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Micro-Concentrators for a Microsystems-Enabled Photovoltaic System

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Abstract: A 100X magnification, ±3° field of view micro-concentrating optical array has been developed with better than 90% transmission for a microsystems-enabled photovoltaic (MEPV) prototype module using 250 µm diameter multi-junction "stacked" PV cells.

OCIS codes: (040.5350) Photovoltaic; (220.3620) Lens System Design; (220.4610) Optical Fabrication; (350.3950) Micro-Optics

1. MEPV Introduction

Sandia National Laboratories has been investigating a novel, low cost photovoltaic system architecture that combines the high conversion efficiencies of concentrated photovoltaics (CPV) with the form factor and low system costs of flat panel PV. MEPV marries fully integrated stacked multi-junction PV cells having lateral dimensions smaller than 1 mm with micro-optic concentrators to reduce the use of expensive semiconductor materials and to increase solar conversion efficiency [1]. While a first generation module demonstrated the viability of the MEPV construct using Si cells with a 720 µm diameter [2], recent research has developed a second generation prototype to improve device performance and to examine the viability of mass producing MEPV at competitive costs.

2. Micro-Concentrator Design

The micro-concentrating optics for the second generation prototype were designed to achieve 100X magnification and greater than 90% optical transmission across a pass band of roughly 400 to 1600 nm. A ±3° field of view was selected to insure compatibility with commercial course sun tracking systems. Environmental considerations for the optics and module design included a 20 year service life; operating ambient temperatures from -40° C to 80° C; and exposure to hail, rain, humidity, dust and UV radiation. Figure 1 shows the resulting optical design and ray tracing for the two lens, aspheric design with a 100X magnification and ±3° field of view. Incident rays onto the PV cell were constrained to less than 30° as the front optic entrance aperture is 2.75 mm with an exit aperture onto the PV cell of 0.25 mm. The thickness of the lens "sandwich" is only 5.30 mm, a 65% reduction from the first generation prototype [3], and an even greater reduction from traditional CPV systems. Polycarbonate was selected as the high index (n = 1.59) concentrator lens material due to its low cost; availability for mass production molding; and resistance to damage under UV exposure. The low index gap between the two lenses is filled with Sylgard® 184 PDMS (n = 1.40) to prevent moisture diffusion into the concentrator array, to insure high optical transmission, and to minimize Fresnel reflections without UV degradation. The optics are arranged in a 240 element hexagonal closed packed array across a roughly 40 mm square collection area using a 15 x 16 format with 2.381 mm and 2.058 mm pitch spacing respectively, Figure 1.

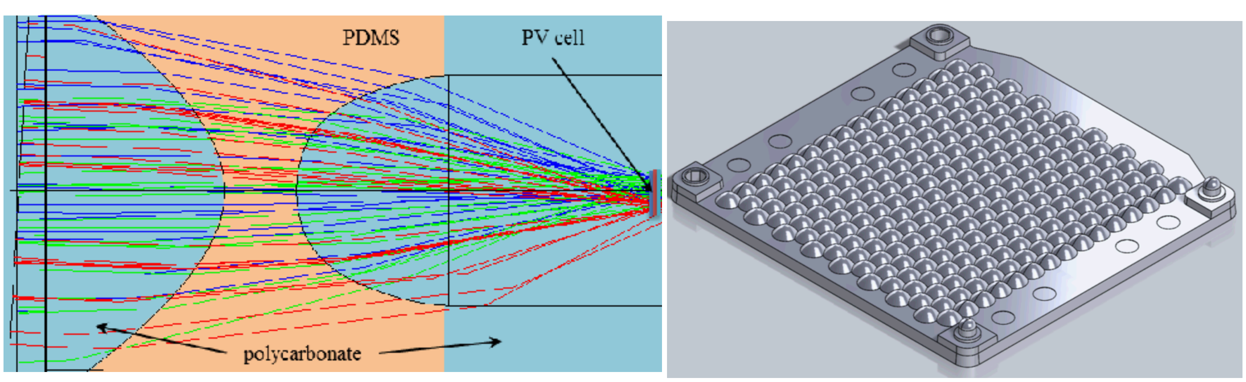

FIGURE 1. Second generation MEPV micro-concentrator optical design (left) and front lens array solid model (right).

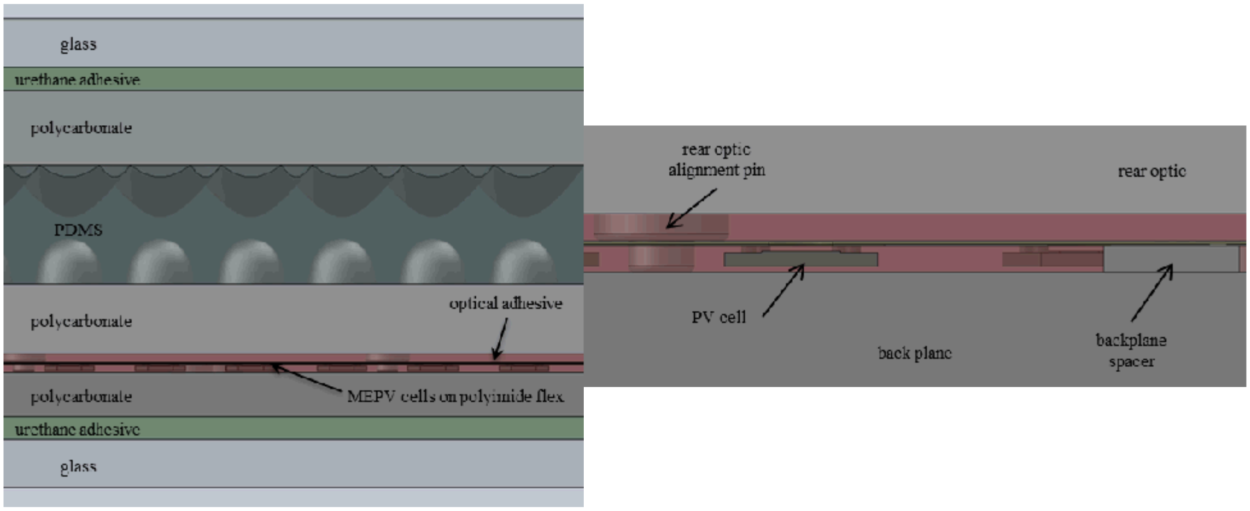

FIGURE 2. MEPV module cross-section (left) and cell to optic array alignment features (right).

Figure 2 provides a cross-section of the complete prototype module design. The lens and MEPV cell arrays are assembled between two glass plates using urethane adhesives for an overall module thickness of only 9.96 mm. Isolation from environmental contamination is achieved with a butyl sealant around the outside perimeter. Assembly and alignment of the front and rear optic arrays is achieved passively using pin-in-slot features that are molded into each part, Figure 1. The symmetric geometry of the mating features provides a semi-kinematic, athermal mounting configuration with expected alignment tolerances better than 25 µm. Alignment and assembly of the cell array is also performed passively using monolithic "wedding cake" features in the rear optic array that mate to holes in the polyimide flex, Figure 2. AR coatings are found on the front face of the top glass and on the front face of the PV cell stack; reducing the air to glass reflective loss from 4% to 1% and the urethane to GaAs cell reflective loss from 20% to 2%. No coatings are used at the polycarbonate-PDMS interfaces since their losses are on the order of only 0.4% per interface. Due to large differences in thermal expansion coefficients for glass, polycarbonate and PDMS; thermo-mechanical modeling was performed to examine stresses in the PDMS. Analyses of an initial optical design revealed internal stresses approaching the cohesive failure limit of PDMS in the gap between the two lenses. A 5x increase in the gap thickness for the final optical design proved adequate to reduce stress levels below the limits for both cohesive and adhesive failure.

3. Micro-Concentrator Fabrication

Fabrication of the second generation prototype optics has investigated techniques amenable to low cost, volume manufacturing. The polycarbonate lens arrays are being injection molded using 6061-T6 aluminum mold inserts that are machined using micro-milling for rough figuring and ultra-precision diamond milling for final finishing. Process development has focused on reducing optic surface finish to improve system efficiency; increasing process throughput to reduce manufacturing costs, and reducing diamond tool wear to minimize performance variations across the lens arrays. Constraints implicit from both machining and molding processes were incorporated into the opto-mechanical design process. While final insert fabrication remains in process, a 4 x 4 hexagonal test array was produced in 6061-T6 to demonstrate the integrated machining process. Figure 3 shows the machined test part as the form accuracy of the optical elements is roughly 1.5 µm with a surface finish of 30 nm S_a near the optic apex. Similarly, fabrication of the mold insert for the "wedding cake" features on the rear optic has demonstrated feature dimensional and position accuracies of 10 µm or better.

Initial optic molding has also been examined by molding a simplified test part, Figure 4. Conventional ball milling was utilized to fabricate the mold insert "optic" array since process development, material shrinkage and array distortion were the metrics of interest; not optic surface finish or form. In-plane material shrinkage across the part was less than 0.2% as the optics were located in X and Y with an accuracy of ±5 µm. Out-of-plane distortion of the entire part, however, approached 100 µm since achieving proper part filling at the corners with minimal distortion has proven difficult. As a result, design changes have been incorporated into the optic design to improve filling and reduce distortion.

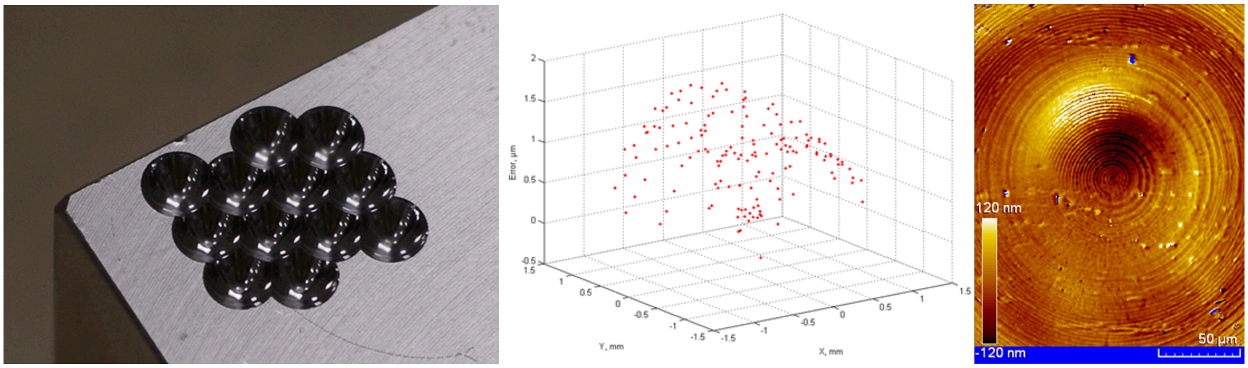

FIGURE 3. 4x4 array test cut (left) with 1.5 µm form accuracy (center) and 30 nm S_a surface finish (right).

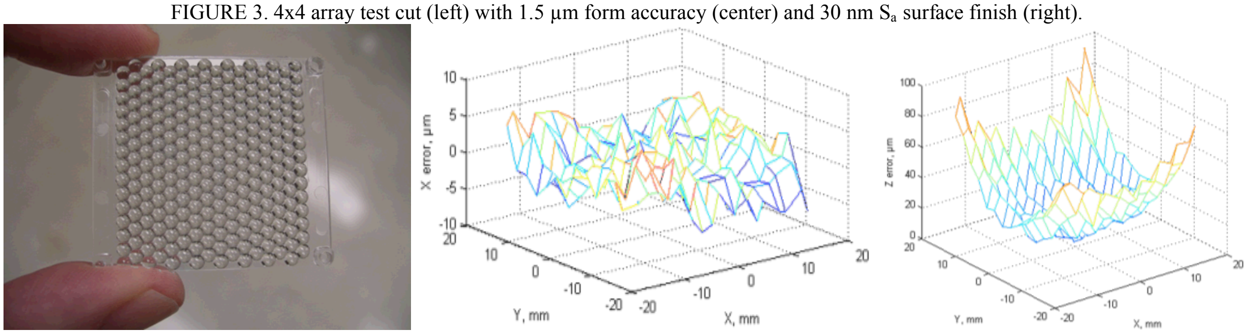

FIGURE 4. Test sample molded part (left) with 5 µm in-plane X positioning accuracy (center) and 100 µm distortion out-of-plane (right).

4. Future Work

Continued work on prototype MEPV systems is focused on increasing collection efficiencies, reducing module size, improving module integration and packaging, and demonstrating cost effective manufacturing strategies. The second generation MEPV system is currently in the fabrication and assembly stage. Final assembly is expected by September as performance data will be available for conference presentation.

5. Acknowledgements

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