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Concentrating photovoltaic panels for the rooftop

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Embedding a network of highly efficient microscale solar cells between a pair of plastic lenslet arrays leads to fixed-tilt concentrating photovoltaic panels that are less than 1cm thick.

For many of us, the image that comes to mind when we think of solar energy is a house with photovoltaic (PV) panels on the roof. Panels such as these are currently based on either silicon or thin-film semiconductor cells and achieve efficiencies typically between 15 and 20%. Advances in manufacturing have decreased the cost of these cells dramatically over the past few years. So much so, in fact, that in many cases they no longer make up the dominant cost component of the power that they generate, with a greater percentage of the overall cost going toward more mundane expenses, such as the inverter, mounting hardware, installation labor, and permitting fees. Because generating more power from a given panel leverages all of these costs over the system lifetime, there is a strong incentive to increase efficiency. This has motivated the combination of multijunction cells with concentrating optics. Together, these devices can enable module efficiencies of more than 35%.[1]

There is currently a great deal of effort aimed at the commercialization of these concentrating PV (CPV) systems. The current paradigm, however, relies on large-scale assemblies of Fresnel lenses or mirrors that must be pointed toward the Sun throughout the day to concentrate its light. Although this approach is well-suited for large, open-land areas, it is incompatible with the limited space and compact panel profile required for rooftop installation.

Working together with our collaborators at the University of Illinois at Urbana-Champaign, we have developed a route toward addressing this challenge. In our design, high-efficiency microscale PV cells are embedded in the concentrator optic itself, enabling us to exploit an alternate, translation-based tracking scheme in which the cells slide laterally to track the Sun.[2] This concept, outlined in Figure 1, consists of a central glass or acrylic sheet sandwiched between an upper refractive and lower reflective lenslet array. A corresponding array of microcell PVs,

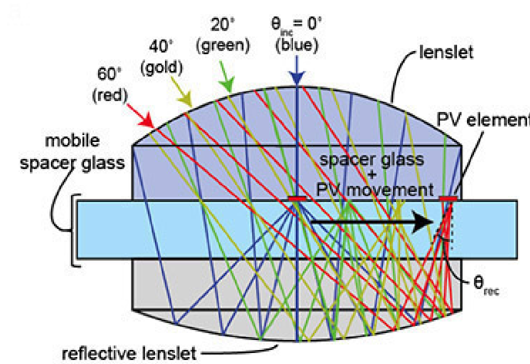

Figure 1. *Ray-tracing diagram of the folded optical path within a unit cell of the concentrator stack. The photovoltaic (PV) cell (red rectangle) faces downward and slides laterally, together with the middle spacer sheet, to track different solar incidence angles. θ_{inc}: Incidence angle of the sunlight with respect to the panel normal (i.e., perpendicular to the panel surface). θ_{rec}: Range of angles for the light rays incident on the solar cell.*

which are grown in releasable multilayer stacks and transfer-printed onto the central sheet,[3] slides freely between the surrounding lenslet arrays, which are lubricated by index-matching oil. This bi-element geometry folds the optical path and maintains a planar, intermediate focal plane over a wide range of incidence angles (0–60°). Solar tracking is thereby possible via small lateral translation (<1cm) of the microcell-patterned middle sheet.

This approach solves the Petzval curvature problem, which has limited the angular acceptance of previous translational tracking concentrators (restricting them to ∼2 hours of operation per day), by effectively cancelling the positive and negative Petzval curvatures of the refractive and reflective lenslets, respectively. The result is a CPV panel with an approximate thickness of 1cm. This panel achieves ∼200× concentration with an optical efficiency of 80–93% for solar incidence within a 120° full field of view: see Figure 2(a). When the panel is fixed at latitude tilt, this angular range enables year-round operation

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for approximately 8 hours per day—see Figure 2(b)—for a hypothetical installation in central Pennsylvania.[4]

To test this concept, we constructed two optical systems: one single-cell concentrator using a pair of commercial off-the-shelf lenses, and a seven-cell concentrator array using 3D-printed lenslets, produced by our collaborators at LUXeXcel Inc.: see Figure 3(a). For proof-of-concept testing, we used $0.7 \times 0.7mm^2$ gallium arsenide PV cells, transfer-printed together with electrical interconnects onto a thin sheet of glass. Figure 3(b) shows the result of outdoor testing for each concentrator, carried out over the course of a sunny day.

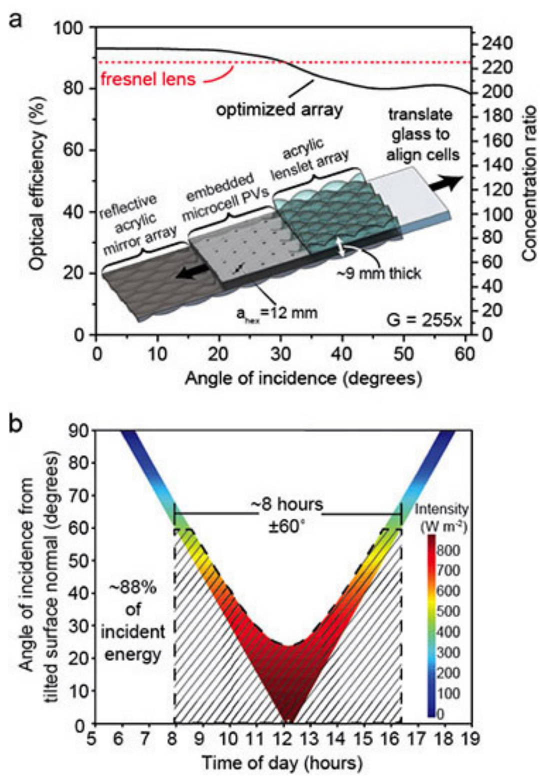

Figure 2. *(a) Optical efficiency and concentration ratio simulated for a planar microtracking concentrator (solid black line) and a traditional orientation-based Fresnel lens concentrator (dashed red lines), both operating at a geometric gain (G) of 255. The inset provides a cutaway view of the simulated panel. (b) Annual range of solar incidence angles on a latitude-tilted surface in central Pennsylvania, computed using the National Renewable Energy Laboratory solar position algorithm. The colored contour overlay indicates the approximate direct solar irradiance, accounting for cosine losses. a_{hex}: Lattice constant of the hexagonally patterned solar cell array. (Figure adapted and reprinted with permission.[2] Copyright Nature Publishing Group 2015.)*

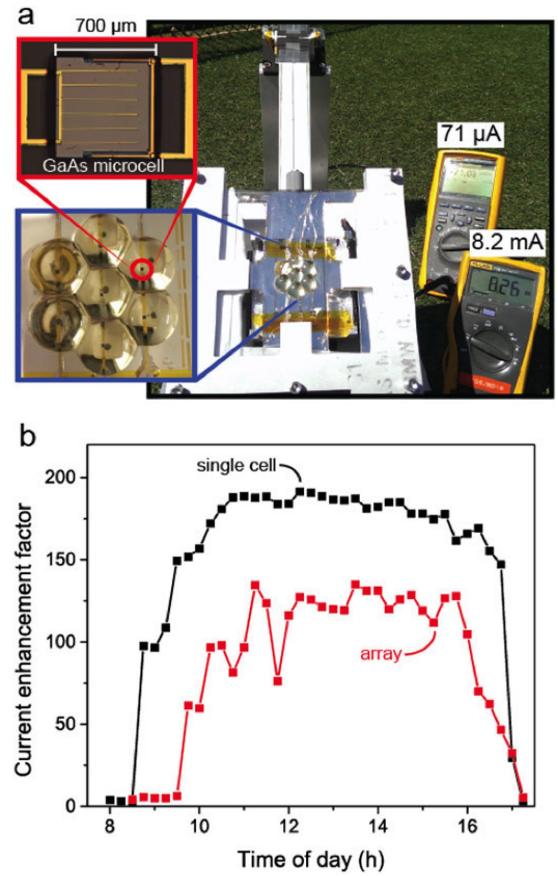

Figure 3. *(a) A photograph showing the concentrator array being tested outdoors. Insets show a typical microcell and the 3D-printed top lenslet array. (b) Short-circuit current enhancement obtained for the off-the-shelf single cell concentrator (black) and the custom-printed array (red). The ratios were calculated relative to the current recorded simultaneously for adjacent, unconcentrated control cells, as indicated by the respective multimeter readings highlighted in (a). GaAs: Gallium arsenide. (Figure adapted and reprinted with permission.[2] Copyright Nature Publishing Group 2015).*

In the case of the single cell concentrator, the short-circuit current is 150–200× higher than that of an adjacent bare control cell over the course of 8 hours. This is in good agreement with the intensity enhancement predicted by ray-tracing simulation. Combined with an open-circuit voltage and fill factor that were similarly maintained, this enhancement corresponds directly to the increase in power output. Despite substantial surface error in the 3D-printed lenslets, the seven-element concentrator still managed to achieve a concentration of more than 100× for the

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majority of the day, demonstrating that the requisite patterning and alignment between the microcell and lenslet arrays can be achieved.

In summary, the compact form factor and quasi-static nature of our microtracking CPV approach may expand CPV applications onto rooftops and other limited-space environments in locations with abundant direct sunlight. Simulating the comparison of an optimized planar microtracking CPV panel with a typical silicon PV module, both tilted at latitude, we conservatively estimate an $\sim 1.3\times$ increase in energy output over the course of a sunny day.[2] Although it is difficult to make cost projections at this stage, inexpensive acrylic-plastic lenslet arrays combined with manufacturing-scale microcell fabrication and transfer printing[5] provide the requisite ingredients for a low-cost system. We are currently focused on developing larger-area, automated-microtracking CPV panels incorporating multi-junction microcells.[6] We expect this to further improve system performance and intend to evaluate the reliability of these devices with an aim to making rooftop CPV a reality.

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References

1. M. Buljan, J. Mendes-Lopes, P. Benítez, and J. C. Miñano, *Recent trends in concentrated photovoltaics concentrators' architecture*, **J. Photon. Energy 4** (1), p. 040995, 2014.
2. J. S. Price, X. Sheng, B. M. Meulblok, J. A. Rogers, and N. C. Giebink, *Wide-angle planar microtracking for quasi-static microcell concentrating photovoltaics*, **Nat. Commun. 6**, p. 6223, 2015.
3. J. Yoon, S. Jo, I. S. Chun, I. Jung, H.-S. Kim, M. Meitl, E. Menard, *et al.*, *GaAs photovoltaics and optoelectronics using releasable multilayer epitaxial assemblies*, **Nature 465**, pp. 329–333, 2010.
4. I. Reda and A. Andreas, *Solar position algorithm for solar radiation applications*, **Sol. Energy 76** (5), pp. 577–589, 2004.
5. http://semprius.com/news/press-releases/ Semprius, Inc. *Semprius to open its first solar module production facility*. Press release. Accessed 2 March 2015.
6. X. Sheng, C. A. Bower, S. Bonafede, J. W. Wilson, B. Fisher, M. Meitl, H. Yuen, *et al.*, *Printing-based assembly of quadruple-junction four-terminal microscale solar cells and their use in high-efficiency modules*, **Nat. Mater. 13**, pp. 593–598, 2014.