The International Society for Optical Engineering

SPIE Newsroom

10.1117/2.1200602.0132

How innovative optics are serving the photovoltaic revolution

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The confluence of recent advances in photovoltaic technologies and advanced optical design has resulted in unprecedented capabilities for ultra-efficient, yet affordable solar electricity generation at high concentration.

A quiet revolution in solar electricity generation is underway, thanks to progress in the parallel tracks of advanced photovoltaic (PV) materials and innovative optics. Commercial multi-junction PV technologies have already demonstrated solar cell efficiencies of about 40%. These efficiencies can only be realized at flux levels of hundreds to thousands of suns. At such elevated concentration values, the cost of these new ultra-efficient cells becomes attractively small, even though they are far more expensive on an area basis than conventional silicon and thin-film PVs. The burden to provide a practical and affordable system then shifts to the optical design.

High-flux PV systems (all of which require dual-axis solar tracking) have rapidly evolved to modular one-concentrator/one-cell configurations. Both the concentrator and cell are miniaturized, with cell areas not exceeding 1cm^2 and concentrator unit areas up to 400cm^2. Large systems are assembled from numerous identical modular units. With inexpensive lens-based optics, net (delivered) flux concentration in commercial PV installations has been limited to about 100–400 suns (one sun referring to maximum clear-sky solar normal-beam irradiation, about 1mW/mm^2). Lens geometric and chromatic aberrations have combined with incompact designs (depth-to-diameter ratios of around 1.0) to limit the achievable flux and the practicality of many such systems. These factors preclude development of optical systems that simultaneously satisfy high collection efficiency, high flux, and compactness.

Thermal engineering is also a factor, because material integrity and cell efficiency typically suffer with excessive heating. Large concentrators, which by their very nature ordain sizable PV targets, mandate problematic forced-circulation water cooling, as well as noticeable parasitics. In addition, since voltage requirements dictate connecting many cells in series within a single module, the inhomogeneous flux map typical of large concentrators can result in substantial power dissipation as the module operates at the current of the most weakly irradiated cell.

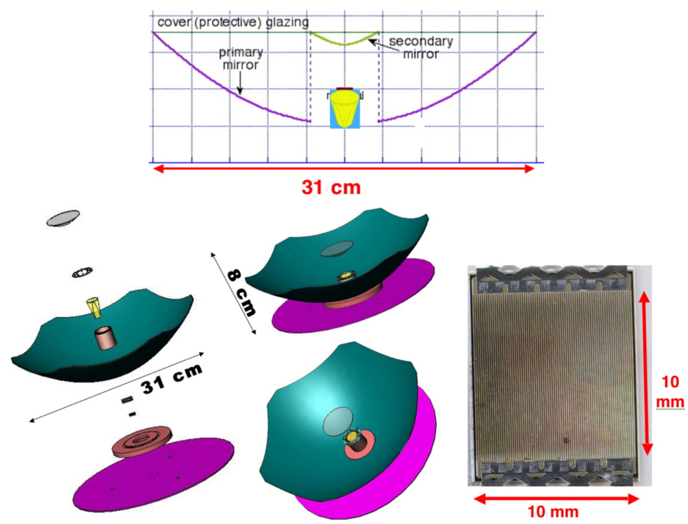

Figure 1. *(a) Cross-section of the optical design (dual-mirror aplanat) of Generation 1 H_2Go/SolFocus PV concentrators. It consists of two tailored mirror contours, a protective entry glazing, and a tapered glass rod, at the narrow end of which the cell is optically bonded. This example achieves the fundamental 1/4 aspect ratio (compactness) limit. (b) Engineering exploded view, including the metal-sheet heat sink. (c) Photograph of the 100mm^2 triple-junction cell around which the concentrator was designed for a net flux of 500 suns (650X)*

We recently developed tailored optics that are aplanatic and planar, with efficient high-flux concentration,[1,2] (see Figures 1–2). Two mirror contours are tailored to achieve the complete elimination of spherical and comatic aberration. The aim, however, is unrelated to image formation and instead focuses on

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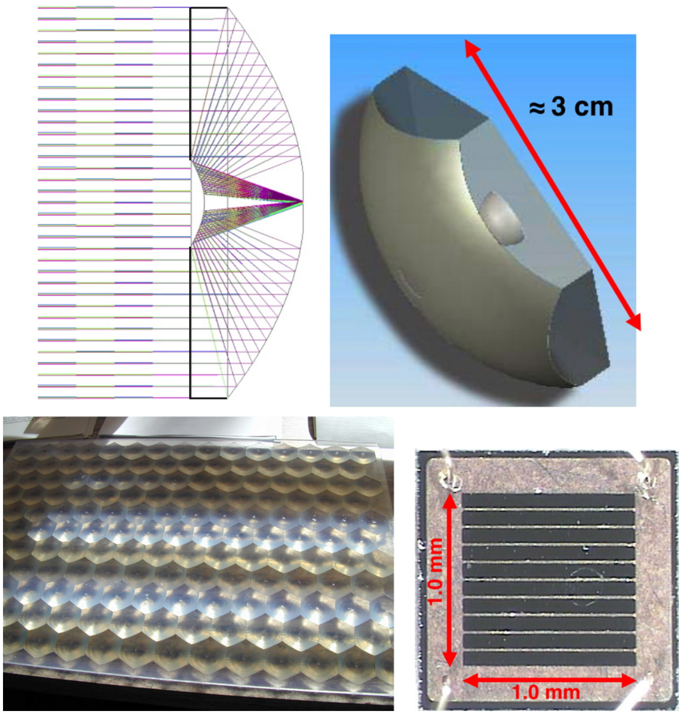

Figure 2. *(a) Cross-section and raytrace of the glass-filled achromatic aplanat of Generation 2 H_2Go/SolFocus PV concentrators (blackened lines indicate the unmirrored glass surfaces). (b) Schematic view of the concentrator unit. (c) Photograph of the top view of a sample module. (d) Photograph of the 1.0mm^2 triple-junction cell for which the concentrator is designed.*

efficient maximum flux transfer. The achromatic dual-mirror aplanat can also achieve the fundamental limit[2] for concentrator compactness: an aspect ratio of 1/4.

If the concentrator is filled with transparent dielectric of refractive index n (e.g., glass with $n \approx 1.5$), then with proper optics, either the concentration can be increased by n^2 (provided the cell is optically coupled to the concentrator), or overall optical tolerance can be relaxed by a factor of n thereby reducing system cost. Because the entrance aperture is the only refracting interface and is normal to the solar beam, chromatic aberration is negligible. The dielectric slab concentrator is essentially achromatic.

Figures 1–3 illustrate the evolution of our optical designs for two generations of these aplanats to experimental and commercial realization by the H_2Go/SolFocus Corporation of Saratoga, CA, with commercially available Spectrolab solar cells. Generation 1 was tailored to a square 100mm^2 triple-junction cell. The air-filled concentrator incorporates a tapered glass rod that contributes toward a liberal optical tolerance and flux homogenization, as well as allowing the cell to be conveniently sited near the vertex of the primary mirror. A protective glazing tops the unit

Figure 3. *Prototype modules of Generations 1 (right, on a two-axis solar tracker) and 2 (left).*

and a thin metal sheet encloses the back of the module, serving as a passive heat sink that limits cell temperature to no more than around 20°C above ambient. Net delivered flux values of 500 suns were measured in the field. The geometric concentration is 650X.

The success of Generation 1 prompted a thin, all-glass second generation predicated on a 1.0mm^2 cell of higher efficiency thanks to lowered internal resistance. Amenable to existing precision mass-production techniques from the semiconductor industry, prototype fabrication and testing are currently underway: first manufactured for a net flux of 500 suns, then scaled to 1000-2000 suns, subject to economic optimization.

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The author's recent research and teaching have focused on innovative applicatons of ultra-bright incoherent light in medical, solar concentration, and illumination applications.

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