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From Component to Multi-junction Solar Cells for Spectral Monitoring

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Abstract. Concentrator photovoltaic usually embeds multi-junction solar cells, which exhibit high spectral sensitivity due to the internal series connection of the sub-cells. The use of so-called isotype or component cells with the same spectral response as the corresponding sub-cell, is widely applied for characterizing the spectral content of the impinging irradiance. These isotype sensors can be substituted by the multi-junction cells themselves, which are inherently spectrally tuned to any evolution of the multi-junction technology. To convert a multi-junction cell in a spectral sensor, it is necessary to add bias light within the spectral response of all but one of the sub-cells to saturate the corresponding junctions, so the non-saturated limits the current under any specified impinging spectrum. This paper shows indoor and outdoor side-by-side comparison of the so-called pseudo isotypes, based on a triple-junction solar cell, and genuine isotypes. The conditions to ensure an accurate spectral response, particularly for the bottom pseudo-isotype, are presented and discussed.

INTRODUCTION

Concentrator photovoltaic devices (CPV) employing multi-junction (MJ) solar cells exhibit strong spectral sensitivities due to their series-connected nature. The use of “isotype” or “component” cells for spectral monitoring is widely used in CPV [1-3] to fix the spectral conditions of the impinging irradiance. Component or isotype cells are spectrally-matched sensors to a particular MJ technology, i.e., devices whose spectral response is as similar as possible to a single sub-cell of the MJ cell to be characterized, and are made by epitaxially growing an identical MJ stack with only one electrically active p-n junction while the others act purely as optical filters.

Such cells, which have been packaged into commercial sensors, are used to calculate Spectral Matching Ratios (SMR). A set of SMRs can be used as a set of spectral indices for CPV applications [4-5] capable of defining and constraining the solar spectral irradiance condition in terms relevant to the MJ solar cells performance. One of the main advantages of these indices is that they can be measured with isotypes or component cells installed into an instrument similar to a pyrheliometer. In addition, they can be used not only outdoors but also indoors since its fast response is compatible with flash lamps used in solar simulators [6-7]. SMR indices have been included in the International Electrotechnical Commission (IEC) standards for power rating of CPV [8] as a mean of defining a prevailing spectral condition similar to the reference spectrum for both indoor and outdoor power rating of CPV modules. However, because manufacturing these cells requires multiple custom epitaxial growths, they are usually expensive and not always available for all MJ technologies.

These indices are device-dependent since they are based on the relationships among the photocurrents generated by the sub-cells within the MJ device, so they can also be used to assess the influence of the spectrum variation on MJ solar cells. The use of spectrally-matched sensors is also useful for determining the internal current ratios of a solar cell under concentration; and determining the sub-cell limitation of the device current under a particular spectral condition [9]. Nevertheless, the CPV community tries to demonstrate that a set of isotypes of a particular technology

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can be used to predict the prevailing conditions for other technologies [10-11]. This approach will be limited by the outdoor power rating and the characterization possibilities. However the use of the isotype cells of the same technology for this characterization is useful for a better understanding of the technology and to determine the limiting sub-cell under a particular spectral condition, probably being mandatory for indoor measurements with solar simulators. These last are based on Xenon flash lamps which provide strong irradiance peaks at certain wavelengths in the infrared range. If the bandgaps of the MJ cells and spectral sensors vary in that range, a significant difference in the performance can be expected. MJ solar cells are an ever-evolving technology, where the spectral performance depends on the bandgaps and number of junctions of each technology. As the amount of different types of commercially available MJ solar cells increases, it becomes more difficult and expensive for laboratories and CPV manufactures to obtain a set of isotypes for each cell technology they need to characterize. Therefore, an alternative method would benefit for determining the equivalent direct normal irradiance (DNI) in each sub-cell band.

The objective of this work is to develop spectrally-matched sensors for a particular MJ technology, based on the MJ cells instead of isotype devices. In this way, the commercial MJ devices will serve as spectral sensors, avoiding the need of commonly expensive isotype sensors. To do that it is necessary to ensure the current limitation of a particular sub-cell in the MJ device under any impinging spectrum, within a particular spectral range, so a bias light to saturate the non-limiting sub-cells must be added. The concept is simple and is based on the measurement principles of quantum efficiencies (QE) of MJ solar cells. But in practice, likewise QE measurements, effects such as luminescent coupling among sub-cells [12-14] and voltage-biasing [15] must be carefully considered to achieve the objective. When the measurements are well-carried out, the MJ spectral sensor provides exactly the same spectral responses as of the corresponding sub-cells.

The design of the spectral sensors are described in section 2, considering the requirements for its integration in spectro-heliometers used both outdoors and indoors for spectral characterization of DNI and solar simulators. Section 3 includes a side-by-side comparison with conventional isotype cells, carried out both outdoors under natural DNI and indoors with the CPV solar simulator. In addition, the specific requirements for measuring the current of the bottom sub-cell are discussed.

**PSEUDO-ISOTYPE CONCEPT AS IRRADIANCE SPECTRAL SENSORS**

The spectral sensors, which we will call pseudo-isotypes, are composed of MJ solar cells and LED diodes to provide the bias light. The design specification are the following:

- Each sensor has two independent sets of LEDs with different spectrum to saturate the corresponding junctions of the MJ cell, so the non-saturated limits the current under any specified impinging spectrum. Peak wavelength emission of the selected LEDs: 475nm (top range), 760 nm (middle range) and 940 nm (bottom range).
- Compatibility and easy integration with data-loggers typically used in meteorological stations for the measurement of the solar irradiance.
- Low power consumption to enhance power autonomy: analog control signal to switch on/off bias light (outdoors, switch on typically 1-2 secs per minute), in a similar way to other active sensors used in weather stations (temperature probes, wind sensors...).
- High level of integration: a ring shaped printed circuit board (PCB) substitutes one of the baffles of the collimator tubes, with outer and inner diameters of 32 and 12 mm respectively. The PCB includes LED diodes for bias light, power conditioning and control system. The design is compatible with previous versions based on true isotype devices.
- Fast response, suitable Xenon flash pulses in the range 100 µs - 10 ms used in flash solar simulators.
- Wide range of spectral conditions: from $0.3 < SMR_{top} < 1.2$ and $0.5 < SMR_{mid} < 1.2$.
- Biasing of the MJ sensors between -3 V and +3 V

A tri-band spectro-heliometer has been equipped with lattice matched triple junction solar cells and the three bias light PCBs, each one tuned to ensure current saturation of two of the three sub-cells. For the case of lattice matched GaInP/InGaAs/Ge, additional bias light for the Ge sub-cell is commonly not necessary under the spectral range defined in the specification. Figure 1 shows the designed PCB with two sets of 4 LEDs each, its integration as a baffle in the collimator tubes and the installation of the device in the meteorological station sited at the roof of the main building of the Institute of Solar Energy in Madrid. The sensor is connected to a data-logger that switches on the LEDs during
A warm up period before the measuring period. Both are configurable and have been set to one second, so LED are running during only 2 seconds at a sampling time of 1 minute. The figure also shows a picture, on the right, with the device installed on the Helios 3198 solar simulator.

FIGURE 1. Tri-band spectro-heliometer equipped both with isotype sensors (reference device) and pseudo-isotypes (DUT) based on lattice matched GaInP/InGaAs/Ge solar cells and LEDs for bias light. The picture on the top left shows the designed PCB including two sets of LEDs and the power conditioning. The PCB were designed to be installed as a baffle in the collimator tubes of the devices according to the sketch. The pictures on the bottom left shows the instrument installed in the meteorological station at IES-UPM for a side-by-side comparison with a reference device equipped with 3 isotypes. On the right, the picture shows the instrument installed in the Helios 3198 solar simulator at IES-UPM laboratories.

SIDE-BY-SIDE COMPARISON AND RESULTS

A side-by-side comparison of two instruments, one based on the pseudo-isotypes and a second based on conventional isotypes, has been carried out. Results of this comparison are shown in figure 2, both outdoors (left) under direct normal irradiance and indoors with the solar simulator (right). The pseudo-isotypes have been installed outdoors since the beginning of November in Madrid. The results of several sunny days are plotted in the figure, providing a huge spectral variation for the $SMR_{\text{top}}$ ($0.35 < SMR_{\text{top}} < 1.03$), mainly achieved during sunrise and sunset. Conversely, the value of $SMR_{\text{bot}}$ is highly dependent on the water content (Precipitable Water) whose variation was very limited during the measuring period ($0.9 < SMR_{\text{bot}} < 1.01$). Particularly relevant is the excellent agreement in the bottom sub-cell (correlation coefficient $R \geq 0.999$), although there is also a noticeable offset between the bottom pseudo-isotype and isotype. This is caused by the different illumination condition in the upper sub-cells, provided by the bias light, which leads to uneven luminescent coupling in the bottom pseudo-isotype and the isotype cells, thus introducing an offset in the response of the bottom pseudo-isotype. This luminescent coupling effect is particularly important between the middle and bottom sub-cells, caused by the radiative recombination in the middle junction [15]. Nevertheless, as long as the excess in the radiative coupling is caused by the bias light and can be accurately controlled, this offset remains constant as a systematic error which can easily be determined and corrected. In this regard an accurate control of the current of the LEDs is very important in order to ensure, that the amount of bias light remains invariant over time.
Figure 2 (right side) also shows the comparison obtained with flash pulse decay of the Helios 3198 solar simulator, which is able to provide a very wide spectral condition (0.6 < $SMR_{mid}^{top}$ < 1.25 and 0.8 < $SMR_{bot}^{mid}$ < 1.05). Again, the same offset is observed in the relationship between the bottom pseudo-isotype and isotype.

**FIGURE 2.** Comparison between the pseudo isotypes (MJ cell + LEDs) and its corresponding isotype cell. (Left) outdoor comparison, obtained in autumn in Madrid (0.35 < $SMR_{mid}^{top}$ < 1.03 and 0.9 < $SMR_{bot}^{mid}$ < 1.01); (Right) indoors comparison, obtained during the flash pulse decay of the Helios 3198 Solar Simulator (0.6 < $SMR_{mid}^{top}$ < 1.25 and 0.8 < $SMR_{bot}^{mid}$ < 1.05)
The electrical bias of the pseudo-isotype sensor is also very relevant to achieve a proper response. The MJ cells used in the figure 2 showed a good response, for the three cases (top, middle and bottom), with the MJ device biased closely to short-circuit (0 V), but this is not always the case for any MJ cells. Barrigon et al. [15] reported the need of applying a positive voltage bias to the triple-junction solar cell to measure the current of the bottom sub-cell, even under bottom cell limiting illumination. The minimum voltage bias is:

\[
V_{\text{min}}^{3f} = V_{oc}^{\text{top}} + V_{oc}^{\text{mid}} - V_{br}^{\text{bot}}
\]  

(1)

where \(V_{oc}^{\text{top}}\) and \(V_{oc}^{\text{mid}}\) are the open voltage of top and middle subcells and \(V_{br}^{\text{bot}}\) is the breakdown voltage of the bottom subcell. According to this condition (1), to measure the bottom sub-cell current at short circuit condition \((V_{\text{short}}^{3f} = 0)\), the minimum breakdown voltage of the bottom sub-cell should be higher than 2V. Bottom Ge sub-cells, in both lattice-matched and upright metamorphic triple-junction solar cells, commonly exhibit lower breakdown voltage than 2V, which forces to apply a positive voltage bias to the triple junction solar cells to obtain a pseudo-isotype bottom measurement.

The effect of the bias voltage on the current of a pseudo-isotype bottom is shown in Figure 3. Unlike results shown in figure 2, in this case, a triple junction solar cell of a different manufacturer has been used, which suffers of low breakdown voltage in the Ge bottom cell. For this particular device, there is a narrow voltage range between 1.9 V and 2.3 V in which the pseudo-isotype bottom performs well, with a non-linearity error below 2%. Outside this bias range, the errors are as high as 60%, for instance, at short circuit condition.

**CONCLUSIONS**

Multi-junction solar cells can be used as spectral sensors, substituting isotype cells, to determine spectral matching ratios both outdoors for spectral characterization of the DNI and indoors with solar simulators. Pseudo-isotype sensors have been developed composed of MJ cells and LEDs to add the necessary bias light. The requirements to achieve an identical performance to a genuine isotype have been determined. Particularly remarkable is the performance of the
bottom sub-cell, which often suffers of low breakdown voltage which obliges to bias the MJ solar cell within a narrow voltage range to measure the bottom photocurrent under limiting lighting conditions. The bias light causes an excess of light coupling which must be minimized and corrected. For state of the art triple-junction solar cells, this effect, luminescent coupling appeared only between the middle and bottom sub-cells, which manifests as an offset in the pseudo-isotype bottom.

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