# ADVANCED RECEIVER/CONVERTER EXPERIMENTS FOR LASER WIRELESS POWER TRANSMISSION

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## ABSTRACT

For several years NASA, ENTECH, and UAH have been working on various aspects of space solar power systems, some of which include four process elements:

(1) space solar radiation collection and conversion to electrical power
(2) conversion of this electrical power to laser radiation
(3) wireless power transmission of this laser radiation to an end-use location
(4) collection of the laser radiation and conversion to electrical power

For the first element above, photovoltaic concentrator systems using ultra-light Fresnel lenses to focus space sunlight onto small solar cells have demonstrated significant performance, mass, and cost advantages over competing solar arrays. Recently, the photovoltaic concentrator approach has also been proposed for the fourth element, to provide similar performance, mass, and cost advantages over competing laser receiver/converters. This paper describes the new laser receiver/converter approach, including very encouraging test results on early-stage proof-of-concept prototype hardware.

## INTRODUCTION

Prior studies and experiments have shown that photovoltaic concentrator technology can provide significant performance, cost, and mass benefits for the first process element listed in the ABSTRACT, the solar collector/converter. As discussed in later paragraphs, solar concentrator arrays have already demonstrated net solar-to-electric conversion efficiencies of 28% at room temperature, and technology roadmaps anticipate solar concentrator array efficiencies over 50% within the next two decades. Furthermore, the specific power of solar concentrator arrays should move from 180 W/kg today to over 1,000 W/kg during the next two decades. Most importantly, solar concentrator arrays are far more cost-effective than conventional planar photovoltaic arrays, because they replace expensive semiconductor material (the solar cells) with much lower cost Fresnel lenses, which collect and focus the sunlight onto small cells, saving 85% or more of the cell area per Watt of power produced.

Ongoing studies by the authors are indicating that photovoltaic concentrator technology could likewise provide significant performance, cost, and mass benefits for the fourth process element listed in the ABSTRACT, the laser receiver/converter, which could be located on Earth, on another celestial body (e.g., the Moon or Mars or asteroids or comets), or on a spacecraft, depending on the application. These advantages of photovoltaic concentrators for the laser receiver/converter are identical to the advantages of photovoltaic concentrators for solar collection and conversion. The use of ultra-light Fresnel lenses to capture and focus the laser light onto small photovoltaic cells minimizes the mass and cost of the cells, and the overall conversion efficiency is much higher for monochromatic laser light than for the broad-spectrum sunlight.

As a low-cost proof-of-concept experiment, using available lens and cell hardware, several small prototype photovoltaic concentrators have recently been built and tested under laser illumination. Each prototype includes a silicone mini-dome Fresnel lens, which collects and focuses laser radiation onto a GaAs single-junction photovoltaic cell. The geometric concentration ratio (lens aperture area divided by cell active area) is about 86X for this prototype. Equipped with a prismatic cell cover to eliminate metal gridline shadowing loss, the photovoltaic cell is mounted onto a radiator for passive waste heat rejection. The available lenses and cells were optimized for the collection and conversion of space sunlight, not laser light, significantly limiting their optical and electrical performance under laser illumination. Nevertheless, under 0.81-micron-wavelength laser input (0.29 W), a mini-dome-lens GaAs-cell prototype has already demonstrated over 45% net laser-to-electric conversion efficiency in a room-temperature laboratory environment. With the lens removed, the cell has demonstrated over 56% net laser-to-electric conversion efficiency under 0.83-micron-wavelength laser input (0.52 W) in the same room-temperature laboratory environment. Modeling for next-generation laser-optimized lenses and cells indicates that these proof-of-concept performance levels can be dramatically improved.

## BACKGROUND

Since 1986, ENTECH and NASA have been developing and refining space photovoltaic arrays using refractive concentrator technology [1]. Unlike reflective concentrators, these refractive Fresnel lens concentrators can be configured to minimize the effects of shape errors, enabling straightforward manufacture, assembly, and operation on orbit. By using a unique arch shape, these Fresnel lenses provide more than 100X larger slope error tolerance than either reflective concentrators or conventional flat Fresnel lens concentrators [2].

In the early 1990's, the first refractive concentrator array was developed and flown on the PASP Plus mission, which included a number of small advanced arrays [3]. The refractive concentrator array used ENTECH mini-dome lenses over Boeing mechanically stacked multi-junction (MJ) cells (GaAs over GaSb). The mini-dome lenses were made by ENTECH from space-qualified silicone (DC 93-500), and coated by Boeing and OCLI to provide protection against space ultraviolet (UV) radiation and atomic oxygen (AO). Fig. 1 shows the mini-dome lens array which flew on PASP Plus. This array performed extremely well throughout the year-long mission in a high-radiation, 70-degree inclination, 363 km by 2,550 km elliptical orbit, validating both the high performance and radiation hardness of the refractive concentrator approach [3]. In addition, in high-voltage space plasma interaction experiments, the refractive concentrator array was able to withstand cell voltage excursions to 500 V relative to the plasma with minimal environmental interaction [3].

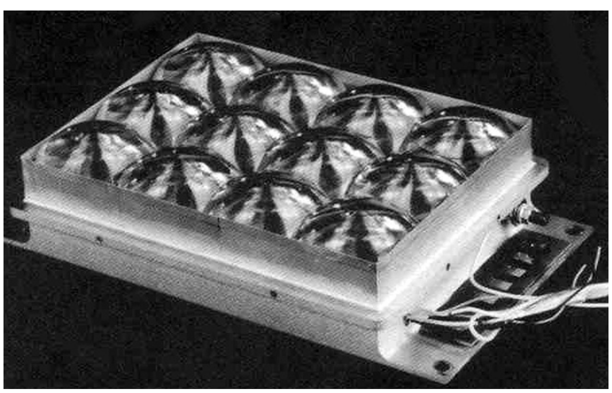

**FIGURE 1.** *Mini-Dome Lens* Array for PASP Plus (1994-1995).

In the middle 1990's, ENTECH and NASA developed a new line-focus Fresnel lens concentrator, which is easier to make and more cost-effective than the mini-dome lens concentrator. Using a continuous roll-to-roll process, 3M can now rapidly mass-produce the line-focus silicone lens material in any desired quantity.

In 1994, ABLE joined the refractive concentrator team and led the development of the SCARLET® (Solar Concentrator Array using Refractive Linear Element Technology) solar array [4]. SCARLET used a small (8.5 cm wide aperture) silicone Fresnel lens to focus sunlight at 8X concentration onto radiatively cooled triple-junction cells. Launched in October 1998, a 2.5 kW SCARLET array powered both the spacecraft and the ion engine on the NASA/JPL Deep Space 1 probe, shown in Fig. 2. SCARLET achieved over 200 W/m$^2$ areal power density and over 45 W/kg specific power, the best performance metrics up to that time [5]. The SCARLET array was the first solar array to fly using triple junction solar cells as the principal power source for a spacecraft. With SCARLET working flawlessly, Deep Space 1 had a spectacularly successful rendezvous with the comet, Borrelly, in September 2001, capturing the highest-resolution images of a comet to that date and other unprecedented comet data. At the end of the 38-month extended mission, in December 2001, SCARLET's power was still within + 2% of predictions. The SCARLET array won the Schreiber-Spence Technology Achievement Award in 1999, and the NASA Turning Goals into Reality Award in 2001.

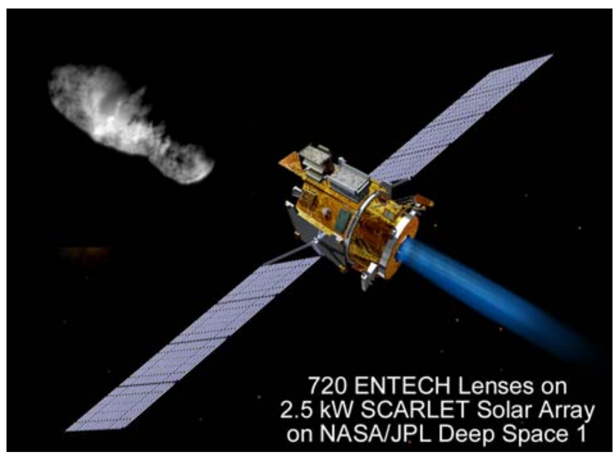


**FIGURE 2.** *SCARLET* Array on Deep Space 1 (1998-2001).

Over the past four years, the team, now including Auburn University, has developed an ultra-light version of the flight-proven SCARLET array, called the Stretched Lens Array (SLA), with much better performance metrics, as described in the following paragraphs [6].

The Stretched Lens Array (SLA) is an evolved version of SCARLET, retaining the essential power-generating elements (the silicone Fresnel lens, the multi-junction solar cells, and the composite radiator sheet) while discarding many of the non-power-generating elements (the lens glass arch superstrates, the lens support frames, the photovoltaic receiver support bars, and most of the honeycomb and back face sheet material in the panels). Fig. 3 shows the near-term, low-risk, rigid-panel version of SLA. The defining feature of SLA that enables the elimination of so many elements of the SCARLET array is the stretched lens optical concentrator (Fig. 4). By using pop-up arches to stretch the silicone Fresnel lens in the lengthwise direction only, these lenses become self-supporting stressed membranes. SCARLET's glass arches are thus no longer needed, eliminating their complexity, fragility, expense, and mass in the new, patented SLA [7]. With this substantial lens-related mass reduction, the supporting panel structural loads are reduced, making ultra-light panels practical for SLA. This cascading mass-reducing effect of the stretched lenses continues throughout the SLA wing structure, resulting in unprecedented performance metrics. Because of its 8.5X geometric concentration ratio, SLA saves over 85% of the required area, mass and cost of the multi-junction solar cells per Watt of power produced. Significantly, the total combined areal mass density (kg per $m^2$ of sun-collecting aperture area) of the lens material, the radiator sheet material, and the fully assembled photovoltaic receiver is much less (about 50%) than for a one-sun multi-junction cell assembly alone (unmounted). Thus, SLA has a substantial inherent mass advantage over planar, one-sun multi-junction-cell solar arrays. Similarly, due to its 85% cell area and cost savings, SLA has a substantial inherent power cost advantage ($/W) over such planar multi-junction-cell arrays.

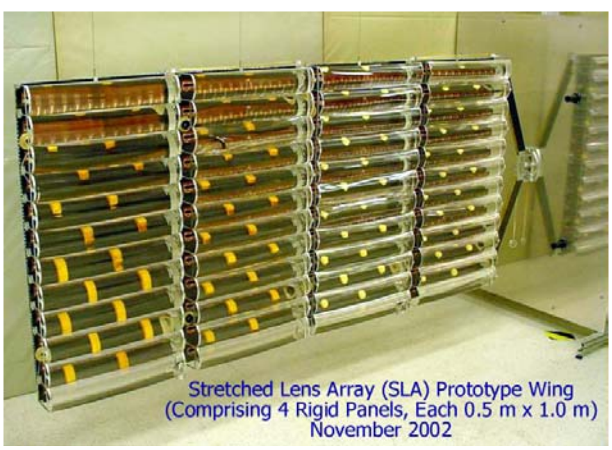


**FIGURE 3.** Rigid-Panel *Stretched Lens Array* (SLA) Wing.

All three refractive concentrator arrays discussed above, the mini-dome lens, SCARLET, and SLA, use Fresnel lens optical elements based on the same symmetrical refraction principle, shown schematically in Fig. 5. Solar rays intercept the smooth convex outer lens surface and are each refracted by the curved outer

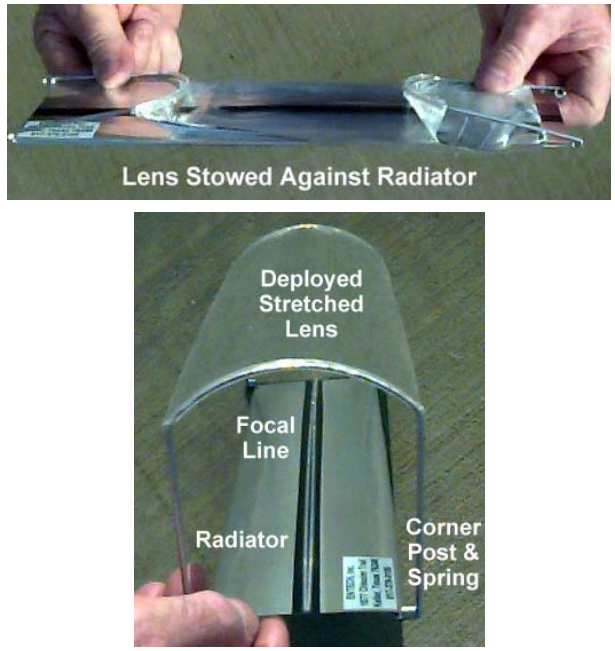


**FIGURE 4.** Stretched Lens Approach.

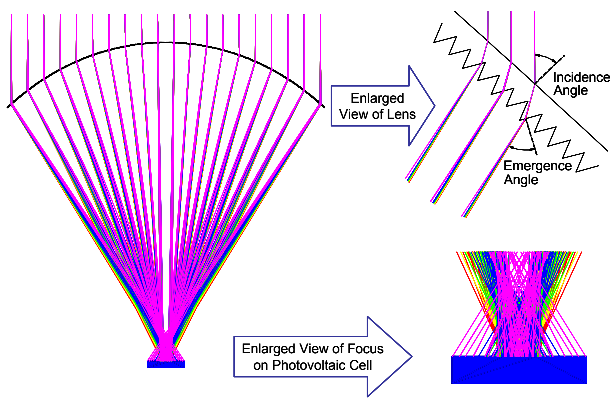


**FIGURE 5.** Symmetrical-Refraction Fresnel Lens.

surface by one half the angular amount needed to focus these rays onto the solar cell. The other half of the required refraction is performed as the rays leave the inner prismatic lens surface. Thus, the solar ray incidence angle at the smooth outer surface equals the solar ray emergence angle at the prismatic inner surface for every ray, as shown in the enlarged view of the lens in Fig. 5. This symmetrical refraction (angle in = angle out) condition minimizes reflection losses at the two lens surfaces, thereby providing maximal optical performance, while also offering unprecedented error tolerance for the mini-dome, SCARLET, and SLA lenses [2]. The mini-dome lens array uses a point-focus (3D) version of the symmetrical refraction lens, while both SCARLET and SLA use a line-focus (2D) version of the symmetrical refraction lens. The multitude of prisms in the symmetrical-refraction lens allows the individual prism angles to be tweaked to tailor the photon flux profile over the solar cell, both spatially and spectrally. For example, a patented optical innovation incorporated into the SCARLET and SLA lenses is an alternating-prism color-mixing feature that is critical to the optimal performance of monolithic multi-junction cells placed in the focus of such lenses [8].

Built and successfully tested in 2002, the rigid-panel SLA prototype wing in Fig. 3 included several complete photovoltaic receivers, each 0.5 m long and containing 14 series-connected triple-junction solar cells. The solar-to-electric conversion efficiency of each lens/receiver assembly was measured in a state-of-the-art solar simulator, using NASA Lear-Jet-flown reference cells for calibration. The net aperture area efficiency of the best lens/receiver assembly was 27.5% under simulated space sunlight (AM0 spectrum) at 28C cell temperature [9]. This net efficiency corresponds to 31% cell efficiency times 90% lens optical efficiency, and also matches separate NASA Lear Jet measurements on lens/cell units. On geostationary earth orbit (GEO), the operating cell temperature for SLA cells of this efficiency will be about 80C, resulting in a cell efficiency reduction factor of 87%. Combining this factor with the geometrical packing loss factor (95%), the net SLA efficiency at operating temperature on GEO at beginning of life (BOL) will be about 23%, corresponding to a wing-level areal power density well above 300 W/m$^2$. At a 7 kW wing size, which is typical of current GEO communication satellites, the corresponding specific power is over 180 W/kg (BOL) at operating temperature. In addition, the well insulated photovoltaic receivers in the prototype SLA wing of Fig. 3 were wet hi-pot tested for possible leakage current with a 500 V potential applied between the cell circuits and the panel, and the measured leakage current was less than 1 micro-Amp for each receiver [9]. SLA's high-voltage capability is facilitated by the small size of the photovoltaic cells, which allows super-encapsulation of the cell circuits at low mass penalty. A flight test of the rigid-panel SLA is currently being planned under the NASA New Millennium Program Space Technology 8 (NMP-ST8) technology validation project.

In addition to the near-term, low-risk rigid-panel version of SLA, an advanced version of SLA is also under development. The advanced version is a flexible-blanket SLA, similar to the small prototype array shown in Fig. 6.

For this SLA version, the lenses form one flexible blanket while the radiator elements, containing the photovoltaic receivers, form a second flexible blanket. Both blankets fold up into a very compact stow volume for launch, and automatically deploy on orbit. One of the most efficient platforms for deploying and supporting the flexible-blanket version of SLA is the SquareRigger platform, developed by ABLE Engineering [10]. The SquareRigger platform was originally developed by ABLE under funding from the Air Force Research Laboratory for use with thin-film photovoltaic blankets in space. However, with the much higher efficiencies achievable with SLA compared to thin-film photovoltaics, the marriage of SLA and SquareRigger provides unprecedented performance metrics, summarized in Table 1 [11].

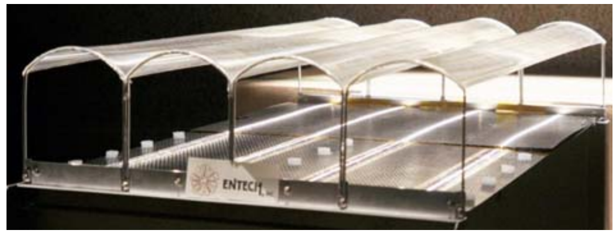

**FIGURE 6.** Flexible-Blanket Stretched Lens Array (*SLA*) Prototype.

**TABLE 1.** Performance Attributes of *SLA* on ABLE's *SquareRigger* Platform.

| Time Frame | < 5 Years | 5-10 Years |
|---|---|---|
| Power Capability (kW) | 100 | 1,000 |
| BOL Specific Power (W/kg) | 330 | 500 |
| Stowed Power (kW/m$^3$) | 80 | 120 |
| Voltage | 1,000 | TBD |

Initial development of the SLA/SquareRigger technology, including a small prototype demonstrator, has recently been completed by ABLE Engineering, with ENTECH subcontract support, under a NASA Small Business Innovation Research (SBIR) Phase I contract [10]. Additional development, including much larger scale hardware development, is being done under a Phase II SBIR contract. All of this development work is directed toward the SLA/SquareRigger array approach shown schematically in Fig. 7. Analysis of this type of SLA/SquareRigger system led to the near-term and mid-term performance metric estimates of Table 1. Note that SLA/SquareRigger enables giant space solar arrays in the 100 kW to 1 MW class, with spectacular performance metrics (300 to 500 W/kg specific power, 80 to 120 kW/m$^3$ stowed power, and operational voltages above 1,000 V) in the near-term (2010) to mid-term (2015). In the longer term (2020-2025), with constantly improving solar cell efficiencies and incorporation of new nanotechnology materials into the lens and radiator elements, SLA's technology roadmap leads to 1,000 W/kg solar arrays, as shown in Fig. 7 [12].

The following paragraphs discuss the unique concept to use a new version of SLA as a laser receiver/converter.

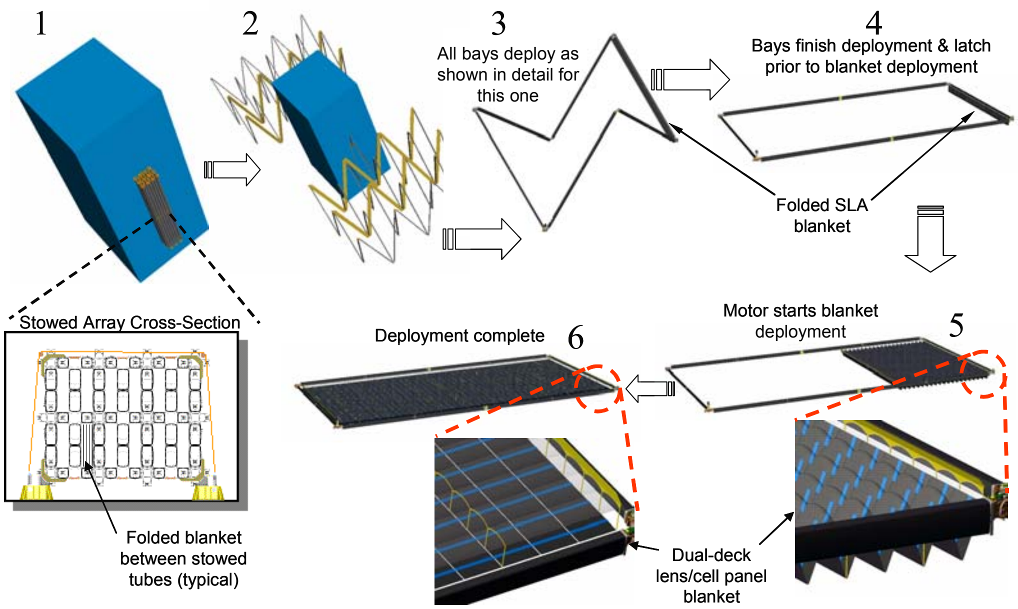


**FIGURE 7.** Stretched Lens Array (*SLA*) on *SquareRigger* Platform.

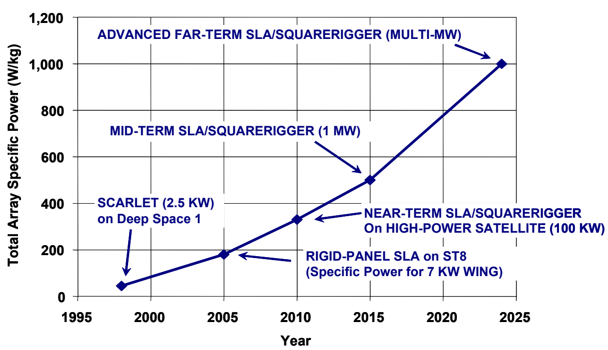


**Figure 8**. Long-Term Technology Roadmap for the Stretched Lens Array (SLA)

## NEW LASER RECEIVER/CONVERTER

As discussed in the earlier paragraphs, SLA offers substantial benefits in performance metrics, mass savings, and cost savings, compared to other solar array technologies. Since these same benefits would apply to laser receiver/converter arrays for space power, our team is working on the development of a new version of SLA that can be used to collect and convert laser light to usable power. For laser light conversion, a different type of photovoltaic cell is required. Today's state-of-the-art solar cells use monolithic multi-junction cells, which use different semi-conductor layers grown on a common wafer to convert the various regions of the solar spectrum into power. These multiple junctions are electrically connected in series, and therefore require the same current in each junction to function efficiently. For laser light, only one wavelength is available for collection and conversion, and these monolithic multi-junction solar devices would not work in their normal series-connected structure. However, variations on these multi-junction device structures can be made to work with laser light, if independent electrical contact access is provided to the single junction which is tuned to the laser light wavelength. Such special multi-junction photovoltaic cells could be used to enable the same SLA array to be used for both solar energy collection and conversion and laser energy collection and conversion. Our team is pursuing this dual-use solar/laser converter approach, since it offers substantial benefits. Alternatively, a single-junction cell can be used for laser collection and conversion. Both of these approaches are currently under investigation as part of a NASA SBIR Phase I contract.

As part of this Phase I SBIR contract, our team has conducted proof-of-concept prototype tests of photovoltaic concentrator modules. Due to budget constraints of the Phase I contract, no new lens or cell tooling or masks could be procured, and available hardware elements had to be utilized in these tests. Unfortunately, no compatible single-junction cells were available for use with the SLA line-focus lens (Figs. 3, 4, and 6). Fortunately, however, single-junction GaAs cells were available for an older point-focus version of the silicone lens, the mini-dome lens previously shown in Fig. 1. These available GaAs cell were made by Varian Associates in the late 1980's and clearly do not represent the state-of-the-art in performance. Similarly, the mini-dome lenses used in the experiments discussed below were developed in the late 1980's, and these lenses were optimized for use with the full solar spectrum and not monochromatic laser light. Nonetheless, this available lens and cell hardware enabled us to make proof-of-concept measurements which provided valuable data, as discussed below.

The first prototype mini-dome lens GaAs concentrator module for laser testing is shown in Fig. 9. The lens has an aperture diameter of 3.7 cm and focuses sunlight (or laser light) onto a 4.0 mm diameter GaAs cell. The overall geometric concentration ratio (lens aperture area over cell active area) is about 86X. In Fig. 9, the prototype is shown focusing sunlight onto the cell. The lens design as optimized to utilize sunlight's broad spectrum of wavelengths, in combination with the chromatic aberration of the lens (due to the refractive index varying with wavelength), to create a relatively mild focal spot centered on the round solar cell. A dark peripheral ring outside the focal spot but inside the cell edges was used to tolerate sun-pointing errors up to 1 degree in any direction. When a 1 degree pointing error occurs, the focal spot moves laterally just to the edge of the cell but not beyond, maintaining excellent performance up to this pointing error limit. Mini-dome lenses were not only flown on the PASP+ flight test, they were also flown by NASA Glenn on the Lear Jet test platform, and their optical performance and pointing error tolerance were validated. Typically, the uncoated mini-dome lens provides 90% net optical efficiency when used with the 4 mm GaAs cell.


**Figure 9. Mini-Dome Lens GaAs Cell Module**

During the course of the Phase I program, improvements were made in the configuration of the prototype mini-dome lens GaAs cell module, to enable more accurate data to be obtained. Fig. 10 shows the final test module which was built under the Phase I program. This unit enabled the lens-to-cell spacing to be varied during the test, and incorporated several other electrical, thermal, and mechanical improvements over the earlier module of Fig. 9.

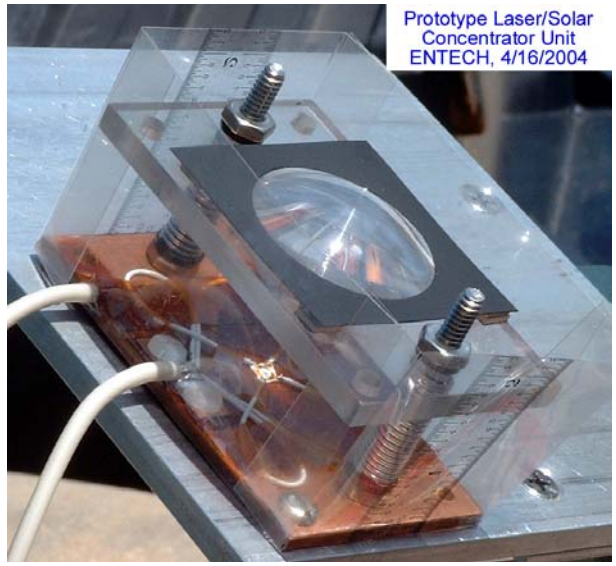


**Figure 10.** Improved Prototype Mini-Dome Lens GaAs Cell Photovoltaic Concentrator

The improved module is shown in Fig. 10 under solar illumination of the lens. Performance was characterized by a solar-to-electric conversion efficiency of about 22%, corresponding to about 90% lens optical efficiency times about 24% cell conversion efficiency at operating temperature (passive cooling by the outside air). The measured current-voltage (IV) curve of the unit under sunlight is shown in Fig. 11. Compared to the current state-of-the-art for the Stretched Lens Array (SLA), this solar-to-electric conversion efficiency is relatively modest, since SLA modules with multi-junction cells typically achieve over 30% net efficiency under terrestrial sunlight [11]. This modest performance is related to the use of a late-1980's vintage single-junction solar cell in the prototype of Fig. 10. After testing under sunlight, the unit in Fig. 10 was delivered to UAH for testing under laser irradiance, as discussed in the following paragraphs.

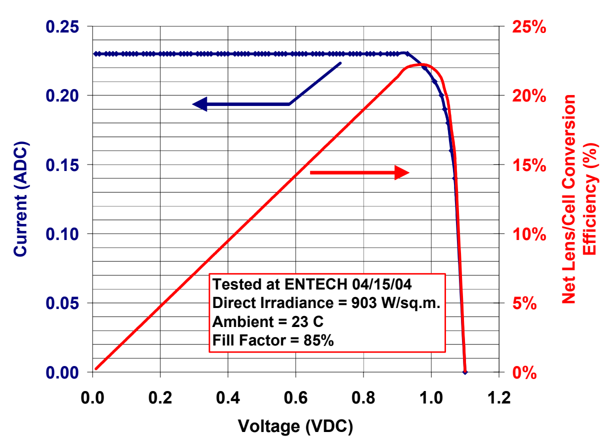


**Figure 11.** Measured Performance of Prototype Lens/Cell Concentrator Under Sunlight

## LASER TEST RESULTS

UAH performed a number of tests on the early prototype unit shown in Fig. 9, to establish a repeatable and accurate test approach, which was subsequently used to test the new prototype shown in Fig. 10. UAH's final test setup is shown in Fig. 12.

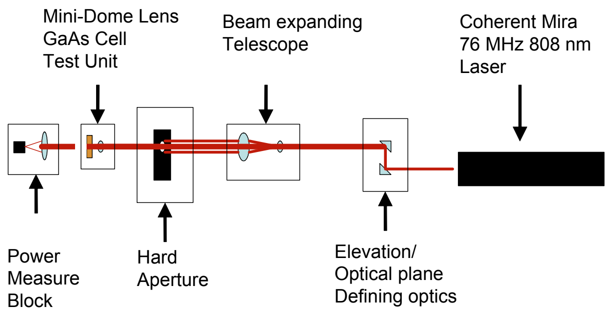


**Figure 12.** UAH Laser Test Setup

As expected, it was found during testing that the monochromatic laser light was much more tightly focused than sunlight, since the chromatic aberration used to smooth out the focal spot produced by the mini-dome lens was ineffective for laser light. The very spiked intensity profile produced by the lens under laser illumination caused large electrical resistance losses in the solar cell, especially in the high resistance emitter layer at the top surface of the solar cell. To reduce the intensity in the focal spot produced under laser illumination of the mini-dome lens, the lens-to-cell spacing was varied using the bolt/spring mechanism shown in Fig. 10. By severely defocusing the unit, respectable performance was obtained, as shown in Fig. 13. The overall net lens/cell conversion efficiency was over 45%, despite the electrical resistance losses due to the too-intense focal spot. This problem will be easy to correct with a new lens design optimized for use with laser light, and is only an artifact of the use of an old late-1980's vintage lens optimized for use with sunlight.

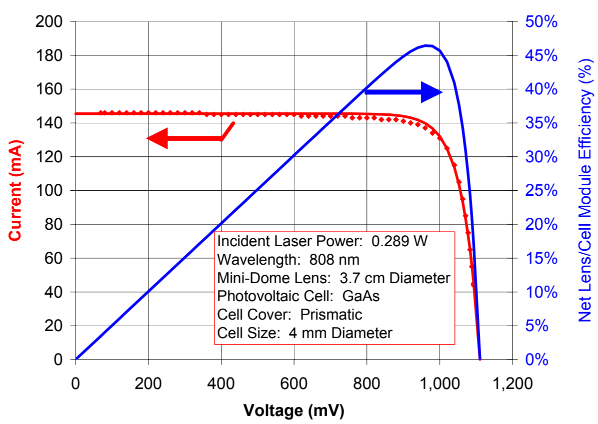


**Figure 13.** Measured Results for Mini-Dome Lens GaAs Cell Prototype Under Laser Illumination

In fact, ENTECH routinely tailors the hundreds (or thousands) of individual prism angles comprising their various Fresnel lenses to provide the desired focal plane irradiance profile over the photovoltaic cell [2 and 8]. However, the only existing lens and cell available for testing in the limited-budget Phase I of the NASA SBIR program were the mini-dome lens and GaAs cell used in the prototypes shown in Figs. 9 and 10. In Phase II of the SBIR program, lenses and cells optimized for use with laser light will be developed and utilized in much higher performance Stretched Lens Array (SLA) prototypes.

Note also in Fig. 13 that the incoming laser power level is relatively low at 0.289 W. Since the 3.7 cm diameter mini-dome lens aperture area is about 10.7 $cm^2$, the incoming irradiance is only 0.027 $W/cm^2$, equivalent to only about 20% of space sunlight irradiance (0.1366 $W/cm^2$). This low incoming laser power level further restricts cell performance, since properly designed photovoltaic cells improve in conversion efficiency with increasing incoming irradiance levels. This low laser power is related to constraints on the current laser test setup at UAH, which UAH will improve during Phase II of the SBIR program.

To eliminate the effects of the too-intense focal spot produced on the photovoltaic cell by the old mini-dome lens, this lens was removed from the prototype in Fig. 10, and UAH conducted tests of the cell alone. Typical results are shown in Fig. 14. Note that the cell efficiency exceeds 56% under slightly higher laser power and slightly longer laser wavelength than for the full lens/cell unit results of Fig. 13. The efficiency results of Fig. 14 would increase with higher laser irradiance levels, but the current UAH test setup is constrained to these relatively low levels. UAH plans to improve the test setup in Phase II of the SBIR program to enable higher power levels to be reached, for either pulsed or continuous wave laser output.

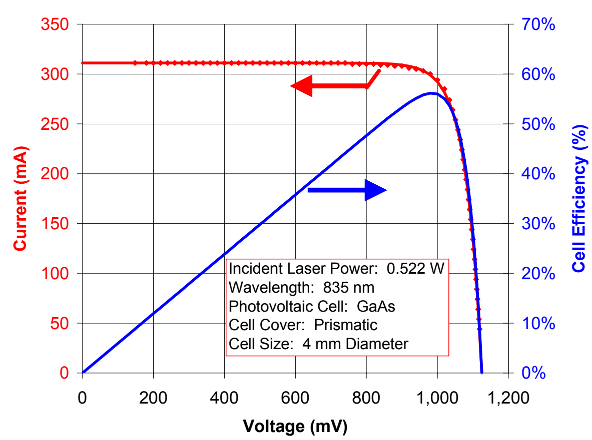


**Figure 14.** Measured Results for the GaAs Cell Without the Mini-Dome Lens

Additional performance improvements can be obtained on future units by using an antireflection (AR) coating on the prismatic cell cover which was used on the top of the solar cell. AR coatings for monochromatic laser light are much simpler to implement than for broad-spectrum solar radiation, not only for the prismatic cell cover, but also for the Stretched Lens Array (SLA) lenses themselves, which will be used in Phase II of the SBIR program.

Modeling of future optimized systems indicates that array-level laser-to-electric conversion efficiencies of 70% and higher should be achievable for the Stretched Lens Array (SLA), while maintaining SLA's desirable attributes of ultra-light mass, stowed volume efficiency, radiation hardness, high-voltage capability, and cost-effectiveness.

## CONCLUSIONS

Several conclusions have been drawn from the Phase I study and proof-of-concept testing conducted to date on the new laser receiver/converter approach, including:

- The Stretched Lens Array (SLA) can be adapted to laser collection and conversion by simply modifying the photovoltaic cell structure.
- Prototype hardware using solar-optimized 1980's-vintage lenses and cells has demonstrated over 45% net lens/cell conversion efficiency and over 56% cell conversion efficiency under laser illumination.
- Much higher performance levels will be achieved with laser-optimized lenses and cells, as planned for Phase II of the program.
- Since SLA's long-term roadmap shows over 1,000 W/kg specific power under solar irradiance, and since conversion efficiencies and irradiance levels will both be higher under laser irradiance, SLA will be able to provide several thousand W/kg specific power for laser receiver/converters.
- Applications for the new photovoltaic concentrator laser receiver/converter include spacecraft in Earth orbits (LEO, MEO, GEO), spacecraft in the Earth-Moon neighborhood, spacecraft in lunar or Martian orbit, and surface power plants on the Moon or Mars (e.g., lunar polar exploration installations).

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