violated by diffraction, for example. But the thermodynamic basis of this theorem shows that the search for a nontracking concentrator with high concentration is doomed to fail.

By restricting the acceptance angles to the region of the sky where the sun is actually found, modest concentrations on the order of 2 to 3 are possible. A further factor of 2 is obtained by using bifacial cells that can accept light from both top and bottom. If the cell is immersed in a dielectric of $n = 1.4$, then yet another factor of 2 is possible. This means that it is possible in principle to obtain concentration ratios of up to around 8 to 12 without tracking the sun. The search for practical, cost-effective static concentrators is ongoing and discussed in Section 11.5.

11.4.2 Reflection and Refraction

Most concentrators use reflection, refraction, or a combination of both to effect their concentration, and standard geometric optics is appropriate for their analysis. Some concepts use diffraction gratings or graded index materials, but that is beyond the scope of this discussion. It is assumed that the reader is familiar with elementary optics. The laws governing light rays at reflective and refractive interfaces are well known; the angle of reflection equals the angle of incidence in the case of reflection and Snell's law in the case of refraction. For three-dimensional analysis, a vector formulation is convenient. Figure 11.21 shows the incident and reflected rays at a reflective surface where the unit vector normal to the surface, and pointing in the direction from which the rays are coming, is **n**. The following vector equation is easily derived relating the reflected ray to the incident ray and **n**:

$$\mathbf{r}_r = \mathbf{r}_i + 2(\mathbf{n} \cdot \mathbf{r}_i)$$

In the case in which a ray is incident at a boundary between two dielectric media, Snell's law applies. This is usually expressed as $n_2 \sin\theta_2 = n_1 \sin\theta_1$, where the coplanarity of the rays is understood. A vector form that expresses this is

$$n_1\mathbf{r}_1 \times \mathbf{n} = n_2\mathbf{r}_2 \times \mathbf{n}$$

Simple geometric shapes can be analyzed analytically using these relations, but modern practice is to use one of the many available ray-tracing packages that solve these equations numerically. This allows for incorporating various imperfections such as surface waviness and imperfections, and can give plots of the intensity profile at the receiver, and so on.

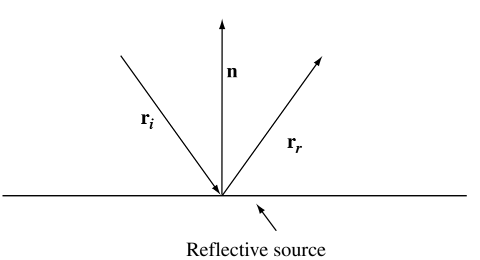

Figure 11.21 Relationship of the incident and the reflected rays to the surface normal