CHAPTER 4

Reflection and Refraction in a Homogeneous Medium

In this chapter, we undertake our first quantitative examination of the interaction of radiation with matter. We will focus initially on the behavior of EM waves when they encounter, and propagate through, a *homogeneous* medium.

By “homogeneous,” we mean a medium that is smooth and uniform on scales comparable to the wavelength of the radiation. Water, glass, air, red wine, maple syrup, liquid mercury, and solid gold are all effectively homogeneous with respect to radiation in the visible, infrared and microwave bands, because the size and spacing of the individual molecules and other irregularities are much smaller than the wavelength of the radiation. If this were not the case, then glass and water, for example, would have a cloudy or milky appearance rather than being perfectly transparent to the eye. In fact, milk looks “milky” precisely because of the presence of suspended particles that are larger than the wavelengths of visible light.

To radiation in the X-ray and gamma bands, these and all other substances appear quite lumpy, or *inhomogeneous,* because the wavelength of the radiation is comparable to or smaller than the spacing between the molecules. Likewise, centimeter- and meter-scale turbulent eddies and fluctuations in humidity may make even the atmosphere appear inhomogeneous with respect to radio and microwave radiation. On the other hand, consider a cloud that is made up of 10 μm-diameter water droplets: it behaves like a homogeneous medium with respect to the long wavelengths of microwave radiation even though it is quite inhomogeneous with respect to visible and infrared radiation.

At the microscopic level, interactions of radiation with even homogeneous media are quite complex, involving the constructive and destructive interference of waves scattered by the countless individual atoms or molecules in the medium. From a macroscopic point of view, however, all of this complexity is hidden in a single parameter, the complex index of refraction $N = n_r + n_i i$ of the medium. As discussed in Chapter 2, the real part n_r controls the effective phase speed of EM waves propagating through the medium while the imaginary part n_i describes the rate of absorption of the wave.

The phase speed of radiation in a medium may seem uninteresting to the uninitiated; after all, even in the densest medium, it's too fast to directly observe without highly specialized equipment. However, it is the sudden change in this phase speed at boundaries between media such as air and water that gives rise to the phenomena of *reflection* and *refraction*.

It is important to keep in mind that N is not a constant for any substance but rather depends strongly on wavelength and, to a lesser degree, temperature, pressure and other variables. It is the variation of n_r with wavelength in raindrops that gives rise to rainbows; it is a sharp variation of n_i with wavelength that makes wine red.

It is also worth pointing out in passing that, in any real material, n_r and n_i are not free to vary independently of one another but rather are tightly coupled to one another via the so-called *Kramer-Kronig* relations. Although the equations describing these relationships, and their physical interpretation, are beyond the scope of this book, suffice it to say that knowledge of the value of n_i over the full range of frequency is sufficient to compute n_r at any frequency, and vice versa. See BH83, Chapter 2 for a detailed discussion.

4.1 A Closer Look at N

4.1.1 The Real Part

Recall from Chapter 2 that, in a nonabsorbing medium, the imaginary part of the index of refraction $n_i = 0$ and $N = n_r$, where n_r is real and the phase speed c' in the medium is given by

$$\boxed{c' = \frac{c}{n_r} ,} \tag{4.1}$$

where c is the speed of light in a vacuum. For virtually all real substances $n_r > 1$, so that the phase speed of light in a physical medium is somewhat slower than that in a vacuum.

The values of n_r for both water and ice are given as functions of wavelength in the top panel of Fig. 4.1. In the visible band ($0.4 < \lambda < 0.7$), the value of n_r for water is approximately 1.33, though it is slightly larger for the shorter wavelengths (e.g. blue and violet) than for longer wavelengths (red and orange).

For air at standard temperature and pressure, $n_r \approx 1.0003$ in the visible band and is thus so close to unity that the difference between air and a vacuum may be ignored for some purposes. Nevertheless, the difference does sometimes matter: it is variations in n_r associated with changes in atmosphere density that give rise to mirages and the twinkling of stars, for example.

4.1.2 The Imaginary Part

When the imaginary part n_i of the index of refraction is nonzero, absorption of an EM wave occurs as it passes through the medium. In fact, n_i is sometimes referred to as the *absorption index*. Values of n_i for water and ice are shown as functions of wavelength in the bottom panel of Fig. 4.1. Note that n_i for both substances is extremely small in the visible band but increases sharply as you move into either the ultraviolet or infrared bands.

In Section 2.5, we found that the rate of power attenuation per unit distance is given by the *absorption coefficient* β_a (dimensions of

Return to: A First Course in Atmospheric Radiation