Stretched Lens Array (SLA) for Collection and Conversion of Infrared Laser Light: 45% Efficiency Demonstrated for Near-Term 800 W/kg Space Power System

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ABSTRACT

For the past 2½ years, our team has been developing a unique photovoltaic concentrator array for collection and conversion of infrared laser light. This laser-receiving array has evolved from the solar-receiving Stretched Lens Array (SLA). The laser-receiving version of SLA is being developed for space power applications when or where sunlight is not available (e.g., the eternally dark lunar polar craters). The laser-receiving SLA can efficiently collect and convert beamed laser power from orbiting spacecraft or other sources (e.g., solar-powered lasers on the permanently illuminated ridges of lunar polar craters). A dual-use version of SLA can produce power from sunlight during sunlit portions of the mission, and from beamed laser light during dark portions of the mission. SLA minimizes the cost and mass of photovoltaic cells by using gossamer-like Fresnel lenses to capture and focus incoming light (solar or laser) by a factor of 8.5X, thereby providing a cost-effective, ultra-light space power system.

INTRODUCTION AND BACKGROUND

ENTECH, NASA, and other team members have been developing refractive photovoltaic concentrator systems for producing space power from sunlight since the middle 1980's [1]. The first such technology developed and successfully flown in space was the point-focus mini-dome lens array, shown in Fig. 1. This array used mechanically stacked GaAs/GaSb cells from Boeing in the focal point of ENTECH's silicone mini-dome Fresnel lens concentrators. The lenses were coated with a multi-layer oxide coating to protect the silicone lens material from solar ultraviolet (UV) radiation and monatomic oxygen (AO). The mini-dome lens array in Fig. 1 flew in 1994-95 on the NASA/USAF year-long PASP-Plus flight test in a very high radiation elliptical orbit (363 km by 2,550 km at 70-degree inclination). Of the 12 advanced photovoltaic array types included on PASP Plus, the mini-dome lens provided the highest performance and the least degradation [2].

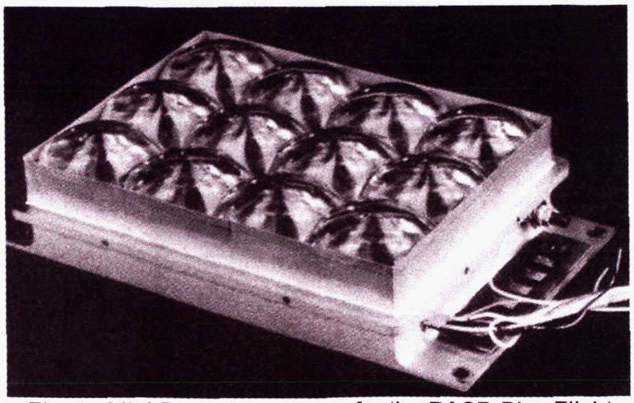


Fig. 1. Mini-Dome Lens Array for the PASP-Plus Flight Test (1994-1995).

After the mini-dome lens array success, ENTECH, NASA, and other team members next developed the line-focus arched lens array, which evolved into the SCARLET array that performed flawlessly for the full thirty-eight-month mission on NASA's Deep Space 1 probe, shown in Fig. 2. SCARLET (acronym for Solar Concentrator Array using Refractive Linear Element Technology) employed silicone Fresnel lens material made by 3M using a high-speed continuous process. ENTECH laminated this silicone lens material to 75-micron-thick ceria-doped glass arches, which provided support and UV protection for the lenses. Monolithic triple-junction (GaInP/GaAs/Ge) cells were placed in the focal lines of the SCARLET lenses. The SCARLET array powered both the spacecraft and the ion engine on Deep Space 1 and performed as predicted on this highly successful mission [3].

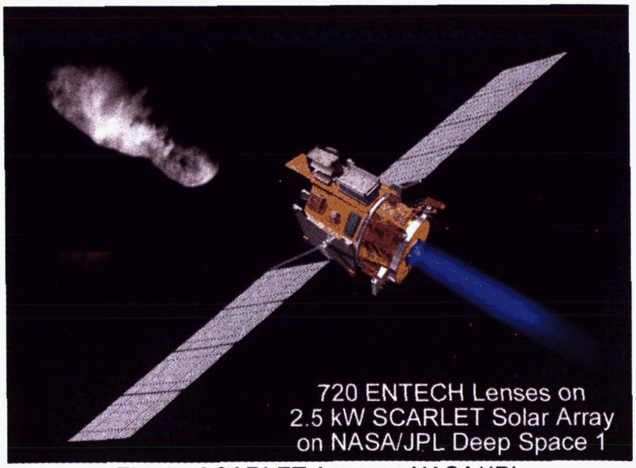


Fig. 2. SCARLET Array on NASA/JPL Deep Space 1 Probe (1998-2001).

Shortly after the SCARLET array delivery, ENTECH discovered a simpler means of deploying and supporting the line-focus silicone lenses, thereby eliminating the fragility, mass, and cost of the glass arches used on SCARLET. The new approach uses simple lengthwise tensioning of the lens material between end arches for lens deployment and support on orbit, as shown in Fig. 3. Called the Stretched Lens Array (SLA), the new ultra-light concentrator array also enables a very compact stowage volume for launch [4]. Over the past 2½ years, our team has been developing a new version of SLA which can provide power in the absence of sunlight, by collecting and converting infrared laser light beamed from another location. Results to date have been outstanding, as further discussed below.

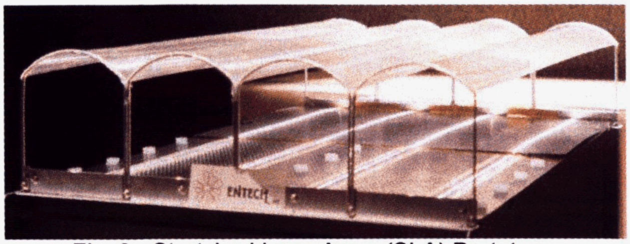


Fig. 3. Stretched Lens Array (SLA) Prototype.

LASER VERSION OF STRETCHED LENS ARRAY (SLA)

The laser version of SLA uses single-junction photovoltaic cells in place of the multi-junction cells used in the solar version of SLA. For infrared laser light in the wavelength range of 0.80-0.85 microns, GaAs is an ideal photovoltaic cell. To demonstrate the achievable conversion efficiency of the laser version of SLA, a number of prototype SLA modules were developed using GaAs cells made by EMCORE. Fig. 4 shows one of these SLA modules during outdoor testing at ENTECH under sunlight irradiance. Of course, under sunlight irradiance, the SLA performance is significantly lower with single-junction GaAs cells than with triple-junction GaInP/GaAs/Ge cells. Fig. 5 shows a typical IV curve and corresponding net SLA module efficiency curve for the SLA module of Fig. 4 under terrestrial sunlight irradiance. The net SLA module efficiency of 22% with a GaAs cell is much lower than the typical 30% net SLA module efficiency measured under terrestrial sunlight with a triple-junction cell. Testing under sunlight was done to ensure that the prototype SLA modules were fully functional prior to delivering them to UAH for testing under laser irradiance. Fig. 6 shows a typical UAH measurement of the SLA module of Fig. 4 under 0.805 micron laser irradiance. Note that the IV curve of Fig. 6 is very similar to the IV curve of Fig. 5, but that the overall net SLA module conversion efficiency has more than doubled for the monochromatic laser light compared to sunlight. The 45.5% net SLA module conversion efficiency corresponds to the product of about 50% cell efficiency times about 92% lens optical efficiency. The much higher SLA module efficiency under laser irradiance is due to the module's much better current response for laser light (about 0.52 A/W) than for solar irradiance (about 0.25 A/W), since the laser wavelength is very near the peak spectral response of the GaAs cell.

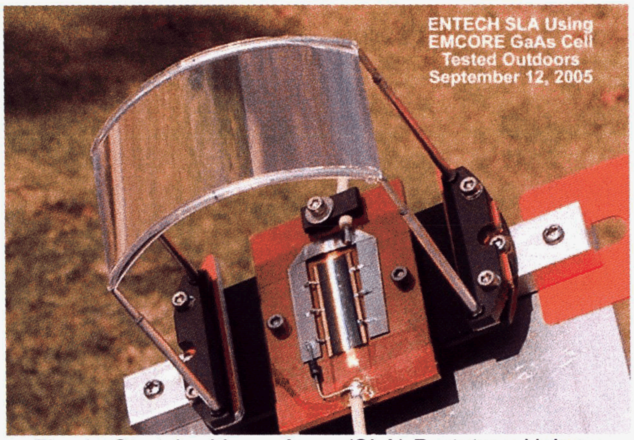


Fig. 4. Stretched Lens Array (SLA) Prototype Using a Single-Junction GaAs Cell Under Outdoor Sunlight Testing.

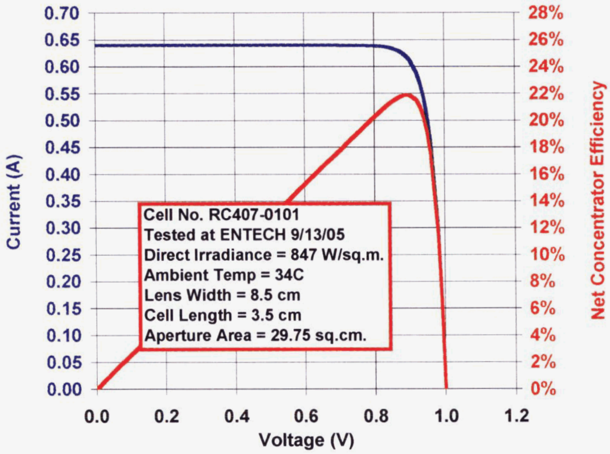
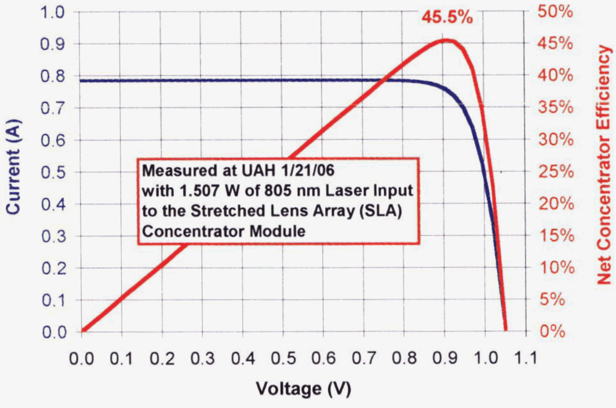


Fig. 5. Measured IV Curve for SLA Prototype Under Outdoor Sunlight Irradiance.



The UAH laser measurements were conducted with collimated laser light using a rectangular aperture slightly smaller than the SLA module's aperture. The laser input power was measured by removing the SLA module and then measuring the total power of the laser light transmitted through the rectangular aperture.

Parametric performance measurements were made for the SLA concentrator modules by varying the 805 nm laser power input to the stretched lens, and the lens-to-cell spacing, with typical results for one module shown in Fig. 7. Note that once the laser power exceeds a value of about 0.75 W, the net SLA module conversion efficiency is relatively constant for all laser power levels and all lens-to-cell spacings between 8.8 cm and 9.1 cm.

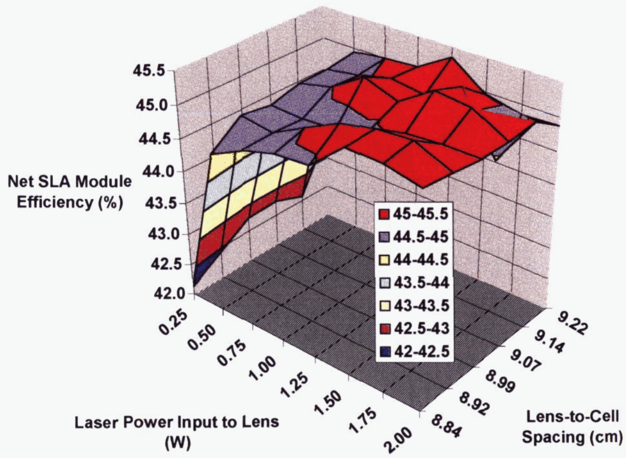


Fig. 7. Stretched Lens Array (SLA) Prototype Performance for Various Laser Input Power Levels and Lens-to-Cell Spacing Variations.

In addition to measurements on the SLA concentrator module as an assembly, the lens was removed and direct laser irradiance tests were performed on the cell alone. One of the key measurements for the cell was the current response as a function of laser wavelength, as shown in Fig. 8. The measured current response results were well bracketed by calculated curves for quantum efficiency values of 86% and 88%. Dividing the current response at 805 nm with (0.52 A/W) and without (0.56 A/W) the lens verifies that the lens net optical efficiency is about 92%.

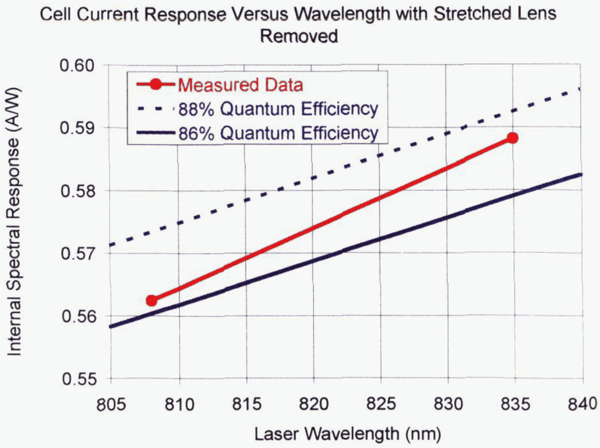


Fig. 8. GaAs Cell Current Response for Different Laser Wavelengths.

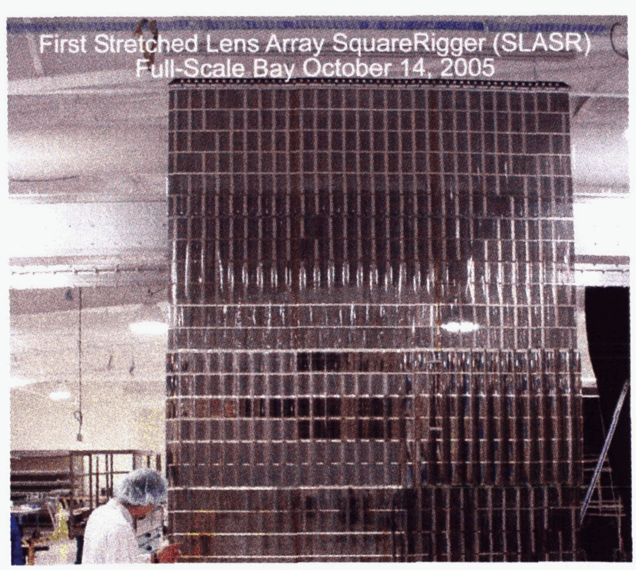
All of the UAH measurements on the SLA assembly, including those presented in Figs. 6 and Fig. 7 above, were made with a 30 W laser operating at a wavelength of 805 nm. Inspection of Fig. 8 shows that significantly higher current response is obtainable with a longer wavelength laser. For example, at 835 nm wavelength, the current response is 4.6% higher than at 808 nm. This implies that the 45.5% net SLA module conversion efficiency at room temperature, shown in Fig. 6 and Fig. 7, would be over 47.5% for a future flight system using 835 nm laser input instead of 805 nm laser input.

SYSTEM-LEVEL PERFORMANCE METRICS

The laser version of SLA is being developed to utilize the same deployment and support structures as the solar version of SLA. One very attractive SLA deployment and support structure approach is ATK Space Systems' SquareRigger platform. SLA on SquareRigger (SLASR) has an unprecedented portfolio of performance metrics [5]. A full-scale prototype of one rectangular building block of SLASR is shown in Fig. 9. Large SLASR arrays will be comprised of multiple rectangular building blocks, or bays, of the relatively large size (about 2.5 m x 5.0 m) shown in Fig. 9. SLASR is particularly well suited to large space power applications.

Due to the much higher conversion efficiency of the laser version of the SLA compared to the solar version, proportionally less waste heat is generated by the laser version. Therefore, the irradiance of the laser can be increased to a value significantly higher than the normal space solar constant of 1,366 W/m^2 while maintaining the cell temperature at the same value as for the solar version of SLA. With higher input irradiance and higher conversion efficiency, the areal power density of the laser version of SLA is very much higher than for the solar version of SLA.

A direct comparison of the key performance metrics of both versions of the SLA on the SquareRigger platform is



shown in Table 1. These performance metrics are based on already demonstrated cell and SLA concentrator module efficiency levels for both versions of SLA. These performance metrics are also based on today's lens, radiator, cell, structure, and deployment mechanism materials and mass estimates. For a nominal 100 kW solar version of SLA on SquareRigger, the total areal mass density of the SLASR array has been estimated by ATK Space and ENTECH at 0.86 kg/m^2. Using these current values for performance and mass, note that the key performance metrics for the solar version of SLASR are outstanding at **309 W/m^2**, **359 W/kg**, and **80 kW/m^3**. Note that the key performance metrics for the laser version of SLASR are extraordinary at **690 W/m^2**, **803 W/kg**, and **179 kW/m^3**.

CONCLUSION

A new version of the Stretched Lens Array (SLA) has been developed for collecting and converting infrared laser light instead of sunlight. The new laser version of SLA extends the unprecedented performance metrics of the solar version of SLA to much higher values due to the higher conversion efficiency and allowable irradiance of the laser version. The laser version of SLA represents an excellent candidate for providing lunar surface power for NASA lunar exploration missions. Many of these missions will require power in locations without sunlight, including the lunar polar craters. In addition, even for lower lunar latitudes, the long lunar night (about two weeks long) presents huge energy storage challenges for conventional solar power systems. Beamed infrared laser light from lunar-orbiting spacecraft could be efficiently collected and converted by the laser version of SLA on the lunar surface to provide power for such missions.

ACKNOWLEDGEMENT

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Comparison of Laser Version and Solar Version of SLA on SquareRigger Platform on GEO

Item	Parameter	Value for Solar SLA	Value for Laser SLA	Note
1	Lens Transmittance	92%	92%	No Antireflection Coating
2	Cell Absorptance	95%	95%	For Thermal Calculations
3	Cell Efficiency @25C	30%	49.5%	Already Demonstrated for Both
4	Net Lens/Cell Efficiency @25C	27.6%	45.5%	Item 1 Times Item 3 (Demonstrated Values)
5	Cell Temperature on GEO	71C	71C	Same by Design
6	Cell Temperature Knockdown Factor	91%	91%	Slightly Conservative for Laser Cell
7	Operational Array Efficiency	25.1%	41.4%	Item 4 Times Item 6
8	Waste Heat Fraction	62.3%	46.0%	Item 1 Times Item 2 Minus Item 7
9	Input Irradiance to SLA Lens	1,366 W/sq.m.	1,851 W/sq.m.	Laser Irradiance for Same Cell Temperature (Laser Irradiance = Solar Item 8 Divided by Laser Item 8 Times Solar Constant Item 9)
10	Waste Heat Flux	851 W/sq.m.	851 W/sq.m.	Item 8 Times Item 9 (Same by Design)
11	SLA SquareRigger Gross Areal Power Density	343 W/sq.m.	767 W/sq.m.	Item 7 Times Item 9
12	Wiring/Mismatch/Packing Knockdown Factor	90%	90%	Typical Factor for Other Losses
13	SLA SquareRigger Net Areal Power Density	**309 W/sq.m.**	**690 W/sq.m.**	Item 11 Times Item 12
14	SLA SquareRigger Wing Mass Density	0.86 kg/sq.m.	0.86 kg/sq.m.	Based on 100 kW Solar Point Design
15	SLA SquareRigger Net Specific Power	**359 W/kg**	**803 W/kg**	Bottom-Line Wing-Level Specific Power
16	SLA SquareRigger Stowed Power Density	**80 kW/cu.m.**	**179 kW/cu.m.**	Solar Item 16 Times Laser Item 13 Divided by Solar Item 13

Table 1. Comparison of the Laser Version and the Solar Version of SLA on the ATK Space Systems' SquareRigger Platform Operating on Geostationary Earth Orbit (GEO) with the Same Cell Temperature of 71C.