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Research Article

Construction of Tungsten Halogen, Pulsed LED, and Combined Tungsten Halogen-LED Solar Simulators for Solar Cell *I-V* Characterization and Electrical Parameters Determination

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I-V characterization of solar cells is generally done under natural sunlight or solar simulators operating in either a continuous mode or a pulse mode. Simulators are classified on three features of irradiance, namely, spectral match with respect to air mass 1.5, spatial uniformity, and temporal stability. Commercial solar simulators use Xenon lamps and halogen lamps, whereas LED-based solar simulators are being developed. In this work, we build and test seven simulators for solar cell characterization, namely, one tungsten halogen simulator, four monochromatic (red, green, blue, and white) LED simulators, one multicolor LED simulator, and one tungsten halogen-blue LED simulator. The seven simulators provide testing at nonstandard test condition. High irradiance from simulators is obtained by employing elevated supply voltage to tungsten halogen lamps and high pulsing voltages to LEDs. This new approach leads to higher irradiance not previously obtained from tungsten halogen lamps and LEDs. From *I-V* curves, electrical parameters of solar cell are made and corrected based on methods recommended in the IEC 60891 Standards. Corrected values obtained from non-STC measurements are in good agreement with those obtained from Class AAA solar simulator.

1. Introduction

Solar simulators for solar cell testing can be broadly classified into 3 groups, namely, AM 1.5 G terrestrial system solar simulators, AM 1.5 D concentrating PV solar simulators, and AM 0 space system solar simulators. Major building blocks of solar simulators, are light sources and light quality control components, such as filters and lenses, rendering AM 1.5 spectrum as specified in the IEC 60904-3 Standards and ASTM G173-03 Standards or AM 0 specified in ASTM E490-00a [1–3]. The IEC 60904-9 and ASTM E927-10 classify solar simulators in terms of spectral match, uniformity and temporal stability into simulator classes [4, 5].

Solar simulators have been continuously developed for nearly five decades, with differing approaches on lamp selection, combined light sources and filtering. Xenon arc lamps and metal halide arc lamps are employed in commercial solar simulators. Research solar simulator works during the last two decades are reported on light emitting diodes (LED) as they are inexpensive, consume small power and can be combined to produce required spectrum outputs, and promising a new approach to low cost. Current-voltage characterizations of solar cells are done at standard test condition (STC) (1,000 $W \cdot m^2$, 1.5 AM spectrum, cell at 25°C) as specified in IEC 60904-1 Standards [6]. As there are simulators not conforming to AM 1.5 G, notably simulators based on metal halide lamps and LEDs, the IEC 60891 Standards provide correction methods to convert the non-STC test results to the STC [7]. During the present decade the major research trend in solar simulators for terrestrial solar cells is on low cost and high intensity LED solar simulators and translation of non-STC results. This paper focuses on construction and

characteristics of simulators not conforming to AM 1.5 G, with emphasis on LED-based simulators, and applications of the IEC 60891 Standards on non-STC results.

Solar simulators using Xenon lamps and metal halide sources were reported over forty years ago, initially for space radiation simulation and afterwards for terrestrial solar cell characterization. An excellent review on early works is undertaken by Emery [8]. Compact source iodide (CSI) lamps were introduced in 1980s, as reported by Beeson [9]. After that multi-CSI solar simulators for large scale testing have become commercially available. On pioneering LED-based solar simulators, Kohraku and Kurokawa measure spectral responses of solar cells using 4-color and 6-color LED simulators [10]. Potential low cost and simplicity of LED-based simulators are pointed out. During the past decade, numbers of research work are published on LED simulators, all showing low intensity limitations of LED-based simulators. Bliss et al. develop an LED-based solar similar prototype producing light at variable flash speeds and pulse shapes [11]. Color and UV LEDs and halogen light sources are employed.

This paper is on construction and testing of seven solar simulators for solar cell characterization using tungsten halogen lamps and monochromatic red, green, blue, and white LEDs. High irradiance is achieved by operating lamps at elevated supply voltage above rated voltage, and in LEDs by applying voltage high pulses. This approach leads to higher irradiance that has not been previously obtained. Solar cell electrical parameters are derived and corrected according to the IEC 60891 Standards for I-V characterization at non-STC obtained under the seven simulators.

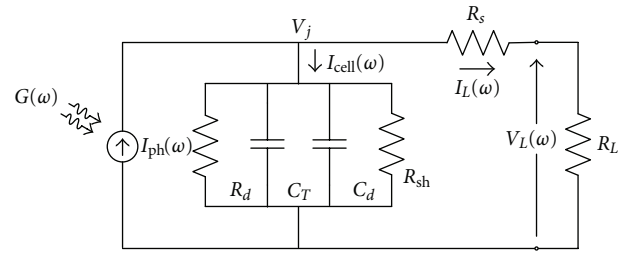

Figure 1: AC equivalent circuit of a solar cell.

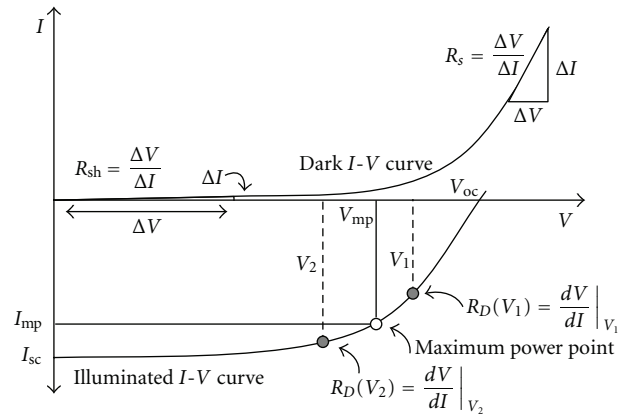

Figure 2: Dark and illuminated I-V curves of a solar cell.

2. Electrical Parameters of Solar Cells

In representing solar cells (and modules) one uses a DC equivalent circuit or an AC equivalent circuit. The DC circuit consists of three resistances, namely, series resistance (R_S), shunt resistance (R_{sh}), and internal dynamic resistance (R_d). The AC equivalent circuit has two additional parameters, that is, junction capacitance (C_T) and diffusion capacitance (C_D). C_T is voltage dependent whereas C_D is voltage and frequency dependent. Figure 1 shows an AC equivalent circuit.

Series and shunt resistances are determined from dark I-V characteristics or dark IV curves. Dark or illuminated IV curves are employed to determine internal dynamic resistance. The IEC 60904-1 Standards provide guidelines on performing I-V characteristics measurements under natural sunlight, steady-state simulated sunlight, and pulsed simulated sunlight [6].

Impedance spectroscopic techniques, not covered in this paper, are employed to determine dynamic parameters. Spectroscopic measurements can be done by expensive impedance spectroscopy equipment, reported by Kumar et al. [12]. Alternatively, Chenvidhya et al. has determined dynamic parameters utilizing laboratory equipment, with small periodic signals superimposing on AC signal as inputs to solar cells and FFT analysis of output signals [13].

From a dark I-V curve as showen in Figure 2, R_S is a slope in the first quadrant and depends on resistances of bulk semiconductors and contacts. R_{sh} can be derived from a slope at near-zero voltage, and depends on defects and traps in semiconductors. For each solar cell, R_S and R_{sh} are constant at all operating conditions. On the other hand, R_d is operating point dependent and is a slope at of an I-V curve (under dark or illumination) at a particular operating point.

In comparing performance of solar cells, apart from series and shunt resistance, other electrical parameters are also required. These are open circuit voltage (V_{OC}), short circuit current (I_{SC}), maximum power (P_{pm}) (and corresponding current and voltage), solar cell efficiency (η), and fill factor (FF).

3. Equipment

For characterization of solar cell under Class AAA simulator according to IEC 60904-9 Standards [4], natural sunlight and seven solar simulators fabricated in this study, we use a solar cell obtained from a local module manufacturer. It is a monocrystalline silicon solar cell with a dimension of $12.5 \times 12.5\,\text{cm}^2$. The solar cell is encapsulated with EVA and has a Tedlar backsheet.

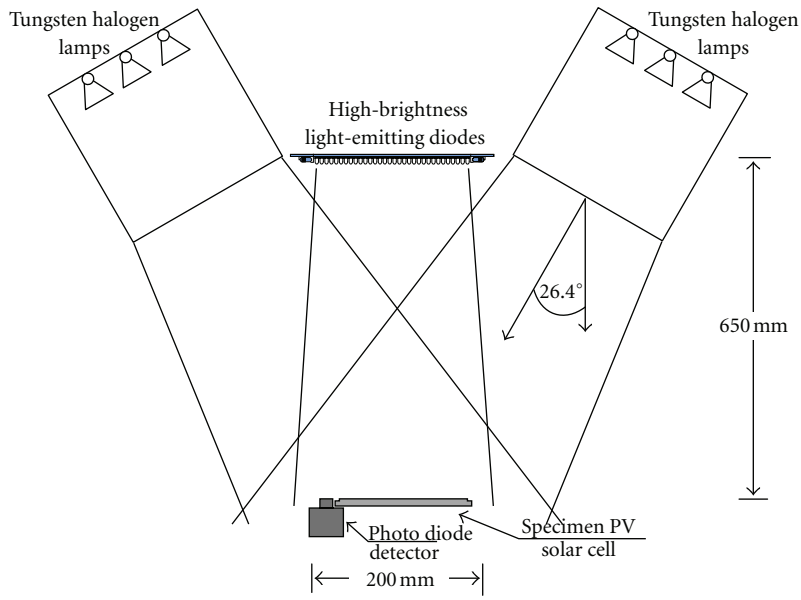

Figure 3: A schematic structure of combined tungsten halogen and blue LED solar simulator.

3.1. Solar Simulators

3.1.1. Tungsten Halogen Solar Simulator. The basic lamp array consists of 3×3 Philips tungsten halogen lamps, each rated at 12 V and 50 W. The array is naturally ventilated. Supply voltages can be varied from 100%, 120%, and 140% of rated voltage to increase lamp light outputs. This, however, affects color temperature of lamps, and resultant spectra.

As lamp supply voltage increases, lamp light outputs increase and the spectra are blueshifted. To maintain a constant irradiance of $1{,}000\,\mathrm{W \cdot m^{-2}}$ on a test plane, spacing distances between the array and the test plane are adjusted. For supply voltages at 100%, 120%, and 140% of rated voltage, the spacing distances are 42 cm, 62 cm, and 78 cm, respectively.

3.1.2. LED Solar Simulators. Study on five LED simulators, four monochromatic LED arrays, and one combined color LED array, used in this work, has been reported by Namin et al. [14]. Four monochromatic LEDs are red-R at 632 nm, green-G at 525 nm, blue-B at 468 nm and white-W. Each array has 1,024 LEDs and is 227.5 mm $\times$ 227.5 mm. The LED array is 3 mm above a glass diffuser, under which is a test plan. Supply voltages to LEDs are pulse signals whose amplitudes are increased above rated voltages to raise light outputs. Amplitudes of pulse signals can be continuously varied from 0–150 V with a pulse width of 10 ms and a period of 1 s. Heat from LEDs is removed with LED heat sinks and forced air cooling. This helps maintain steady temperature of heat sink at 25°C.

3.1.3. Combined Tungsten Halogen-Blue LED Solar Simulator. Tungsten halogen lamp light outputs are deficient in the blue part of the spectrum. To augment the blue part, we incorporate a blue LED array with tungsten halogen lamps as shown in Figure 3. The simulator combined light sources consisting of two 3×3 tungsten halogen lamp arrays and one blue LED array, similar to the one described above. The blue LED array is located directly 65 cm above the test plane. Two tungsten halogen lamp arrays are placed along opposite sides of the blue LED array, and at an inclined angle of 26 degrees with respect to the horizon.

3.1.4. Class AAA Solar Simulator. PASAN Class AAA Sun Simulator IIIc is used as a reference solar simulator. It is a commercial short-pulse solar simulator employing 4 flash Xenon lamps. Light pulses can be varied between 2–10 ms. Up to 2×2 m solar cells modules can be tested.

4. Measurements and Analysis

4.1. Measurements on Solar Simulator Characteristics. The following measurements are made.

Tungsten Halogen Solar Simulator. Spectral characteristics, irradiance spatial uniformity, and temporal stability are maintained when lamps are supplied at 100%, 120%, and 140% of rated voltage.

LED Solar Simulators. The above-mentioned study of Namin et al. covers

(i) thermal characteristics of LED arrays under continuous and pulsed operations. This is to compare temperature profiles of arrays under the two operating conditions. Infrared pictures of LED heat sinks are taken and used to determine corresponding temperature,

(ii) continuous and pulsed operations of LEDs at different amplitudes, pulse widths, and pulse periods. The

Table 1: Irradiance uniformity and temporal instability of seven solar simulators.

Light sources	Average irradiance (Wm^{-2})	Uniformity		Temporal instability	
		% Uniformity	Uniformity class	% Temporal instability	Temporal instability class
Tungsten halogen lamps					
Supply voltage and separation distance					
100% rated voltage, 42 cm	1004	9.8	C	1.25	A
120% rated voltage, 62 cm	1006	4.85	B	1.25	A
140% rated voltage, 78 cm	1005	2.60	B	1.25	A
Tungsten halogen lamps with blue LEDs					
120% rated voltage, 62 cm	1,040	3.60	B	0.47	A
Light emitting diodes					
Blue LED	1,015	2.68	B	1.40	A
Red LED	1010	2.60	B	1.50	A
Green LED	410	3.92	B	2.50	B
White LED	415	2.92	B	2.75	B
Combined R-G-B LED	810	3.84	B	3.10	B

shortest pulse duration that can be used would be governed by the sweeping time from the short circuit condition to the open circuit condition in I-V curve measurement,

(iii) spatial uniformity and temporal stability of irradiance are examined.

Table 1 shows irradiance levels, uniformity, and temporal stability of the seven solar simulators. Averaged irradiance levels are calculated from measured irradiance at 64 locations on the test plane.

4.2. Determination of IV Curves. The seven solar simulators used to measure I-V curves are (i) one tungsten halogen simulator, (ii) four monochromatic LED solar simulators, (iii) one combined RGB LED solar simulator, and (iv) one combined tungsten halogen-blue LED solar simulator. IV curves of a solar cell are made under STC condition PASAN Class AAA solar simulator, non-STC conditions (seven simulators) and under natural sunlight. The I-V characterization method follows the IEC 60904-1 Standards [6].

4.3. Analysis of Electrical Parameters

STC Condition. Calculations are made on solar cell electrical parameters (I_{SC}, V_{OC}, P_{mp}, efficiency, fill factor) and resistances (R_S, R_{sh}, R_d).

Non-STC Conditions. At present, there are correction methods based on the IEC 60891 Standards for measurements at non-STC conditions. I-V curves at different irradiances and temperatures were characterized by Class AAA solar simulator. The R_S and temperature coefficients of current (α) and voltage (β) and curve correction factor (κ) are determined.

The equations to translate or correct the non-STC results are as follows:

$$I_2 = I_1 + I_{SC}\left[\frac{I_{SR}}{I_{MR}} - 1\right] + \alpha(T_2 - T_1),$$
$$V_2 = V_1 - R_s(I_2 - I_1) - \kappa I_2(T_2 - T_1) + \beta(T_2 - T_1). \quad (1)$$

In the above equations, I_1, V_1 are measured current and voltage at non-STC; I_2, V_2 are corrected current and voltage; I_{SC} is the short circuit current of the test solar cell; I_{MR} is the short circuit current of the reference cell; I_{SR} is the short circuit current of the reference cell under standard light intensity; T_1 is the measured temperature of the test solar cell; T_2 is the standard temperature or other specified temperatures; α and β are temperature coefficients of current and voltage, respectively; κ is the curve correction factor.

Based on the equations outlined above, we correct results obtained from seven solar simulators using the IEC 60891 Standards and compared with the STC results. Figure 4 is a flowchart on solar simulator construction and corrections of electrical parameters using the IEC 60891 Standards.

5. Results and Discussions

5.1. Spectral Irradiance of Tungsten Halogen and Combined Tungsten Halogen-Blue LED Solar Simulators. For simplicity, we herein will use the term "spectral irradiance" of solar

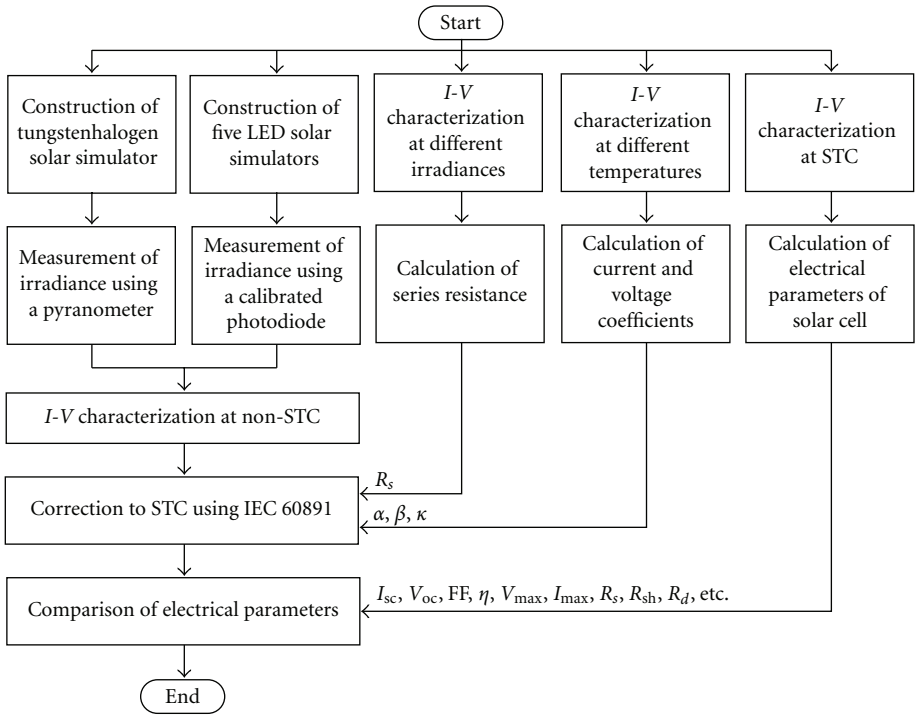

Figure 4: Flowchart of solar simulator construction and corrections of electrical parameters using IEC 60891 Standards.

simulator instead of spectral intensity. It can be seen from Figure 5 that spectra of the tungsten halogen simulator are different from the reference spectral irradiance [1]. The spectra are more "red" in contents. As the supply voltages are increased, the lamps get hotter and the output light spectra shift towards shorter wavelengths—blue-shifting. As a consequence, better spectrum matching with the AM 1.5 spectrum can be expected at elevated supply voltages. Thus, one can improve the spectral match of tungsten halogen solar simulators by raising supply voltages. The disadvantages would be higher power consumption and shorter lamp life. Adopting pulsed supply voltages would reduce such disadvantages, permit even higher supply voltages, and improve spectral match. We do not pursue such idea with tungsten halogen lamps, but carrying this out with LED simulators. The results are reported in later parts of the paper.

The spectral irradiance and intensity of a combined tungsten halogen-blue LED solar simulator is shown in Figure 6. The spectral match is improved by adding a blue irradiance component in the range of 400–500 micron. Temporal stability of irradiance of tungsten halogen solar simulators, obtained from an ordinary power supply with simple rectifier and a high quality power supply, shown in Figure 7, are compared and evaluated. It is seen that a Class A temporal stability is achieved using a high quality power supply.

Tables 2 and 3 compare spectral matches obtained from the tungsten halogen solar simulators using three supply voltages, and a combined tungsten halogen-blue LED solar simulator.

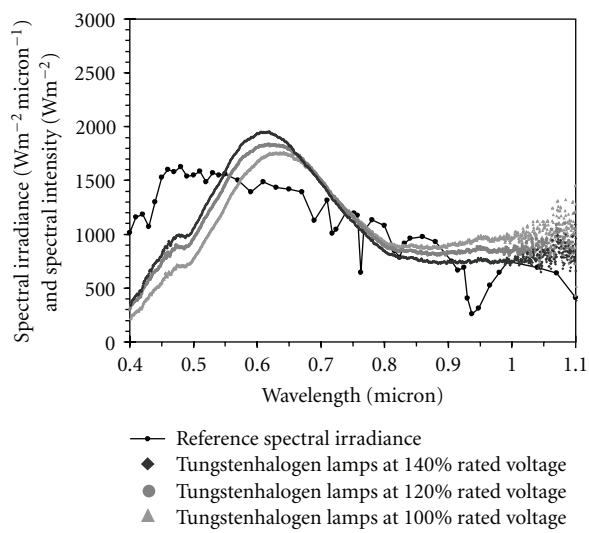

Figure 5: Reference spectral irradiance [1] and spectral intensity of tungsten halogen simulator under various supply voltage.

It is clearly seen form Tables 2 and 3 that combining blue LEDs with tungsten halogen lamps produce a better spectral match. Better I-V characterization and more accurate electrical parameters can be expected. This opens new avenues for low cost solar simulator construction.

5.2. LED Array Characterization. Followings are salient features on LED array characterization undertaken by Namin et al.

Table 2: Spectral match of tungsten halogen solar simulator at three different supply voltages.

Wavelength range (nm)	Supply voltage at 100% of rated voltage		Supply voltage at 120% of rated voltage		Supply voltage at 140% of rated voltage	
	Spectral match	Class	Spectral match	Class	Spectral match	Class
400–500	0.40	C	0.49	C	0.55	C
500–600	0.84	A	0.95	A	1.04	A
600–700	1.21	A	1.25	A	1.28	B
700–800	1.05	A	1.04	A	1.00	A
800–900	0.94	A	0.88	A	0.82	A
900–1100	1.65	C	1.38	B	1.29	B
Classification	1,010 $W \cdot m^{-2}$	C	1,009 $W \cdot m^{-2}$	C	1,010 $W \cdot m^{-2}$	C

Note: In the IEC 60904-9 Standards, six wavelength ranges are used to determine a spectral match with standard AM 1.5 G [9].

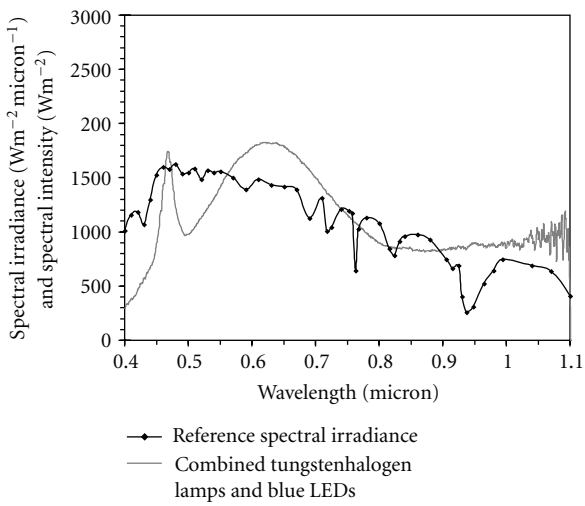

Figure 6: Reference spectral irradiance [1] and spectral intensity of combine tungsten halogen operated at 120% rated voltage and blue LEDs.

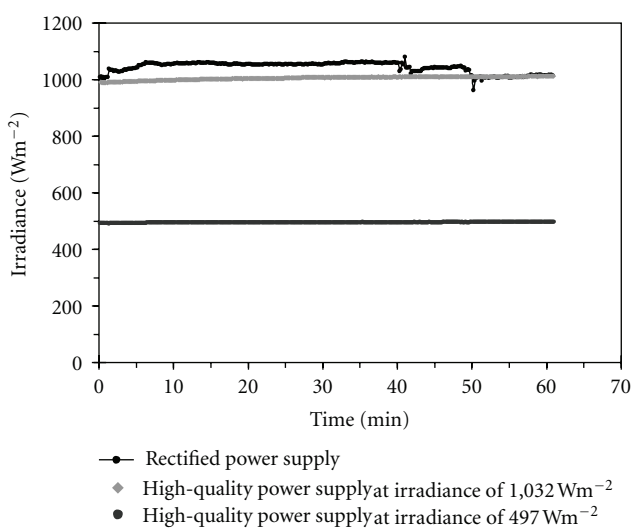

Figure 7: Temporal stability of irradiance of tungsten halogen solar simulator under different supply voltages.

Table 3: Classification of tungsten halogen solar simulator and combined tungsten-halogen blue LED solar simulator.

Classification	Light sources at irradiance of 1,000 Wm^{-2}	
	Tungsten halogen lamps at 140% rated voltage	Combined tungsten halogen lamps (120% rated voltage) and blue LEDs
Spectral match class	C	B
Nonuniformity class	B	B
Temporal instability class	A	A
Standard classification	CBA	BBA

Thermal Characteristics of LED Arrays. Under continuous voltage, heat sink temperature rises substantially (63°C). However, under pulse operation mode the array remains cool at room temperature (27°C). The merit of the pulse operation mode is evident.

Stability of Irradiance from LED Arrays under Pulse Operations. Irradiance stability of the R, G, B, and W LED arrays and the RGB array under 10 ms pulse operations is studied. Pulse amplitudes at one, two, and three times LED-rated voltages are applied, and irradiance stability is recorded. It is found that amplitudes of pulses can be increased to at least twice the rated voltage, and the array still provides a stable light output. Temporal stability is under 5%, and, the 5 simulators are Class B.

Spatial Uniformity of Irradiance. On the test plane, the spatial uniformity is better than 5%. The 5 simulators are Class B.

Relationship between the LED Current and Irradiance. LED light outputs and irradiance levels initially increase with increasing LED current but level off, due to temperature rises. Among the four monochromatic R, G, B, and W arrays and the combined RGB array, only R and G arrays provide irradiance higher than 1000 Wm^{-2}. Less than 1000 $W \cdot m^{-2}$ is available from G, W, and RGB arrays. Blue and white LEDs

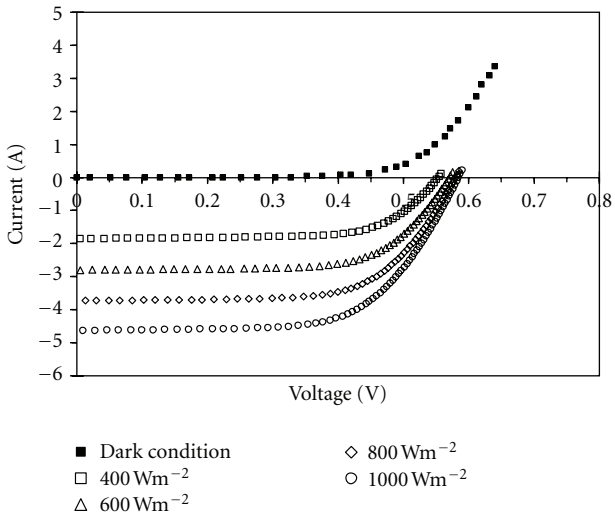

Figure 8: Dark and illuminated I-V curves of an X-Si solar cell obtained from Class AAA solar simulator.

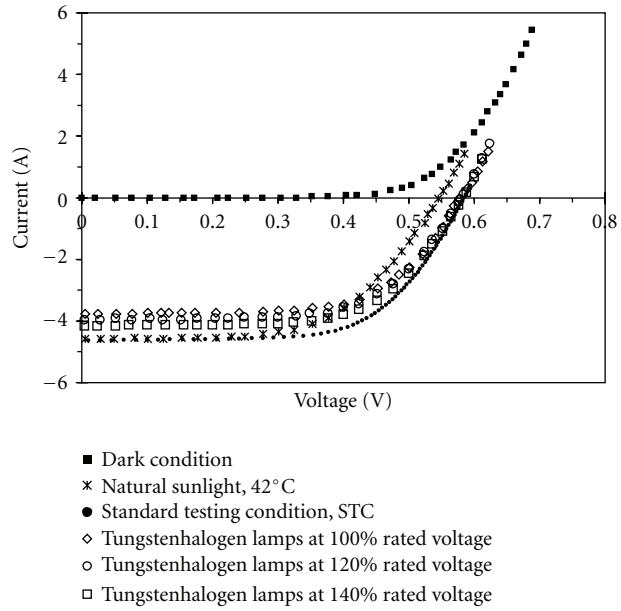

Figure 9: Uncorrected I-V curves obtained from tungsten halogen simulator under three supplied voltages, natural lighting, and Class AAA solar simulator at irradiance of 1,000 W·m^{-2}.

are more temperature dependent and are less efficient as their light outputs rapidly fall with increasing supply current.

In principle we can further increase LED light outputs by using higher pulse amplitudes while keeping LED temperature down. Chilled air, instead of room temperature air, could possibly be used in the cooling. But LED array structures would be complex and more expensive.

5.3. *I-V Characteristics Obtained from the Seven Solar Simulators*

5.3.1. Uncorrected I-V Curves Obtained from the Non-STC Simulators. We compare I-V curves obtained from seven non-STC solar simulators with I-V curves from a reference STC solar simulator (PASAN Class AAA Sun Simulator IIIc). Results are plotted in Figures 10 and 11.

From the Figures 8, 9, and 10, we note the following.

(a) PASAN Sun Simulator can be adjusted to provide an irradiance over 400–1,000 W·m^{-2}, Figure 8.

(b) Tungsten halogen simulator supply voltage can be adjusted to 140% of rated voltage, resulting in changes in irradiance and spectrum shift.

(c) For all 5 LED simulators, voltages and current can varied to provide irradiance in the range of 400–1,000 W·m^{-2}, and light spectra being different from AM 1.5. Out of the 5 simulators, only the red and blue LED simulators provide an irradiance of 1,000 W·m^{-2}. Results are previously reported and not shown here [14].

For the tungsten halogen simulator, at the irradiance level of 1,000 W·m^{-2}, Figure 10, uncorrected I-V curves measured with the three supply voltages are of the same shape as the I-V curve of the Class AAA simulator, with some deviations. The curve of the simulator operated at 140% rated

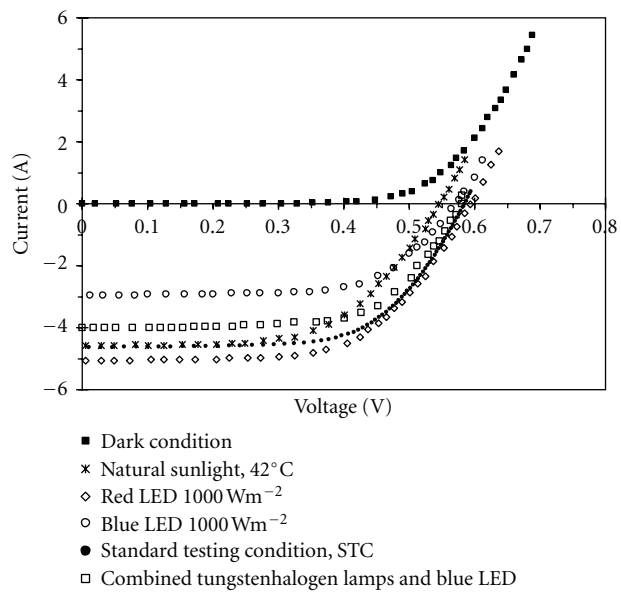

Figure 10: Uncorrected I-V curves from natural sunlight, Class AAA solar simulator, red LED, blue LED, and combined tungsten halogen-blue LED simulators at irradiance of 1,000 W·m^{-2}·

voltage is the best fit. This is understandable as at elevated voltages, the lamp temperature increases with accompanying spectrum shift towards the short wavelength. On the other hand, I-V curves of the red and blue LED simulators are significantly different from that of the Class AAA simulator, Figure 11. Red LED simulator results in higher current than blue LED simulator. This could be explained partly by the fact that at the same irradiance there are more red photons

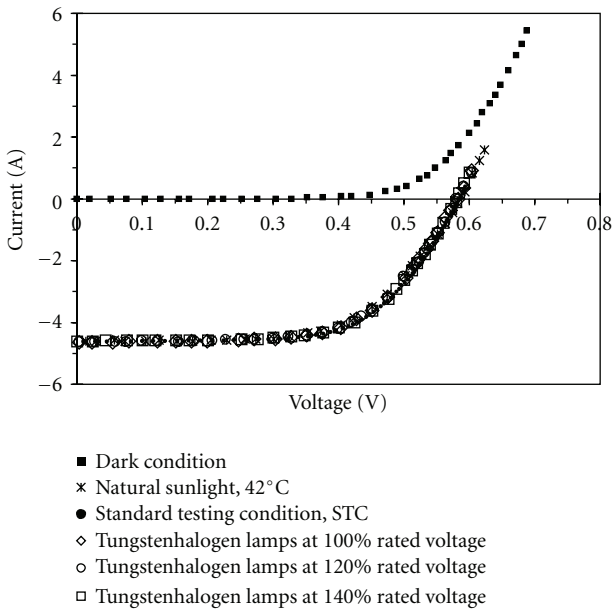

Figure 11: Corrected I-V curves measured under natural sunlight, Class AAA solar simulator, and tungsten halogen simulator (at 100%, 120%, and 140% rated voltage) after IEC 60891 Standards correction.

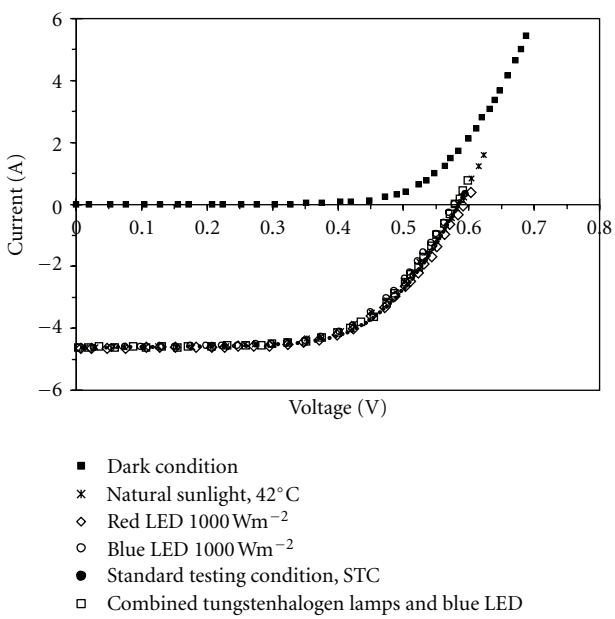

Figure 12: Corrected I-V curves measured under natural sunlight, Class AAA solar simulator, red LED simulator, blue LED simulator, and combined tungsten halogen-blue LED simulator after IEC 60891 Standards correction.

(at lesser energy) than blue photons. Hence, photocurrent due to red photons is greater.

5.3.2. Corrected I-V Curves at STC Based on the IEC 60891 Standards. We undertake corrections of the non-STC measurements of the seven non-STC simulators using the IEC 60891 Standards, outlined in Section 4.3, and plot results as Figures 11 and 12.

The corrected I-V curves and that of the Class AAA simulator are quite similar. We wish to point out that this is the first instance that the IEC 60891 correction method is applied for tungsten halogen, LED and tungsten halogen-LED simulators. Kohraku and Kurokawa have proposed a different correction method, called the Two-curve method.

5.3.3. Electrical Parameters of Solar Cell at STC. From the corrected I-V curves of the tungsten halogen simulator, the red and blue simulators, and the tungsten halogen-blue LED simulator at 1,000 W·m^{-2}, we derive electrical parameters (I_{SC}, V_{OC}, P_{mp}, efficiency, fill factor) at the STC. The results are shown in Table 4.

Comparing electrical parameters obtained from the seven non-STC simulators after corrections based on the IEC 60891 Standards and those obtained from Class AAA simulator, very good agreement is seen. Differences in values of electrical parameters are about 2% or less. This level of result accuracy is essential in adopting tungsten halogen lamps, LED and combined tungsten halogen-LED simulators in solar cell characterization. Less expensive but yet excellent-performance solar simulators can be constructed from these light sources.

6. Conclusions

We construct and test seven solar simulators with tungsten halogen lamps and LEDs as light sources for solar cell characterization. The seven simulators are one simulator using tungsten halogen lamps, four simulators using monochromatic red, green, blue, and white LEDs, one with combined red-green-blue LEDs and one tungsten halogen lamps—blue LEDs. Higher irradiance are achieved with tungsten halogen lamps and LEDs, by operating lamps at elevated supply voltage above rated voltage and pulsing LEDs by at voltage, respectively. Irradiance uniformity and instability qualify the seven simulators as Class B. Their spectral match with air mass 1.5 is varied. Using these simulators, I-V curves of solar cell are measured under non-STC conditions. Solar cell electrical parameters are derived. Applying correction methods recommended in the IEC 60891 Standards, for I-V characterization at non-STC, results on electrical parameters obtained with the tungsten halogen simulator, the combined tungsten halogen-blue LED simulator, and the monochromatic red and blue LED simulators are in good agreement with Class AAA simulator. Less expensive and excellent performance solar simulators can be fabricated with tungsten halogen lamps and LEDs as light sources.

Acknowledgments

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Table 4: Electrical parameters of solar cell measured under natural sunlight, Class AAA solar simulator, and non-STC solar simulators after IEC 60891 Standards correction.

Parameters	Light sources							
	Tungsten halogen lamps under three supply voltages			Red LED	Blue LED	Combined tungsten halogen and LEDs	Natural sunlight	Class AAA (STC)
	100% rated voltage	120% rated voltage	140% rated voltage					
G (W·m^{-2})	1000	1000	1000	1000	1000	1000	1000	1002
T (C)	25	25	25	25	25	25	25	25
V_{oc} (V)	0.58	0.58	0.58	0.59	0.57	0.58	0.58	0.58
I_{sc} (A)	4.63	4.63	4.63	4.63	4.63	4.63	4.59	4.63
P_{max} (W)	1.65	1.68	1.67	1.69	1.65	1.68	1.66	1.72
V_{mp} (V)	0.41	0.42	0.41	0.41	0.41	0.42	0.41	0.42
I_{mp} (A)	4.07	4.04	4.07	4.11	4.03	4.04	4.07	4.06
FF (%)	61.8	62.7	62.8	61.9	62.1	62.7	62.2	63.5
η (%)	11.3	11.5	11.4	11.5	11.1	11.5	11.4	11.7
R_s (Ω)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
R_{sh} (Ω)	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.08
R_d @ V_{mp} (Ω)	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

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