filled with a dielectric of index n, the incoming ray is refracted downward according to Snell's law so that the ray enters the CPC at angle $\theta'_{\text{max,in}}$, giving $C = 1/\sin\theta'_{\text{max,in}}$. Now $n\sin\theta'_{\text{max,in}} = \sin\theta_{\text{max,in}}$, which gives $C = n/\sin\theta_{\text{max,in}}$, and so the CPC is still ideal.

Three-dimensional CPC concentrators can be made by revolving the two-dimensional cross section about the central axis. It turns out that, while the three-dimensional CPC has near-ideal concentration, it is not strictly ideal. Some rays (those that come near the edge with a large skew component) are rejected.

A problem with CPC concentrators is that they are rather long and narrow for high concentration. For dielectric-filled CPCs, this problem can be somewhat ameliorated by doming the top surface to get some initial concentration from the resulting lens. Figure 11.25 shows how doming the top affects CPC shape [2] in concentrators operating by total internal reflection (called DTIR for Direct Total Internal Reflection), which are also ideal in two dimensions.

CPCs are often used as secondary concentrators at the focus of a primary concentrator, particularly for Fresnel lens systems, because then they have a rather large acceptance angle and the resulting design is rather compact.

At the time of writing this, there were no known ideal three-dimensional concentrators that image onto a flat surface (unless with graded index of refraction, not treated here). The author knows of only one ideal three-dimensional concentrator, and it is shown in Figure 11.26. This images all rays striking a sphere onto a smaller sphere imbedded in a dielectric. If the radius of the outer sphere is r_1 and the inner sphere is r_2, where $r_2 = r_1/n$, then the concentration ratio is n^2, referenced to the surface areas of the spheres. Unfortunately, solar cells are generally not spherical.

11.4.5 The V-trough Concentrator

The CPC, while admittedly ideal, has some drawbacks. One is that the intensity pattern at the exit aperture is quite nonuniform under typical illumination conditions. It can be

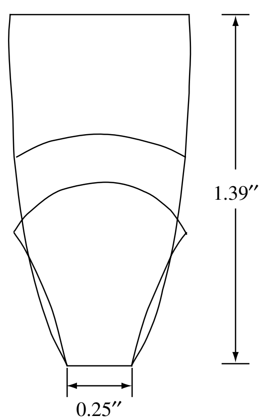

Figure 11.25 A series of dielectric-filled CPCs with flat and domed tops [2], all having the same concentration and a 10° acceptance angle. Adapted from Luque A, *Solar Cells and Optics for Photovoltaic Concentration*, 1989, Adam Hilger, © 2002 with permission by IOP Publishing Limited