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Space Power by Laser Illumination of PV Arrays

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Introduction

There has recently been a resurgance of interest in the use of beamed power to support space exploration activities. This paper will examine the utility of photovoltaics and identify problem and research areas for photovoltaics in two beamed-power applications: to convert incident laser radiation to power at a remote receiving station, and as a primary power source on space-based power station transmitting power to a remote user.

A particular application of recent interest is to use a ground-based free-electron laser as a power source for space applications. Specific applications include: night power for a moonbase by laser illumination of the moonbase solar arrays; use of a laser to provide power for satellites in medium and geosynchronous Earth orbit, and a laser powered system for an electrical-propulsion orbital transfer vehicle. These and other applications are currently being investigated at NASA Lewis as part of a new program to demonstrate the feasibility of laser transmission of power for space.

Example Case: Laser Night Power for the Moon

Providing power over the 354 hour lunar night provides a considerable challenge to solar power concepts for a moonbase. While some systems can be run at reduced power, others, such as air recycling, may even have increased power consumption during the night. The storage required for night operation is the major mass component of a photovoltaic system. An alternative possibility is to beam power to the lunar base to eliminate the need for storage. Solar arrays on the lunar base can be illuminated by laser power beamed directly from the Earth. The advantage is that electric power is cheap on Earth, and there is no need to transport a large solar array or power beaming equipment to space.

No added elements are needed for the base night power system over the system used for daytime operation. The solar array needed to receive the beamed power is already in place. At each laser station, laser power is required for 12 hours a day for two-week periods. This allows ample time for laser refurbishment and preventative maintenance. The fact that the laser is on the Earth allows considerable design simplification; unlike in-space systems, where any failure is fatal, terrestrial systems can be easily repaired, so highly redundant systems are not required.

The best photovoltaic cells have been shown to convert 60% of monochromatic incident light at the optimum wavelength into electricity. The efficiency drops to zero for wavelengths much longer than the optimum. For wavelengths shorter than the optimum, the conversion efficiency for monochromatic light is approximately proportional to the wavelength.

The minimum spot radius of a transmitted laser beam is set by diffraction,

$$r_{spot} = 0.61\, d\, \lambda / r_{lens} \qquad (1)$$

The opacity of the atmosphere to short-wavelength ultraviolet places a lower limit to the wavelength at about 350 nm. A key element in achieving small spot sizes is the use of a large optical aperture on the ground system. For optimal systems, the lens size should be in the scale of meters. Pointing accuracy and atmospheric turbulence degrade the effective spot size. Achievable pointing accuracy is high enough that this is not a limiting factor. Atmospheric turbulence can be corrected by use of optical systems which correct for atmospheric distortion. Such techniques have been demonstrated to give nearly diffraction-limited performance.

Candidate laser technologies are the semiconductor diode laser and the free-electron laser.

The highest power GaAs diode lasers operate at about 795-820 nm, which is nearly optimal for existing silicon solar cells. Arrays of diode lasers have recently demonstrated power densities as high as 100 W/cm^2. 25-watt CW integrated arrays have been demonstrated. An array consisting of a very large number of individual diode lasers could yield the required power.

Free-electron lasers (FELs) have potentially very high high power and are, in principle, tunable over a range of wavelengths down to as low as <200 nm.

Consider a baseline system with a wavelength λ of 400 nm ($4 \cdot 10^{-7}$ m). The distance d at maximum is $4 \cdot 10^8$ m, and the lens diameter is 2 meters. For diffraction limited beam spread, the diffraction-limited spot radius at the moon is is 100 m. The illuminated area is 31,000 m^2.

For 100 kw of baseline daytime power, the required solar array area is about 400 m^2. This is augmented by supplementing the array area by a factor of four using fixed, reflective sheets of thin plastic. Libration, the apparent motion of Earth in the lunar sky, limits the maximum possible concentration achievable by a non-tracking concentrator. The total solid angle subtended by libration is 1.1 steradians; thus, the maximum concentration without tracking is 11x. The array area is then increased over that required for daytime power by an additional factor of two. The array intercepts 10% of the incident power, and the laser power needed is ~2 MW.

The required 2 MW could be provided, for example, by twenty 100-kw laser units, to allow any single unit to be taken off line without system failure. Twice as many stations will be required as are actually in use, since half will be on the wrong side of the Earth.

PV Issues

Eight issues are identified as subject areas for development in the photovoltaic receiver area:

1. Choice of cell type and material and verification of cell performance under laser (monochromatic) light.

Cell theoretical models must be made and measurements of cell parameters (efficiency; spectral response; intensity variation of efficiency; temperature coefficients) to verify the models.

2. Investigation of cell operation in pulsed mode

The duty cycle of the baseline free electron laser system is 10^{-6}, with a typical pulse width of 1 to 10 ns. Thus, the cell operates at extremely high power levels for very brief periods, separated by longer unilluminated periods. Cell operation depends on pulse width and rate compared to minority carrier lifetime (τ) of solar cell. If pulse spacing (1/rep rate) is less than τ, then the pulsed input is effectively continuous to the solar cell. If pulse spacing > τ, there are two cases:

pulse width > τ : solar cell reaches equilibrium during pulse.

pulse width < τ : solar cell does not reach equilibrium during pulse.

Since typical τ is 1-10 ns for GaAs and 10-100 µsec for Si, silicon cells and GaAs cells operate in different regimes under pulsed power conditions.

The pulse rate is high compared to the thermal time constant of the system. Overall, the system will behave thermally as a continuous wave system.

High peak power will produce series resistance losses by I^2R. The cell, system and PMAD resistance all may be important; the cell grid will have to be designed to handle peak current, not average.

3. Power management and distribution (PMAD)

The PMAD must be capable of utilizing power from pulsed input. Capacitance or inductance can be deliberately added to the system, either distributed or lump, to smooth the pulse. The RC time constant of the array, junction capacitance in the cell, and capacitance and inductance in the wiring will all increase the pulse width.

4. Ambient temperature

Lunar: Daytime maximum ~85°C, night minimum temperature ~100°K; satellites may see slightly lower temperature variations between eclipse and in-sun operation. The temperature coefficient for power conversion for monochromatic light is different than for solar spectrum, since the temperature coefficient of Eg leads to large changes in absorption with temperature near the band edge.

5. Array issues

PV Array design issues will have to be addressed; in particular, design for deployment; maintanance; dust avoidance, and optimum thermal design.

6. Design of cells for dual use.

For many applications (such as the lunar base described), the cells will be required to operate under laser illumination during "night" operation, and solar illumination during "day" operation.

7. Optimum design of cells for laser conversion

Trade-off of high-performance vs. llightweight, low efficiency arrays. The cell will be designed to maximize performance at wavelengths close to band edge, cells may include light trapping to maximize long-wave response. Cells design for high peak power levels may includes large coverage of grid metallization and use of a prismatic cover. Optimum thermal design is required to maximize α/ε.

8. Radiation Damage

Radiation preferentially damages the long wavelength response of a solar cell, which is the most efficient part for laser conversion. On the moon, there is some radiation damage effect due to solar flare protons. This is expected, on the average, to degrade the cells by a few percent per year on the average, although actual degradation will be in discrete events. Transfer vehicles will experience severe radiation damage effects due to crossing the Van Allen belts. This radiation damage will likely drive the mission mass due to the requirement of shielding. It will be important to evaluate the use of radiation-tolerant cells such as InP, radiation-tolerant cell design strategies, and the possibility of in-situ annealing (possibly using the ground based laser as the heat source) to periodically remove the radiation damage.

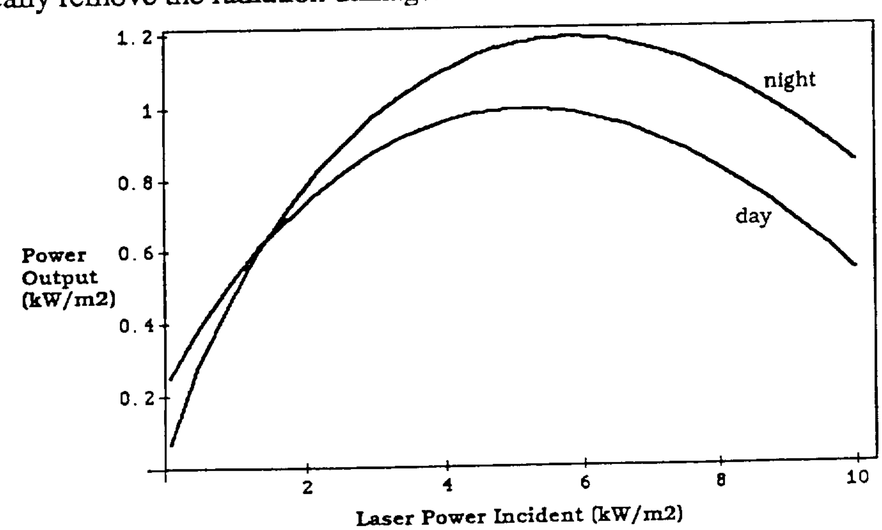

Figure 1.
Power output from a laser-illuminated GaAs array on the Moon.
The power produced by a PV array increases as the intensity of the laser illumination increases. The temperature rise at high power levels means that there is a maximum power density that can be achieved before the actual power decreases as the intensity of illumination increases. The maximum is higher at night, when the lunar ambient temperature is low and the array is not heated by the sun.

Table 1: PV Converters for Laser Beamed Power
Approaches

Flat-Plate Array	GaAs (Efficiency ~ 50%) or Si (Efficiency ~40%) Cell cost may be important for large areas and for GaAs cells Thermal management not required for power <~2 kW/m2 low pointing accuracy required (cosine loss)
Thin-Film Array	amorphous Si, $CuInSe_2$ or CdTe. Efficiencies will low (≤20%) Cost and Mass are low Roll-out "carpet" approach possible but needs development
Concentrator Array	GaAs developed; other III-V possible; High efficiencies (>70%?) Cell cost not a major driver since area is low Thermal management required High pointing accuracy required Dust is more of a problem

Table 2: PV Converters for Laser Beamed Power
Choice of Converters for VariousWavelength Choice

Wavelength Range		Cell
Visible	0.4 to 0.8 μ	η of Si or GaAs cells decreases linearly with λ. Specially designed cell will have high η and good temperature coefficient; development needed
GaAs Optimum	0.8 to 0.86 μ (GaAs) 0.8 to 0.90 μ (InP)	Optimum for GaAs; InP and a-Si; η of GaAs cells ~50%;temperature coefficient moderate
Si Optimum	0.8 to ~1.0 μ	Optimum for Si and $CuInSe_2$; η of Si cells ~40% Temperature coefficient worse
Nd:YAG	1.06 μ	Standard Si bad; a new cell design may give ok response should be okay for $CuInSe_2$ Optimum for InGaAs quaternary (development needed) η of $CuInSe_2$ cells ~20% Temperature coefficient worse
Near IR	1-2 μ	Specially designed cell needed; III-V quaternary or HgCdTe will have low η and poor temperature coefficient; development needed
Mid IR	>2 μ	Not practical for PV conversion Specially designed cell needed may need cooling to operate

Table 3: Radiation Environment

LEO
Negligible radiation; any cell type okay
(atomic oxygen and debris are the problem in LEO)

Transfer orbits
Pass through the radiation belts; high doses (mostly protons)--Si or GaAs cells with 3 mil cover will lose ~30% in ~100 days . Want radiation-resistant cell, concentrator, or shielding.

GEO
Moderate radiation; subject to solar flare protons and electrons from the outer fringe of belts. Standard Si cells can be used with coverglass; some degradation.

Moon
No trapped radiation; subject to solar flare protons
Expect slight degradation after large solar flares.