Design of a Low Cost Solar Simulator by using Light Emitting Diode (LED)

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Abstract. Solar simulators based on light emitting diodes (LEDs) have shown great promise as alternative light sources for indoor testing of PV cells with certain characteristics that make them superior to the traditional solar simulators. However, large-area uniform illumination, more suitable for larger cells and module measurements still remain a challenge today. In this paper, we discuss the development and fabrication of a scalable large-area LED-based solar simulator that consists of multiple tapered light guides. We demonstrate fine intermixing of many LED light rays and power delivery in the form of a synthesized air mass (AM) 1.5 spectrum over an area of 25 cm by 50 cm with better than 10\% spatial non-uniformity. We present the spectral output, the spatial uniformity and the temporal stability of the simulator in both the constant current mode and the pulsed-mode LED operation, and compare our data with the International Electro technical Commission (IEC) standards on solar simulators for class rating. Although the light intensity with our current design and settings falls short of the standard solar AM 1.5 intensity, this design and further improvements open up the possibility of achieving large-area, high power indoor solar simulation with various desired spectra.

1. Introduction
Solar simulator produces the operating conditions which are necessary for the solar cell to work. Hence a solar simulator is called as a fundamental instrument to make the characterization of the solar cell. These systems are basically big, bulky, and costly but a small solar simulator can be a good contribution to test small device manufactured in research scale. But the designed solar simulator should be covering the entire irradiation wavelength. The solar cell can be illuminated by solar simulators during the properties measurement like I-V curves, external quantum efficiency, or electrochemical impedance. The existing solar simulators which uses tungsten filament or xenon lamps as the source of illumination, has more limitations \cite{2,3}, like only the spectral irradiance of the solar spectrum can only be marginally approximated. Also the Xe lamp shows more strong variations in intensity from near UV to NIR \cite{2}. The standard for solar simulator is provided by International Electrotechnical Comission (IEC) or American society for testing of PV cells. The light output from a sun simulator must give calibrated spectral content, temporal stability and irradiance spatial uniformity. These characteristics of the simulator provides different classes of the sun simulator \cite{4,5}.
With the advancements in light emitting diodes (LEDs) and high power LED technology have contributed to the increase in radiant emittance and spectral variety which gives wide range of application in the market. Thus LED based solar simulators are made to replace the Xenon lamp simulator in the past decades. Since with the blue LED input in the market, wide spectral range of emission is possible [6]. LEDs have some more advantages like longer lifetime and an order of magnitude longer than the conventional sources as tungsten and Xenon lamps, with these advantages and advancements. LEDs are emerging as the good alternative source for solar simulators. Several papers have reported the LED based solar simulators for steady state and flashed operations on the basis of concept, design and fabrication [7-12]. Some of the groups have explained that 1 sun illumination can be achieved by using selected number of high power LEDs at wavelength ranging from near IR to visible [7,8]. But for higher illumination area and a better uniformity to match (AM) 1.5 spectrum, advanced LED simulator designs must be made.

To accomplish this, a controllable and scalable solar simulator based on LEDs of multiple wavelengths and spectral range was designed. The light guide provides better mixing of the light rays and yields more uniform power delivered over a large area. In generally used LED based solar simulators limited range of LED wavelengths are being used because of the limitation that each and every wavelength LED fabrication is not possible.

In this work we have used some of the phosphor converted LEDs to cover a good spectral response over the standard irradiance spectra. By using the phosphor converted LEDs the total no. of LEDs required to cover the whole spectra reduces to half of that required in regular designing. In one phosphor converted LED there can be maximum three colors contributed to three different wavelengths can be achieved, hence total spectral to power contribution also increases. Hence this designing of Solar Simulator based on phosphor converted i.e. PC-LEDs is entirely new and cost effective too.

2. Experimental

In this work to design a LED based solar simulator, high power 15 watt metal core PCB CREE. LEDs are used. For the visible range LEDs 450nm blue, 470nm blue, 530nm green, 560nm yellow, 610 nm red, wavelengths are used. For UV the wavelengths used are 352 nm, 385 nm, 410 nm LEDs, these LEDs in the UV range are low wattage (1 watt). For the NIR LEDs we have used phosphor converted visible to NIR emitting LEDs, these LEDs have excitation in visible region and gives emission in NIR regions. The wavelength of NIR LEDs used ranges in between 700 nm to 1200 nm. A summary of the LEDs used in the designing along with their wattages is given in the table below,

| S.No. | Type     | Wavelength range (nm) | Wattage (watt) |
|-------|----------|-----------------------|----------------|
| 1     | near-UV  | 352 nm                | 1 watt         |
| 2     | UV       | 385 nm                | 1 watt         |
| 3     | far-UV   | 410 nm                | 1 watt         |
| 4     | Visible  | 450 nm                | 15 watt        |
| 5     | Visible  | 530 nm                | 15 watt        |
| 6     | Visible  | 560 nm                | 15 watt        |
| 7     | Visible  | 610-700 nm            | 15 watt        |
| 8     | NIR      | 700-1200 nm           | 15 watt        |

Table 1: List of all the LED wavelengths used along with their wattages.

All these LEDs, which are going to be used in the designing of LED based solar simulator, were first tested on the Lumen Meter (ZWL-6000) and some of the respective spectra are shown in the figure below,
Results and Discussions
The design and construction of the fabricated solar simulator using LEDs is depicted as shown in the Fig. 3. The different wavelength LEDs are connected in the form of LED panels, each LED panel is consisting an array of 3X4 matrix, in which each LED is consisting more than 10 Chips mounted on a metal PCB. These LEDs are than coated with a transparent epoxy resin procured from Wells Electronics. The whole set of LEDs contain three panels of 3X4 matrix each, where LEDs are mounted randomly so as the whole illumination should be uniform in the effective area. Each panel is connected with LED drivers, which controls the amount of current supplied to each diode separately. These LED drivers are than controlled by the De-multiplexer circuit, driven by the microcontroller which is being interfaced with a PC. The user define program written on the PC controls and initializes the on-off and intensity of each LED in a particular LED panel. These LEDs can be operated in either pulsed mode or constant current mode as required by the application. The set of LED panel is being cooled by mounting on a water controlled heat sink which is acting as a chiller device. The light output from each LED panel is the allowed to pass through an optical diffused material coated on the outer ring of the light guide, which mixes the different wavelength and concentrate the whole illumination at a single point. Fig. 4 shows the detailed working circuit of the Solar Simulator, from this circuit the designing of the whole system is well explained. At the output of the simulator, the
source of light can be seen as a light coming from the sun. The photo voltaic device can be kept in front of the simulator and can be characterized for its different responses.

Fig. 3: Block diagram of the scalable LED-based solar simulator.

Fig. 4: Detailed diagram of the LED based Solar Simulator showing all the functioning blocks.

For the reference of measuring the spectral distribution of sunlight at Air Mass 1.5 is defined globally in ASTM G173-03 [3, 10] and IEC 60904-3. The values defined by this standard are being used for defining the performance of the fabricated solar simulator. The conventional simulators make use of optical filters to cover the standard spectrum. However in LED based simulators, narrow bands of LED responses helps in matching the responses to the standard spectrum. In this work also, to provide the matching with standard spectrum we have used high power LEDs.

The standard parameter in qualifying the quality of the solar simulator is called as the spectral Match, it is one of the three parameters used to classify commercial solar simulators. In this design we have made a lab scale solar simulator based on LEDs, where some of the phosphor converted LEDs are also used. The Spectral Match parameter defines the level of matching of the light source with that of the standard spectrum (AM 1.5 G). In our work the light spectra is compared with the standard spectrum as shown in the Fig. 5, this figure shows that the results are not perfectly matching with the standard one because the spectral illumination of all the LED wavelengths are not matching. This is because the UV LEDs used in this work are not that intense enough.
4. Conclusions
In this work we have successfully made the LED based solar simulator on lab scale basis. The spectral performance of the obtained spectrum is also compared with the standard spectrum (AM 1.5). The result shows that there is about 60% spectral match between the two spectrum. But the basic aim for this work is fully achievable which is that the whole setup is made very cost effective. The cost of any solar simulator depends more on the cost of LEDs used because the cost of high power UV and NIR LED is very high. In our work we have used phosphor converted NIR LED obtained by coating the phosphor YAG:Ce,Yb on the blue LEDs which are available in the market with very less cost. Hence the designed LED solar simulator in this work is actually low cost and easy to be used in the laboratory research work on photovoltaics.

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