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Homogeneity and Lifetime Performance of a Tunable Close Match LED Solar Simulator

D. Kolberg*, F. Schubert, K. Klameth, and D.M. Spinner

Aescusoft GmbH, Emmy-Noether-Straße 2, 79110 Freiburg, Germany

Abstract

Our commitment is the development of an industrial-grade Class AAA solar simulator based on LED technology [1]. Presently, the LEDSim™ covers the full wavelength range of interest for Si-PV with an extension in the UV, matching AM1.5g from 350 nm to 1100 nm. To achieve user-defined target spectra we apply 22 different LED packages including several uncommon types. We present a measured spectrum tuned to AM1.5g. It follows from rare lifetime information for some LED species that we need to set a strong focus on reliability determination for our lightheads. In this paper we show how we confirm the lifetime promise of the LED technology with reliability testing. Modern design-for-reliability methods are taken into account in order to increase the reliability of the LEDSim™. Beam shaping and homogeneity are key functions of a sun simulator, and a large effort is made on achieving Class A homogeneity for each wavelength interval as specified in IEC 60904-9 [2]. We are testing different kinds of LED optics and add mirror channels to achieve the best relation between homogeneity and intensity.

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1. Introduction

The experimental setup consists of an industrial-style electronics cabinet containing 38 linear current drivers. The output current of each driver is adjustable via a PC graphical user interface. A lighthead with 22 different LED types is cooled using a combination of controlled peltier elements and water cooling. Electronics and active temperature control are key to achieve temporal stability of the light intensities and predictable spectra in the tuning process [1]. The overall spectrum, measured with the FlashSpec™, is

* Corresponding author. Tel: +049-761-3843434 ; fax: +049-761-3843433
E-mail address: dkolberg@aescusoft.de
presented in fig. 1 as a green line. Our extension in the UV range was particularly successful; it shows only minor differences between the LEDsim™ curve and the sun’s wavelength dependent light intensities. In contrast to Xenon (Xe) lamps no sharp peaks are seen in the IR range, and the bumps occurring at several wavelengths, e.g., 950 nm are highly stable in wavelength position as well as in their light intensities.

Fig. 1. Typical measured LEDsim™ light intensity curve, green line, tuned to almost perfectly match the sun's spectrum AM1.5g, amber line

The sun simulator spectrum IEC 60904-9 [2] splits the Si range in six parts and defines the percentage of light intensity in each of these parts. Because we decided to extend the LEDsim™ range to below 400 nm, the splitting of our spectrum includes an additional part and the percentages are adjusted accordingly. Detailed analysis of our example in fig. 1 is given in table 1. The spectral deviation from the standard spectrum can be tuned to zero which is nearly impossible with other sun simulator technologies.

<table>
<thead>
<tr>
<th>Wavelength range</th>
<th>Light intensity sum AM1.5g on 200x200mm² [mW/nm]</th>
<th>%</th>
<th>Light intensity sum LEDsim™ [mW/nm]</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 – 399 nm</td>
<td>1268</td>
<td>4.0</td>
<td>1205</td>
<td>3.8</td>
</tr>
<tr>
<td>400 – 499 nm</td>
<td>5574</td>
<td>17.6</td>
<td>5610</td>
<td>17.7</td>
</tr>
<tr>
<td>500 – 599 nm</td>
<td>6042</td>
<td>19.1</td>
<td>6183</td>
<td>19.6</td>
</tr>
<tr>
<td>600 – 699 nm</td>
<td>5573</td>
<td>17.6</td>
<td>5884</td>
<td>18.6</td>
</tr>
<tr>
<td>700 – 799 nm</td>
<td>4532</td>
<td>14.3</td>
<td>4437</td>
<td>14.0</td>
</tr>
<tr>
<td>800 – 899 nm</td>
<td>3788</td>
<td>12.0</td>
<td>3669</td>
<td>11.6</td>
</tr>
<tr>
<td>900 – 1099 nm</td>
<td>4841</td>
<td>15.3</td>
<td>4630</td>
<td>14.6</td>
</tr>
</tbody>
</table>

Table 1. Spectral split of the sun’s spectrum AM1.5g. Integrated intensity for each wavelength range is given in column 2, and respective values are calculated for the LEDsim™ curve in fig. 1 and written in column 4. Columns 3 and 5 contain the percentages of such splittings assuming the net light intensity between 350 nm and 1100 nm defines 100 %.

2. Lifetime determination

In LED applications product lifetimes are often derived from the lifetimes of the LED packages alone. It is suggested by the ASSIST group [3] and LED manufacturers therein to consider all other components of an LED containing luminaire as well, to derive and/or measure equipment lifetime [4]. Without reliability and/or maintenance data it will certainly be difficult to establish complex new devices in production lines. In our LEDsim™ [1] we are building the spectrum of the sun using 22 different wavelengths between 350 nm and 1100 nm. To reduce complexity we first split the spectrum in the same
Fig. 2 demonstrates the case of 800 nm to 900 nm with the light intensities of basically 3 LED types and minor contributions from 3 other types.

The light intensity at design level is given by 6 different wavelengths

\[ I_{800-900} = \sum_{\lambda=1}^{6} \int_{800}^{900} I(\lambda) d\lambda \]  

(1)

and two of these contributions are realized with rather common LED types delivered with reliability information. Manufacturer’s reliability data are taken to calculate the light intensity curves expected for each particular array (i.e., wavelength) in our lighthead design, see fig 3. However, of the net intensity in this spectral range still about 70% are lacking reliability data. For such LED we must assume they lose intensity unpredictably fast. For each wavelength/ LED array the reliability is calculated from the single package reliability. Single LED reliability \( R \) is given by [5]

\[ R = \exp(-\frac{1}{\lambda} t) \]  

(2)

with \( \frac{1}{\lambda} = \text{Mean Time To Failure, (MTTF)} \).

From that, array reliability \( R_a \) calculation is done using the R-out-of-N-failure model [6]

\[ R_a(t) = \sum_{i=1}^{n} \binom{n}{i} R(t)^i (1-R(t))^{n-i} \]  

(3)

Fig. 3. (left) Contribution of different wavelengths in their respective array configurations to the light intensity between 800 nm and 900 nm. Before lifetest, four types of LED might lose intensity unpredictably fast. Net secured intensity is considerably smaller than needed. (right) Comparison before and after lifetest, the red line shows the total \( P_{opt} \) before the lifetest. After lifetest an additional LED array contributes with reliable intensity, green line. The sum of secured light intensities now reaches the IEC requirements [5]
We are doing the lifetest with a larger number of LEDs to cut the test down to an acceptable time span. Another test acceleration is realized via temperature increase. Using the Arrhenius model \[6\] the acceleration factor $B$ is calculated with

$$B = \exp \left[ \frac{E_{\text{Act}}}{k_B} \left( \frac{1}{T_{\text{Jmin}}} - \frac{1}{T_{\text{Jmax}}} \right) \right]$$

where $E_{\text{Act}}$, $k_B$, $T_{\text{Jmin}}$, $T_{\text{Jmax}}$ are the activation energy, Boltzmann’s constant, the LED’s junction temperature under nominal conditions, and the LED’s junction temperature under accelerated conditions, respectively. Since in the LEDSim™ we are using active temperature control and in the lifetest we control as well the temperature, acceleration factors can be calculated confidently. This shrinks the test time assuming we do not provoke failure mechanisms in the lifetest which are unrealistic in the product to be assured. We check the validity of our acceleration by ascertain constant spectral emission of all LEDs under test throughout the course of the lifetest (using FlashSpec™). A second means to assure the validity of the Arrhenius model is to measure the temperature dependence of the forward voltage, which is expected to be constant during the test time. Test planning is completed when one takes care to exclude data from a possible burn-in phase of the LED packages to calculate lifetimes. Test equipment contains a Si detector to measure optical intensity and the spectrometer FlashSpec™ with its reflection target aligned. On the other side of the test unit we have an adjustment system capable of positioning each LED in the optical path with an accuracy considerably smaller than its chip size. All LED packages and two temperature sensors are reflow soldered on a metal core printed circuit board. Each of the high power LEDs got its own driving circuit and sufficiently stable power supplies are added to complete the electronics. To exclude parasitic effects of our electronics, commercially available switching-mode drivers are used.

3. Beam Shaping/ Homogeneity

Homogeneity scans are performed using an XY-stage which carries a Hamamatsu photodiode (PD) with integrated transimpedance amplifier. The signal is measured with a Keithley 1600DMM digital multimeter and transmitted to the PC via RS232. In front of the photodiode a combination of neutral density (ND) filter and pin hole is placed. The ND filter assures the PD is operated in its designed intensity range, which is much lower than 1 sun. The pin hole sets the spatial scan resolution always much better than required by IEC 60904-9 \[2\] in order to learn more about and develop further the details of the beam shaping. With this measurement setup, a large selection of

- LED packages with their specific primary optics
- position of the LEDs on the lighthead and different LED array geometries
- additional combinations of secondary optics (lenses, reflectors)
- mirror channel and tertiary diffusor optics

are investigated. The effects of these combined optics are analyzed in terms of homogeneity and intensity losses over the complete spectrum. Here we provide the discussion on a simple example configuration. Light of different wavelengths originates from different spots distributed over an area of 200 x 200 mm². The beams of different wavelengths pass through a mirror channel and are mixed on the way from their sources to the specimen. The detected light intensity at each point of the test area is the sum of a direct contribution and light which is reflected at the mirrors once, twice, and more times, see fig. 4. Thereby,
we get the full spectrum at each point of the measurement area, but this technique tends to concentrate the light intensity in the middle of this area. Additionally, effects due to the edges of the mirror channel can be seen in the homogeneity scans.

Fig. 5 shows exemplary light intensity distributions in the scan area for the same packages (i.e., wavelength) but essentially different spatial LED arrangements. The single Luxeon Rebel’s position in the left part of the figure was the midpoint of the lighthead and a very steep intensity bump is formed by using an additional, secondary optics on the package. Careful balancing of the light intensity versus its distribution over the scan field is shown in the right part of fig. 5. This is achieved by changing the secondary optics and arranging 6 LEDs of the same type on the lighthead in an array as indicated already in fig. 4. The secondary optics used in this example graph narrows the beam of each single LED to a lesser extent than in the left figure.

Fig. 5. Light intensity distributions (left) 1 Luxeon Rebel, middle position with narrow secondary optics. (right) 6 Luxeon Rebels, with broader optics
4. Conclusion and Outlook

In summary, we developed further an LED based sun simulator. We presented measured data matching the sun’s spectrum AM1.5g. LED based sun simulator spectra can be set by the operator according to his wishes and the possible spectral match is nearly 100%. In order to assure that this new technology can be used in production lines with small/calculable risk, we are using design-for-reliability methods and perform a lifetest to determine the lifetime of our lighthheads. The lifetest planning is realized with modern statistical methods of product assurance. Lifetime data is being gathered by using large numbers of LEDs under test as well as by carefully accelerating the life tests. Another ongoing task is to further improve the beam shaping in the LEDSim™ in order to increase the area of homogeneous light intensity distribution in the solar cell/specimen plane. This is achieved by designing the lighthouse according to the spectral and intensity contribution of each single package to the overall and to partial spectral requirements as defined by IEC 60904-9 [2].

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References