Toward ultrahigh-flux photovoltaic concentration

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We report experimental results with a miniature fiber-optic photovoltaic concentrator with (a) deliverable power density up to $10^4$ suns (10 W/mm²), (b) solar cell efficiencies above 30%, (c) completely passive cooling, (d) uniform and individualized cell illumination, and (e) assembly from readily available components. Measurements include the sensitivity of the conversion efficiency of tandem III–V cells to (1) power input, (2) flux distribution, and (3) the modified spectrum from the fiber-optic concentrators. Our results augur favorably for the feasibility of such designs at concentration levels as high as thousands of suns. © 2004 American Institute of Physics.

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A recently proposed concept for photovoltaic concentrators [Fig. 1(a)] offers potential benefits such as flux levels of the order of thousands of suns at high collection and device efficiency, miniaturized collection units which can be assembled into arrays that produce prescribed levels of electrical power, totally passive cooling, and use of only readily available elements. Here we report experimental detailed measurements of such a system.

The appeal of high-concentration photovoltaic systems lies in (a) improved conversion efficiency ($\eta$ is the ratio of power output to impinging solar radiation) from the increase of open-circuit voltage $V_{oc}$ with flux (commercial III–V tandem and multi-junction cells have reached $\eta > 0.3$ at flux levels of several hundred suns,$^2,6$ where one sun = 1 mW/mm²), and (b) high-efficiency cells comprising a small fraction of system cost and size at concentration values of order $10^3$. Because inherent limitations of earlier photovoltaic concentrators constrained pragmatic flux values to no more than ~400 suns, the cells were tailored accordingly. The fiber-optic mini-dish offers the possibility of surmounting essentially all the obstacles that had limited the collection efficiency, attainable flux and/or heat rejection adequacy of earlier photovoltaic concentrators.$^1$ Miniaturization allows high heat rejection densities with passive heat sinks, which obviates the complication and expense of active cooling.

Two such concentrators originally developed for maximum-flux solar surgery applications$^7–10$ were exploited here for photovoltaic concentration [Fig. 1(b) and Table I]. Dedicated photovoltaic concentrators tailored to maximum collection efficiency$^1$ would differ moderately in dimensions and numerical aperture NA. Based on our measurements of absorptive and reflective losses of each element,$^7,11,12$ the optical efficiency of modules redesigned exclusively for photovoltaics is expected to be ~80%.

All measurements were conducted on two commercially available tandem Ga0.35In0.65P/Ga0.83In0.17As solar cells,$^2,3,6$ 13.3 and 16.0 mm² in area, thermally bonded to a passive copper heat sink. Systematically studying the sensitivity of photovoltaic performance to key variables such as flux distribution, spectrum, and power input is problematic with outdoor modules. Reconfigured concentrators with optical fibers 5–7 m in length [Fig. 1(b)] transported concentrated sunlight indoors. Flux uniformity was achieved by optically coupling a quartz kaleidoscope between the fiber(s) and cell$^1$ [Fig. 1(c)]. To vary cell irradiation continuously, a pizza-slice iris that preserves the angular distribution of delivered sunlight was mounted on the dish window [Fig. 1(b)].

The proportionality of short-circuit current $I_{sc}$ with delivered solar irradiation $P_s$ was confirmed for both prototypes. With the kaleidoscope removed, fiber height was varied such that all light struck the cell, and $I_{sc}$ proved insensitive to fiber height and radial position. We measured $P_s$ with a pyrometer of 5% accuracy, calibrated both calorimetrically and against a precision solar pyranometer. Measurements were repeated during clear-sky periods, 2 h about solar noon, over the course of one year in Sede Boqer, Israel where the mid-day clear-sky global and direct-beam solar spectra are nearly invariant and close to the AM1.5 spectrum commonly used in cell testing.$^{13,14}$

Prototypes 1 and 2 yielded $I_{sc}/P_s$ values of 0.150 ± 0.008 and 0.170 ± 0.009 A/W, independent of flux. For outdoor global solar measurements, the corresponding value was 0.145 ± 0.005 (the difference for basing this value on global versus direct solar radiation is only 1%–2%$^6$). The differences in $I_{sc}/P_d$ derive from cell spectral sensitivity$^{2,3}$ to the three distinct spectra (Fig. 2) which were measured with a FieldSpecPro spectroradiometer produced by Analytical Spectral Devices (Boulder, CO). Naturally varying spectral conditions lead to a sacrifice in yearly energy delivery, in sun-belt locations, of only a few percent relative to the AM1.5 spectrum for which high-performance cells are usually optimized.$^{2,3,6,15–17}$ The greater $I_{sc}/P_d$ value evidences an unintended favorable spectral filtering effect of the fiber-optic concentrators.

The cell area, combined with the dimensions of the available concentrators, restricted attainable flux to well un-
der 1000 suns (for uniform cell illumination with the kaleidoscope). In order to generate ~1000 suns on a uniformly irradiated cell, we coupled the fibers of both prototypes to the kaleidoscope [Figs. 1(c) and 3(a)]. This also mimics a properly redesigned concentrator, about 180 mm in diameter (tailored to the photovoltaic application\(^1\)), which transmits 15–20 W of solar radiation.

Our results for cell efficiency as a function of flux appear in Fig. 3(b), determined from measured current–voltage curves [Fig. 3(a)]. For comparison, the cell manufacturer reported a peak efficiency of 0.313 at ~300 suns, with a broad

maximum as a function of concentration (but with most of the 12% metallization shading losses eliminated by a prismatic cover that was absent in the cells we procured).\(^2,3\) This is consistent with the 0.28–0.30 cell efficiencies we measured with prototype 1 (where \(I_{sc}/P_s\) is close to that obtained with unmodified sunlight) at corresponding flux levels.

To explore cell performance at markedly higher flux, we adopted a “hot-spot” method, where the kaleidoscope is removed, and the fiber tip is placed on the cell, so that the radiation projected outside the tip is negligible. The performance of a cell that would be the size of the fiber tip, at the heightened (local) flux, is then taken as that of the isolated hot spot. Namely, the high-flux operation would pertain to a smaller cell in the same concentrator, rather than the same cell in a larger concentrator (the two instances would not yield identical efficiencies due to series resistance effects). This is not a rigorous or general claim for photovoltaics. It should, however, prove to be an adequate approximation for high-performance cells of the type used in our experiments, with ultrafine metallization and advanced cell architecture.\(^2,3,6,18\)

Toward checking this assertion, we measured current–voltage curves for assorted fiber positions on the cell surface, with no detectable differences. Employing this method to probe cell performance at flux values approaching 10\(^4\) suns was only possible with prototype 1 because of its higher NA and smaller fiber diameter. For example, the results from the current–voltage trace of a hot spot 1.0 mm in diameter, irr-

TABLE I. Prototype properties.

<table>
<thead>
<tr>
<th>Prototype No.</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dish coating</td>
<td>Silver</td>
<td>Silver</td>
</tr>
<tr>
<td>Focal length</td>
<td>120 mm</td>
<td>216 mm</td>
</tr>
<tr>
<td>Dish diameter</td>
<td>200 mm</td>
<td>180 mm</td>
</tr>
<tr>
<td>Flat mirror coating</td>
<td>Silver</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Fiber NA</td>
<td>0.66</td>
<td>0.40</td>
</tr>
<tr>
<td>Fiber diameter (quartz core)</td>
<td>1.0 mm</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>Maximum solar power delivery</td>
<td>8 W</td>
<td>10 W</td>
</tr>
</tbody>
</table>

FIG. 1. (Color) Fiber-optic mini-dish photovoltaic concentrator. (a) Schematic. A mirrored parabolic dish is encased and topped with an anti-reflective coated glazing. A small flat mirror re-images the sun to the tip of an optical fiber or rod which channels concentrated sunlight to a square cross-section kaleidoscope (flux homogenizer) placed on the solar cell behind the dish. One extreme ray is traced. The unit is mounted on a dual-axis solar tracker. (b) Two prototypes, reconfigured for controlled indoor testing, mounted on a dual-axis solar tracker. Prototype 1 (right) is retrofitted with an adjustable iris for continuous variation of input power. (c) Indoor close-up of the fibers, kaleidoscope, and cell (mounted on a heat sink).

FIG. 2. (Color) Spectral input to the cell. All curves are normalized to have the same area, so cell efficiency can be calculated per W of delivered radiation.
individual cell, and both promising for high-concentration for assorted input conditions.

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