216 Cell Microconcentrator Module with Moderate Concentration, ±4° Acceptance Angle, and 13.3 mm Focal Length

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Abstract — **We report on a demonstration prototype module created to explore the viability of using microscale solar cells combined with microlens array concentrators to create a thin, flat-plate concentrator module with a relatively large acceptance angle for use with coarse two-axis tracking systems designed for flat-plate, one-sun modules. The demonstration module was comprised of an array of 216 cell/microlens units and was manufactured using standard tools common to the integrated circuit, microelectromechanical system (MEMS), and electronics assembly industries. The module demonstrated an acceptance angle of ±4°, an optical concentration level of 36X, and a focal depth of 13.3 mm. The acceptance angle and focal depth of the system successfully demonstrated adequate performance for integration into a system using a coarse two-axis tracker for flat-plate modules. To fully take advantage of this system approach, significant future work is required to reduce optical losses, increase cell and module efficiency, reduce the focal length to approximately 5 mm, and increase the concentration level to greater than 100X while maintaining an acceptance angle of at least ±2°.**

Index Terms — **photovoltaic cells, solar energy, silicon solar system.**

I. INTRODUCTION

In this paper, we describe a new approach to a photovoltaic microconcentrator system that takes advantage of the small form factor and low-cost balance of system (BOS) benefits of flat-plate PV while also leveraging the unique benefits of concentrated PV. We have designed and manufactured a simple proof-of-concept system to demonstrate the key functionality required for this approach, specifically, a very short focal length and a relatively wide acceptance angle.

Flat-plate solar panels have dominated the solar market since the earliest days of the industry. This dominance has resulted in robust and low-cost balance of system (BOS) components for flat-plate PV panels. However, flat-plate solar panels cannot cost effectively take advantage of advanced cell technologies to achieve conversion efficiencies above approximately 20%.

Currently, concentrated PV is the only solar module approach able to achieve reasonable costs with advanced, high-performance cells. Concentrated PV takes advantage of inexpensive lenses or mirrors to focus light onto a solar cell. By focusing the light with a low-cost optical element on a high-cost cell, the cell costs per module are significantly reduced. The cell cost reduction is approximately equal to the concentration level of the light, although additional costs are incurred in the module due to the need for optics; more complicated cell protection circuitry; and, usually, the need for thermal management structures.

While there have been a wide variety of concentrated PV system designs developed, typical concentration levels range from 500 to over 1000X. Concentrated PV systems have demonstrated impressive performance, with conversion efficiencies in excess of 30%. However, concentrating the light constrains the system in a number of ways. First, for high levels of concentration the system has a very small acceptance angle, typically well below ±1°. Furthermore, concentrating systems tend to be both bulky and heavy. These characteristics of concentrating PV systems result in trackers that are required to be extremely accurate, stiff, and strong which in turn results in high BOS costs relative to flat plate PV.

It is possible to design a system that has the low-profile, light-weight nature of flat plate PV and the cell cost reduction and performance benefits of concentrated PV. By using microscale PV cells, the primary lens aperture and the focal length both become significantly smaller. This allows the thickness of the module to be significantly reduced, down to the range of flat plate PV module thicknesses. At the same time, improved optical performance is possible since refractive microlens arrays can be used instead of large, single-element Fresnel lenses (refractive lenses are more optically efficient than Fresnel lenses). The refractive microlenses have the potential to provide better optical transmission while also allowing more sophisticated optical designs to be utilized in a cost-effective manner. One significant benefit of these microlens optical systems is that the acceptance angle can be extended to well above the range where the coarsely adjustable, flat-plate two-axis trackers perform; thus allowing a flat-plate concentrator system that utilizes low-cost BOS components from flat-plate, one-sun PV systems.

In this paper, we describe the design and manufacture of a demonstration microconcentrator PV module with a focal length of 13.3 mm and an acceptance angle of ±4°. This demonstration module provides a pathway for using high efficiency cells in a flat plate module in a cost-effective manner.

II. SYSTEM CONCEPT AND DESIGN

Scaling the thickness of a concentrator module can be accomplished by several methods including guided mode concentrators, reemission, and other techniques [1], [2]. In our demonstration prototype, we took advantage of existing microsystem technologies to allow the scaling down of the entire PV cell/lens system. This allows a straightforward path to a low-loss, high-performance optical system. The cells for the demonstration system were single junction silicon cells with microscale dimensions in both lateral dimensions and thickness.

The optical system for the demonstration prototype was designed to be relatively simple with an optical concentration of approximately 36X. The optical design used a series of three PMMA microlens arrays with a planar front surface on the primary microlens array. The primary lenses were arranged in a hexagonal packing arrangement with a 100% fill factor. Each primary lens had a diameter of 3.5 mm. The optical design provided a field of view of ±4°. The two rear lenses image the primary lens onto the PV cell to give uniform illumination across the cell throughout the entire field of view. Fig. 1 is a ray-trace simulation of the optical design.

Front lens D = 3.5 mm
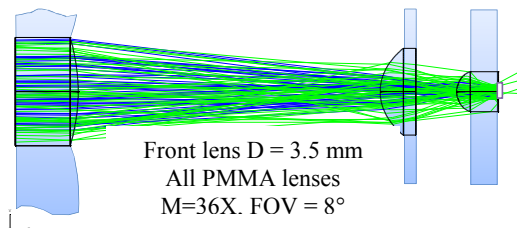All PMMA lenses
M=36X. FOV = 8°

Fig. 1.   Ray trace of microlens optical concentrating system.

The optical design was selected based on simplicity of manufacturing and aligning the lenses (both in-plane as well as in-depth) while also providing the desired ±4° acceptance angle set as the goal of the demonstration system. Further details of microlens optical system designs for microconcentrators are available in [3].

The cells for this system were designed using principles described in [4] and [5]. The cells were designed to be hexagonal with a vertex to vertex dimension of 720 μm and a thickness of 20 μm. The cells are single junction silicon cells with backside point contacts. The cells do not have light trapping features included but the back of the cells have a nearly full aluminum coating, providing a reflected double pass for the light through the cell. A silicon nitride film was used to passivate the front, back, and sides of the cell and was

also used to create an anti-reflection coating on the front of the cell. Fig. 2 is a microscope image of representative cells with copper stud/solder bumps electroplated on the cells.
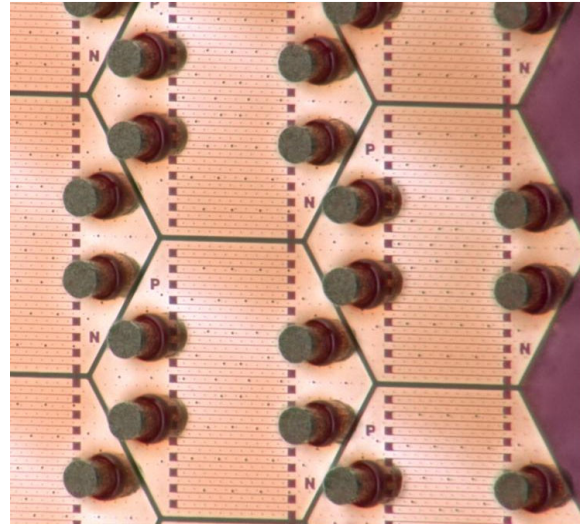

Fig. 2. Image of silicon cells with solder bumps in an array.

The system design for the cell interconnects called for the cells to be surface mounted through solder bumps to a PCB. Two different PCB designs were created to provide as much flexibility in testing as possible. The first board allowed connections to each of the cells so each cell could be independently tested. The second board utilized an interconnect network of 3 series, 3 parallel, 6 series, 4 parallel connections to provide for added reliability and shade tolerance [6]. Fig. 3 illustrates the interconnect architecture used for the interconnected PCB.
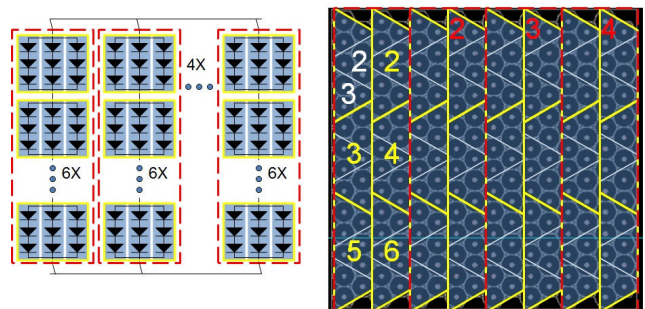
■ 10.80V module (0.6V cells)   Total cells = 216

Fig. 3 Interconnection architecture for the module interconnect network. Each PV cell is connected in groups and subgroups to add current and voltage while achieving increased shading and fault tolerance.

III. CELL AND MODULE MANUFACTURE AND ASSEMBLY

The manufacture and assembly of the prototype was performed using standard manufacturing processes and techniques. The cells for the system were manufactured using fabrication methods developed for the integrated circuit (IC) and microelectromechanical systems (MEMS) industries. This approach allows the use of existing toolsets and wafers to fully form the very thin and very small cells complete with solder bumps [4]. The cells were then assembled on the PCB using standard pick-and-place tools followed by a solder reflow step in a traditional surface mount approach. Hand placement of the cells from the wafer to a custom waffle pack was required for the prototype assembly (production tools exist to automate this step). The additional handling of the cells required for this prototype resulted in damage to some of the cells which was apparent in viewing the cells on the assembled prototype PCB boards.

The microlens arrays for the demonstration prototype were manufactured by diamond milling of the PMMA blanks. Diamond turning was a preferred solution to provide lower surface roughness (and lower optical losses) [7]; however, time constraints forced the use of the more rapid diamond milling approach. In addition, the optical design had called for one of the elements to be a polycarbonate lens, however, the surface finish on the diamond milled polycarbonate was not acceptable so an all PMMA design was used, resulting in a small reduction in the performance parameters of the optical assembly due to the lower index of PMMA (i.e., 36X concentration rather than 50X).

Metal frames were machined to provide for assembly of all

Fig. 5. Image of assembled prototype microconcentrator module under illumination.

of the components to the necessary tolerances. Lens arrays were aligned kinematically using pin in groove features. Fig. 4 is a CAD model indicating the different components comprising the prototype. Fig. 5 is an image of the assembled prototype.

IV. INITIAL TEST RESULTS

The module was tested under a solar simulator to measure electrical characteristics and optical acceptance angle of the lenses. The solar simulator used is a class AAA solar simulator that generates $1000 W/m^2$ with an AM 1.5g spectrum. An Agilent B1500 was used to capture the electrical response.

Fig. 6 shows an efficiency map of each individual cell resulting from the module with the PCB that allowed pogo-pin interconnections between each cell and a fan-out test board. This test was performed without optics at one-sun, AM 1.5g spectrum. The average cell efficiency was 12.1% with a standard deviation of 1.2%. The spread in the cell performance was primarily a result of damage due to the additional manual handling of the cells required for the prototype. A secondary effect that also reduced performance of some cells was variability in the anti-reflection coating of the cells. Also of note is the relatively large number of opens/shorts in the module. Fig. 7 shows optical micrograph images that illustrate
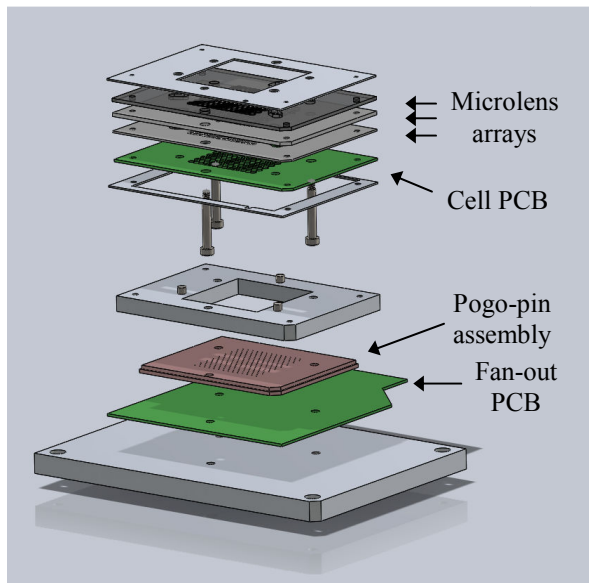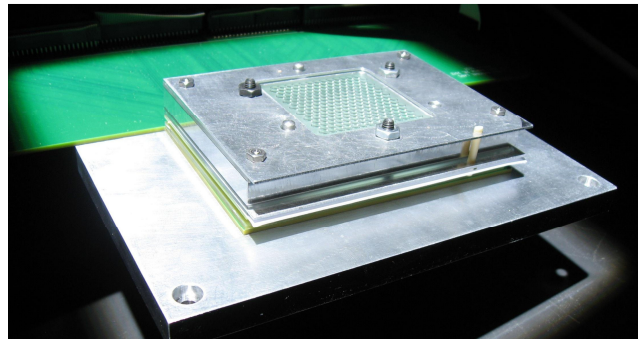

Fig. 4. Exploded view of the microconcentrator demonstration prototype that includes a pogo-pin array for independent connections to each individual cell.

Measured cells	216
working cells	190
shorts	11
open cells	8
open pogos	7
Temperature	22.4°C

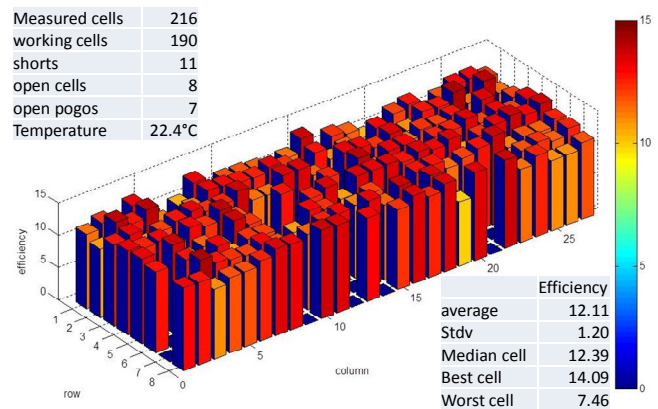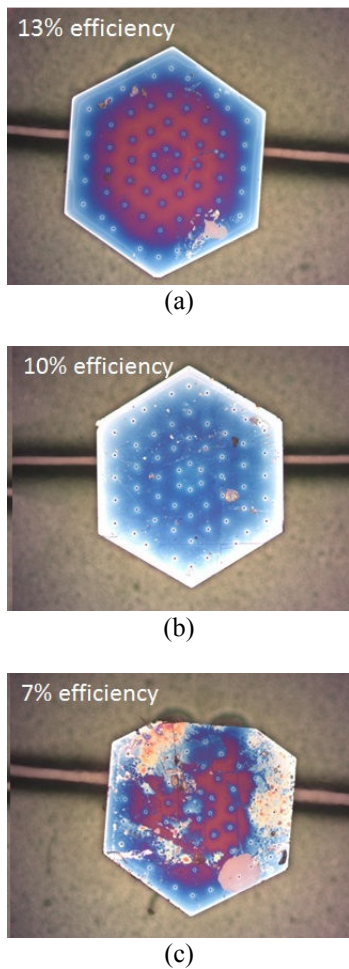|	Efficiency
average	12.11
Stdv	1.20
Median cell	12.39
Best cell	14.09
Worst cell	7.46

Fig. 6 Efficiency map of 216 cells at 22.4°C.

Fig. 7 (a) representative cells of (a) 13% efficiency, (b) 10% efficiency, and (c) 7% efficiency. Indicating the effect of handling damage and non-optimal anti-reflection coatings on the cells.
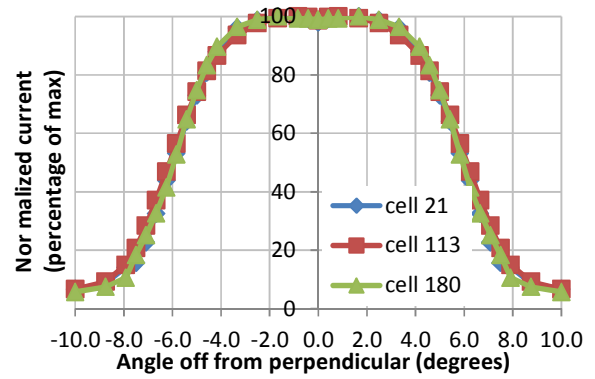

Fig. 8. Normalized current output of three different cells vs. the angle from normal incidence.

the optical intensity reaching the cells after transmission through the concentrating optics corresponded to a 14X concentration level (the one-sun measurements were performed without the microlens arrays). When measured at one sun and the effective 14 sun concentration level, the efficiencies were 9.6% and 11.4% respectively. (Note that the 11.4% efficiency is the efficiency of the combined interconnected cell array, not the overall module efficiency.)

Due to the fully interconnected nature of this module, it was impossible to determine whether there were opens or shorts present in this module. However, visual inspection indicated that the cells were similar in appearance to the cells in the independently contacted module. Based on this, it is reasonable to assume that some of the cells may have been open or shorted. At a minimum, a similar spread in cell efficiency was likely. Given the likelihood of cell performance variation, this module experimentally demonstrates that the effects of variations in the cell performance, and even possibly the effects of opens/shorts, can be mitigated by using an interconnect network within modules rather than a simple series connection arrangement [6].

the impact on efficiency seen due to cell damage and anti-reflection coating variation.

In order to test for the acceptance angle, the module was set on top of a goniometer, perpendicular to the rays of the 1 sun solar simulator. The goniometer changed the angle of the module with respect of the light. The current output of three cells was measured for angles between 0° and 10°. We found the acceptance angle to be ±4° for greater than 90% of peak optical transmission, in line with the optical simulation results. Fig. 8 shows the normalized current output (current at an angle/Current at 0°) for different incident angles.

Fig. 9 shows the current vs. voltage obtained for the module with the fully interconnected cells using the interconnect network described in Section II.

It was observed that the optical losses of the concentrating optics exceeded 50%. This loss is obviously quite high but is in line with the anticipated scattering losses due to surface roughness of the lenses (resulting from diamond milling) combined with losses due to a slight axial misalignment of the cells to the microlens arrays. Taking these losses into account,
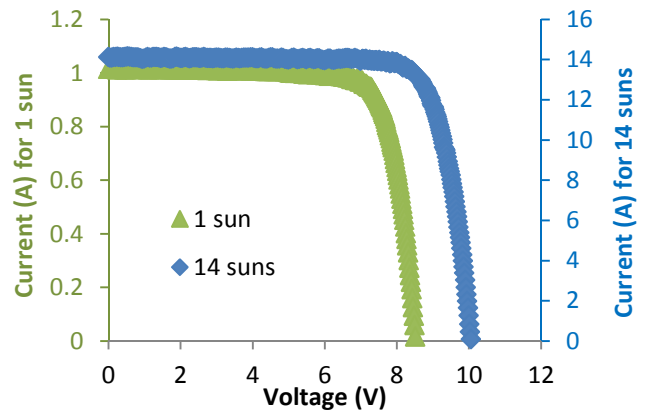

Fig. 9. I-V characteristics of the module measured under one sun and under concentration through the microlens arrays.

V. Discussion and Future Work

The prototype system successfully demonstrated a short focal length, large acceptance angle microconcentrator system capable of providing a low-profile, flat-plate concentrated PV module that could be used with a coarse, two-axis flat-plate tracker. In future designs, significant improvements in both cell and optical efficiency will be necessary. In addition, future system goals include increasing concentration up to as high as 200X and reducing the focal length down to as low as 5 mm while maintaining an acceptance angle greater than $\pm 2°$, which appears to be a safe limit for using coarse two-axis tracking systems based on internal market surveys.

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