Chapter 21

Photonic Materials

Have You Ever Wondered?

- *Why does the sky appear blue?*
- *How does an optical fiber work?*
- *What factors control the transmission and absorption of light in different materials?*
- *What does the acronym LASER stand for?*
- *What is a ruby laser made from?*
- *Does the operation of a fluorescent tube light involve phosphorescence?*
- *How did the invention of blue lasers enable high definition DVDs?*

Photonic or optical materials have had a significant impact on the development of the communications infrastructure and information technology. Photonic materials have also played a key role in many other technologies related to medicine, manufacturing, and astronomy, just to name a few. Today, millions of kilometers of optical fiber have been installed worldwide. The term "optoelectronics" refers to the science and technology that combine electronic and optical materials. Examples include light-emitting diodes (LEDs), solar cells, and semiconductor lasers. Starting with simple mirrors, prisms, and lenses to the latest photonic band gap materials, the field of optical materials and devices has advanced at a very rapid pace. The goal of this chapter is to present a summary of fundamental principles that have guided applications of optical materials.

Optical properties of materials are related to the interaction of a material with electromagnetic radiation in the form of waves or particles of energy called photons. This radiation may have characteristics that fall in the visible light spectrum or may be invisible to the human eye. In this chapter, we explore two avenues by which we can use the optical properties of materials: emission of photons from materials and interaction of photons with materials.

21-1 The Electromagnetic Spectrum

Light is energy, or radiation, in the form of waves or particles called **photons** that can be emitted from a material. The important characteristics of the photons—their energy E, wavelength λ, and frequency ν—are related by the equation

$$E = \mathrm{h}\nu = \frac{\mathrm{h}c}{\lambda} \tag{21-1}$$

where c is the speed of light (in vacuum, the speed c_0 is 3×10^{10} cm/s), and h is Planck's constant (6.626×10^{-34} J · s). Since there are 1.6×10^{-19} J per electron volt (eV), the value of "h" is also given by 4.14×10^{-15} eV · s. This equation permits us to consider the photon either as a particle of energy E or as a wave with a characteristic wavelength and frequency.

The spectrum of electromagnetic radiation is shown in Figure 21-1. Gamma and x-rays have short wavelengths, or high frequencies, and possess high energies; microwaves and radio waves possess low energies; and visible light represents only a very narrow portion of the electromagnetic spectrum. Figure 21-1 also shows the response of the human eye to different colors. Bandgaps (E_g) of semiconductors (in eV) and corresponding wavelengths of light are also shown. As discussed in Chapter 19, these relationships are used to make LEDs of different colors.

21-2 Refraction, Reflection, Absorption, and Transmission

All materials interact in some way with light. Photons cause a number of optical phenomena when they interact with the electronic or crystal structure of a material (Figure 21-2). If incoming photons interact with valence electrons, several things may happen. The photons may give up their energy to the material, in which case *absorption* occurs. Or the photons may give up their energy, but photons of identical energy are immediately emitted by the material; in this case, *reflection* occurs. Finally, the photons may not interact with the electronic structure of the material; in this case, *transmission* occurs. Even in transmission, however, photons are changed in velocity, and *refraction* occurs. A small fraction of the incident light may be scattered with a slightly different frequency (Raman scattering).

As Figure 21-2 illustrates, an incident beam of intensity I_0 may be partly reflected, partly absorbed, and partly transmitted. The intensity of the incident beam I_0 therefore can be expressed as

$$I_0 = I_r + I_a + I_t \tag{21-2}$$

where I_r is the portion of the beam that is reflected, I_a is the portion that is absorbed, and I_t is the portion finally transmitted through the material. Reflection may occur at both the front and back surfaces of the material. Figure 21-2(a) shows reflection only at the front surface. Also, reflection occurs at a certain angle with respect to the normal of the surface (specular reflection) and also in many other directions [diffuse reflection, not shown in Figure 21-2(a)]. Several factors are important in determining the behavior of the photon, with the energy required to excite an electron to a higher energy state being of particular importance.

Let's examine each of these four phenomena. We begin with refraction, since it is related to reflection and transmission.

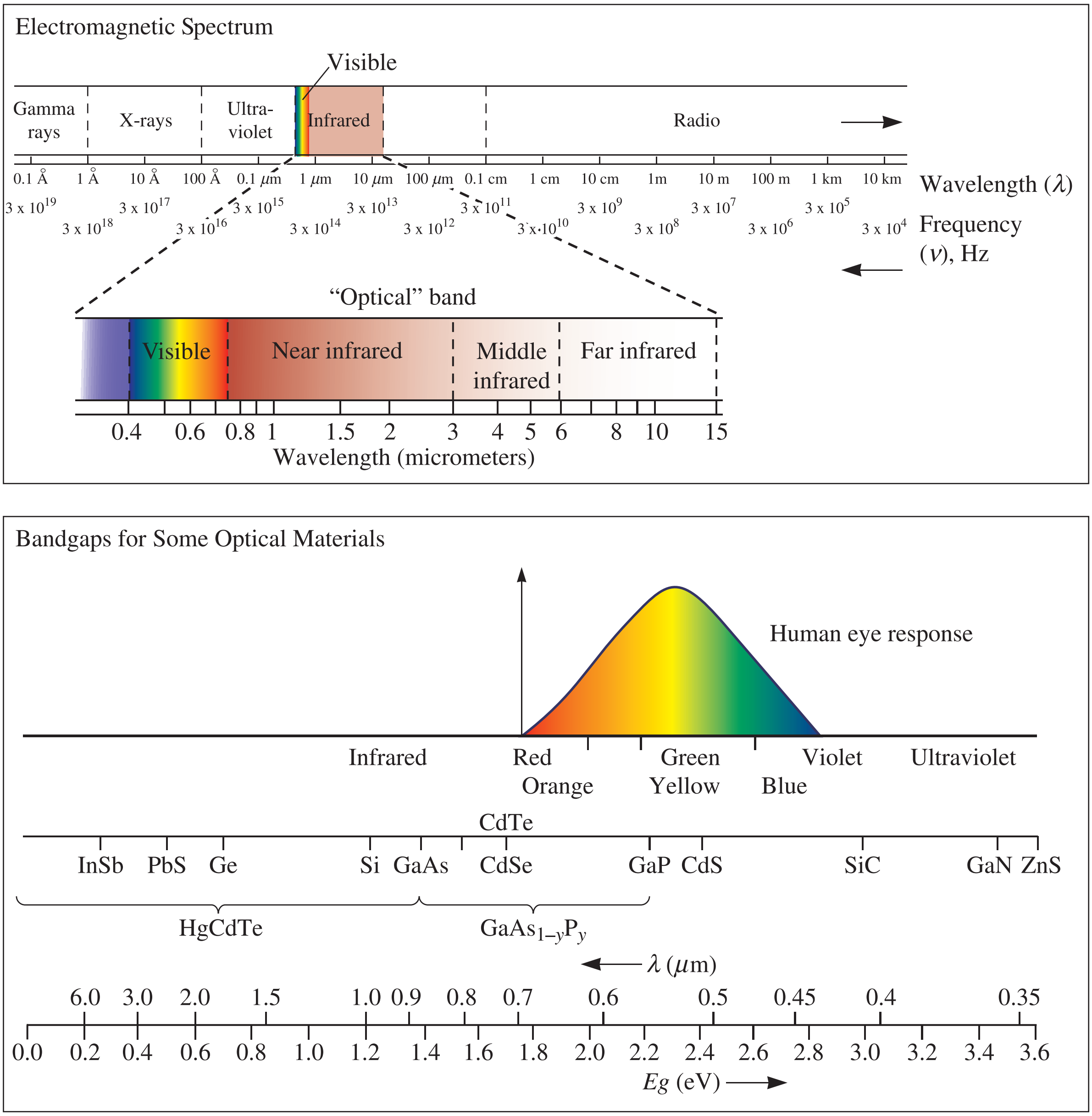
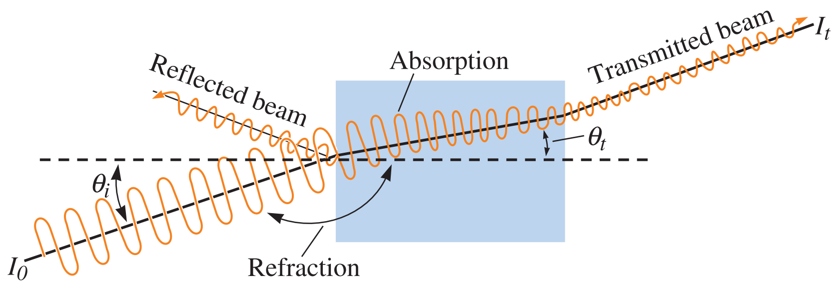


Figure 21-1 The electromagnetic spectrum of radiation; the bandgaps and cutoff frequencies for some optical materials are also shown. (*From Optoelectronics:* An Introduction to Materials and Devices, *by J. Singh. Copyright © 1996 The McGraw-Hill Companies. Reprinted by permission of The McGraw-Hill Companies.*)

Refraction Even when a photon is transmitted, the photon causes polarization of the electrons in the material and, by interacting with the polarized material, loses some of its energy. The speed of light (c) can be related to the ease with which a material polarizes both electrically (permittivity ε) and magnetically (permeability μ) through

$$c = \frac{1}{\sqrt{\mu\varepsilon}} \tag{21-3}$$



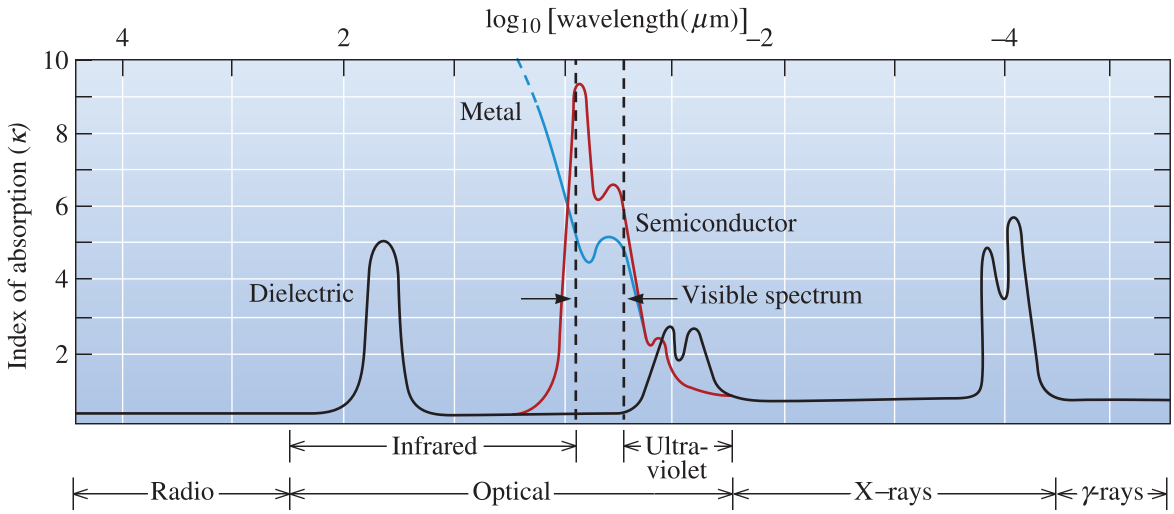


Figure 21-2 (a) Interaction of photons with a material. In addition to reflection, absorption, and transmission, the beam changes direction, or is refracted. The change in direction is given by the index of refraction *n*. (b) The absorption index (κ) as a function of wavelength.

Generally, optical materials are not magnetic, and the permeability can be neglected. Because the speed of the photons decreases, the beam of photons changes direction when it enters the material [Figure 21-2(a)]. Suppose photons traveling in a vacuum impinge on a material. If θ_i and θ_t respectively, are the angles that the incident and refracted beams make with the normal of the surface of the material, then

$$n = \frac{c_0}{c} = \frac{\lambda_{\text{vacuum}}}{\lambda} = \frac{\sin \theta_i}{\sin \theta_t} \tag{21-4}$$

The ratio n is the **index of refraction**, c_0 is the speed of light in a vacuum (3×10^8 m/s), and c is the speed of light in the material. The frequency of light does not change as it is refracted. Typical values of the index of refraction for several materials are listed in Table 21-1.

We can also define a complex refractive index (n^*). This includes κ, a parameter known as the absorption index:

$$n^* = n(1 - i\kappa) \tag{21-5}$$

TABLE 21-1 ■ *Index of refraction of selected materials for photons of wavelength 5890 Å*

Material	Index of Refraction (n)	Material	Index of Refraction (n)
Air	1.00	Polystyrene	1.60
Ice	1.309	TiO_2	1.74
Water	1.333	Sapphire (Al_2O_3)	1.8
Teflon™	1.35	Leaded glasses (crystal)	2.50
SiO_2 (glass)	1.46	Rutile (TiO_2)	2.6
Polymethyl methacrylate	1.49	Diamond	2.417
Typical silicate glasses	~1.50	Silicon	3.49
Polyethylene	1.52	Gallium arsenide	3.35
Sodium chloride (NaCl)	1.54	Indium phosphide	3.21
SiO_2 (quartz)	1.55	Germanium	4.0
Epoxy	1.58		

In Equation 21-5, $i = \sqrt{-1}$ is the imaginary number. The absorption index is defined as

$$\kappa = \frac{\alpha\lambda}{4\pi n} \tag{21-6}$$

In Equation 21-6, α is the **linear absorption coefficient** (see Equation 21-12), λ is the wavelength of light, and n is the refractive index. Figure 21-2(b) shows the variation in index of absorption with the frequency of electromagnetic waves. Drawing an analogy, the refractive index is similar to the dielectric constant of materials, and the absorption index is similar to the dielectric loss factor.

If the photons are traveling in Material 1, instead of in a vacuum, and then pass into Material 2, the velocities of the incident and refracted beams depend on the ratio between their indices of refraction, again causing the beam to change direction:

$$\frac{c_1}{c_2} = \frac{n_2}{n_1} = \frac{\sin\theta_i}{\sin\theta_t} \tag{21-7}$$

Equation 21-7 is also known as Snell's law.

When a ray of light enters from a material with refractive index (n_1) into a material of refractive index (n_2), and if $n_1 > n_2$, the ray is bent away from the normal and toward the boundary surface [Figure 21-3(a)]. A beam traveling through Material 1 is reflected rather than transmitted if the angle θ_t becomes 90°.

More interaction of the photons with the electronic structure of the material occurs when the material is easily polarized. We saw different dielectric polarization mechanisms in Chapter 19. Among these, the electronic polarization (i.e., displacement of the electron cloud around the atoms and ions) is the one that controls the refractive index of materials. Consequently, we find a relationship between the index of refraction n and the high-frequency dielectric constant k_∞ of the material. From Equations 21-3 and 21-4 and for nonferromagnetic or nonferrimagnetic materials,

$$n = \frac{c_0}{c} = \sqrt{\frac{\mu\varepsilon}{\mu_0\varepsilon_0}} \cong \sqrt{\frac{\varepsilon}{\varepsilon_0}} = \sqrt{k_\infty} \tag{21-8}$$

In Equation 21-8, c_0 and c are the speed of light in a vacuum and in the material, respectively, μ_0 and μ are the magnetic permeabilities of the vacuum and material,

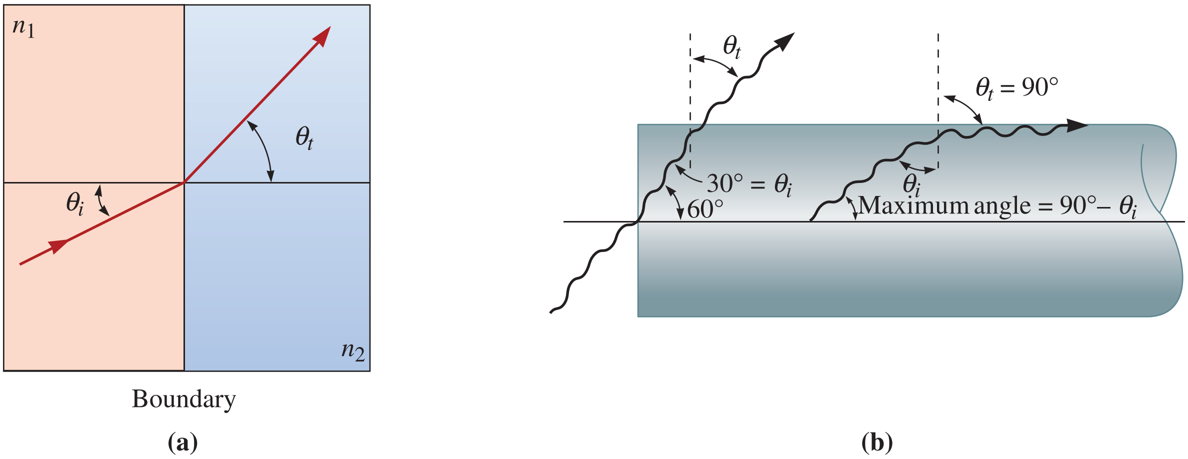


Figure 21-3 (a) When a ray of light enters from Material 1 into Material 2, if the refractive index of Material 1 (n_1) is greater than that of Material 2 (n_2), the ray bends away from the normal and toward the boundary surface. (b) Diagram of a light beam in a glass fiber for Example 21-1.

respectively, and ε_0 and ε are the dielectric permittivities of the vacuum and material, respectively. As we discussed in Chapter 19, the material known as "lead crystal," which is actually amorphous silicate glass with up to ~30% lead oxide, has a high index of refraction ($n \sim 2.4$), since Pb^{2+} ions have high electronic polarizability. We use a similar strategy to dope silica fibers to enhance the refractive index of the core of optical fibers as compared to the outer cladding region. This helps keep the light (and hence information) in the core of the optical fiber. The difference in the high-frequency dielectric constant and the low-frequency dielectric constant is a measure of the other polarization mechanisms that are contributing to the dielectric constant.

The refractive index n is not a constant for a particular material. The frequency, or wavelength, of the photons affects the index of refraction. **Dispersion** of a material is defined as the variation of the refractive index with wavelength:

$$(\text{Dispersion})_\lambda = \frac{dn}{d\lambda} \tag{21-9}$$

This dependence of the refractive index on wavelength is nonlinear. The dispersion within a material means light pulses of different wavelengths, starting at the same time at the end of an optical fiber, will arrive at different times at the other end. Thus, material dispersion plays an important role in fiber optics. This is one of the reasons why we prefer to use a single wavelength source of light for fiber-optic communications. Dispersion also causes chromatic aberration in optical lenses.

Since dielectric polarization (P) is equal to the dipole moment per unit volume, and the high-frequency dielectric constant is related to the refractive index, we expect that (for the same material), a denser form or polymorph will have a higher refractive index (compare the refractive indices of ice and water or glass and quartz).

The following example illustrates how an optical fiber is designed to minimize optical losses during insertion. It is followed by an example calculating the index of refraction.

Example 21-1 Design of a Fiber Optic System

Optical fibers are commonly made from high-purity silicate glasses. They consist of a core with a refractive index that is higher than the refractive index of the coating on the fiber (the coating is called the cladding). Even a simple glass fiber in air can serve as an optical fiber because the fiber has a refractive index that is greater than that of air.

Consider a beam of photons that is introduced from a laser into a glass fiber with an index of refraction of 1.5. Choose the angle of introduction of the beam with respect to the fiber axis that will result in a minimum of leakage of the beam from the fiber. Also, consider how this angle might change if the fiber is immersed in water.

SOLUTION

To prevent leakage of the beam, we need total internal reflection, and thus the angle θ_t must be at least 90°. Suppose that the photons enter at a 60° angle to the axis of the fiber. From Figure 21-3(b), we find that $\theta_i = 90 - 60 = 30°$. If we let the glass be Material 1 and if the glass fiber is in air ($n = 1.0$), then from Equation 21-7:

$$\frac{n_2}{n_1} = \frac{\sin\ \theta_i}{\sin\ \theta_t} \quad \text{or} \quad \frac{1}{1.5} = \frac{\sin\ 30°}{\sin\ \theta_t}$$

$$\sin\ \theta_t = 1.5\ \sin\ 30° = 1.5(0.50) = 0.75 \ \text{ or } \ \theta_t = 48.6°$$

Because θ_t is less than 90°, photons escape from the fiber. To prevent transmission, we must introduce the photons at a shallower angle, giving $\theta_t = 90°$.

$$\frac{1}{1.5} = \frac{\sin\ \theta_i}{\sin\ \theta_t} = \frac{\sin\ \theta_i}{\sin\ 90°} = \sin\ \theta_i$$

$$\sin \theta_i = 0.6667 \ \text{ or } \ \theta_i = 41.8°$$

If the angle between the beam and the axis of the fiber is $90 - 41.8 = 48.2°$ or less, the beam is reflected.

If the fiber were immersed in water ($n = 1.333$), then

$$\frac{1.333}{1.5} = \frac{\sin \theta_i}{\sin \theta_t} = \frac{\sin \theta_i}{\sin 90°} = \sin \theta_i$$

$$\sin \theta_i = 0.8887 \ \text{ or } \ \theta_i = 62.7°$$

In water, the photons would have to be introduced at an angle of less than $90 - 62.7 = 27.3°$ in order to prevent transmission.

Example 21-2 Light Transmission in Polyethylene

Suppose a beam of photons in a vacuum strikes a sheet of polyethylene at an angle of 10° to the normal of the surface of the polymer. Polyethylene has a high-frequency dielectric constant of $k_\infty = 2.3$. Calculate the index of refraction of polyethylene, and find the angle between the incident beam and the beam as it passes through the polymer.

SOLUTION

The index of refraction is related to the high-frequency dielectric constant:

$$n = \sqrt{k_\infty} = \sqrt{2.3} = 1.52$$

The angle θ_t is

$$n = \frac{\sin \theta_i}{\sin \theta_t}$$

$$\sin \theta_t = \frac{\sin \theta_i}{n} = \frac{\sin 10°}{1.52} = \frac{0.174}{1.52} = 0.1145$$

$$\theta_t = 6.57°$$

Reflection

When a beam of photons strikes a material, the photons interact with the valence electrons and give up their energy. In metals, the radiation of almost any wavelength excites the electrons into higher energy levels. One might expect that, if the photons are totally absorbed, no light would be reflected and the metal would appear black. In aluminum or silver, however, photons of almost identical wavelength are immediately re-emitted as the excited electrons return to their lower energy levels—that is, reflection occurs. Since virtually the entire visible spectrum is reflected, these metals have a white, or silvery color.

The **reflectivity** R gives the fraction of the incident beam that is reflected and is related to the index of refraction. If the material is in a vacuum or in air:

$$R = \left(\frac{n-1}{n+1}\right)^2 \tag{21-10}$$

If the material is in some other medium with an index of refraction of n_i, then

$$R = \left(\frac{n-n_i}{n+n_i}\right)^2 \tag{21-11}$$

These equations apply to reflection from a single surface and assume a normal (perpendicular to the surface) incidence. The value of R depends upon the angle of incidence. Materials with a high index of refraction have a higher reflectivity than materials with a low index. Because the index of refraction varies with the wavelength of the photons, so does the reflectivity.

In metals, the reflectivity is typically on the order of 0.9 to 0.95, whereas the reflectivity of typical glasses is nearer to 0.05. The high reflectivity of metals is one reason that they are *opaque.*

There are many applications for which we want materials to have very good reflectivity. Examples include mirrors and certain types of coatings on glasses. In fact, these coatings must also be designed such that much of a certain part of the electromagnetic spectrum (e.g., infrared, the part that produces heat) must be reflected. Many such coatings have been developed for glasses. There are also many applications for which the reflectivity must be extremely limited. Such coatings are known as antireflective (AR) coatings. These coatings are used for glasses, in automobile rear view mirrors, on windows, or for the glass of picture frames so that you see through the glass without seeing your own reflection.

Absorption That portion of the incident beam that is not reflected by the material is either absorbed or transmitted through the material. The fraction of the beam that is absorbed is related to the thickness of the material and the manner in which the photons interact with the material's structure. The intensity of the beam after passing through the material is given by

$$I = I_0 \exp(-\alpha x) \tag{21-12}$$

where x is the path through which the photons move (usually the thickness of the material), α is the linear absorption coefficient of the material for the photons, I_0 is the intensity of the beam after reflection at the front surface, and I is the intensity of the beam when it reaches the back surface. Equation 21-12 is also known as Bouguer's law, or the Beer–Lambert law. Figure 21-4 shows the linear absorption coefficient as a function of wavelength for several metals.

Absorption in materials occurs by several mechanisms. In *Rayleigh scattering*, photons interact with the electrons orbiting an atom and are deflected without any change in photon energy; this is an example of "elastic" scattering. Rayleigh scattering is more significant for higher photon energies and is responsible for the color of the sky. Since the blue (high energy) end of the visible spectrum scatters most efficiently, the sunlight scattered by molecules and atmospheric particles that reaches our eyes is mostly blue. The effect is quite strong as the intensity of scattering is proportional to the energy of the photons raised to the fourth power. Rayleigh scattering also depends on the particle size and is most efficient for particles that are much smaller than the wavelength of the light. Scattering from particles much larger than the wavelength of light occurs because of the *Tyndall effect.* This is why clouds, consisting of water droplets, look white. *Compton scattering* also occurs when a photon interacts with an electron, but because the incoming photon loses some of its energy to the electron, the wavelength of the light increases; this is an example of "inelastic" scattering.

The *photoelectric effect* occurs when the energy of a photon is fully absorbed, resulting in the ejection of an electron from an atom. The atom thus becomes ionized. No electrons are ejected when the incoming photons have energies less than the electron binding energy, regardless of the intensity of the light. When the photons have energies greater than the binding energy, electrons are ejected with a kinetic energy equal to the photon energy minus the binding energy. As the energy of the photon increases (or the wavelength

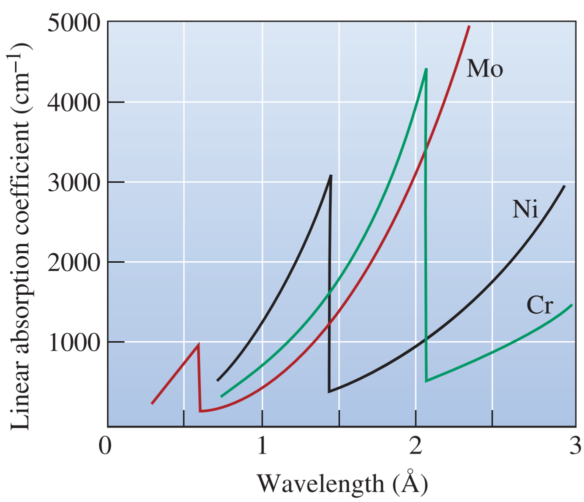


Figure 21-4
The linear absorption coefficient relative to wavelengths for several metals. Note the sudden decrease in the absorption coefficient for wavelengths greater than the absorption edge.

decreases, see Figure 21-4), less absorption occurs until the photon has an energy equal to that of the binding energy. At this energy, the absorption coefficient increases abruptly because electrons may now be ejected, thereby providing an efficient means for photons to be absorbed. The energy or wavelength at which this occurs is referred to as the **absorption edge** because of the shape of the peaks in Figure 21-4. The abrupt change in the absorption coefficient corresponds to the energy required to remove an electron from the atom; this absorption edge is important to certain x-ray analytical techniques. Albert Einstein received the Nobel Prize in Physics in 1921 for explaining the photoelectric effect.

In some cases, the effect of scattering can be written as

$$I = I_0 \exp\left[(-\alpha_i + \alpha_s)x\right] \tag{21-13}$$

In Equation 21-13, α_i is what we previously termed α, the intrinsic absorption coefficient, and α_s is the scattering coefficient.

Examples of a portion of the characteristic spectra for several elements are included in Table 21-2. The K_α, K_β, and L_α lines correspond to the wavelengths of radiation emitted from transitions of electrons between shells, as discussed later in this chapter.

Transmission

The fraction of the beam that is not reflected or absorbed is transmitted through the material. Using the following steps, we can determine the fraction of the beam that is transmitted (see Figure 21-5).

1. If the incident intensity is I_0, then the loss due to reflection at the front face of the material is RI_0. The fraction of the incident beam that actually enters the material is $I_0 - RI_0 = (1 - R)I_0$:

$$I_{\text{reflected at front surface}} = RI_0$$
$$I_{\text{after reflection}} = (1 - R)I_0$$

2. A portion of the beam that enters the material is lost by absorption. The intensity of the beam after passing through a material having a thickness x is

$$I_{\text{after absorption}} = (1 - R)I_0 \exp(-\alpha x)$$

3. Before the partially absorbed beam exits the material, reflection occurs at the back surface. The fraction of the beam that reaches the back surface and is reflected is

$$I_{\text{reflected at back surface}} = R(1 - R)I_0 \exp(-\alpha x)$$

TABLE 21-2 *Characteristic emission lines and absorption edges for selected elements*

Metal	K_α (Å)	K_β (Å)	L_α (Å)	Absorption Edge (Å)
Al	8.337	7.981	—	7.951
Si	7.125	6.768	—	6.745
S	5.372	5.032	—	5.018
Cr	2.291	2.084	—	2.070
Mn	2.104	1.910	—	1.896
Fe	1.937	1.757	—	1.743
Co	1.790	1.621	—	1.608
Ni	1.660	1.500	—	1.488
Cu	1.542	1.392	13.357	1.380
Mo	0.711	0.632	5.724	0.620
W	0.211	0.184	1.476	0.178

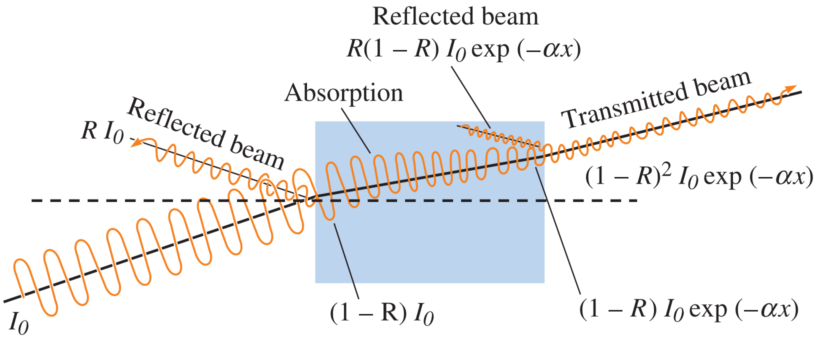


Figure 21-5 Fractions of the original beam that are reflected, absorbed, and transmitted.

4. Consequently, the fraction of the beam that is completely transmitted through the material is

$$\begin{aligned} I_{\text{transmitted}} &= I_{\text{after absorption}} - I_{\text{reflected at back}} \\ &= (1 - R)I_0 \exp(-\alpha x) - R(1 - R)I_0 \exp(-\alpha x) \\ &= (1 - R)(1 - R)I_0 \exp(-\alpha x) \\ I_t &= (1 - R)^2 I_0 \exp(-\alpha x) \end{aligned} \tag{21-14}$$

The intensity of the transmitted beam may depend on the wavelength of the photons in the beam. In metals, because there is no energy gap, virtually any photon has sufficient energy to excite an electron into a higher energy level, thus absorbing the energy of the excited photon [Figure 21-6(a)]. As a result, even extremely thin samples of metals are opaque. Dielectrics, on the other hand, possess a large energy gap between the valence and conduction bands. If the energy of the incident photons is less than the energy gap, no electrons gain enough energy to escape the valence band and, therefore, absorption does not occur [Figure 21-6(b)]. In intrinsic semiconductors, the energy gap is smaller

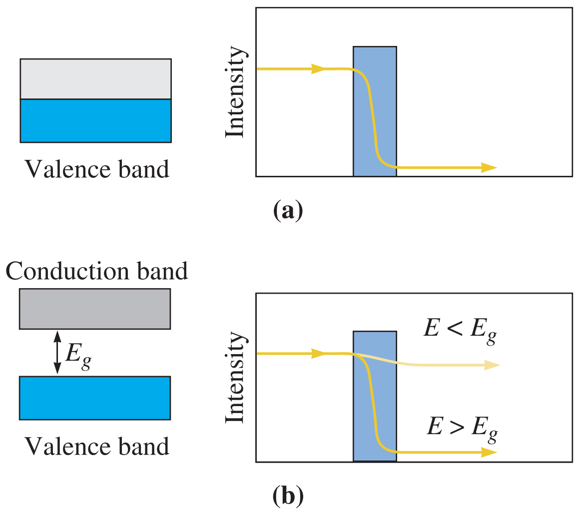


Figure 21-6 Relationships between absorption and the energy gap: (a) metals and (b) dielectrics and intrinsic semiconductors. The diagram on the left represents the band structure of the material under consideration. The diagram on the right represents the intensity of light as it passes from air into the material and back into air.

than that for insulators, and absorption occurs when the photons have energies exceeding the energy gap E_g, whereas transmission occurs for less energetic photons [Figure 21-6(b) also applies to semiconductors]. In other words, only the light below a certain wavelength is absorbed. Extrinsic semiconductors include donor or acceptor energy levels within the bandgap that provide additional energy levels for absorption. Therefore, semiconductors are opaque to short wavelength radiation but transparent to long wavelength photons (see Example 21-3). For example, silicon and germanium appear opaque to visible light, but they are transparent to longer wavelength infrared radiation. Many of the narrow bandgap semiconductors (e.g., HgCdTe) are used for detection of infrared radiation. These detector materials have to be cooled to low temperatures (e.g., using liquid nitrogen) since the thermal energy of electrons at room temperature is otherwise enough to saturate the conduction band.

The intensity of the transmitted beam also depends on microstructural features. Porosity in ceramics scatters photons; even a small amount of porosity (less than 1 volume percent) may make a ceramic opaque. For example, alumina that has relatively low mass density (owing to porosity) is opaque, while high density alumina is optically transparent. High density alumina is often used in the manufacture of lightbulbs. Crystalline precipitates, particularly those that have a much different index of refraction than the matrix material, also cause scattering. These crystalline *opacifiers* cause a glass that normally may have excellent transparency to become translucent or even opaque. Typically, smaller pores or precipitates cause a greater reduction in the transmission of light.

Photoconduction occurs in semiconducting materials if the semiconductor is part of an electrical circuit. If the energy of an incoming photon is sufficient, an electron is excited into the conduction band from the valence band, thereby creating a hole in the valence band. The electron and hole then carry charge through the circuit [Figure 21-7(a)]. The maximum

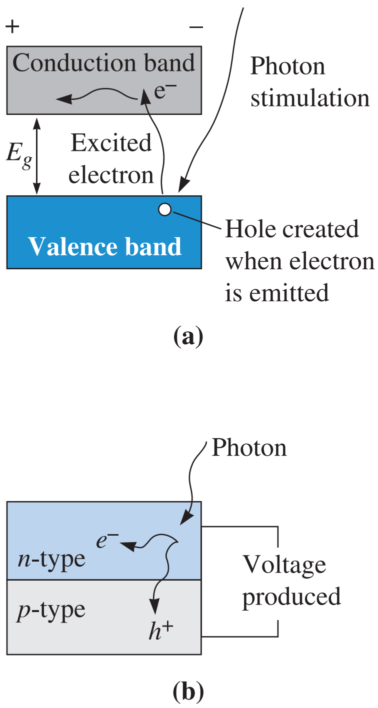


Figure 21-7
(a) Photoconduction in semiconductors involves the absorption of a stimulus by exciting electrons from the valence band to the conduction band. Rather than dropping back to the valence band to cause emission, the excited electrons carry a charge through an electrical circuit. (b) A solar cell takes advantage of this effect.

wavelength of the incoming photon that will produce photoconduction is related to the energy gap in the semiconducting material:

$$\lambda_{\text{max}} = \frac{hc}{E_g} \tag{21-15}$$

We can use this principle for photodetectors or "electric eyes" that open or close doors or switches when a beam of light focused on a semiconducting material is interrupted.

Solar cells also use the absorption of light to generate voltage [Figure 21-7(b)]. Essentially the electron-hole pairs generated by optical absorption are separated, and this leads to the development of a voltage. This voltage causes a current flow in an external circuit. Solar cells are *p*-*n* junctions designed so that photons excite electrons into the conduction band. The electrons move to the *n*-side of the junction, while holes move to the *p*-side of the junction. This movement produces a contact voltage due to the charge imbalance. If the junction *p*-*n* is connected to an electric circuit, the junction acts as a battery to power the circuit. Solar cells make use of antireflective coatings so that maximum key elements of the solar spectrum are captured.

LEDs

As discussed in Chapter 19, the light that is absorbed by a direct band gap semiconductor causes electrons to be promoted to the conduction band. When these electrons fall back into the valence band, they combine with the holes and cause emission of light. Many semiconductor solid solutions can be tailored to have particular bandgaps, producing LEDs of different colors. This phenomenon is also used in semiconductor lasers (Figure 21-8). The design of LEDs is discussed later in this chapter.

The following examples illustrate applications of many of these concepts related to the absorption and transmission of light.

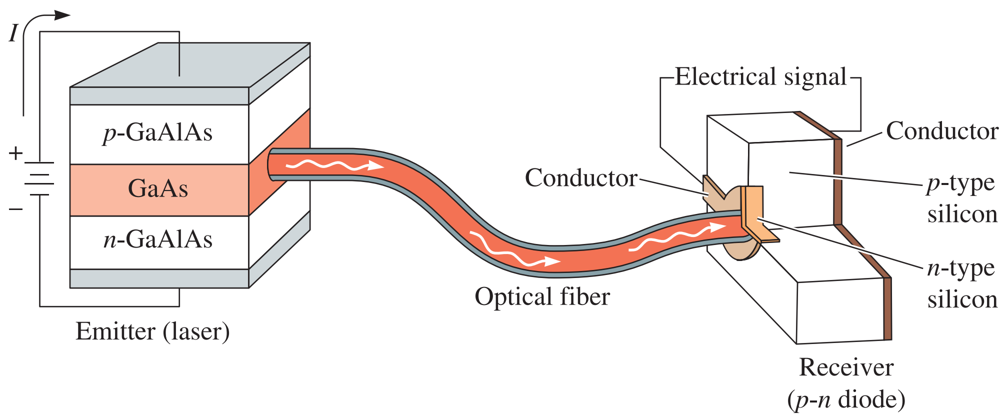


Figure 21-8 Elements of a photonic system for transmitting information involves a laser or LED to generate photons from an electrical signal, optical fibers to transmit the beam of photons efficiently, and an LED receiver to convert the photons back into an electrical signal.

Example 21-3 *Determining Critical Energy Gaps*

Determine the critical energy gaps for a semiconductor that provide complete transmission and complete absorption of photons in the visible spectrum.

SOLUTION

In order for complete transmission to occur, the bandgap of the semiconductor must be larger than the energies of all photons in the visible spectrum. The visible light spectrum varies from 4×10^{-5} cm to 7×10^{-5} cm. The photons with shorter wavelengths have higher energies. Thus, the minimum band gap energy E_g required to ensure that no photons in the visible spectrum are absorbed (and all photons are transmitted) is

$$E_g = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34}\,\mathrm{J \cdot s})(3 \times 10^{10}\,\mathrm{cm/s})}{(4 \times 10^{-5}\,\mathrm{cm})(1.6 \times 10^{-19}\,\mathrm{J/eV})} = 3.1\,\mathrm{eV}$$

If the semiconductor band gap is 3.1 eV or larger, all photons in the visible spectrum will be transmitted.

In order for a photon to be absorbed, the energy gap of the semiconductor must be less than the photon energy. The photons with longer wavelengths have lower energies. Thus, the maximum bandgap energy that will allow for complete absorption of all wavelengths of the visible spectrum is

$$E_g = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34}\,\mathrm{J \cdot s})(3 \times 10^{10}\,\mathrm{cm/s})}{(7 \times 10^{-5}\,\mathrm{cm})(1.6 \times 10^{-19}\,\mathrm{J/eV})} = 1.8\,\mathrm{eV}$$

If the bandgap is 1.8 eV or smaller, all photons in the visible spectrum will be absorbed. For semiconductors with an E_g between 1.8 eV and 3.1 eV, a portion of the photons in the visible spectrum will be absorbed.

Example 21-4 *Design of a Radiation Shield*

A material has a reflectivity of 0.15 and an absorption coefficient (α) of 100 cm^{-1}. Design a shield that will permit only 1% of the incident radiation to be transmitted through the material.

SOLUTION

From Equation 21-14, the fraction of the incident intensity that will be transmitted is

$$\frac{I_t}{I_0} = (1 - R)^2 \exp(-\alpha x)$$

and the required thickness of the shield can be determined:

$$0.01 = (1 - 0.15)^2 \exp(-100x)$$

$$\frac{0.01}{(0.85)^2} = 0.01384 = \exp(-100x)$$

$$\ln(0.01384) = -4.28 = -100x$$

$$x = 0.0428\ \mathrm{cm}$$

The material should have a thickness of 0.0428 cm in order to transmit 1% of the incident radiation.

If we wished, we could determine the amount of radiation lost in each step:

$$\text{Reflection at the front face: } I_r = RI_0 = 0.15I_0$$
$$\text{Intensity after reflection: } I = I_0 - 0.15I_0 = 0.85I_0$$
$$\text{Intensity after absorption: } I_a = (0.85)I_0 \exp[(-100)(0.0428)] = 0.0118I_0$$
$$\text{Absorbed Intensity: } 0.85I_0 - 0.0118I_0 = 0.838I_0$$
$$\text{Reflection at the back face: } I_r = R(1 - R)I_0 \exp(-\alpha x)$$
$$= (0.15)(1 - 0.15)I_0 \exp[-(100)(0.0428)] = 0.0018I_0$$

21-3 Selective Absorption, Transmission, or Reflection

Unusual optical behavior is observed when photons are selectively absorbed, transmitted, or reflected. We have already seen that semiconductors transmit long wavelength photons but absorb short wavelength radiation. There are a variety of other cases in which similar selectivity produces unusual optical properties.

In certain materials, replacement of normal ions by transition or rare earth elements produces a *crystal field*, which creates new energy levels within the structure. This phenomenon occurs when Cr^{3+} ions replace Al^{3+} ions in Al_2O_3. The new energy levels absorb visible light in the violet and green-yellow portions of the spectrum. Red wavelengths are transmitted, giving the reddish color in ruby. In addition, the chromium ion replacement creates an energy level that permits luminescence (discussed later) to occur when the electrons are excited by a stimulus. Lasers made from chromium-doped ruby produce a characteristic red beam because of this.

Glasses can also be doped with ions that produce selective absorption and transmission (Table 21-3). Similarly, electrons or hole traps called *F-centers*, can be present in crystals. When fluorite (CaF_2) is formed with excess calcium, a fluoride ion vacancy is produced. To maintain electrical neutrality, an electron is trapped in the vacancy, producing energy levels that absorb all visible photons—with the exception of purple.

Polymers—particularly those containing an aromatic ring in the backbone—can have complex covalent bonds that produce an energy level structure which causes selective absorption. For this reason, chlorophyll in plants appears green, and hemoglobin in blood appears red.

TABLE 21-3 ■ *Effect of ions on colors produced in glasses*

Ion	Color	Ion	Color
Cr^{2+}	Blue	Mn^{2+}	Orange
Cr^{3+}	Green	Fe^{2+}	Blue-green
Cu^{2+}	Blue-green	U^{6+}	Yellow

21-4 Examples and Use of Emission Phenomena

Let's look at some particular examples of emission phenomena which, by themselves, provide some familiar and important functions.

Gamma Rays—Nuclear Interactions Gamma rays, which are very high-energy photons, are emitted during the radioactive decay of unstable nuclei of certain atoms. Therefore, the energy of the gamma rays depends on the structure of the atom nucleus and varies for different materials. The gamma rays produced from a material have fixed wavelengths. For example, when cobalt 60 decays, gamma rays having energies of 1.17×10^6 and 1.34×10^6 eV (or wavelengths of 1.06×10^{-10} cm and 0.93×10^{-10} cm) are emitted. The gamma rays can be used as a radiation source to detect defects in a material (a nondestructive test).

X-rays—Inner Electron Shell Interactions **X-rays**, which have somewhat lower energy than gamma rays, are produced when electrons in the inner shells of an atom are stimulated. The stimulus could be high-energy electrons or other x-rays. When stimulation occurs, x-rays of a wide range of energies are emitted. Both a continuous and a characteristic spectrum of x-rays are produced.

Suppose that a high-energy electron strikes a material. As the electron decelerates, energy is given up and emitted as photons. Each time the electron strikes an atom, more of its energy is given up. Each interaction, however, may be more or less severe, so the electron gives up a different fraction of its energy each time and produces photons of different wavelengths (Figure 21-9). A **continuous spectrum** is produced (the smooth portion of the curves in Figure 21-10). If the electron were to lose all of its energy in one impact, the minimum wavelength of the emitted photons would correspond to the

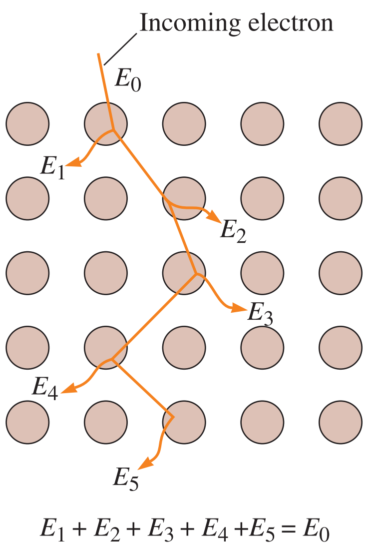


Figure 21-9
When an accelerated electron strikes and interacts with a material, its energy may be reduced in a series of steps. In the process, several photons of different energies E_1 to E_5 are emitted, each with a unique wavelength.

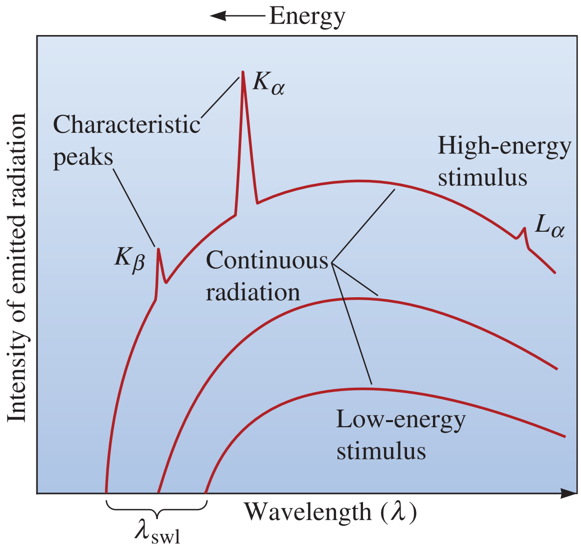


Figure 21-10
The continuous and characteristic spectra of radiation emitted from a material. Low-energy stimuli produce a continuous spectrum of low-energy, long wavelength photons. A more intense, higher energy spectrum is emitted when the stimulus is more energetic until, eventually, characteristic radiation is observed.

original energy of the stimulus. The minimum wavelength of x-rays produced is called the **short wavelength limit** λ_{swl}. The short wavelength limit decreases, and the number and energy of the emitted photons increase, when the energy of the stimulus increases.

The incoming stimulus may also have sufficient energy to excite an electron from an inner energy level to an outer energy level. The excited electron is not stable and, to restore equilibrium, electrons from a higher level fill the empty inner level. This process leads to the emission of a **characteristic spectrum** of x-rays that is different for each type of atom.

The characteristic spectrum is produced because there are discrete energy differences between any two energy levels. When an electron drops from one level to a second level, a photon having the corresponding energy and wavelength is emitted. This effect is illustrated in Figure 21-11. We typically refer to the energy levels by the *K, L, M,* . . .designation, as described in Chapter 2. If an electron is excited from the *K* shell, electrons may fill that vacancy from an outer shell. Normally, electrons in the closest shells fill the vacancies. Thus, photons with energy $\Delta E = E_K - E_L$ (K_α x-rays) or $\Delta E = E_K - E_M$ (K_β x-rays) are emitted. When an electron from the M shell fills the L shell, a photon with energy $\Delta E = E_L - E_M$ (L_α x-rays) is emitted; it has a long wavelength, or low energy. Note that we need a more energetic stimulus to produce K_α x-rays than that required for L_α x-rays.

As a consequence of the emission of photons having a characteristic wavelength, a series of peaks is superimposed on the continuous spectrum (Figure 21-10). The wavelengths at which these peaks occur are unique to each type of atom (Table 21-2). Thus, each element produces a different characteristic spectrum, which serves as a "finger-print" for that type of atom. If we match the emitted characteristic wavelengths with those expected for various elements, the identity of the material can be determined. We can also measure the intensity of the characteristic peaks. By comparing measured intensities with standard intensities, we can estimate the percentage of each type of atom in the material and, hence, we can estimate the composition of the material. The energy (or wavelength) of the x-rays emitted when an electron beam impacts a sample (such as that in a scanning or transmission electron microscope) can be analyzed to get chemical information about

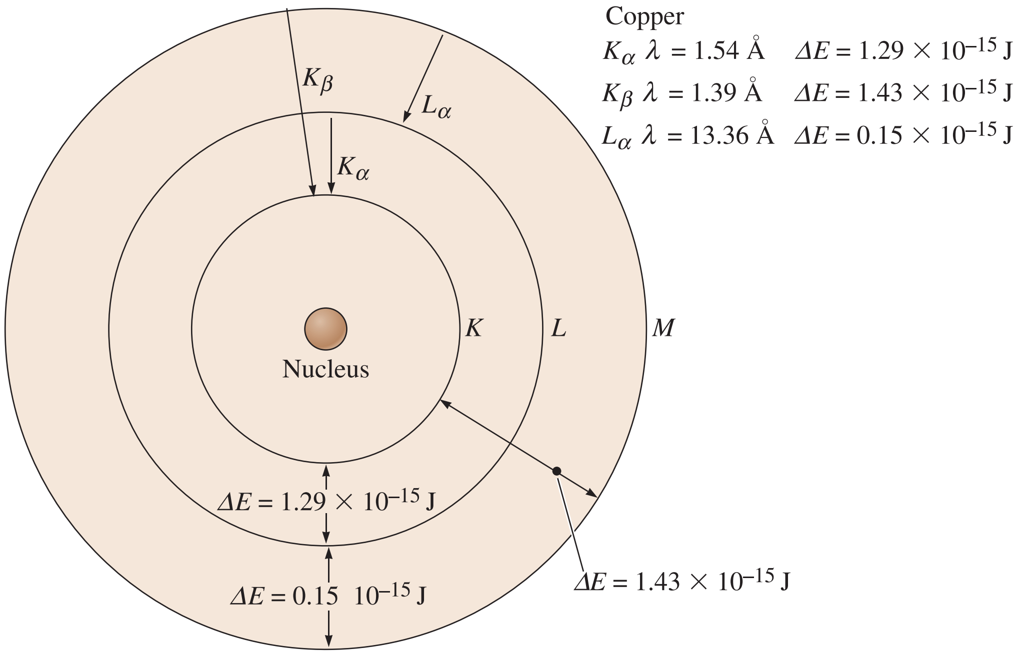


Figure 21-11 Characteristic x-rays are produced when electrons transition from one energy level to a lower energy level, as illustrated here for copper. The energy and wavelength of the x-rays are fixed by the energy differences between the energy levels.

a sample. This technique is known as energy dispersive x-ray analysis (EDXA). The examples that follow illustrate the application of x-ray emission as used in x-ray diffraction (XRD) and EDXA analytical techniques.

Example 21-5 *Design/Materials Selection for an X-ray Filter*

Design a filter that preferentially absorbs K_β x-rays from the nickel spectrum but permits K_α x-rays to pass with little absorption. This type of filter is used in x-ray diffraction (XRD) analysis of materials.

SOLUTION

When determining a crystal structure or identifying unknown materials using various x-ray diffraction techniques, we prefer to use x-rays of a single wavelength. If both K_α and K_β characteristic peaks are present and interact with the material, analysis becomes much more difficult.

To avoid this difficulty, we can use selective absorption to isolate the K_α peak. Table 21-2 includes the information that we need. If a filter material is selected such that the absorption edge lies between the K_α and K_β wavelengths, then the K_β is almost completely absorbed, whereas the K_α is almost completely transmitted. In nickel, $K_\alpha = 1.660$ Å and $K_\beta = 1.500$ Å. A filter with an absorption edge between these characteristic peaks will work. Cobalt, with an absorption edge of 1.608 Å, would be our choice. Figure 21-12 shows how this filtering process occurs.

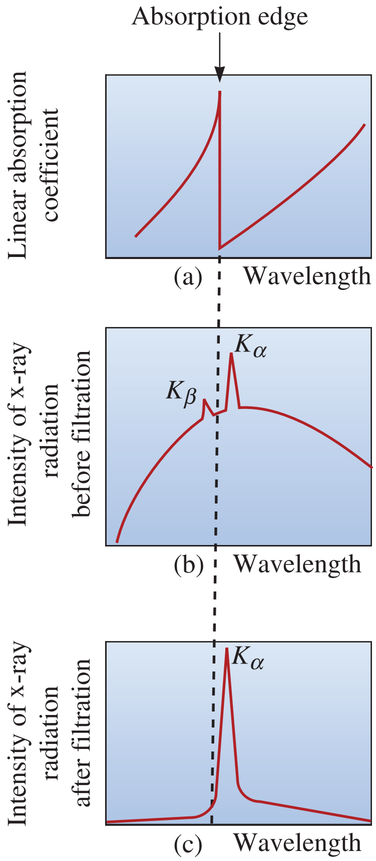


Figure 21-12
Elements have a selective lack of absorption of certain wavelengths. If a filter is selected with an absorption edge between the K_α and K_β peaks of an x-ray spectrum, all x-rays except K_α are absorbed (for Example 21-5). (a) The linear absorption coefficient of a filter material as a function of wavelength; (b) the intensity of the x-ray radiation before filtration; and (c) the intensity of the x-ray radiation after filtration.

Example 21-6 *Design of an X-ray Filter*

Design a filter to transmit at least 95% of the energy of a beam composed of zinc K_α x-rays, using aluminum as the shielding material. (The aluminum has a linear absorption coefficient of 108 cm^{-1}.) Assume no loss to reflection.

SOLUTION

Assuming that no losses are caused by the reflection of x-rays from the aluminum, we simply need to choose the thickness of the aluminum required to transmit 95% of the incident intensity. The final intensity will therefore be $0.95I_0$. Thus, from Equation 21-12,

$$\ln\left(\frac{0.95I_0}{I_0}\right) = -(108)(x)$$

$$\ln(0.95) = -0.051 = -108x$$

$$x = \frac{-0.051}{-108} = 0.00047 \text{ cm}$$

We would like to roll the aluminum to a thickness of 0.00047 cm or less. The filter could be thicker if a material were selected that has a lower linear absorption coefficient for zinc K_α x-rays.

Example 21-7 *Generation of X-rays for X-ray Diffraction (XRD)*

Suppose an electron accelerated at 5000 V strikes a copper target. Will K_α, K_β, or L_α x-rays be emitted from the copper target?

SOLUTION

The electron must possess enough energy to excite an electron to a higher level, or its wavelength must be less than that corresponding to the energy difference between the shells:

$$E = (5000\,\text{eV})(1.6 \times 10^{-19}\,\text{J/eV}) = 8 \times 10^{-16}\,\text{J}$$

$$\lambda = \frac{hc}{E} = \frac{(6.626 \times 10^{-34}\,\text{J} \cdot \text{s})(3 \times 10^{10}\,\text{cm/s})}{8 \times 10^{-16}\,\text{J}}$$

$$= 2.48 \times 10^{-8}\,\text{cm} = 2.48\,\text{Å}$$

Note that one electron volt (eV) is the kinetic energy acquired by an electron moving through a potential difference of one volt.

For copper, K_α is 1.542 Å, K_β is 1.392 Å and L_α is 13.357 Å (Table 21-2). Therefore, the L_α peak may be produced, but K_α and K_β will not.

Example 21-8 *Energy Dispersive X-ray Analysis (EDXA)*

The micrograph in Figure 21-13 was obtained using a scanning electron microscope at a magnification of 1000. The beam of electrons in the SEM was directed at the three different phases, creating x-rays and producing the characteristic peaks. From the energy spectra, determine the probable composition of each phase. Assume each region represents a different phase.

SOLUTION

All three phases have an energy peak of about 1.5 keV = 1500 eV, which corresponds to a wavelength of

$$\lambda = \frac{hc}{E} = \frac{(6.626 \times 10^{-34}\,\text{J} \cdot \text{s})(3 \times 10^{10}\,\text{cm/s})}{(1500\,\text{eV})(1.6 \times 10^{-19}\,\text{J/eV})(10^{-8}\,\text{cm/Å})} = 8.283\,\text{Å}$$

In a similar manner, energies and wavelengths can be found for the other peaks. These wavelengths are compared with those in Table 21-2, and the identity of the elements in each phase can be found, as summarized in the table.

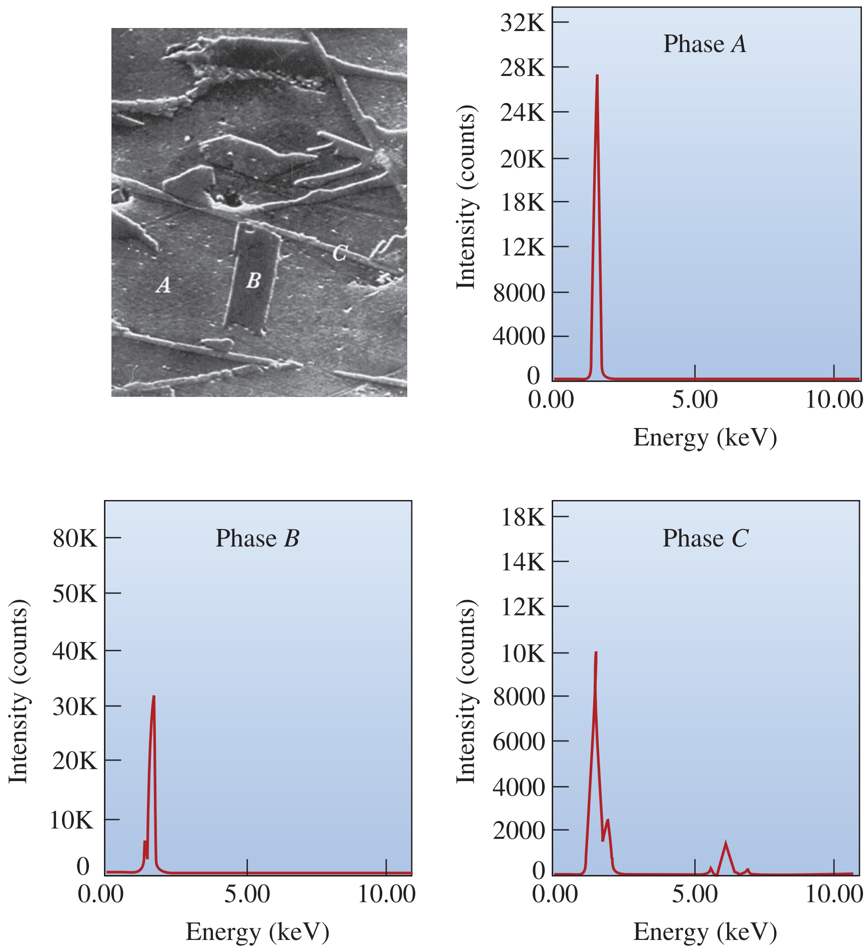


Figure 21-13 Scanning electron micrograph of a multiple phase material. The energy distributions of emitted radiation from the three phases marked *A*, *B*, and *C* are shown. The identity of each phase is determined in Example 21-8. (*Reprinted courtesy of Don Askeland.*)

Phase	Peak Energy	λ	λ (Table 21-2)	Line
A	1.5 keV	8.283 Å	8.337 Å	K_αAl
B	1.5 keV	8.283 Å	8.337 Å	K_αAl
	1.7 keV	7.308 Å	7.125 Å	K_αSi
C	1.5 keV	8.283 Å	8.337 Å	K_αAl
	1.7 keV	7.308 Å	7.125 Å	K_αSi
	5.8 keV	2.142 Å	2.104 Å	K_αMn
	6.4 keV	1.941 Å	1.937 Å	K_αFe
	7.1 keV	1.750 Å	1.757 Å	K_βFe

Thus, Phase *A* appears to be an aluminum matrix, Phase *B* appears to be a silicon needle (perhaps containing some aluminum), and Phase *C* appears to be an Al-Si-Mn-Fe compound. Actually, this is an aluminum-silicon alloy. The stable phases are aluminum and silicon with inclusions forming due to the presence of manganese and iron as impurities.

Luminescence—Outer Electron Shell Interactions

Whereas x-rays are produced by electron transitions in the inner energy levels of an atom, **luminescence** is the conversion of radiation or other forms of energy to visible light. Luminescence occurs when the incident radiation excites electrons from the valence band to the conduction band. The excited electrons remain in the higher energy levels only briefly. When the electrons drop back to the valence band, photons are emitted. If the wavelength of these photons is in the visible light range, luminescence occurs.

Luminescence does not occur in metals. Electrons are merely excited into higher energy levels within the unfilled valence band. When the excited electron returns to the lower energy level, the photon that is produced has a very small energy and a wavelength longer than that of visible light [Figure 21-14(a)].

In certain ceramics and semiconductors, however, the energy gap between the valence and conduction bands is such that an electron dropping through this gap produces a photon in the visible range. Two different effects are observed in these luminescent materials: fluorescence and phosphorescence. In **fluorescence,** all of the excited electrons drop back to the valence band and the corresponding photons are emitted within a very short time ($\sim 10^{-8}$ seconds) after the stimulus is removed [Figure 21-14(b)]. One wavelength, corresponding to the energy gap E_g, predominates. Fluorescent dyes and microscopy are used in many advanced techniques in biochemistry and biomedical engineering. X-ray fluorescence (XRF) is widely used for the chemical analysis of materials.

Phosphorescent materials have impurities that introduce a donor level within the energy gap [Figure 21-14(c)]. The stimulated electrons first drop into the donor level and are trapped. The electrons must then escape the trap before returning to the valence band. There is a delay before the photons are emitted. When the source is removed, electrons in the traps gradually escape and emit light over some additional period of time. The intensity of the luminescence is given by

$$\ln\left(\frac{I}{I_0}\right) = -\frac{t}{j} \qquad (21\text{-}16)$$

where τ is the **relaxation time**, a constant for the material. After time t following removal of the source, the intensity of the luminescence is reduced from I_0 to I. Phosphorescent

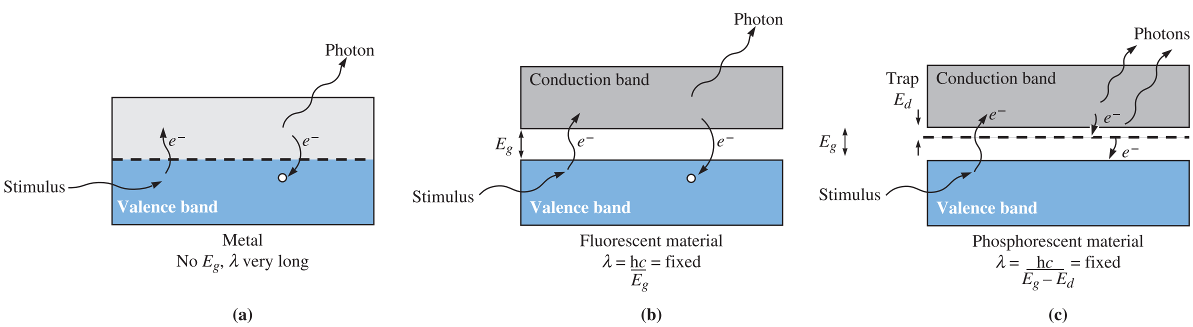


Figure 21-14 Luminescence occurs when photons have a wavelength in the visible spectrum. (a) In metals, there is no energy gap, so luminescence does not occur. (b) Fluorescence may occur if there is an energy gap. (c) Phosphorescence occurs when the photons are emitted over a period of time due to donor traps in the energy gap.

materials are very important in the operation of television screens. In this case, the relaxation time must not be too long or the images begin to overlap. In color television, three types of phosphorescent materials are used; the energy gaps are engineered so that red, green, and blue colors are produced. Oscilloscope and radar screens rely on the same principle. Fluorescent lamps contain mercury vapor. The mercury vapor, in the presence of an electric arc, fluoresces and produces ultraviolet light. The inside of the glass of these lamps is coated with a phosphorescent material. The role of this material is to convert the small wavelength ultraviolet radiation into visible light. The relaxation times range from 5×10^{-9} seconds to about 2 seconds. The following example illustrates the selection of a phosphor for a television screen.

Example 21-9 *Design/Materials Selection for a Television Screen*

Select a phosphor material that will produce a blue image on a television screen.

SOLUTION

Photons having energies that correspond to the color blue have wavelengths of about 4.5×10^{-5} cm (Figure 21-1). The energy of the emitted photons therefore is

$$E = \frac{hc}{\lambda} = \frac{(4.14 \times 10^{-15}\,\text{eV}\cdot\text{s})(3 \times 10^{10}\,\text{cm/s})}{4.5 \times 10^{-5}\,\text{cm}}$$
$$= 2.76\,\text{eV}$$

Figure 21-1 includes energy gaps for a variety of materials. None of the materials listed has an E_g of 2.76 eV, but ZnS has an E_g of 3.54 eV. If a suitable dopant were introduced to provide a trap $3.54 - 2.76 = 0.78$ eV below the conduction band, phosphorescence would occur.

We would also need information concerning the relaxation time to ensure that phosphorescence would not persist long enough to distort the image. Typical phosphorescent materials for television screens might include $CaWO_4$, which produces photons with a wavelength of 4.3×10^{-5} cm (blue). This material has a relaxation time of 4×10^{-6} s. ZnO doped with excess zinc produces photons with a wavelength of 5.1×10^{-5} cm (green), whereas $Zn_3(PO_4)_2$ doped with manganese gives photons with a wavelength of 6.45×10^{-5} cm (red).

Light-Emitting Diodes—Electroluminescence Luminescence can be used to advantage in creating **light-emitting diodes** (LEDs). LEDs are used to provide the display for watches, clocks, calculators, and other electronic devices. The stimulus for these devices is an externally applied voltage, which causes electron transitions and **electroluminescence**. LEDs are *p-n* junction devices engineered so that the E_g is in the visible spectrum (often red). A voltage applied to the diode in the forward-bias direction causes holes and electrons to recombine at the junction and emit photons (Figure 21-15). GaAs, GaP, GaAlAs, and GaAsP are typical materials for LEDs.

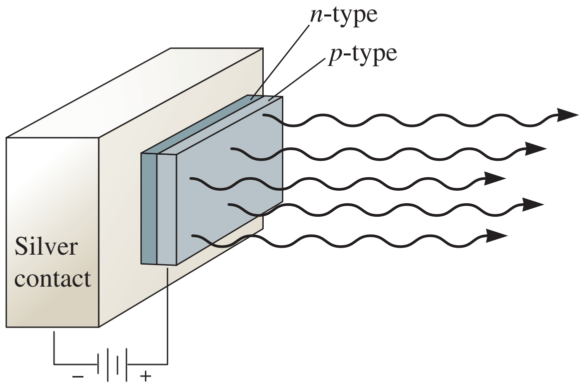


Figure 21-15
Diagram of a light-emitting diode (LED). A forward-bias voltage across the *p-n* junction produces photons.

Lasers—Amplification of Luminescence

The **laser** (*l*ight *a*mplification by *s*timulated *e*mission of *r*adiation) is another example of a special application of luminescence. In certain materials, electrons excited by a stimulus produce photons which, in turn, excite additional photons of identical wavelength. Consequently, a large amplification of the photons emitted in the material occurs. By proper choice of stimulant and material, the wavelength of the photons can be in the visible range. The output of the laser is a beam of photons that are parallel, of the same wavelength, and coherent. In a *coherent* beam, the wavelike nature of the photons is in phase, so that destructive interference does not occur. Lasers are useful in heat treating and melting of metals, welding, surgery, and transmission and processing of information. They are also useful in a variety of other applications including reading of compact discs and DVDs. Blu-ray^{TM} technology has enabled high-resolution DVDs to be commercialized. The shorter wavelength of the blue–violet light from a laser can read finer pits that encode the digital information than longer wavelength light. This has enabled a nearly six-fold increase in data storage capability compared to conventional DVDs, making it possible to store a two hour, high-definition movie on a single disc.

A variety of materials are used to produce lasers. Ruby, which is single crystal Al_2O_3 doped with a small amount of Cr_2O_3 (emits at 6943 Å) and yttrium aluminum garnet ($Y_3Al_5O_{12}$ YAG) doped with neodymium (Nd) (emits at 1.06 μm) are two common solid-state lasers. Other lasers are based on CO_2 gas.

Semiconductor lasers, such as those based on GaAs solid solutions which have an energy gap corresponding to a wavelength in the visible range, are also used (Figure 21-16).

Thermal Emission

When a material is heated, electrons are thermally excited to higher energy levels, particularly in the outer energy levels where the electrons are less tightly bound to the nucleus. The electrons immediately drop back to their normal levels and release photons, an event known as **thermal emission**.

As the temperature increases, thermal agitation increases, and the maximum energy of the emitted photons increases. A continuous spectrum of radiation is emitted, with a minimum wavelength and an intensity distribution dependent on the temperature. The photons may include wavelengths in the visible spectrum; consequently, the color of the material changes with temperature. At low temperatures, the wavelength of the radiation is too long to be visible. As the temperature increases, emitted photons have shorter wavelengths. At 700°C, we begin to see a reddish tint; at 1500°C, the orange and red wavelengths are emitted (Figure 21-17). Higher temperatures produce all wavelengths in the

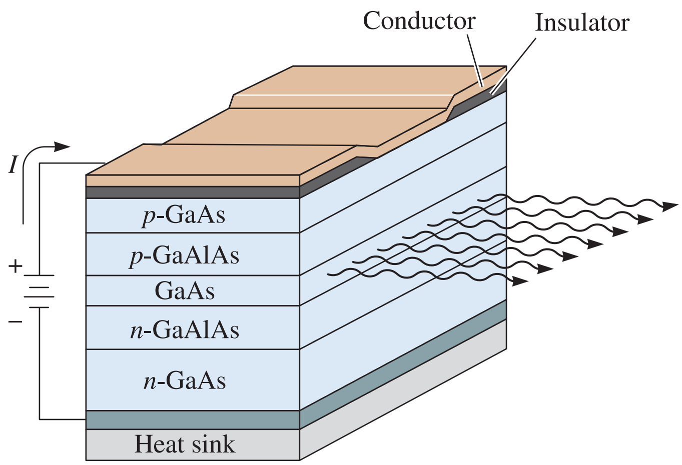


Figure 21-16
Schematic cross-section of a GaAs laser. Because the surrounding *p*- and *n*-type GaAlAs layers have a higher energy gap and a lower index of refraction than GaAs, the photons are trapped in the active GaAs layer.

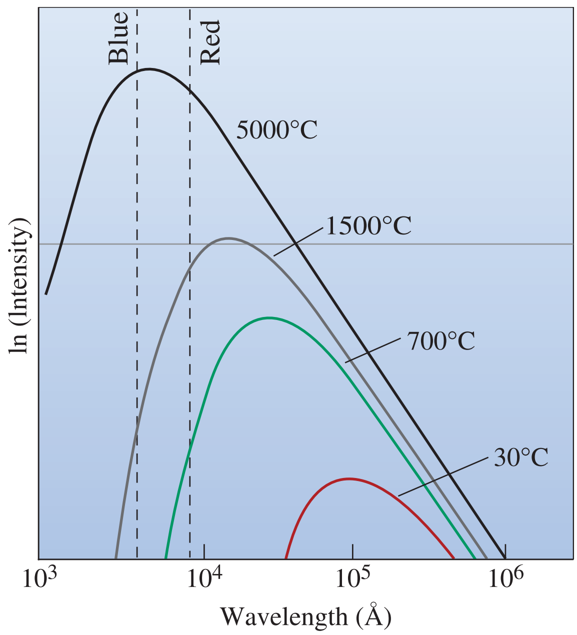


Figure 21-17
Intensity in relation to wavelengths of photons emitted thermally from a material. As the temperature increases, more photons are emitted in the visible spectrum.

visible range, and the emitted spectrum is white light. By measuring the intensity of a narrow band of the emitted wavelengths with a pyrometer, we can estimate the temperature of the material.

21-5 Fiber-Optic Communication System

In 1880, Alexander Graham Bell invented a light-based communication system known as the photophone, and William Wheeler was granted a patent (U.S. Patent 247,229) in 1881 for a system that used pipes to light distant rooms. These two inventions were the predecessors of the fiber-optic communications systems that exist today. The other key invention that helped commercialize fiber-optics technologies was the invention of the laser in 1960. The laser provided a monochromatic source of light so fiber optics could be used effectively. Another advancement came when high-purity silica glass fibers became available. These fibers provide very small optical losses and are essential for carrying information over longer distances without the need for equipment to boost the signal. Optical fibers are also free from electromagnetic interference (EMI) since they carry signals as light, not radio waves.

A fiber-optic system transmits a light signal generated from some other source, such as an electrical signal. The fiber-optic system transmits the light to a receiver using an optical fiber, processes the data received, and converts the data to a usable form. Photonic materials are required for this process. Most of the principles and materials presently used in photonic systems have already been introduced in the previous sections.

Summary

- The optical properties of materials include the refractive index, absorption coefficient, and dispersion. These are determined by the interaction of electromagnetic radiation, or photons, with materials. The refractive index of materials depends primarily upon the extent of electronic polarization and is therefore related to the high-frequency dielectric constant of materials.
- As a result of the interaction between light and materials, refraction, reflection, transmission, scattering, and diffraction can occur. These phenomena are used in a wide variety of applications of photonic materials. These applications include fiber optics for communication and lasers for surgery and welding. Devices that use optoelectronic effects include LEDs, solar cells, and photodiodes. Other applications include phosphors for fluorescent lights, televisions, and many analytical techniques.
- Emission of photons occurs by electron transitions or nuclear decay within an atom. Fluorescence, phosphorescence, electroluminescence (used in light-emitting diodes), and lasers are examples of luminescence. Photons are emitted by thermal excitation, with photons in the visible portion of the spectrum produced when the temperature is sufficiently high. X-ray emission from materials is used in EDXA and XRF analysis.

Glossary

Absorption edge The wavelength at which the absorption characteristics of a material abruptly change.

Characteristic spectrum The spectrum of radiation emitted from a material. It shows peaks at fixed wavelengths corresponding to particular electron transitions within an atom. Every element has a unique characteristic spectrum.

Continuous spectrum Radiation emitted from a material having all wavelengths longer than a critical short wavelength limit.

Dispersion Frequency dependence of the refractive index.

Electroluminescence Use of an applied electrical signal to stimulate photons from a material.

Fluorescence Emission of light obtained typically within $\sim 10^{-8}$ seconds of stimulation.

Index of refraction Relates the change in velocity and propagation direction of radiation as it passes through a transparent medium (also known as the refractive index).

Laser The acronym stands for light amplification by stimulated emission of radiation. A beam of monochromatic coherent radiation produced by the controlled emission of photons.

Light-emitting diodes (LEDs) Electronic *p-n* junction devices that convert an electrical signal into visible light.

Linear absorption coefficient Describes the ability of a material to absorb radiation.

Luminescence Conversion of radiation to visible light.

Phosphorescence Emission of radiation from a material after the stimulus is removed.

Photoconduction Production of a voltage due to the stimulation of electrons into the conduction band by radiation.

Photons Energy or radiation produced from atomic, electronic, or nuclear sources that can be treated as particles or waves.

Reflectivity The percentage of incident radiation that is reflected.

Refractive index See Index of refraction.

Relaxation time The time required for $1/e$ of the electrons to drop from the conduction band to the valence band in luminescence.

Short wavelength limit The shortest wavelength or highest energy radiation emitted from a material under particular conditions.

Solar cell A *p-n* junction device that creates a voltage due to excitation by photons.

Thermal emission Emission of photons from a material due to excitation of the material by heat.

X-rays Electromagnetic radiation in the wavelength range $\sim$0.1 to 100 Å.

Section 21-1 The Electromagnetic Spectrum

Section 21-2 Refraction, Reflection, Absorption, and Transmission

21-1 State the definitions of refractive index and absorption coefficient. Compare these with the definitions of dielectric constant, loss factor, Young's modulus, and viscous deformation.

21-2 What is Snell's law? Illustrate using a diagram.

21-3 Upon what does the index of refraction of a material depend?

21-4 What is "lead crystal?" What makes the refractive index of this material so much higher than that of ordinary silicate glass?

21-5 What polarization mechanism affects the refractive index?

21-6 Why is the refractive index of ice smaller than that of water?

21-7 What is dispersion? What is the importance of dispersion in fiber-optic systems?

21-8 What factors limit the transmission of light through dielectric materials?

21-9 What is the principle by which LEDs and solar cells work?

21-10 A beam of photons strikes a material at an angle of 25° to the normal of the surface. Which, if any, of the materials listed in Table 21-1 could cause the beam of photons to continue at an angle of 18 to 20° from the normal of the material's surface?

21-11 A laser beam passing through air strikes a 5-cm-thick polystyrene block at a 20° angle to the normal of the block. By what distance is the beam displaced from its original path when the beam reaches the opposite side of the block?

21-12 A length of 6000 km of fiber-optic cable is laid to connect New York to London. If the core of the cable has a refractive index of 1.48 and the cladding has a refractive index of 1.45, what is the time needed for a beam of photons introduced at 0° in New York to reach London? Assume that dispersion effects can be neglected for this calculation. What is the maximum angle of incidence at which there is no leakage of light from the core?

21-13 A block of glass 10 cm thick with $n = 1.5$ transmits 90% of light incident on it. Determine the linear absorption coefficient (α) for this material. If this block is placed in water, what fraction of the incident light will be transmitted through it?

21-14 A beam of photons passes through air and strikes a soda-lime glass that is part of an aquarium containing water. What fraction of the beam is reflected by the front face of the glass? What fraction of the remaining beam is reflected by the back face of the glass?

21-15 We find that 20% of the original intensity of a beam of photons is transmitted from air through a 1-cm-thick material having a dielectric constant of 2.3 and back into air. Determine the fraction of the beam that is

(a) reflected at the front surface,
(b) absorbed in the material, and
(c) reflected at the back surface.

Determine the linear absorption coefficient of the photons in the material.

21-16 A beam of photons in air strikes a composite material consisting of a 1-cm-thick sheet of polyethylene and a 2-cm-thick sheet of soda-lime glass. The incident beam is 10° from the normal of the composite. Determine the angle of the beam with respect to the normal of the composite as it

(a) passes through the polyethylene,
(b) passes through the glass, and
(c) passes through air on the opposite side of the composite.

By what distance is the beam displaced from its original path when it emerges from the composite?

21-17 A glass fiber ($n = 1.5$) is coated with Teflon. Calculate the maximum angle that a beam of light can deviate from the axis of the fiber without escaping from the inner portion of the fiber.

21-18 A material has a linear absorption coefficient of 591 cm^{-1} for photons of a particular wavelength. Determine the thickness of the material required to absorb 99.9% of the photons.

Section 21-3 Selective Absorption, Transmission, or Reflection

21-19 What is a photochromic glass?

21-20 How are colored glasses produced?

21-21 What is ruby crystal made from?

Section 21-4 Examples and Uses Of Emission Phenomena

21-22 What is the principle of energy dispersive x-ray analysis (EDXA)?

21-23 What is fluorescence? What is phosphorescence?

21-24 What is XRF?

21-25 How does a fluorescent lamp work?

21-26 What is electroluminescence?

21-27 A scanning electron microscope has three settings for the acceleration voltage (a) 5 keV, (b) 10 keV, and (c) 20 keV. Determine the minimum voltage setting needed to produce K_α peaks for the materials listed in Table 21-2.

21-28 The relaxation time of a phosphor used for a TV screen is 5×10^{-2} seconds. If the refresh frequency is 60 Hz, then what is the reduction in intensity of the luminescence before it is reset to 100% by the refresh?

21-29 Calcium tungstate ($CaWO_4$) has a relaxation time of 4×10^{-6} s. Determine the time required for the intensity of this phosphorescent material to decrease to 1% of the original intensity after the stimulus is removed.

21-30 The intensity of radiation from a phosphorescent material is reduced to 90% of its original intensity after 1.95×10^{-7} s. Determine the time required for the intensity to decrease to 1% of its original intensity.

21-31 A phosphor material with a bandgap of 3.5 eV with appropriate doping will be used to produce blue (475 nm) and green (510 nm) colors. Determine the energy level of the donor traps with respect to the conduction band in each case.

21-32 What is a laser?

21-33 Determine the wavelength of photons produced when electrons excited into the conduction band of indium-doped silicon
(a) drop from the conduction band to the acceptor band and
(b) then drop from the acceptor band to the valence band (See Chapter 19).

21-34 Which, if any, of the semiconducting compounds listed in Chapters 19 and 21 are capable of producing an infrared laser beam?

21-35 What type of electromagnetic radiation (ultraviolet, infrared, visible) is produced when an electron recombines with a hole in pure germanium and what is its wavelength?

21-36 Which, if any, of the dielectric materials listed in Chapter 19 would reduce the speed of light in air from 3×10^{10} cm/s to less than 0.5×10^{10} cm/s?

21-37 What filter material would you use to isolate the K_α peak of the following x-rays: iron, manganese, or nickel? Explain your answer.

21-38 What voltage must be applied to a tungsten filament to produce a continuous spectrum of x-rays having a minimum wavelength of 0.09 nm?

21-39 A tungsten filament is heated with a 12,400 V power supply. What is
(a) the wavelength and
(b) the frequency of the highest energy x-rays that are produced?

21-40 What is the minimum accelerating voltage required to produce K_α x-rays in nickel?

21-41 Based on the characteristic x-rays that are emitted, determine the difference in energy between electrons in tungsten for
(a) the K and L shells,
(b) the K and M shells, and
(c) the L and M shells.

21-42 Figure 21-18 shows the results of an x-ray fluorescent analysis in which the intensity of x-rays emitted from a material is plotted relative to the wavelength of the x-rays. Determine
(a) the accelerating voltage used to produce the exciting x-rays and
(b) the identity of the elements in the sample.

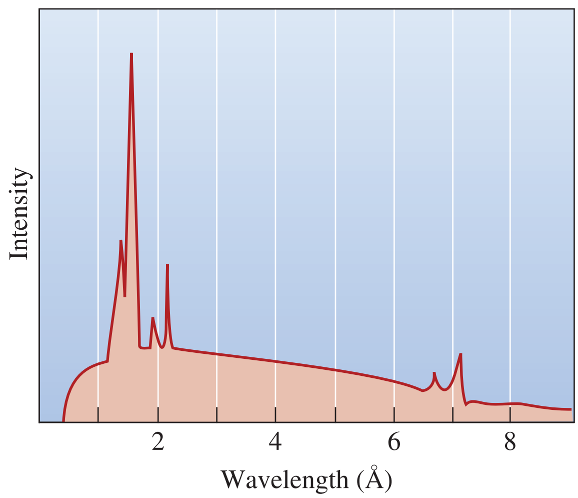


Figure 21-18 Results from an x-ray fluorescence analysis of an unknown metal sample (for Problem 21-42).

21-43 Figure 21-19 shows the intensity as a function of energy of x-rays produced from an energy-dispersive analysis of radiation emitted from a specimen in a scanning electron microscope. Determine the identity of the elements in the sample.

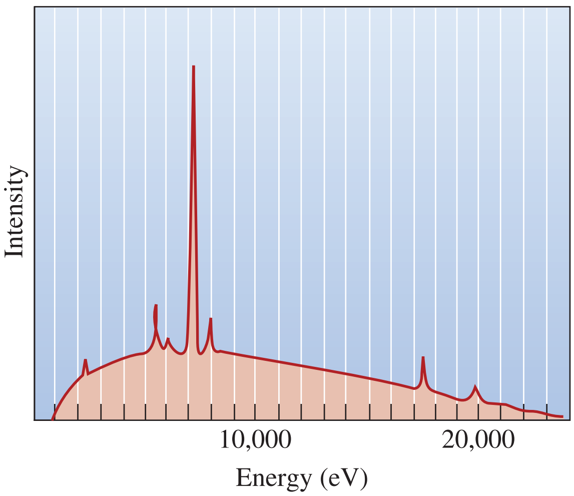


Figure 21-19 X-ray emission spectrum (for Problem 21-43).

Section 21-5 Fiber Optic Communication System

21-44 What is the principle by which information is transmitted via an optical fiber?

21-45 What material is used to make most optical fibers? From what material is the cladding made? What material is used to enhance the refractive index of the core?

Design Problems

21-46 Nickel x-rays are to be generated inside a container, with the x-rays being emitted from the container through only a small slot. Design a container that will ensure that no more than 0.01% of the K_α nickel x-rays escape through the rest of the container walls, yet 95% of the K_α nickel x-rays pass through a thin window covering the slot. The following data give the mass absorption coefficients of several metals for nickel K_α x-rays. The mass absorption coefficient α_m is α/ρ, where α is the linear mass absorption coefficient and ρ is the density of the filter material.

Material	α_m (cm^2/g)
Be	1.8
Al	58.4
Ti	247.0
Fe	354.0
Co	54.4
Cu	65.0
Sn	322.0
Ta	200.0
Pb	294.0

21-47 Design a method by which a photoconductive material might be used to measure the temperature of a material from the material's thermal emission.

21-48 Design a method, based on a material's refractive characteristics, that will cause a beam of photons originally at a 2° angle to the normal of the material to be displaced from its original path by 2 cm at a distance of 50 cm from the material.

21-49 Amorphous selenium is used in photocopiers. Conduct a literature search and find out how amorphous selenium works in this application.

Computer Problems

21-50 *Calculating Power in Decibels.* In an optical communications system or electrical power transmission system, the power or signal often is transferred between several components. The decibel (dB) is a convenient unit to measure the relative power levels. If the input power to a device is P_1 and the output power is P_2, then P_2/P_1 is the ratio of power transmitted, thus representing efficiency. This ratio in decibels is written as

$$\mathrm{dB} = 10 \log \frac{P_2}{P_1}$$

Power must be expressed in similar units. Write a computer program that will calculate the dB value for the transmission of power between two components of a fiber-optic system (e.g., light source to fiber). Then, extend this calculation to three components (e.g., light transmitted from source to fiber and then fiber to a detector).

Knovel® Problem

K21-1 A beam of light passes through benzene to glass (silicon dioxide). The angle of incidence of the light is 30°. What is the angle of the refracted light?

K21-2 Calculate the reflectivity of mercury in air from the index of refraction *n*.