N95-20538

PULSED LASER ILLUMINATION OF PHOTOVOLTAIC CELLS

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SUMMARY

In future space missions, free electron lasers may be used to illuminate photovoltaic array receivers to provide remote power. The induction FEL and the radio-frequency (RF) FEL both produce pulsed rather than continuous output. In this work, we investigate cell response to pulsed laser light which simlulates the RF FEL format, producing 50 ps pulses at a frequency of 78 MHz. A variety of Si, GaAs, GaSb and $CdInSe_2$ (CIS) solar cells are tested at average incident powers between 4 mW/cm^2 and 425 mW/cm^2. The results indicate that if the pulse repetition is high, cell efficiencies are only slightly reduced by using a pulsed laser source compared to constant illumination at the same wavelength. Because the pulse separation is less than or approximately equal to the minority carrier lifetime, the illumination conditions are effectively those of a continous wave laser. The time dependence of the voltage and current response of the cells are also measured using a sampling oscilloscope equipped with a high frequency voltage probe and current transformer. The frequency response of the cells is weak, with both voltage and current outputs essentially dc in nature. Comparison with previous experiments shows that the RF FEL pulse format yields much more efficient photovoltaic conversion of light than does an induction FEL pulse format.

INTRODUCTION

The use of high power lasers has been proposed for beaming power to remote photovoltaic arrays in space. Power beaming during eclipses, for instance, would eliminate the need for batteries on satellites in Geosynchronous Earth Orbit, thus reducing the mass of the satellite power system (ref. 1). Night operation of a moon base can also be facilitated through earth-based laser illumination of photovoltaic arrays, again simplifying the power system requirements of the moonbase (ref. 2). Photovoltaics can have very high efficiencies under monochromatic illumination compared to solar light (ref. 3), creating another advantage for use of laser power beaming. Many of the issues involved in designing an appropriate laser and optical system have been discussed elsewhere (refs. 4 and 5) and will influence the ultimate selection of lasers and cell materials.

The free electron laser (FEL) is an attractive choice of power source. It can produce megawatts of power and can be tuned to wavelengths appropriate for atmospheric transmission as well as

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the solar cell requirements. Two FEL designs have been proposed, the induction FEL and the radio-frequency (RF) FEL (refs. 6 and 7). Both produce pulses of light with high power rather than continuous output. The induction laser produces pulses ranging from 10 to 50 nanoseconds wide at frequencies of 20 to 50 kHz. The RF FEL operates at MHz frequencies, producing 10 to 40 picosecond "micropulses" which are spaced tens of nanoseconds apart. While the average laser power reaching the cell must be sufficient to generate the required output power, the peak pulse power is hundreds or thousands of times higher than the average level. The response of the photovoltaic receiver to the input pulses depends on the minority carrier lifetime of the solar cell material (refs. 8 and 9). Carriers created by the incident pulses have a finite lifetime before being collected at the junction and thus produce an elongated output signal. When the pulses arrive in rapid succession relative to the lifetime, the cells effectively see the input as a continuous source. However, if the pulse separation is greater than the minority carrier lifetime, the cell must respond to the peak power of each pulse. For Si cells, lifetimes range from 10 to 100 μs for undamaged material, while radiation damage can lower the value to 1 μs. Direct bandgap semiconductors such as GaAs have a much shorter minority carrier lifetime, in the range of 10 to 100 ns (ref. 10). Hence, the ability to convert FEL pulses to power depends on the particular laser format and the cells being used.

Previous experimental studies and 1-D computer simulations have focused on the induction FEL format (refs. 11-15). Cell efficiencies are significantly reduced, especially for direct bandgap semiconductors. Issues such as minimizing series resistance and designing cells to avoid LC oscillations are challenges that must be met to successfully utilize the induction FEL. However, studies of cell efficiency and behavior must also be made using other laser pulse formats. In this work, we investigate the response of conventional PV cells to laser light with the RF FEL format. Using a laser with a pulse separation of about 10 ns, we expect the cells to respond to the average illumination power. The results are compared with those of a previous experiment where a copper vapor laser was used to simulate the induction FEL pulse format (ref. 12).

EXPERIMENTAL PROCEDURE

A Coherent Antares mode-locked Nd:YAG laser with 50 ps pulses at a frequency of 78 MHz is used to simulate the output of an RF FEL. As illustrated in figure 1, the duty cycle of the laser, with pulses separated by 13 ns, is 1:260. The peak power per pulse is therefore 260 times higher than the average laser power. In contrast, the copper vapor laser used in the previous induction-format experiment produced 511 nm pulses which were 38 ns wide and spaced 116 μs apart. The corresponding duty cycle of 1:3000 was significantly larger.

The experimental apparatus is depicted in figure 2. The laser is focused by a microscope objective into a 300 μm optical fiber and then collimated upon exiting the fiber. PV cells are mounted on an electrically isolated vacuum chuck which moves on a rail aligned normal to the optical path. A calibrated power meter, also mounted on the rail, is slid into the laser path to measure the time averaged power. Apertures block out all but the portion of the laser beam which illuminates the PV cell. The spatial uniformity of the beam over the area of the cells is within 10%.

The frequency doubled 532 nm wavelength is used to illuminate the collection of solar cells listed in Table 1, many of which were tested in the induction FEL experiment (ref. 12). Use of the 532 nm wavelength facilitates comparison with the data taken using the 511 nm Cu-vapor laser. Si, an indirect bandgap semiconductor, and several direct bandgap materials are included in order to examine the dependence of cell efficiency on minority carrier lifetime. All are planar cells, except for several Si and the GaSb concentrator cells. Since concentrator cells are designed with low series resistance in order to respond to high illumination intensities and peak currents, they may yield a better efficiency in converting high power laser pulses.

The cells are tested at average illumination intensities between 4 mW/cm^2 and 425 mW/cm^2. The measurement circuit is shown in figure 3. The average dc output power (P_{out} =$I_{out}\times V_{bias}$) is determined by applying a constant dc voltage across the cell with a variable bipolar power supply that can sink and source current. The average dc current is measured with a digital ammeter. The average power is a measure of the output available in an operational situation. Because of pulse to pulse variation in the laser energy, the readings are averaged over several hundred laser pulses. The conversion efficiency is calculated at the maximum power point using the relation

$$\eta = \frac{P_{out}}{P_{in}A}, \tag{1}$$

where A is the total cell area, P_{in} is the average incident laser power and P_{out} is the output power as defined above. The time dependence of the cell voltage and current is measured using a Tektronix 11802 digital sampling oscilloscope equipped with a 200 MHz inductive current pickup and a 3.5 GHz high-impedance sampling head. Lead lengths are kept to below 3 cm to minimize induced voltage caused by current transients during each laser pulse.

RESULTS

The time dependence of the voltage and current under pulsed illumination is one indication of the solar cell response to the short pulses. The voltage waveform observed on the oscilloscope shows the time evolution of the bias voltage across the cell, which is maintained at a nominally constant level through feedback control. However, current transients during the laser pulses can force the voltage towards the open circuit value. Figure 4a shows voltage and current waveforms for a Si concentrator cell illuminated with Nd:YAG pulses at 425 mW/cm^2. With an applied bias voltage of almost 400 mV, the resultant voltage waveform is essentially a dc signal, with a small sawtoothed ac component repeating every 13 ns as the laser pulses hit. The corresponding current waveform also shows a small response, with 10 mA current transients also following the laser pulses. Similar behavior is seen for all the cells tested. The ac signal is largest at short circuit conditions, and under the highest laser intensities. At the maximum power point where cells are generally operated, the peak response is negligible, as seen in figure 4a.

In contrast, figure 4b shows the voltage and current waveforms for the same cell and bias voltage, but illuminated with the copper vapor laser pulses at 279 mW/cm^2. With a significantly higher duty cycle and pulse separations of over 100 μs, the cell obviously exhibits a strong frequency response. The voltage rises in a spike as a laser pulse hits, with a slow decay over tens of microseconds down to the dc bias level. The current transients of over half an amp decays equally slowly as carriers diffuse to the depletion region. With these voltage and current pulses occurring every 116 μs, the cell output can hardly be maintained at a constant dc level. The response to the induction format pulses varied considerably from cell to cell, with the most dramatic LC oscillations occuring with the GaAs concentrator cells (ref. 12). However, every cell exhibited a strong frequency response and a corresponding reduced conversion efficiency. The RF-type pulses produce a very weak frequency response and, as the data will show, good efficiencies.

Figure 5 shows current-voltage curves for a 10 Ω-cm planar Si cell illuminated with both the RF (Nd:YAG) and induction (Cu-vapor) type pulses. While the laser wavelength is comparable, the incident intensity is not identical. However, the cell performs better at 170 mW/cm^2 under the RF-simulated pulses than at the higher average power of 263 mW/cm^2 with the induction pulses. Both the fill factor and efficiency are significantly better, while J_{sc} is comparable for both cases. The Si cell is able to convert the incoming Nd:YAG pulses more efficiently than the Cu-vapor pulses, as already suggested by the ac waveforms discussed above. Even for Nd:YAG pulses at 470 mW/cm^2 (peak power = 800 suns), where series resistance limiting of the current might cause deterioration of the cell performance, the fill factor and efficiency are essentially constant. Comparisons of direct bandgap cells illuminated with both pulse formats, though not shown here, are even more striking. The GaAs and CIS cells perform well under the Nd:YAG illumination (although the 532 nm wavelength is far from optimal, especially for GaSb and CIS), whereas efficiencies are exceedingly low for the Cu-vapor pulse experiments. J_{sc} is several milliamps for the induction case but hundreds of milliamps under RF pulse conditions at comparable average intensities.

Efficiencies are calculated at the maximum power point, indicated by a cross on the I-V curves, and are compiled in table 2 for AM0, cw (514 nm), and pulsed illumination conditions using both the Nd:YAG (532 nm) and Cu-vapor (511 nm) laser pulses. An Argon ion laser was used in the previous experiment to collect cw data (ref. 12). Efficiencies for the Si and GaAs cells tend to be a bit higher under monochromatic cw light than the solar spectrum, an effect which would be even more noticeable at the optimum wavelength of each semiconductor material. A comparison of results from the 532 nm pulses and the 514 nm continuous illumination, both at 170 mW/cm^2, shows that the pulsed laser efficiency is slightly lower for the planar cells but higher for the concentrator cells. However, while the PV conversion efficiency remains 70% to 99% of the cw value using RF-type pulses, the detrimental effect of induction-type pulses is more extreme. Si cells show an additional reduction in efficiency, while direct bandgap efficiencies drop to almost zero.

Typical I-V curves of Si and GaAs cells are shown in figure 6 for 532 nm pulsed illumination at 425, 170 and 41 mW/cm^2. These average power levels correspond to approximately 3.1, 1.25 and 0.3 suns, respectively, while the equivalent peak powers are 810, 325 and 80 suns. The dependence of cell efficiency on average laser power is plotted in figure 7 for several different cells, while table 3 compiles the power dependence for all cells tested. Some variation in efficiency with laser power is evident, with a maximum tending to occur at 170 mW/cm^2. However, the curves at 425 mW/cm^2 show no sign of current saturation due to series resistance limiting at the highest peak pulse powers and the fill factors remain constant. Previous results with the induction formatted laser indicated current saturation at the highest laser intensities, where the peak power increased to 6000 suns.

DISCUSSION

As noted previously, the efficiencies tabulated in this paper do not represent the peak efficiencies expected at laser wavelengths matched to the PV bandgap. The 532 nm light used in this experiment is chosen so that previous results can be compared and trends noted. The wavelength of peak monochromatic efficiency for undamaged Si is about 950 nm (shorter for damaged material), 850 nm for GaAs, 1600 nm for GaSb and 1000 nm for CIS. Corrections to the efficiency can be estimated by using the equation (ref. 4)

$$\frac{\eta(\lambda_{\text{peak}})}{\eta(\lambda_{\text{532nm}})} = \frac{\lambda_{\text{peak}}}{\lambda_{\text{532nm}}} \times \frac{QE(\lambda_{\text{peak}})}{QE(\lambda_{\text{532nm}})}, \tag{2}$$

where QE is the quantum efficiency of the cell at the selected wavelength. Assuming that the quantum efficiency is nearly constant with wavelength over the range of interest below the bandgap (confirmed by measurements of external quantum yield), the correction factor is approximately the ratio of the chosen wavelengths. This wavelength term simply describes the inverse proportionality between incident laser power and wavelength.

For the 532 nm Nd:YAG laser pulses, no substantial difference in efficiency is evident between the various materials, with all planar cells performing at 70% to 99% of the cw level. The minority carrier lifetime, significantly longer for Si than the other semiconductors, is not a limiting factor in the ability of the cells to respond to the short pulses. The I-V curves show no evidence of current saturation at the highest pulse intensity, where peak output currents due to individual pulses would be 260 times larger than the average current. Consider the limiting equation

$$I < V_{oc}/R_{\text{series}}, \tag{3}$$

where the series resistance of the cells was measured previously (ref. 12). If the incident laser pulses were spaced sufficiently far apart so that generated carriers were all collected before the next pulse, every cell tested should have displayed current saturation at the higher laser powers. Such is not the case, indicating approximately continuous wave illumination conditions. The Si concentrator cells, designed to respond to higher current densities than planar cells, exhibit a modest increase in efficiency under the RF-type laser pulses. Despite temporal stretching of the incident pulse due to minority carrier diffusion, carrier concentrations rise above the average value as each pulse arrives. The concentrator cells are better able to collect these carriers than are the planar cells, as the results confirm. All the PV cells, however, convert the incident laser pulses to nearly dc output power with little or no loss compared to cw laser results.

The time dependent current and voltage waveforms also indicate that the cells see quasi-cw illumination conditions. For GaAs, the peak to peak amplitude is never more than 20 mV, with corresponding current variations of about 10 mA. Si cells sometimes exhibit larger voltage amplitudes, up to 125 mV under short circuit conditions, but the waveform at the maximum power point decreases to values similar to those indicated for the GaAs. As the bias voltage is increased, the load impedence (at the voltage supply) also increases, thereby reducing the current transients. The oscilloscope shows essentially dc output with a small ac signal. Analysis of the waveforms is not pursued given the small magnitude of the peaks and the noise often obscuring the exact shape. Some observations, such as a slight rounding off at the peak of the sawtooth-like voltage signal or the non-linear decay of some curves, could give insight into cell design for maximum efficiency under these pulses. However, a detailed discussion of the many factors affecting cell response to individual pulses can be found in the referenced studies (refs. 11-15), while the main result of this work is that conventional PV cells yield almost dc outputs when illuminated with high frequency pulses.

CONCLUSIONS

Experimental results indicate that the conversion efficiency of conventional PV cells illuminated with high frequency laser pulses is not reduced significantly. The 532 nm wavelength of a mode-locked Nd:YAG laser is used to simulate the RF FEL pulse format, with the resultant cell performance improved compared to previous results using a Cu-vapor laser to simulate the induction FEL format. Direct bandgap cells exhibit the most significant enhancement in cell efficiency for incident laser intensities up to 425 mW/cm^2. The ac frequency response of the cells to the short pulses is weak, while time averaged currents and fill factors are comparable those under cw illumination conditions. Because the pulse separation is as short as the minority carrier lifetime, the cells respond as if the incident illumination is quasi-continuous in nature.

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Cell Type	Type	Material	Area (cm 2)
ASEC #10	Planar	Si	4.0
ASEC 10 Ω-cm BSR	▪	▪	▪
ASEC 0.2 Ω-cm			
MSFC - ATM			
ASEC 10 Ω-cm BSR	Rad. Damaged	▪	▪
ASEC string	Planar		1.25
Sunpower HECO 250	Concentrator	Si	1.44
ASEC 10 Ω-cm	▪		1.0
ASEC 0.15 Ω-cm			▪
Varian	Planar	GaAs	4.0
ASEC MANTEC		▪	▪
ASEC #2	▪	GaAs/Ge	
ASEC #16		▪	▪
BOEING #6701	Concentrator	GaSb	0.196
BOEING A096A	Planar	CIS	4.0

Table I. Cells Tested Under Pulsed Laser Illumination Using Nd:YAG Laser

	AM0	cw 514 nm	RF Pulsed 532 nm	Induction Pulsed 511 nm
Average Intensity, mW/cm^2	137	170	170	250
Cell Type	Cell Efficiency, %			
Silicon				
ASEC #10	15.0		13.3	
ASEC 10 Ω-cm BSR	11.0	14.5	10.1	5.6
ASEC 0.2 Ω-cm	15.6	19.0	14.5	7.2
MSFC - ATM	10.4	12.6	10.8	
ASEC 10 Ω-cm (rad. damaged)	10.5	13.9	13.4	1.9
ASEC planar string	11.1		7.5	
Sunpower HECO 250 (conc.)	17.2		19.2	
ASEC 10 Ω-cm (conc.)	13.0	13.7	15.3	7.6
ASEC 0.15 Ω-cm (conc.)	15.2	15.3	19.0	12.1
GaAs				
Varian	17.2	29.0	20.5	0.15
ASEC MANTEC	16.5	28.3	23.0	
ASEC #2	17.5		24.1	
ASEC #16	18.0	26.0	25.7	
KOPIN Super (conc.)	20.7	26.6		1.3
GaSb				
BOEING #6701 (conc.)	5.8	1.26	2.9	0.25
CIS				
BOEING A096A	8.2	5.5	5.3	0.01

Table II. Cell Efficiencies Under Illumination with AM0, cw Laser, and RF and Induction FEL Laser Format

	Pulsed Nd:YAG Laser at 532 nm (simulating RF FEL format)			
Average Intensity, mW/cm^2	425	170	41	4
Cell Type	Cell Efficiency, %			
Silicon				
ASEC #10	12.2	13.3	13.1	9.9
ASEC 10 Ω-cm BSR	9.5	10.1	10.3	8.5
ASEC 0.2 Ω-cm	12.6	14.5	14.3	10.6
MSFC - ATM	10.2	10.8	9.8	5.2
ASEC 10 Ω-cm (rad. damaged)	12.1	13.4	13.3	9.8
ASEC planar string	7.5	7.5	6.5	5.1
Sunpower HECO 250 (conc.)	19.2	19.2	18.0	14.3
ASEC 10 Ω-cm (conc.)	13.4	15.3	15.3	11.5
ASEC 0.15 Ω-cm (conc.)	19.0	19.0	18.8	14.9
GaAs				
Varian	14.0	20.5	17.8	
ASEC MANTEC	21.7	23.0	21.7	17.5
ASEC #2	25.0	24.1	21.8	15.4
ASEC #16	26.3	25.7	23.5	
GaSb				
BOEING #6701 (conc.)	3.9	2.9	1.5	1.9
CIS				
BOEING A096A	3.7	5.3	5.3	3.3

Table III. Cell Efficiencies at Different Laser Powers for RF FEL Simulated Format

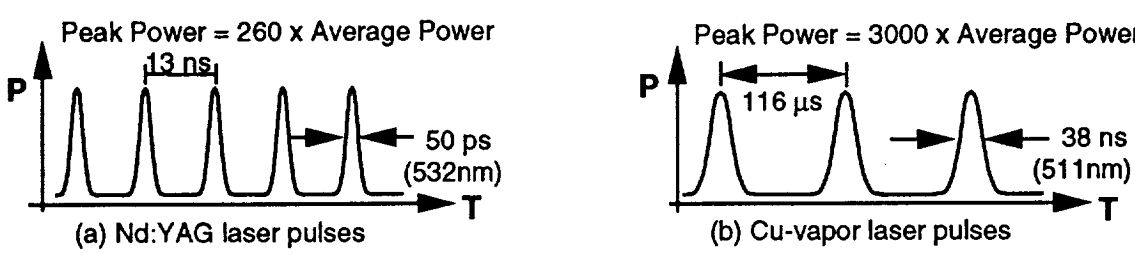

Figure 1. RF (a) and Induction (b) FEL pulse formats

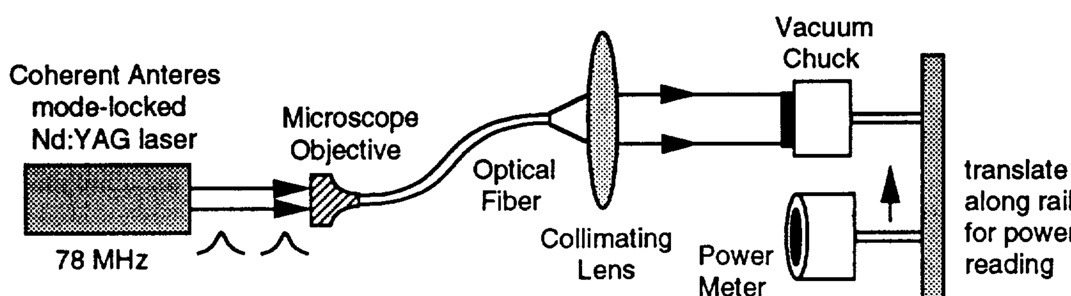

Figure 2. Experimental Apparatus

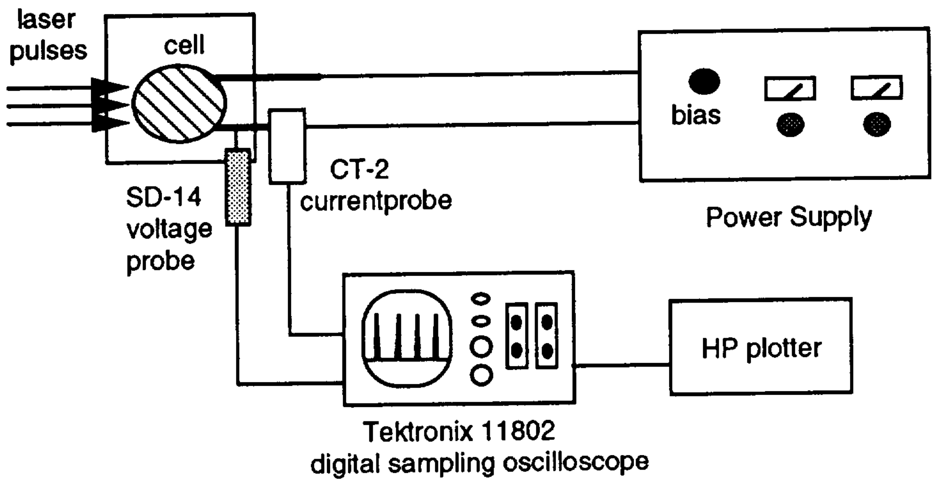

Figure 3. Schematic of Measurement Circuit

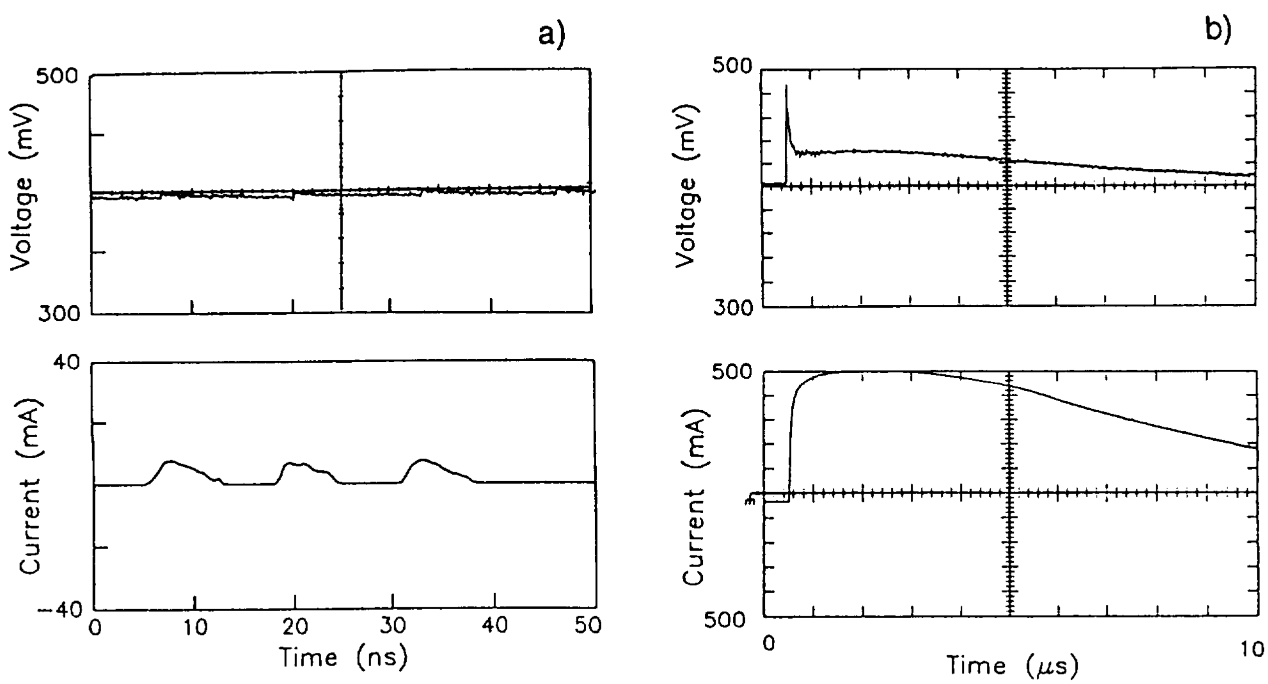

Figure 4. Voltage and Current Waveforms for Si Concentrator Cell. a) Illumination is with 532 nm Nd:YAG Pulses at a Repetition Rate of 13 ns. Average Power is 425 mW/cm^2. b) Same Cell Illuminated with 511 nm Copper Vapor Laser Pulses Arriving at 116 μs Intervals. Average Power is 263 mW/cm^2.

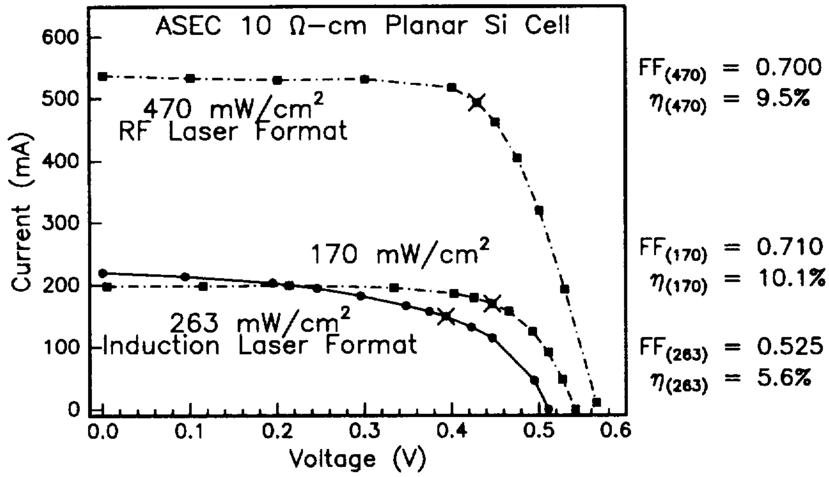

Figure 5. I–V Curves for Planar Si Cell as a Function of Pulse Format and Average Laser Power. Maximum Power Points are Indicated by an X.

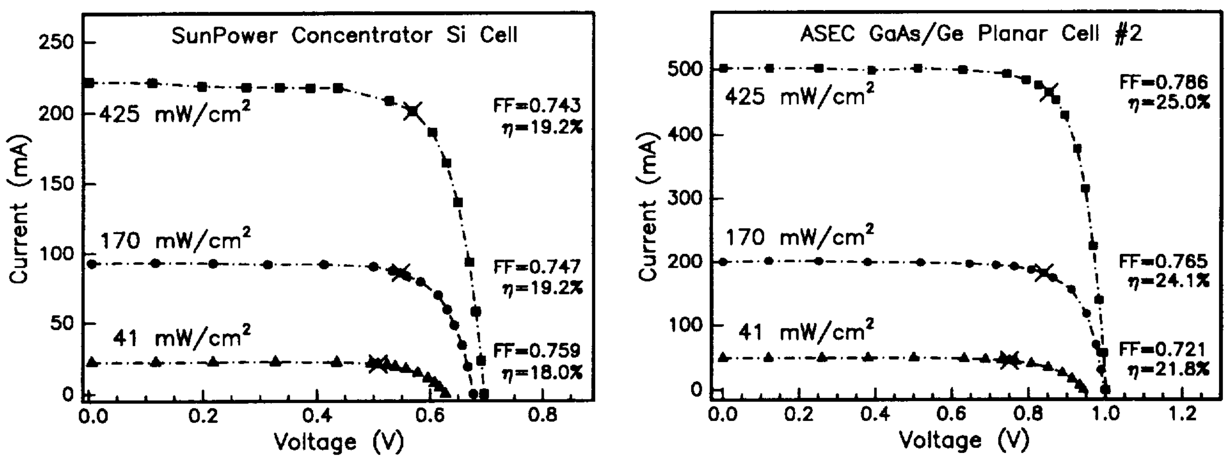

Figure 6. I–V Curves for Si Concentrator and GaAs Planar Cell. The Fill Factor and Efficiencies Correspond to Each of the 3 Powers.

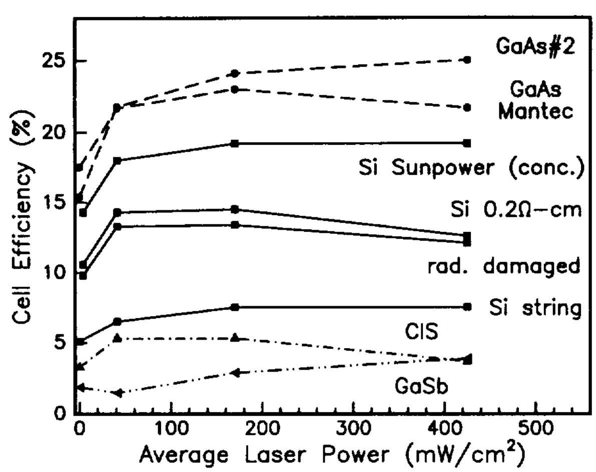

Figure 7. Efficiency as a Function of Nd:YAG Laser Power for Various Cells.