Modular, Mass-Producible, Eye-Safe, Heat-Safe Laser Power Beaming System for Space and Ground Applications

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Abstract*—Laser power beaming systems have been explored for several decades to provide wireless power transfer for space and ground applications, but they have not become widely adopted. Recent technology advances in lasers and photovoltaic cells have renewed interest in laser power beaming by NASA and DOD for space applications, and by DOD and DOE for ground applications. This paper presents a novel architecture for laser power beaming that offers several benefits over previous approaches, especially in safety, mass, performance, and cost. The new approach will be presented, and its advantages explained, with both space and ground examples.

***Keywords*—laser, Gaussian, Fresnel, lens, photovoltaic, cell**

I. INTRODUCTION

Laser power beaming systems contain at least three key elements, including:

- Laser
- Collimating Optics
- Photovoltaic Receiver

Lasers of several different wavelengths have been explored in recent years for laser power beaming systems with single-junction photovoltaic cells chosen to match the laser wavelength for good conversion efficiency. An excellent summary of some of these matched lasers and cells is provided in [1].

Excellent cell conversion efficiencies have been achieved for lasers operating near 800 nm wavelength and GaAs cells. Fraunhofer has demonstrated over 67% cell conversion efficiency at a relatively high irradiance of 96,000 W/m^2 [1]. Earlier work by the author and others demonstrated over 57% cell conversion efficiency at a relatively high irradiance of 41,000 W/m^2 [2]. In this same earlier work, a Fresnel lens concentrator was combined with a GaAs cell to demonstrate over 46% net lens-cell module conversion efficiency at a very low irradiance on the lens aperture of only 270 W/m^2 [2]. This earlier work demonstrated the advantage of using a Fresnel lens to concentrate low incident laser irradiance onto a small cell at much higher irradiance to improve the cell conversion efficiency.

Despite these excellent conversion efficiencies for wavelengths of about 800 nm, such wavelengths are not eye-safe. Furthermore, irradiance levels greater than one peak terrestrial sun (AM1.5) equivalent irradiance (1,000 W/m^2) are not heat-safe for skin.

Fortunately, wavelengths above 1,400 nm are both eye-safe and heat-safe at irradiance levels of 1,000 W/m^2 or lower [3]. This is the wavelength range and irradiance range of interest for the system presented in this paper.

Collimating optics for lasers can take many different forms, from lenses to reflectors. The preferred collimating optics presented in this paper use a "diffractive" Fresnel lens approach pioneered by Lawrence Livermore National Laboratory [4]. Such Fresnel lenses can be made very thin and ultra-light for space applications. The design of such collimating lenses is much different from the design of Fresnel lenses for concentrating photovoltaics (CPV), but the same materials and mass-production techniques can be used for both.

The preferred photovoltaic receiver presented in this paper makes full use of Fresnel lens concentrators to accept the low-irradiance laser input and focus this onto small photovoltaic cells at much higher irradiance to significantly improve cell conversion efficiency, while saving cell area, mass, and cost.

The author and others have developed several generations of Fresnel lenses for NASA and other customers for solar photovoltaic concentrators over recent decades, and the same technology can be used for both the laser collimating lenses and the laser concentrating lenses presented in this paper [5].

II. DESCRIPTION OF THE SYSTEM

Fig. 1 shows the basic architecture of the modular, eye-safe, heat-safe laser power beaming system presented in this paper.

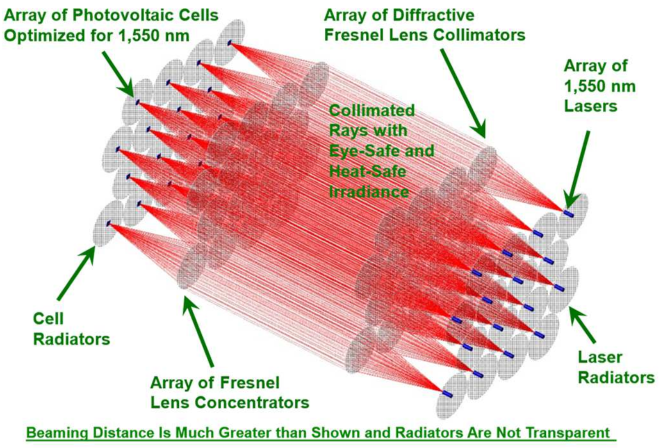


Fig. 1. Modular Eye-Safe, Heat-Safe Laser Power Beaming System

Proceeding from right to left in Fig. 1, the key elements of the modular, eye-safe, heat-safe laser power beaming systems shown are:

- Thin, lightweight waste heat radiators (falsely shown as transparent to expose the lasers) for the lasers to maintain moderate laser operating temperature
- Small lasers operating at approximately 1,550 nm wavelength (shown simplistically as a small blue cylinder rather than a number of different components)
- Thin, lightweight "diffractive" Fresnel lens collimators which receive the laser light and collimate it into beams for transmission over a significant distance
- The laser beams which are eye-safe and heat-safe from beginning to end (the beaming distance is much greater than shown in Fig. 1)
- Thin, lightweight Fresnel lens concentrators which receive the laser beams and focus them into small focal spots
- Small, single-junction photovoltaic cells (InGaAsP, InGaAs and GaSb are the leading candidates) which absorb the laser light and efficiently convert a substantial portion into usable electricity
- Thin, lightweight waste heat radiators for the photovoltaic cells to maintain moderate operating temperature

The geometry shown in Fig. 1 shows circular radiators and lenses to correspond to the circular laser beams with Gaussian irradiance profiles. The circular geometry is shown merely as one option. Other options include hexagonal and square geometries which may be mechanically and structurally easier to integrate and assemble than the circular geometry. Likewise, the small 4 x 4 modular array geometry of Fig. 1 is just for example. Typical systems would have many more modules integrated into larger arrays.

One key feature of the modular system shown in Fig. 1 is the use of small key elements from end to end. Small lasers with small power outputs are much easier to maintain at moderate temperatures than large lasers with large power outputs. This thermal advantage is especially relevant to space applications where only radiation cooling is available. Small lasers are also simpler to mount and power than large lasers, requiring smaller conductors for smaller currents.

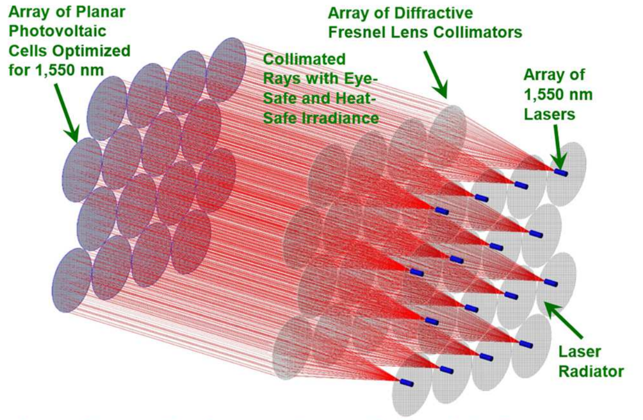
Small Fresnel lenses are much easier to tool and mass-produce than large Fresnel lenses. This small lens advantage applies to both the collimating lenses and the concentrating lenses.

Small photovoltaic cells are more efficient, lighter, and lower cost than large photovoltaic cells. Since each cell receives the same concentrated laser irradiance and thus produces the same current, such cells can be interconnected in series to build up array voltage without major current mismatch losses.

Small cell radiators are much thinner and lighter than large cell radiators, due to the lower waste heat amount and the shorter distances to conduct this heat to spread it over the full radiator surface area.

Small elements also offer much better economies of scale than large elements. Each element used in the system shown in Fig. 1 can be replicated over and over in cookie-cutter fashion to produce and aggregate as many elements as needed to meet the power output required by any application. Small elements also provide outstanding scalability from watts to kilowatts to even larger sizes by simply adding more elements.

An alternate version of the basic architecture of the modular, eye-safe, heat-safe laser power beaming system is shown in Fig. 2, with the receiver modified to use larger planar cells (or groups of smaller planar cells connected in parallel) rather than concentrators and small cells. This alternate version will have similar performance to the concentrator version, but the cells and their cover glass and encapsulation will be much larger, heavier, and more expensive than for the concentrator version.



Beaming Distance Is Much Greater than Shown and Radiators Are Not Transparent

Fig. 2. Modular Eye-Safe, Heat-Safe Laser Power Beaming System

The use of concentrating lenses (Fig. 1) to capture and focus the laser light at the receiver offers advantages over planar cells (Fig. 2) covering the same collection area:

- The cells required to convert eye-safe and heat-safe laser beams (about 1,550 nm wavelength at a peak irradiance of about 1,000 W/m^2 peak irradiance) to electrical power are inherently low-voltage devices which are less efficient at low laser irradiance. Concentration by 100X or more significantly improves cell efficiency as discussed later in this paper.
- By focusing about 100X, the cell area per unit power delivered is reduced by about 99%, reducing cell assembly mass and cost almost proportionally.
- The smaller concentrator cells can be heavily shielded from damaging radiation and fully encapsulated and insulated from electrical discharge damage with a very small mass penalty compared to the 100X larger planar cells.
- The small concentrator cells and the large planar cells will have very similar output currents, which are much easier to collect efficiently from the full cell area for the 90% smaller current flow distances in the concentrator cells.

III. BEAM GEOMETRY AND TRUNCATION CONSIDERATIONS

Laser beams are generally characterized as Gaussian in profile, as shown for one example in Fig. 3. This Gaussian beam has a peak irradiance of 1,000 W/m^2 and a total power of 4.8 Watts, with 99% of this power contained within a 17 cm diameter circle. Note that the irradiance goes to less than 10 W/m^2 at the outer edge of the profile. If the full beam were to be utilized in a laser power beaming system, the integrated average irradiance would be about 200 W/m^2, only one-fifth of the peak irradiance. A better approach which applies to the present architecture is to truncate the beam at 5 cm radius (10 cm diameter) and discard the small amount of laser irradiance outside this smaller circle. This would allow the use of 10 cm wide lenses to collect about 80% of the laser beam (about 3.8 Watts) with an integrated average irradiance of about 500 W/m^2, one half of the peak value. By using this geometry rather than trying to capture the entire laser beam, the system will be more energy dense with an integrated average beam irradiance of 500 W/m^2, allowing more power to be beamed over a smaller beam cross-sectional area.

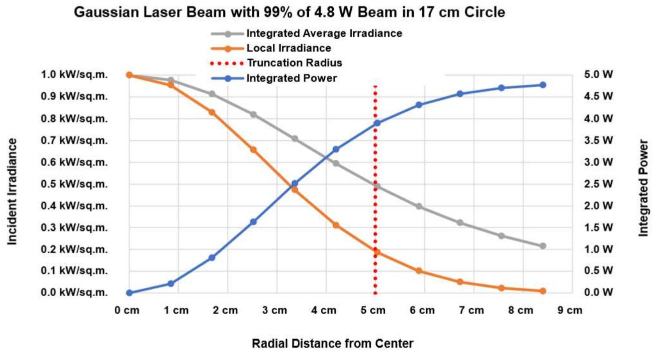


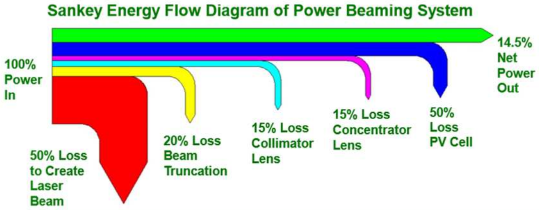
Fig. 3. Example Eye-Safe, Heat-Safe Gaussian Laser Beam

IV. PERFORMANCE

The end-to-end performance is a critical parameter for any power beaming system, and is the result of combining the performance of each key element:

- Lasers in the 1,550 nm range have been shown to reach over 50% "wall-plug" efficiency in laboratory settings [6]. Such lasers are also being employed for laser imaging, detection and ranging (LIDAR) in connected and automated vehicles (CAVs) with performance improvements and cost reductions expected to continue rapidly.
- Fresnel lenses have been produced in ultra-light form for NASA at typical optical efficiency levels of 85% for mesh-strengthened lenses and 90% for superstrate-strengthened lenses [5].
- Photovoltaic cells converting laser light at about 1,550 nm with 45-46% efficiency have been demonstrated [7 and 8]. With 100X concentration of low-irradiance laser light in the present system, 50% is a realistic near-term efficiency value as further discussed later in this paper.
- To maintain an average irradiance level in the beam equal to one-half the peak irradiance level in the beam of 1,000 W/m^2, 20% of the beam's power must be discarded.
- If the modular elements are small, comprising about 10 cm wide lenses and beams and radiators, and about 1 cm wide photovoltaic cells, the waste heat radiators for both laser and cell can be very thin and lightweight while maintaining very reasonable operating temperatures for both the laser and the cell. The proven approaches used in space to radiatively dissipate waste heat from multi-junction solar photovoltaic concentrator cells are directly applicable to lasers and cells [5]. The same radiator approaches can also be easily adapted to ground applications, where the radiator thermal effectiveness will be improved by the added benefit of convective heat transfer to the surrounding air.

Fig. 4 shows a Sankey energy flow diagram for the concentrator system of Fig. 1. Fig. 4 also includes a table of the corresponding efficiency cascade and an example set of power values for a 10 cm diameter beam. Note the end-to-end efficiency of 14.5%. The planar system of Fig. 2 would have similar performance, since the lower cell efficiency will be offset by the elimination of the concentrator lens transmittance loss.



	Efficiency Cascade	Example Power for 10 cm Diameter Beam	Irradiance
Input Laser	100.0%	11.55 W	
After 50% Laser	50.0%	5.77 W	
After 20% Trim	40.0%	4.62 W	
After 85% Collimator	34.0%	3.93 W	500 W/sq.m.
After 85% Concentrator	28.9%	3.34 W	
After 50% Cell	14.5%	1.67 W	

Fig. 4. Sankey Energy Flow Diagram

V. APPLICATIONS

The architecture shown in Figs. 1 and 2 is optimized for applications where people, animals, or heat-sensitive equipment can encounter the beam at any point from the transmitting site to the receiving site. This requires the beam to be eye-safe and heat-safe from beginning to end, a condition which can be met with low irradiance and a near-constant beam diameter.

There are other applications which do not require the architecture shown in Figs. 1 and 2. For example, if the beam does not need to be eye-safe or heat-safe anywhere between the transmitting site and the receiving site, shorter wavelength lasers operating at higher beam irradiance levels will be a better choice because of their higher overall efficiency [1 and 2]. For another example, if the beam does not need to be eye-safe and heat-safe at the transmitting end but does need to be eye-safe and heat-safe at the receiving end, the beam can be much smaller with much higher irradiance at the transmitting site than at the receiving site. Fraas has described such a system for beaming power from an unmanned solar power satellite to a ground station on the earth [9 and 10].

For the present architecture shown in Figs. 1 and 2, space applications can include missions where astronauts may be present near both the transmitting site and the receiving site. One example is power beaming from lunar polar crater ridges in eternal sunlight to lunar polar crater valleys in eternal darkness. For this application, the beamed power could be used for extraction of water and other resources, where astronauts may encounter the beam at either the transmitting end or the receiving end. (If the astronauts have adequately protective clothing and visors, the beam irradiance could be increased above 1,000 W/m^2.) Terrestrial applications are more numerous, including power beaming of emergency power from a major power generation facility to medical facilities and communication centers, including ship to shore power beaming after hurricanes, tsunamis, or other natural disasters. Another example terrestrial application is power beaming to forward military bases or mobile assets or remote villages from an elevated power beaming facility.

For the present architecture, the most attractive applications which can use the small modular lasers, lenses, and receivers of Figs. 1 and 2 will have shorter beaming distances, as further described later in this paper.

VI. THERMAL CONSIDERATIONS DRIVE SIZING

To maintain a simple, robust, reliable system architecture, planar passive radiators for waste heat dissipation are preferred. For space applications, these waste heat radiators must dissipate waste heat from both the lasers and the photovoltaic receivers to the surrounding environment by thermal radiation exchange. The amount of waste heat is much greater for each laser than for each photovoltaic receiver because transmission losses in the lenses, beam truncation, and power extraction from the photovoltaic cells all reduce the amount of waste heat at the receiver compared to the laser. Small dimensions for the lenses, laser beam, and radiators enable the use of thinner, lighter radiators. The amount of waste heat is proportional to the beam area and the distance over which this heat must be spread from a centrally located laser or cell to use the full radiator area is proportional to the radius of the radiator. It is easily shown that the required radiator thickness to maintain the same temperature profile increases with the square of the beam diameter.

Fig. 5 shows an example result for a 10 cm diameter beam and waste heat radiator for a 50% efficient laser (half the laser power input converted to laser beam and half to waste heat). This example is for a space application using a 200 μm graphene radiator, assuming negligible solar irradiance (direct or reflected) onto the radiator and a cold background temperature (e.g., dark lunar crater). The average radiator temperature is easily calculated from the total amount of waste heat. For a simplistic model with the laser located near the center of the radiator, the actual radial temperature profile to achieve that average temperature has a central peak where the radiator contacts the laser and falls toward the outer edge of the radiator where the slope is horizontal. Note that the peak radiator temperature near the laser is less than 325 K, implying a reasonable operating temperature for the laser.

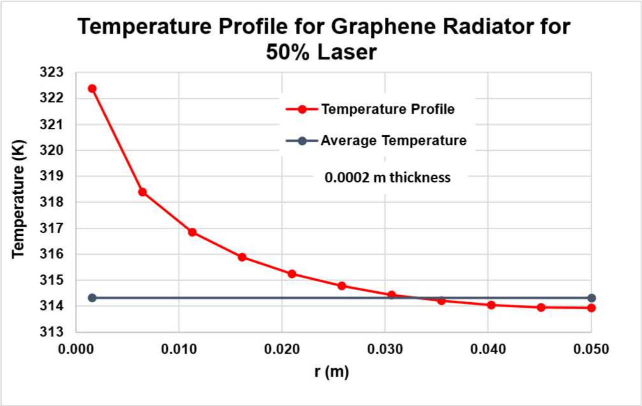


Fig. 5. Laser Radiator Thermal Analysis for 10 cm Diameter

Fig. 6 shows the results for the photovoltaic cell radiator for the same example space application using 10 cm diameter beams, lenses, and radiators. This example uses a 100 μm graphene radiator and assumes negligible direct or reflected solar irradiance on the radiator and a cold background temperature (e.g., dark lunar crater). The temperatures are much lower for the cell radiator (Fig. 6) than for the laser radiator (Fig. 5) because of the much lower amount of waste heat for the cell. Note that the radiator temperature near the cell will be less than 240 K, far below room temperature, implying that the cell efficiency will be higher as further discussed later in this paper.

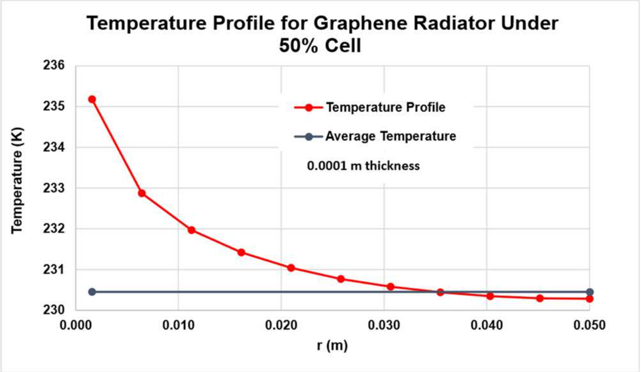


Fig. 6. Cell Radiator Thermal Analysis for 10 cm Diameter

The thermal models used to provide the results in Figs. 5 and 6 were developed for space photovoltaic concentrators [5]. On-orbit results have validated the accuracy of these models.

VII. DIFFRACTION LIMITS ON BEAMING DISTANCE

For the architecture shown in Figs. 1 and 2, the beam diameter is the same from the collimating lens to the photovoltaic receiver. This geometry and laser beam diffraction together set limits on the beaming distance as shown in Fig. 7. Each curve in Fig. 7 shows the minimum common diameter of the collimator and receiver containing 80% of the Gaussian laser beam as a function of beaming distance for a laser wavelength of 1,550 nm. The lowest curve is for an ideal

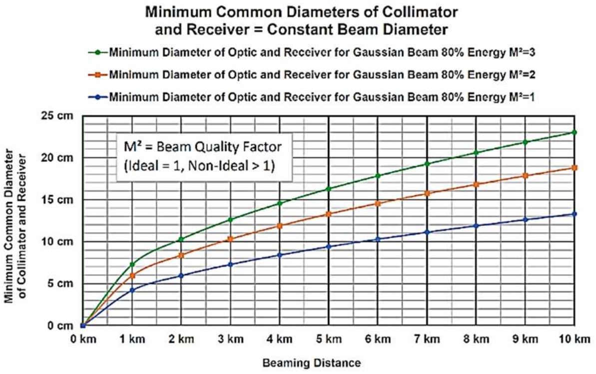


Fig. 7. Laser Diffraction and Beaming Distance for the System

laser and collimator (the diffraction limit for perfect optics). The next higher curve is for a beam quality factor of 2 compared to an ideal beam quality factor of 1 for the lowest curve. The highest curve is for a beam quality factor of 3, still less ideal than the middle curve. We believe that these three curves bracket the expected performance. Note that for a 10 cm beam diameter, the beaming distance is about 6 km for the lowest curve and about 2 km for the highest curve. Slightly larger lenses can extend the beaming distance substantially. Fig. 7 therefore shows that the use of small beam diameters (and correspondingly small lenses and radiators) is well matched to beaming distances less than 10 km for the wavelength of interest (1,550 nm).

VIII. CELL PERFORMANCE LIMITS AND CONCENTRATION

For photovoltaic cells optimized for performance with infrared lasers in the 1,550 nm range, the conversion efficiency is significantly dependent on the cell bandgap and the laser irradiance level. Limiting cell efficiency models for such cells have been developed by Pena and Algora [11 and 12]. These simple models assume 100% quantum efficiency for laser light below the bandgap wavelength of the cell and only radiative recombination for the dark current, with no losses due to series or shunt resistances. We have used the equations provided in References 11 and 12 to estimate the maximum performance of two types of cells, InGaAsP with a bandgap of 0.78 eV and GaSb with a bandgap of 0.726 eV, for laser irradiance of 1,550 nm wavelength (0.80 eV photon energy). Fig. 8 shows the results for the higher bandgap cell. To crudely include the effects of realistic quantum efficiency, additional recombination losses, and series and shunt resistances, the three curves include "knockdown" factors of 70%, 80%, and 90% of the limiting cell efficiencies from the models of References 11 and 12. We also show an actual demonstrated efficiency value from Mukherjee [8] for this type of cell under this type of monochromatic irradiance. Note that the data point is between the 70% and 80% curves. We also show with a dashed vertical line the expected cell irradiance from the 100X concentrator lens shown in Fig. 1. Extrapolating from the data point to the higher irradiance level, we see that a cell efficiency above 50% should be achievable in the near term with the cell near room temperature.

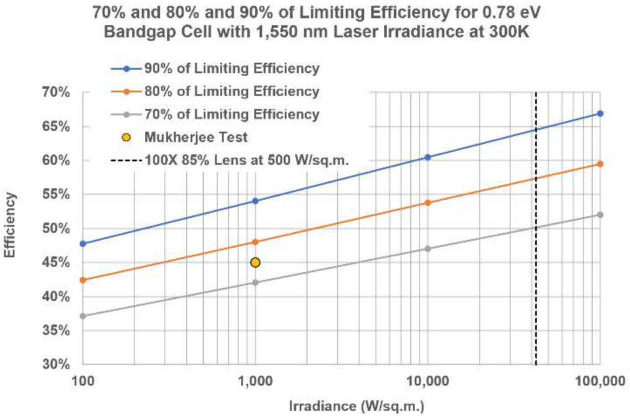


Fig. 8. Maximum Efficiency of Cell with 0.78 eV Bandgap

Fig. 9 shows the same type of results for a cell temperature of 240K. Note that the cell efficiency improves with colder temperatures corresponding roughly to the temperatures shown previously in Fig. 6. These results further confirm that 50% cell efficiency is an achievable goal for space applications in the near term.

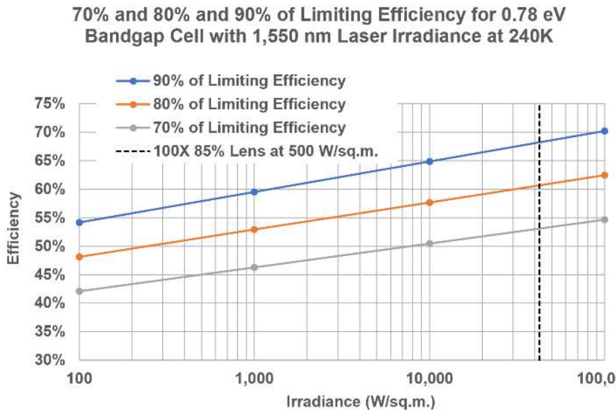


Fig. 9. Maximum Efficiency of Cell with 0.78 eV Bandgap

Fig. 10 shows similar results for the lower bandgap GaSb cell. Note that the efficiency values are lower because the cell bandgap (0.726 eV) is further offset from the photon energy (0.80 eV) of the laser than for the higher bandgap cell (0.78 eV). We also show an actual demonstrated efficiency value from Andreev [7] for this type of cell under this type of monochromatic irradiance. Note that this data point is slightly below the 70% of limiting efficiency curve and slightly to the

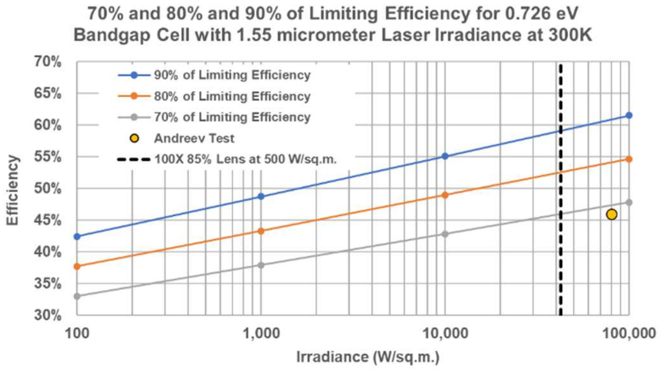


Fig. 10. Maximum Efficiency of Cell with 0.726 eV Bandgap

right of the 100X lens irradiance level shown by the dashed vertical line.

Fig. 11 shows similar results for the GaSb cell at 240K, corresponding roughly to the radiator thermal analysis results of Fig. 6. Note that a 50% cell efficiency is achievable at the 100X lens irradiance level shown by the vertical dashed line if the cell can reach about 72% of the limiting efficiency value. We believe this is an achievable goal for space applications in the near term for GaSb cells.

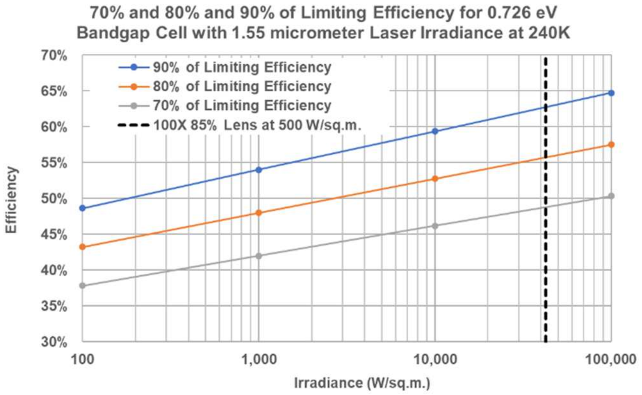


Fig. 11. Maximum Efficiency of Cell with 0.726 eV Bandgap

IX. ULTRA-LIGHT SPACE SYSTEM COMPONENTS

With the exception of the laser, we have already developed the key components of the proposed system under NASA-funded programs related to space photovoltaic concentrators [5]. For example, Fig. 12 shows a titanium mesh reinforced silicone lens with an aperture area of 10 cm x 10 cm. We have developed a process to make such lenses with a total mass of only 1.1 gram [5]. This technology can be applied to both the collimating lens and the concentrator lens for the laser power beaming system shown in Fig. 1.

We have also developed 10 cm x 10 cm graphene-based waste heat radiators with emittance-enhancing coatings that weigh about 2.7 grams for 100 µm graphene thickness and about 4.9 grams for 200 µm graphene thickness. A small 1 cm x 1 cm concentrator cell assembly including shielding, encapsulation, and adhesives would weigh less than 0.2 gram. The total of all these elements (lenses + radiators + cell assembly) would amount to less than 10 grams for a 10 cm diameter eye-safe and heat-safe beam providing a net electrical power output of about 1.7 Watts. Ultra-light deployment and support platforms have also been developed by major aerospace firms for our space photovoltaic concentrator systems [5]. These platforms could be adapted to both the transmitting end and the receiving end of the power beaming system shown in Fig. 1. For ground applications, cost trumps mass, and acrylic lenses and aluminum radiators can replace their more expensive space counterparts.

Fig. 12. Silicone Lens with Embedded Titanium Mesh

X. CONCLUSION

A novel modular, eye-safe, heat-safe laser power beaming system has been described and its performance characteristics have been quantified. We believe this new architecture represents an attractive option for power beaming applications in space and on the ground.

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