI problems. The term "emitter" is commonly used to denote the source of EMI, while the term "susceptor" is used to designate a victim device. Tables 14.1 and 14.2 present typical causes of both intrasystem and intersystem problems. Both intrasystem and intersystem EMI generally can be controlled by the system design engineer by following some design guidelines and techniques. For in-

TABLE 14.1 Intrasystem EMI Causes

Emitters	Susceptors
Power supplies	Relays
Radar transmitters	Radar receivers
Mobile radio transmitters	Mobile radio receivers
Fluorescent lights	Ordnance
Car ignition systems	Car radio receivers

TABLE 14.2 Intersystem EMI Causes

Emitters	Susceptors
Lightning strokes	Radio receivers
Computers	TV sets
Power Lines	Heart pacers
Radar transmitters	Aircraft navigation systems
Police radio transmitters	Taxicab radio receivers
Fluorescent lights	Industrial controls
Aircraft transmitters	Ship receivers

trasystem EMI problems, for example, the design engineer may apply proper grounding and wiring arrangements, shielding of circuits and devices, and filtering.

The sources of EMI can be classified as natural or artificial (man-made). The origins of EMI are basically undesired conducted emissions (voltages and/or currents) or radiated emissions (electric and/or magnetic fields). Conducted emissions are those currents that are carried by metallic paths (the unit's power cord) and placed on the common power network where they may cause interference with other devices that are connected to this network. Radiated emissions concern the electric fields radiated by the device that may be received by other electronic devices causing interference in those devices. Figure 14.5 illustrates the conceptual difference between conducted and radiated paths.

No single operating agency has jurisdiction over all systems to dictate actions necessary to achieve EMC. Thus, EMC is usually achieved by industrial association, voluntary regulation, government-enforced regulation, and negotiated agreements between the affected parties. Frequency plays a significant role in EMC. Frequency allocations and assignments are made according to the constraints established by international treaties. The Radio Regulations resulting from such international treaties are published by the Interna-

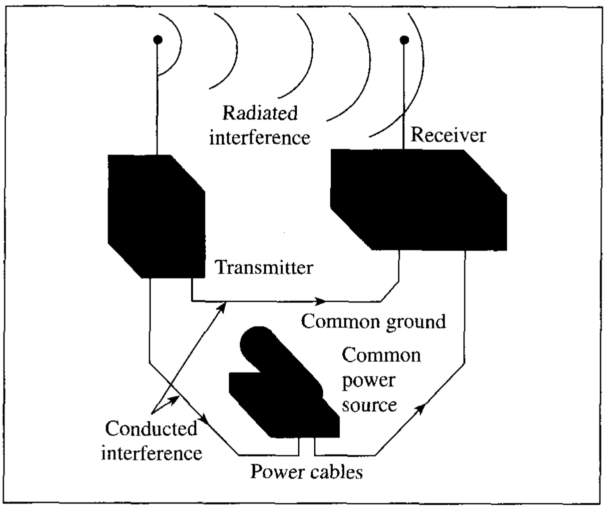


Figure 14.5 Differences between conducted and radiated emissions.

tional Telecommunication Union (ITU). The Federal Communications Commission (FCC) has the authority over radio and wire communications in the United States. The FCC has set limits on the radiated and conducted emissions of electronic devices including electronic typewriters, calculators, televisions, printers, modems, and personal computers. It is illegal to market an electronic device in the United States unless its radiated and conducted emissions have been measured and do not exceed the limits of FCC regulations. Therefore, any electronic device designed today that is designed without incorporating EMC design principles will probably fail to comply with the FCC limits.

B. EMI Control Techniques

To control or suppress EMI, the three common means employed in the design process are grounding, shielding, and filtering. Although each technique has a distinct role in system design, proper grounding may sometimes minimize the need for shielding and filtering; also proper shielding may minimize the need for filtering. Therefore, we discuss the three techniques, grounding, shielding, and filtering in that order.

Grounding:

Grounding is the establishment of an electrically conductive path between two points to connect electrical and electronic elements of a system to one another or to some reference point, which may be designated the *ground.* An ideal ground plane is a zero-potential, zero-impedance body that can be used as a reference for all signals in associated circuitry, and to which any undesired current can be transferred for the elimination of its effects.

The purpose of the floating ground is to isolate circuits or equipment electrically from a common ground plane. This type of grounding technique may cause a hazard. The single-point grounding is used to minimize the effects of facility ground currents. The multiple-point grounding minimizes ground lead lengths. The ground plane might be a ground wire that is carried throughout the system or a large conductive body.

Bonding is the establishment of a low-impedance path between two metal surfaces. Grounding is a circuit concept, while bonding denotes the physical implementation of that concept. The purpose of a bond is to make a structure homogeneous with respect to the flow of electrical currents, thus avoiding the development of potentials between the metallic parts, since such potentials may result in EMI. Bonds provide protection from electrical shock, power circuit current return paths, and antenna ground plane connections, and also minimize the potential difference between the devices. They have the ability to carry large fault current.

There are two types of bond: direct and indirect bonds. The direct bond is a metal-to-metal contact between the elements connected, while the indirect bond is a contact through the use of conductive jumpers.

The dc resistance R_{dc} of a bond is often used as an indication of bond quality. It is given by

$$R_{dc} = \frac{\ell}{\sigma S} \tag{14.10}$$

where ℓ is the length of the bond, σ is its conductivity, and S is its cross-sectional area. As frequency increases, the bond resistance increases due to skin effect. Thus the ac resistance R_{ac} is given as

$$R_{ac} = \frac{\ell}{\sigma \delta w} \tag{14.11}$$

where w is the width of the bond and δ is the skin depth.

Bonding effectiveness can be expressed as the difference (in dB) between the induced voltages on an equipment case with and without the bond trap.

Shielding:

The purpose of shielding is to confine radiated energy to a specific region or to prevent radiated energy from entering a specific region. Shields may be in the form of partitions and boxes as well as in the form of cable and connector shields.

Shield types include solid, nonsolid (e.g., screen), and braid, as is used on cables. In all cases, a shield can be characterized by its *shielding effectiveness.* The shielding effectiveness (SE) is defined as

$$SE = 10 \log_{10} \frac{\text{incident power density}}{\text{transmitted power density}} \tag{14.12}$$

where the incident power density is the power density at a measuring point before a shield is installed and the transmitted power is the power density at the same point after the shield is in place. In terms of the field strengths, the shielding effectiveness may also be defined as the ratio of the field E_t transmitted through to the inside to the incident field E_i. Thus, SE is given by

$$SE = 20 \log_{10} \frac{E_i}{E_t} \tag{14.13}$$

For magnetic fields,

$$SE = 20 \log_{10} \frac{H_i}{H_t} \tag{14.14}$$

For example, aluminum has $\sigma = 3.5 \times 10^7$ S/m, $\varepsilon = \varepsilon_o$, $\mu = \mu_o$, an aluminum sheet at 100 MHz has an SE of 100 dB at a thickness of 0.01 mm. Since an aluminum sheet for a computer cabinet is much thicker than this, an aluminum case is considered a highly effective shield. A cabinet that effectively shields the circuits inside from external fields is also highly effective in preventing radiation from those circuits to the external world. Because of the effective shield, radiated emission from the computer system is caused by openings in the cabinet such as cracks, holes from disc drives, etc. and from wires that penetrate the cabinet such as power cord and cables to external devices.

Filtering:

An electrical filter is a network of lumped or distributed constant resistors, inductors, and capacitors that offers comparatively little opposition to certain frequencies, while blocking the passage of other frequencies. Filter provides the means whereby levels of conducted interference are substantially reduced.

The most significant characteristic of a filter is the *insertion loss* it provides as a function of frequency. Insertion loss (*IL*) is defined as

$$IL = 20 \log_{10} \frac{V_1}{V_2} \tag{14.15}$$

where V_1 is the output voltage of a signal source with the filter in the circuit, and V_2 is the output voltage of the signal source without the use of the filter. Low-pass filters are commonly used in EMC work. The insertion loss for the low-pass filters is given by

$$IL = 10 \log_{10} (1 + F^2) \text{ dB} \tag{14.16}$$

where

$$F = \begin{cases} \pi fRC, & \text{for capacitive filter} \\ \pi fL/R, & \text{for inductive filter} \end{cases} \tag{14.17}$$

and f is the frequency.

14.4 OPTICAL FIBER

In the mid 1970s, it was recognized that the existing copper technology would be unsuitable for future communication networks. In view of this, the telecommunication industry invested heavily in research into optical fibers. Optical fiber provides an attractive alternative to wire transmission lines such are twisted pair and coaxial cable (or coax). Optical fiber[3] has the following advantages over copper:

- *Bandwidth:* It provides a very high capacity for carrying information. It has sufficient bandwidth that bit-serial transmission can be used, thereby considerably reducing the size, cost, and complexity of the hardware.
- *Attenuation:* It provides low attenuation and is therefore capable of transmitting over a long distance without the need of repeaters.
- *Noise susceptibility:* It neither radiates nor is affected by electromagnetic interference. The immunity from EMI is due to the fact that there are no metal parts so that there can be no conduction currents.

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[3] There are several excellent books that can provide further exposition on optical fiber. See, for example, S. L. W. Meardon, *The Elements of Fiber Optics,* Englewood Cliffs, NJ: Regents/Prentice Hall, 1993.

- *Security:* It is more secure from malicious interception because it is not easy to tap a fiber-optic cable without interrupting communication.
- *Cost:* The cost of optical fibers has fallen considerably over the past few years and will continue to fall. So is the cost of related components such as optical transmitters and receivers.

These impressive advantages of fiber optics over electrical media have made it a popular transmission medium in recent times. Although optical fiber is more expensive and is used mainly for point-to-point links, there has been a rapid changeover from coax and twisted pair to optical fibers for telecommunication systems, instrumentation, cable TV networks, industrial automation, and data transmission systems.

An **optical fiber** is a dielectric waveguide operating at optical frequency.

Optical frequencies are on the order of 100 THz. As shown in Figure 14.6, an optical fiber consists of three concentric cylindrical sections: the core, the cladding, and the jacket. The core consists of one or more thin strands made of glass or plastic. The cladding is the glass or plastic coating surrounding the core, which may be step-index or graded-index. In the step-index core, the refractive index is uniform but undergoes an abrupt change at the core–cladding interface, while the graded-index core has a refractive index that varies with the radial distance from the center of the fiber. The jacket surrounds one or a bundle of cladded fibers. The jacket is made of plastic or other materials to protect against moisture, crushing, etc.

A ray of light entering the core will be internally reflected when incident in the denser medium and the angle of incidence is greater than a critical value. Thus a light ray is reflected back into the original medium and the process is repeated as light passes down the core. This form of propagation is multimode, referring to the variety of angles that will reflect, as shown in Figure 14.7. It causes the signal to spread out in time and limits the rate

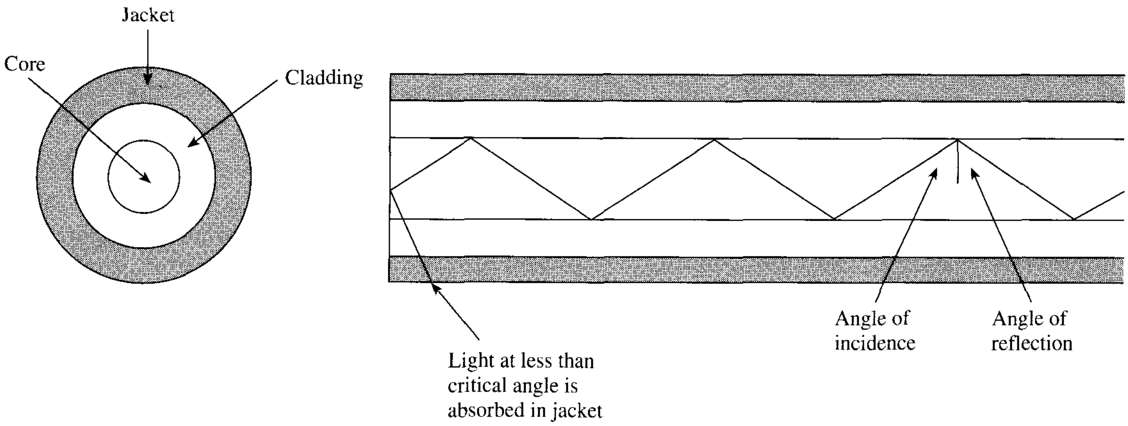

Figure 14.6 Optical fiber.

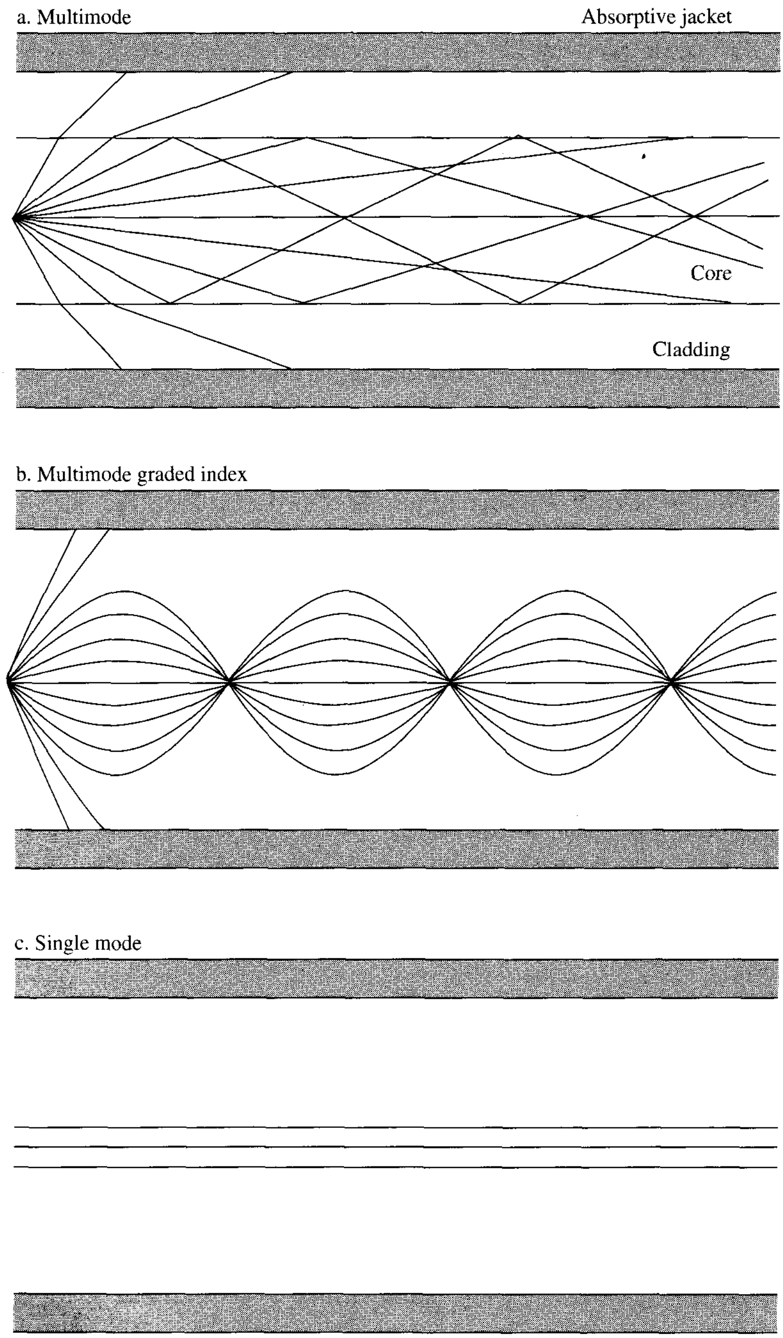

Figure 14.7 Optical fiber transmission modes. *Source:* W. Stallings, *Local and Metropolitan Area Networks,* 4th ed. New York: Macmillan, 1993, p. 85.

at which data can be accurately received. By reducing the radius of the core, a single-mode propagation occurs. This eliminates distortion.

A fiber-optic system is similar to a conventional transmission system. As shown in Figure 14.8, a fiber-optic system consists of a transmitter, a transmission medium, and a receiver. The transmitter accepts and converts input electrical signals in analog or digital form to optical signals. The transmitter sends the optical signal by modulating the output of a light source (usually an LED or a laser) by varying its intensity. The optical signal is transmitted over the optical fiber to a receiver. At the receiver, the optical signal is converted back into an electrical signal by a photodiode.

The performance of a fiber-optic link depends on the numerical aperture (NA), attenuation, and dispersion characteristics of the fiber. As signals propagate through the fiber, they become distorted due to attenuation and dispersion.

Numerical Aperture:

This is the most important parameter of an optical fiber. The value of NA is dictated by the refractive indices of the core and cladding. By definition, the refractive index n of a medium is defined as

$$n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in the medium}} = \frac{c}{u_m} = \frac{\dfrac{1}{\sqrt{\mu_o \varepsilon_o}}}{\dfrac{1}{\sqrt{\mu_m \varepsilon_m}}} \tag{14.18}$$

Since $\mu_m = \mu_o$ in most practical cases,

$$n = \sqrt{\frac{\varepsilon_m}{\varepsilon_o}} = \sqrt{\varepsilon_r} \tag{14.19}$$

indicating that the refractive index is essentially the square root of the dielectric constant. Keep in mind that ε_r can be complex as discussed in Chapter 10. For common materials, $n = 1$ for air, $n = 1.33$ for water, and $n = 1.5$ for glass.

As a light ray propagates from medium 1 to medium 2, Snell's law must be satisfied.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \tag{14.20}$$

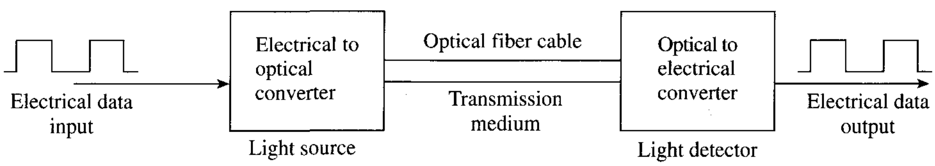

Figure 14.8 A typical fiber-optic system.

where θ_1 is the incident angle in medium 1 and θ_2 is the transmission angle in medium 2. The total reflection occurs when $\theta_2 = 90°$, resulting in

$$\theta_1 = \theta_c = \sin^{-1}\frac{n_2}{n_1} \tag{14.21}$$

where θ_c is the *critical angle* for total internal reflection. Note that eq. (14.21) is valid only if $n_1 > n_2$ since the value of $\sin\theta_c$ must be less than or equal to 1.

Another way of looking at the light-guiding capability of a fiber is to measure the *acceptance angle* θ_a, which is the maximum angle over which light rays entering the fiber will be trapped in its core. We know that the maximum angle occurs when θ_c is the critical angle thereby satisfying the condition for total internal reflection. Thus, for a step-index fiber,

$$\boxed{\text{NA} = \sin\theta_a = n_1 \sin\theta_c = \sqrt{n_1^2 - n_2^2}} \tag{14.22}$$

where n_1 is the refractive index of the core and n_2 is the refractive index of the cladding, as shown in Figure 14.9. Since most fiber cores are made of silica, $n_1 = 1.48$. Typical values of NA range between 0.19 and 0.25. The larger the value of NA, the more optical power the fiber can capture from a source.

Due to the numerous modes a fiber may support, it is called a *multimode step-index* fiber. The mode volume V is given by

$$V = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2} \tag{14.23}$$

where d is the fiber core diameter and λ is the wavelength of the optical source. From eq. (14.23), the number N of modes propagating in a step-index fiber can be estimated as

$$N = \frac{V^2}{2} \tag{14.24}$$

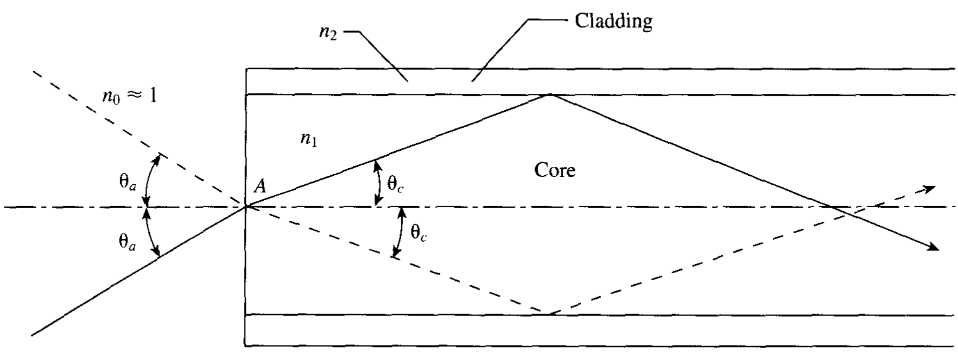

Figure 14.9 Numerical aperture and acceptance angle.

Attenuation:

As discussed in Chapter 10, attentuation is the reduction in the power of the optical signal. Power attenuation (or fiber loss) in an optical fiber is governed by

$$\frac{dP}{dz} = -\alpha P \tag{14.25}$$

where α is the attenuation and P is the optical power. In eq. (14.25), it is assumed that a wave propagates along z. By solving eq. (14.25), the power $P(0)$ at the input of the fiber and the power $P(\ell)$ of the light after ℓ are related as

$$P(\ell) = P(0)e^{-\alpha\ell} \tag{14.26}$$

It is customary to express attenuation α in dB/km and length ℓ of the fiber in km. In this case, eq. (14.26) becomes

$$\boxed{\alpha\ell = 10 \log_{10} \frac{P(0)}{P(\ell)}} \tag{14.27}$$

Thus, the power of the light reduces by α decibels per kilometer as it propagates through the fiber. Equation (14.27) may be written as

$$P(\mathcal{P}) = P(0) = 10^{-\alpha\ell/10} \tag{14.28}$$

For $\ell = 100$ km,

$$\frac{P(0)}{P(\ell)} \sim \begin{cases} 10^{-100} & \text{for coaxial cable} \\ 10^{-2} & \text{for fiber} \end{cases} \tag{14.29}$$

indicating that much more power is lost in the coaxial cable than in fiber.

Dispersion:

This is the spreading of pulses of light as they propagate down a fiber. As the pulses representing 0s spread, they overlap epochs that represent 1s. If dispersion is beyond a certain limit, it may confuse the receiver. The dispersive effects in single-mode fibers are much smaller than in multimode fibers.

EXAMPLE 14.2

A step-index fiber has a core diameter of 80 μm, a core refractive index of 1.62, and a numerical aperture of 0.21. Calculate: (a) the acceptance angle, (b) the refractive index that the fiber can propagate at a wavelength of 0.8 μm, (c) the number of modes that the fiber can propagate at a wavelength of 0.8 μm.

Solution:

(a) Since $\sin\theta_a = \text{NA} = 0.21$, then

$$\theta_a = \sin^{-1} 0.21 = 12.12°$$

(b) From $\text{NA} = \sqrt{n_1^2 - n_2^2}$, we obtain

$$n_2 = \sqrt{n_1^2 - \text{NA}^2} = \sqrt{1.62^2 - 0.21^2} = 1.606$$

(c)

$$V = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2} = \frac{\pi d\,\text{NA}}{\lambda}$$
$$= \frac{\pi(80 \times 10^{-6}) \times 0.21}{0.8 \times 10^{-6}} = 65.973$$

Hence

$$N = \frac{V^2}{2} = 2176 \text{ modes}$$

PRACTICE EXERCISE 14.2

A silica fiber has a refractive index of 1.48. It is surrounded by a cladding material with a refractive index of 1.465. Find: (a) the critical angle above which total internal reflection occurs, (b) the numerical aperture of the fiber.

Answer: (a) 81.83°, (b) 0.21.

EXAMPLE 14.3

Light pulses propagate through a fiber cable with an attenuation of 0.25 dB/km. Determine the distance through which the power of pulses is reduced by 40%.

Solution:

If the power is reduced by 40%, it means that

$$\frac{P(\ell)}{P(0)} = 1 - 0.4 = 0.6$$

Hence

$$\ell = \frac{10}{\alpha}\log_{10}\frac{P(0)}{P(\ell)}$$
$$= \frac{10}{0.25}\log_{10}\frac{1}{0.6}$$
$$= 8.874 \text{ km}$$

PRACTICE EXERCISE 14.3

A 10-km fiber with an attenuation of 0.2 dB/km serves as an optical link between two cities. How much of input power is received?

Answer: 63.1%.

SUMMARY

1. Microwaves are EM waves of very short wavelengths. They propagate along a straight line like light rays and can therefore be focused easily in one direction by antennas. They are used in radar, guidance, navigation, and heating.
2. Electromagnetic compatibility (EMC) is the capability of electrical and electronic devices to operate in their intended electromagnetic environment without suffering or causing unacceptable degradation as a result of EMI.
3. Electromagnetic interference (EMI) is the lack of EMC. It can be suppressed by grounding, shielding, and filtering.
4. An optical fiber is a dielectric waveguiding structure operating at optical frequencies and it consists of a core region and a cladding region.
5. Advantages of optical fiber over copper wire include: (1) large bandwidth, (2) low attenuation, (3) immunity to EMI, and (4) low cost.

REVIEW QUESTIONS

14.1 Microwaves have long wavelengths.

(a) True
(b) False

14.2 The wavelength in free space of a microwave signal whose frequency is 3 GHz is:

(a) 1 mm
(b) 10 mm
(c) 10 cm
(d) 1 m

14.3 Which of the following is not a source of EMI?

(a) Optical fiber
(b) Personal computer
(c) Police radar
(d) Aircraft
(e) Fluorescent lamp

14.4 Optical fiber is:

(a) A transmission line
(b) A waveguide
(c) Both

14.5 Unlike coax and twisted pair, optical fibers are immune to:

(a) High-frequency transmission
(b) Signal attenuation
(c) Power loss
(d) Electromagnetic interference

14.6 As a consultant, you have been asked to design a network for an auditorium. Speed and cost are no issues. However, interference with a nearby radio station is of concern. Which of the following media could be appropriate to implement the network?

(a) Microwave
(b) Coaxial cable
(c) Fiber optic
(d) Radio

14.7 Applications of optical fiber include:

(a) Undersea cable
(b) Long-distance telecommunication
(c) High-speed data transmission
(d) Medical instrumentation
(e) All of the above

14.8 Light rays are confined within a simple optical fiber by means of:

(a) Total internal reflection at the outer edge of the cladding
(b) Total internal reflection at the core–cladding interface
(c) Reflection at the fiber's jacket
(d) Refraction
(e) Defraction

14.9 An optical fiber has a core with a refractive index of 1.45 and a cladding with a refractive index of 1.42. The numerical aperture of the fiber is:

(a) 0.12
(b) 0.18
(c) 0.29
(d) 0.38

14.10 A 20-km long fiber-optic cable has an output power of 0.02 mW. If the fiber loss is 0.48 dB/km, what is the input power to the fiber?

(a) 52 μW
(b) 19 μW
(c) 7 μW
(d) 2 μW

Answers: 14.1b, 14.2c, 14.3a, 14.4b, 14.5d, 14.6c, 14.7e, 14.8b, 14.9c, 14.10a.

PROBLEMS

14.1 Discuss briefly some applications of microwaves other than those discussed in the text.

14.2 A useful set of parameters, known as the *scattering transfer parameters,* is related to the incident and reflected waves as

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix}$$

(a) Express the T-parameters in terms of the S-parameters.
(b) Find T when

$$S = \begin{bmatrix} 0.2 & 0.4 \\ 0.4 & 0.2 \end{bmatrix}$$

14.3 The S-parameters of a two-port network are:

$$S_{11} = 0.33 - j0.16, S_{12} = S_{21} = 0.56, S_{22} = 0.44 - j0.62$$

Find the input and output reflection coefficients when $Z_L = Z_o = 50\ \Omega$ and $Z_g = 2Z_o$.

14.4 Why can't regular lumped circuit components such as resistors, inductors, and capacitors be used at microwave frequencies?

14.5 In free space, a microwave signal has a frequency of 8.4 GHz. Calculate the wavelength of the signal.

14.6 An electrostatic discharge (ESD) can be modeled as a capacitance of 125 pF charged to 1500 V and discharging through a 2-km resistor. Obtain the current waveform.

***14.7** The insertion loss of a filter circuit can be calculated in terms of its A, B, C and D parameters when terminated by Z_g and Z_L as shown in Figure 14.10. Show that

$$IL = 20 \log_{10} \left| \frac{AZ_L + B + CZ_gZ_L + DZ_g}{Z_g + Z_L} \right|$$

14.8 A silver rod has rectangular cross section with height 0.8 cm and width 1.2 cm. Find:

(a) The dc resistance per 1 km of the conductor
(b) The ac resistance per 1 km of the conductor at 6 MHz

14.9 The speed of light in a given medium is measured as 2.1×10^8 m/s. Find its refractive index.

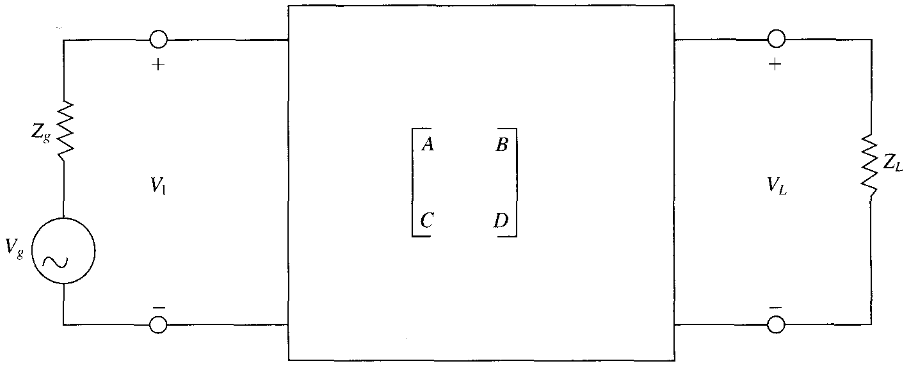

Figure 14.10 For Problem 14.5.

14.10 How will optical fiber be useful in EMI isolation?

14.11 A glass fiber has a core diameter of 50 μm, a core refractive index of 1.62, and a cladding with a refractive index of 1.604. If light having a wavelength of 1300 nm is used, find:

(a) The numerical aperture
(b) The acceptance angle
(c) the number of transmission modes

14.12 An optical fiber with a radius of 2.5 μm and a refractive index of 1.45 is surrounded by an air cladding. If the fiber is illuminated by a ray of 1.3 μm light, determine:

(a) V
(b) NA
(c) An estimate of how many modes can propagate.

14.13 An optical fiber with an attenuation of 0.4 dB/km is 5 km long. The fiber has $n_1 = 1.53$, $n_2 = 1.45$, and a diameter of 50 μm. Find:

(a) The maximum angle at which rays will enter the fiber and be trapped
(b) The percentage of input power received

14.14 A laser diode is capable of coupling 10 mW into a fiber with attenuation of 0.5 dB/km. If the fiber is 850 m long, calculate the power received at the end of the fiber.

14.15 Attenuation α_{10} in Chapter 10 is in Np/m, whereas attenuation α_{14} in this chapter is in dB/km. What is the relationship between the two?

14.16 A lightwave system uses a 30-km fiber link with a loss of 0.4 dB/km. If the system requires at least 0.2 mW at the receiver, calculate the minimum power that must be launched into the fiber.

14.17 (a) Discuss the advantages derived from using a fiber optic cable.
(b) What is pulse dispersion?