An Introduction to Solar Simulator Devices

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Solar simulators are popular in the photovoltaic industry. These devices provide a controlled way to characterize and evaluate photovoltaic devices due to the simple problem of the sun being an inconsistent and periodically unavailable optical source. Though solar simulators are used to characterize photovoltaic devices, they themselves may be characterized based on three categories: spectral match, spatial non-uniformity, and temporal instability. Recent developments in this field have implemented LEDs as an optical source for solar simulators, which outperforms the currently popular xenon arc-lamp. The LED-based solar simulator also carries implications of potential usage in a commercial setting to provide buyers with LED lightbulbs closely mimicking natural light.

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I. INTRODUCTION

Solar simulator optical sources are mainly implemented for the purpose of characterizing photovoltaic devices in a controlled and consistent environment. Solar simulators can themselves be characterized in three categories based on how well their optical output matches that of the sun. Recent developments in this field point towards a potential business opportunity in the commercial lighting industry, whereby indoor light sources can be made to closely replicate the colour and overall atmosphere provided by natural light. This proves useful due to the adverse health effects associated with chronic exposure to artificial light sources.[1]

Photovoltaic characterization occurs by measuring the electrical characteristics of the device while light is incident upon the active region. The efficiency of the device is then obtained by measuring the output electrical power as a fraction of the power provided by the incident light. This can be carried out with a sufficient degree of accuracy only after the characteristics of the solar simulator are known.

To characterize the solar simulator itself, three characteristics are of utmost importance, namely: spectral match, spatial non-uniformity, and temporal instability. These components are central to most, if not all, optical systems. Spectral match refers to the distribution of intensity across the wavelength emission spectrum of the solar simulator. Spatial non-uniformity refers to the degree of inconsistency as one moves along the length and width of *the entire test region at an instant in time*. Temporal instability refers to the degree of inconsistency in *one spot of the test region over time*.

The goal in creating a good solar simulator is to have these parameters match the sun's parameters as closely as possible. It is important to note: in characterizing a solar simulator, each of these three categories are measured *relative to the sun*. If we were to measure the sun as an optical source, the scores would read 0% in all categories since the sun's deviation from itself is zero, simply by definition!

The American Society for Testing and Materials (ASTM) has published documentation outlining the requirements for each of these three categories, and allows scientists to assign a letter-grade to each category based on a solar simulator's performance in that area. This provides a simple way of immediately communicating how well a solar simulator performs in each category. The quantities associated with these properties are obtained by conducting optical measurements pertaining to each property. Spectral match is addressed via a spectral analysis while spatial non-uniformity and temporal instability are both addressed via an optical detector array. The two measurements are determined by controlling each of two variables; time is held constant for spatial non-uniformity, and a spatial average is analyzed over a time interval for temporal instability. The following table outlines the characteristics of each category corresponding to each letter grade.

TABLE I. The values for optical parameters corresponding to each letter-grade of a solar simulator as specified by ASTM, where SM is Spectral Match, SNU is Spatial Non-Uniformity, and TI is Temporal Instability[2].

Grade	**SM**	**SNU**	**TI**
A	$0.75\% - 1.25\%$	$\leq 2\%$	$\leq 0.5\%$
B	$0.60\% - 1.40\%$	$\leq 5\%$	$\leq 2.0\%$
C	$0.40\% - 2.00\%$	$\leq 10\%$	$\leq 10\%$

The typical optical source for a solar simulator is a xenon arc lamp. These lamps have served as an adequate optical source for the purpose of characterizing photovoltaic devices, and have been implemented in AAA-rated solar simulators. Alternative sources have been considered, with more recent implementations using LED sources. LED-based sources have a very high electrical-to-optical conversion efficiency, meaning these devices are highly energy efficient which leads to a reduced operating cost. LED devices are also highly scalable, in the sense that one can combine many LEDs into a structure such as an array to create a large effective source. LED solar simulator arrays have been tested and proven to be more favourable than xenon-lamp-based simulators, especially in the spectral match category.[3] Due to the wave-nature of light, and using the concept of a Fourier series, one can produce an output spectrum of any shape using a sufficient number of LEDs emitting at different wavelengths. By using more wavelengths, the scores in each category are increased; spectral match is better (via Fourier theorem), the light is more spatially uniform (more LEDs overlapping onto one area), and the light is more stable in time (many optical fluctuations will cancel out).

II. RESULTS

This section briefly summarizes the comparison of quantitative data pertaining to the solar spectrum, a xenon arc-lamp source, and an LED array source. Figure 1 shows the irradiance of the sun as a function of wavelength. This plot follows the characteristic shape given by Planck's blackbody radiation equation, which is as follows:

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left[\frac{hc}{\lambda k_B T}\right] - 1}$$

Similar plots may be obtained by scanning over the wavelength range shown in the x-axis of Figure 1, most closely to the AM0 spectrum, since the Planck blackbody formula does not account for losses due to atmospheric absorption and scattering.

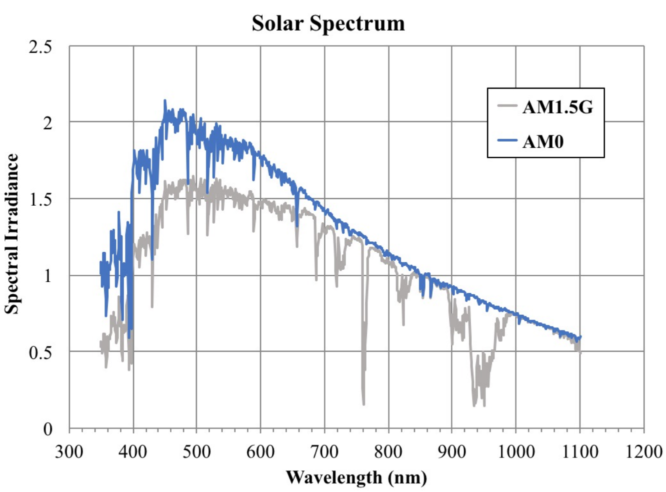

FIG. 1. Actual solar spectrum.[4] "AM1.5G" refers to the average irradiance after accounting for atmospheric absorption, whereas AM0 refers to the irradiance measured after the light has only passed through vacuum.[5] Spectral Irradiance is given in units of $Wm^{-2}nm^{-1}$.

As mentioned in the Introduction section, xenon arc-lamps are the most popular optical source in most solar simulators. Although widely used, these lamps do not necessarily provide the best spectral match. Figure 2 shows the output spectrum of a typical xenon arc-lamp versus the solar spectrum.[3]

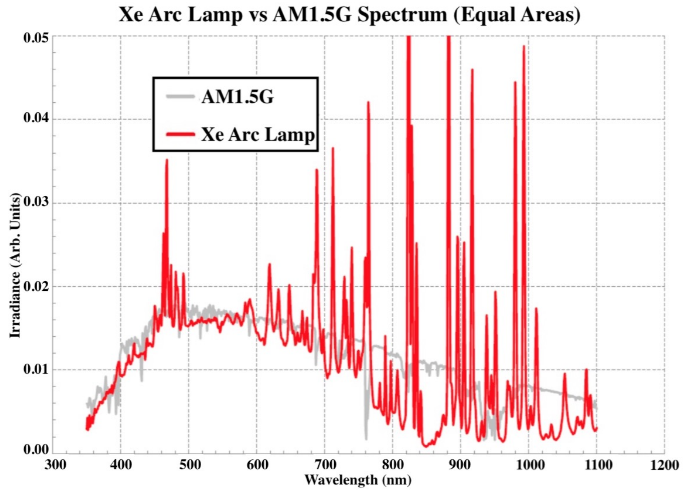

FIG. 2. Xenon arc-lamp irradiance (red) compared to the AM1.5G spectrum (grey), as a function of wavelength.[3]

An obvious series of mismatches are seen beginning in the 650nm region continuing along the rest of the wavelength range up until 1100nm. Given that most solar cells are silicon-based, with an absorption peak at approximately 1100nm, this region of wavelengths is particularly important in characterizing most solar cells.[6]

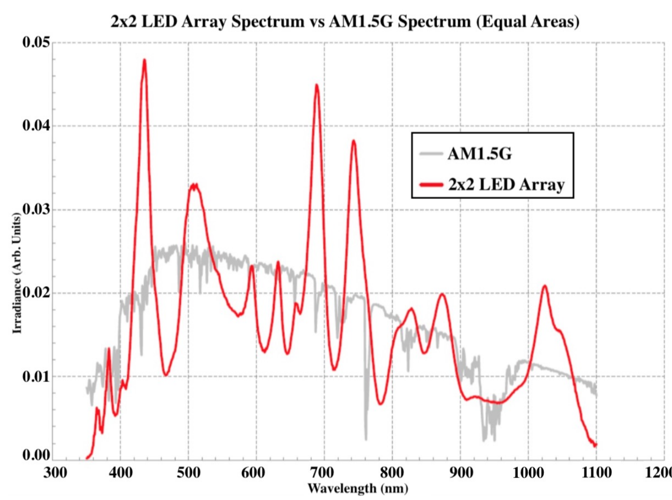

FIG. 3. Irradiance of 23-wavelength LED array (red) compared to the AM1.5G spectrum (grey), as a function of wavelength.[3]

This mismatch in the 650nm-1100nm region is rectified by the LED-based solar simulator, as shown above in Figure 3. The sharp spikes are smoothed and provide a much closer fit to the shape of the AM1.5G spectrum, offering a much cleaner irradiance distribution with a better overall match.

III. DISCUSSION

Although Linden, Neal, and Serreze[3] do not explicitly discuss which wavelengths were used in their LED-based solar simulator, it is safe to assume that the 23 wavelengths span the 350nm-1100nm range. This assumption is valid since any wavelengths outside of this range are not characteristic of sunlight with respect to silicon photovoltaic devices, so they can be omitted entirely with little to no effect on the spectral match factor. They did, however, specify that the individual LEDs can be turned on or off, which allows the output spectrum to be tuned. This is something the xenon arc-lamp cannot do, which further advances the position of the LED-based device.

For photovoltaic devices based on different semiconductors with smaller band gaps than silicon, such as germanium, the wavelength range past 1100nm must be considered. This is especially important when characterizing multijunction solar cells. A multijunction solar cell is a layered solar cell composed of different semiconductors with different band gaps. This is done so that more of the solar spectrum can be captured by the total device. Since the output spectrum of the LED solar simulator can be tuned by turning on/off certain wavelengths, each layer of a multijunction solar cell can be characterized individually. This allows for diagnosis of each individual layer, which can indicate a manufacturing or design inefficiency.

Now we compare the spectra of the Xenon arc-lamp (Figure 2) and the LED-based device (Figure 3). Looking back at Figure 3, some overshoot still exists. However, the overall shape matches the AM1.5G spectrum much more closely, putting the LED-based device in a superior position. The measure of intensity at one wavelength relative to the rest (ie. the basic shape of the spectrum) is far more important than the absolute measure of the output intensity of any individual emission wavelength (ie. the sum of differences in intensity across the entire wavelength range).

The reasoning for this claim is as follows: if the shape is correct, then one may simply scale the power to make the LED's irradiance match the sun's; however, with the Xenon arc-lamp, scaling the power will largely affect the many spikes seen in Figure 2. Note the two major spikes between 800nm and 900nm which extend above the range of the y-axis, further solidifying this point. One must also consider that, due to the fact that solar simulators are used for characterizing photovoltaic devices, having one of these spikes from the Xenon arc-lamp line up with the semiconductor band gap will easily produce false results since the sun simply does not provide those same spikes.

This absence of sharp spikes in Figure 3 is characteristic of the LED emission wavelengths being close to one another. Taking 23 wavelengths across the range of 350nm to 1100nm provides an average spacing of 34nm between each emission wavelength. This is then the average resolution of the device with respect to wavelength when tuning the output via switching LEDs on or off.

In addition to the average resolution of 34nm, the relative smoothness of the spectrum in Figure 3 is attributed to broadening effects. The broadening seen here is characteristic of minor fluctuations in the band gap. These fluctuations occur due to quantum effects pertaining to the Heisenberg Uncertainty Principle in its energy-time uncertainty form,[7] given by

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

Because the *exact* time it takes for an electron to transition among energy levels is unknown, then the *exact* change in energy is also unknown. This uncertainty manifests in the form of a distribution in emission wavelengths, which are centred at the peak emission wavelength.

Due to the scalability of the LED-based solar simulator devices, the inclusion of many wavelengths of light can be applied to indoor lighting to synthesize natural light. Overexposure to artificial light has been proven to have negative health effects,[1] which itself makes these products marketable. Integrated circuits can be built into lightbulbs and can allow the user to tune the colour to their liking.

IV. CONCLUSION

Solar simulator devices were originally created for characterizing photovoltaic devices. New implementations of this idea have birthed technology which is more cost effective, more environmentally friendly, and which is much smaller than previous models.

These newer devices, typically based on LEDs, are able to compete with and out-perform the xenon arc-lamp. The xenon arc-lamp has historically been the most popular solar simulator optical source, and its usage is still common in modern solar simulators.

The quality-determining factors for a solar simulator are spectral match, spatial non-uniformity, and temporal instability. These parameters and their associated performance ranges for each letter-grade are outlined by the ASTM. These letter grades allow clear and concise communication of how well a solar simulator performs in each area.

In conclusion, the demand for these devices should not decrease any time in the near future given their intrinsic relevance to the photovoltaic industry. The need for these devices is further solidified by considering the imminent commercialization of this technology within the lighting industry.

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Notes and References

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