HIGH PERFORMANCE, ENHANCED UV SPECTRUM, COMPACT SOLAR SIMULATORS FOR ACCURATE TESTING OF ADVANCED PV MODULES

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ABSTRACT: Advanced PV modules often require final testing under simulated sunlight conditions that far surpass those specified by current solar simulator standards. A compact solar simulator of novel design operating from 300 to 1100 nm is described that far exceeds IEC Class A performance in spectral accuracy and irradiance uniformity, and which provides constant-intensity, 1-sun flash durations in excess of 130 ms. Simulator performance of this quality is needed to accurately characterize many of today's advanced design and new materials based modules. Preliminary results showing statistically significant power output increase for a selective-emitter crystalline Si-based module under these UV-enhanced test conditions are presented. Data also demonstrating the excellent measurement repeatability of this instrument are shown.
Keywords: characterization, module manufacturing, spectral response, solar simulator

1 INTRODUCTION

Advanced PV modules often require that final testing be made under simulated sunlight conditions that far surpass those specified by current solar simulator standards. These new, high performance modules can possess significant optical sensitivity outside of the normal 400 to 1100 nm spectral range. Additionally, they may be of a physical design that utilizes long, narrow individual cells monolithically interconnected instead of the more traditional square or near-square geometry of large crystalline silicon cells. Finally, they may have temporal characteristics that require illumination using extended duration optical pulses for the module to reach performance equilibrium.

Although terrestrial sunlight specified by the Air Mass 1.5G standard contains useful energy from 300 nm to well beyond 2000 nm, the spectrum described by the current principal solar simulator standard (IEC 60904-9) covers only 400 to 1100 nm [1]. To be designated as a Class A spectrum, the simulator output must fall within ± 25% of the mean target value in each of six wavelength intervals or bins within this range. Not only can this large ±25% variation lead to inaccurate and inconsistent simulation of natural sunlight, but many advanced cell and module technologies respond to wavelengths shorter than 400 nm or longer than 1100 nm.

IEC 60904-9 further specifies a Class A irradiance uniformity as one that does not exceed ±2% variation about the irradiance mean and where the size of the individual test points or areas can be as large as 400 cm^2 (i.e., an equivalent "pixel density" resolution of 25 pixels/m^2). For modules using large silicon cells typically >200 cm^2 or larger in area, this standard is generally adequate. However, modules using monolithically interconnected thin film cells may have individual cell areas significantly smaller and cell geometries that are much more rectangular than square. For these cases, this standard may also be inadequate.

Finally, the use of pulsed light to test PV modules is standard practice and offers many advantages. For modules that fully respond quickly to the pulse (e.g., traditional crystalline silicon), simulators that can only provide relatively short pulses (20 ms or less) may be adequate. However, longer pulse durations, often up to or exceeding 100 ms are required before full and stable module output is realized for some of the newer materials (e.g., CIGS/CIS) or advanced cell designs (e.g., HIT or n-base monocrystalline Si).

2 RESULTS AND DISCUSSION

With these three key requirements in mind, Spire has developed a new simulator, the Spi-Sun 5600SLP Blue. In contrast to previous compact simulator designs by both Spire and other manufacturers of compact simulators, the internal optical design of this tool is very novel. Extensive computer-based optical ray tracing was utilized to develop this tool allowing us to dramatically surpass the performance of Class A simulators using a more optically efficient design resulting in longer pulse durations with the same electrical input power. Key performance characteristics are illustrated in Figures 1 to 3.

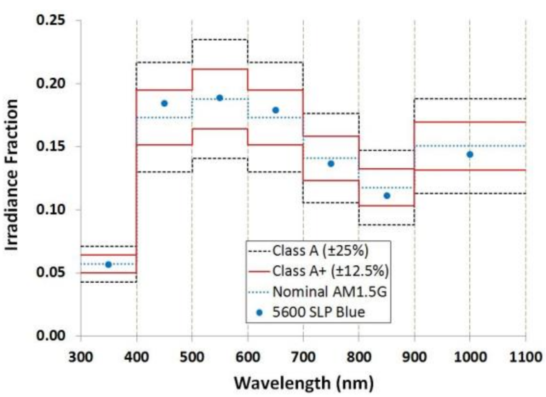

Figure 1: Spectrum by wavelength bin from 300 to 1100 nm for the Spire 5600SLP Blue simulator. The red lines (Class A+) indicate ±12.5% deviation from AM1.5G.

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Figure 1 shows the spectrum of the 5600SLP Blue by bin from 300 to 1100 nm. Over this entire range, the spectrum deviates less than ±12.5% from AM1.5G (i.e., Class A+). Figure 2 shows the short wavelength portion of the simulator spectrum in comparison to AM1.5G where many new cell and module technologies are showing improved sensitivity. The extremely good match between the 5600SLP Blue and AM1.5G is apparent.

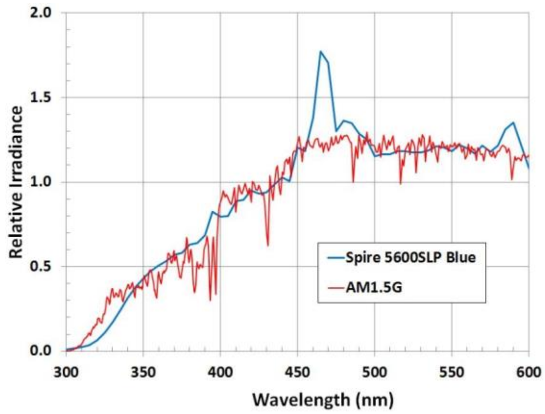

Figure 2: Comparison from 300 to 600 nm of the 5600SLP Blue spectrum to AM1.5G showing the excellent match over this wavelength region.

Figure 3 shows a high resolution spatial irradiance uniformity map for this tool. The resolution of the measurement shown here is approximately 570 pixels/m^2, far in excess of the 25 pixels/m^2 minimum required by IEC 60904-9. The equivalent 25 pixel/m^2 uniformity for this example is ~0.7%. The temporal stability of 5600SLP Blue uniformity is illustrated in Figure 4. During the 14-week duration of these uniformity measurements, no changes or adjustments were made to the simulator hardware that controls the irradiance spatial uniformity.

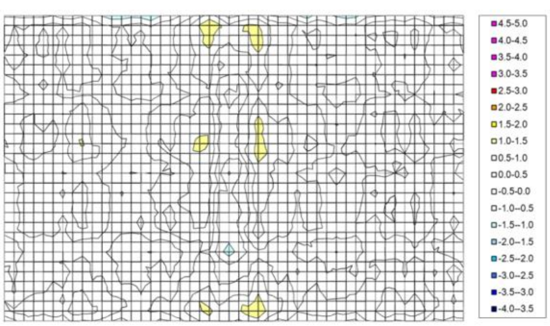

Figure 3: High resolution (570 pixels/m^2) uniformity map over the 1.37 m x 2.00 m output test plane of a 5600SLP Blue. White areas correspond to less than ±1% irradiance variation at high resolution from the mean, while the yellow and blue areas correspond up to ±1.5% deviation, respectively. The corresponding standard resolution 25 pixel/m^2 uniformity defined by the IEC standard is ±0.72%.

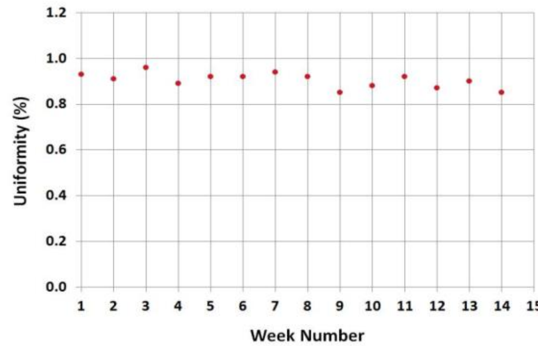

Figure 4: Temporal stability of spatial uniformity of a 5600SLP Blue simulator over a 14-week period. No adjustments to the uniformity hardware or to the lamp balance were made during this period.

An example where simulator spectrum below 400 nm is required is illustrated in Figure 5 and Table 1 which summarize data from the following experiment:

● A crystalline silicon module employing selective emitter (SE) technology to enhance its response below 400 nm was selected.
● The spectrum of the 5600SLP Blue simulator was temporarily modified to eliminate optical output at wavelengths shorter than 385 nm.
● Irradiance output of the simulator was then adjusted to 1 sun using a calibrated Si module traceable to NREL and known to have no response below 400 nm.
● The SE module was measured.
● The spectrum of the 5600SLP Blue simulator was then restored to its normal spectral condition shown in Figures 1 and 2.
● Irradiance output was once again adjusted using the same short-wavelength insensitive calibration module so that the irradiance from 400 to 1100 nm was the same as the first test.
● The SE module was finally remeasured.

Representative I-V curves for these two measurements are shown in Figure 5 and a tabulated summary for multiple measurements of the same module under both sets of conditions appears in Table I.

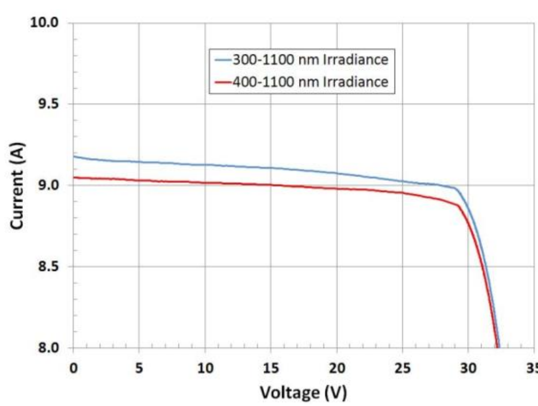

Figure 5: 1-sun IV curves for a selective emitter (SE) crystalline Si module tested under standard 400-1100 nm illumination and UV-enhanced (300-1100 nm) illumination.

Spectrum	I_{sc} (A)	V_{oc} (V)	P_{max} (W)
Standard	9.05	37.8	264.3
UV-enhanced	9.18	37.8	267.3

Table I: Summary of 5600SLP Blue simulator test results for a selective emitter Si module under standard 400-1100 nm illumination and UV-enhanced (300-1100 nm) illumination. These data are the averages for 5 consecutive tests under each illumination condition.

AM1.5G irradiance from 300 to 400 nm makes up approximately 5.2% of the total 300 to 1100 nm solar irradiance. This sets the upper limit for output power increase if a module could utilize this entire extra spectrum. The measured increase in the output power of the SE module tested here when subjected to this added irradiance was ~1.1%, a significant value. From a manufacturer's viewpoint, testing modules with this full, more accurate and realistic spectrum can significantly reduce revenue loss associated with possible underestimation of the power output capability of the module if not measured properly.

Similar considerations hold for the 1100-1300 spectral region, and modules that can respond to this include those based on CIS and CIGS. Consequently, we are currently developing capability to address this wavelength region as well.

Recent advances in cell and module technology frequently require pulse durations over 100 ms to achieve stability and assure certification of maximum power output. The long pulse duration capability of the 5600SLP Blue is illustrated in Figure 6 which shows a flash duration at 1000 W/m^2 of nearly 157 ms.

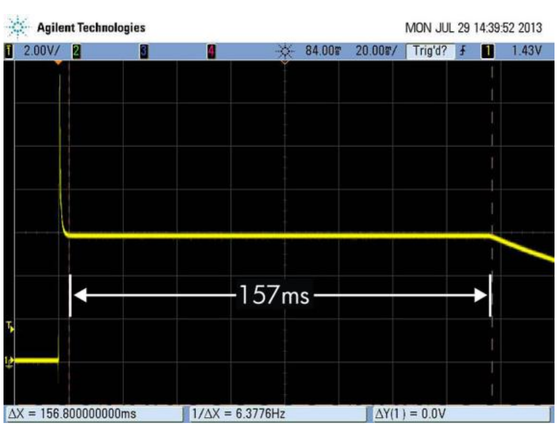

Figure 6: Oscilloscope trace of the optical pulse intensity of the 5600SLP Blue simulator at an irradiance level of 1000 W/m^2. The flat portion of the pulse has a duration of nearly 157 ms.

Flash durations less than 100 ms frequently yield P_{max} values which can be several percent lower than those measured using longer pulses. Testing of state-of-the-art CIGS modules has shown that measured values of P_{max} can be underestimated by as much as 2 to 3% or more by utilizing a pulse of insufficient duration. This same effect has also been observed on some newer design, higher performance Si modules. An example of this effect is shown in Figure 7. [2]

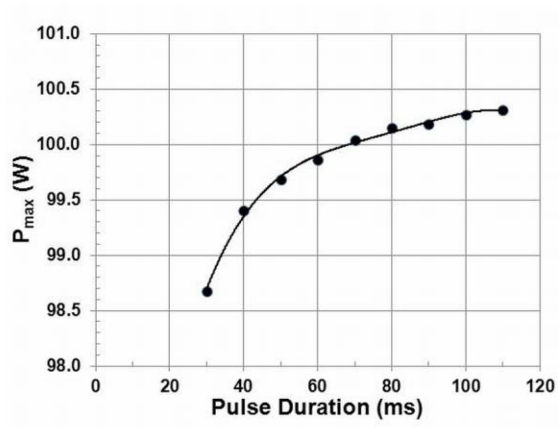

Figure 7: Dependence of measured maximum output power (P_{max}) for a commercial thin-film CIGS module on the duration of the light pulse used to test the module. For this module, it is apparent that an underestimate of possible maximum output power of nearly 2% can occur if one were to utilize a pulsed simulator of insufficient pulse duration.

Shown in Figures 8 and 9 are examples of the short and long term measurement repeatability of the 5600 SLP Blue. Figure 8 illustrates the P_{max} repeatability during a 50-flash test of a Si module over a total time of approximately 30 minutes. The measurement variation characterized as (Maximum – Minimum) / Mean is approximately 0.11% and the corresponding coefficient of variation C_v (Standard Deviation / Mean) is 0.024%.

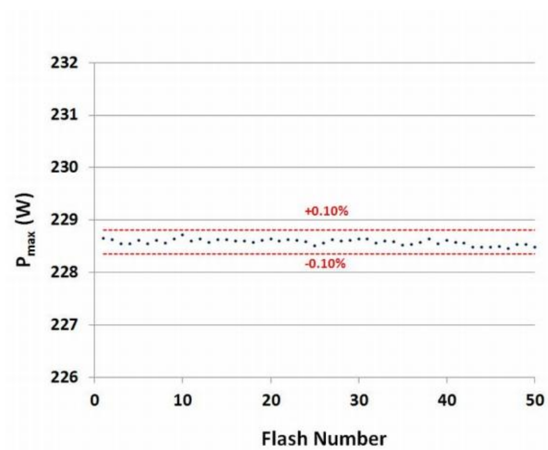

Figure 8: Short term P_{max} measurement repeatability of the 5600SLP Blue. A total of 50 flashes was made over a ~30 minute period. Reference lines indicating ±0.10% about the mean are shown.

An example of the long term measurement repeatability is illustrated in Figure 9. Here the same module as in Figure 8 was measured regularly over a 6-month period. During this period occasional scheduled maintenance was performed on the simulator, slight changes to the measurement procedure were implemented, or different operators performed the test. In spite of these, there was little variation in the measurement result with the P_{max} coefficient of variation remaining under 0.085% and the total peak-to-peak variation remaining under ±0.25% over the entire 6-month test period.

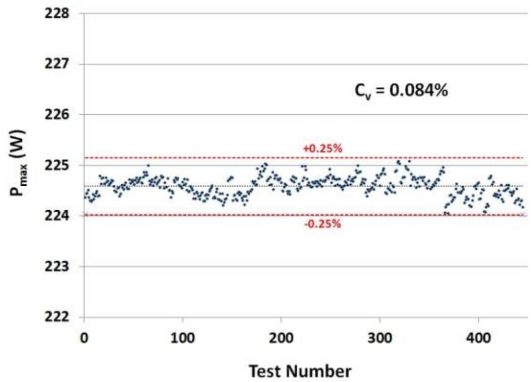

Figure 9: Long term P_{max} measurement repeatability of the 5600SLP Blue. Here a total of over 450 measurements was conducted during a 6-month period. The C_v for these tests was approximately 0.084%. Reference lines indicating ±0.25% about the mean are shown.

3 SUMMARY AND CONCLUSIONS

Accurate testing of advanced PV modules that either possess substantial short-wavelength sensitivity or require long duration pulses to reach operating equilibrium is becoming increasingly important. The recently announced Spire 5600SLP Blue solar simulator is a measurement tool whose characteristics far surpass IEC Class A and newer Class A+ solar simulator specifications. It is unique in its combination of small physical size, wide spectral range, high spectral accuracy, spatially uniform illumination, long pulse capability, excellent measurement repeatability, and low cost-of-ownership. This high quality instrument has the versatility to allow use in either a production or an R&D setting.

4 REFERENCES

[1] "International Standard – Photovoltaic Devices – Part 9. Solar simulator performance requirements", IEC 60904-9, Edition 2.0, 2007-10, International Electrotechnical Commission (IEC), Geneva, Switzerland.

[2] H.B. Serreze, J.E. Burns, M. Stein, and N. Chandrasekhar, "A New Generation of Compact Solar Simulators", presented at the IEEE 38th Photovoltaic Specialists Conference, Austin, TX, June 2012.

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