Saturation in Solar Cells from Ultra-Fast Pulsed-Laser Illumination

Tasshi Dennis

National Institute of Standards and Technology, Boulder, CO 80305, USA

***Abstract* — We investigate the potential saturation of a silicon solar cell in response to excitation from continuous-wave and ultra-fast pulsed lasers of equivalent average optical power. Because ultra-fast pulsed sources, such as the super-continuum laser, have very high peak powers, they may be expected to cause solar cells to exhibit nonlinear and saturation effects at much lower irradiance levels compared to continuous-wave lasers and solar simulator lamps. Our experimental results strongly suggest that this is not the case, and that ultra-fast lasers do not intrinsically give rise to enhanced nonlinearities caused by their pulsed nature.**

***Index Terms* — concentrator photovoltaic, efficiency, super-continuum laser, solar simulator, nonlinearity**

I. Introduction

Traditional laboratory light sources used for solar-cell testing include broadband lamps [1], lasers [2], and LEDs [3]. These sources are typically operated continuous-wave, or CW, with a constant temporal amplitude characteristic like the sun. Xenon arc lamps may be run in a pulsed mode with a low duty-cycle for the testing of concentrator solar cells. Recently, a new type of solar simulator based on a super-continuum laser has been demonstrated [4]. The super-continuum laser is a high-power, broadband light source with the potential to provide vastly improved optical excitation for photovoltaic materials and devices. This novel laser is rapidly pulsed at repetition rates up to 80 MHz, resulting in a quasi-continuous beam of light. This novel source offers coverage from the short-wavelength blue out to the infrared, with tens of watts of optical beam power in a single spatial mode.

Previously, NIST has shown that this source can be spectrally-shaped efficiently, and appears sun-like to a variety of photovoltaic materials [4]. That work was performed at irradiances of 1 sun, at which nonlinearity and saturation effects in solar cells would not typically be expected. Other researchers have made use of a wavelength tunable lasers to study two-photon absorption in silicon solar cells using ultra-short pulses [5]. In that work a comprehensive theoretical treatment for the nonlinearities was developed; however, the laser source was not nearly as broadband as a super-continuum.

The single spatial mode of a super-continuum laser allows the output beam to be highly concentrated for the testing of multi-junction, concentrator photovoltaic cells of small area [6]. In these instances, saturation and non-linear effects may be occurring. The high average power combined with a pulse duration of picoseconds results in extremely high peak powers of tens of kilowatts. This situation raises the question of whether solar cell materials are "blind" to this stimulus, or whether they are able to respond by generating photoelectrons and a measurable current. At some high level of irradiance, all solar cell materials will reach a state of saturation. In this work, we present results which strongly suggest that this doesn't occur any sooner for pulsed lasers as it does for CW lasers of the same average optical power.

II. Experimental Challenges

Significant technical challenges are presented when trying to conduct experiments which compare ultra-fast pulsed to CW excitation of a solar cell. In order for the results to be conclusive, the ideal measurement scenario must be able to isolate the potential measurement effects as originating solely from the temporal characteristics of the light. Some of these challenges originate from the light sources themselves. CW lasers by nature have very narrow spectral bandwidths, often described in terms of frequency rather than wavelength. The common helium-neon (He-Ne) laser operates with a gain medium having a bandwidth of 1.5 GHz, or 2 picometers at a wavelength of 632.8 nm. By contrast, ultra-fast pulsed lasers can have bandwidths ranging from 10 nm to more than 100 nm. The wide bandwidth is a consequence of the ultra-fast, pulsed characteristic in the time domain. By design, the broadest super-continuum lasers used for solar simulators [4] have bandwidths of 2000 nm. The primary impact of

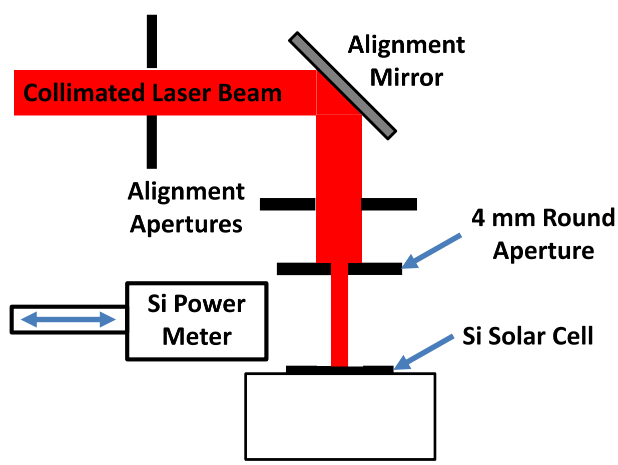

Fig. 1. The experimental apparatus for comparing a pulsed and CW laser on a silicon solar cell with collimated light and low irradiance.

illuminating solar cells with dramatically different optical bandwidths results in efficiency variations caused by a non-uniform spectral responsivity.

Another technical challenge presented by the light sources themselves is optical beam quality. CW sources such as lamps and LEDs radiate into large solid angles, making it difficult to collimate them into a beam capable of propagation over practical working distances without losing excessive optical power through divergence. Divergence makes illuminating a solar cell over a well-controlled, finite area difficult.

The spectral mismatch between pulsed and CW sources dictates that only single junction solar cells should be considered for comparison. Multi-junction solar cells are often designed to operate under high-concentration, high-irradiance conditions in which saturation effects are more likely to be observed, but would be subject to junction current-limiting which is spectrally dependent.

Other practical considerations include having to illuminate only a small, sub-area of a solar cell to maintain high optical concentration. Also, precisely the same sub-area of a solar cell should be illuminated by each light source so that grid lines and surface non-uniformity of the cell do not impact the measured efficiency.

III. Collimated Light Measurement

Even without concentration, past measurements of efficiency with pulsed, super-continuum laser light have contained measurement uncertainties sufficient to mask possible pulse effects [4]. Without a need for concentration, collimated beams can be used to conduct a CW-to-pulsed comparison, greatly easing experimental complexity. For CW illumination, we used a 632.8 nm He-Ne laser, with its output expanded into a collimated beam of 6 mm diameter. For the pulsed source, a super-continuum laser with a repetition rate of 80 MHz and sub-nanosecond pulses was spectrally filtered to a bandwidth of 16 nm centered on a wavelength of 633 nm. The filtered output of the super-continuum laser was expanded into a beam of 8 mm diameter.

Fig. 1 illustrates the experimental apparatus we constructed to compare pulsed and CW illumination of a solar cell at low irradiance. Alignment apertures and alignment mirrors were used to direct each of the laser beams down the same optical path to the solar cell sample. A round ~4 mm aperture restricted the beam illumination area on the solar cell sample. By overfilling the aperture with the collimated beams from the lasers, the irradiance incident on the solar cell had an approximately uniform, square-top profile. With collimated light, the aperture could be positioned a sufficient distance away from the solar cell surface to allow an optical power meter head to be brought into position to sample the exact beam power incident on the solar cell. The short circuit current of the solar cell was measured with a 4-wire current-voltage meter. The solar cell was a crystalline silicon device, with a phosphorus-diffused emitter, full area Al-BSF, p-type Czochralski (100) structure and a total area of about 1 cm^2.

	Irradiance	I_{sc}
He-Ne Laser	20.5 mW/cm^2	1.171 mA
Super-Continuum Laser	20.5 mW/cm^2	1.174 mA

Table. 1. Results for the comparison of a silicon solar cell illuminated with a He-Ne laser and a filtered super-continuum laser in terms of incident optical power and measured short-circuit current.

Table 1 shows the precise setting of the optical irradiance on the silicon solar cell from each of the laser sources. The currents measured from each of the laser sources differ by just 0.3 %, demonstrating no appreciable difference between the two sources of illumination. The AM 1.5 solar reference spectrum [7] contains 2.3 mW of integrated power between the wavelengths of 624 nm and 640 nm over which the super-continuum laser was filtered. Over a 4 mm aperture this power corresponds to an irradiance of 18.3 mW/cm^2. Therefore, on a per-wavelength basis the irradiance considered in this

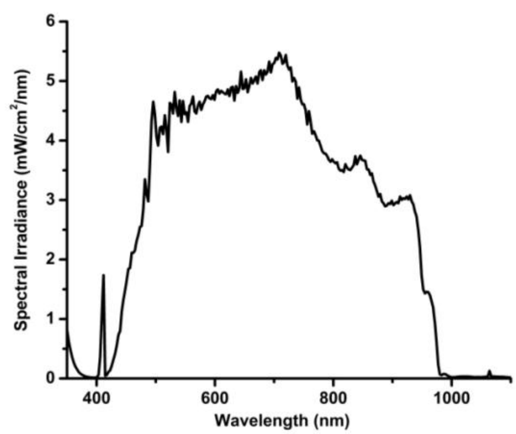

Fig. 2. The measured spectrum of the pulsed super-continuum laser narrowed to the spectral responsivity range of silicon solar cells and optical power sensors.

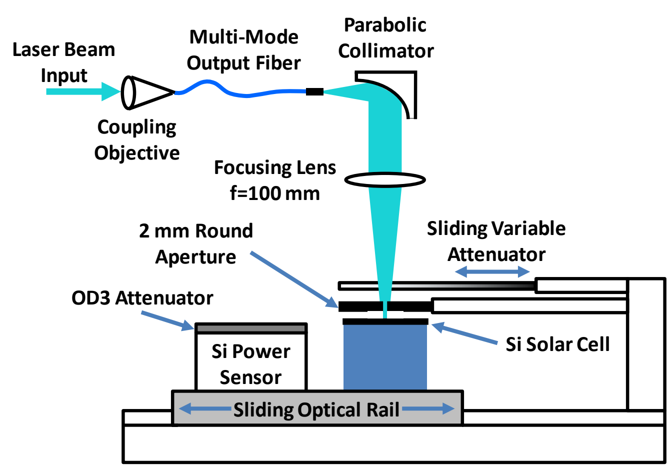

Fig. 3. The experimental apparatus for comparing a pulsed and CW laser on a silicon solar cell with concentrated light and high irradiance.

experiment is on par with a 1-sun illumination of the solar cell. At this relatively low level of irradiance, saturation effects would not normally be expected.

Unfortunately, this experiment was inconclusive because it amounted to a comparison between two silicon solar cells, not two different light sources. The optical power meter sensor was a large-area, silicon photodiode operating without bias, in photovoltaic mode. By use of a silicon photovoltaic device to set the incident optical power, any effect of the pulsed nature of the super-continuum light may have been compensated for and masked.

As an alternative, thermopile-based power meters can be used to measure the average power of both pulsed and CW laser sources, although they typically lack sensitivity sufficient for measurements of a few milliwatts or less. Pyroelectric energy meters are too slow to respond directly to the 80 MHz repetition rate of a super-continuum laser. Optically chopping the beam to create a slow modulation of a few tens of hertz would allow a pyroelectric meter to measure both the super-continuum as well as the He-Ne laser. Radiometers and calorimeters may also be used to measure the average optical power of either light source, but their bulk may require a significant redesign of the experimental apparatus.

IV. Concentrated Light Measurement

In order to achieve precise concentration through beam focusing, our experiment at high-irradiance made use of laser sources for both CW and pulsed illumination. A super-continuum laser with a repetition rate of 80 MHz and sub-nanosecond pulses was spectrally narrowed to span between 400 nm and 1000 nm thereby coinciding with the spectral responsivity bandwidth of silicon solar cells. The filtered super-continuum laser spectrum is shown in Fig. 2, and was able to provide up to 400 mW of optical power. A frequency-doubled diode laser operating at 532 nm was used as the CW laser source, and was capable of generating more than 5 watts of optical power.

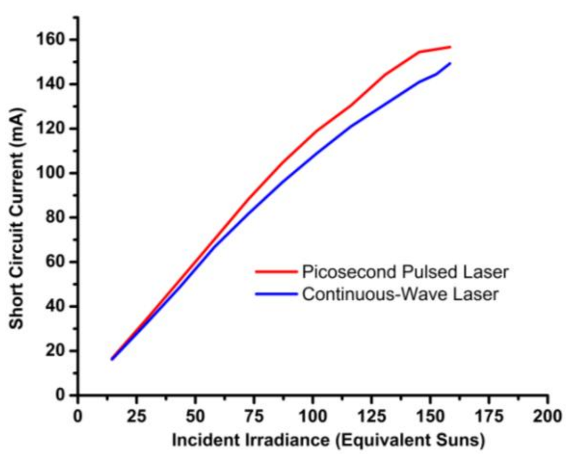

Fig. 4. The high-irradiance comparison of a CW laser and a picosecond pulsed laser. The incident irradiance is report as "equivalent suns" to indicate the magnitude of the excitation.

Figure 3 illustrates the experimental apparatus we constructed for concentrated light measurements performed on the same crystalline solar cell used in our collimated light measurements. In order to remove alignment issues with focused light, the lasers were each coupled into optical fibers that could be connected precisely to the experimental setup. The collimated light from the lasers was focused with a lens having a focal length of 100 mm, creating a soft focus on the solar cell surface. The focused beam passed through a sliding variable attenuator plate and a circular aperture of 2 mm in diameter. The focused light over-filled the aperture so the area of the transmitted light was well defined. By placing the solar cell at the beam waist of the focused light and the aperture as close to the solar cell as possible, diffraction effects were kept to a minimum.

During measurement operation, the optical power of the light incident on the solar cell was adjusted with the sliding variable attenuator. Adjusting the control settings of the super-continuum laser would have also influenced its relative spectral shape. The solar cell was mounted together with a silicon diode power sensor on the sliding stage of an optical rail. The optical rail allowed the solar cell and the power sensor to each be positioned precisely under the focused illumination for each measured data point. An optical attenuator of density equal to three was place in front of the power sensor to ensure that it was operated in a low-power, linear regime. Unlike the experiment with collimated light, the use of a silicon photodiode power meter did not inherently compromise the measurement integrity because the experiment was a relative comparison. The experiment attempted to resolve whether pulsed illumination would cause a nonlinear response at substantially lower optical power than CW illumination.

Figure 4 presents the measurement of short circuit current from the silicon solar cell as a function of incident irradiance. The horizontal axis has been converted to equivalent suns based on the integrated irradiance of the AM 1.5 reference spectrum between 400 nm and 1000 nm. While this may not be a precise definition, the unit helps convey the magnitude of the irradiance being considered by the experiment. The maximum measurement value was 158 equivalent suns.

We see from the sub-linear curves of Fig. 4 that the two laser sources each cause the solar cell to exhibit some nonlinear behavior that might be associated with saturation. Localized heating could also have been at play at high irradiance. To minimize transient thermal effects, the cell current was measured after more than 10 seconds of illumination. Regardless, the illumination by both laser sources causes similar measured effects, and indicates, at the very least, that the pulsed laser source is not intrinsically more likely to cause nonlinear cell performance at these irradiance levels. We note that the two curves have slightly different slopes, and there could still be some influence from spectral mismatch. Because the optical bandwidth of the pulsed laser source is substantially greater than the CW laser, it is possible that the optical powers are not as equivalent as presented. A silicon power sensor was used with the silicon solar cell to minimize this impact. Various thermal and pyroelectric power sensors would have avoided the errors associated with wavelength dependence, but would have been more difficult to incorporate into the experimental apparatus because of their bulk.

V. Conclusion

Our efforts to make a precise comparison of cell efficiency measurements with collimated illumination would suggest that ultra-fast pulsed lasers do not intrinsically cause saturation effects in silicon solar cells at low irradiance. Unfortunately, our results are far from conclusive because a second silicon solar cell was essentially used to quantify the incident irradiance. This difficulty further illustrates the challenge of making valid comparisons between pulsed and CW illumination.

Our concentrated light measurements support the notion that even at high-irradiance, ultra-fast pulsed lasers do not cause saturation or nonlinear effects substantially more than CW lasers of nominally equivalent optical power. These results have been obtained with a crystalline silicon material which is known to have minority carrier lifetimes of a few tens of microseconds. Other materials such as the III-V semiconductor material GaAs have lifetimes of a few nanoseconds, and therefore represent interesting subjects for future comparisons.

Acknowledgement

The author gratefully acknowledges former colleague J. Schlager for the concept of using super-continuum lasers as solar simulators, and for initially motivating the comparison of pulsed and CW illumination of solar cells. The author also gratefully acknowledges M. Spidel of NIST for use of the frequency doubled diode laser at 532 nm.

References

[1] K. Emery, D. Myers, and S. Rummel, "Solar simulation – problems and solutions", in *Twentieth PVSC*, Las Vegas, NV, pp. 1087-1091, 1988.

[2] C. H. Seager, "The determination of grain-boundary recombination rates by scanned spot excitation methods," *J. Appl. Phys.*, vol. 53, no. 8, pp. 5968-5871, 1982.

[3] B. H. Hamadani, J. Roller, B. Dougherty, and H. Yoon, "Fast and reliable spectral response measurements of PV cells using light emitting diodes," in *Thirty-ninth PVSC*, Tampa, FL, 2013.

[4] T. Dennis, J. B. Schlager, and K. A. Bertness, "A Novel Solar Simulator Based on a Super-Continuum Laser for Solar Cell Device and Materials Characterization," *IEEE J. Photovoltaics*, vol. 4, no. 4, pp. 1119-1127, 2014.

[5] M. Mundus, J. A. Giesecke, P. Fisher, J. Hohl-Ebinger, and W. Warta, "Interaction of ultrashort laser pulses and silicon solar cells under short circuit conditions," *J. Appl. Phys.*, vol. 117, 085702, 2015.

[6] T. Dennis, B. Fisher, M. Meitl, and J. Wilson, "A High-Concentration Programmable Solar Simulator for Testing Multi-Junction Concentrator Photovoltaics," in *Forty-second PVSC*, New Orleans, LA, 2015.

[7] Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surfaces, G173003, 2008. Available: http://astm.org