

Understanding Causes and Effects of Non-Uniform Light Distributions on Multi-Junction Solar Cells: Procedures for Estimating Efficiency Losses

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Abstract. This paper presents the mechanisms of efficiency losses that have to do with the non-uniformity of the irradiance over the multi-junction solar cells and different measurement techniques used to investigate them. To show the capabilities of the presented techniques, three different concentrators (that consist of an acrylic Fresnel lens, different SOEs and a lattice matched multi-junction cell) are evaluated. By employing these techniques is possible to answer some critical questions when designing concentrators as for example which degree of non-uniformity the cell can withstand, how critical the influence of series resistance is, or what kind of non-uniformity (spatial or spectral) causes more losses.

INTRODUCTION

In the design of concentrator photovoltaic (CPV) modules, the distribution of irradiance at the receiver plane becomes critical due to several aspects. For instance, it determines the performance of the multi-junction (MJ) solar cell that has to be used, and thus the concentration achievable to guarantee a certain energy collection by the module. The MJ solar cells must be chosen based on economic and technological aspects in terms of cost reduction and efficiency increase in the CPV module. However, the market availability regardless of the criteria of optimum performance of the CPV module (most MJ cell manufacturers have standardized their products) determines the MJ cell choice. Thus, to study the actual irradiance distribution and to evaluate if the selected receiver size is cost-effective is highly recommended. Moreover, there are different mechanisms of efficiency losses in modules that have to do with the non-uniformity of the irradiance over the cell (*e.g.*, series resistance or tunnel junction breakdown) that should be studied.

NON-UNIFORM LIGHT DISTRIBUTION ON MULTI-JUNCTION CELLS.

We can distinguish two different kinds of possible non-uniform light distributions caused by CPV optical systems over MJ solar cells:

- A spatial non-uniform light distribution on the MJ cell: equal (if normalized) irradiance distribution for all subcells within the MJ solar cell.
- A spatial and spectral non-uniform light distribution on the MJ cell: different (if normalized) irradiance distribution for all subcells within the MJ solar cell.

Spatial Non-Uniform Light Distributions on Multi-Junction Solar Cells

This kind of irradiance profile is given by reflective concentrators that produce the same normalized irradiance distribution for every subcell comprising the MJ cell. The absolute level of the irradiance distribution for each

subcell varies depending on the optical transmittance of the concentrator and the light spectrum reaching its aperture.

The effect of spatial non-uniform light distribution on MJ solar cells is directly related to the well-known effect of series resistance in single junction solar cells. This series resistance effect is manifested as a decrease in the fill factor (FF) and, at very high currents or with very high resistance values, also as a decrease in the short-circuit current density (1). Since losses due to series resistance scale as the square of the current density at the solar cell, eventually they become the dominant factor for the cell efficiency with increasing current. There are different approaches to reduce the series resistance as to increase the density of front-contact grid fingers optimizing the front grid (2), or to raise the emitter conductivity in the top subcell by raising the emitter doping and/or the thickness.

Spatial non-uniformities imply that some cell areas are illuminated at higher irradiances than others, translating into an increase in effective series resistance and, therefore, a decrease in FF. At the same time, other cell areas are very poorly illuminated, or even dark. Hence, those areas will work as dark diodes, contributing only with recombination current but not with photo-generation leading to a possible small reduction of the open circuit voltage (V_{oc}).

Methods for Testing the Efficiency Losses in MJ Cells with Spatial Non-Uniform Irradiance Patterns

We can evaluate the electrical performance of MJ cells when illuminated by spatial non-uniform light distributions by the so-called “mask method”. The idea is to replicate irradiance patterns of different concentrator systems by the inclusion of masks when illuminating the cell in a solar simulator (3).

The masks used to reproduce different distributions may be printed on transparent film using a high-resolution photo plotter similar to those used in photolithography. When a masked cell is illuminated with uniform irradiance, the mask provides a variable shading value across the cell surface. The synthetic profile of the light transmitted is similar to that produced by a reflective CPV optical system on the three subcells. The peak-to-average ratio (PAR) defined as the maximum to average irradiance ratio is used to describe the degree of non-uniformity of a given light distribution.

To evaluate relative losses on efficiency and FF due to non-uniform light patterns, I–V curves of MJ solar cells (masked and uniformly illuminated) are compared. In order to ensure the cell is measured under the same nominal irradiance (*i.e.*, concentration level) for all tests (*i.e.*, for all masks), the total irradiance is adjusted to have a constant photo-generated current regardless of the mask used.

At Instituto de Energía Solar (IES-UPM), the I-V curve measurements are carried out using an in-house developed pulsed solar simulator for solar cells in multi-flash mode. The cell assemblies are attached to a temperature-controlled plate, and the irradiance and spectrum of the light arriving at the device are controlled by means of component solar cells that have been characterized under the reference spectrum AM1.5D G173-03 (4). The component cell (also called ‘isotype’) has a similar stack of semiconductors as the multi-junction (MJ) solar cell. However, all layers are optically active and electrically inactive except the one corresponding to the spectral range that the isotype cell represents (*e.g.*, top, middle or bottom in 3J cells).

The spectral matching ratio (SMR) (measured by means of component reference cells) is used to define how similar the spectrum of the light reaching the cell under test is if compared with the reference spectrum AM1.5D.

$$SMR = \frac{I_{L,Top}^E / I_{L,Middle}^E}{I_{L,Top}^{AM1.5D} / I_{L,Middle}^{AM1.5D}} \quad (1)$$

where I_L^E represents the photocurrent of a subcell (top or middle component cell) when illuminated with a particular spectral irradiance distribution reaching the device under test (for example, the simulator spectrum), and $I_L^{AM1.5D}$ stands for the photocurrent of a subcell (top or middle component cell) under the reference spectrum AM1.5D. The SMR calculated with top and middle subcells is often used in the case of 3-junction lattice matched solar cells (GaInP/GaAs/Ge) as an indicator of how blue-shifted ($SMR > 1$) or red-shifted ($SMR < 1$) the spectrum of the cell tester is with respect to the reference spectrum AM1.5D (perfect similarity implies $SMR = 1$). For any other kind of MJ cells which can be largely limited by bottom subcell, the SMR given by middle-to-bottom must be also used to describe the spectrum (Osterwald et al., 2014).

Spatial and Spectral Non-Uniform Light Distribution on Multi-Junction Solar Cells

Refractive optical systems can produce not only spatial but also spectral differences in the light profile distributions between subcells because of the chromatic aberration.

Experimental analyses were carried out by several authors to determine the influence of non-uniform irradiance distributions on the cell caused at different primary-to-receiver distances by either maintaining spectrum and irradiance conditions constant (5–7) or varying them (8). MJ devices are usually designed to be current matched (*i.e.*, the ratio between subcell currents is 1) under AM1.5D spectrum. Although the reference spectrum AM1.5D is likely to be a good estimate of the average spectrum used by a concentrator, it is not assured that this spectrum is observed everywhere at the receiver plane. The spectral content of the light reaching the cell is modified due to the optical transmittance function of the system. Also the light patterns on the different subcells of the MJ solar cell are slightly different due to the refractive index variation with the wavelength. These spatial and spectral non-uniformities can cause current mismatch between the subcells in the MJ solar cell decreasing the cell current. For the case of high differences between irradiance profiles in the different subcells, the current spreading that depends on the lateral resistances of the cells (layers which make up the connection between two subcells) can be the dominant factor of efficiency losses in high concentration systems (5,9–11).

If the lateral resistance for each connection layer is low enough, the current will spread out across the cell without adding any losses, and the cell efficiency will be determined by the overall current mismatch between subcells. Contrary to this, if the lateral resistance is too high to support the lateral current flow, at each point of the cell the current will be limited by the lowest generated current subcell. The actual performance of a concentrator system with high chromatic aberration is expected to be within these two extremes cases as already proven by experimental results (12). Predicting this behavior is not intuitive at all, therefore simulations based on distributed model are very useful to understand this phenomenon (2,11,13–18).

CASE-STUDY: IRRADIANCE PATTERNS OF FRESNEL BASED CONCENTRATORS AND THEIR EFFECT ON THE MULTI-JUNCTION SOLAR CELL PERFORMANCE

This section presents the different measurement techniques developed at IES-UPM to study the mechanisms of efficiency losses due to non-uniformity.

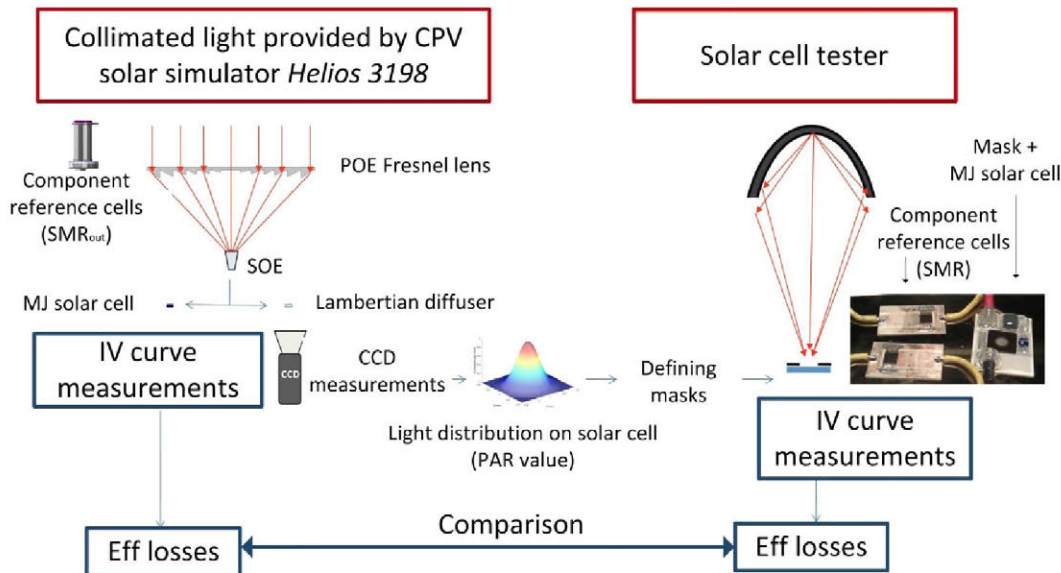


FIGURE 1. Efficiency loss measured at cell level by the mask method is compared with the loss measured at module level with the solar simulator for CPV modules (Helios 3198).

In particular, three different concentrators are evaluated by the developed techniques, as a case-study, by means of:

- Measurement of the electrical performance of the MJ cell covered by a mask. The spatial non-uniform irradiance distribution reproduced by the mask has a PAR value that emulates the irradiance distributions generated by the concentrators under study (known by measurements already performed with a CCD camera).
- Measurement of the electrical performance of the concentrators (the optical system and the MJ solar cell) in a solar simulator for CPV modules.

The electrical characterization of concentrators can be performed in an appropriate solar simulator for CPV modules as the Helios 3198 developed at IES-UPM (19). The efficiency losses caused by the spatial non-uniform distribution can be determined by comparing the cell performance under uniform and non-uniform irradiance patterns (characterization carried out in the solar cell tester using a set of masks of different PAR values). On the other hand, the effect of the chromatic aberration causing uneven irradiance profiles at the different subcells can be calculated by comparing the I-V curve of the whole system at the solar simulator and the I-V curve of the MJ cell (without concentrator) under uniform illumination at the cell tester.

Concentration Photovoltaic Optical Systems under Study

The three concentrators investigated in this study consist of an acrylic Fresnel lens and different SOEs: a refracting dome shaped integrator made out of silicone (20), a dielectric truncated pyramid (homogenizer glass prism) (21), and a bare cell (without SOE). The size of the lens aperture is 25 cm X 25 cm while the receiver is formed by a SOE bonded to a lattice matched MJ solar cell (GaInP/GaAs/Ge) with an active area of 1 cm². Thus, the three CPV systems under evaluation have the same geometrical concentration C_{geo} of 625X (*i.e.*, ratio of the lens aperture area to the active cell area). All the MJ solar cells of these receivers are from the same manufacturer and technology so similar electrical characteristics are expected. Nevertheless, a first electrical characterization was performed at the cell tester to gather information about the I-V curve and the spectral sensitivity of the cells. After this, the SOE was bonded to the MJ solar cell by means of SYLGARD 184 silicone. The Fresnel lens and the receiver are both mounted in a rigid structure that allows the focal distance to be varied to adjust it to its optimum value (*i.e.*, maximum optical efficiency).

Causes and Effects of the Non-Uniform Patterns of the Concentrators under Study

Results: Effects of Spatial Non-Uniform Light Distributions

The irradiance profile of the three optical system under study was evaluated and captured over the entire CCD spectral range (400-900 nm) and also over both top and middle wavelengths (if including appropriate band-pass filters during the measurement) (22). The PAR values for these experimental profiles are presented in Table 1.

TABLE 1. PAR values obtained from the measured irradiance patterns of the three optical systems under study. The measurements are done by means of a CCD camera with (and without) the inclusion of filters to distinguish top and middle patterns.

OPTICAL SYSTEM	PAR TOP	PAR MIDDLE	PAR (NO FILTER)
FRESNEL LENS (FL) + BARE	10.5	7	9.9
FL + DOME	3.2	3.2	2.7
FL + PYRAMID	1.2	1.2	1.2

Efficiency losses are defined as the variation of efficiency related to a given irradiance profile compared with the efficiency obtained with uniform illumination. Efficiency losses measured for a bare cell covered by masks with different PAR irradiance distributions (around the PAR values measured for dome and pyramid systems without high or low filters) are presented in FIGURE 2 (black dots). The measurement conditions are 500 suns (1 sun equals 1000 W·m⁻² under AM1.5D) and SMR=1. In this case-study, the SMR is calculated based on top and middle component cells as the device under test has a Ge-bottom subcell. These losses are related to series resistance effects and not to chromatic aberration (as the masks create the same light distribution in every subcell within the MJ solar cell). Losses seem to experiment a linear increase with the PAR value which means that the effective series resistance of these two cells also increase linearly with the PAR value.

The I-V curve for each concentrator under study was measured in a solar simulator for CPV modules (at $1000 \text{ W}\cdot\text{m}^{-2}$ and $\text{SMR}=1$ at the entrance of the Fresnel lenses, hereinafter referred to as $\text{SMR}_{\text{out}}=1$). These curves are compared with the I-V curves of the MJ cells uniformly illuminated (500 suns and $\text{SMR}=1$) to calculate the efficiency losses due to the non-uniform distributions of the concentrators. The transmittance response of the concentrator optics can modify the spectrum impinging the cell leading to different electrical performance of the MJ cell than under $\text{SMR}=1$. Consequently, the following comparison analysis accounts not only for the effect of the chromatic aberration but also for the spectral transmission of the optics.

In order to present the electrical losses of the concentrators for the same nominal optical concentration, the I-V curves of the optical systems measured at the solar simulator were translated from its optical concentration to 500 suns (that is the concentration used when measuring the cell under uniform illumination and with masks at the cell tester). Assuming that there is not a loss of linearity between the irradiance and the short circuit current, the optical concentration η_c can be calculated provided that the current at one sun ($1000 \text{ W}\cdot\text{m}^{-2}$ AM1.5D) for the different subcells is already known:

$$\eta_c(\text{sun}) = \frac{I_{\text{SC},\text{MJ}}(\text{A})}{I_{\text{subcell},\text{MJ}}(\text{A}/\text{sun})} \quad (2)$$

where $I_{\text{SC},\text{MJ}}$ is the short circuit current of the MJ cell under the concentrator, and $I_{\text{subcell},\text{MJ}}$ the current of each subcell of the MJ cell at 1 sun ($1000 \text{ W}\cdot\text{m}^{-2}$ AM1.5D) previously measured at the cell tester (the subscript ‘subcell’ stands for top, middle or bottom whichever is applicable).

The optical concentration η_c must be calculated using the 1-sun I_{sc} ($I_{\text{subcell},\text{MJ}}$) of the subcell that is limiting the photo-generated current of the cell under concentration. Thus current limitation must be studied by means of the so-called subcell-limitation diagram (12). This diagram represents the ratios of the cell current and component reference cells concentrations in suns (1 sun equals $1000 \text{ W}\cdot\text{m}^{-2}$ under AM1.5D) plotted against the spectral span in terms of SMR.

The diagrams of both dome and pyramid based concentrator reveal that the top subcell limits the MJ cell photocurrent at $\text{SMR}_{\text{out}}=1$. Thus the optical concentration for these CPV optical systems is calculated based on top subcell 1-sun I_{sc} ($I_{\text{subcell},\text{MJ}}$). Efficiency losses calculated for these two concentrators (Fresnel lens, dome/pyramid and MJ cell) are presented in FIGURE 2 (color squares) together with the efficiency losses obtained for the MJ cell covered by masks (black dots).

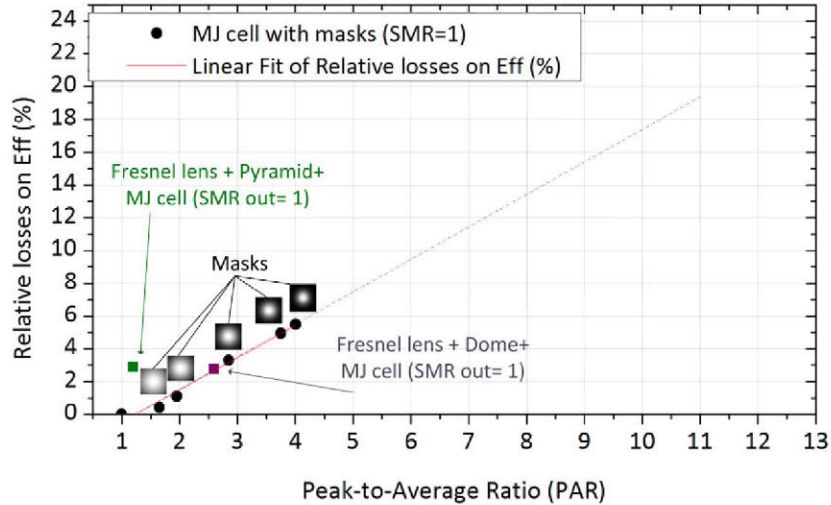


FIGURE 2. Percent variation of efficiency (Eff): black dots: mask-based method (solar simulator for high concentration photovoltaic (HCPV) cells, 500 suns nominal irradiance and $\text{SMR}=1$) color dots: optical system and cell measurements (solar simulator for HCPV modules, 500 suns over the cell and $\text{SMR}=1$ at the entrance of the lens). PAR, peak-to-average ratio; MJ, multi-junction; SMR, spectral matching ratio.

For the dome-based system, the efficiency loss seems to be governed by the series resistance as it is coincident with the mask method result. For the case of the pyramid-based system, measured losses are higher than expected by the mask method. The pyramid produces very similar irradiance profiles (both spatially and spectrally) in all the subcells. The lack of chromatic aberration produces a good lateral current flow that avoids inhomogeneous current-matching distribution over the cell. This was already proven by a clear top subcell limitation revealed in the subcell limitation diagram of the pyramid-based system. Therefore, differences between measured and predicted losses by the mask method could be due to differences between light patterns over the cell. As expected, the more similar the patterns generated by the CPV systems at the different subcells to the corresponding Gaussian distribution of the mask, the better the agreement between both measurements (cell tester and solar simulator for modules). This is not the case for the approximation of the irradiance distribution of the inverted pyramid (which has maximum values at the cell corner) if compared with a Gaussian distribution (which has a maximum at its center).

In the case of the Fresnel lens and the bare cell, the subcell-limitation diagram (FIGURE 3) shows a clear top limitation for $SMR_{out} < 0.85$ (showed by a monotonic horizontal trend) but neither of the subcells limits the current independently for SMR values higher than 0.84, and in particular for $SMR_{out}=1$ (coincident with the spectral conditions at which the evaluation at the solar simulator is performed). In this region, the current of the MJ cell is lower than the minimum of the two subcell photo-currents ($I_{subcell,MJ}$) clearly revealing a loss of current. This loss depends on the lateral current flow in the cell and is caused by the inhomogeneous current-matching distribution produced by chromatic aberration (12).

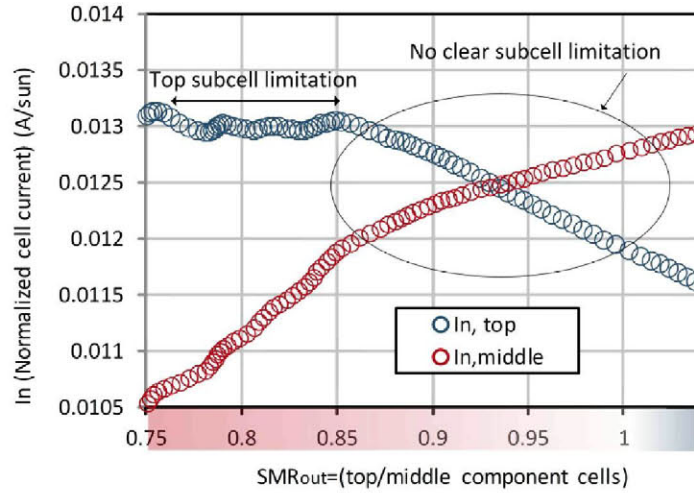


FIGURE 3. Subcell limitation diagram for the top and middle subcells of the MJ solar cell illuminated by a Fresnel lens

For this CPV system (Fresnel lens and bare cell), two different optical efficiency values can be calculated depending on which value of cell current ($I_{SC,MJ}$) is considered:

- η_C^{losses} (Equation 3) is calculated assuming the MJ cell is limited by the top subcell (because the bare cell was top limited at $SMR=1$, as well as in the case of the other concentrators under study) but assuming a current loss if compared with $SMR < 0.85$

$$\eta_C^{losses} = \frac{I_{SC, MJ}(SMR < 0.85)}{I_{subcell} (A/sun)} \quad (3)$$

- η_C (Equation 4) is also calculated as if the MJ cell is limited by the top subcell but considering the current generated by the concentrator at $SMR_{out}=1$ (assuming there are no loss of current due to chromatic aberration).

$$\eta_C = \frac{I_{SC, MJ}(SMR=1)}{I_{subcell} (A/sun)} \quad (4)$$

The efficiency losses calculated for the Fresnel lens and bare cell considering the two different optical concentrations are presented in FIGURE 4. The difference between both values can be considered a coarse estimation of minimal losses due to chromatic aberration. It can be observed that the efficiency losses calculated discounting the effect of the chromatic aberration coincides with the extrapolation (for the correspondent PAR value) of the efficiency losses vs PAR trend line (obtained with the mask measurements). If we assume that this linear fit is valid (there are no data to probe it for such a high PAR value), additional losses due to chromatic aberration can be considered to be mainly caused by the current loss and to be less dependent on FF variation (only current losses are considered in the performed estimation). The strong decrease in FF is assumed to be mainly caused by the spatial non-uniformity (losses are coincident with the mask method extrapolation).

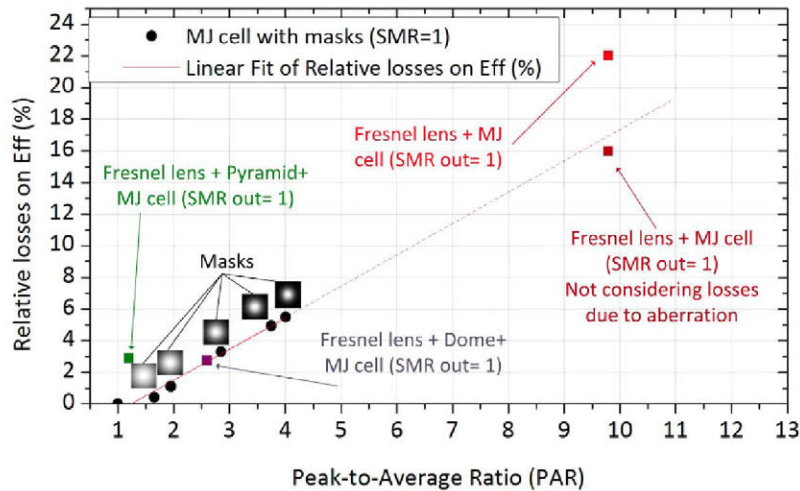


FIGURE 4. Percent variation of efficiency (Eff): black dots: mask-based method (solar simulator for high concentration photovoltaic (HCPV) cells, 500 suns nominal irradiance and SMR=1) color dots: optical system and cell measurements (solar simulator for HCPV modules, 500 suns over the cell and SMR=1 at the entrance of the lens).

CONCLUSIONS

Some important issues concerning the causes and effects of the non-uniform profiles on the solar cells have been addressed through the case-study presented in this paper. Note that these results are obtained for a particular MJ cell and cannot be generalized for the whole set of MJ cells as they are closely dependent on the cell design and characteristics. Nevertheless, the proposed methods have been confirmed to be valid in answering some important questions when designing concentrators (for a given solar cell technology), for example:

- Which degree of non-uniformity can the cell withstand without a significant decrease in its electrical performance?

Relative losses on efficiency are lower than 6% for PAR values of up to 4. However, losses increase to more than 16% for PAR value close to 10. Adding a SOE significantly improves the performance of the concentrator system by reducing the degree of non-uniformity.

- How critical is the influence of series resistance on the effect of non-uniform light profiles?

The effect of series resistance seems to be the dominant factor in the cell performance under non-uniform light distribution over chromatic aberration for the evaluated concentrators.

- Which kind of non-uniformity (spatial or spectral) causes more losses?

For the CPV systems under evaluation, only significant losses due to chromatic aberration has been found for the case of the Fresnel lens and bare cell increasing the relative losses from 14% to 22%.

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REFERENCES

1. Olson J.M. *et al.*, “High-Efficiency III-V Multijunction Solar Cells” in *Handbook of Photovoltaic Science and Engineering* (John Wiley & Sons, Ltd; 2005) p. 359–411.
2. García I. *et al.*, “Study of non-uniform light profiles on high concentration III-V solar cells using quasi-3D distributed models”. In 33rd IEEE Photovoltaic Specialists Conference Proceedings (Institute of Electrical and Electronics Engineers, 2008) p. 92.
3. Antón I. *et al.*, “IV Testing of Concentration Modules and Cells with Non-Uniform Light Patterns” Proceedings of the 17th European Photovoltaic Solar Energy Conference and Exhibition. (2001). p. 611–4.
4. G03 Committee. Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37 Tilted Surface (ASTM International, 2012)
5. S.R. Kurtz and M.J. O’Neill, “Estimating and controlling chromatic aberration losses for two-junction, two-terminal devices in refractive concentrator systems” Conference Record of the Twenty Fifth IEEE Photovoltaic Specialists Conference (1996) p. 361–4.
6. H. Cotal and R. Sherif, “The effects of chromatic aberration on the performance of GaInP/GaAs/Ge concentrator solar cells from Fresnel optics” Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference (2005). p. 747–50.
7. V. Andreev *et al.*, “Weakening of the chromatic aberration negative effect on the performance of concentrator multi-junction solar cells” 22nd European Photovoltaic Solar energy Conference (2007)
8. M. Victoria *et al.*, “Characterization of the spatial distribution of irradiance and spectrum in concentrating photovoltaic systems and their effect on multi-junction solar cells” *Prog Photovolt Res Appl*. 21(3):308–18 (2013)
9. L.W. James, “Effects of concentrator chromatic aberration on multi-junction cells” IEEE Photovoltaic Specialists Conference (1994). p. 1799–802 vol.2.
10. I. García *et al.*, “Analysis of Chromatic Aberration Effects in Triple-Junction Solar Cells Using Advanced Distributed Models”. *IEEE J Photovolt*. (2011) 1(2):219–24.
11. P. Espinet, “Advances in the modeling, characterization and reliability of concentrator multijunction solar cells” PhD Thesis, E.T.S.I. Telecomunicación (UPM, 2012).
12. C. Domínguez *et al.*, “Probing the effects of non-uniform light beams and chromatic aberration on the performance of concentrators using multijunction cells. 8th International Conference on Concentrating Photovoltaic Systems” (American Institute of Physics, 2012).
13. R.A LaRue. *et al.*, “A distributed resistance model of an AlGaAs/GaAs concentrator solar cell illuminated with a curved groove Fresnel lens”. *IEEE Electron Device Lett*. (1981) Feb;2(2):41–3.
14. Nielsen L.D., Nielsen L.D. “Distributed series resistance effects in solar cells” *E E E Trans Electron Devices*. (1982) 29(5):821–7.
15. K. Araki and M.Yamaguchi, “Extended distributed model for analysis of non-ideal concentration operation” *Sol Energy Mater Sol Cells*. Feb 1;75(3–4):467–73 (2003)
16. K. Nishioka *et al.*, “Evaluation of InGaP/InGaAs/Ge Triple-Junction Solar Cell under Concentrated Light by Simulation Program with Integrated Circuit Emphasis”. *Jpn J Appl Phys*. 43(3):882–9. (2004)
17. B. Galiana *et al.*, “A 3-D model for concentrator solar cells based on distributed circuit units”. *IEEE Trans Electron Devices*. (2005) 52(12):2552–8.
18. I. García, “Desarrollo de células solares de doble unión de GaInP/GaAs para concentraciones luminosas elevadas (Development of GaInP/GaAs dual-junction solar cells for high light concentrations)” PhD Thesis, E.T.S.I. Telecomunicación (UPM, 2010).
19. C. Domínguez *et al.*, Solar simulator for concentrator photovoltaic systems. *Opt Express*. 16(19):14894–901. (2008)
20. L.W. James, “Use of imaging refractive secondaries in photovoltaic concentrators”. NASA STIRecon Tech Rep N. (1989) 29833.
21. K. Araki *et al.*, “Experimental proof and theoretical analysis on effectiveness of passive homogenizers to 3J concentrator solar cells” Proceedings of 3rd World Conference on Photovoltaic Energy Conversion (2003) p. 853–6 Vol.1.
22. R. Herrero *et al.*, “Concentration photovoltaic optical system irradiance distribution measurements and its effect on multi-junction solar cells” *Prog Photovolt*. 20(4):423–30 (2011)