Photos: WAVELABS

The 18 color SINUS-220 LED solar simulator (device with orange accents) integrated into a fully automated tester/sorter line.

LEDs copy the sun

Metrology: Higher solar cell efficiencies are essential for further cost reduction of PV electricity. But the way efficiency is measured also has to keep up with the increasing requirements of the maturing PV industry. The CEO of Wavelabs, Dr. Torsten Brammer, and Christian Leers of Accelios Solar report on the benefits and challenges of replacing conventional Xenon lamps in solar simulators with LED technology.

Pulsed (AC) and continuous (DC) xenon lamps have been the standard light sources for efficiency measurement since the beginning of industrial solar cell manufacturing. As a result of giant leaps in solid-state lighting technology, LED-based light sources promise to be a better approach for various reasons. The main reason is that LEDs provide the opportunity to combine various colors to match the sun's spectrum more accurately and reliably. This article discusses the strengths and weaknesses of xenon simulators and what needs to be considered when LEDs are used as a simulator light source.

The most prominent weakness of xenon lamps, the large deviation from the standard spectrum, is mainly caused by the xenon peaks at wavelengths greater than 750 nm. This can be seen in the graph "Xenon vs. the sun" (see p. 54). The deviation of the xenon spectrum is well outside the tolerances specified for class A devices. The result can be an efficiency rating of 19.9% instead of 20%.

The second most prominent feature is the short-term and long-term drift of the xenon spectrum due to aging (see Herrmann and Rimmelspacher 2012). The simplified data in the graph "Spectral change of Xenon" shows the relative change of the spectrum at end-of-life in comparison to the spectrum emitted by the lamp when it was new. In the short and long wavelength regions, the change in spectrum is greater than 5%. The specified life span is usually 500,000 flashes, which corresponds to less than half a month of operation. Usually, the lamps are used up to 3 months or longer, so that the drift in spectrum is larger than shown in the graph "Spectral change of Xenon" (see p. 54). This drift can cause significant errors when measuring efficiency. A solar cell with an efficiency of 20%, for instance, might be rated at 20.1%. It can be partly compensated for by frequent calibration which, however, results in high operating expenses (labor, downtime, costs for reference cells). But re-calibration only fixes the issue for solar cells that are identical to the reference cells. Solar cells with a different spectral response will not be measured correctly despite re-calibration.

Herrmann and Rimmelspacher also address short-term spectrum drift during the duration of the flash. At the beginning, the flash has a higher red portion than at the end. This can also cause the efficiency measurement to be incorrect. New tester and sorter lines aim for tact times of one second or less. Xenon lamps usually need long breaks between flashes.

Another frequently discussed issue is that high efficiency solar cells require long exposure times. In the past, an exposure time of only 10 ms was sufficient to measure solar cells correctly. High efficiency solar cells, however, do not "wake up" quickly, meaning such solar cells require a long time to reach full power. This behavior is often described as the capacitive effect. It can be observed in the graph "The capacitive effect of solar cells" (see p. 55), which depicts the performance of a solar cell with 20.8% efficiency. The measured efficiency is plotted against the exposure time expressed in milliseconds per volt (ms/V). The exposure time is divided by the voltage scan width during the efficiency measurement. As shown, an exposure time of as much as 150 ms/V is required to measure the true efficiency. Using a shorter exposure time of only 20 ms/V would lead to a significant underestimation of cell efficiency.

There are various techniques to improve the efficiency measurement of highly efficient solar cells despite short flash durations. The following are four of the most commonly used methods:

Forward/reverse method: One efficiency measurement is done under increasing voltage, one measurement is done under decreasing voltage. Using the average of both measurements (requires flashing twice, reducing lamp life by 50%) allows an estimation of the true efficiency.

Multi-step method: The full measurement is subdivided into two or more measurements of parts of the IV curve. Increasing the number of flashes has a negative impact on lamp life as mentioned.

Dark biased and multi-speed IV sweeps: The solar cell is biased in the dark, which is followed by a slow IV sweep at the presumed maximum power point.

Xenon plus 1-color LED method: This method measures the short-circuit current with the Xenon light source and the voltage sweep is done with a single LED, which provides a poor approximation of the sun's spectrum.

All methods can improve accuracy considerably but remain workarounds and are based on certain assumptions, which might not always be applicable. The extra operating expenses mentioned previously together with the added process complexity do not inspire confidence when what is needed is a workhorse capa-

STRENGTHS AND WEAKNESSES OF XENON		
STRENGTH	**WEAKNESS**	**EFFECT OF WEAKNESS**
Well established	Large deviation from standard spectrum	Efficiency measurement is not accurate
Wide spectral range	Short-term and long-term spectrum drift	Efficiency measurement is not precise
High proportion of direct incident light (in some cases, a diffuser is used for enhanced homogeneity)	Spectrum varies with intensity	Efficiency measurement from 0.1 up to 0.9 suns is not accurate
	AC-Xenon: limited to short pulses	Inadequate for high-efficiency solar cells
	Short life cycle of lamp	High operating costs
	Limited throughput	Not suited for new high-throughput lines

ble of operating on a 24/7 production schedule.

LED-based solar simulators

Recent advances in LEDs have turned this technology into a viable alternative for solar simulation without the drawbacks of conventional xenon-based systems. But creating a perfect simulation of the sun's rays with LEDs is not as simple as merely satisfying the requirements of international standards. Manufacturers of these devices must overcome a number of additional challenges to ensure their products are suitable for real-world solar simulation:

- Achieving high color diversity
- Ensuring good color mixing
- Maintaining high spectral stability

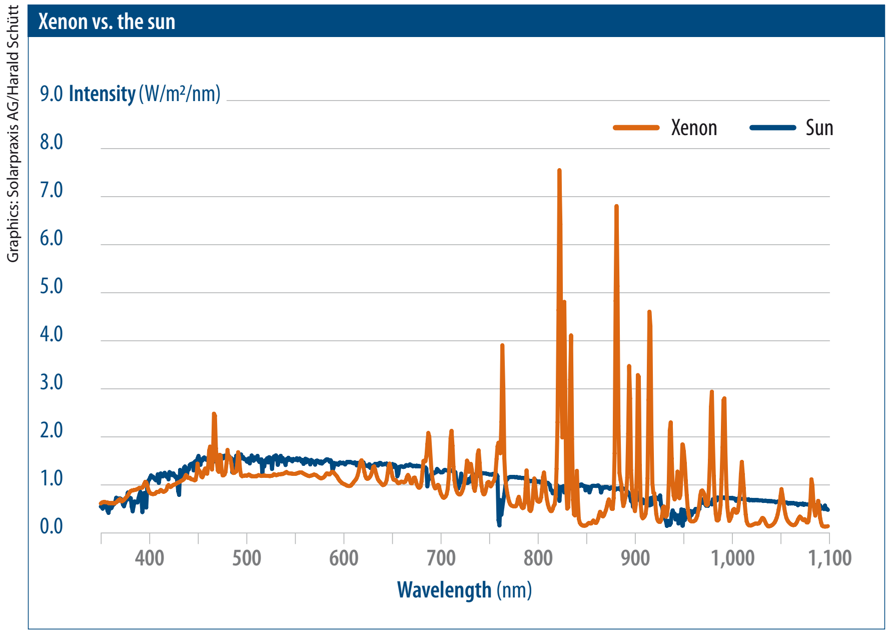
Color diversity

In principle, it is easy to achieve a class A rating with LEDs. Using six different colors of LED is sufficient to achieve a class A rating. A schematic spectrum of this kind is shown in the graph "Simple 6-color LED light source" (see p. 56), but the spectrum is not continuous. Also the lack of intensity in some wavelength ranges is compensated by a very high intensity for a few, narrow wavelength ranges: In the example given here, there is no light for wavelengths larger than 1,000 nm.

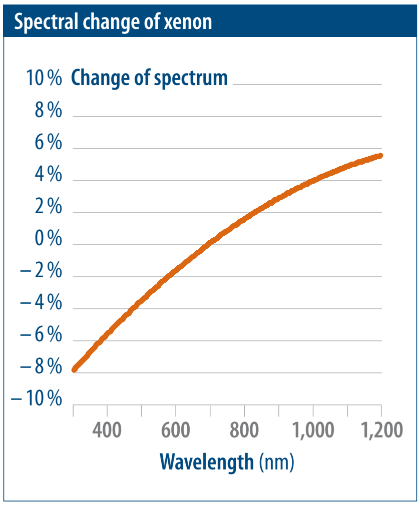
Consequently, the difference between solar cells with differing spectral sensitivities can be largely over- or underestimated with such a simple LED spectrum (this disparity is described by the spectral mismatch factor). A solar cell with a true efficiency of 18% might receive a rating of 17.4% if the individual spectral mismatch factor is not applied correctly. The key insight here is that a simulation of the sun's spectrum should be done using a continuous spectrum, not merely 6 different colors with a narrow intensity distribution. The graph "18-color LED light source" (see p. 56) shows an example of 18 sets of LEDs instead of only 6 being used to copy the sun's spectrum. The spectrum is continuous and hardly deviates from the sun's spectrum. The deviation from the solar spectrum is less than 2%. A maximum deviation of 25% is required for a rating as class A solar simulator. With such a light source, different types of solar cells with largely differing spectral responses can be measured without requiring separate calibrations for each type. Even if the identical spectrum and intensity of this 18 color LED light source is used for a standard multicrystalline, a standard monocrystalline and a novel 20% high efficiency solar cell, the maximum inaccuracy is less than 0.05%. The inaccuracy caused by a xenon lamp for this specific set of solar cells is above 0.6%.

Color mixing

Spectral quality is essential. And it is essential to not only have the right mix of colors in aggregate, but to also have a perfect blend of colors at every individual location on the solar cell. This is illus-



Comparison of AM 1.5 solar spectrum with a state-of-the-art xenon spectrum currently used in mass production.

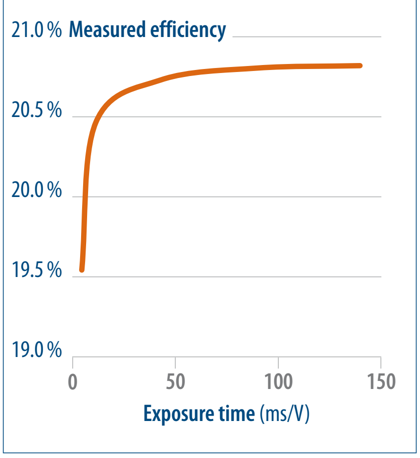


Change in spectrum of a xenon lamp after life cycle (graph based on Herrmann and Rimmelspacher 2012, figure 12).

SUMMARY OF KEY CHALLENGES IN USING LEDS FOR SIMULATING THE SUN'S SPECTRUM		
	CHALLENGE	SOLUTION
1	High color diversity for low mismatch factor	Continuous spectrum with at least 18 different LEDs
2	Good color mixing for high spectral homogeneity	Special optical lens system between LEDs and solar cells
3	High stability of spectrum for good repeatability	Built-in spectrometer including real-time feedback loop

trated in the graph "Bad and good color mixing" (see p. 56). Let us assume that the objective is to expose an area having

The capacitive effect of solar cells



Efficiency of a high performance solar cell measured using various exposure times.

an arbitrary shape and size with a certain mixture of green, red and blue light. In both illustrated cases, the objective has been achieved for the target area when it is viewed as a whole. However, in case A, most individual locations within that area are only exposed to some subset of the three colors. In case B, however, all regions (except for the edge) receive a balanced blend of all three colors.

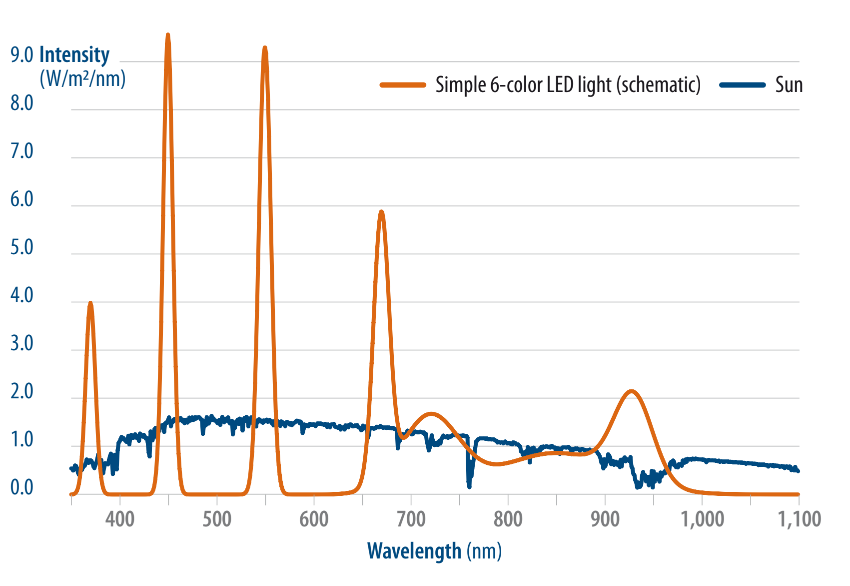
Case A is the schematic depiction of a simple 2-dimensional LED array. The solar cell might receive a good spectrum when the total area of the cell is considered. However, individual regions of the solar cell may deviate greatly from the desired spectrum. This can lead to incorrect efficiency measurements. Consequently, it is essential to achieve a good color mix. Employing a special lens system between the LEDs and the solar cell ensures less than 1% inhomogeneity.

Stability

LEDs are very reliable light sources. Their useful life usually extends far beyond 100,000 hours if they run within their specified power and temperature ranges. Still, the color of some LEDs can change depending on the energy consumed. This can affect color composition, which would be detrimental to the accuracy and precision of efficiency measurements. Therefore, monitoring of the actual color emitted by all LEDs must be implemented.

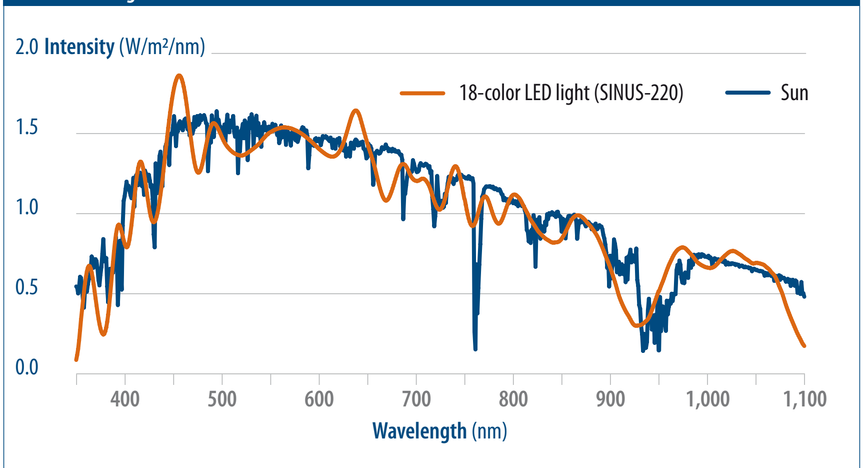
This can be achieved by integrating a spectrometer into the solar simulator. The spectrometer needs to be exposed to a representative sample of the light that actually hits the solar cell. Combining the spectrometer measurements with a rapid feedback loop which adjusts the power of the LEDs ensures a highly stable and accurate light source.

Simple 6-color LED light source



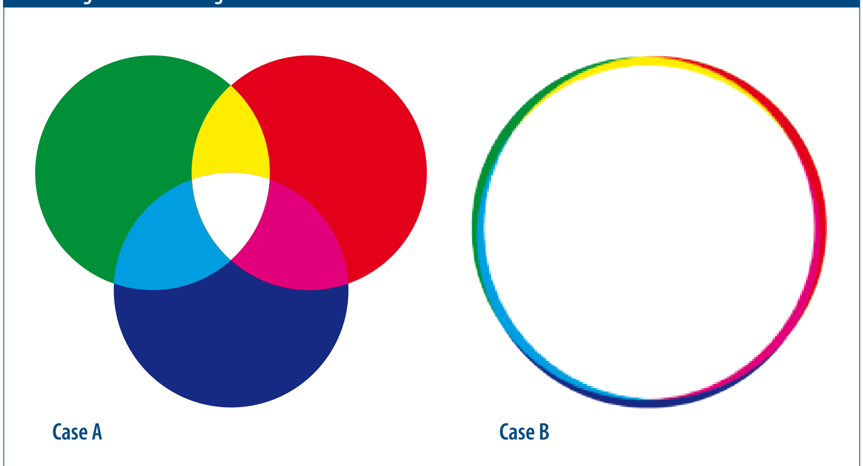
Simple LED light source with only six colors which causes large errors in efficiency measurements despite its class A rating.

18-color LED light source



Comparison of the sun with a solar simulator that uses 18 different sets of LEDs (solar simulator SINUS-220 from WAVELABS).

Bad and good color mixing



Schematic demonstration of insufficient (Case A) and good (Case B) color mixing.

In summary, the three major challenges and possible solutions are given in the table "Summary of key challenges in using LEDs for simulating the sun's spectrum" (see p. 55).

Benefits of LED

Using a well designed LED solar simulator brings a standard of measurement quality to the production floor, which can usually only be found in R+D labs. This new level of precision and accuracy can generate additional earnings of more than €500,000 per 100 MW production each year.

An accurate replication of sunlight eliminates the necessity of safety margins when classifying cells. A stable light source eliminates the need for frequent re-calibration, establishing reliable monitoring of the production process. Both aspects contribute significantly to increasing the competitiveness of a solar cell manufacturer.

An LED light source also provides the option of monochrome illumination. These measurements enable early detection of process problems. For instance, the current of a solar cell measured only under blue light allows the detection of problems related to the front contact (e.g. SiN or emitter profile). A small current under red light pinpoints issues relating to the wafer quality or back contact.

Consequently, process instabilities in the production line are uncovered rapidly and consistently. In addition, new processes developed in the lab can be more quickly and easily integrated into the production process.

For solar module manufacturers, a light source that does not need to be recalibrated is ideal for inspecting incoming materials. Regardless of the quality offered by the solar cell supplier, cells are measured accurately. This allows defective shipments to be easily identified. The accurate classification of incoming solar cells also increases the percentage of solar modules rolling off the line with high performance characteristics.

REFERENCES

Herrmann, W., and L. Rimmelspacher. 2012. "Uncertainty of Solar Simulator Spectral Irradiance Data and Problems with Spectral Match Classification." 27th EU PVSEC Proceedings: 3015 - 3021.

For new production lines, LED solar simulators appear to be the future. They allow long exposure times that high efficiency solar cells require and offer lower operating costs. Additionally, the tact time can be reduced to less than one second, allowing a big step forward in terms of productivity.

Outlook

LEDs not only improve the quality of current efficiency measurements, they also present several new measurement options. LEDs allow, for instance, the integration of spectral response measurements into production lines. This capability could increase the speed at which the efficiency of solar cells improves. Lock-in- or Fourier-based approaches promise to be suitable techniques. LEDs also allow modification of the spectrum used to measure efficiency. Natural light is not the same in Berlin as it is in Singapore, for instance. Sunlight also changes over the course of the day. These effects can easily be simulated with an LED-based solar simulator, since all colors can be adjusted individually, quickly, and easily.

Existing LED-based solar simulators for modules have not yet addressed the challenges inherent in LED-based light sources we have described here. Therefore, the application of LEDs for accurate and precise efficiency measurements of not only solar cells but also of solar modules is the next step. ◆

Torsten Brammer, Christian Leers

The SINUS-220.

ABOUT WAVELABS

WAVELABS Solar Metrology Systems GmbH was founded in October 2011 by Dr. Torsten Brammer, Jörn Suthues and Dr. Thankmar Wagner. When Jörn Suthues and Torsten Brammer joined forces in early 2011, they had been working in the field of photovoltaics for many years, in both academic and industrial settings. One issue they kept encountering in their work was the limitations posed by the way efficiency, the most important parameter in photovoltaics, is measured. This was the motivation behind establishing WAVELABS — to improve the way solar cell efficiency is measured with the help of LEDs. WAVELABS launched its new SINUS-220 LED-based solar simulator in May of 2013. In July, WAVELABS celebrated its first customer: Hanwha Q CELLS, one of the world's leading photovoltaics companies, placed the first order for what may be the best simulator of solar rays under the sun.

www.wavelabs.de