CHAPTER 2

INTERACTION OF LIGHT WITH MATTER

2.1 INTRODUCTION

When light enters matter, its elecromagnetic field interacts with the localized electromagnetic field of atoms. The result is that if and when light emerges from matter, its characteristics and properties may not be the same. How light is affected by matter depends on the strength of the field of the light, its wavelength, and the matter itself. In addition, external influences on matter, such as temperature, pressure, and other external fields (electrical, magnetic), influence the interaction of light with matter. The interaction of light with matter may be undesirable, but it may also be taken advantage of to construct optical devices.

In this chapter, we examine the interaction of light with matter.

2.2 TRANSPARENT VERSUS OPAQUE MATTER

Some matter allows all light energy (all photons) to propagate through it and it is called *optically transparent.* In contrast, *opaque* matter does not.

Example

Clear glass is transparent; a sheet of iron is not.

Semitransparent matter passes a portion of light energy through it and absorbs the remainder. Such matter attenuates the optical power of light, and it may be used to make an optical device known as *optical attenuator.* ■

Example

Most transparent matter, semitransparent mirrors.

An *optical filter* allows selected frequencies to be propagated through it. ■

Example

Red, green, yellow, or blue glass (each allows a selected range of frequencies to be propagated through it).

Some matter in the ionized state absorbs selected frequencies and passes all others. ■

Example

The sun's ionized surface. ■

2.3 PROPERTIES OF OPTICALLY TRANSPARENT MATTER

When light enters matter, its electromagnetic field reacts with the near fields of its atoms. In dense matter, light is quickly absorbed within the first few atomic layers and, because it does not emerge from it, that matter is termed *nonoptically transparent.* In contrast to this, some types of matter do not completely absorb light. Such matter, termed *optically transparent* matter, allows light to propagate through it and emerge from it. Examples of optically transparent matter include water and clear glass. We are more interested in optically transparent matter; thus, we examine the interaction of light with it. In particular, we examine the following:

- Reflection and refraction
- Diffraction
- Interference
- Holography
- Polarization
- Birefringence
- Dispersion
- Nonlinear phenomena
- Optical isotropy and anisotropy
- Optical homogeneity and nonhomogeneity
- Effects of impurities and microcracks
  - Absorption
  - Scattering

2.3.1 Reflection and Refraction: Index of Refraction

The *index of refraction* of a transparent medium (n_{med}) is defined as the ratio of the speed of light in vacuum (c) to the speed of light in a medium (v_{med}).

$$n_{med} = \frac{c}{v_{med}}$$

Then, between two media (1 and 2) the relationship

$$n_2/n_1 = v_1/v_2$$

is true (Figure 2.1), where n_1, v_1 and n_2, v_2 are the index of refraction and the speed of light in the two media, respectively. The index of refraction, or refractive index, for vacuum is 1; for other materials it is greater than 1, typically between 1 and 2. For example, polyurethane has $n = 1.46$.

The following basic relationships are useful:

Speed of light in vacuum: $c = \lambda f$
Speed of light in medium: $v_{med} = \lambda_{med} f$
Index of refraction: $n_1/n_2 = \lambda_2/\lambda_1$

Here f is the frequency of light and λ the wavelength. Usually, f or ν is used for frequency. Here, we use f to eliminate confusion between v (for speed) and ν (for frequency).

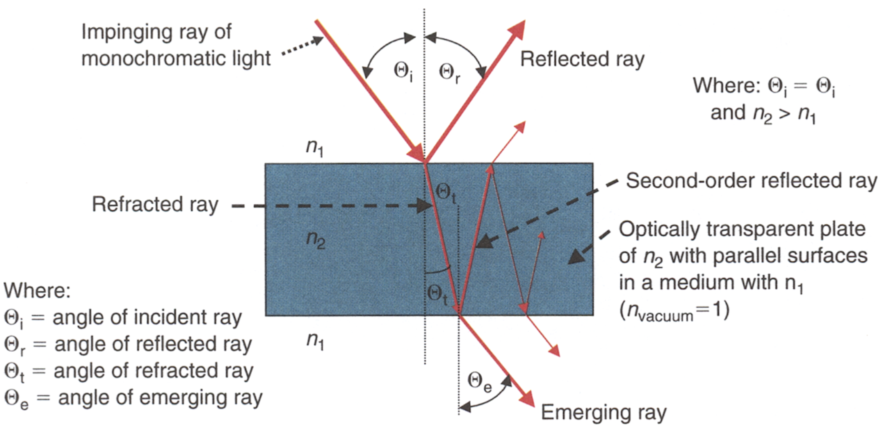

Figure 2.1 Reflection and refraction.

2.3.2 Snell's Law

Snell's law links the ratio of index of refraction with the angle of the incident (Θ_i) and of the refracted (Θ_t) rays

$$n_2/n_1 = \sin \Theta_i / \sin \Theta_t,$$

where Θ_i and Θ_t are defined in Figure 2.1.

2.3.3 Critical Angle

The *critical angle,* $\Theta_{critical}$, is the (maximum) angle of incidence of light (from an optically denser to optically thinner material) at which light stops being refracted and is totally reflected (Figure 2.2). The critical angle depends on the refractive index and the wavelength of light. We write

$$\sin \Theta_{critical} = n_1/n_2$$

for $n_1 = 1$ (air) and then

$$\sin \Theta_{critical} = 1/n_2.$$

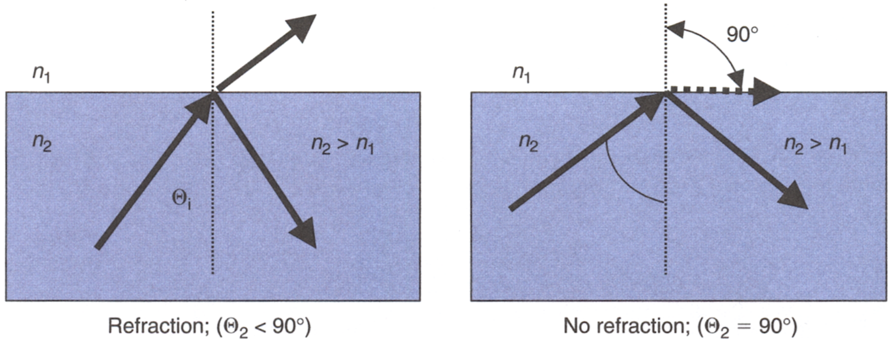

Figure 2.2 Definition of critical angle.

In certain cases, a continuous change of the refractive index may take place. When light rays enter from one side, the rays are refracted and may emerge from the same side (Figure 2.3).

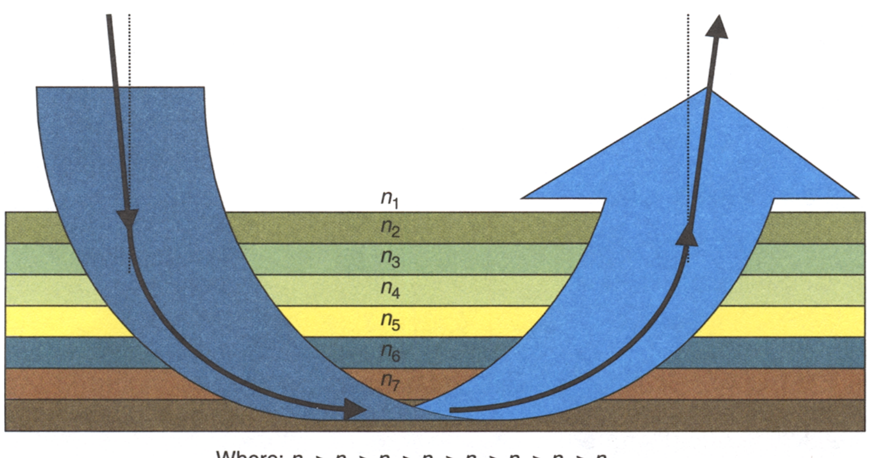

Figure 2.3 Refraction through variable refractive index.

2.3.4 Optical Prisms

Consider two planes of a plate that intersect to form a *prism* at an angle Θ_2. When a polychromatic narrow beam of light impinges one of the prism surfaces, each frequency component is refracted differently. When each frequency reaches the other surface, it is refracted again. The output light from the second surface of the prism consists of the frequency components separated by a small angle. The angle of each frequency component with the original composite beam is known as the *angle of deflection,* ϵ. That is, the angle of deflection varies with frequency (Figure 2.4).

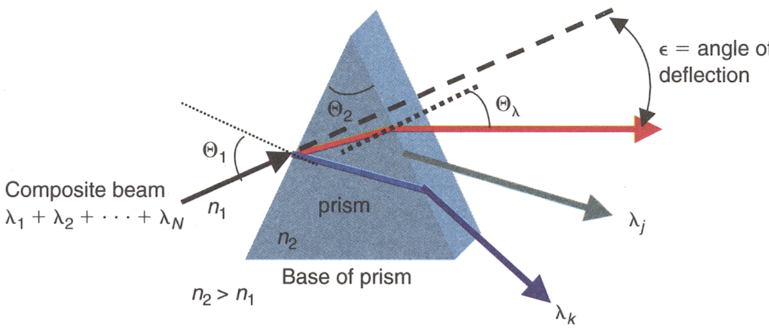

Figure 2.4 The angle of deflection is different for each frequency component.

In Figure 2.4, when $n_1 = 1$, Snell's law yields:

$$n_2 = \frac{\sin[(\Theta_2 + \epsilon)/2]}{\sin(\Theta_2/2)}.$$

The following prism laws hold:

- The angle Θ_λ increases as the index of refraction increases.
- The angle Θ_λ increases as the prism angle Θ_2 increases.
- The angle Θ_λ increases as the angle of incidence Θ_1 increases.
- The angle Θ_λ increases as the frequency of light increases (or the wavelength decreases).

The angular variability of each frequency component of the prism is known as *angular dispersion* and it is given by

$$d\theta/d\lambda = [(d\theta/dn)(dn/d\lambda)],$$

where n is the index of refraction and λ the wavelength. The first term depends on the geometry of the prism, whereas the second term depends on the material.

2.3.5 Diffraction

Consider a parallel beam of light that impinges first on a screen with a small round hole in it with sharp edges and then on a second screen behind the first at a distance *d* (Figure 2.5). Although light travels in a straight line and a small round projection is expected, D_{EXP}, a wider projection is seen instead, D_{ACT}. This round projection is encircled by more circles with decreasing intensity as we move away from the center of the projection. This phenomenon is due to the edge of the hole that diffracts light. This is known as *diffraction of light* or *Fresnel's phenomenon.* The smaller the diameter, the wider the projection.

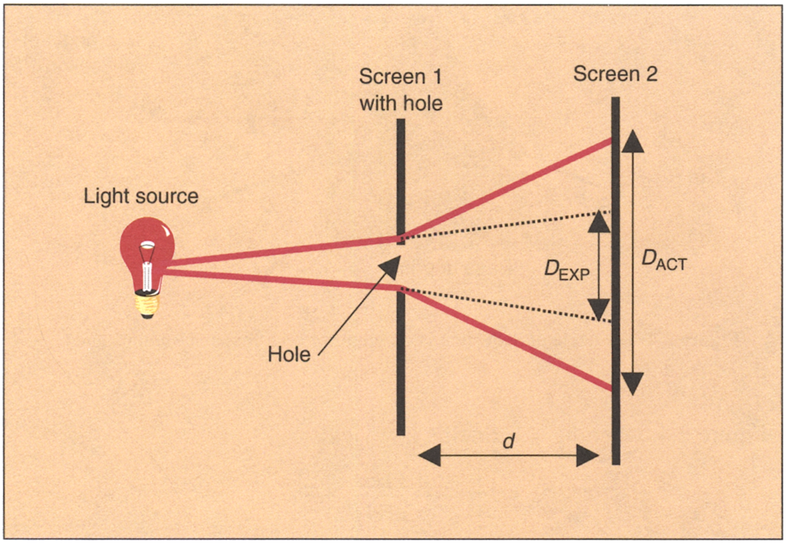

Figure 2.5 Diffraction by a hole in the order of wavelength.

2.3.6 Diffraction at Infinity

If the hole were a narrow rectangle, what would the projection look like? Let parallel (collimated) light, also known as *light from a source at infinity,* pass through a rectangular slit of height *h* and width *w*. Then diffraction causes the projection on a screen to be a rectangle rotated by 90°. That is, the diffracted pattern is narrow in the direction in which the aperture of the slit is wide (see Section 2.3.5) (Figure 2.6). In addition, because of two-dimensional (2-D) Fourier expansion, the diffracted light forms many rectangles on the screen in the *x*–*y* plane with an intensity that fades as one moves away from the axis of symmetry. The condition of rectangles on the screen are

$R(x, y) = \text{Rect}(x/w_0)\text{Rect}(y/h_0) = 1$, for $|x| < w_0/2$ and $|y| < h_0/2$, and
$R(x, y) = 0$ elsewhere.

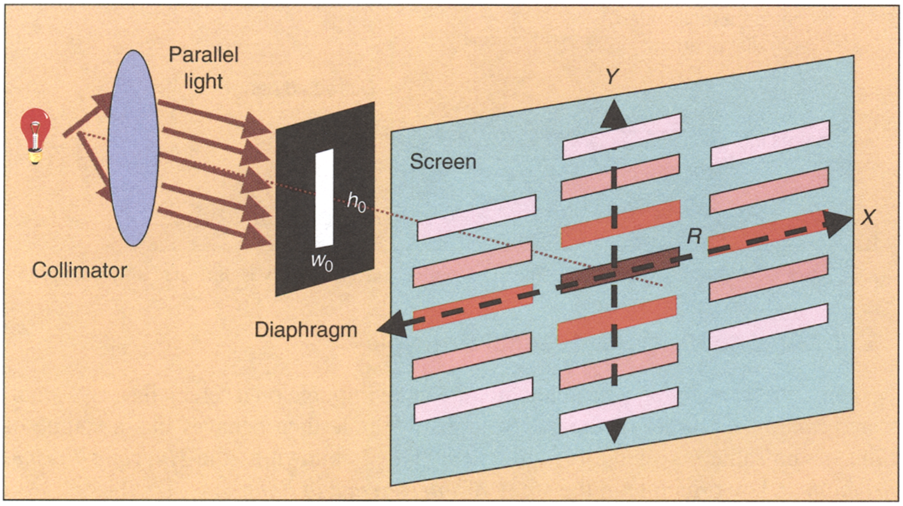

Figure 2.6 Diffraction at infinity.

2.3.7 Gaussian Beams

In our descriptions, we have assumed so far that the monochromatic beam of light has a uniform cross-sectional distribution of intensity. In reality, this is not true. Most beams have a radial intensity distribution that is most intense in the center of the beam and it reduces radially away from the center, closely matching a Gaussian distribution. Such beams are known as Gaussian beams. Because of the Gaussian distribution of intensity, even if the beam is initially parallel, it does not remain so owing to spatial diffraction within the beam. Spatial diffraction causes the beam to first narrow and then diverge at an angle Θ. The narrowest point in the beam is known as the waist of the beam. Even laser beams with a Gaussian distribution exhibit such behavior.

2.3.8 Diffraction Gratings

A *diffraction grating* is a passive optical device that diffracts incident parallel light in specific directions according to the angle of incidence on the grating, the optical wavelength of the incident light, and the design characteristics of the grating, *line spacing d,* and *blaze angle* Θ_B (Figure 2.7).

A common form of a diffraction grating consists of a glass substrate with adjacent epoxy strips that have been blazed. The number of strips per unit length is a parameter known as the *grating constant.* The blaze angle Θ_B, the wavelength λ, and the line spacing d are related by

$$\Theta_B = \sin^{-1}(\lambda/2d).$$

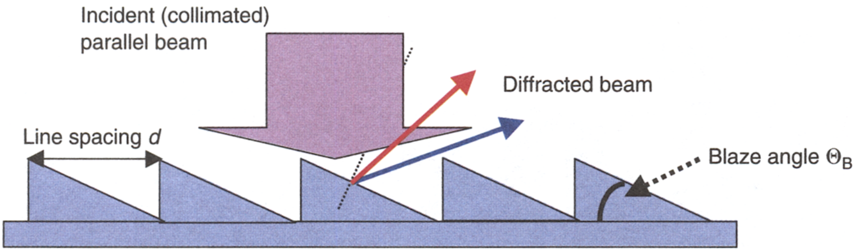

Figure 2.7 When collimated light falls on a grating, each frequency is diffracted differently.

2.3.9 The Huygens–Fresnel Principle

Let the light from a monochromatic point source impinge on a screen having a small round hole in the order of the wavelength. The hole then behaves like a source of light of the same wavelength (Figure 2.8). This is known as the *Huygens–Fresnel principle,* a key principle in the study of *interference of light.*

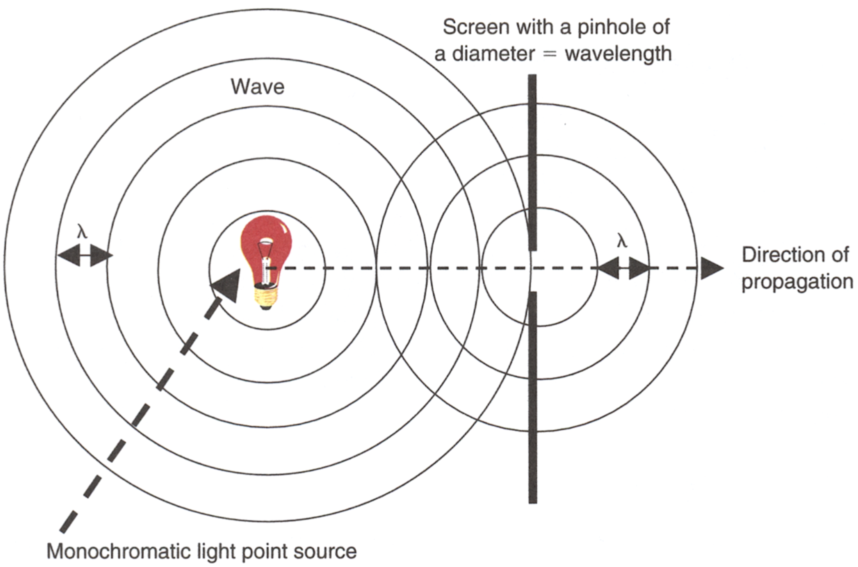

Figure 2.8 The Huygens–Fresnel principle.

2.3.10 Interference of Light

Consider a monochromatic light source, a screen with two pinholes equidistant from the axis of symmetry, and a second screen behind the first and parallel to it (Figure 2.9). Based on the Huygens–Fresnel principle, the two pinholes become two sources of coherent light, and alternating bright and dark zones are seen on the second screen. Bright zones (*constructive interference*) are formed when the travel difference between two rays $\Delta = |r_2 - r_1|$ or $\Delta = |r_4 - r_3|$ is an integer multiple of λ, and

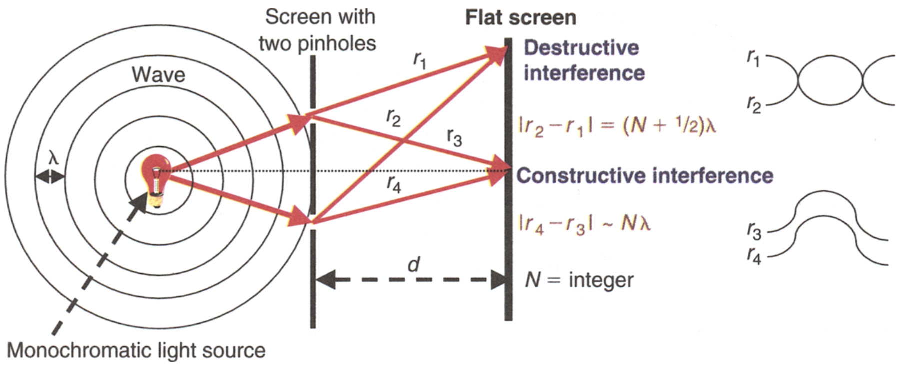

Figure 2.9 Interference (constructive or destructive) of two coherent sources of the same wavelength.

dark zones (*destructive interference*) are when the travel difference between two rays is half-integer multiple of λ. The Mach–Zehnder filter is based on this principle.

2.3.11 Antireflection Coatings

Many optical devices or components require the maximum possible optical power of a specific wavelength range to be coupled in, and thus zero or a minimal reflected power. This is accomplished by using *antireflection coatings* at the air–component interface. Antireflection coatings consist of one or more thin layers (films) of material, each layer having a specific thickness and a specific refractive index. For example, to minimize the reflected optical power on incident light on glass, the layer that interfaces glass with air has a low refractive index. In this arrangement, the relationships $n_2 d_2 = m(\lambda/4)$ and $n_2 = \sqrt{n_1 n_3}$ must be satisfied, where d_2 is the film thickness, n_2 is the refractive index of film, and m is an odd integer (1, 3, 5, . . .). Such material is MgF_2 ($n = 1.38$).

In a two-layer coating system the next layer may be PbF_2 ($n = 1.7$), and the last is glass ($n = 1.5$). Each layer has a quarter-wavelength thickness so that rays reflected by each layer interfere destructively and thus the *extinction of reflection* at the designed wavelength is complete. This means that the antireflection coating is also wavelength selective (Figure 2.10). Because of the wavelength selectivity of coatings, they are also used as optical filters (see Section 4.6).

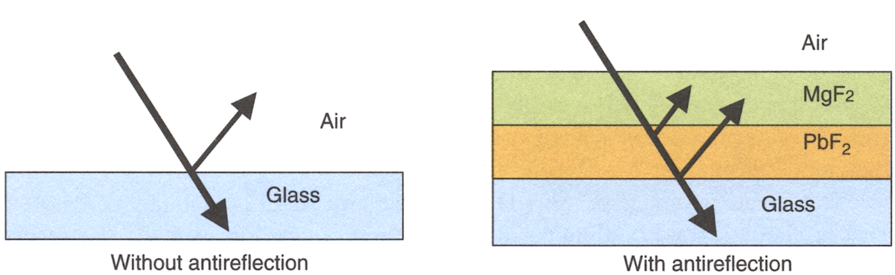

Figure 2.10 Refraction by a glass plate without and with antireflection coating.

2.3.12 Holography

Holography is a method by which coherent light (laser light) is used to capture the phase and amplitude characteristics of a three-dimensional (3-D) object on a 2-D photographic plate. Both diffraction and interference of light are employed in holography.

Consider a monochromatic coherent light source split into two beams A and B. Beam A impinges the 3-D object and is diffracted on a photographic film (Figure 2.11). Beam B is reflected by a prism and it, too, impinges the photographic plate. At the plate, beams A and B interfere and, depending on the travel difference of rays in the two beams, because of the three-dimensionality of the object, the amplitude and the phase difference from each point of the object are recorded on the photographic plate. The end result is an incomprehensible image of dense stripes and whorls on the plate. This is known as a *hologram.*

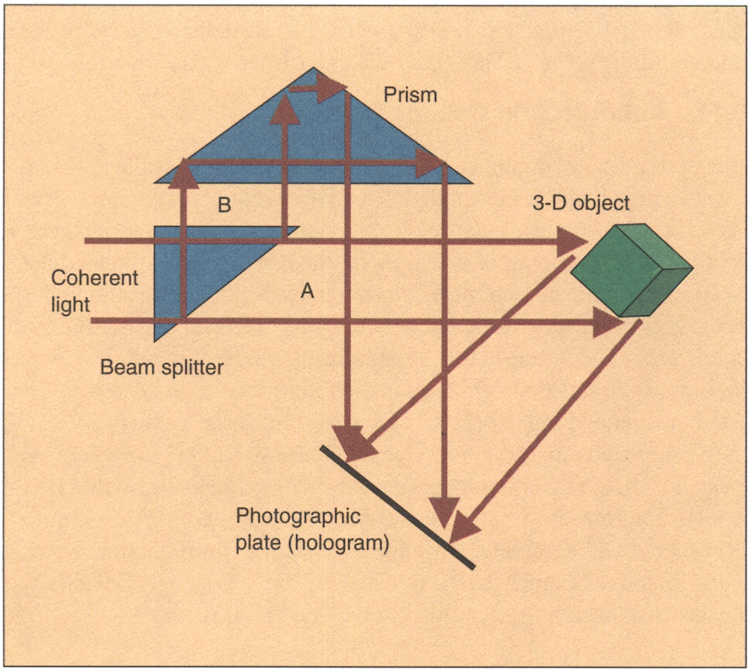

Figure 2.11 Principles of holography: generating a hologram.

According to "diffraction at infinity," the information relating to the phase and the amplitude of a 3-D object has been recorded in a myriad of places on the hologram. Thus, even a small segment of the hologram contains all information (phase and amplitude) for the 3-D object.

To recreate an image of the 3-D object, the process of holography is reversed. That is, the hologram is illuminated with coherent light (Figure 2.12). The dense stripes and whorls in the plate act as a diffraction grating that interacts with the in-

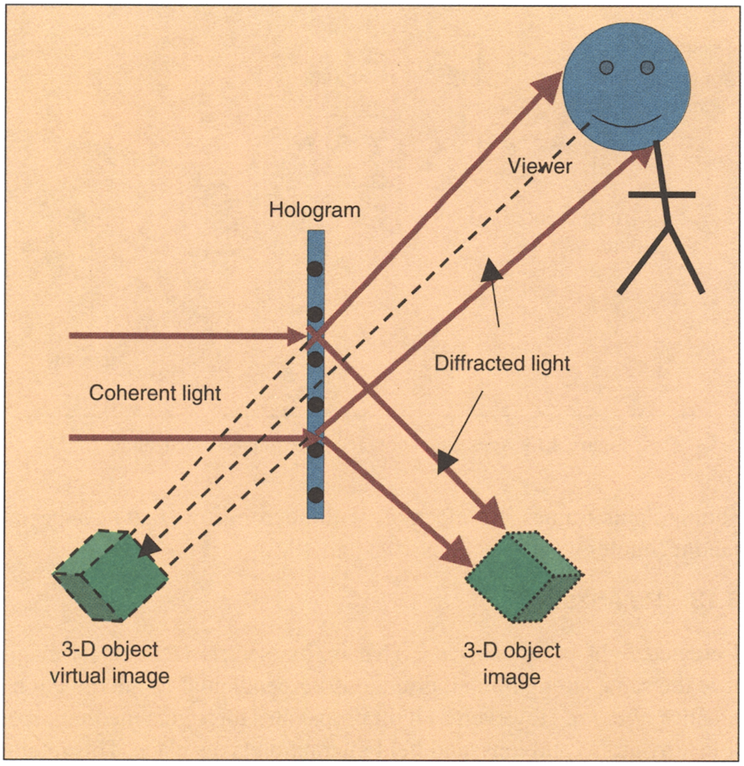

Figure 2.12 Principles of holography: creating a holographic image.

cident coherent beam, which decodes the phase and amplitude information to recreate an image replica of the original 3-D object.

One of the salient features of holography is its image recognition. When coherent light passes through a transparent plate with a set of images, then through a hologram, an image is seen on a screen, one that matches an image previously recorded, in the hologram. It turns out that two conjugate inverted images appear about the axis of symmetry. If there is no match, a blurred dot is seen (Figure 2.13).

Holograms are so small that many thousands may be contained in a square millimeter of a holographic plate. Thus, if each hologram contains an individual image, thousands of different images may be stored in few square millimeters of a holographic plate. If these images correspond to the frames of a movie, or the pages of an encyclopedia, and if they are selectable in a specified order, then clearly the applicability of holograms in storage is enormous. Hence, holography is a promising technology in very large capacity optical storage as well as in communications. In optical storage, Fe-doped $LiNbO_3$ and organic photopolymers have been used to construct WORM (write once, read many) devices. The write capability in WORMs is accomplished with high-power, low-cost semiconductor lasers (see Section 6.2),

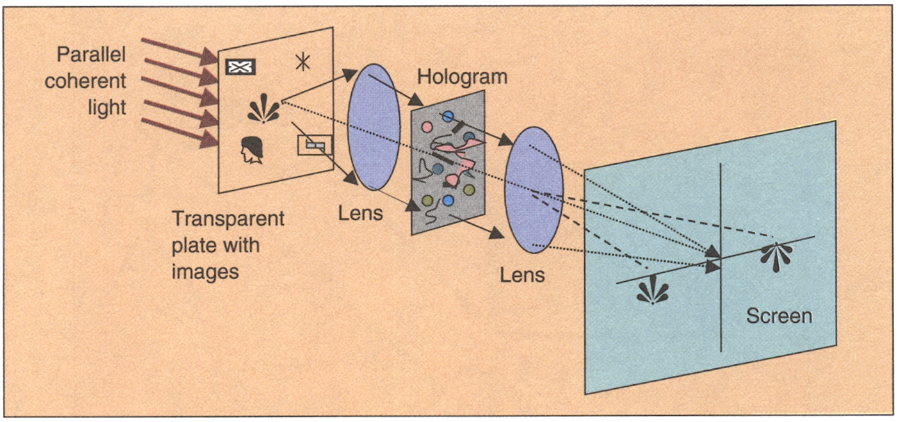

Figure 2.13 Application of holography in image recognition.

and the holographic frames are selectable with micromirrors that have been made by using nano technology (see Sections 10.5 and 10.6).

2.3.13 Polarization

Typical created light is *unpolarized.* That is, its electric (E) and its magnetic (H) fields have the same strength in all directions perpendicular to the direction of propagation, hence *circular.* However, as light propagates through a medium, it enters the fields of nearby atoms and ions, and field interaction takes place. This interaction affects the electric dipole moment per unit volume, or the polarization vector, and the strength of the electric and/or magnetic fields of light in certain directions to the degree that the end result may produce an elliptical or a linear field distribution. Linear polarization is an extreme case of the field existing in one direction perpendicular to the propagation of light. In practice, the dielectric constant ϵ is a tensor, that may have different values in each direction x, y, z and thus the components of the electric field may be unequal and be in or out of phase. Similarly, with the magnetic field.

Consider that polarized light is separated into two components, one that is fully polarized, I_P, and one that is unpolarized, I_U. The degree of polarization, P, is defined by

$$P = \frac{I_P}{(I_P + I_U)}$$

2.3.14 Polarization Examples

Figure 2.14 illustrates some polarization distributions (polarization modes) around the axis of propagation of a ray.

2.3.15 Polarization by Reflection and Refraction

Polarization may take place by reflection, by refraction, or by scattering. When unpolarized light impinges a surface, its reflection is polarized. The degree of

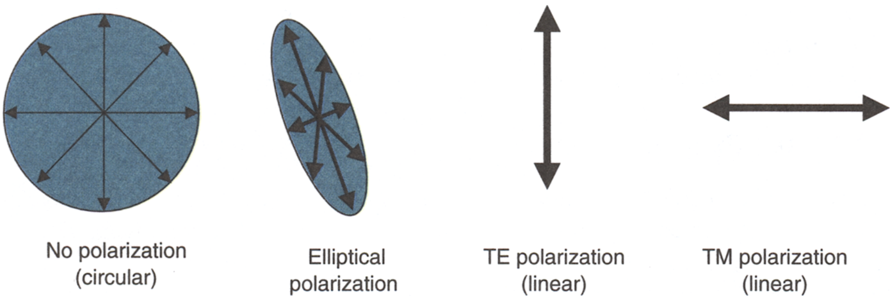

Figure 2.14 Example of polarization modes (direction of light is perpendicular to page).

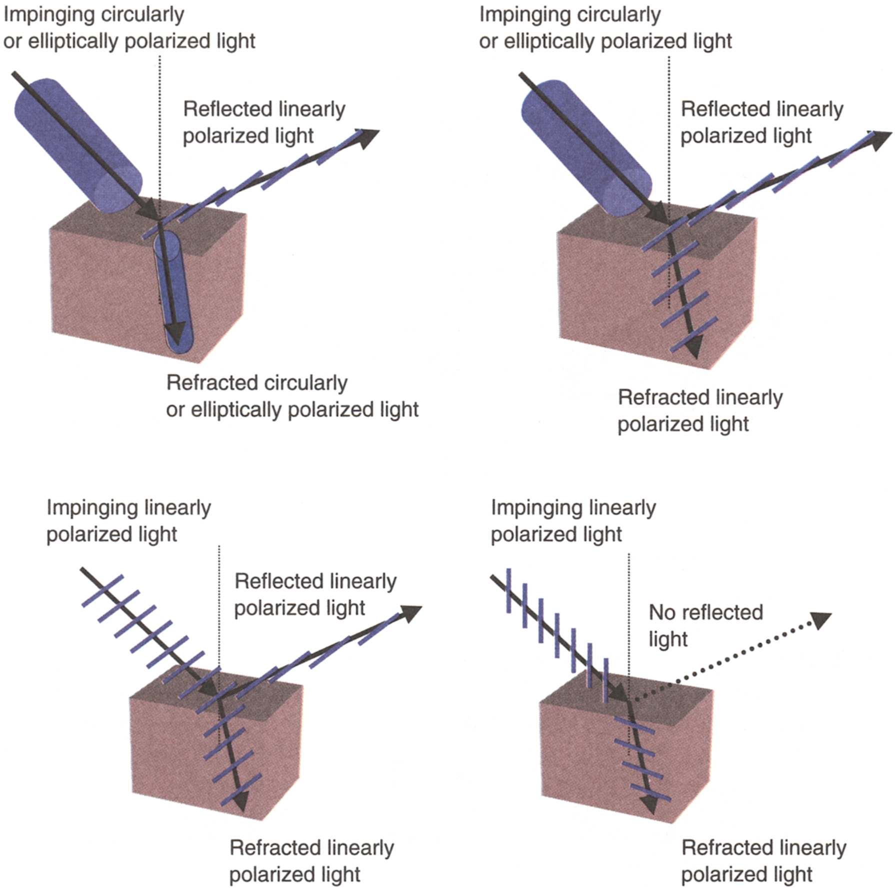

Figure 2.15 Four examples of polarization by reflection and refraction.

polarization depends on the angle of incidence and the refractive index of the material, given by *Brewster's law:* $\tan(I_P) = n$, where n is the refractive index and I_P the polarizing angle. Figure 2.15 offers some examples of reflected and refracted polarization.

2.3.16 Extinction Ratio

Consider polarized light traveling *through a polarizer.* When transmittance is maximum, T_1, it is termed major *principal transmittance,* and when minimum, T_2, it is termed *minor principal transmittance.* The ratio major to minor *principal transmittance* is known as the *principal transmittance*. The inverse, minimum to maximum, is known as the *extinction ratio.*

Consider two polarizers in tandem, one behind the other with parallel surfaces. If their polarization axes are parallel, the transmittance is $T_1^2/2$. If their axes are crossed (perpendicular), the transmittance is $2T_2/T_1$. This is also (but incorrectly) termed the *extinction ratio.*

2.3.17 Polarization Mode Shift: The Faraday Effect

When a material shifts the direction of polarization of transmitted light through itself, the shift is also known as the *Faraday effect* (Figure 2.16). Devices based on the Faraday effect are known as *rotators.* Such materials are α-quartz, crystalized sodium chlorate, as well as cane sugar solution (liquid) and camphor (gas).

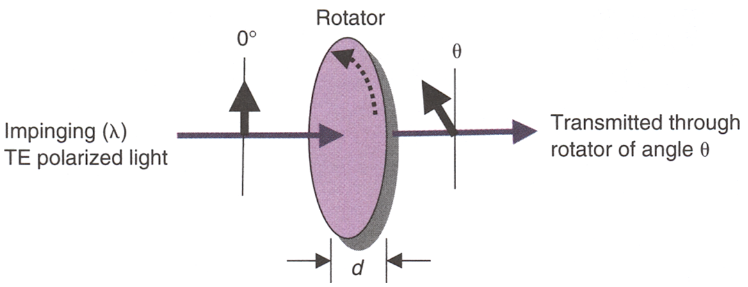

Figure 2.16 Principle of polarization rotator: Faraday effect.

The amount of the rotation angle or *mode shift*, θ, depends on the thickness of material d (cm), the magnetic field H [oersted (Oe)], and a constant V, known as the Verdet constant (measured in min/cm · Oe). The mode shift is expressed by

$$\theta = VHd.$$

Devices with strong Verdet constant, magnetic field, and length may also shift the TE (transverse electric) polarization mode to TM (transverse magnetic) polarization mode (Figure 2.17).

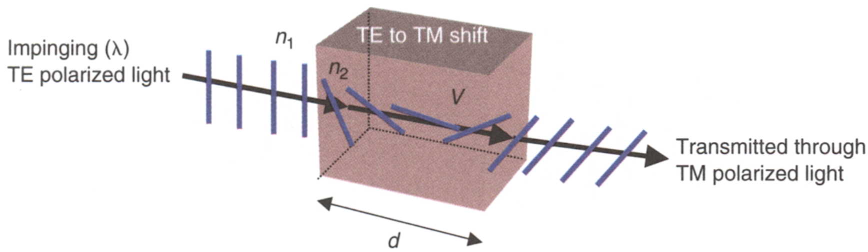

Figure 2.17 Polarization shift from TE to TM mode.

2.3.18 Phase Shift

When a dielectric material in contrast to rotating polarization, shifts the phase of transmitted light through itself (Figure 2.18), the amount of phase shift $\Delta\phi$ depends on the wavelength λ, the dielectric constant ϵ, the refractive index ratio n_1/n_2, and the optical path (thickness) of material.

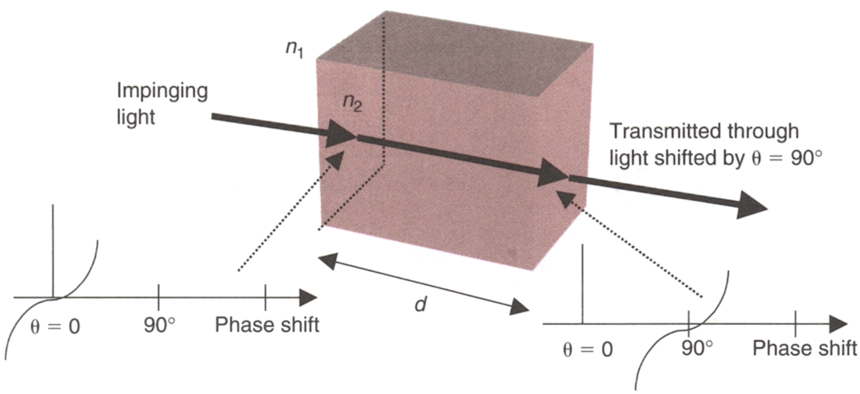

Figure 2.18 Principle of phase angle shift.

2.3.19 Isotropy and Anisotropy

Isotropic optically transparent materials are those that have the same index of refraction, the same polarization, and the same propagation constant in every direction throughout the material. Materials that do not exhibit these properties are known as *anisotropic* (Figure 2.19).

In crystals (such as calcite; $CaCO_3$), electrons move with different amounts of freedom in specific directions, in the crystal. As a result, as rays of light enter the crystal, they interact differently in different directions of the crystal. Such crystals also are termed anisotropic.

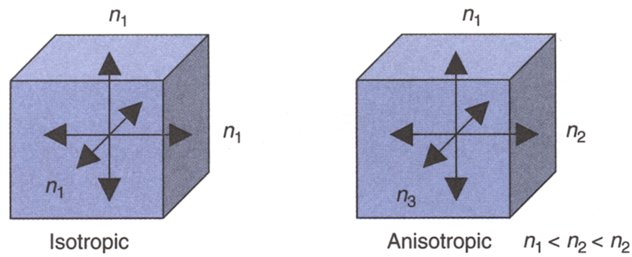

Figure 2.19 Principles of isotropic and anisotropic materials.

2.3.20 Birefringence

Anisotropic materials have a different index of refraction in specific directions. As such, when a beam of monochromatic unpolarized light travels through it in a specific direction, it is refracted differently along the directions of different indices (Figure 2.20). That is, when an unpolarized ray enters the material, it is separated into two rays, each with a different polarization, different direction, and different propagation constant, called the ordinary ray (*O*) and the extraordinary ray (*E*). This property of anisotropic crystals is known as *birefringence*. Such crystals are calcite ($CaCO_3$), mica, quartz, and magnesium fluoride (MgF_2).

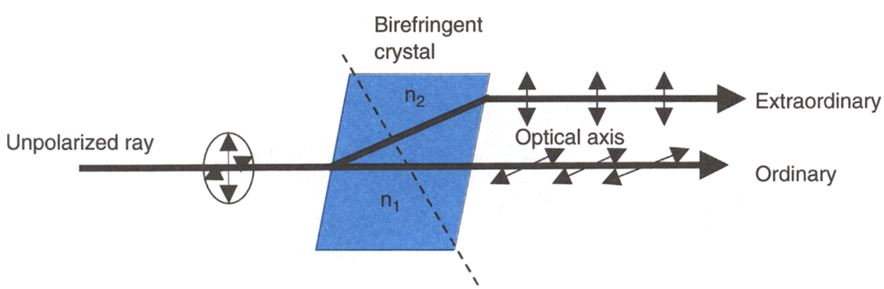

Figure 2.20 Birefringent materials split the incident beam in the ordinary and extraordinary rays, which differ in polarization.

Some optically transparent isotropic materials, when they are under stress, become anisotropic. Mechanical forces (pulling, bending, twisting), thermal forces (ambient temperature variations), and electrical fields may exert stress. Under such conditions, the index of refraction, polarization, and propagation characteristics become different in certain directions within the material.

Birefringence in fiber transmission is undesirable. Birefringence alters the polarization and the propagating characteristics of the transmitted signal and while the receiver expects one polarization, it receives another.

To minimize birefringence in fibers, several techniques have been devised. One technique monitors and controls the received polarization by changing the polarization of the receiver or by using polarization-maintaining fibers. Another technique uses transmitting and receiving strategies to "immunize" the system from fiber polarization variations, such as polarization spreading (polarization scrambling, data-induced polarization), or polarization diversity.

However, engineers have also taken advantage of birefringence to construct filters that may also be used as wavelength multiplexers and demultiplexers (see Section 4.12). Figure 2.21 gives an example of a circularly polarized light ray traversing a birefringent plate.

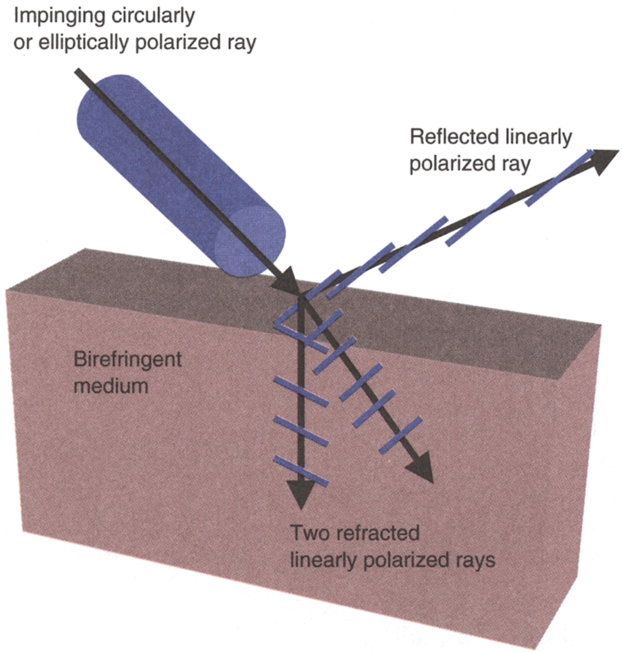

Figure 2.21 Example of birefringence on a nonpolarized beam before and after.

2.3.21 The Quarter-Wavelength Plate

A birefringent plate of one-quarter wavelength ($\lambda/4$) thickness and with the surfaces parallel to the optical axis has some important properties in the realm of polarized light.

If the linearly-polarized light is at 45° to the fast optical axis, the polarization is transformed into circularly polarized light, and vice versa.

If the linearly-polarized light is parallel to the fast or slow axis, the polarization remains unchanged.

If the linearly-polarized light is at any other angle with the optical axis, linear polarization is transformed into elliptical, and vice versa.

If the plate consists of quartz or mica, the thickness d is related to wavelength by the relationship:

$$d = \mathrm{R}\lambda/\Delta n,$$

where $\Delta n = n_e - n_0$ is the refractive index difference between the extraordinary and ordinary paths, and R is a constant real number.

The phase difference, $\Delta\phi$, is related to R by:

$$\Delta\phi = 2\pi R$$

For $\lambda/4$ plates, $R = \pm 0.25$.

2.3.22 The Half-Wavelength Plate

Similar to $\lambda/4$ plates, a plate of half-wavelength ($\lambda/2$) thickness and with surfaces parallel to the optical axis has some other important properties on polarized light.

If the linearly-polarized light is at 0° to the fast optical axis, the polarization remains linear but the orientation is rotated by 20°. Thus, if the angle is 45°, the linear polarization is rotated by 90°.

For $\lambda/2$ plates, $R = \pm 0.5$.

2.3.23 Material Dispersion

The refractive index is related to the dielectric coefficient of the material and to the characteristic resonance frequencies of its dipoles. The dipoles of the material, therefore, interact more strongly with (and absorb more) optical frequencies that are closer to their resonance frequencies. Consequently, the refractive index $n(\omega)$ is optical frequency dependent. The dependency of the refractive index of the material on the optical frequency is termed *material dispersion.*

Silica, a key ingredient of optical fiber cable, has a refractive index that varies with optical frequency. Therefore, dispersion plays a significant role in fiberoptic communications.

2.3.24 Nonlinear Phenomena

The polarization of an electromagnetic wave *P,* which is induced in electric dipoles of a medium by an electric field *E,* is proportional to susceptibility, $\varkappa$:

$$P = \epsilon_0 \left[\varkappa^1 \cdot E + \varkappa^2 \cdot E.E + \varkappa^3 \cdot E \cdot E \cdot E + \ldots\right]$$

The factor ϵ_0 is known as the permittivity in vacuum.

For an isotropic medium, the first-order term expresses the linear behavior of matter, and the second-order term is orthogonal. Therefore, the second-order term vanishes, and higher order terms are negligible. Thus, for an isotropic medium the series relation above is simplified to $P = \epsilon_0 \varkappa \cdot E$. However, nature is not so simple, and most materials are either not isotropic or become anisotropic under certain conditions. In such cases, higher order terms should also be considered. In particular, the third-order term becomes significant, and nonlinear effects that may affect and limit optical transmission result.

The most influential nonlinear effects in optical transmission, particularly when many wavelengths at high *optical power* are transmitted over the same medium (e.g., DWDM), *are four-wave mixing (FWM), stimulated Raman scattering* (SRS), and *stimulated Brillouin scattering (SBS).*

2.3.25 Homogeneity and Heterogeneity

A *homogeneous* optically transparent medium has the same consistency (chemical, mechanical, electrical, magnetic, or crystallographic) throughout its volume (Figure 2.22). A *heterogeneous* optically transparent medium does not have the same consistency (chemical, mechanical, electrical, magnetic, or crystallographic) throughout its volume.

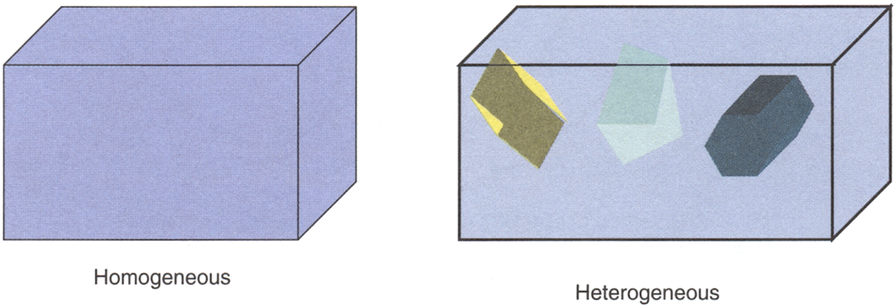

Figure 2.22 Schematic illustrations of homogeneous and nonhomogeneous (heterogeneous) matter.

2.3.26 Effects of Impurities in Matter

An *impurity* is the presence of unwanted elements or compounds in matter. During the purification process of matter (e.g., silica), certain elements cannot be removed in their entirety and some traces will remain. These undesired elements or compounds alter the optical characteristics of the transparent material (e.g., fiber) and either have an absorptive effect or result in optical throughput loss by scattering photons in other directions. Figure 2.23 captures the absorptive and scattering effect of photons as they transverse matter.

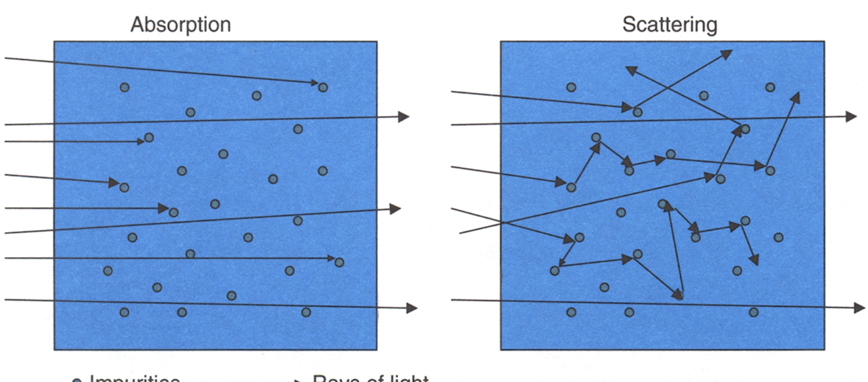

Figure 2.23 Matter with absorption center and with scattering centers.

Examples of impurities that affect optical transmission are the elements iron, copper, and cobalt, and their oxides. The result is selective optical wavelength absorption. For instance, blue glass is the result of cobalt or copper in glass, (which looks blue because it absorbs all wavelengths but the blue. One of the most difficult "impurities" to remove from glass fiber is the hydroxyl radical (OH). Hydroxyl radicals in fiber cable are responsible for increased absorption in the range below 1400 nm (Figure 2.24).

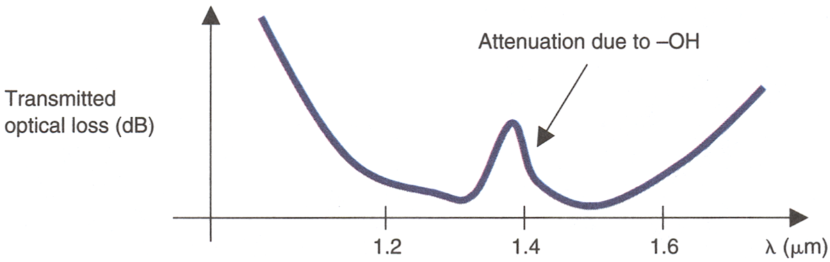

Figure 2.24 Optical loss (or attenuation) by impurities in transparent matter.

2.3.27 Effects of Microcracks

Cracks may be viewed as discontinuities in the index of refraction of the material with planes that are not necessarily flat (Figure 2.25). Microcracks in the crystallized matrix of matter, or in amorphous solid matter, are generated by stresses (mechanical or thermal) or material aging. Microcracks are invisible to the naked eye and become visible only under a strong microscope or with specialized interferometric techniques. As light travels through matter in which there are cracks, its propagation is disrupted or distorted.

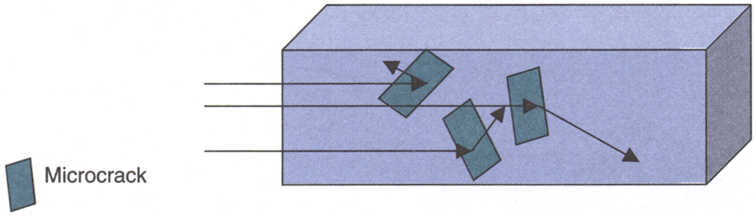

Figure 2.25 Matter with microcracks.

2.3.28 Effects of Mechanical Pressure

When mechanical pressure is applied, the internal microstructure of the material is disturbed (Figure 2.26). As a result, there is a variation of the refractive index determined by the pressure distribution in the material. Mechanical pressure is also exerted on the fibers as they are pulled or bent. Thus, assuming a circular bend, the outer periphery experiences stretching points while the inner experiences compression points. Pressure and stretching points are clearly points of optical disturbances that are generally undesirable in optical communications. The safe bend radius recommended by ITU-T is the widely accepted radius of 37.5 mm (ITU-T G.652, para. 5.5, note 2).

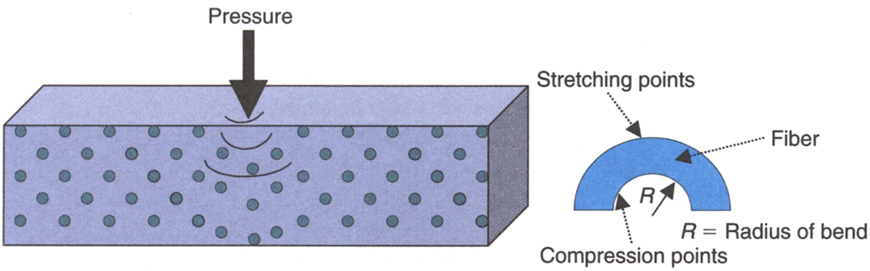

Figure 2.26 Dislocation of orderly molecules in matter by pressure distribution and pressure effects on fiber due to bending.

2.3.29 Effects of Temperature Variation

The properties of materials vary as temperature varies. In addition to changing its physical properties, the electrical, magnetic, and chemical properties also change. As a result of this, the index of refraction is affected (Figure 2.27). Clearly, in optical communications, temperature variations are undesirable, although in certain cases temperature control has been used productively to vary the refractive index of optical devices.

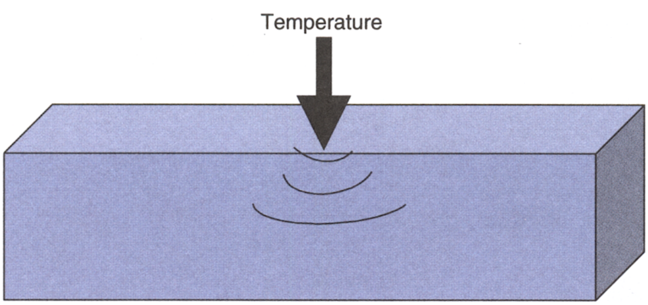

Figure 2.27 Dislocation of orderly molecules in matter by temperature distribution.

EXERCISES

1. Could a moving photon particle stop moving in vacuum by itself?
2. When monochromatic light of frequency ν travels in vacuum, then $E = mc^2 = h\nu$, and when it travels in dense matter its speed changes but its energy is preserved. What changes then?
3. Could the refractive index n be smaller than 1?
4. If in Figure 2.1, Θ_i becomes zero (i.e., rays are perpendicular to surface), then would there be a reflected ray?
5. If, in Figure 2.2, $n_1 > n_2$, is $\Theta_t < \Theta_i$ or $\Theta_t > \Theta_i$?
6. If in the prism of Figure 2.4 $n_1 < n_2$, is $\lambda_k < \lambda_j$ or $\lambda_k > \lambda_j$?
7. What physical phenomenon describes refraction through a continuously variable index of refraction?

8. A pond appears to be only 2 feet deep. A coin lies on its bottom. We try to reach the coin with a 2.5-foot-long stick, but we discover that we cannot even reach the coin. Why not?
9. Two coherent light sources impinge on a screen as shown (Figure 2.28). Identify points of minima and maxima contributions within the highlighted area.

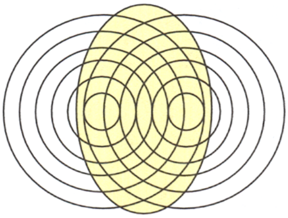

Figure 2.28

10. Consider the setup of Figure 2.29. Device G splits a monochromatic beam A into two, beams, B and C. Beam B travels straight through and impinges at point F on a screen. Beam C is further reflected by mirror M. Mirror M, however, slowly moves vertically and simultaneously rotates so that the reflected ray C also impinges at point F on the screen. As the mirror moves, what would we expect to observe at point F?

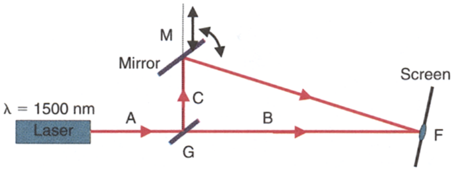

Figure 2.29

11. Could a moving photon be captured and stored?
12. What happens when a photon interacts with an atom?
13. A monochromatic light source has a frequency $f = 192{,}843$ GHz. Calculate the wavelength.

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