Generally, module improvements have followed the increase in cell efficiencies, with a lag in time to incorporate the cell into suitable packages. Noteworthy recent results are the 20% record held by point-contact silicon-based modules since 1995 [34, 35], and the recent 28% multijunction module based on an Entech domed Fresnel lens [45].

11.4 OPTICS OF CONCENTRATORS

The basic concept of light concentration by reflective or refractive means is conceptually simple and straightforward. Simple lenses are generally imaging devices. Some thought, however, will reveal that in a concentrator system, an image of the sun is not needed, or even desired. What is desired is to gather the light as efficiently as possible onto a receiver that is smaller than the concentrator's entrance aperture. As a further requirement, it is often desirable to have the receiver illuminated as uniformly as possible. Another important consideration is that it is generally desirable to have the concentrator accept light from as large an angular region as possible. This minimizes the accuracy at which the concentrator must be pointed toward the sun and thereby relaxes structural requirements and assembly tolerances. These factors, which are generally different from the ones encountered in traditional optical system design, spurred a whole new discipline called *nonimaging* optics. This field was pioneered by Professor Roland Winston and his group at the University of Chicago [46]. Another center of excellence in nonimaging optics developed at the Polytechnical University of Madrid. It is beyond the scope of this chapter to cover the principles of nonimaging optics, for that is a difficult topic that is well covered in textbooks [2, 47].

11.4.1 Basics

One of the remarkable theorems of nonimaging optics is that there exists a relationship between the maximum angle that is accepted by the concentrator and the maximum possible concentration that is attainable, $C_{\max}$. Consider the schematic representation of a general concentrator shown in Figure 11.19. Here the light that hits the entrance aperture, of area A_{conc}, at an angle less than $\theta_{\text{max,in}}$ from the normal is transmitted to the exit aperture where the receiver of area A_{rec} is located (PV cells in our case), emerging at an angle less than $\theta_{\text{max,out}}$ to the normal of the receiver. For one-axis, or two-dimensional, concentrators the following relationship holds:

$$C = A_{\text{conc}}/A_{\text{rec}} \le C_{\max} = \sin(\theta_{\text{max,out}})/\sin(\theta_{\text{max,in}})$$

For two-axis, or three-dimensional, concentrators the corresponding maximum is

$$C = A_{\text{conc}}/A_{\text{rec}} \le C_{\max} = \sin^2(\theta_{\text{max,out}})/\sin^2(\theta_{\text{max,in}})$$

If the receiver is immersed in a dielectric medium of index of refraction n, then these relationships become

$$C = A_{\text{conc}}/A_{\text{rec}} \le C_{\max} = n\sin(\theta_{\text{max,out}})/\sin(\theta_{\text{max,in}})$$