Ultralight Energy Converter Tile for the Space Solar Power Initiative

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Abstract **— We have fabricated a functional prototype of an ultralight power converter tile; a modular building block for a space-based solar power system. The tile is ~10 x 15 cm in area, and weighs ~1.5 kg/m^2. It comprises a photovoltaic (PV) solar energy collector, a radio-frequency (RF) power converter, and an array of transmission antennas. The PV collector subassembly utilizes ~15x, 1D parabolic trough reflective concentrators with triple-junction (3J) solar cells. It has areal mass of ~0.8 kg/m^2, 74% optical efficiency, and a peak specific power of ~230 W/kg. We demonstrated wireless power transmission over a distance of ~50 cm in our lab. Analysis of the sources of mass and inefficiency suggest a path towards achieving dramatically higher performance with future designs.**

I. INTRODUCTION

Space-based solar power (SSP) has long been recognized as a technologically feasible but economically daunting means of providing baseload renewable energy at the global scale.[1-3] Solar energy is abundant in space; in particular, satellites placed in geostationary orbit receive sunlight nearly continuously, and are in constant view of a large geographic area on earth. Wireless power beaming at microwave frequencies could enable delivery of this vast energy resource to earth.

Despite the favorable environmental and strategic value of SSP, no system has yet been realized due primarily to the prohibitively high costs associated with building and launching SSP satellites. The Space Solar Power Initiative (SSPI) at Caltech is seeking to develop technologies that will enable cost-effective space-based solar power, by dramatically increasing the specific power (that is, power per mass) of deployable space PV and wireless power beaming technologies. [4-6]

We propose an ultralight, modular power station comprising free-flying ~60x60 m spacecraft, as shown in Figure 1.[7] The building block of the spacecraft is the 'tile,' a self-contained ~10x10 cm element that performs solar energy collection via ultralight PV cells, conversion to RF power via custom integrated circuits, and wireless power transmission via phased antennas; and which also folds flat for deployment.

Motivated in part by the tremendous technological achievements that have occurred since the early government-funded SSP concept studies of the 1960s–80s, [8, 9] SSP has recently experienced a resurgence in interest. Numerous SSP concept studies have promoted modular systems with solid-state RF power converters and phased-array antennas. [10, 11] In particular, high-efficiency (70%) GaN solid-state amplifiers have been developed for wireless power transmission, [12, 13] offering increasingly favorable performance vs. high-power vacuum tube RF converters. A functional "sandwich module" has been demonstrated at NRL which included 55% efficient (PAE) GaAs power converter. [14] PV concentrators have also been demonstrated as means of increasing the specific power of space solar panels, including stretched lens array (SLA) [15] and "venetian blinds"-style reflective concentrators such as SLATS and FAST programs.[16]

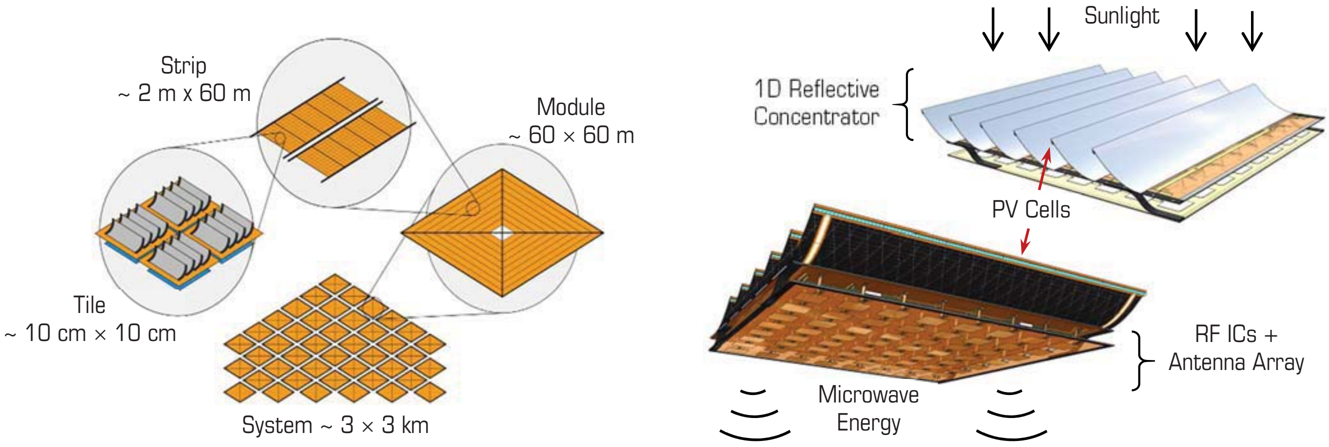

Fig. 1. Conceptual illustrations of the proposed space solar power station (left) and the energy conversion tile (right).

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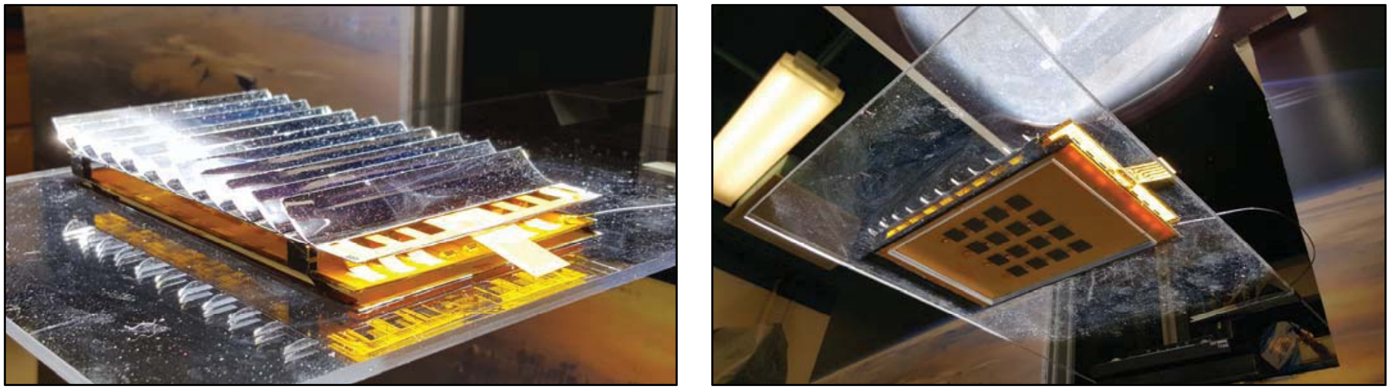

Fig. 2. Photographs of the tile prototype in operation beneath a solar simulator, view from above (left) and below (right)

II. PROTOTYPE FABRICATION

We present experimental results from the fabrication of a prototype of the fundamental tile component of our proposed SSP system. The tile prototype consists of separate PV and RF subassemblies that were integrated as a final step of assembly. This approach enabled independent testing and tuning of each subsystem to ensure that each was capable of achieving the required performance. This manuscript primarily describes the fabrication of the PV concentrator subassembly.

The RF conversion electronics required at least 2 W of DC electrical input power to ensure a successful demonstration of wireless power transfer. To provide wide margins for early-stage prototyping issues including low optical efficiency, voltage mismatch, series resistance, and the possibility of inadvertent damage, we decided to make the PV collection area substantially larger than that nominally required. Although this ensures that ample power is available for a single-tile demonstration, it is important to note that combining power from multiple tiles in the far field will require contiguous filling of the RF aperture, and thus that the PV and RF apertures are equal in area. This will be achievable by improving the optical efficiency and operating voltage of the PV subsystem.

The selected PV tile design comprised (10) active concentrator elements of 10 cm length and 15 mm nominal spacing, for a total active aperture area of ~150 cm^2. Because of the staggered nature of the venetian-blinds style concentrator, an additional concentrator is required to direct sunlight at the first bank of cells; thus the physical size of the concentrator was ~16.5 x 10 cm.

Solar cells were prepared from commercial 3J Ge wafers (Spectrolab XTJ) into a custom form-factor for integration with the concentration scheme. We used a 3-step photolithographic process to pattern the front contacts and antireflective coatings (both deposited by electron-beam evaporation) and cell mesas (formed by chemical etching). The processed wafers were then diced to produce ~1 mm-wide cells of 10, 20, and 50 mm length (American Precision Dicing). Cells were mounted onto 10 cm-long, flex circuit 'strips' using a combination of conductive and insulating epoxies to connect the top and bottom contacts to nearby electrical traces. The strips were made from 1-mil adhesiveless polyimide with 1/2 oz Cu traces (Epec). With the exception of one cell strip, all cells were connected in parallel. Cerium-doped, antireflective-coated cover glass (Qioptiq, 75 μm thick) was diced to size, then attached to the cells using PDMS (Dow Corning 93-500).

Carbon-fiber concentrator mirrors were prepared as described previously. [17] Our concentrator mirrors were made from 8-ply T800 17 gsm fibers in a $[0/90/+45/-45]_s$ configuration, cast against a parabolic mandrel, and laser-cut to size. A smoothing polymer was applied, then the mirror surface was metalized with Ag. The shape of each reflector was scanned with a Faro Arm tool and analyzed with ray-tracing software to evaluate its suitability for use in the concentrator. An adjustable assembly jig was used to determine where to place the cell strips on the back of each reflector. [6] After the cell strips were glued in place, a final alignment of the reflectors was performed prior to bonding the mirrors to the circuit plane.

The PV circuit plane was procured as a 2-layer polyimide flex circuit. It featured bonding and alignment points for the reflectors and cell strips, as well as diagnostic connectors and linear voltage regulators to facilitate the demonstration. The mass of the circuit plane, including the carbon fiber frame, was 4.2 g. The mass of the (11) completed reflectors totaled 9.1 g. Final electrical connections between the cell strips, the PV circuit plane, and the RF circuit plane, were made by soldering.

III. RESULTS

The completed tile prototype is show in Figure 2. The PV subsystem produced 3.1 W at maximum power point under an AM0 solar simulator, giving an active-area aperture efficiency of 16%. Peak efficiency was observed at an incidence angle of -1° to normal. We have performed extensive I–V characterization at elevated temperatures, and light beam-induced current (LBIC) imaging of the entire tile, shown in Fig. 3. The peak optical efficiency was 74%, as determined by the ratio of the concentrator's aperture-area J_{SC} to the cell's J_{SC} measured prior to assembly. Optical efficiency was also determined by LBIC

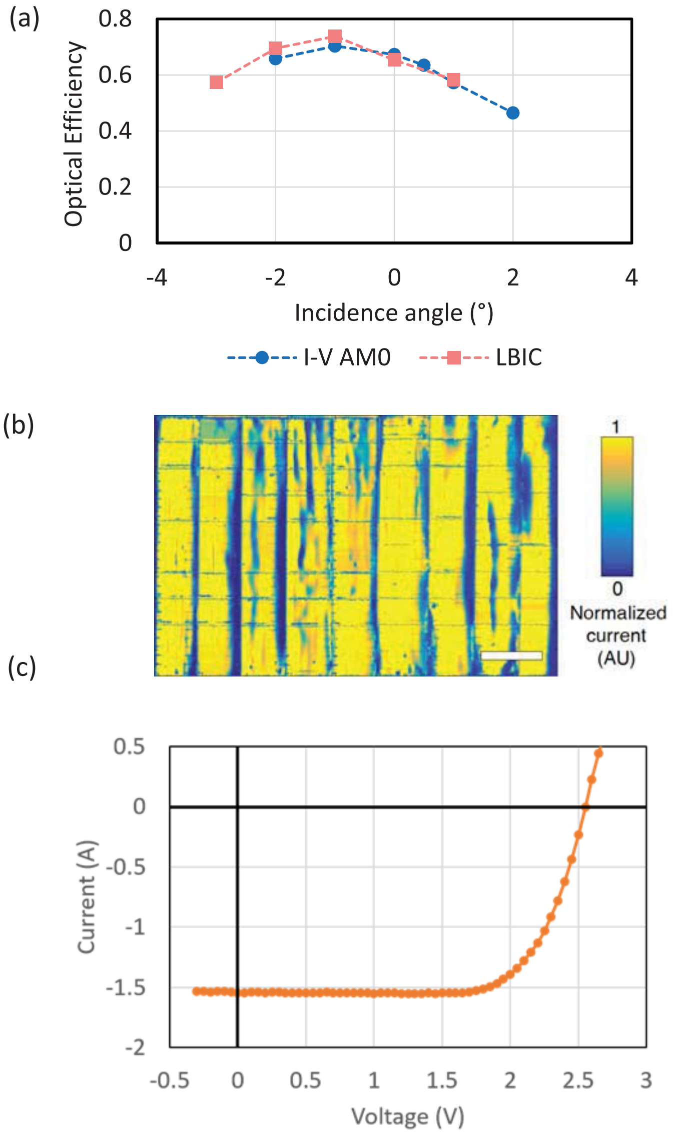

Fig 3. (a) Concentrator optical efficiency vs. incidence angle as determined by AM0 JSC (I-V) and LBIC imagery. (b) LBIC image at peak efficiency illumination angle (-1°). The scale bar is 2cm. (c) AM0 I–V sweep data at peak efficiency illumination angle. Panels (b) and (c) correspond only to the (9) cell strips that are wired in parallel. Panel (a), and all reported efficiency numbers, consider contributions from all 10 active concentrator elements.

imaging using a custom-built, parallax-free LBIC scanner. The primary optical loss is due to concentrator shape errors, which we seek to address in future designs. We also observed the temperature of the cells during continuous operation, as shown in Fig. 4. Future work will study operating temperatures under vacuum.

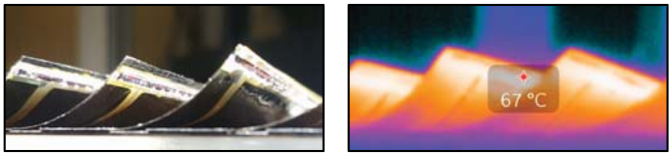

Fig 4. Optical and thermal infrared photographs of the PV concentrator cells operating under simulated AM0 illumination. The cells reach a peak temperature of ~70 °C under ambient lab conditions.

After bonding and soldering the PV and RF subassemblies, we performed a demonstration of wireless power beaming. The tile prototype was placed under an AM0 solar simulator. A reference signal was provided by an off-board crystal oscillator, however, no DC power or control signals were provided to the tile. Upon illumination, the tile emitted broadside RF radiation from 12 of its 16 patch antennas, illuminating a LED on a rectenna board up to ~50 cm away. At our talk, we plan to present further details of the tile design and fabrication, and show videos of the lab demonstration.

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