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Photovoltaic Receivers for Laser Beamed Power in Space

Geoffrey A. Landis*
Sverdrup Technology, Inc., Cleveland, Ohio 44135

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.

Nomenclature

D_{lens} = diameter of the lens or reflector
D_{spot} = spot radius (defined as first zero in the diffraction pattern)
d = source-to-receiver distance
E_g = solar cell bandgap, eV
FF = curve fill factor (dimensionless)
$h\nu$ = photon energy, eV
I = current (at operating point; during a pulse), A
J_{SC} = short-circuit current density, A/cm²
K(intensity) = multiplication factor to account for increase in efficiency due to intensity
k = Boltzmann constant
L = inductance, H
(laser) = indicates value measured under monochromatic (laser) illumination
N = photon flux, photons $cm^{-2}s^{-1}$
P = power, W
P_{in} = input power, W/cm²
$P_{resistance}$ = power lost to resistance, W
P_{sun} = solar intensity, equal to 0.137 W/cm² for AMO measurement and 0.100 W/cm² for measurements under ASTM AM1.5 conditions
QE = internal quantum efficiency at selected wavelength (electrons/photon)
q = electron charge, C
R = series resistance, Ω
(solar) = indicates value measured under solar illumination
T = temperature, K
V_{oc} = open circuit voltage, V
V = voltage at the cell operating point, V
α = constant related to the bandgap variation with temperature
β = constant related to the bandgap variation with temperature
ΔV = theoretical voltage increase due to intensity, V
η = conversion efficiency of solar cell
λ = wavelength, nm
λ_c = cutoff wavelength, nm
$'$ = indicated value for changed value of bandgap

Subscript
0 = baseline value

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*Senior Engineer, NASA Lewis Research Center, Aerospace Power Systems Group.

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-h 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.[4,5] Demonstration of the technology to provide laser power to photovoltaic (PV) arrays in space is the object of the space laser energy program (SELENE), a recently initiated NASA project.

Placing the laser on the Earth, rather than in space, 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 than in space. 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 (or at least clean-room) environment. Reliability can be easily verified without requirements for space qualification; unlike in-space systems, where any failure is fatal, minor component failures on terrestrial systems can be easily required, 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 Fig. 1. Depending on the application and the requirements for redundancy, lasers may be situated at one or several ground locations. The laser system includes a track-

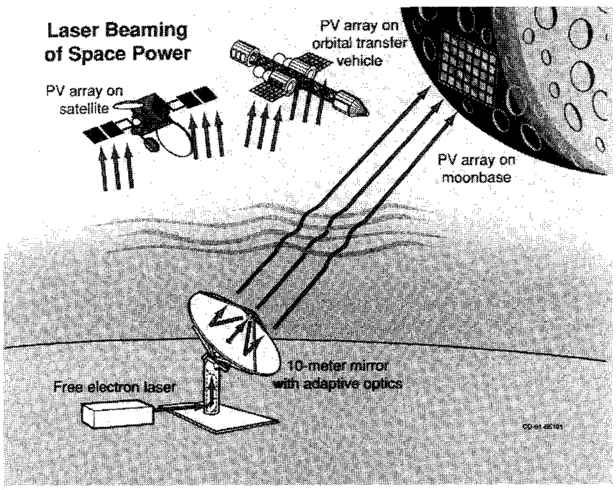

Fig. 1 Applications for Earth to space power beaming by laser.

ing 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 min, or about 5% 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-h lunar night provides a considerable challenge to solar power systems operation on the moon.[1,6] Use of a laser to illuminate the moonbase during night operation can considerably reduce the required mass of the power system. The same array can be used for both daytime solar power and night laser power.

A third application 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

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

The spot radius defined 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 may be desirable to decrease the wavelength to put more of the power on the array, even at the price of decreasing the efficiency.

Ten-m scale mirrors of telescope quality are currently being produced.[7] For low Earth orbit (LEO) altitude, such a mirror diameter would allow a diffraction-limited spot on the order of 10-cm diam; at GEO, 8-m-diam; and at the distance of the moon the diffraction-limited spot would be about 800-m diam.

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 s of arc, or about 4 μrad, 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[8,9] have been developed to reduce the beam 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 than 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 path-length through the atmosphere increases, and it is likely that the maximum angle for zenith for which the system can be used will be in the range of 45–60 deg.

Some additional defocusing effects are encountered by high-energy lasers, such as thermal blooming.[8] However, for the power levels discussed here 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

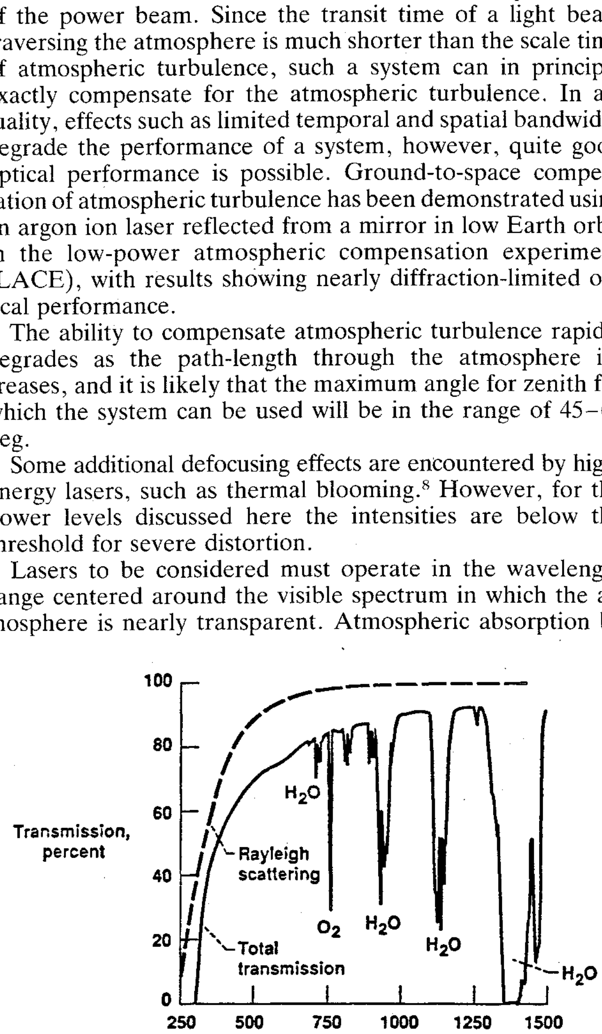

Fig. 2 Atmospheric transmittance (in percent) vs wavelength.

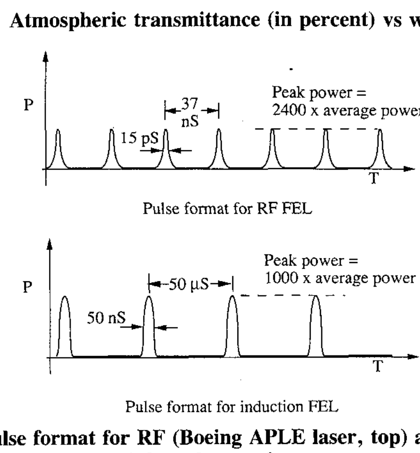

Fig. 3 Pulse format for RF (Boeing APLE laser, top) and induction (data from SRL, bottom) free electron lasers.

Table 1 PV converters for laser beamed power

Choice of converters for various wavelength lasers		
Wavelength range		Cell characteristics
Visible	400–800 nm	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/InP Optimum	800–860 nm (GaAs) 800–900 nm (InP)	Optimum for GaAs; InP and a-Si. η ~50%; temperature coefficient moderate.
Si Optimum	800–~1000 nm	Optimum for Si. η of cells ~40%; temperature coefficient slightly worse than GaAs.
Nd:YAG	1060 nm	Standard Si poor; new cell design may give good response near optimal for $CuInSe_2$ thin film cells; η of $CuInSe_2$ ~20% InGaAs quaternary possible (development needed). Temperature coefficient worse.
Near IR	1000–2000 nm	Specially designed cell needed. Ge, GaSb, HgCdTe, or specially developed ternary will have low η and poor temperature coefficient; development needed.
Mid-IR	>2000 nm	Not practical for PV conversion. Specially designed cell needed; likely to need cooling to operate.

ozone and Raleigh scattering set the minimum wavelength at about 350 nm. This is shown in Fig. 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.[10] 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, APLE, is currently under construction; this laser is to be operated at a wavelength of 10 μ, but is designed to be 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 Fig. 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-ps wide with a spacing of ~15 ns. The induction laser produces wider pulses, typically 10–50-ns long, with a spacing of ~20–50 μs. 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[10,11] 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 W average power have been constructed, and research is continuing into higher power levels. For a space power system very large numbers of 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 shorter wavelengths the efficiency will decrease roughly linearly with wavelength. For longer wavelengths the efficiency will drop rapidly to zero.[1] Response is zero for photon energies lower than the bandgap E_g. The cutoff wavelength λ_c is

$$\lambda_c = hc/qE_g = 1240/E_g \qquad (2)$$

Thus, it is important to select a wavelength near the optimum value. The efficiency of a solar cell illuminated by monochromatic illumination near the optimum wavelength 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,[12–14] and conventional Si cells over 40%.[13]

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/m²; 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.

Wavelengths away from the range of about 700–950 nm require development of solar cells of other materials. For example, there is some interest in using a laser with a wavelength greater than 1400 nm. 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 therefore, the safety restrictions are considerably less stringent. Unfortunately, photovoltaic receivers become both less efficient and more sensitive to temperature as the wavelength increases, as discussed in the Appendix.

For some systems it may be desirable to decrease the wavelength to the minimum allowed by the atmospheric transparency (Fig. 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 is optimized by using a material with the widest bandgap consistent with the cutoff shown in Eq. (2). For long wavelengths, low bandgap materials such as gallium antimonide[15] 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,[16] and monolithically interconnected in place. This has the potential for lower costs and lighter weight but has not yet been

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% to 40% 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.

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 LEO and GEO. This is summarized in Table 3.

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 at high peak power.

The characteristic response time of a photovoltaic cell to pulsed excitation is related to the minority carrier lifetime.[17] Typical minority carrier lifetimes for GaAs solar cells are in the range of ~10–100 nS in unirradiated material. For silicon solar cells, lifetimes are in the range of ~5–100 μS for a cell without radiation damage, and can be less than 1 μS for cells after radiation damage. If the time between pulses (1/frequency) is much shorter than the minority carrier lifetime, the cell responds to the laser effectively as a continuous wave source. If the pulse separation is much longer than a minority carrier lifetime, the cell responds to each individual pulse at a concentration equal to the peak of the pulse, which can be 10^3–10^4 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, 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 a pulse energy of 0.3–1.0 J/cm^2, depending on the absorption depth of the incident beam.[18,19] This corresponds to an intensity of about 2×10^6 W/cm^2 for a pulse length of 50 nS. 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 the cell is to the lasers 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:

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

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 V and series resistance of 0.05 Ω-cm^2. At 150 times this current, 50% 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 pulse format will have to have much lower series resistance than standard nonconcentrator solar cells.

For the low-duty cycles, the high-peak intensities may also result in peak carrier concentrations high enough that bandgap narrowing and free-carrier effects may have an effect on efficiency. These effects have not yet been investigated.

Operating under high-peak concentration, the cell open-circuit voltage will increase logarithmically [Eq. (14)], which will increase the efficiency slightly. This increase will be lost due to dark reverse current when the 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 capacitance of the solar cell *p-n* junction tends to average the laser pulse. A typical solar cell junction capacitance is typically on the order of 0.1 μF/cm^2, and a typical resistance may be in the range of 0.01–0.1 Ω-cm^2 (may be lower for concentrator cells). Thus, the expected RC time constants for the photovoltaic elements are on the order of 1–10 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, therefore increasing the pulse width seen by the power management system.

For short pulses, the inductance of the interconnect wiring will 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:

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

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 is less than nanohenrys 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, all of the photon energy can be usefully absorbed.

2) 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

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

where

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

$$h\nu = q(1240/\lambda) \tag{7}$$

thus

$$J_{sc}(\text{laser}) = QE\, P_{in}(\lambda/1240) \tag{8}$$

For high-efficiency solar cells, quantum efficiency will be very close to unity at the wavelengths of interest.

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

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

Under laser illumination, the power is thus

$$P_{laser} = V_{oc} FF\, QE\, P_{in}(\lambda/1240) \tag{10}$$

thus

$$\eta_{laser} = P/P_{in} = V_{oc} FF\, QE\, (\lambda/1240) \tag{11}$$

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

$$\eta_{solar} = P/P_{solar} = V_{oc} FF\, J_{sc}/P_{solar} \tag{12}$$

thus

$$\eta_{laser} = \eta_{solar} P_{sun} J_{sc} (QE)(\lambda/1240) \tag{13}$$

where J_{sc} is measured under the solar spectrum.

For an example, one of the highest efficiency solar cells manufactured to date is the GaAs cell reported by Tobin et al.[20] For this cell the AMO 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 850 nm, 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 et al.[21] 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 1000 nm. Hence, the multiplying factor to convert solar efficiency to laser efficiency equals 1.75. The efficiency under a laser at 1000 nm is therefore expected to be 42.3%.

This calculation will give the efficiency at the incident laser intensity which gives the 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:

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

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

$$K(\text{intensity}) = (1 + \Delta V/V)$$

$$= 1 + (0.025/V_{oc}) \ln[J_{sc}(\text{laser})/J_{sc}(\text{solar})] \tag{15}$$

From Eq. (3) this efficiency multiplier is

$$K(\text{intensity}) = 1 + (0.025/V_{oc}) \ln[(QE\, P_{in}\lambda/1240)/J_{sc}(\text{solar})] \tag{16}$$

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, although to a rough approximation the normalized coefficient $(1/\eta)\, d\eta/dT$ is the same. The decrease in efficiency is

$$\eta(T) = \eta(25°\text{C}) + \eta(25°\text{C})\left[\frac{(1/\eta)d\eta}{dT}\right](T - 25°\text{C}) \tag{17}$$

This equation does not hold at very low temperature (typically under −100°C) where the temperature dependence of efficiency becomes nonlinear. 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 has three components: 1) variations in open circuit voltage; 2) short circuit current; and 3) fill factor. However, for monochromatic illumination the variation in short-circuit current is only due to changes in quantum efficiency, which is only weakly dependant on temperature except for cells well on the long-wavelength side of the efficiency peak. The change in fill factor is also slight. The significant component is the decrease with temperature of the 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[22]

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

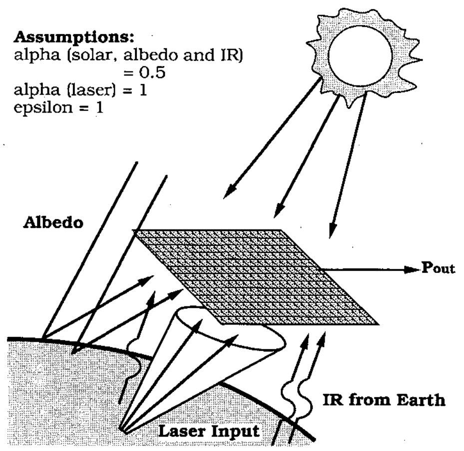

Fig. 4 Thermal model of a photovoltaic array in low Earth orbit illuminated by a ground-based laser. Worst case "day" thermal conditions (sun on back of array, laser on front) is shown.

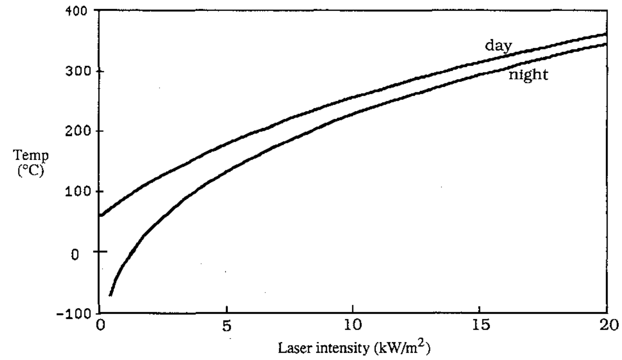

Fig. 5 Temperature of a photovoltaic array in LEO as a function of incident laser intensity calculated according to linearized version of model shown in Fig. 4 (two-sided thermal radiation).

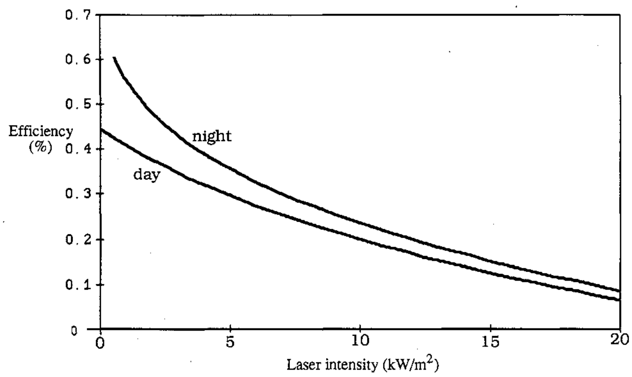

Fig. 6 Calculated laser conversion efficiency of a photovoltaic array in LEO as a function of incident laser intensity (two-sided thermal radiation).

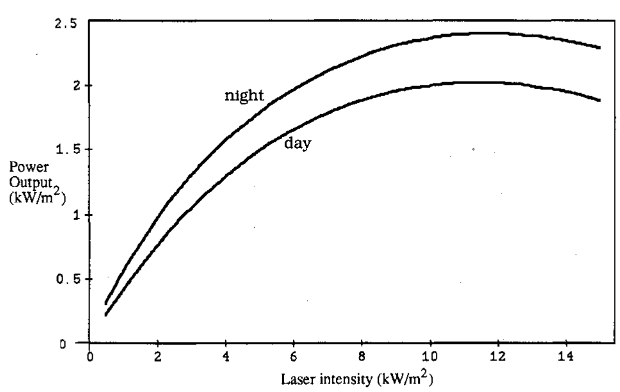

Fig. 7 Calculated power output of a photovoltaic array in LEO as a function of incident laser intensity (two-sided thermal radiation).

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 Ref. 23).

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 proportional to the efficiency is converted to electricity.

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 nonlinear.

Figures 5 and 6 shows a result of applying this model, assuming an 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 7 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

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

Prediction of Monochromatic Performance

Accurate predictions of laser performance will require good theoretical models of photovoltaic cell performance and experimental measurements of cell parameters including efficiency, spectral response, intensity variation of efficiency, and temperature coefficients to adjust and confirm the theoretical models.

Operation in Pulsed Mode

The duty cycle of free electron laser will be on the order of 10^{-3}–10^{-4}, with a pulse width of 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 the dark reverse current is suppressed when the cell is not illuminated.

Solar Cells for Long Wavelength Lasers

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

Temperature

The thermal environment, including both in-sun and shadowed conditions, must be modeled and the solar cell response under temperature verified. The temperature coefficient for power conversion for monochromatic light should be theoretically modeled as a function of incident laser intensity and wavelength and the values compared with experimental measurements. The possibility of designing solar cells to have low temperature coefficients should be explored if high laser intensities are to be required. 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. Temperature-related degradation mechanisms include degradation due to the mechanical stress of thermal cycling, and, for high intensity, thermal degradation due to long exposures at high temperature.

Array Issues

A solar array design must be made taking engineering factors into account. A choice must be made between planar and concentrating arrays for receivers. Questions to be answered included finding the optimum intensity, refractive vs reflective concentrators, the possible advantages 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 nontracking concentrator. The amount of motion is ± 7.6 deg E-W ("libration"); ± 6.7 deg N-S ("nodding"), leading to a total solid angle of 1.1 sr. 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 deg/min. In higher orbits this decreases; at GEO the source is stationary.

The PV array must be designed for deployment and maintenance. There is a tradeoff 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.

Power Management and Distribution (PMAD)

The power management system must be capable of making usable power from a pulsed input. Discrete or distributed capacitance and inductance can be added to the system 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 be high in the center of the distribution and lower at the edges.

Optimum Design of Cells for Laser Conversion

There remain many unexplored approaches to 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 so as to allow use of solar power when it is available, and laser power during the eclipse or night operation.

Design issues include effective use of light-trapping to maximize long-wave response, and optimize junction depth, doping, and 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 current. 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 incident solar IR without increasing the laser reflectance and maximization of the thermal emissivity.

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

Radiation Damage

Radiation preferentially damages the long wavelength response of a solar cell; the part of the spectrum most efficiently used 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. If the operating temperature is high enough continuous annealing of radiation damage may be possible.

Conclusions

It may be 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 radiation damage. Many research issues remain to be addressed.

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 absorption characteristics of real materials. Results of a model using the diode equation with bandgap variation of I_0 is provided by Olsen et al.[11] This is plotted in Fig. 8, along with experimental efficiencies of existing cells. Real cells are less efficient than the theoretical maximum but show the same variation 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, by assuming both cells have the same performance except for the bandgap variation. 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

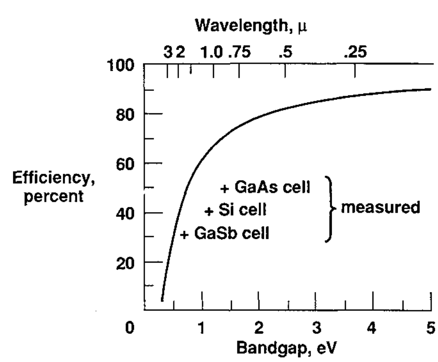

Fig. 8 Theoretical conversion efficiency of photovoltaic cells for monochromatic light (intensity 500 mW/cm², temperature 25°C; after Olsen et al.[11]). Also shown are measured monochromatic efficiencies for a GaAs cell (850 nm), a Si cell (950 nm), and a GaSb cell (1500 nm).

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_{g0} involves scaling the appropriate parameters by the ratio E'_g/E_{g0}. The bandgap is scaled by the photon energy, or inversely with the wavelength

$$E'_g/E_{g0} = \lambda_0/\lambda' \tag{A1}$$

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

$$I' = I_0[E'_g/E_{g0}] \tag{A2}$$

(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

$$\frac{d\eta}{d(\ln I)'} = \left[\frac{d\eta}{d(\ln I)}\right]_0 \left[\frac{E_{g0}}{E'_g}\right] \tag{A3}$$

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

$$T' = T_0(E'_g E_{g0}) \tag{A4}$$

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

The normalized temperature coefficient scales inversely with bandgap

$$\left[\frac{(1/\eta)d\eta}{dT}\right]' = \left[\frac{(1/\eta)d\eta}{dT}\right]_0 \left[\frac{E'_g}{E_{g0}}\right] \tag{A5}$$

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

$$\eta'(T) = \eta(T')\{1 + \left[\frac{(1/\eta)d\eta}{dT}\right]' \Delta T\} \tag{A6}$$

For 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 $(1/\eta)\ d\eta/dT'$ extrapolates to = $-0.0032\ K^{-1}$ (note that this calculated temperature coefficient is considerably lower than that achieved by existing Ge cells[24]). 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, and the estimated 25°C efficiency is 25.1%.

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