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PHOTEVOLTAIC RECEIVERS FOR LASER BEAMED POWER IN SPACE

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ABSTRACT

There has recently been a resurgence of interest in the use of beamed power to support space exploration activities. One of the most promising beamed power concepts uses a laser beam to transmit power to a remote photovoltaic array. Large lasers can be located on cloud-free sites at one or more ground locations, and illuminate solar arrays to a level sufficient to provide operating power. Issues involved in providing photovoltaic receivers for such applications are discussed

INTRODUCTION

There has recently been a resurgence of interest in the use of beamed power to support space exploration activities. One of the most promising beamed power concepts uses a ground-based laser to transmit power to a remote photovoltaic array.

Recently Landis [1,2] and Rather [3], working independently, proposed using a ground-based laser to provide power for a lunar base over the 354 hour lunar night. Laser illumination could also be used instead of the conventional battery system used to power a satellite during the eclipse period, or as a means to bring a satellite with degraded solar arrays back to full operational power [4].

Placing the laser on the Earth has several advantages:

(1) The mass of the laser system is relatively unimportant. Free electron lasers, for example, require a linear accelerator, which is likely to be extremely massive.

(2) The power efficiency of the laser is much less important. Power on Earth is ~1000 times less expensive to provide than power in orbit, and heat rejection is much easier on Earth than in space (a 10% efficient laser must reject 1 MW of heat for every 100 kW beam power).

(3) Maintenance is easier on Earth. To date no high-power laser systems run for long periods without an operator. A space-based laser must be designed to run without human intervention, while on Earth technicians and technical specialists are available and can work in a shirt-sleeve environment. Reliability can be easily verified without requirements for space qualification; unlike in-space systems, where any failure is fatal, terrestrial systems can be easily repaired, so highly redundant systems are not required.

(4) Systems are easier to develop for ground operation, where the operating conditions can be achieved without any extensive space simulation.

Using photovoltaic arrays as the receiver also has many advantages. Photovoltaics have been well tested in space, with a long record of operational use, have no moving parts, and can have extremely high efficiencies for conversion of monochromatic (laser) light at selected wavelengths.

APPLICATIONS

Several applications for laser-beamed power are shown in schematic in figure 1. Depending on the application and the requirements for redundance, lasers may be situated at one or several ground locations. The laser system includes a tracking system to follow the satellites (or moonbase), a lens or mirror of sufficient size to reduce the beam spread due to diffraction, and adaptive-optics to compensate for the atmospheric turbulence.

One application for laser power is to power a satellite during eclipse [4]. In geosynchronous Earth orbit (GEO), the maximum eclipse duration is nearly 70 minutes, or about 5 percent of the orbit, at the equinox. The solar array needed to receive the beamed power is already in place on the satellite. Laser power is required for only 90 days out of the year. This allows ample time for laser refurbishment and preventative maintenance. Likewise, supplementary power may also be transmitted to satellites with degraded solar arrays, in order to bring a partially functioning satellite up to full capability.

Another possible application is providing supplementary power or night power to a lunar base. Providing power over the 354 hour lunar night provides a considerable challenge to solar power system operation on the moon [2,5]. Use of a laser to illuminate the moonbase during night operation can considerably reduce the required mass of the power system [1-3]. The same array can be used for both daytime solar power and night laser power.

A third application for laser beamed power is to provide power for an electrically propelled orbital transfer vehicle (OTV). Electrical propulsion systems can have extremely high values of specific impulse compared to conventional chemical rocket propulsion, however, the required power can be extremely high, especially at high thrust levels. Such high power levels may be obtained by laser power beaming.

LASER AND OPTICAL SYSTEM

The minimum spot diameter of a transmitted laser beam is set by the diffraction limit,

$$D_{spot} = 2.44\ d\ \lambda / D_{lens} \qquad (1)$$

where D_{lens} is the diameter of the lens or reflector used to focus the beam, d the source to receiver distance, and λ the wavelength. The spot radius is here defined as the first zero in the diffraction pattern; this contains 84% of the beam energy. As discussed below, this limit can only be achieved if adaptive optics are used to eliminate atmospheric beam spread.

If the spot size is smaller than the receiving array, the laser wavelength is preferably chosen for optimum solar cell performance. If the diffraction-limited spot size is larger than the receiving array, it is desirable to decrease the wavelength to put more of the power on the array, even at the price of decreasing the efficiency.

Ten meter-scale mirrors of telescope quality are currently being produced [6]. In low Earth orbit (LEO), such a mirror diameter would allow a diffraction-limited spot on the order of 10 cm diameter; at geosynchronous orbit (GEO), eight meters diameter; and at the distance of the moon, the diffraction-limited spot would be about 80 meters diameter.

Pointing accuracy and atmospheric turbulence will degrade the laser spot size. Achievable pointing accuracy is high enough that this is not a limiting factor. Atmospheric turbulence limits the resolution limit of astronomical telescopes to slightly less than 1 second of arc, or about 4 microradians, increasing slightly at shorter wavelengths. At the distance of GEO, this would contribute about 135 m to the spot diameter; at the distance of the moon, about 1600 m.

Fortunately, adaptive optical techniques [7,8] have been developed to reduce the beam jitter and distortion due to atmospheric turbulence. A "pilot" beam is transmitted down through the atmosphere, and the distortions in the phase of the wavefront due to atmospheric turbulence are measured. Precisely opposite distortions are then introduced into the output mirror of the power beam. Since the transit time of a light beam traversing the atmosphere is much shorter then the scale time of atmospheric turbulence, such a system can in principle exactly compensate for the atmospheric turbulence. In actuality, effects such as limited temporal and spatial bandwidth degrade the performance of a system, however, quite good optical performance is possible. Ground to space compensation of atmospheric turbulence has been demonstrated using an argon-ion laser reflected from a mirror in low Earth orbit in the Low-power Atmospheric Compensation Experiment (LACE), with results showing nearly diffraction-limited optical performance.

The ability to compensate atmospheric turbulence rapidly degrades as the pathlength through the atmosphere increases, and it is likely that the maximum angle from zenith for which the system can be used will be in the range of 45° to 60°.

Some additional defocusing effects are encountered by high energy lasers, such as thermal blooming [7]. For the power levels discussed here, however, the intensities are below the threshold for severe distortion.

Lasers to be considered must operate in the wavelength range centered around the visible spectrum in which the atmosphere is nearly transparent. Atmospheric absorption by ozone and Raleigh scattering set the minimum wavelength at about 350 nm. This is shown in figure 2. The maximum wavelength is set by the response of the solar cells, about 850 nm for GaAs cells and about 950-1000 nm for Si cells.

Several types of lasers are possible for the power source [9]. Free-electron lasers (FELs) offer the possibility of megawatt and higher power levels in a single unit, with the possibility of tuning the wavelength to the solar cell and atmospheric transmission. A high power free electron laser is currently under construction and should be operational by 1995; this laser is capable of being adapted to operation in the desired range near the 850 nm efficiency peak of typical photovoltaic cells. Two concepts for free electron lasers exist; the "RF" FEL and the "induction" FEL. As shown in figure 3, both types operate in a pulsed output mode with extremely high peak powers. The RF FEL produces a series of micropulses), typically ~20-40 picoseconds wide, with a spacing of ~15 nanoseconds. The induction laser produces wider pulses, typically ten to fifty nanoseconds long, with a spacing of ~20 to 50 microseconds. The RF FEL is more easily made at low average power levels (<1 MW), while induction FEL is expected to be more easily scaled to very high power levels (>10 MW).

Alternatively, the semiconductor diode laser [9,10] also operates at high efficiency in the right wavelength range, and can be run in true continuous wave operation. Semiconductor diode laser arrays of about 100 watts average power have been constructed, and research is continuing into higher power levels. For a space power system, very large numbers such diode arrays would be operated in phase to provide the power levels needed; the problems of phasing such large arrays have not yet been solved.

PHOTOVOLTAIC RECEIVERS

Existing solar cells have peak response to monochromatic illumination at about 850 nm (for GaAs cells) and about 950 nm (for Si cells). For wavelengths shorter than the peak, the efficiency will decrease roughly linearly with wavelength. For longer wavelengths, the efficiency will drop rapidly to zero. Response is zero for photon energies lower than the bandgap, or wavelengths longer than the cutoff wavelength λ_c:

$$\lambda_c = 1.24 / E_g \tag{2}$$

for E_g the bandgap in electron volts and λ_c in microns.

Thus, it is important to select a wavelength near the optimum value. Near the optimum wavelength, the response of a solar cell to monochromatic illumination is much higher than the efficiency produced by the broad solar spectrum. As discussed below, high efficiency GaAs cells can produce over 50% efficiency under laser illumination [11-13], and conventional Si cells over 40% [12].

Wavelengths away from the range of about 700-950 nm require development of different solar cell materials. For example, there is some interest in using a laser with a wavelength greater than 1.4 µm. These long IR wavelengths are in the "eyesafe" range, where the opacity of the eye does not allow light to penetrate to the retina, and hence the safety restrictions are considerably less stringent. Unfortunately, photovoltaic receivers become both less efficient and more sensitive to temperature as the wavelength increases.

For some systems it may be desirable to decrease the wavelength to the minimum allowed by the atmospheric transparency (figure 2). This decreases the diffraction-limited spot-size and also allows the use of solar cells of higher bandgap, with correspondingly lower sensitivity to temperature.

Table 1 shows some of the options for photovoltaic cells which might be used for laser energy conversion in various wavelength ranges. For short wavelengths, most solar cells will respond. Efficiency can be optimized by using a material with the widest possible bandgap consistent with the cutoff shown in equation 2. For long wavelengths, low bandgap materials such as gallium antimonide [14] or InGaAs must be used.

There are three basic approaches to making photovoltaic arrays for use in space, as shown in Table 2. The conventional approach is to use a "flat-plate" array, consisting of individual cells electrically interconnected. An alternative is to use thin-film cells manufactured directly on a thin flexible substrate [15], and monolithically interconnected in place. This has the potential for lower costs and lighter weight, but has not yet been demonstrated in space. Thin-film cells are also typically more tolerant to radiation than conventional technologies. A third approach is to concentrate the incident light onto a small area cell. This approach allows the individual solar cells to be more expensive, and allows the cells to be well protected from radiation. However, thermal management of concentrator systems can be a major issue, especially for high incident power levels.

Radiation tolerance can be an important factor for some uses in space, especially for transfer orbits between low earth orbit (LEO) and geosynchronous orbit (GEO). This is summarized in table 3.

Table 1. PV Converters for Laser Beamed Power

Choice of Converters for VariousWavelength Lasers

Wavelength Range		Cell Characteristics
Visible	0.4 to 0.8 μ	η of Si or GaAs cells decreases linearly with λ. Specially designed cell will have high η (potentially over 70%) 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; η of Si cells ~40% Temperature coefficient slightly worse than GaAs
Nd:YAG	1.06 μ	Standard Si poor; a new cell design may give ok response near optimal for $CuInSe_2$ thin film cells; η of $CuInSe_2$ ~20% InGaAs quaternary possible (development needed) Temperature coefficient worse
Near IR	1-2 μ	Specially designed cell needed; Ge, GaSb, HgCdTe,InGaAs, or specially developed quaternary will have low η and poor temperature coefficient; development needed
Mid IR	>2 μ	Not practical for PV conversion Specially designed cell needed; likely to need cooling to operate

Table 2. PV Arrays 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/m^2

low pointing accuracy needed (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 3. Radiation and Environmental Effects

Low Earth Orbit

Low radiation; any cell type okay; Atomic oxygen and debris are problem.

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 . Requires a radiation-resistant cell, concentrator, or shielding.

Geosynchronous Orbit

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.

Dust can be a problem.

THEORETICAL PERFORMANCE OF SOLAR CELLS UNDER LASER ILLUMINATION

OPERATION OF SOLAR CELLS UNDER PULSED ILLUMINATION

Free electron lasers inherently run in a pulsed mode, where the pulses may be very short and the pulse rate high enough that sufficient average power is achieved. For this mode of operation, the peak power may be much higher than the average power. For example, for the induction FEL discussed above, with a pulse width of 50 nS and pulse spacing 50 μS, the peak power level is a thousand times higher than the average power. For this case, it is important that the photovoltaic cell be capable of operating under high-peak power operation.

The characteristic response time of a photovoltaic cell to pulsed excitation is related to the minority carrier lifetime [16]. Typical minority carrier lifetimes for GaAs solar cells are in the range of ~10 to 100 nS for undamaged material. For silicon solar cells, lifetimes are in the range of ~10-100 μS for a cell without radiation damage, and as short as 1 μS or less for cells after radiation damage. If the time between pulses (1/frequency) is less than the minority carrier lifetime, the cell responds to the laser effectively as continuous wave operation. If the pulse separation is greater than minority carrier lifetime, the cell responds to each individual pulse at a concentration equal to the peak of the pulse, which can be 10^3 to 10^4 times higher than the average power.

For the induction FEL discussed above, the pulse spacing is much greater than the minority carrier lifetime in GaAs, and hence the cell will respond to the individual pulses. A silicon cell without radiation degradation of lifetime, on the other hand, will respond to the average power. For the RF FEL, the pulse spacing is comparable to a minority carrier lifetime in GaAs. Information from pulsed annealing of semiconductors indicates that the damage (melting) occurs at an intensity of about 10^7 W/cm^2 for a pulse length of 50 nS [17]. Although this value depends on the absorption depth, typical intensities considered for power beaming are many orders of magnitude lower, and surface damage is not likely to be a problem. Since thermal time constants are much longer than typical pulse durations under consideration, the thermal response of cell is to laser average power.

For the induction FEL, where the pulse separation is much greater than the minority carrier lifetime, the peak power during the pulse will be very high. This means that series resistance will be a very important factor in the efficiency. The output power of the cell is proportional to the current times the voltage, while the losses due to series resistance are proportional to the current squared times the resistance. Thus, the fractional loss to resistance increases linearly with the peak power:

$$P_{resistance}/P_{output} = IR/V \tag{3}$$

Therefore, for this pulse format the cell must be designed to minimize series resistance. For example, a high-efficiency GaAs cell at 100 mW/cm^2 (roughly one sun) laser intensity would produce a current density of 0.065 A/cm^2, with an operating voltage near 1 volt and series resistance of 0.05 Ω-cm^2. At 150 times this current, fifty percent of the cell power will be lost by resistance. Thus, at one sun average intensity the ratio of peak power to average power (*i.e.,* one over the duty cycle) cannot be more than 150 before series resistance losses dominate the power. Cells designed for the induction FEL duty cycle will have to have much lower series resistance than standard non-concentrator solar cells.

Operating under high peak concentration, the cell open-circuit voltage will increase logarithmically (equation (14)), which will increase the efficiency slightly. This increase will be lost due to dark reverse current when cell is not illuminated if the power management and distribution system maintains a constant voltage on the array. This loss can be avoided if reverse current through the cell is blocked, *e.g.*, by a low-leakage, low-loss blocking diode.

For the power profile delivered to the user, the RC time constant of the solar cell must also be taken into account. The junction capacitance of the solar cell p-n junction tends to average the laser pulse. A typical solar cell junction capacitance $0.1\mu F/cm^2$, and a typical resistance may be in the range of 0.01 to 0.1 Ω-cm^2 (may be lower for concentrator cells). Thus, the expected RC time constants for the photovoltaic elements are on the order of 1 to 10 nS. This is for the solar cell alone (*i.e.*, short circuit conditions). The array, wiring, and load will add resistance, distributed capacitance and inductance, thus increasing the pulse width seen by the power management system.

For short pulses, the inductance of the interconnect wiring will also be a significant factor. Inductance will increase the time required for the current to increase from zero to the maximum power point. The maximum current rise rate is:

$$dI/dt = V/L \tag{4}$$

where V is at most the cell open circuit voltage. High inductance will tend to hold the cell at V_{oc}. For a rise time of ~10 nS, the maximum allowed inductance will be nano-henries or less per cell.

CALCULATION OF EFFICIENCY

The efficiency of a solar cell for monochromatic (laser) illumination is much higher than that under solar illumination. This is primarily due to two factors: (1) the sun produces a wide-band spectrum, and so all of the solar photons cannot be used efficiently in a solar cell with a single bandgap. Photons with energy less than the bandgap will not be absorbed, and for photons with energy greater than the bandgap, all of the energy greater than the bandgap energy will be lost. The fraction of the solar energy absorbed in the form of electron-hole pairs in a single bandgap solar cell is at most 50%. For a monochromatic wavelength, however, all of the photon energy can be usefully absorbed. (2) In general, a solar cell will only have high quantum efficiency over a limited range. A laser can be tuned to a wavelength where the quantum efficiency is close to unity. As a result, the efficiency of a solar cell under monochromatic illumination at a wavelength near the spectral response peak can be more than twice the solar efficiency.

The short circuit current density of a photovoltaic cell under monochromatic illumination is:

$$J_{sc}(\text{laser}) = q\, N\, QE \tag{5}$$

where

$$N = P_{in}/h\nu \tag{6}$$

and

$$h\nu = q\,(1.24/\lambda) \tag{7}$$

thus,

$$J_{sc}(\text{laser}) = QE\ P_{in}\,(\lambda/1.24) \tag{8}$$

where J_{sc}(laser) = short circuit current in A/cm^2, q = electron charge, N = photons/cm^2/sec, $h\nu$ = energy per photon in eV, λ = wavelength in microns, and QE= (external) quantum efficiency at the wavelength of interest. For high efficiency solar cells, this quantum efficiency will be very close to unity.

In principle, monochromatic performance can be calculated from the solar cell power:

$$P = V_{oc}\ FF\ J_{sc} \tag{9}$$

where P = power in watts, V_{oc} = open circuit voltage in volts, and FF = fill factor. Under laser illumination, the power is thus:

$$P_{laser} = V_{oc}\ FF\ QE\ P_{in}\,(\lambda/1.24) \tag{10}$$

and so:

$$\eta_{laser} = P/P_{in} = Voc\ \ FF\ QE\ (\lambda/1.24) \qquad (11)$$

Since photovoltaic cells are usually tested under solar illumination, it is useful to be able to calculate efficiency under monochromatic (laser) illumination from values measured under simulated solar illumination. This is quite straightforward, given that the efficiency, short circuit current, and quantum efficiency at the wavelength of interest are measured. We have

$$\eta_{solar} = P/P_{solar} = V_{oc}\ \ FF\ J_{sc}/P_{solar} \qquad (12)$$

and thus:

$$\eta_{laser} = \eta_{solar}\ \ P_{sun}/J_{sc}\ \ (QE)(\lambda/1.24) \qquad (13)$$

where J_{sc} is the short circuit current density measured under the solar spectrum and P_{sun} is the solar intensity, equal to 0.137 W/cm^2 for AM0 measurement, and 0.100 W/cm^2 for measurements under ASTM AM1.5 conditions.

For an example, one of the highest efficiency solar cells manufactured to date has been reported by Tobin and co-workers [18]. For this cell the AM0 efficiency is 21.7% (25°C). The short circuit current is 0.0331 A/cm^2, and the external quantum efficiency is 0.85 at a wavelength of 0.85 µm, which is near the peak of the spectral response. Hence, the multiplying factor to convert solar efficiency to laser efficiency equals 2.41. The efficiency under a laser at 850 nm is thus expected to be 52.3%. This number is close to reported values; *e.g.*, 53% efficiency reported for GaAs solar cells under 806 nm illumination [11].

For silicon cells, some of the best cells currently made are the "PERL" cells reported by Green and co-workers [19]. For the best of these cells, the efficiency is 24.2% at AM1.5, the short circuit current is 0.0429 A/cm^2, and the external quantum efficiency about 93% at 1 µm. Hence, the multiplying factor to convert solar efficiency to laser efficiency equals 1.75. The efficiency under a laser at 1000 nm is thus expected to be 42.3%.

This calculation will give the efficiency at the incident laser intensity which gives same short circuit current as the measured value, and at the same temperature as the standard measurement. For other short circuit currents, the change of efficiency with intensity must be included. In general this is a small correction. As long as the cells are not operating in the regime where series resistance is a significant factor in the efficiency, and the changes in fill factor can be ignored, the change in efficiency can be approximated by the theoretical voltage increase:

$$\Delta V = 25\ mV\ \ln[J_{sc}(laser)/J_{sc}(solar)] \qquad (14)$$

In this approximation, the efficiency is thus multiplied by a factor K(intensity):

$$K(intensity)= (1+\Delta V/V) = 1 + (0.025/V_{oc})\ \ln[J_{sc}(laser)/J_{sc}(solar)]. \qquad (15)$$

From equation (3), this efficiency multiplier is:

$$K(intensity) = 1 +(0.025/V_{oc})\ \ln\ [(QE\ \ P_{in}\ \lambda/1.24)/J_{sc}(solar)] \qquad (16)$$

As an example, the multiplier K is calculated for the GaAs cell discussed above assuming the intensity of illumination is 1 W/cm^2. The open circuit voltage of this cell is 1.033 V. K(intensity) is 1+0.024 ln[17.6] = 1.0697. The efficiency of the cell under laser light at 1 W/cm^2 (25°C) is thus expected to be 55.9% (assuming series resistance effects can be neglected).

TEMPERATURE EFFECTS

Another correction to efficiency is that of operating temperature. As the temperature increases, the efficiency of conversion decreases; this decrease is characterized by the temperature coefficient of efficiency. For convenience we define the normalized temperature coefficient of efficiency to be $(1/\eta)d\eta/dT$, and it is typically negative. Clearly, $(1/P)dP/dT = (1/\eta)d\eta/dT$. Note that the unnormalized temperature coefficient of efficiency for monochromatic light $d\eta/dT$ is not the same for monochromatic light as for the solar spectrum, while to a rough approximation the normalized coefficient $(1/\eta)d\eta/dT$ is the same. The decrease in efficiency is:

$$\eta(T) = \eta(25°C) + \eta(25°C)\,[(1/\eta)d\eta/dT]\,[T-25°C] \qquad (17)$$

This equation does not hold at very low temperature (typically under -100°C), where the temperature dependence of efficiency becomes non-linear. In general, spacecraft systems do not operate in this regime except in extremely low intensity conditions, such as operation near the outer planets.

The temperature coefficient is comprised of three components; variations in open circuit voltage, short circuit current, and fill factor. However, for mono-chromatic illumination the variation in short circuit current is only due to changes in quantum efficiency, which is only weakly defendant on temperature except for cells well on the long-wavelength side of the efficiency peak. The change in fill factor is also slight. The only significant factor is the change in voltage, and thus $(1/V_{oc})dV_{oc}/dT = (1/\eta)d\eta/dT$. For monochromatic illumination, the temperature coefficient of open circuit voltage is [20]:

$$dV_{oc}/dT = (V_{oc}-E_g)/T - 3k/q - \alpha T\,(T+2\beta)/(T+\beta^2) \qquad (18)$$

where the first term is the most important. It is seen that as the solar cell open circuit voltage improves, the temperature coefficient becomes smaller. (Values for the constants α and β, related to the bandgap variation with temperature, are given in reference 19.)

Solar cell operating temperature can be an important consideration for many applications, and puts a limit on the highest intensities possible. Figure 4 shows a simple thermal model of a solar array in Earth orbit. The array is heated by irradiation from the sun, by solar radiation reflected from the Earth ("albedo"), by infrared radiation emitted by the Earth, and by the illumination of the laser itself. Each of these sources is characterized by an absorption constant (α). The array emits thermal radiation to space with a T^4 temperature dependence, and a fraction of the incident light energy is converted to electricity proportional to the efficiency.

Increasing the temperature of the array results in a lower conversion efficiency, which in turn means that more of the incident laser power is dissipated as heat. Thus, this problem is highly non-linear.

Figures 5 and 6 shows a result of applying this model, using a standard efficiency of 50% at 25°C and a temperature coefficient $(1/\eta)d\eta/dT$ of 0.0025. This is a linearized model, and does not include series resistance. The temperature increases (fig. 5), and the efficiency decreases (fig. 6), as the laser intensity increases. Two curves are plotted, where the "day" curve is a worst-case condition where the sun is shining on the back side of the array, adding heat but providing no power. A somewhat more comprehensive model gives similar results [21]. Figure 6 shows the power output as a function of illumination intensity. It is interesting to note that the power output increases as input power increases only to a certain maximum value, and above this maximum the output power actually decreases as the input intensity increases. This is because the heating of the cell decreases the efficiency more than the added power increases the output.

TECHNICAL ISSUES TO BE ADDRESSED

Many technical issues must be addressed before high-efficiency transmission of power by laser can become practical in operational use. Engineering and demonstration of high reliability laser, adaptive optic systems, mirrors, and spacecraft systems are of great importance. With respect to the photovoltaic receivers, several issues deserve consideration.

1. Prediction of monochromatic performance

Need good theoretical photovoltaic cell models and measurements of cell parameters: efficiency; spectral response; intensity variation of efficiency; temperature coefficients. Experimental confirmation of the theoretical models are needed.

2. Operation in pulsed mode

The duty cycle of free electron laser will be on the order of 10^{-3} to 10^{-4}, with pulse width = 10-50 nS for an induction FEL, and 20-40 pS for a RF FEL. The response of solar cells to such pulse operation must be modeled theoretically and experimentally verified. High peak power will produce series resistance losses proportional to the peak power squared. The cell, system and PMAD resistance all may be important; the cell grid will have to be designed to handle peak current, not average. Increased performance is possible if dark reverse current is suppressed when cell is not illuminated.

3. Solar Cells for Long Wavelength Laser

If the laser wavelength is not chosen to match an existing solar cell, a solar cell material will have to be chosen based on the laser wavelength. Operation at 1060 nm (Nd:YAG laser) requires a light-trapping silicon cell, or a new material. Operation in 1700 nm (eyesafe) regime requires low-bandgap PV material such as InGaAs, Si, and GaSb. Low bandgap materials have better response to concentration but worse response to temperature; avoiding high temperature operation is critical. Low bandgap cells may need advanced thermal management.

4. Temperature

The thermal environment must be modeled and the solar cell response under temperature verified. Lunar operation must include both day and night temperatures; orbital operation must include eclipse and in-sun temperatures. The temperature coefficient for power conversion for monochromatic light may be different than for solar spectrum; the temperature coefficient of E_g leads to large changes in absorption with temperature near the band edge. Monochromatic temperature coefficient as a function of intensity should be theoretically derived and compared with experimental values. The possibility of designing solar cells to have low temperature coefficients should be addressed if high performance is required at high laser intensities. This can be accomplished by increasing the bandgap, at the price of requiring shorter wavelength lasers. An advanced thermal design may be helpful.

Finally, the cell operating lifetime is an issue for most systems. Thermal degradation mechanisms include both degradation due to mechanical stress due to thermal cycling, and degradation due to long exposures at high temperature.

5. Array Issues.

A solar array design must be made taking all of the engineering factors into account. A choice must be made between planar and concentrating arrays for receivers. Questions to be answered include finding the optimum intensity, refractive vs reflective concentrators, the possible advantages in weight of using thin-film solar arrays, and the possibility of low cost concentration by lightweight fixed mirrors.

For a lunar base, the motion of Earth in sky (period approximately 29 days) limits the maximum possible concentration achievable by a non-tracking concentrator. The amount of motion is ±7.6° E-W ("libration"); ±6.7° N-S ("nodding"), leading to a total solid angle of 1.1 steradians. Thus, the maximum concentration without tracking = 11x. For an orbital transfer vehicle: concentration requires tracking. The required slew rate in LEO is on the order of 20°/minute. In higher orbits this decreases; at GEO the source is stationary.

The PV array must be designed for deployment and maintenance. There is a trade-off of small, high-performance arrays vs. large, lightweight, low efficiency arrays. For lunar surface arrays, dust avoidance or clearing must be included. For high intensity, an optimal thermal design must be used.

6. Power management and distribution (PMAD)

The power management system must be capable of making power from pulsed input. Capacitance or inductance can be deliberately added to the system, either distributed or lump, to smooth the pulse. The question of whether the pulse format allows an all-AC PMAD system possible without DC rectification should be addressed.

Another issue concerns the fact that the illumination intensity will not be uniform across the surface of the array, but will have the highest intensity in the center of the distribution and lower intensity toward the edges. This will require a power management system capable of dealing with non-uniform illumination

7. Optimum design of cells for laser conversion

There remain many unsolved problems in increasing the efficiency of solar cells for monochromatic light. For many applications it is desirable to design the cell for both laser and solar conversion, to allow use of solar power when it is available, and laser power during the eclipse or night operation.

Design issues include designing for peak performance at close to band edge to maximize performance, effective use of light trapping to maximize long-wave response, and optimized AR coatings for long-wave response. For high power applications and for pulsed application in the lifetime range where the cell responds to peak power, it will be necessary to design the device for high peak power. This implies use of a high metallization coverage, and likely use of a prismatic cover or other system to avoid grid coverage losses. Optimum thermal design requires rejection of the incident solar IR without increasing the laser reflectance; and maximization of the thermal emissivity.

Finally, new cell materials and new cell designs for higher efficiency and lower cost should be considered.

8. Radiation Damage

Radiation preferentially damages the long wavelength response of a solar cell, which is the most efficient part for laser conversion. It will be important to consider use of radiation-tolerant cells such as InP or $CuInSe_2$ for belt-crossing missions and to evaluate cell design strategies for high radiation tolerance.

CONCLUSIONS

It is possible to eliminate or reduce the energy storage system mass of a photovoltaic power system in space by illuminating the photovoltaic arrays by a ground based laser during the period when the cells are not illuminated by the sun. For some applications, this may significantly reduce the power system mass. There are many issues involved in the selection of a photovoltaic cell for the conversion of laser radiation, including the effects of pulsed illumination, the temperature coefficient of operation, and the radiaiton damage. Many research issues remain to be addressed.

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Appendix: Effect of bandgap on efficiency and temperature coefficient

For system design, it is desirable to know the potential efficiency of a cell with a bandgap optimized for a particular wavelength. A complete calculation includes the variation of material parameters with bandgap, including the mobility, minority carrier lifetime and optical absorption of real materials. Results of a model using the diode equation with bandgap variation of I_o is provided by Olsen *et al.* [ref. 10]. This is plotted in figure 8 along with experimental efficiencies of existing cells. Real cells are less efficient than the theoretical maximum but show the same trend of efficiency with wavelength.

It is sometimes useful to estimate the efficiency of a cell of one bandgap from measured performance parameters of a cell with a different bandgap, without accounting for the effects of real material properties. Given the monochromatic performance of a cell of one bandgap, that of another bandgap can be estimated by a scaling law.

The bandgap scaling law is derived from the following premise:

If the photon flux is kept the same and the photon energy is scaled with the bandgap, then the performance of two cells will be the same if the ratio of bandgap to thermal voltage (E_g/kT) is kept fixed.

Thus, estimating the performance of a cell at bandgap E_g' from measured performance of one at $E_g(0)$ involves scaling the appropriate parameters by the ratio $E_g'/E_g(0)$. The bandgap is scaled by the photon energy, or inversely with the wavelength:

$$E_g'/E_g(0) = \lambda_0/\lambda' \qquad \text{(A1)}$$

Constant photon flux means scaling the intensity I (W/m^2) linearly with bandgap:

$$I' = I(0)\,[E_g'/E_g(0)] \qquad \text{(A2)}$$

(Since the intensity has a logarithmic effect on the efficiency, this is a small correction and can usually be ignored.)

The (log) intensity coefficient scales inversely with bandgap:

$$d\eta/d(\ln I)' = [d\eta/d(\ln I)]_o\,[E_g(0)/E_g'] \qquad \text{(A3)}$$

Constant E_g/kT means scaling the (absolute) operating temperature linearly with the bandgap:

$$T' = T_o\,[E_g'/E_g(0)] \qquad \text{(A4)}$$

Since temperature has a linear effect on efficiency, this is a major correction.

The normalized temperature coefficient scales inversely with bandgap:

$$[(1/\eta)d\eta/dT]' = [(1/\eta)d\eta/dT]_o\,[E_g'/E_g(0)] \qquad \text{(A5)}$$

To compare cells of different bandgaps at constant temperature, the performance must be corrected for temperature effect:

$$\eta'(T) = \eta(T')\,[1+[(1/\eta)d\eta/dT]'\,\Delta T] \qquad \text{(A6)}$$

Example:

Assume a GaAs cell (E_g=1.42 eV) has an efficiency of 50% at 25°C (298°K) under an illumination of 200 mW/cm^2 at 900 nm wavelength, and a temperature coefficient of $(1/\eta)d\eta/dT = -0.0015$ °K^{-1}.

A hypothetical germanium cell (E_g=0.66) with the same performance as the GaAs cell would scale by a factor of (0.66/1.42)=0.465. Thus at a wavelength of 1940 nm and an intensity of 90 mW/cm^2, the performance would be 50% at an operating temperature of 139°K. The temperature coefficient $(1/\eta)d\eta/dT' = -0.0032$ °K^{-1}. To correct this back to 25°C, assuming that the temperature coefficient is linear over the required range, the temperature correction is (-0.0032 °C^{-1}) (154°K)=0.5. The cell loses half its efficiency due to temperature; the 25°C efficiency is 25.1%.

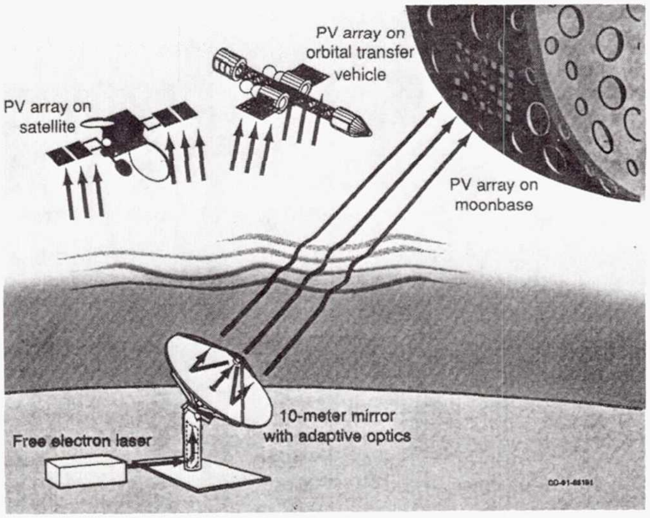

Figure 1.—Applications for earth to space power beaming by laser.

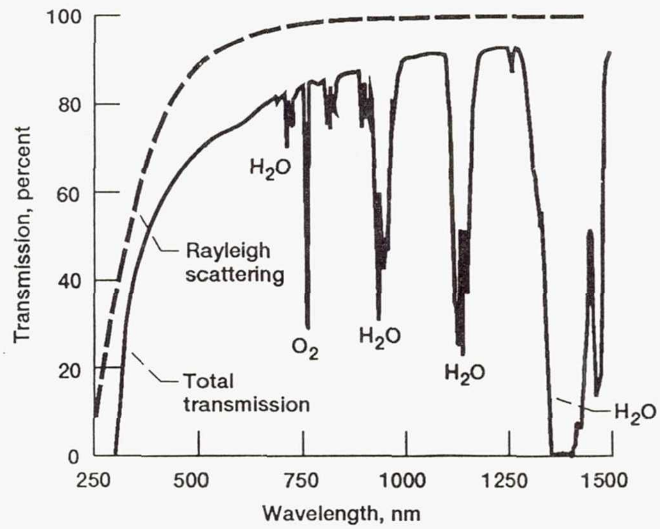

Figure 2.—Atmospheric transmittance (in percent) versus wavelength.

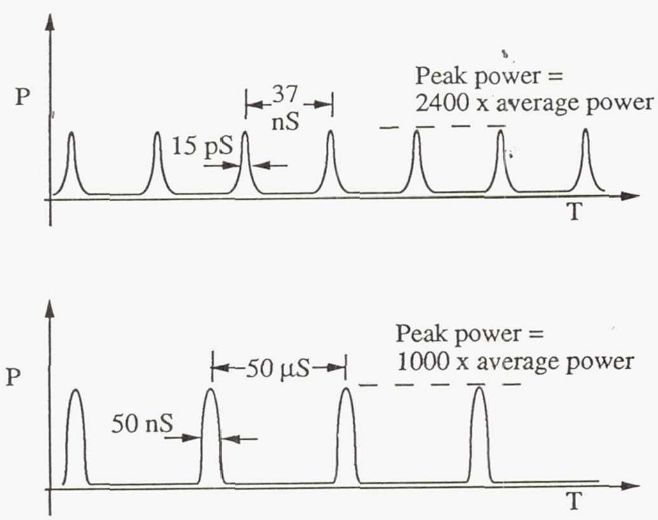

Figure 3.—Pulse format for RF (Boeing APLE laser, top) and induction (data from SRL, bottom) free electron lasers.

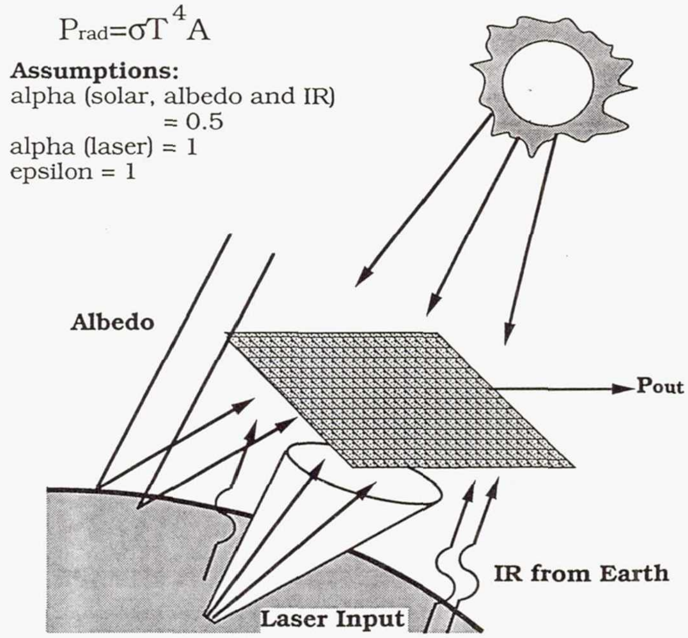

Figure 4.—Thermal model of a solar array in low Earth orbit.

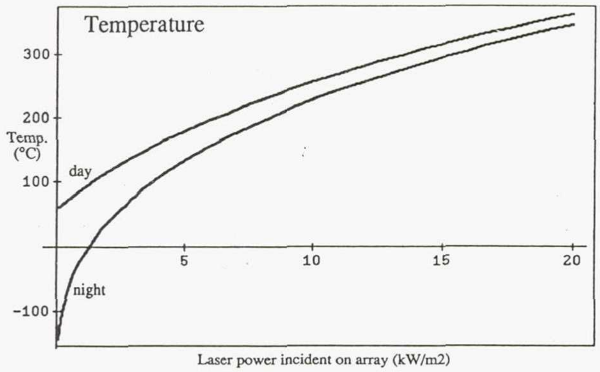

Figure 5.—Temperature of the solar array model as a function of incident laser intensity (two-sided thermal radiation).

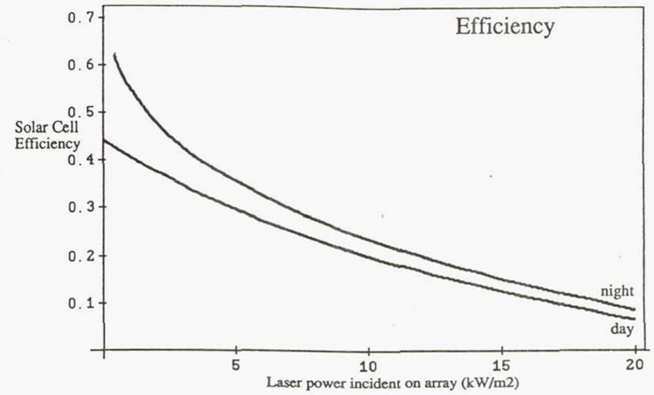

Figure 6.—Laser conversion efficiency of the solar array model as a function of incident laser intensity.

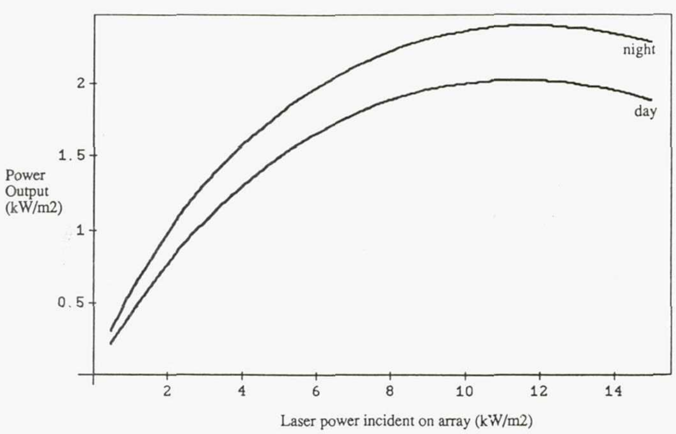

Figure 7.—Power output of the solar array model as a function of incident laser intensity.

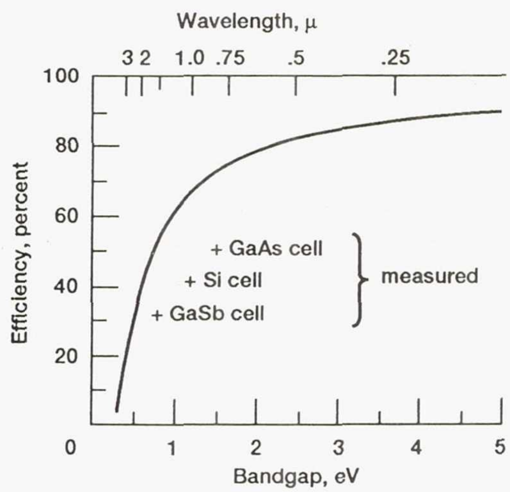

Figure 8.—Theoretical conversion efficiency of a photovoltaic cell for monochromatic light as a function of the bandgap of the material (after Olsen et al.). Also shown are measured conversion efficiencies for three cell types: GaAs (850 nm), Si (950 nm), and GaSb (1500 nm).

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13. ABSTRACT *(Maximum 200 words)*

There has recently been a resurgence of interest in the use of beamed power to support space exploration activities. One of the most promising beamed power concepts uses a laser beam to transmit power to a remote photovoltaic array. Large lasers can be located on cloud-free sites at one or more ground locations, and illuminate solar arrays to a level sufficient to provide operating power. Issues involved in providing photovoltaic receivers for such applications are discussed.

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