

Closing the Accuracy Gap in Tandem Photovoltaic Testing: An Accessible and Efficient Spectral Tuning Method Using LED-Based Simulators for Research Laboratories and Industry

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Accurate performance calibration of multijunction (MJ) solar cells is critical for advancing this technology toward large-scale terrestrial application, yet existing testing methods developed by photovoltaics calibration laboratories remain prohibitively complex and resource intensive for most research laboratories. Current approaches rely on expensive multisource simulators and/or intricate spectral tuning algorithms, limiting accessibility and hindering standardized comparisons of emerging MJ technologies such as perovskite-based tandems. This paper introduces a streamlined spectral irradiance adjustment method for light-emitting diode (LED)-based solar simulators, which are increasingly adopted in the photovoltaics community due to their versatility and cost-effectiveness. The method we present bins LED channels into groups based on the number of junctions of the MJ photovoltaic device under test (DUT) and their corresponding band gaps and incorporates an automated tuning algorithm that eliminates the need to adjust each channel's irradiance individually. This tuning algorithm requires the relative spectral responsivities of both the DUT and a broadband reference cell, as well as a calibrated spectroradiometer. Measurement validation across various MJ devices, including III-V and perovskite/silicon tandems, demonstrates excellent agreement within 1% with well-established xenon-tungsten multisource simulators and associated tuning algorithms. By enabling precise spectral tuning with readily available equipment and a simple tuning algorithm, our approach bridges the measurement accuracy gap between research laboratories and accredited testing facilities, fostering more reliable device comparisons and accelerating the translation of MJ technologies into real-world energy systems.

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I. INTRODUCTION

Multijunction (MJ) photovoltaic (PV) devices based on GaAs and related III-V materials have long been used in space applications for which the high cost of III-V devices is viable. In recent years, the development of different multijunction solar cell approaches for cost-effective terrestrial applications has grown rapidly, driven mainly by the surge in emerging perovskite-based tandems. This progress has led to remarkable increases in their efficiencies. Notably, perovskite (PVSK)/Si tandem cells have achieved a certified efficiency of 34.85%, surpassing the efficiency of

two-junction (2J) III-V cells by two percentage points [1,2]. Furthermore, there is an evolution toward wafer-size (greater than $16 \times 16 \text{ cm}^2$) tandems with a best efficiency greater than 33% [1,3] and commercial module production, signaling a critical transition from laboratory innovation to industrial deployment [4]. Concurrently, the MJ technology portfolio has diversified to incorporate various PV material combinations (e.g., PVSK/organic, PVSK/copper indium gallium selenide, and CdTe/Si, in addition to the more established III-V cells) and architectures with more than two junctions as well as three-terminal and four-terminal (4T) designs [2,5–8]. With an increasing number of research groups engaging in the study of MJ devices and efforts toward commercialization of these MJ technologies, accurate performance measurement of MJ devices has become crucial for meaningful device comparisons that can guide the selection of the most promising technologies.

Accurate MJ cell characterization hinges on precise spectral irradiance matching under the standard testing conditions (STCs), i.e., AM1.5G solar spectrum with a total irradiance of 1000 W/m^2 and a cell temperature of

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25 °C [9,10]. Referencing PV performance measurements to STCs allows a fair comparison between PV cell and module technologies [2,11]. Even minor spectral deviations disrupt current balancing across junctions, distorting fill factor (FF) and efficiency measurements [12–15]. Since laboratory light sources, such as light-emitting diodes (LEDs) or xenon lamps, do not replicate the AM1.5G spectrum perfectly, spectral mismatch between the simulator and reference spectra can cause errors in performance assessments, particularly for MJ cells where the individual junctions respond to a narrow spectral region, and their operation under illumination can therefore be influenced by seemingly small changes in the spectrum. For example, in perovskite/silicon tandems, the perovskite junction primarily absorbs the UV and visible light, while the silicon absorbs the near-infrared (NIR) light. Unlike single-junction devices, MJ solar cell performance calibration, especially for two-terminal (2T) cells, requires meticulous spectral irradiance adjustment to ensure all junctions generate the same photocurrents as they would if measured under the reference spectrum. Simple adjustments of the total irradiance (as routinely done for single-junction cells) are insufficient, as each junction requires a specific irradiance change based on its own spectral mismatch. The series-connected nature of most tandems particularly exacerbates this sensitivity since the current-voltage (I - V) characteristics (particularly the fill factor) are dominated by the current-limiting junction, which may change as a function of the spectrum [12–15].

To conduct these measurements, a multisource simulator and a corresponding spectral irradiance adjustment procedure are indispensable. At present, well-established PV testing laboratories typically use multisource simulators with a combination of Xe and tungsten-halogen lamps for official MJ performance calibration. Specific spectral adjustment procedures, although covered under IEC and ASTM standards [16,17], may differ among laboratories using different instruments [13,15,18–22], posing a challenge for broader accessibility to PV research laboratories.

In contrast, new LED-based simulator designs, equipped with numerous spectrally different LED light sources, are increasingly available for MJ device measurements in research laboratories. While these LED-based simulators have the theoretical advantage of being easily spectrally adjustable, many of the reported performance results rely on the preset spectrum from manufacturers without spectral irradiance adjustment being performed. Our prior study [12] demonstrated that such manufacturer-defined spectrum settings do not ensure that all the junctions generate the same current as they would under the reference spectrum, leading to large measurement error in MJ cell characterization. Despite this, limited efforts have been directed toward evaluating the measurement accuracy of these LED-based simulators. Recently, Chojniak *et al.* [15] introduced a robust spectrum adjustment method

for LED simulators based on a least-squares optimization algorithm. The method demonstrated high measurement accuracy through delicate calibration of individual LED channels' spectral properties and solving an indeterminate nonlinear system of equations. While this method is different from the spectral tuning we have implemented with a nine-channel xenon-tungsten lamp-based simulator in the past [20], both approaches yield consistent results that comply with international standards [16,17] and are recognized as best practices for MJ performance testing.

The scope of this paper is to provide an alternative spectral tuning method featuring a simple and efficient adjustment algorithm tailored for LED-based simulators and designed to be easily adopted by research laboratories. Instead of requiring detailed calibration of each LED channel, our method groups LED channels based on the number of junctions of the device under test (DUT) and their band gaps. It then uses an iterative approach to adjust each group's irradiance based on feedback from a spectroradiometer. This approach eliminates the need for prior knowledge of each LED channel's irradiance characteristic, thereby somewhat simplifying the tuning process as well as mitigating issues associated with LED aging. The number of LED groups matches the number of junctions; for instance, in a two-junction MJ cell, the tuning algorithm operates on just two LED groups instead of managing the drive current of over all individual channels (e.g., more than 20 channels is typical in most modern LED simulators).

This work also examines key factors affecting the accuracy of performance measurements with LED simulators, such as spectrum quality (e.g., spatial irradiance nonuniformity and LED temperature-induced spectral deviations) and testing plane reflectivity sensitivity. By providing practical and actionable insights, this work equips researchers with tools to ensure measurement integrity across diverse MJ technologies—a prerequisite for meaningful efficiency comparisons, reliable technoeconomic analyses, and the eventual integration of MJ systems into global energy grids.

II. SPECTRAL IRRADIANCE ADJUSTMENT METHOD

A. General principles

Since no solar simulator emits a spectral irradiance that perfectly matches the reference spectrum, test operators must adjust the simulator spectrum so that the DUT would achieve the same photocurrent as it would have under the reference spectrum. The photocurrent of the cell is given by

$$I_{\text{DUT}} = A \int E(\lambda) s_{\text{DUT}}(\lambda) d\lambda, \quad (1)$$

where $E(\lambda)$ is the spectral irradiance of the light reaching the cell as a function of wavelength λ (in watts per square centimeter per nanometer), $s_{\text{DUT}}(\lambda)$ is its spectral responsivity (SR) at a given wavelength λ (in amperes per watt), and A is the illuminated area of the cell (in square centimeters). The spectral irradiance that produces photocurrent lies within the wavelength range that overlaps with the cell's spectral responsivity. Therefore, achievement of the correct photocurrent requires adjustment of irradiance within this region—a process accomplished through spectral correction [18].

For single-junction cells, irradiance adjustment is relatively straightforward. Typically, one can modify the total irradiance without specifically considering the spectral overlap with the SR of the DUT, such as by simply adjusting the driving current of the light source combined with a spectral mismatch correction factor M [18]. Since changes in irradiance outside the DUT's SR region do not affect its performance, no further spectral refinement is necessary. In contrast, adjustment of the simulator output for an STC measurement of a multijunction cell is more complicated. The operator must *simultaneously* account for the SRs of *all* junctions when tuning the irradiance. Simply adjusting the total irradiance to match the photocurrent of one junction is insufficient, as it is unlikely to result in the correct irradiance for the other junctions. Hence, for multijunction cells, proper simulator adjustment requires tuning irradiance within specific wavelength bands while also fine-tuning the overall irradiance. A well-adjusted spectrum ensures that *each junction* of the DUT generates the same photocurrent as it would under the reference spectrum.

Evaluation of how well a spectrum is adjusted for a multijunction cell measurement at STC is usually done by one calculating the *current-matching factors of each junction*, Z_i :

$$Z_i = \frac{I_{\text{DUT},i}^{\text{ref}}}{I_{\text{DUT},i}^{\text{sim}}}, \quad (2)$$

where $I_{\text{DUT},i}^{\text{ref}}$ and $I_{\text{DUT},i}^{\text{sim}}$ refer to the photocurrents of the i th junction of the DUT under the reference and simulator spectra, respectively [16,17]. $Z_i = 1$ means that the photocurrent of the i th junction under the solar simulator is the same as the photocurrent of that junction under the reference spectrum. To avoid confusion with the commonly used *current-matching requirement* for series-connected MJ cells, we clarify that in this work *current mismatch* denotes a difference between the photocurrent of a junction under the solar simulator and the photocurrent of a junction under the reference spectrum; it does not denote a current mismatch *between junctions* as would occur in a poorly optimized series-connected MJ cell. The *current matching condition*, $Z_i = 1$ must be achieved for the same spectrum for *all junctions* within a predefined tolerance, usually

$Z_i = 1 \pm 0.01$. Deviations of *any* Z_i outside this range, caused by an improperly adjusted spectrum, affects the short-circuit current (I_{SC}), the FF, and the overall efficiency of the cell [12–15].

In short, the current-matching condition for MJ devices cannot be achieved simply by adjusting the total irradiance of a simulator. Thus, a spectrally adjustable simulator is required, allowing independent tuning of spectral irradiance for each junction so that each junction produces the photocurrent aligned with the one under the reference spectrum. Single-source simulators (e.g., xenon arc lamps) can be modified with filters to achieve spectral tuning; however, the tuning process is iterative and time-consuming [19]. Multisource simulators with independently adjustable spectral channels, such as xenon-tungsten or LED-based systems [13,15,19–22], are favored for this application due to their flexibility and efficiency. In the following we discuss the specific approaches to guide the spectral irradiance adjustment for achieving current-matching conditions on MJ devices.

B. Spectrum tuning method

Spectrum adjustment procedures can differ across PV testing laboratories depending on the instruments used [13,15,19–22], but they generally involve three core components: a spectrally adjustable simulator, a calibrated spectroradiometer, and calibrated reference cells. As mentioned earlier, the primary goal is to adjust a simulator's intensity and spectral profile so that the photocurrent of each junction under the adjusted spectrum matches its corresponding current $I_{\text{DUT},i}^{\text{ref}}$ under the reference spectrum. Equation (1) is modified for multijunction cells as follows:

$$I_{\text{DUT},i}^{\text{ref}} = A \int E_{\text{ref}}(\lambda) s_{\text{DUT},i}(\lambda) d\lambda, \quad (3)$$

where $E_{\text{ref}}(\lambda)$ is the reference spectral irradiance (in watts per square centimeter per nanometer) and $s_{\text{DUT},i}(\lambda)$ is the spectral responsivity of the DUT's i th junction [16–19].

Even after spectrum adjustments, differences between the simulator and reference spectra are unavoidable [18]. Additionally, the spectral responsivities of the DUT's junctions and the reference cells are often nonidentical, introducing errors in measured I_{SC} . These errors are quantified with the use of the spectral mismatch factor M [18,19]. For MJ devices, the spectral mismatch factor M_i of the i th junction can be written as

$$M_i = \frac{\int E_{\text{sim}}(\lambda) s_{\text{DUT},i}(\lambda) d\lambda \int E_{\text{ref}}(\lambda) s_{\text{RC},i}(\lambda) d\lambda}{\int E_{\text{ref}}(\lambda) s_{\text{DUT},i}(\lambda) d\lambda \int E_{\text{sim}}(\lambda) s_{\text{RC},i}(\lambda) d\lambda}, \quad (4)$$

where $s_{\text{RC},i}(\lambda)$ is the spectral responsivity of a calibrated reference cell that is used to set the irradiance of the i th junction of the DUT. The corrected photocurrent of

the i th junction under the reference spectrum can then be expressed as

$$I_{\text{DUT},i}^{\text{ref}} = \frac{I_{\text{DUT},i}^{\text{sim}}}{M_i} \frac{I_{\text{RC},i}^{\text{ref}}}{I_{\text{RC},i}^{\text{sim}}}, \quad (5)$$

where $I_{\text{RC},i}^{\text{sim}}$ and $I_{\text{RC},i}^{\text{ref}}$ are the photocurrents of the i th reference cell under the simulator and calibrated with the reference spectrum, respectively. According to Eq. (2), the current-matching factor Z_i can thus be rewritten as

$$Z_i = \frac{I_{\text{DUT},i}^{\text{ref}}}{I_{\text{DUT},i}^{\text{sim}}} = \frac{1}{M_i} \frac{I_{\text{RC},i}^{\text{ref}}}{I_{\text{RC},i}^{\text{sim}}}. \quad (6)$$

As illustrated in Eq. (6), for single-junction devices, test operators can simply set the total irradiance of the simulator to match the corrected irradiance level under the reference spectrum with a single M factor. However, for MJ devices to operate under STC, the current-matching factors Z_i are required to equal 1 within a small tolerance (usually 1%) for all junctions, and adjustment of a single total irradiance alone is insufficient.

C. Junction current ratio R_{ij} approach

Besides the current-matching factor Z_i for each individual junction, the current balance between junctions under a simulator can be quantified relative to the reference spectrum independently of the total irradiance by defining [20,23] the junction current ratio between junction i and junction j :

$$R_{ij} \equiv \frac{Z_i}{Z_j} = \frac{M_j}{M_i} \left(\frac{I_{\text{RC},i}^{\text{ref}}}{I_{\text{RC},i}^{\text{sim}}} \bigg/ \frac{I_{\text{RC},j}^{\text{ref}}}{I_{\text{RC},j}^{\text{sim}}} \right), \quad (7)$$

where the current balance of a multijunction solar cell is achieved when $R_{ij} = 1$ within a small tolerance for all combinations of i and j .

When choosing reference cells, researchers can opt for either *multiple reference cells matched* to each junction's SR or a *broadband reference cell* that encompasses all individual junction SRs. While both methods produce comparable measurement accuracy when a good measurement of the spectrum can be obtained [24,25], spectrally matched reference cells are often unavailable, and even when they are, large measurement errors from reference cell calibration may arise. For example, certain types of NIR-long-pass-filtered reference cell have large measurement errors caused by the irradiation-induced filter heating [26]. Additionally, for emerging technologies where the SRs of the junctions are still evolving, stable matched reference cells cannot be obtained. This study uses the single reference cell method, significantly simplifying the adjustment process. In this case, $I_{\text{RC},i}^{\text{ref}} = I_{\text{RC},j}^{\text{ref}}$ and $I_{\text{RC},i}^{\text{sim}} = I_{\text{RC},j}^{\text{sim}}$

for all i and j , so all variables related to the single reference cell cancel out in Eq. (7), and the junction current ratio R_{ij} calculation method therefore eliminates the need for reference cell measurements during spectrum shape optimization. After introduction of Eq. (4), R_{ij} can be rewritten as

$$R_{ij} = \frac{M_j}{M_i} = \frac{\int E_{\text{ref}}(\lambda) s_{\text{DUT},i}(\lambda) d\lambda \int E_{\text{sim}}(\lambda) s_{\text{DUT},j}(\lambda) d\lambda}{\int E_{\text{ref}}(\lambda) s_{\text{DUT},j}(\lambda) d\lambda \int E_{\text{sim}}(\lambda) s_{\text{DUT},i}(\lambda) d\lambda}. \quad (8)$$

Now, the spectrum tuning relies only on the relative spectral irradiance of each channel and the relative spectral responsivity of each DUT junction, making the process reliant solely on measurements from a spectroradiometer. Once the relative spectral profile is optimized, M_i values for all junctions, calculated with a broadband reference cell, will converge to the same value, usually close to 1 if the adjusted spectrum aligns closely with the reference spectrum. The absolute irradiance is then adjusted to 1000 W/m² by adjustment of the total irradiance of only one of the junctions (i) using a single calibrated broadband reference cell [$Z_i = 1$ with the use of Eq. (6)]. After this adjustment, the Z factors for the remaining junctions should also be very close to 1 according to Eq. (7), since R_{ij} has also been adjusted to 1 for all $j \neq i$.

This approach has been demonstrated to be both robust and accurate for conventional multisource xenon-halogen simulators [20]. In the following we present our modification of this method that is specifically designed for LED multichannel simulators with a large number of channels (more than 30).

III. GROUP TUNING WITH LED SIMULATORS

LED-based solar simulators have gained increasing popularity for PV device performance testing due to several advantages over conventional xenon and halogen lamps, including flexible spectral tuning, stable light output, longer lifespans, and lower energy consumption. These simulators use a large number of spectrally different LED light sources to create a spectrum that roughly approximates the reference spectrum. For this study, we used a G2V Optics Sunbrick LED-based solar simulator (the testbed photograph shown in Fig. 8 in Appendix A). This customized LED simulator features 35 tunable LED channels with an extended spectral irradiance range of 350–1250 nm, as depicted in Fig. 1. The spectral profiles of all LED channels are also illustrated in Fig. 1, with several channels using multiple identical LEDs to increase irradiance output (e.g., four channels using the same LED type with a primary peak emission at 595 nm and secondary emission peak at 446 nm to boost irradiance output in the visible range). A “base spectrum” was constructed with the

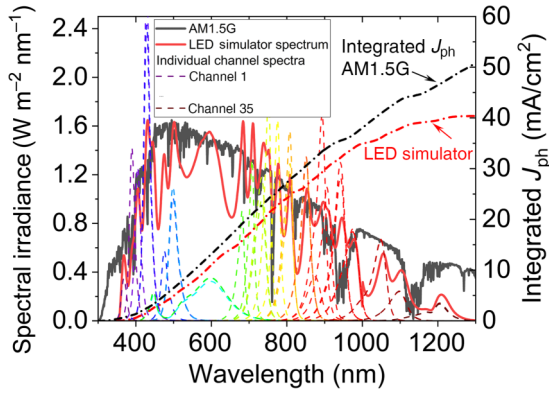


FIG. 1. Spectra of all 35 LED channels at their 50% intensity output settings (dashed lines), the base spectrum approximating the reference spectrum (solid red line), the reference AM1.5G (solid black line), and the integrated photocurrent density vs wavelength (dot-dashed lines) for the reference and LED simulator spectra assuming an ideal EQE (i.e., 100% for all wavelengths).

use of manufacturer-defined settings to approximate the AM1.5G reference spectrum, depicted as the solid red line in Fig. 1.

However, while the base spectrum resembles the AM1.5G spectrum in shape and can achieve an “A+” classification regarding spectral match to AM1.5G [27], it does not guarantee that a PV device measured under this base spectrum will yield the same performance parameters as under AM1.5G since there still exists an inevitable spectral mismatch. For example, the spectral mismatch factors M_1 and M_2 of a $\text{Ga}_{0.68}\text{In}_{0.32}\text{As}_{0.34}\text{P}_{0.66}/\text{Ga}_{0.79}\text{In}_{0.21}\text{As}$ (band gaps of 1.7 and 1.1 eV, hereafter referred to as GaInAsP/GaInAs for simplicity) 2J cell (with its SRs detailed later), calculated with a Si reference cell under this base spectrum, are 0.9286 and 1.0549 for its top and bottom junctions, respectively. This mismatch corresponds to $R_{12} = 1.0549/0.9286 = 1.136$, so there is an approximately 14% current imbalance between the two junctions under the simulator’s base spectrum compared to the reference spectrum. Such a spectral mismatch can lead to significant systematic errors in cell performance parameters [12]. Moreover, as illustrated in Fig. 1, the integrated photocurrent density discrepancies between the LED base and reference spectra vary across wavelengths, assuming an ideal external quantum efficiency (EQE) of 100% for all wavelengths. This variation demonstrates that the spectral similarity alone does not ensure the desired photocurrent at STC, and even adjustment of the total simulator irradiance output is inadequate for accurately measuring MJ cells. To address this, a spectral adjustment process must be performed on this base spectrum to ensure the junction photocurrents are balanced.

LED-based simulators often feature dozens of spectrally different LED channels, far more than the number of junctions in a typical MJ cell (currently up to six junctions

[23]). The method presented by Chojniak *et al.* [15] tunes an LED multisource simulator by precisely calibrating all individual light channels and iteratively solving a set of irradiance-related equations.

In this paper, we propose a straightforward and efficient group-tuning approach for spectrum adjustment that eliminates the need for precise irradiance calibration of individual channels and the use of matrix mathematics for spectrum tuning. As indicated by Eq. (8), the integrals are in principle over the entire wavelength range, but in practice they are calculated over the spectral range where the corresponding junction SR is nonzero. Therefore, the spectral irradiance of a simulator can be divided into regions based on their overlap with each junction’s SR. Hence, in this method, LED channels are binned into groups based on the DUT’s junction quantity and band gaps $E_{g,i}$. For instance, for tuning a 2J cell with $E_{g,1} > E_{g,2}$, two LED groups are defined as follows:

- (1) G1: channels with peak emission wavelengths (λ_{peak}) smaller than the wavelength corresponding to the top junction band gap [$\lambda(E_{g,1})$], i.e., $\lambda_{\text{peak}} < \lambda(E_{g,1})$.
- (2) G2: channels with $\lambda_{\text{peak}} > \lambda(E_{g,1})$.

Similarly, the LED groups for a three-junction (3J) cell with $E_{g,1} > E_{g,2} > E_{g,3}$ can be categorized as G1 for channels with $\lambda_{\text{peak}} < \lambda(E_{g,1})$, G2 for channels with $\lambda(E_{g,1}) < \lambda_{\text{peak}} < \lambda(E_{g,2})$, and G3 for channels with $\lambda_{\text{peak}} > \lambda(E_{g,2})$.

All LED light channels have drive current input settings associated with their irradiance intensities for the base spectrum. Instead of adjusting each LED channel’s current individually, spectral irradiance adjustments are made simultaneously for all channels within a group based on the junction current ratio R_{ij} . Figure 2 shows the flowchart outlining our spectral irradiance adjustment steps applied to this LED simulator. The process begins by activating the simulator and loading preset LED channel intensity settings from the “base spectrum” file. After the simulator irradiance output stabilizes, an ASD FieldSpec 4 spectroradiometer coupled with an OL IS-470 integrating sphere (2.54 cm entrance port diameter) captures the base spectrum. The spectral mismatch correction factor M_i for each junction and the junction current ratios R_{ij} are then calculated with use of the acquired base spectrum and a broadband Si reference cell. The band gaps $E_{g,i}$ are determined from the derivative of the external quantum efficiency [$Q(\lambda)$] with respect to wavelength λ for each individual junction, enabling the categorization of LED channel groups. Spectral irradiance adjustments are made across the LED channels in each group based on the R_{ij} value.

We define an R_{ij} threshold θ_{th} criterion to guide spectral adjustments, which can be expressed as

$$|\Delta R_{ij}| \leq \theta_{\text{th}}, \quad (9)$$

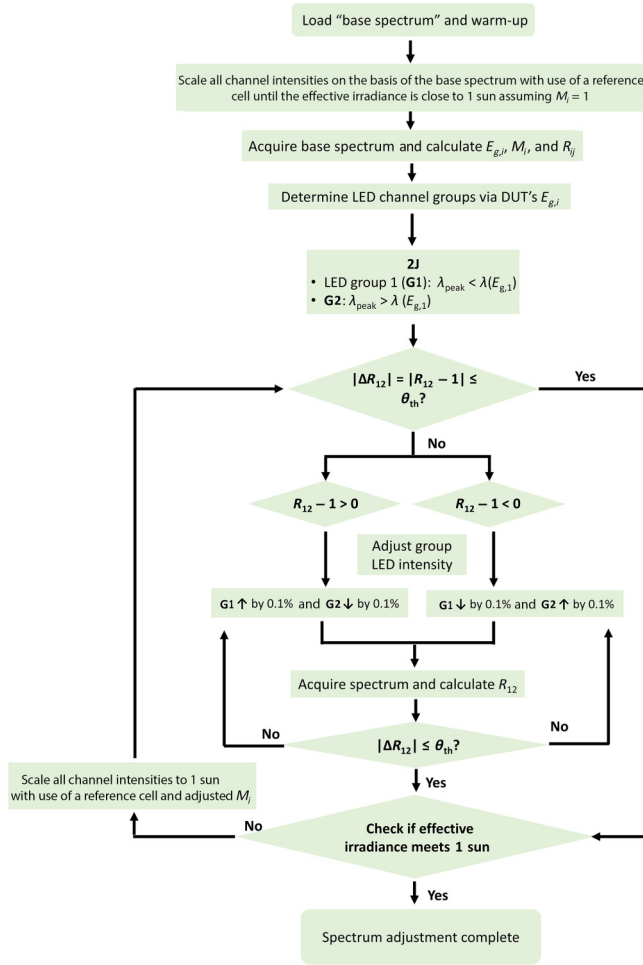


FIG. 2. Flowchart of the spectral irradiance adjustment procedure for a 2J solar cell using the LED-based simulator. The specific tuning for three or more junctions is included in Appendix B.

where $\Delta R_{ij} \equiv R_{ij} - 1$ for all i - j pairs. $\theta_{th} = 1\%$ or smaller is recommended to minimize spectral errors [20]. In this study, Eq. (9) was consistently achieved with $\theta_{th} = 0.2\%$ using the group tuning method for a variety of tandem devices, and this threshold was used by default unless specified otherwise.

As illustrated in Fig. 2, for a 2J tandem cell, if $R_{12} - 1 > 0$ [indicating the top junction photocurrent, i.e., $i = 1$, is relatively lower than the bottom junction's ($j = 2$) value as it would be at STC], the algorithm increases the drive current of all LED channels in G1 by a small relative increment (e.g., 0.1% per iteration) and a corresponding decrement in G2. Conversely, if $R_{12} - 1 < 0$, the adjustments are reversed. After each iteration, a new spectrum is measured, and R_{12} is recalculated. The degree of LED current adjustment may vary with iterations to optimize the spectral irradiance adjustment time. Once R_{12} meets the criterion, i.e., $|\Delta R_{ij}| \leq \theta_{th}$, a broadband reference cell is used to confirm whether the adjusted spectrum delivers the

desired 1 sun total irradiance (i.e., 1000 W/m^2) on junction i . If the effective irradiance is not achieved, all LED channel currents are adjusted proportionally with use of the updated M_i and the reference cell readings. Note that the spectral irradiance changes might not be linear with LED drive currents across all channels, even with each channel undergoing the same current adjustment. Thus, as shown in the flowchart, it is crucial to remeasure the spectrum and recalculate R_{ij} after each total irradiance adjustment to ensure that the ultimate effective irradiance meets the criterion $R_{ij} = 1$ for all i and j , and $Z_i = 1$ (depending on which junction is used for the transfer calibration) within a predefined threshold. This iterative process continues until the target spectrum is reached, completing the spectrum adjustment.

Figure 3(a) shows the two initial base and adjusted spectra for a GaInAsP/GaInAs (1.7 eV/1.1 eV) 2J cell. It is evident that the spectral irradiance of LED channels in G1 increases, while the irradiance of those in G2 decreases [see the inset in Fig. 3(a)]. Note that the changes in spectral irradiance across channels are nonlinear with the LED drive current even within the same LED group. This spectral tuning method eliminates the need to calibrate the complex, nonlinear relationships between irradiance intensity and current input for each LED channel [15,20]. Instead, it relies only on real-time feedback from spectral irradiance measurement using a spectroradiometer, combined with the recalculated R_{ij} , to iteratively guide adjustments to the LED groups.

For a 3J tandem cell, there are three separate R_{ij} values (i.e., R_{12} , R_{13} , and R_{23}). Unlike the 2J case, simultaneous adjustments of LED channel currents across groups are not feasible. Instead, irradiance adjustment for each group in sequence is used as shown in the flowchart in Fig. 9 in Appendix B. The spectrum adjustment algorithm begins with a small current change for LED channels in G3 (e.g., $+0.1\%$ or -0.1% depending on whether $R_{23} - 1$ is positive or negative). The spectrum is then measured, and R_{23} is recalculated. This subprocess repeats until R_{23} meets the threshold. The algorithm then adjusts G1's irradiance intensity using the recalculated R_{13} . If $R_{13} - 1 > 0$, a small current increment is applied to G1; otherwise adjustments are reversed. This process continues until R_{13} meets the threshold. Finally, the spectral irradiance intensity of G2 is adjusted until R_{12} meets the threshold. The algorithm iteratively evaluates all the R_{ij} values, ensuring they meet the threshold. If they do not, the process restarts with G3. The spectrum tuning process for a four-junction (4J) tandem cell is detailed in the flowchart in Fig. 10 in Appendix B.

Figures 3(a) and 3(b) compare the base and adjusted spectra for a GaInAsP/GaInAs (1.7 eV/1.1 eV) 2J tandem cell and a perovskite/perovskite/Si (1.88 eV/1.57 eV/1.12 eV) 3J tandem cell, respectively, for this algorithm. The graphs also show their normalized EQEs. Table I lists the calculated M_i and R_{ij} values of the two

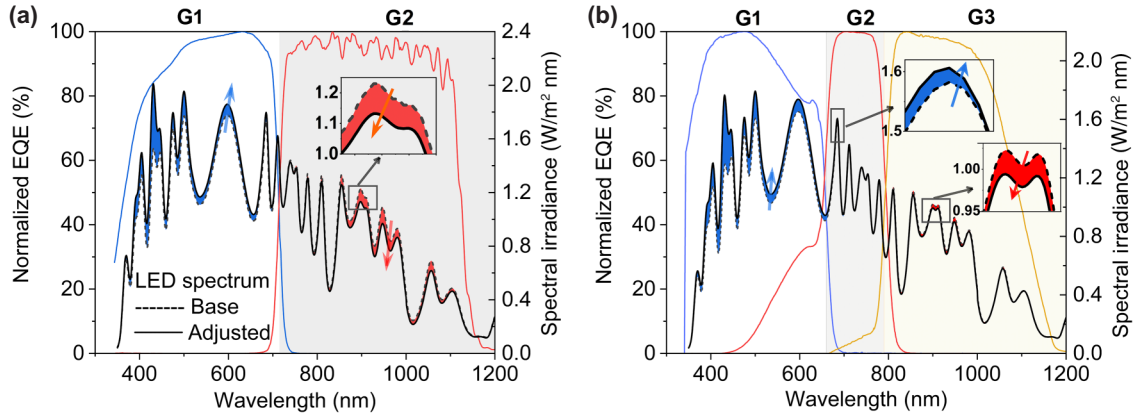


FIG. 3. Spectra acquired with the initial “base spectrum” settings (dashed line) vs those acquired after completion of the spectral adjustment (solid line), along with the normalized EQEs of (a) a GaInAsP/GaInAs 2J cell and (b) a PVSK/PVSK/Si 3J cell. The color-filled regions between the spectra indicate the irradiance changes (see enlarged insets) required for each LED group to meet the defined threshold.

types of tandem cell with the base and adjusted spectra. Note that these values represent a test case of the simulator used here, and they will vary for different simulators. Still, for this high-quality LED simulator with a class-A+ rating for the base spectrum, for the 2J cell, the base spectrum resulted in an approximately 14% current mismatch between junctions, while the 3J cell exhibited up to an approximately 13% mismatch. After adjustment, all R_{ij} values approached 1 within the 0.2% threshold, ensuring balanced junction currents. As all the junction M_i values are close to each other and converge to 1, the simulator’s total irradiance was then easily adjusted by proportionally changing all the LED channel currents to meet the $R_{ij} = 1$ criterion for all i and j , and $Z_i = 1$. However, based on our tuning experience, while M_i convergence to 1 is achievable for most MJ cells, certain MJ cells with narrow SR regions in individual junctions, such as those with a junction quantum efficiency range below 200 nm (e.g., all-perovskite 3J

or 4J cells) that is narrower than the spectra of certain LED channels, may never reach M_i close to 1 due to reduced tuning flexibility. Note that if the R_{ij} values do not meet the threshold following this proportional adjustment, an iterative tuning process, as illustrated in the flowchart, is conducted until both R_{ij} and the total irradiance reach their specific thresholds.

Beyond spectrum adjustments for meeting STC, this method can be easily adapted to study the I - V characteristics of an individual junction in MJ devices under a nonreference spectrum by systematically varying the R_{ij} values other than the desired value of unity. For example, the irradiance level of one junction can be varied by adjusting its corresponding R_{ij} value while maintaining the effective irradiance of the other junction(s) at AM1.5G. This enables a detailed analysis of current-limiting junctions and how cell performance parameters respond under different nonstandard testing conditions [12,21].

Figure 4(a) illustrates the spectral irradiance variations as R_{12} is adjusted while the effective irradiance of the bottom, GaInAs junction is kept unchanged at AM1.5G for the III-V 2J device in Fig. 3(a). In terms of the Z factors [Eq. (2)], this corresponds to varying Z_1 while keeping $Z_2 = 1$. As shown in Fig. 4(b), the resulting I - V parameters can be measured under these spectra to evaluate junction characteristics, such as identifying the current-limiting junction and diagnosing shunt behavior, providing valuable insights for device design [12–15]. I_{SC} increases proportionally with Z_1 until it saturates at $Z_1 \approx 1.01$ while Z_2 is kept fixed at 1, indicating that the top, GaInAsP junction is the current-limiting junction. A symmetric FF behavior with a minimum at the current-matching point ($Z_1 \approx 1.01$) between the two junctions is also observed in this tandem cell, with a detailed explanation provided in Ref. [12]. The V_{OC} behavior is not shown here as it

TABLE I. Calculated M_i and R_{ij} values of the GaInAsP/GaInAs 2J and PVSK/PVSK/Si 3J tandem cells under the base and adjusted spectra, respectively. The numbers of adjustment iterations to achieve the criteria for the 2J and 3J devices are 6 and 13, respectively.

Device type	M_i and R_{ij}	M_i and R_{ij} under spectra	
		Base	Adjusted
GaInAsP/GaInAs 2J	M_1	0.9286	0.9903
	M_2	1.0549	0.9899
	R_{12}	1.1376	1.0010
PVSK/PVSK/Si 3J	M_1	0.9392	1.0028
	M_2	1.0135	1.0049
	M_3	1.0563	1.0045
	R_{12}	1.0791	1.0021
	R_{13}	1.1247	1.0017
	R_{23}	1.0422	0.9996

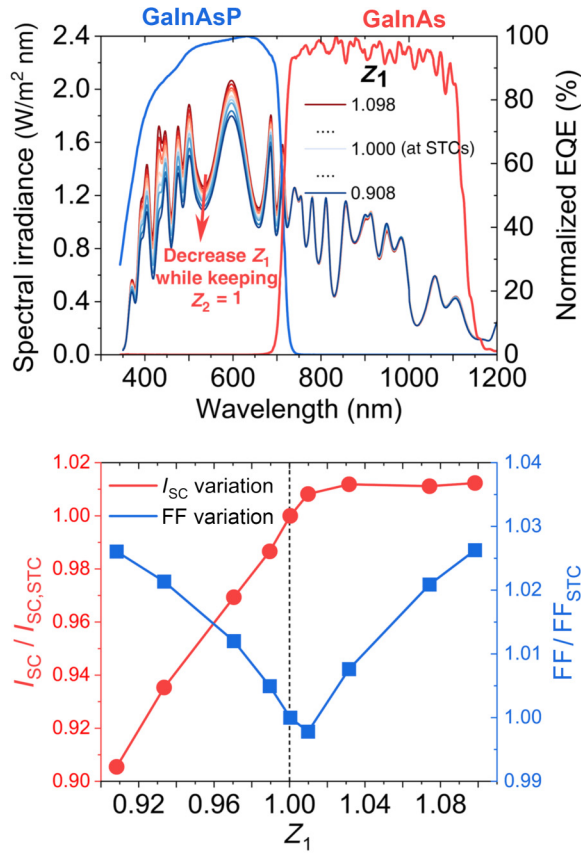


FIG. 4. (a) Comparison of spectra alongside the corresponding EQEs for a GaInAsP/GaInAs 2J cell and (b) its variations of I_{SC} and FF with respect to the STC values as a function of Z_1 while $Z_2 = 1$ is kept.

exhibits minimal change when Z_1 varies within 10% of unity due to the logarithmic dependence of V_{OC} on irradiance. Additionally, this R_{ij} method can be applied to investigate energy yield performance under simulated outdoor conditions, offering a versatile tool for performance analysis and optimization of tandem PV devices.

Overall, this spectrum adjustment process has been successfully applied to various tandem devices, including 2J, 3J, 4J, and five-junction (5J) configurations with material types such as III-V, CdTe, Si, and perovskite-based tandems. The method follows three key steps as shown in Fig. 5: (1) group LED channels and adjust their intensity; (2) acquire the adjusted spectrum with the use of a spectroradiometer; (3) calculate R_{ij} values to determine if they meet the threshold. This iterative process has been proven to be highly efficient, automated with computer control code, and can be completed in minutes, even for complex 4J or 5J devices. Additionally, base spectra tailored to different tandem devices can be preconfigured, enabling rapid adjustments for versatile devices under test. When a pre-configured spectrum is loaded for a DUT with similar SRs, the spectral tuning time can be further reduced to mere seconds due to similar M_i values.

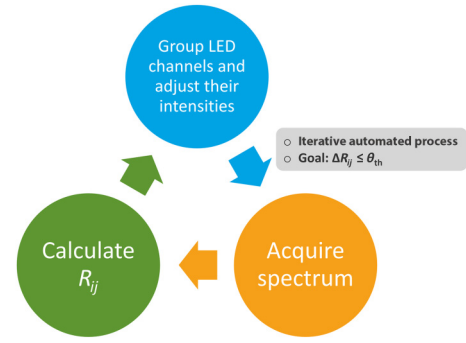


FIG. 5. Three key steps for the spectrum adjustment procedure with an LED simulator.

IV. MEASUREMENT VALIDATION

To assess the effectiveness of our spectral irradiance adjustment procedure and evaluate measurement accuracy, we conducted a comparative performance study on a variety of tandem devices using the LED-based simulator and our benchmark one-sun multisource simulator (OSMSS). The OSMSS incorporates nine adjustable spectral channels split from two 1500 W Xe lamps and two 750 W tungsten lamps and tuned with a more complicated algorithm [20]. Since 2011, it has performed thousands of tandem device measurements, including devices with up to 6 junctions [23]. Its measurement accuracy has been validated through multiple international round-robin interlaboratory comparisons over the years.

Three representative tandem devices are chosen for the comparison: (1) a 0.5×0.5 cm² GaInAsP/GaInAs monolithic III-V tandem cell with band gaps of 1.7 and 1.1 eV, respectively, to mimic the widely studied PVSK/Si tandems with its EQEs shown in Fig. 3(a); (2) a bare 1×1 cm² 2-terminal (2T) PVSK/Si tandem; (3) a packaged 10×10 cm² 4T PVSK/Si tandem minimodule. The first tandem cell was fabricated at the National Renewable Energy Laboratory (NREL) [28], while the latter two were donated by LONGi Green Energy and Tandem PV, respectively. Measurements were conducted under STC with the OSMSS measurements as the baseline, followed by measurements on the LED-based simulator, referred to as the “tunable small-area continuous solar simulator” (TSACSS) hereafter. Figure 6 presents a performance comparison for these devices, with all parameters normalized to the OSMSS baseline. Estimated measurement uncertainties ($k=2$) are also provided for all parameters. Note that the perovskite-containing devices here were measured with the NREL asymptotic I - V scan method to deliver “stabilized” performance parameters [29].

The results show good agreement between the TSACSS and the OSMSS, with all measured values falling within their respective uncertainty ranges (1.2% or less). However, the PVSK/Si 4T minimodule shows higher I_{SC}

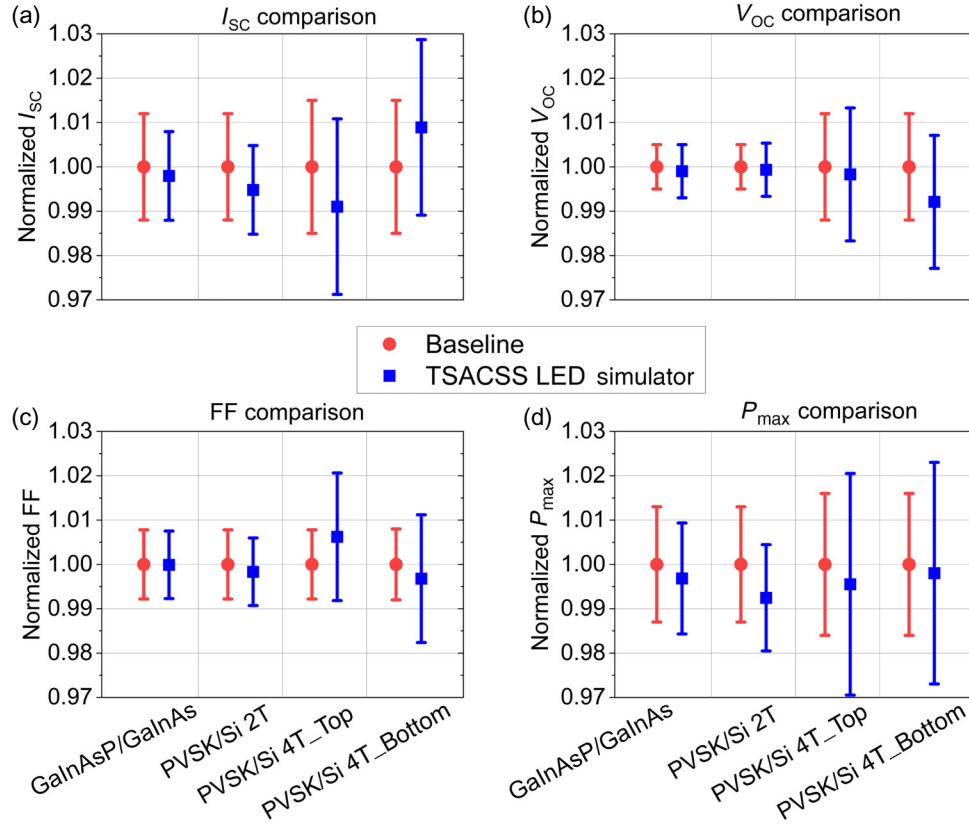


FIG. 6. Performance parameter comparisons (i.e., I_{sc} , V_{oc} , FF, and P_{max}) of three tandem device configurations: (1) $0.5 \times 0.5 \text{ cm}^2$ GaInAsP/GaInAs, (2) $1 \times 1 \text{ cm}^2$ PVSK/Si 2T tandem, (3) $10 \times 10 \text{ cm}^2$ PVSK/Si 4T tandem minimodule (the top and bottom junctions are measured separately). The parameters measured with the TSACSS LED simulator were normalized to the OSMSS baseline. Estimated measurement uncertainty bars ($k=2$) are also provided for all the parameters.

uncertainty (e.g., 2.0% in the TSACSS), which can be attributed to the TSACSS's poorer irradiance uniformity at a larger illumination plane. This issue is further discussed in Sec. V. Additionally, the V_{oc} uncertainties for the packaged minimodule were larger compared with those of the smaller devices due to a higher uncertainty in the device temperature measurement.

This TSACSS testbed using the simplified spectral adjustment procedure has been compared in numerous measurements with the well-established OSMSS for tandem devices from various global customers, ranging from square-centimeter scale cells to industry-sized $16 \times 16 \text{ cm}^2$ tandem wafers. Across all devices, performance parameters showed excellent agreement similar to the results in Fig. 6. These results showcase the robustness and effectiveness of the proposed spectrum adjustment procedure for LED-based simulators.

V. DISCUSSION

While the group spectrum tuning approach in LED-based simulators enables accurate performance measurements for tandem PV devices, various factors in

the measurement setups, such as spectrum quality and testing environment, are found to play a crucial role during the measurements. This section provides a brief discussion of these aspects and guides researchers to develop a suitable testing approach in their own laboratories.

A. Influence of spectrum quality

As previously described, LED-based simulators consist of dozens of LED channels, each with distinct emission peaks. Each channel includes numerous LED nodes and associated optical elements mounted on LED circuit boards. Activating all LED channels simultaneously using base spectrum settings can cause a rapid temperature rise of the LED electronics unit. Chojnijk *et al.* [15] have found that this leads to variations in the LEDs' light output (i.e., efficiency and emission peak wavelength) until the temperature stabilizes, as temperature affects the band gap of LED semiconductors.

Figure 7(a) shows the normalized I_{sc} of a reference cell measured over time with all LED channels activated simultaneously. Note that the cell temperature was maintained at 25°C in the entire data acquisition process. I_{sc} decreases sharply within the first few minutes, followed by gradual

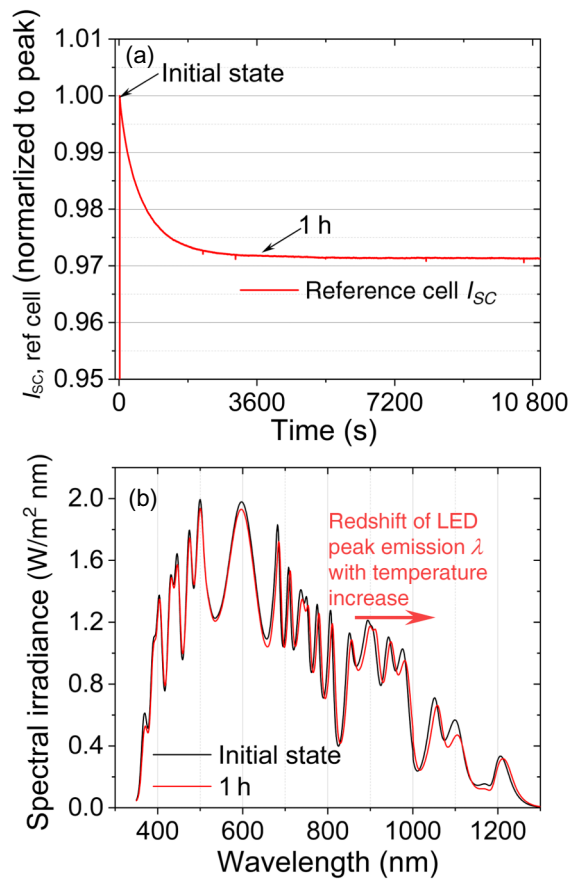


FIG. 7. (a) Normalized I_{SC} of a reference cell measured over time under the LED simulator. (b) Spectra measured after the simulator has been turned on (initial state) vs after 1 h of operation. Note that the cell temperature was maintained at 25 °C in the entire process.

stabilization over 1 h, resulting in an approximately 3% drop due to temperature-induced declines in LED efficiency. As shown in Fig. 7(b), the spectrum shape also undergoes changes, including the peak wavelength undergoing a redshift and magnitude deviation. This can cause an M_i deviation of 0.2%–0.6% for the cells presented in Fig. 6. Once the simulator is turned on, the cooling system (i.e., fan cooling used in this study) reduces the LED operational temperature until conditions stabilize. At this stage, the total irradiance deviation is less than 0.01% per minute over a 2-h period, significantly outperforming conventional xenon lamps, whose temporal instability is usually multiple times higher [30–32]. It is important to note that LED simulators from different manufacturers may exhibit differing thermal stability profiles due to differences in cooling design (e.g., water cooling vs fan cooling). In general, allowing there to be an adequate warm-up period is the first important aspect for ensuring reliable performance measurements with LED-based simulators.

Other factors, such as spatial irradiance nonuniformity and sensitivity to testing plane reflectivity, also affect the performance testing accuracy of LED simulators. Figure 11 presents irradiance uniformity maps for a $20 \times 20 \text{ cm}^2$ testing plane under different spectral conditions, showing that nonuniformity increases with larger test areas. To ensure accurate measurements for larger tandem devices, an irradiance correction factor based on the device size should be applied to account for spatial nonuniformity variations. Additionally, LED-based simulators also produce noncollimated light, causing the irradiance distribution to vary with testing plane height, so an optimized plane should be selected for better spectral uniformity (typically indicated by the simulator manufacturer). The reflectivity of the testing environment further influences spectral properties due to the multiple point light sources in LED simulators. Therefore, maintaining a uniform and controlled testing setup is crucial for accurate measurements. A detailed discussion of these factors is provided in Appendix C2.

Overall, it is important to account for variations in spectral properties to ensure accurate MJ device testing. Admittedly, spectral quality can differ across LED simulator systems due to variations in design from manufacturers. For example, sensitivity to the reflectivity of the testing environment—discussed earlier—would be less significant in simulators with long throw light projection and/or built-in irradiance monitors to compensate for such variations. Testing operators should carefully consider these factors when implementing spectral tuning methods.

B. Implications for research laboratories

This spectrum group tuning method can be readily adopted by any PV research laboratory using LED simulators. A key objective of this work is to make this method accessible to laboratories focused on tandem device research, encouraging researchers to perform more reliable tandem device testing and promoting consistent results across the field.

For laboratories already equipped with an LED simulator and a suitably broadband reference cell, and the capability to measure the EQEs of each of the individual junctions and to correct them for luminescent coupling [33], the only additional equipment required to implement this method is a spectroradiometer to capture the simulator's spectral profile. Notably, this method requires only the acquisition of a relative spectral distribution (not absolute values, as discussed in Sec. II, and no calibration of LED channel intensity vs drive current is needed). Therefore, a variety of spectrometers or spectroradiometers can meet this requirement with acceptable measurement errors. For example, most commercial LED simulators are limited to wavelengths below 1100 nm. Consequently, spectrometers or spectroradiometers with only Si photodiode arrays,

which are typically more affordable for research laboratories, are sufficient for acquiring the relative spectral profile. However, it is crucial to ensure these instruments include appropriate order-sorting filters to eliminate wavelength overlap from higher orders and have reliable third-party calibrations. Lastly, broadband reference cells are readily available and can be calibrated by any accredited PV calibration laboratory.

We note that, given the large number of individual LED channels (more than 30) in modern LED solar simulators, one can come up with many different methods to achieve spectral tuning. For example, one could even keep all channels within one junction's spectral responsivity constant except for one and adjust only that one channel to achieve current balance. A key feature of our spectrum adjustment algorithm, as illustrated in the flowchart in Fig. 2, is that it is instrument independent and does not require LED channel calibration. It provides a "natural" method to bin the LED channels to be adjusted as groups based on the junction SRs of the DUT, so it can be easily adopted by any laboratory equipped with an LED simulator, spectroradiometer, and reference cell, i.e., equipment that a laboratory that tests PV cells already possesses. If this approach is followed, measurement errors in tandem PV devices caused by spectral mismatch and the associated junction current imbalance can be significantly reduced.

A key caveat in adoption of this spectral tuning method is that the LED simulator must have a sufficient number of LED channels to independently cover the spectral responsivity regions of each junction. Without adequate spectral coverage, grouping channels becomes less effective or even unfeasible. An extreme (unrealistic) example would be assuming a 2J cell where each junction has a spectral responsivity region 100 nm wide between 500 and 700 nm. If the simulator has only one LED channel with a peak at 595 nm and a bandwidth of 200 nm, the broad overlap makes meaningful grouping impossible, rendering the method ineffective. A more common case involves partial spectral overlaps, such as an LED channel with a peak at 805 nm and a bandwidth of 100 nm, where the light can be absorbed by two adjacent junctions [e.g., junctions 2 and 3 in Fig. 3(b)]. In such situations, we have found that grouping channels based on the junction band gaps remains highly effective, and no special treatment—such as fixing the intensity of the overlapping channel—is necessary. Even in 4J all-perovskite cells with narrower spectral responsivities in individual junctions [34], our grouping-based tuning method has been verified to work reliably.

VI. CONCLUSIONS

This work presents a robust and efficient spectral irradiance adjustment method tailored for LED-based multichannel solar simulators. By using a simplified group

tuning approach and a single reference cell, the method enables accurate performance measurements of MJ solar cells across a wide range of configurations. Validation results confirmed excellent agreement with a benchmark multisource simulator, underscoring the method's reliability. Furthermore, practical considerations such as spectrum quality and environmental factors were explored, offering actionable insights for researchers. The proposed approach opens up access to precise MJ device testing, fostering advancements in tandem PV technologies. With its accessibility and proven accuracy, this method is poised to become a cornerstone for research laboratories working on next-generation tandem solar cells.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request [37].

APPENDIX A: PHOTOGRAPH OF THE TESTING PLANE

A photograph of the testing plane is shown in Fig. 8.

APPENDIX B: SPECTRUM TUNING PROCESS OVERVIEW

This appendix presents two example flowcharts illustrating our spectrum tuning process for 3J and 4J tandem devices. The tuning approach for devices with more than four junctions follows a similar method. A summary of the autotuning algorithm's input and key logic is provided below.

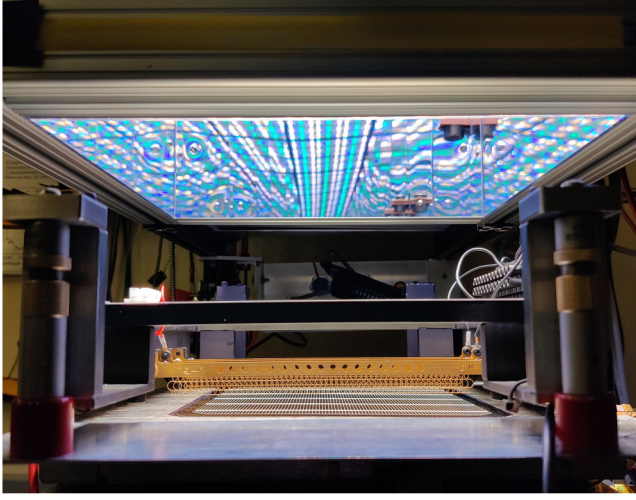


FIG. 8. The testing plane of the TSACSS LED simulator I - V testbed with an M6-size (approximately $16 \times 16 \text{ cm}^2$) perovskite/Si tandem wafer mounted with the NREL continuous probing bar system.

Tuning input:

- (1) R_{ij} acceptance threshold (%)—maximum allowable deviation, i.e., $1 \pm 0.2\%$ in this work.
- (2) Measured R_{ij} array—actual current ratios (matrix).
- (3) Desired R_{ij} —target current ratios, i.e., $R_{ij} = 1$ for all junctions.
- (4) Junction E_g —band gaps.
- (5) LED driving current setup—initial LED driving current levels per channel.
- (6) Relative LED driving current change per iteration (%).

Core algorithm logic:

- (1) Determine the number of junctions and group LED channels by each junction's band gap.
- (2) Loop through all unique R_{ij} combinations (e.g., R_{12} , R_{13} , and R_{23} for a 3J device).
- (3) Compare each measured R_{ij} value with the desired R_{ij} value.

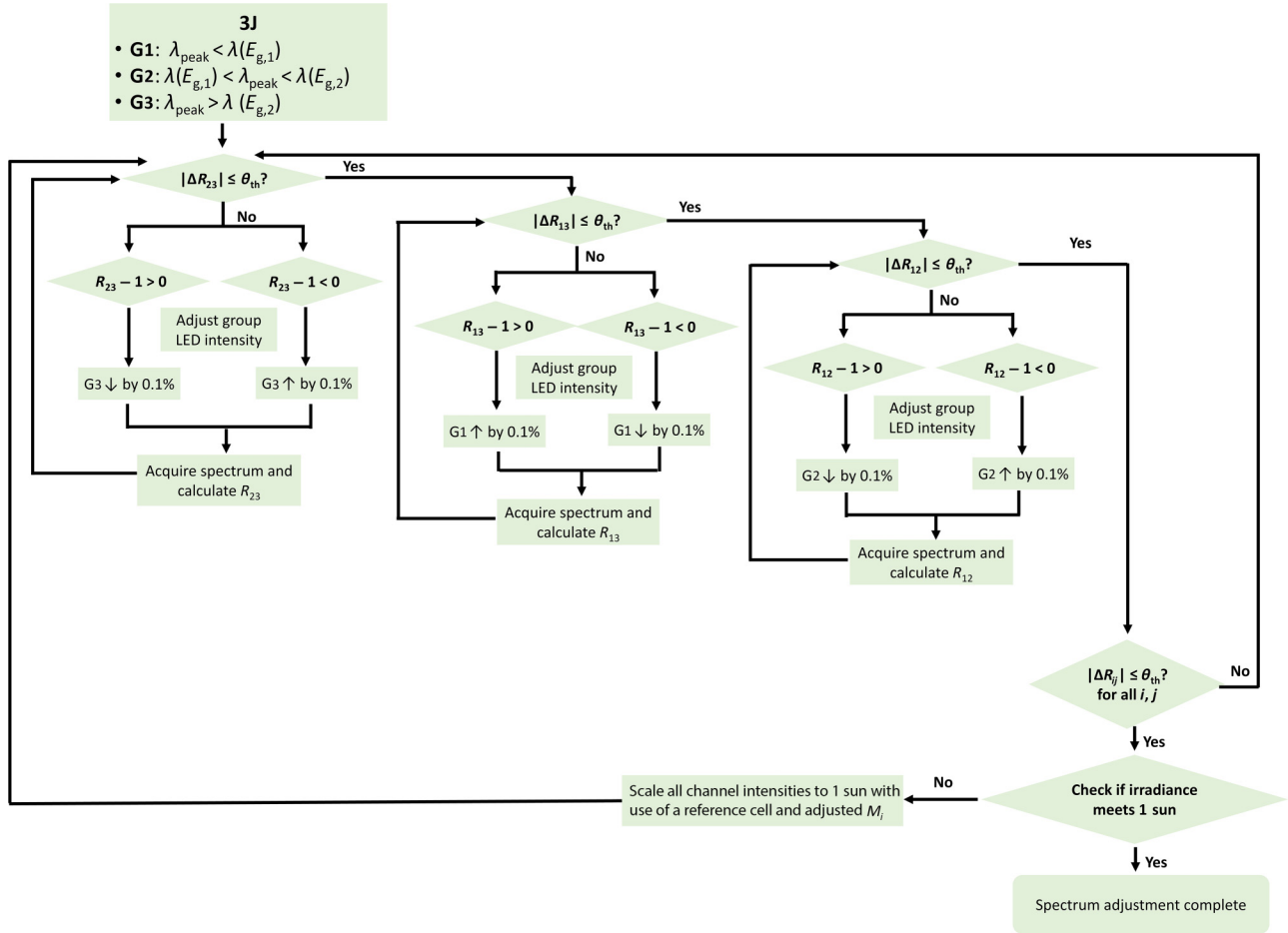


FIG. 9. Spectrum adjustment process for a 3J tandem cell using an LED simulator.

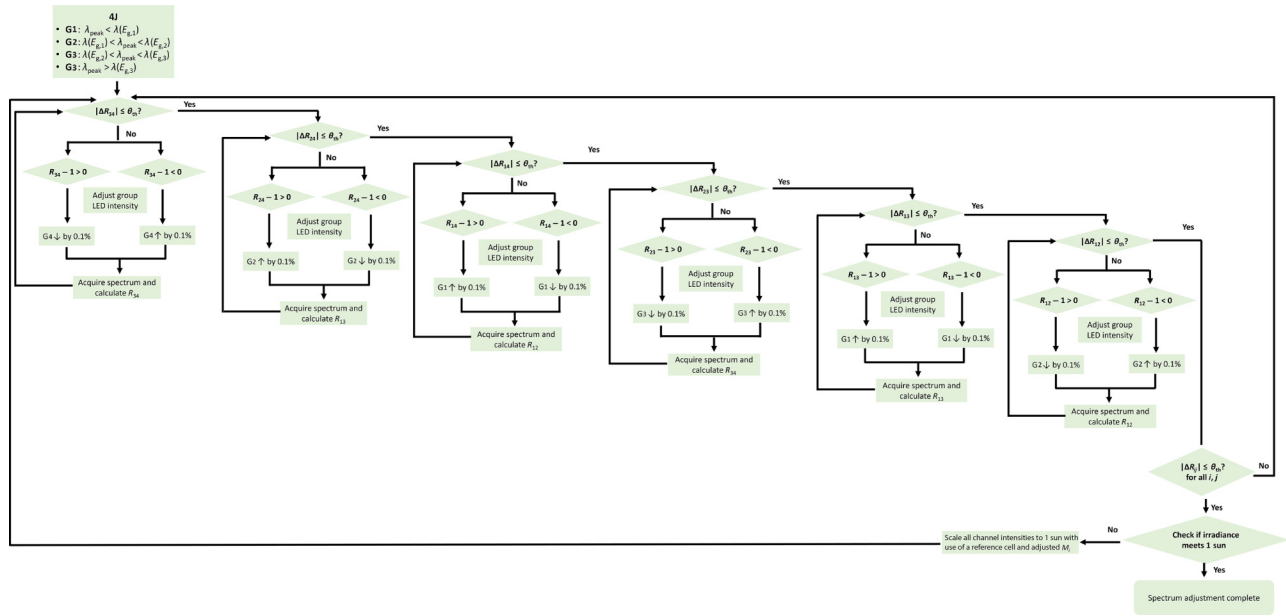


FIG. 10. Spectrum adjustment process for a 4J tandem cell using an LED simulator.

- (4) Check if all deviations are within the threshold.
- (5) If they are not, simultaneously adjust LED channel currents within the corresponding group.
- (6) Repeat until all R_{ij} values meet the threshold.

APPENDIX C1: IMPACT OF SPATIAL IRRADIANCE NONUNIFORMITY

In addition to irradiance stability, spatial irradiance nonuniformity across LED channels plays a key role in ensuring accurate performance measurements. For testing MJ devices, the irradiance uniformity of spectral bands corresponding to each junction's response region is more critical than overall irradiance uniformity. Thus, spatial irradiance nonuniformity across these spectral bands must be carefully evaluated.

Figure 11 presents irradiance uniformity maps for a 20×20 cm² testing plane (positioned 0.5 cm below the

LED simulator frame as recommended by the simulator manufacturer), measured with a 0.5×0.5 cm² Si reference cell, along with 700 nm long-wave-pass (LWP) and short-wave-pass (SWP) filters. These filters correspond to the spectral responsivity regions of typical perovskite/Si tandem cells. The current readings of the reference cell were normalized to the respective peak values under the three scenarios to represent the irradiance nonuniformity maps. According to the solar simulator classification standard [27], the overall spatial irradiance nonuniformity is calculated as approximately 1.3% across the plane, while the nonuniformity with the LWP and SWP filters is 3.6% and 1.8%, respectively. When the testing plane size is reduced to 10×10 cm², the irradiance nonuniformity for all spectral channels decreases to less than 1%, and it becomes negligible for planes smaller than 2×2 cm². This highlights the necessity of applying an irradiance correction procedure to account for spatial nonuniformity when one

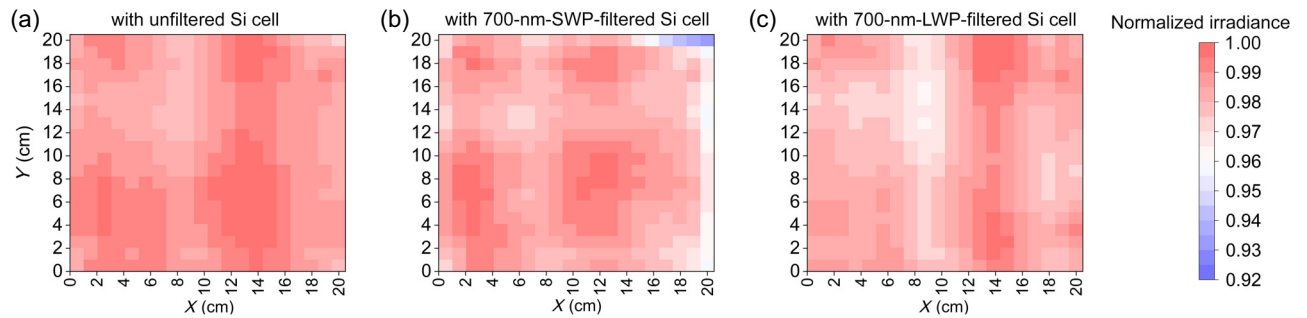


FIG. 11. Spatial irradiance maps taken with (a) an unfiltered Si cell, (b) a 700-nm-SWP-filtered Si cell, and (c) a 700-nm-LWP-filtered Si cell, all positioned 0.5 cm below the LED simulator.

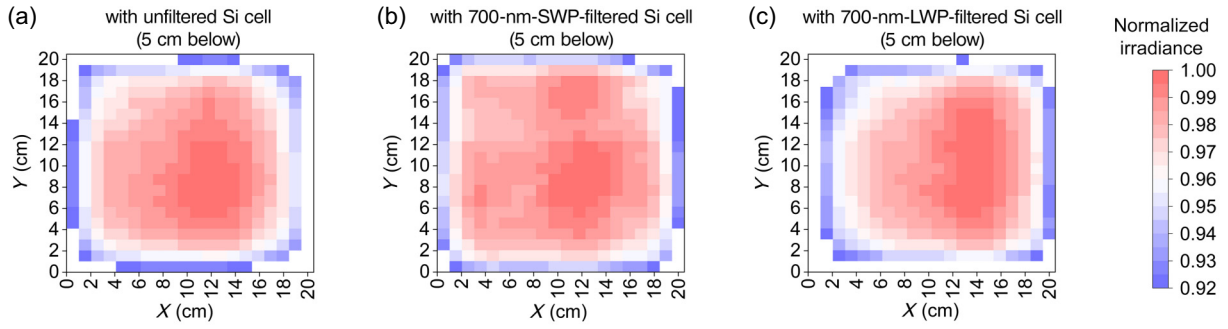


FIG. 12. Spatial irradiance maps taken 5 cm below the LED simulator with (a) an unfiltered Si cell, (b) a 700-nm-SWP-filtered Si cell, and (c) a 700 nm-LWP-filtered Si cell, which show a much worse irradiance uniformity compared with Fig. 11.

is measuring large tandem devices. For example, when one is measuring larger tandem devices exceeding $2 \times 2 \text{ cm}^2$, an irradiance nonuniformity map corresponding to the device's testing area should be captured. The average total irradiance for this area can then be quantified. If the average total irradiance is 99% of the maximum irradiance in the area, an irradiance nonuniformity correction factor $\gamma = 1/0.99$ can be applied during the total irradiance adjustment step in the spectral tuning flowchart to ensure the effective irradiance meets STC requirements [35]. Note that if the current-limiting junction of the DUT is known, the test operator may select the irradiance nonuniformity map specific to that junction's SR to determine the correction factor γ for increased accuracy. Overall, the required correction, based on device size, should be considered when one is adjusting the total irradiance to ensure precise measurements.

It is also noteworthy that LED-based simulators do not produce well-collimated light like certain well-established xenon lamps. Each LED serves as a point light source, leading to varying irradiance distribution across different testing planes and making the spectrum quality dependent on the height of the testing plane. For the simulator used in

this study, the irradiance nonuniformity decreases significantly as the testing plane's distance from the simulator increases, as demonstrated in Fig. 12, where the irradiance maps were taken 5 cm below the simulator (which is not the simulator manufacturer's recommendation for the testing plane). Consequently, unless the operator can verify good spectrum uniformity on the chosen testing plane height, it is recommended to adhere to the simulator manufacturer's recommendation.

APPENDIX C2: IMPACT OF THE TESTING ENVIRONMENT

The reflectivity of the testing environment beneath an LED simulator plays a significant role in determining the output spectral properties. This sensitivity arises from the simulator's numerous single-LED light sources and associated optical elements. Figure 13(a) illustrates the I_{SC} variation of an irradiance monitoring Si cell as the height of the testing stage changes: one with the testing stage covered with nonreflective black felt and one without the covering. The monitoring cell is centered directly beneath the LED simulator. Without black felt coverage, I_{SC} drops

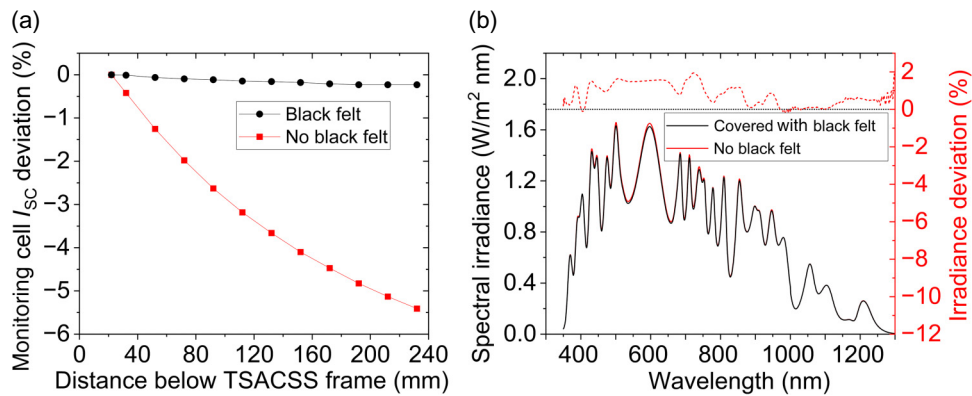


FIG. 13. (a) I_{SC} variation of an irradiance-monitoring Si cell with the distance of the testing stage from the TSACSS simulator changes when the stage is covered with vs without nonreflective black felt. (b) Spectrum difference for a sphere covered in nonreflective black felt except for the light entrance aperture and for a sphere without a covering of nonreflective black felt.

significantly as the stage-to-simulator distance increases, while with black felt coverage, irradiance variations are minimal. Additionally, the spectrum shows a small change with the black felt coverage. Figure 13(b) compares two spectra measured with a spectroradiometer coupled to an integrating sphere. Without the black felt, reflective surfaces such as the sphere's exterior and the testing stage holding the sphere introduce irradiance deviations across all wavelengths, resulting in an approximately 0.8% ΔR_{12} error when a 2J tandem device is measured. This highlights the high sensitivity of LED simulator spectral output to the reflectivity of the testing environment.

To ensure consistent measurement results, it is crucial to maintain a uniform testing stage environment throughout the entire process, from spectrum adjustment to I - V measurements. However, variations in testing setups are often unavoidable, such as differences in size between the reference cell and the DUT. To mitigate irradiance variation caused by the testing environment, the use of an irradiance monitoring cell and a corresponding calibration transfer procedure is essential [36].

The monitoring cell is positioned on the testing plane and measures effective irradiance during performance measurements. After completion of the spectrum adjustment procedure to meet STC, the monitor cell records the effective irradiance. When the DUT is mounted on the testing plane, both the I - V characteristics of the DUT and the monitor cell's current are measured simultaneously. A corrected I - V curve for the DUT under the STC is then obtained by one comparing the monitor cell's current readings across setups. Figure 14 highlights the importance of irradiance correction, showing a difference in I_{SC} measurements with and without correction for the devices presented in Fig. 6. For small devices, such as the 0.25 cm² GaInAsP/GaInAs and 1 cm² PVSK/Si cells (both with a

substrate size of approximately 2 × 2 cm², similar to the reference cell dimensions), the I_{SC} difference is modest (less than 1%), as the overall reflectivity change of the testing stage (25 × 25 cm²) is negligible between the reference cell and DUT setups. However, for a 10 × 10 cm² PVSK/Si 4T minimodule mounted on the testing stage, the overall stage reflectivity decreases prominently, leading to an approximately 2%–3% drop in I_{SC} without irradiance correction. In summary, a consistent and controlled testing environment is critical for accurate measurements with LED simulators, a factor that is often overlooked.

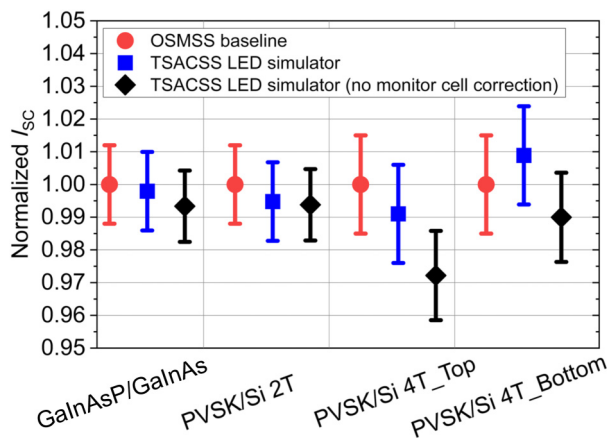


FIG. 14. I_{SC} comparison with and without irradiance correction from a monitoring cell on the three tandem devices discussed in Fig. 6.

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