Refraction and Reflection

Understanding refraction requires an understanding of the speed of light in air and in various other materials. The speed of light has been measured with increasing accuracy over hundreds of years. The earliest measurements were made with people on mountains using various shutters on lights. Light travels so fast that these measurements were doomed to failure; they ended up measuring the response times of the experimenters! Modern measurements have determined this speed with considerable accuracy. In fact, the value is quoted as 299,792,458 meters per second, stated with nine significant figures.

The Speed of Light

Light is the fastest thing in the world. Part of the famous law of relativity, authored by Albert Einstein, is the fact that nothing travels faster than light. In a vacuum it travels at approximately 186,000 miles per second. In metric measure, that is almost 300,000,000 meters (m) per second. In a medium like water, glass, or even air, it travels at a slower rate. It is only a little slower in air, about 0.01%, but it is about 30% slower in water and 50% slower in glass. The ratio of the speed of light in a vacuum to that in a medium is called the *refractive index*. The refractive indices of water and glass, respectively, are about 1.3 and 1.5.

Reflection, Refraction, and Transmission

When light is incident upon a surface, like that shown in Fig. 13, part of it is reflected, part is refracted into the material, where often some is absorbed, and finally it emerges from the other side. The ratio of the amount of light that is reflected to that which is incident is called the *reflectance* or the *reflectivity*. The ratio of that which is transmitted all the way through to the incident amount is the *transmittance* or *transmissivity*. The ratio of that absorbed is called the *absorptivity* or *absorptance*.

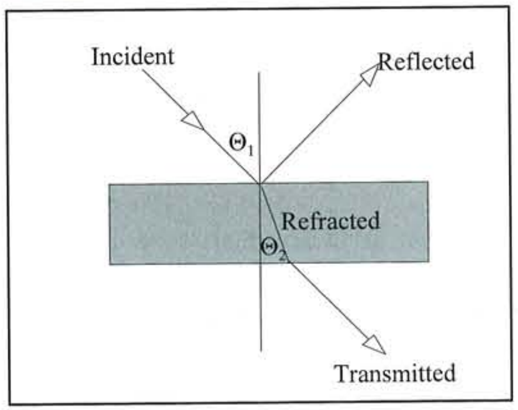

Figure 13 Reflected and refracted rays.

Refraction

Generally, we think of the refractive index of transparent materials like glass, water, and air. It is usually true that the denser (mass per unit volume) a material is, the slower the speed of light in it and the higher the refractive index. It seems reasonable that the speed is lower in a denser material; this is consistent with our observation about other things like running in air and running in water, although the reasons may be different.

As a result of the fact that light travels slower in a medium like glass, it *refracts* or bends. That is, if it is incident on a surface at an angle, the direction the light travels is changed. The change in direction can be calculated by the law of refraction that is usually attributed to Willebrord Snell in Holland in 1621. It states that the angle of refraction is related to the angle of incidence by the product of their sines and the refractive indices.

One reasonable way to understand this refraction is by considering the incidence of plane waves upon a medium of higher density. Figure 14 shows a wavefront first at position A, then at B, then CDE, a little after it first strikes the denser medium. The part of the wavefront in the medium goes slower than the other part because the refractive index is higher (light travels more slowly in a denser medium). It continues this way into wavefront FGH and eventually gets all the way into the medium and then out, where it emerges parallel to its entry direction. An interesting analogy is to assume that the waves represent lines of soldiers marching to the lower right of the page. The dark bar is water. As each soldier enters the water he moves more slowly because it is harder to move through water.

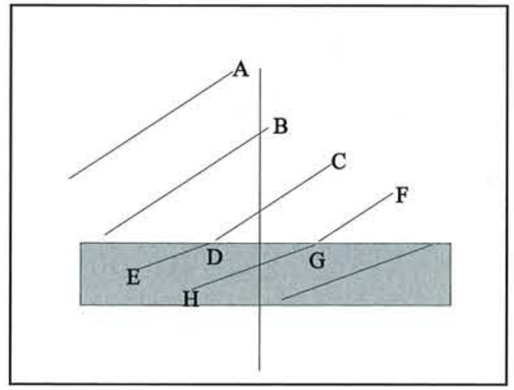

Figure 14 Refraction of waves.

When light travels from a dense medium to a rare one, that is, from a medium of higher index to one of lower index, there are limits on the angles. If the an-

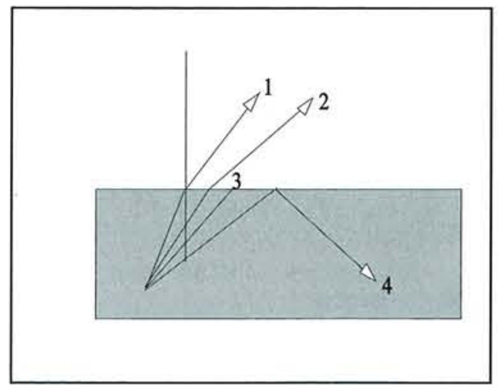

Figure 15 Total internal reflection.

gle of incidence is too large, the light is completely reflected back into the medium of higher index. This is called *total internal reflection*. It can be observed in two simple ways. One is to submerge yourself in a pool and look up and out at increasing angles of incidence. At a sufficiently large angle, the surface of the pool will look silvery, like a mirror.

The angle at which this happens is called the *critical angle*. For water and air, the angle is approximately 37 degrees. In Fig. 15, rays 1 and 2 are refracted as described above; they bend away from the perpendicular to the surface. Ray 3 is at exactly the angle of total internal reflection and travels along the surface. Ray 4 is reflected back into the material. This total internal reflection is an important aspect of fiber optics.