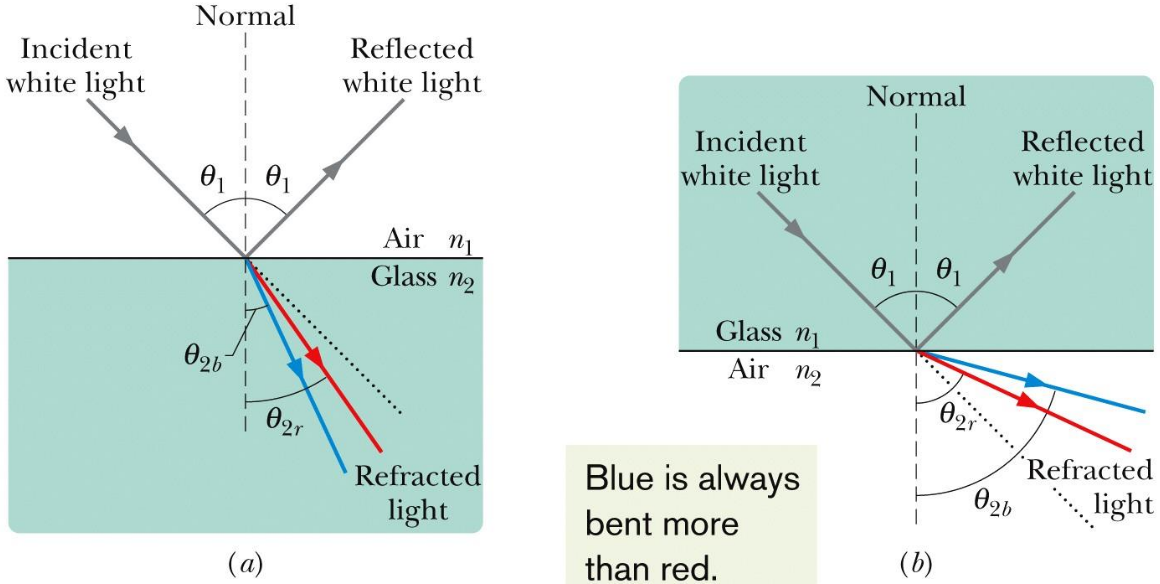
Chapter 33

Electromagnetic Waves

33-5 Reflection and Refraction

Chromatic dispersion of white light. The blue component is bent more than the red component. (a) Passing from air to glass, the blue component ends up with the smaller angle of refraction. (b) Passing from glass to air, the blue component ends up with the greater angle of refraction. Each dotted line represents the direction in which the light would continue to travel if it were not bent by the refraction.



Blue is always bent more than red.

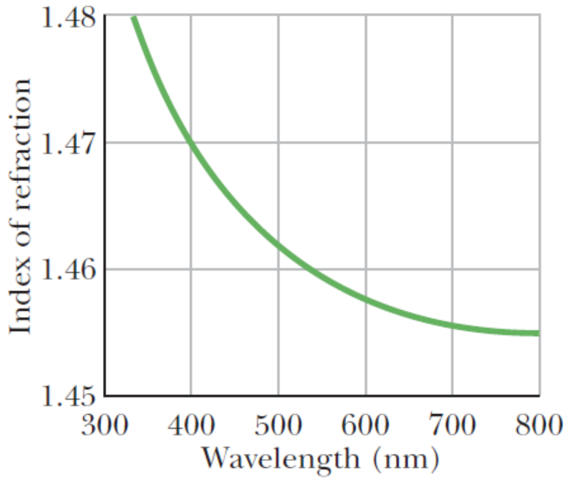
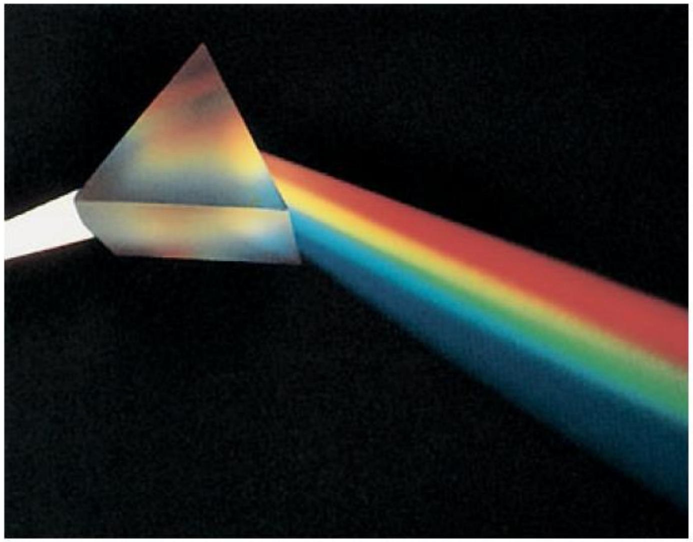


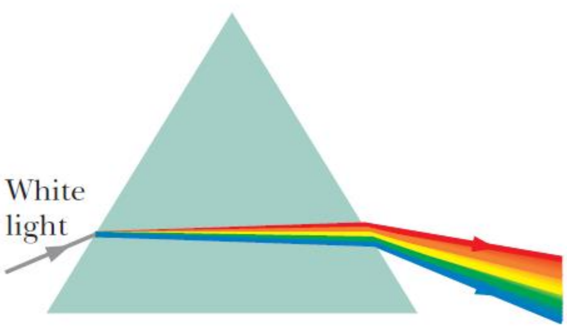
Figure 33-18 The index of refraction as a function of wavelength for fused quartz. The graph indicates that a beam of short-wavelength light, for which the index of refraction is higher, is bent more upon entering or leaving quartz than a beam of long-wavelength light.

To increase the color separation, we can use a solid glass prism with a triangular cross section, as in Fig. 33-20*a*. The dispersion at the first surface (on the left in Figs. 33-20*a*, *b*) is then enhanced by the dispersion at the second surface.



Courtesy Bausch & Lomb

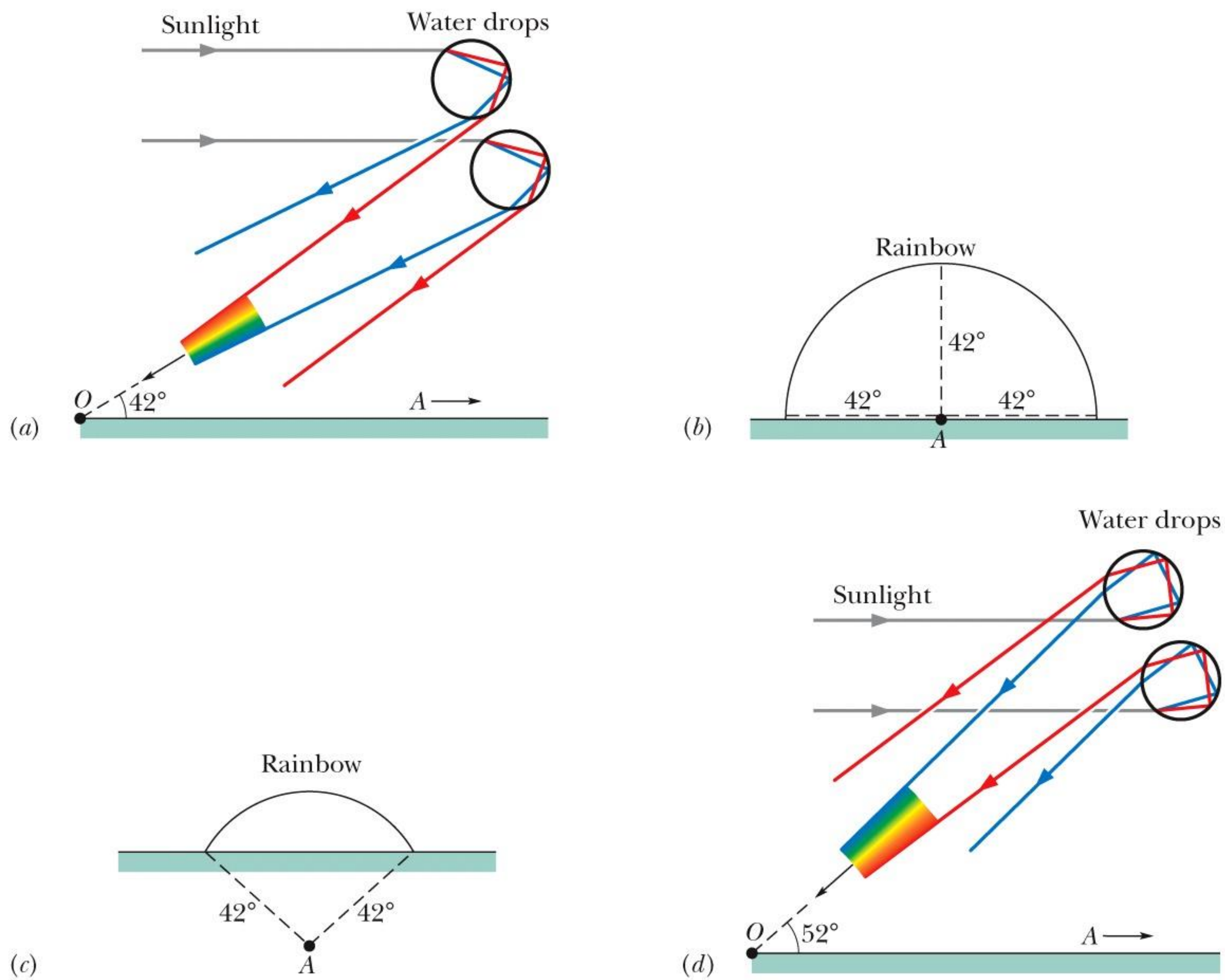
(*a*)



(*b*)

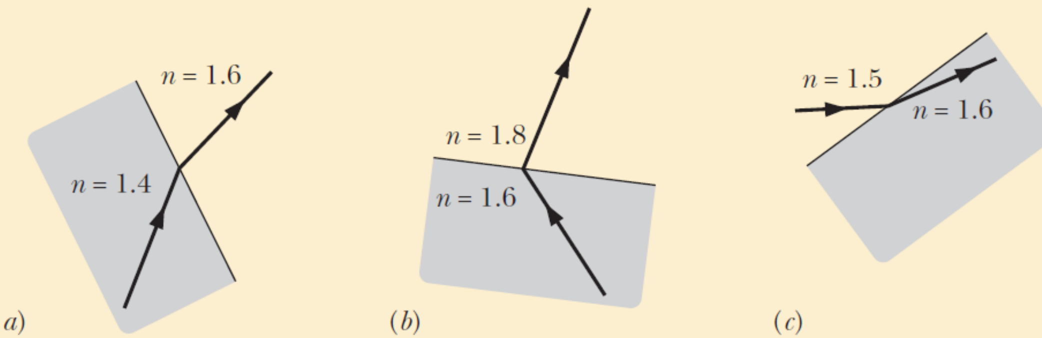
Figure 33-20 (*a*) A triangular prism separating white light into its component colors. (*b*) Chromatic dispersion occurs at the first surface and is increased at the second surface.

Rainbow: (a) The separation of colors when sunlight refracts into and out of falling raindrops leads to a primary rainbow. The *antisolar point A* is on the horizon at the right. The rainbow colors appear at an angle of 42° from the direction of A. (b) Drops at 42° from A in any direction can contribute to the rainbow. (c) The rainbow arc when the Sun is higher (and thus A is lower). (d) The separation of colors leading to a secondary rainbow.



Checkpoint 5

Which of the three drawings here (if any) show physically possible refraction?



(a) (b) (c)

a

Sample Problem 33.03 Reflection and refraction of a monochromatic beam

(a) In Fig. 33-22*a*, a beam of monochromatic light reflects and refracts at point A on the interface between material 1 with index of refraction $n_1 = 1.33$ and material 2 with index of refraction $n_2 = 1.77$. The incident beam makes an angle of 50° with the interface. What is the angle of reflection at point A? What is the angle of refraction there?

KEY IDEAS

(1) The angle of reflection is equal to the angle of incidence, and both angles are measured relative to the normal to the surface at the point of reflection. (2) When light reaches the interface between two materials with different indexes of refraction (call them n_1 and n_2), part of the light can be refracted by the interface according to Snell's law, Eq. 33-40:

$$n_2 \sin \theta_2 = n_1 \sin \theta_1, \qquad (33\text{-}42)$$

where both angles are measured relative to the normal at the point of refraction.

Calculations: In Fig. 33-22*a*, the normal at point A is drawn as a dashed line through the point. Note that the angle of incidence θ_1 is not the given 50° but is 90° − 50° = 40°. Thus, the angle of reflection is

$$\theta_1' = \theta_1 = 40°. \qquad \text{(Answer)}$$

The light that passes from material 1 into material 2 undergoes refraction at point A on the interface between the two materials. Again we measure angles between light rays and a normal, here at the point of refraction. Thus, in Fig. 33-22*a*, the angle of refraction is the angle marked θ_2. Solving Eq. 33-42 for θ_2 gives us

$$\theta_2 = \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta_1\right) = \sin^{-1}\left(\frac{1.33}{1.77}\sin 40°\right)$$

$$= 28.88° \approx 29°. \qquad \text{(Answer)}$$

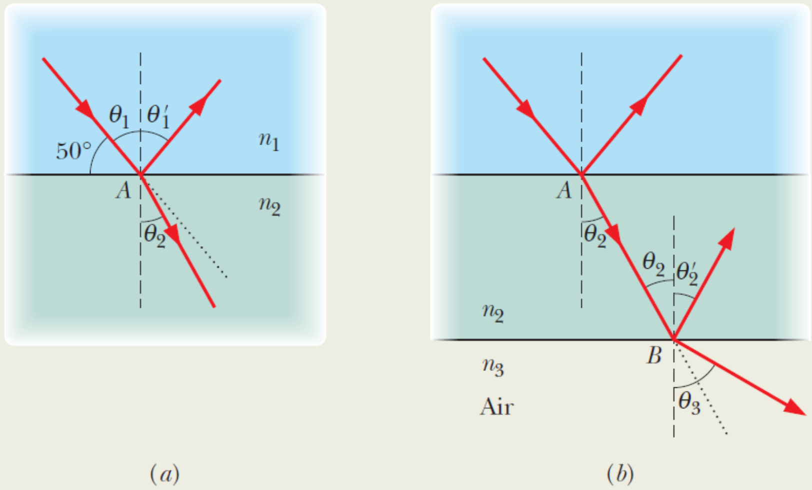


Figure 33-22 (*a*) Light reflects and refracts at point A on the interface between materials 1 and 2. (*b*) The light that passes through material 2 reflects and refracts at point B on the interface between materials 2 and 3 (air). Each dashed line is a normal. Each dotted line gives the incident direction of travel.

This result means that the beam swings toward the normal (it was at 40° to the normal and is now at 29°). The reason is that when the light travels across the interface, it moves into a material with a greater index of refraction. *Caution:* Note that the beam does *not* swing through the normal so that it appears on the left side of Fig. 33-22*a*.

(b) The light that enters material 2 at point A then reaches point B on the interface between material 2 and material 3, which is air, as shown in Fig. 33-22*b*. The interface through B is parallel to that through A. At B, some of the light reflects and the rest enters the air. What is the angle of reflection? What is the angle of refraction into the air?

Calculations: We first need to relate one of the angles at point B with a known angle at point A. Because the interface through point B is parallel to that through point A, the incident angle at B must be equal to the angle of refraction θ_2, as shown in Fig. 33-22*b*. Then for reflection, we again use the law of reflection. Thus, the angle of reflection at B is

$$\theta_2' = \theta_2 = 28.88° \approx 29°. \qquad \text{(Answer)}$$

Next, the light that passes from material 2 into the air undergoes refraction at point B, with refraction angle θ_3. Thus, we again apply Snell's law of refraction, but this time we write Eq. 33-40 as

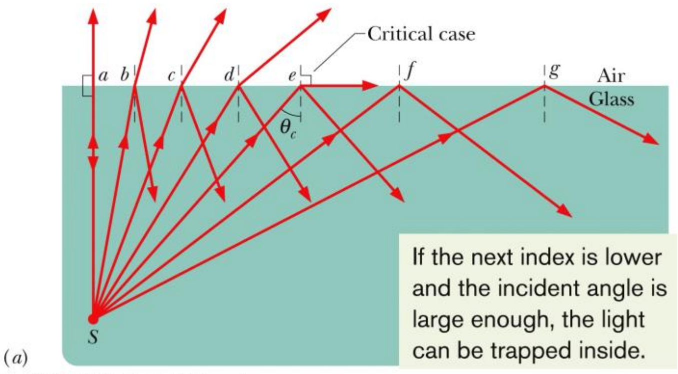
$$n_3 \sin \theta_3 = n_2 \sin \theta_2. \qquad (33\text{-}43)$$

Solving for θ_3 then leads to

$$\theta_3 = \sin^{-1}\left(\frac{n_2}{n_3} \sin \theta_2\right) = \sin^{-1}\left(\frac{1.77}{1.00} \sin 28.88°\right)$$
$$= 58.75° \approx 59°. \qquad \text{(Answer)}$$

Thus, the beam swings away from the normal (it was at 29° to the normal and is now at 59°) because it moves into a material (air) with a lower index of refraction.

33-6 Total Internal Refraction



Ken Kay/Fundamental Photographs

(a) Total internal reflection of light from a point source S in glass occurs for all angles of incidence greater than the critical angle uc. At the critical angle, the refracted ray points along the air – glass interface. (b) A source in a tank of water.

Figure (a) shows rays of monochromatic light from a point source S in glass incident on the interface between the glass and air. For ray a, which is perpendicular to the interface, part of the light reflects at the interface and the rest travels through it with no change in direction. For rays b through e, which have progressively larger angles of incidence at the interface, there are also both reflection and refraction at the interface. As the angle of incidence increases, the angle of refraction increases; for ray e it is 90°, which means that the refracted ray points directly along the interface. The angle of incidence giving this situation is called the **critical angle** θ_c. For angles of incidence larger than θ_c, such as for rays f and g, there is no refracted ray and all the light is reflected; this effect is called **total internal reflection** because all the light remains inside the glass.

Ken Kay/Fundamental Photographs

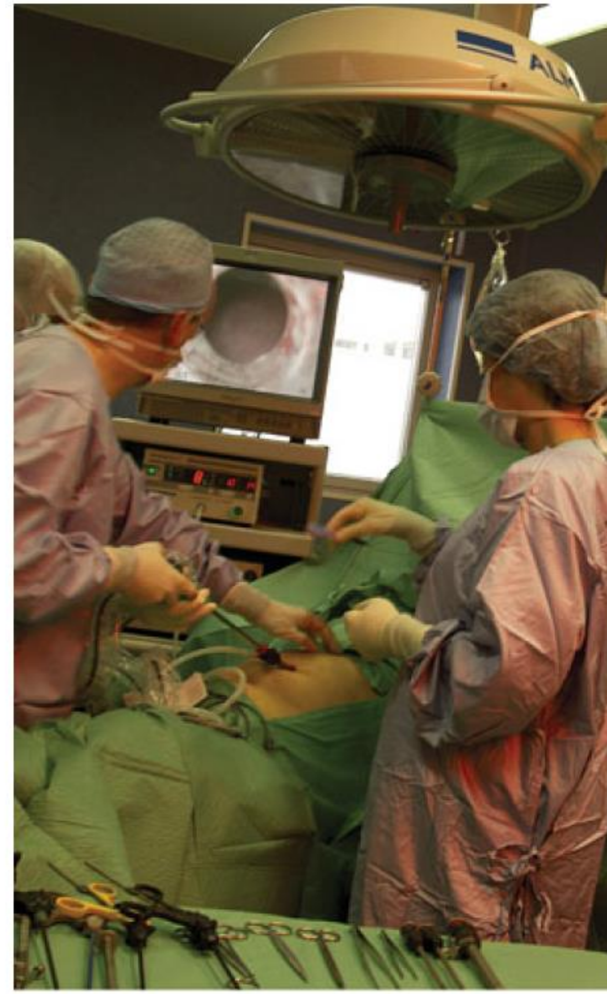


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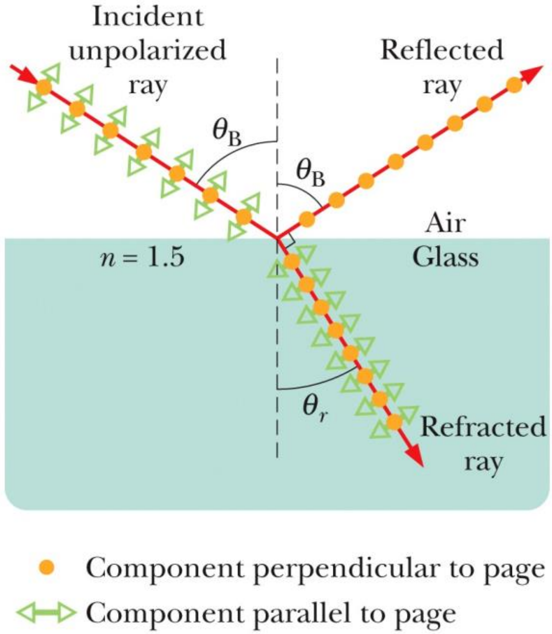
Figure 33-24 An endoscope used to inspect an artery.

33-7 Polarization by Reflection



A ray of unpolarized light in air is incident on a glass surface at the **Brewster angle** θ_B. The electric fields along that ray have been resolved into components perpendicular to the page (the plane of incidence, reflection, and refraction) and components parallel to the page. The reflected light consists only of components perpendicular to the page and is thus polarized in that direction. The refracted light consists of the original components parallel to the page and weaker components perpendicular to the page; this light is partially polarized.

As shown in the figure above a reflected wave will be fully polarized, with its ***E*** vectors perpendicular to the plane of incidence, if it strikes a boundary at the Brewster angle θ_B, where

$$\theta_B = \tan^{-1}\frac{n_2}{n_1} \quad \text{(Brewster angle).}$$

33 Summary

Electromagnetic Waves

- An electromagnetic wave consists of oscillating electric and magnetic fields as given by,

$$E = E_m \sin(kx - \omega t)$$ **Eq. 33-1**

$$B = B_m \sin(kx - \omega t),$$ **Eq. 33-2**

- The speed of any electromagnetic wave in vacuum is *c*, which can be written as

$$c = \frac{E}{B} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$ **Eq. 33-5&3**

Energy Flow

- The rate per unit area at which energy is trans- ported via an electromagnetic wave is given by the Poynting vector ***S***:

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}.$$ **Eq. 33-19**

- The intensity *I* of the wave is:

$$I = \frac{1}{c\mu_0} E_{\text{rms}}^2$$ **Eq. 33-26**

- The intensity of the waves at distance r from a point source of power Ps is

$$I = \frac{P_s}{4\pi r^2}.$$ **Eq. 33-27**

Radiation Pressure

- If the radiation is totally absorbed by the surface, the force is

$$F = \frac{IA}{c}$$ **Eq. 33-32**

- If the radiation is totally absorbed by the surface, the force is

$$F = \frac{2IA}{c}$$ **Eq. 33-33**

33 Summary

Radiation Pressure

- The radiation pressure p_r is the force per unit area.
- For total absorption

$$p_r = \frac{I}{c}$$ **Eq. 33-34**

- For total reflection back along path,

$$p_r = \frac{2I}{c}$$ **Eq. 33-35**

Polarization

- Electromagnetic waves are polarized if their electric field vectors are all in a single plane, called the plane of oscillation.
- If the original light is initially unpolarized, the transmitted intensity I is

$$I = \tfrac{1}{2}I_0.$$ **Eq. 33-36**

- If the original light is initially polarized, the transmitted intensity depends on the angle u between the polarization direction of the original light (the axis along which the fields oscillate) and the polarizing direction of the sheet:

$$I = I_0 \cos^2 \theta.$$ **Eq. 33-26**

Reflection and Refraction

- The angle of reflection is equal to the angle of incidence, and the angle of refraction is related to the angle of incidence by Snell's law,

$$n_2 \sin \theta_2 = n_1 \sin \theta_1$$ **Eq. 33-40**

33 Summary

Total Internal Reflection

- A wave encountering a boundary across which the index of refraction decreases will experience total internal reflection if the angle of incidence exceeds a critical angle,

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

Eq. 33-45

Polarization by Reflection

- A reflected wave will be fully polarized, if the incident, unpolarized wave strikes a boundary at the Brewster angle

$$\theta_B = \tan^{-1}\frac{n_2}{n_1}$$

Eq. 33-49