Planar concentrators near the étendue limit

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Recently proposed aplanatic imaging designs are integrally combined with nonimaging flux boosters to produce an ultracompact planar glass-filled concentrator that performs near the étendue limit. Such optical devices are attractive for high-efficiency multijunction photovoltaics at high flux, with realistic power generation of 1 W from a 1 mm^2 cell. When deployed in reverse, our designs provide collimation even for high-numerical-aperture light sources. © 2005 Optical Society of America

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Motivated by the development of highly efficient multijunction photovoltaic cells tailored to operate under concentrated sunlight, we report maximally compact optical designs capable of delivering a net flux of thousands of suns, and of generating 1 W of electricity from a 1 mm^2 cell (one sun=1 mW/mm^2). Current commercial technologies border on cell efficiencies of 40% at flux levels of hundreds to thousands of suns.[1–3] In these high-concentration systems, even with cells that are 2 orders of magnitude more expensive on an area basis than conventional photovoltaics, the cost contributed by the cell becomes attractively small. The burden shifts to the optical design to provide a cost-effective and practical system. Recently, a family of tailored imaging designs that are aplanatic and planar was shown to be capable of efficient high-flux concentration.[4] (This type of dual-reflector system was originally identified in Ref. 5.) Figure 1 shows one such design, where the secondary mirror is coplanar with the entrance aperture (coplanar meaning that the uppermost points of the primary and secondary mirrors lie in the same plane). The nominal focus resides between the vertices of the primary and secondary. Analytic equations for the contours of both mirrors were presented in Ref. 4, along with illustrative examples.

Solar radiation uniformly incident over angle $2\theta_0$ [numerical aperture $NA_0=\sin(\theta_0)$] is concentrated to the focal plane, where it is distributed over angle $2\theta_1$. The concentration of these designs can approach the constrained (i.e., restricted exit angle) étendue limit[4] of $(NA_1/NA_0)^2$. In an idealized system devoid of optical errors, NA_0 is that of the solar disc, 0.0047. For actual realistic systems, NA_0 comprises the convolution of the Sun with all system optical errors—typically 0.01 or larger.[1,3,4,6] Accordingly, while fully cognizant of the theoretical limit based solely on the finite size of the solar disc, all quantitative estimates presented here relate to practical, fully convolved NA_0 values.

If we fill the concentrator with dielectric (e.g., glass) of refractive index n, then, with $NA_1 = n\sin(\theta_1)$, concentration can be increased by n^2 for the same NA_0 (provided that the absorber is optically coupled to the concentrator).[6] For materials transparent in the solar spectrum, $n^2 \sim 2.25$.

Suppose that we now place a nonimaging concentrator in the focal plane. Both entrance and exit apertures are flat. Which of the numerous examples of dielectric-filled nonimaging concentrators that have been developed[6] is most suitable? The design falls

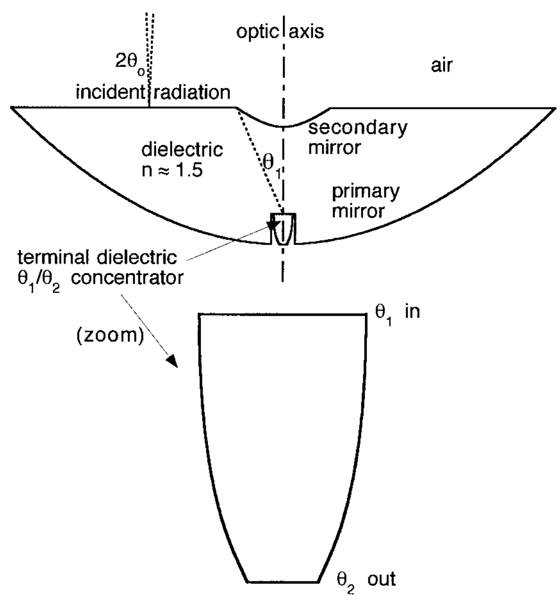

Fig. 1. Aplanatic planar imaging concentrator with two mirrored surfaces tailored to completely eliminate spherical and comatic aberration.[4] Filling the unit with a transparent dielectric (e.g., glass) increases attainable flux by a factor of n^2. A θ_1/θ_2 nonimaging[6] final stage considerably boosts flux concentration at no increase in device depth. In this illustration, $\theta_1=24°$, $\theta_2=72°$, shading is 3%, and the photovoltaic absorber is located at the vertex of the primary.

under the category of θ_1/θ_2 nonimaging concentrators[6] (Fig. 1). θ_1 is chosen to match the exit angle of the dielectric-filled imaging stage, while θ_2 is constrained to satisfy a subsidiary condition such as maintaining total internal reflection (TIR) and (or) accounting for high cell reflectivity at large θ_2. The concentration boost of the terminal stage approaches the fundamental limit[6] $(\mathrm{NA}_2/\mathrm{NA}_1)^2=(n\sin(\theta_2)/(n\sin(\theta_1))^2=(\sin(\theta_2)/\sin(\theta_1))^2$. The combined total concentration can approach the constrained étendue limit[6] $(\mathrm{NA}_2/\mathrm{NA}_0)^2$ [the unconstrained étendue limit refers to the case of $\theta_2=90°$ with concentration $(n/\mathrm{NA}_0)^2$].

The condition for TIR is

$$\theta_1+\theta_2\leqslant\pi-2\theta_c, \tag{1}$$

where θ_c is the critical angle, $\sin^{-1}(1/n)$. Alternatively, the exterior of the θ_1/θ_2 concentrator could be mirrored, thereby not restricting θ_2 but incurring an optical loss of approximately one additional reflection ($\sim 4\%$). Ray tracing representative systems reveals that no more than a few percent of all incident rays either fail to reach the entry plane of the terminal concentrator or are rejected by it.

There is a compactness limit for any concentrator that satisfies Fermat's principle of constant optical path length. Consider the type of concentrator depicted in Fig. 1, but where the secondary mirror is free to reside above or below the primary's entrance. The device aspect ratio AR is the quotient of (1) the distance between the plane of the primary's vertex and the plane of the rim of whichever of the primary or secondary is higher to (2) the diameter of the primary. Now trace a ray to the focus from each of two points on the incident paraxial wavefront: (1) the rim of the primary and (2) along the optic axis. Stipulating a constant optical path length to the focus and requiring that AR be minimized yields the results that (a) the primary and secondary are coplanar (as in Fig. 1) and (b) $\mathrm{AR}_{\min}=1/4$. Because such high-flux devices will ultimately be constrained by dielectric thickness (volume), we confine illustrative examples here to coplanar units.

We find that the design choice for θ_1 has considerable freedom despite the constraint of coplanarity. The most practical design when accounting for fragility, cell attachment, and heat sinking would appear to site the photovoltaic absorber at the vertex of the primary. For a design that is so restricted, there is a trade-off between increasing θ_1 and shading by the secondary. Shading is the fraction of incident rays striking the exterior of the secondary—essentially the ratio of projected areas of the secondary and the primary. For a given design, shading $\propto\sec(\theta_0)$ and hence independent of NA_0 for the small but pragmatic NA_0 values considered here. For example, for shading $\leqslant 3\%$, $\theta_1\leqslant 24°$. Taking $n\approx 1.5$, we have $\theta_c\approx 42°$. Then from Eq. (1), $\theta_1+\theta_2\leqslant 96°$. The illustrative case in Fig. 1 has $\theta_1=24°$, $\theta_2=72°$, and 3% shading.

Ease of manufacturing could militate against the optical coupling of cell to concentrator. In this case, light is extracted into air and then projected onto the cell. Achievable concentration is then reduced by a factor of n^2. The integral ultracompact design of Fig. 1 is still applicable, including siting the cell at the vertex of the primary, but the terminal concentrator must then have $\theta_2<\theta_c$ to avoid ray rejection by TIR. Accommodating relatively greater device depth (i.e., retaining the same cell position) requires redesigning the imaging dielectric concentrator with its focus closer to the secondary.

All dielectrics that are transparent in some wavelength range will have dispersion, a consequence of absorption outside the window of transparency. Even when dispersion is only a few percent over the solar spectrum (as for glass), this significantly limits the solar concentration achievable by any dielectric with a contoured aperture.[1,3,6] The only refracting interface here is the entry aperture, normal to the incident beam, where angular dispersion is

$$\delta\theta_0=-\tan(\theta_0)\delta n/n, \tag{2}$$

which is negligible since $\theta_0\ll 1$. (In designs where light is extracted into air, and hence projected onto the cell at sizable angles, the distance between exit aperture and cell is typically so small as to render additional dispersion losses negligible, too.) For practical purposes, the dielectric slab concentrator is achromatic.

It is helpful to consider examples to illustrate the usefulness of this concept. What are reasonable power densities? Consistent with current technology,[1–3] we assume (a) 30% system conversion efficiency (cell efficiency of 40%[1–3]) and (b) flux on the cell of 3.33 W/mm^2 (3300 suns). The cell then generates ~1 W of electricity per mm^2 of cell area. This would imply a geometric concentration $C_g\approx 4600$ (which accounts for losses from mirror absorption, Fresnel reflections, attenuation in the glass, shading, cell heating, a few percent ray rejection, and a modest dilution of power density to accommodate the full flux map in the focal plane).

With a 1 mm diameter cell, the concentrator of Fig. 1 would be 68 mm in diameter with a maximum depth of 17 mm and a mass per unit area equivalent to a flat slab 8.5 mm thick. Considerably thinner concentrators can be designed (for the same cell size) with a lower concentration and hence lower electricity generation per cell area.[7]

The corresponding angular field of view is given by

$$\mathrm{NA}_0=n\sin(\theta_2)/\sqrt{C_g}, \tag{3}$$

which is ≈ 0.021 for the above example, sufficient to accommodate liberal optical tolerances. A tighter optical tolerance would generate a smaller spot on the cell. Fortunately, experiments have shown that cell performance can be relatively insensitive to such flux inhomogeneities even at flux levels of thousands of suns.[8,9] Ray-trace simulations (both those reported in Ref. 4 and additional runs for the broader range of device parameters considered here) indicate that NA_0 can be as large as 0.02 in air-filled concentrators before (1) the fraction of rays that fail to reach the focal plane exceeds a few percent and (2) the absorber area must be enlarged by more than around 10% to accommodate essentially all rays that do reach the focal plane. The corresponding threshold for dielectric-filled concentrators would be $n\ \mathrm{NA}_0 \approx 0.03$. The cell itself might be 1 or several mm^2. Since the planar concentrator volume grows as the cube of the cell size, this is an engineering optimization. In any case, the heat rejection load of the order of 1 W can be dissipated passively[10,11] such that temperature increases do not exceed ~ 30 K.

So far, our optical systems have been viewed as axisymmetric, with circular apertures and circular cells. Given the relative ease of reaching high flux levels, maximizing collection efficiency is paramount, including concentrator packing within modules. Also, given that economic photovoltaic fabrication and cutting techniques yield square cells, one could consider concentrating from a square (or hexagonal) entrance aperture onto a square target. Producing the same power density at no loss in collection or cell efficiency then ordains increasing geometric concentration (for a square entrance aperture) by a factor of $(4/\pi)^2 \approx 1.62$ (or one could dilute power density at fixed geometric concentration). Our coplanar designs can accommodate high NA_1, but only with the focal plane in close proximity to the apex of the secondary. Inequality (1)—and hence TIR—cannot be satisfied, so the terminal concentrator would need to be externally silvered. In fact, for sufficiently large NA_1, a terminal concentrator may be unwarranted, but cell attachment and heat sinking would be more problematic than in the design of Fig. 1.

Concentrator design and optimization are facilitated by the fact that the equations of all optical surfaces (primary,[4] secondary,[4] and terminal[6] elements) can be expressed in closed form. A fringe benefit is the illumination value of these devices when deployed in reverse as collimators, e.g., for light-emitting diodes. The degree of collimation is approximately NA_0 (NA_0 again accounts for realistic contour and alignment errors) when the light source emits over NA_2. The extent of collimation is essentially the same as presented in Ref. 4 (e.g., NA_0 as low as 0.01–0.02), but with the option of noticeably higher-NA light sources.

The planar all-dielectric designs presented here embody inexpensive high-performance optical systems that should be capable of (a) generating ~ 1 W from advanced commercial 1 mm^2 solar cells at flux levels up to several thousand suns, (b) incurring negligible chromatic aberration even at ultrahigh concentration, (c) passive cooling of the cell, (d) accommodating liberal optical tolerances, (e) mass production with current commercial glass molding techniques, and (f) realizing the fundamental compactness limit of a 1/4 aspect ratio.

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7. Two limiting cases are worth noting: (a) the θ_1/θ_2 concentrator is a cylinder (no concentration boost from the terminal stage), allowing higher NA_1, for the coplanar design with the focal plane closer to the secondary; and (b) the aplanatic unit is without a terminal nonimaging concentrator, while retaining coplanarity as well as the focal plane at the vertex of the primary (concentration is still enhanced by a factor of n^2 relative to the corresponding air-filled device).
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