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PULSED LASER ILLUMINATION OF PHOTOVOLTAIC CELLS

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ABSTRACT

In future space missions, free electron lasers (FEL) may be used to illuminate photovoltaic receivers to provide remote power. Both the radio-frequency (RF) and induction FEL produce pulsed rather than continuous output. In this work, we investigate cell response to pulsed laser light which simulates the RF FEL format. The results indicate that if the pulse repetition is high, cell efficiencies are only slightly reduced compared to constant illumination at the same wavelength. The frequency response of the cells is weak, with both voltage and current outputs essentially dc in nature. Comparison with previous experiments indicates that the RF FEL pulse format yields more efficient photovoltaic conversion than does an induction FEL format.

INTRODUCTION

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

The free electron laser (FEL) is an attractive choice for laser power beaming as it produces megawatts of power. It is also tunable to wavelengths appropriate for atmospheric transmission as well as for solar cell requirements. The two proposed FEL designs both produce pulses of light with high power rather than continuous output. The induction FEL [5] operates in the kHz frequency range, with pulse widths on the order of 10 ns. The RF FEL operates at MHz frequencies, producing pulses 5 to 40 ps wide [6]. While the average laser power reaching the cell must be sufficient to generate the required output power, the peak pulse power will be 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 [7]. When the pulses arrive in rapid succession relative to the lifetime, the cells effectively see the input as a continuous source. However, for pulse separations greater than the minority-carrier lifetime, the cell must respond to the peak power of each pulse. In Si cells, lifetimes range from 10 to 100 μs, 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 [8]. Hence, the ability to convert FEL pulses to power depends on both the laser format and the cells being used.

Other experimental studies [9,10] and 1-D computer simulations [11] have focused on the induction FEL format. Cell efficiencies are significantly reduced, especially for direct bandgap semiconductors. To successfully utilize the induction FEL, cell arrays must be designed that minimize series resistance and avoid LC oscillations. In this work, we investigate the response of conventional PV cells to laser light with the RF FEL format. Using a laser with pulse separations of about 10 ns, we expect the cells to respond to the average illumination power. Results are compared with a previous study where a copper-vapor laser was used to simulate the induction FEL pulse format [9].

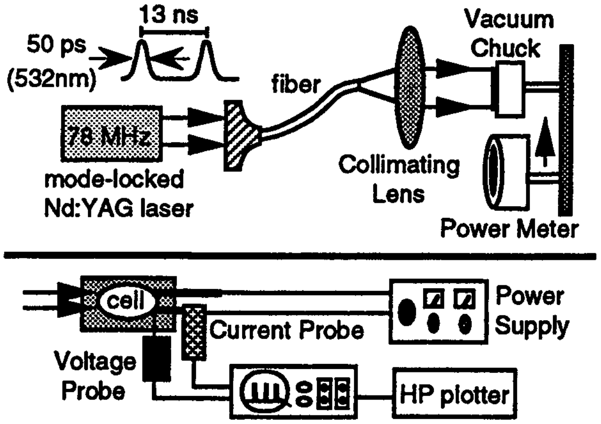

Fig. 1. Experimental apparatus.

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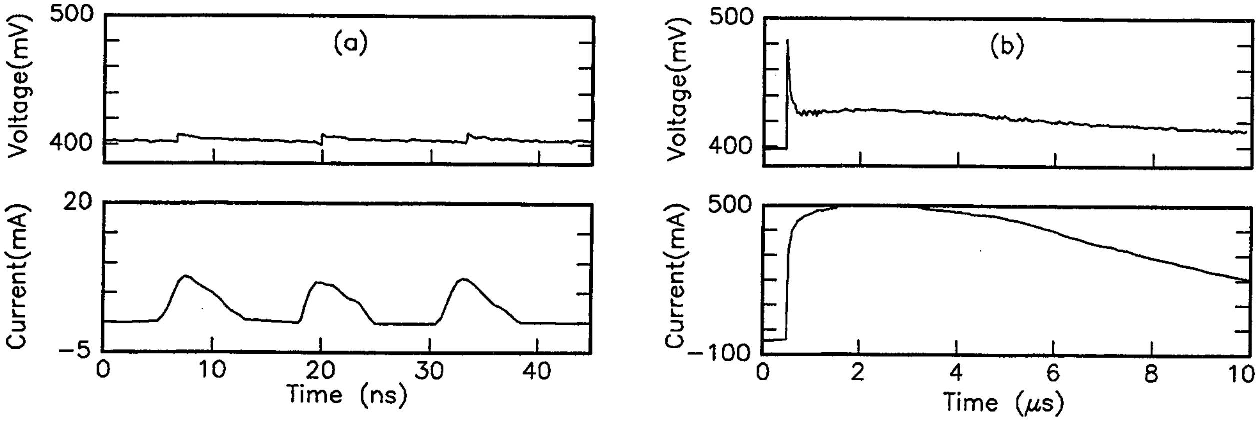

Fig. 2. Voltage and current waveforms for 10 Ω–cm Si concentrator cell biased near 400 mV. a) RF FEL format, laser intensity 425 mW/cm^2. b) Induction FEL format, 279 mW/cm^2.

EXPERIMENTAL PROCEDURE

A Coherent Antares mode-locked Nd:YAG laser with 50 ps pulses at a frequency of 78 MHz simulates the output of an RF FEL. Although typical RF FEL pulse widths may be significantly lower, since the 50 ps pulse width is well below the photovoltaic minority carrier storage time, the output is not expected to be very sensitive to the pulse width. 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 pulses 38 ns wide and spaced 116 μs apart, with a significantly lower duty cycle of 1:3000.

As depicted in Fig. 1, the laser is focused by a microscope objective into a 300 μm optical fiber and collimated upon exiting the fiber. The fiber serves to homogenize the beam to produce a uniform intensity distribution across the cell. PV cells are mounted on an electrically-isolated vacuum chuck which moves on a rail normal to the optical path. A calibrated power meter, also mounted on the rail, is moved into the laser path to measure the time averaged power. 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 Si, GaAs, $CuInSe_2$ (CIS) and GaSb solar cells, many of which were also tested in the induction FEL experiment [9]. Use of the 532 nm wavelength facilitates comparison with the 511 nm copper-vapor laser. Direct and indirect 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 to respond to high illumination intensities and peak currents, they may be more efficient 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 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 and is averaged over several hundred laser pulses. The conversion efficiency is calculated at the maximum power point using the relation

$$\eta = \frac{P_{out}}{P_{in}A}, \qquad (1)$$

where A is the total cell area, P_{in} is the average incident laser power density and P_{out} is the output power. 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.

RESULTS

The voltage waveform observed on the oscilloscope traces the time evolution of the bias voltage, which is maintained at a nominally constant level through feedback control. However, large current transients can interact with the inductance of the output wiring to induce voltage transients. Fig. 2a shows voltage and current waveforms for a Si concentrator cell illuminated with Nd:YAG pulses at 425 mW/cm^2. For an applied bias of 400 mV, the resultant voltage waveform is essentially a DC signal. A small, sawtoothed AC component repeats every 13 ns. The corresponding current waveform is also nearly flat, with 10 mA current transients coinciding with the laser pulses. Similar behavior is exhibited by all the cells tested. The AC signal is largest at short-circuit conditions and under high laser intensities. At the maximum power point where cells are generally operated, such as in Fig. 2a, the transient response is almost negligible.

In contrast, Fig. 2b shows the frequency response for the same cell and bias voltage, but illuminated at 279 mW/cm^2 by the copper-vapor laser[9]. The voltage rises in a spike as a laser pulse hits, slowly decaying over tens of microseconds to the DC bias level. The current transient of over half an amp decays equally slowly, as carriers diffuse to the depletion region. Such a 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 [9]. However, every cell exhibited a strong AC response and a corresponding reduction in conversion efficiency. The

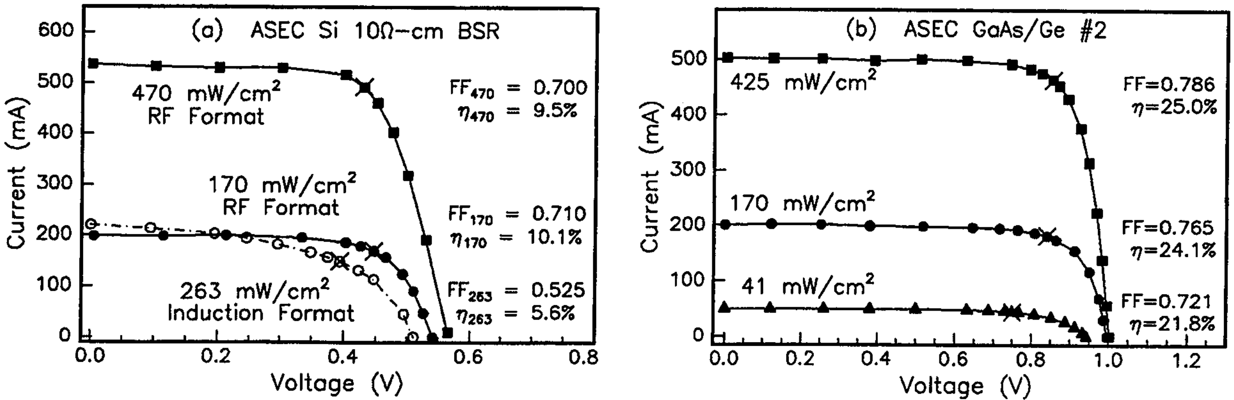

Fig. 3. I–V Curves for a) Si and b) GaAs planar cells. The fill factor and efficiencies are shown for each curve. The maximum power point is marked with an X.

RF-type pulses produce a relatively flat AC response and, as the data will show, good efficiencies.

Fig. 3a shows current-voltage curves for a 10 Ω-cm planar Si cell illuminated with both the RF (Nd:YAG) and induction (copper-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 copper-vapor pulses, as already indicated by the frequency response. 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 cells perform well under the Nd:YAG illumination (although the 532 nm wavelength is far from optimal, especially for GaSb and CIS), as can be seen in the I-V curves of a typical GaAs cell shown in Fig. 3b. In contrast, efficiencies are exceedingly low for the copper-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, calculated at the maximum power point, are compiled in Table 1 for AM0, CW argon-ion laser illumination (514 nm), and pulsed illumination using both the Nd:YAG (532 nm) and copper-vapor (511 nm) laser pulses. Efficiencies for the Si and GaAs cells tend to be a bit higher under monochromatic CW light than under 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 cell efficiency remains 70% to 99% of the CW value using RF formatted pulses, the induction-type pulses cause a more extreme performance degradation. Si cells drop further in efficiency, while direct bandgap efficiencies fall to almost zero.

	AM0	cw 514nm	pulsed 532nm	pulsed 511nm
Intensity(mW/cm^2)	137	170	170	250
	cell efficiency, %			
Silicon				
ASEC #10	15		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 (rad. damage)	10.5	13.9	13.4	1.9
ASEC planar string	11.1		7.5	
Sunpower HECO (c)	17.2		19.2	
ASEC 10 Ω-cm (c)	13.0	13.7	15.3	7.6
ASEC 0.15 Ω-cm (c)	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	
Kopin Super (c)	20.7	26.6		1.3
II-VI				
Boeing GaSb (c)	5.8	1.26	2.9	0.25
Boeing CIS	8.2	5.5	5.3	0.01

Table 1. Cell efficiency for different illumination conditions. Concentrator cells are denoted by (c). Laser intensity is average value.

The dependence of efficiency on average Nd:YAG laser power is plotted in Fig. 4 for representative cells. The average laser power levels of 425, 170, 41 and 4 mW/cm^2 correspond to approximately 3.1, 1.25, 0.3 and 0.03 suns, respectively, with peak powers of 810, 325, 80 and 8 suns. Some variation in efficiency with laser power is evident, with a maximum tending to occur at 170 mW/cm^2. However, the data at 425 mW/cm^2 show no sign of current saturation due to series resistance limiting at such high peak pulse powers, and the fill factors remain constant. Previous results with the induction formatted laser indicated that significant current saturation occurred at the highest laser intensities, where the peak

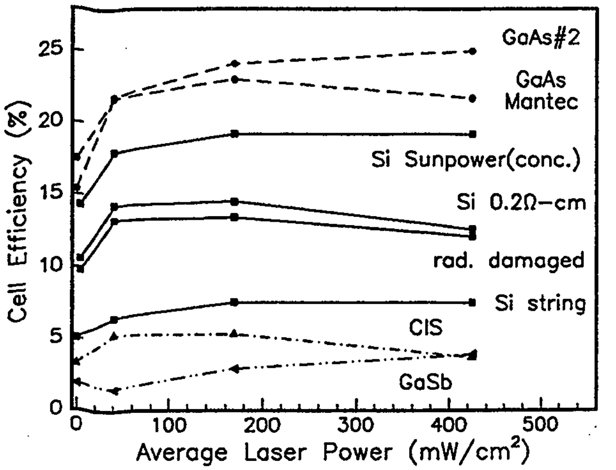

Fig. 4. Efficiency as a function of Nd:YAG laser power.

power increased to 6000 suns.

DISCUSSION

As noted previously, the efficiencies tabulated in this paper do not represent the peak values expected for 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 Si is about 950 nm (shorter for damaged material), 850 nm for GaAs, 1600 nm for GaSb and 1000 nm for CIS. Efficiency corrections can be estimated by the ratio of the wavelengths [1]

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

The wavelength term simply describes the inverse proportionality between incident laser power and wavelength. The quantum efficiency term is essentially equal to 1, assuming that quantum efficiency, QE, is nearly constant over the range of interest below the bandgap (as confirmed by measurements of external quantum yield),

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 shorter for the direct bandgap semiconductors than for Si, does not limit the ability of the cells to respond to the high power pulses. If the cells actually see peak currents 260 times larger than the average current (based on the laser duty cycle), then every cell tested should display current saturation. Saturation is not observed, however, 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. 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 with little loss relative to CW laser results.

CONCLUSIONS

Experimental results indicate that the conversion efficiency of conventional PV cells illuminated with MHz 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. The resultant cell performance is improved compared to previous results using a copper-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, and time averaged efficiencies are comparable to 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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