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Citation: AIP Conference Proceedings **1881**, 030003 (2017); doi: 10.1063/1.5001414
View online: https://doi.org/10.1063/1.5001414
View Table of Contents: http://aip.scitation.org/toc/apc/1881/1
Published by the American Institute of Physics

Design and Characterization of Refractive Secondary Optical Elements for a Point-Focus Fresnel Lens-Based High CPV System

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Abstract. Point-focus Fresnel lens-based High Concentrator Photovoltaic (HCPV) systems are usually equipped with refractive secondary optical elements (SOE) in order to improve their performance. Two basic SOE designs are optically modeled and simulated in this work: Domed-Kaleidoscope (D-K) with breaking-symmetry top and SILO (SIngle-Lens-Optical element). Wavelength-dependent optical material properties like refractive index and absorption coefficient, as well as the spectral response of a typical triple-junction (TJ) solar cell, are included in the ray tracing simulations. Moreover, using a CPV Solar Simulator "Helios 3198", both HCPV units are experimentally characterized. The acceptance angle characteristics of both HCPV units, obtained through optical simulations and through indoor characterization, are compared. The acceptance angle characteristic is better for the HCPV unit with the D-K SOE both in simulations and in experimental measurements, showing concordance between simulation and experiment. However, simulation results underestimate the experimental ones concerning the acceptance angle, which will be investigated in future works.

INTRODUCTION

Refractive secondary optical elements (SOE) are typical in point-focus Fresnel lens-based High Concentrator Photovoltaic (HCPV) systems due to the increase in the acceptance angle of the system and in the uniformity of the concentrated illumination on the solar cell [1]. Two refractive SOEs are chosen in this work: Domed-Kaleidoscope (D-K) with breaking-symmetry top [2], and SILO (SIngle-Lens-Optical element) [3]. The Fresnel lens is chosen to be made of standard poly(methyl methacrylate) PMMA, whereas both SOEs are made of glass. Then, two HCPV units are analyzed, being each one equipped with one of the two SOEs mentioned. See in FIGURE 1 a photograph of both SOEs.

13th International Conference on Concentrator Photovoltaic Systems (CPV-13)
AIP Conf. Proc. 1881, 030003-1–030003-6; doi: 10.1063/1.5001414
Published by AIP Publishing. 978-0-7354-1561-4/$30.00

FIGURE 1. Photograph of both SOEs: left, Domed-Kaleidoscope; right, SILO.

Both HCPV units are analyzed in this work through an optical modeling of the concentrator system that takes into account wavelength-dependent properties of the materials involved like refractive index and absorption coefficient. Moreover, the concentrator solar cell, a typical triple-junction (TJ) one [1], is modeled through the spectral response of each component subcell. Therefore, the optical polychromatic efficiency can be determined in terms of the subcell limiting current. Ray tracing is done for normal alignment and for different tilt angles respect to the incoming rays. This complete optical modeling has been developed and is implemented on a typical ray tracing software (TracePro).

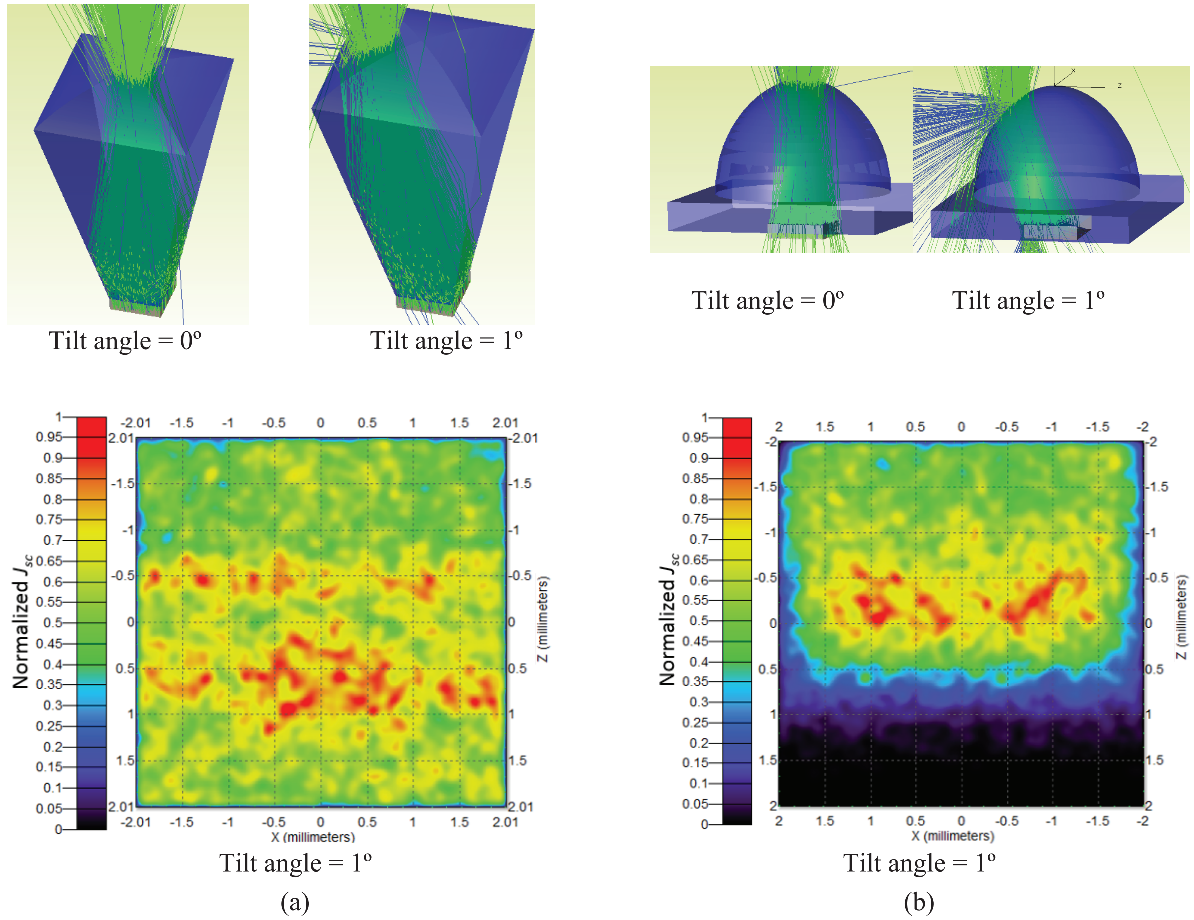
Beside optical simulations, experimental measurements are conducted in order to verify ray tracing results. Both HCPV units are then built and characterized in a CPV Solar Simulator "Helios 3198": the Fresnel lens is maintained fixed, whereas each SOE is mounted on one TJ solar cell, being both TJ solar cells of the same characteristics each other. I-V curve measurements are also obtained for normal alignment and different tilt angles of the HCPV unit respect to the incoming illumination. Then, normalized measured short-circuit current values can be compared to normalized simulated optical efficiency ones for each tilt angle in order to compare both simulated and experimental acceptance angle characteristics. Additionally, simulated short-circuit current density distributions generated on the TJ solar cell for 1º of tilt angle are analyzed to compare both HCPV units each other.

OPTICAL SIMULATIONS

Two HCPV unit designs are modeled and simulated through ray tracing using a typical optical software (TracePro) [4]. Both HCPV units use the same Fresnel lens as primary optical element (POE). One HCPV unit is equipped with a breaking-symmetry top Domed-Kaleidoscope SOE, whereas the other HCPV unit is equipped with a SILO SOE. The Fresnel lens is simulated as made of PMMA, with a square area of 100x100 mm^2 and a focal distance of 162 mm. Both SOEs are simulated as made of fused silica with light absorption neglected.

An optical modeling [5] is developed and includes wavelength-dependent optical material properties through refractive index and absorption coefficient, this last only for the POE [6]. The TJ solar cell is simulated as a square of 4 mm side and defined by the typical spectral response of a TJ solar cell composed by a "top", "mid" (middle) and a "bot" (bottom) subcells. Both HCPV units maintain a geometrical concentration of 625×. Concerning the SOEs, the D-K SOE has a breaking-symmetry top in order to enhance both the acceptance angle and the irradiance uniformity on the solar cell. The D-K SOE has a height of 21 mm, a total effective entrance cross-section of 12x12 mm^2 and a square exit surface of 4x4 mm^2. The SILO SOE has a total height of 9.9 mm. No antireflective coating is simulated. The light source used for the simulations is the standard spectrum ASTM G173-03 with the angular distribution of sunrays (±4.7 mrad of angular size).

Ray tracing simulations of both HCPV units are performed for normal alignment and for different tilt angles respect to the incoming rays in order to simulate the acceptance angle characteristic curve. FIGURE 2 shows ray tracing of both SOEs simulated in the HCPV units, D-K and SILO, under the concentrated rays for both normal alignment and 1º of tilt angle. Normalized current density distributions on the top subcell (limiting the total TJ solar cell current generation) for 1º of tilt angle of each HPCV unit respect to the incoming rays are shown in FIGURE 2 downside.


Tilt angle = 0º Tilt angle = 1º Tilt angle = 0º Tilt angle = 1º

Tilt angle = 1º Tilt angle = 1º

(a) (b)

FIGURE 2. Upper side: detail of ray tracing of concentrated rays on the SOE for both HCPV units, (a) Domed-Kaleidoscope and (b) SILO for normal alignment and for 1º of tilt angle. Bottom: normalized current density distribution on the top subcell for 1º of tilt angle for both HCPV units, (a) Domed-Kaleidoscope and (b) SILO

The normalized short-circuit current density, J_{sc}, distribution of the top subcell for 1º of tilt angle in the case of the HCPV unit with the D-K SOE is relative uniform and covers the whole surface of the TJ solar cell. This is an effect of the ray mixing due to the total internal reflection, TIR, on the walls of the D-K SOE, which is even enhanced by effect of the domed shape of the K-D top. However, in the case of the HCPV unit with the SILO SOE, the shift of the concentrated light spot on the SILO surface produces a dark region on the opposite side of the solar cell of around 20% of the total solar cell surface. Therefore, the D-K SOE presents a better behavior than the SILO one in terms of irradiance uniformity under misalignment of the HCPV unit.

Considering the photovoltaic performance, under normal alignment, the HCPV unit with the D-K SOE presents a greater optical polychromatic efficiency [7], η_{opt}=86.5%, compared to the 80.9% of the HCPV unit with the SILO SOE. About the performance under different tilt angles, the normalized η_{opt} of both HCPV units is plotted in FIGURE 4. The acceptance angle of the HCPV unit with the D-K SOE is 1.42º, whereas with the SILO SOE it is 0.71º. The HCPV unit with the D-K SOE presents a better acceptance angle characteristic than that with the SILO SOE.

EXPERIMENTAL SETUP

The indoor measurements are made using the CPV Solar Simulator "Helios 3198" [8, 9, 10]. The solar cells used with the D-K SOE is larger than those of 4x4 mm^2 side due to availability problems. However, a mask is applied to the TJ solar cell to mitigate the excess of solar cell surface. The mask has a square window of 4x4 mm^2 to match the simulated exit surface. In the case of the SILO SOE, a solar cell of 4x4 mm^2 is available and is used for the measurements. Both SOEs are glued to the TJ solar cell by using an optical adhesive contributing to the optical coupling between SOE and TJ solar cell.

An optical bench is mounted on the orientable support structure of the CPV Solar Simulator, so the orientation of the bench is controlled (FIGURE 3). A Fresnel lens and each ensemble of SOE plus TJ solar cell are mounted on the optical bench. So, each HCPV unit is built using the same Fresnel lens. Then both HCPV units are mounted and their I-V curves measured under controlled conditions for normal alignment and for different tilt angles.

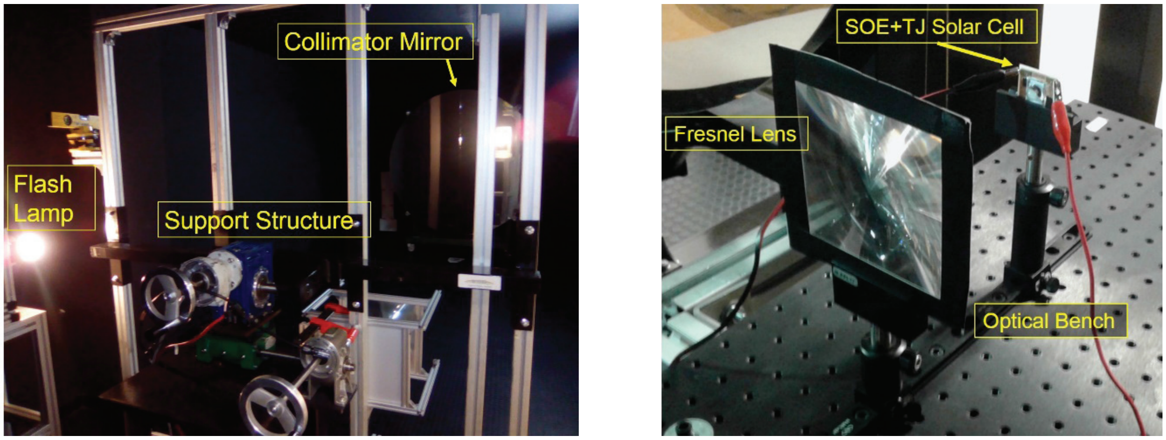


FIGURE 3. (Left) Picture of the CPV Solar Simulator "Helios 3198" measurement setup with the flash lamp, collimator mirror and support structure. (Right) Optical bench mounted on the solar simulator's support structure with the Fresnel lens and the SOE, which is glued on a TJ solar cell.

MEASUREMENT RESULTS AND DISCUSSION

I-V curve measurements of both HCPV units provide their short-circuit current, I_{sc}, values. Normalized I_{sc} values of both HCPV units (see FIGURE 4) are used to be compared to those of normalized η_{opt} from the optical simulations. The measured acceptance angle of the HCPV unit with the D-K SOE is 1.54º, whereas it is 1.01º for the case with the SILO SOE. As in the optical simulations, the HCPV unit with the D-K SOE presents a better acceptance angle characteristic than that with the SILO one. Comparing the measured acceptance angle characteristics with the optical simulated ones, these last underestimate the measurement results. The reason of this underestimation may be related to the ray tracing simulations and has to be investigated. TABLE 1 shows a summary of all the acceptance angle results.

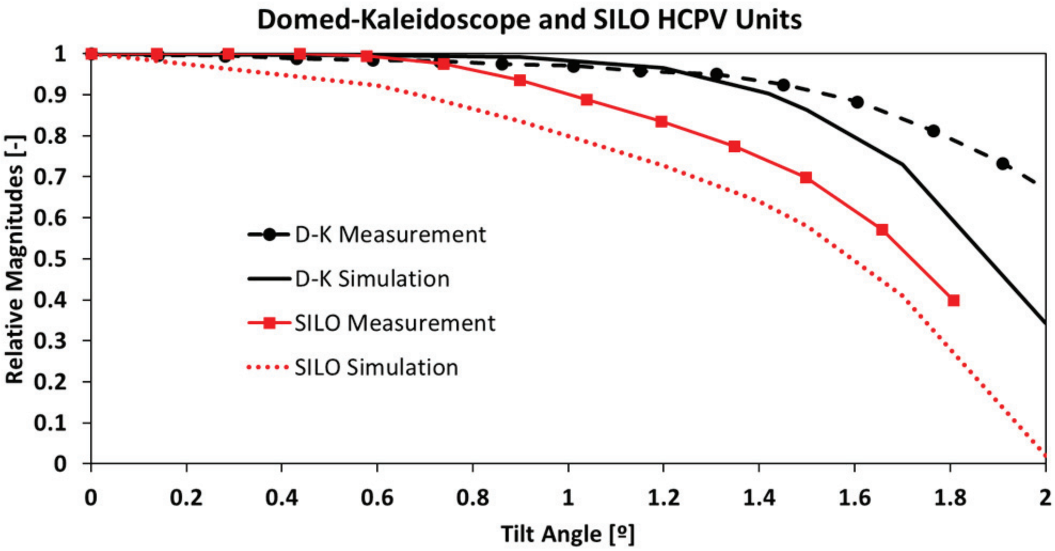


FIGURE 4. Optical simulation (normalized optical polychromatic efficiency) and experimental performance (normalized short-circuit current) results of both HCPV units.

TABLE 1. Summary of acceptance angle results of both HCPV units through both optical simulations and indoor measurements.

SOE	Optical Simulation	Indoor Measurement
Domed-Kaleidoscope	1.42º	1.54º
SILO	0.71º	1.01º

CONCLUSIONS AND FUTURE WORKS

Two point-focus Fresnel lens-based HCPV units equipped with a Domed-Kaleidoscope (D-K) secondary optical element (SOE) and with a SILO SOE are simulated through ray tracing and indoors characterized. A complete optical modeling is developed to conduct the optical simulations. This optical modeling includes the terrestrial standard solar spectrum and angular distribution, and also wavelength-dependent material properties of the optical elements involved. Moreover, the spectral response of a typical triple-junction (TJ) solar cell is utilized in order to calculate the optical polychromatic efficiency. Ray tracing simulations are conducted for normal alignment and for different tilt angles respect to the incoming light. Specifically, short-circuit current density distributions of the top subcell composing the TJ solar cell are obtained for both HCPV units for 1º of tilt angle, resulting in a better result for the D-K SOE due to the combined effect of the breaking-symmetry top with the total internal reflection on the SOE walls. In terms of the acceptance angle characteristic curve, also the HCPV unit with the D-K SOE presents a better result than that with the SILO one.

Indoor experimental measurements using a CPV Solar Simulator "Helios 3198" are conducted for both HCPV units. In concordance with the optical simulations, the D-K SOE provides better measurement results in terms of acceptance angle characteristic curve. However, an underestimation of the acceptance angle results by ray tracing simulations is observed and has to be investigated in future works.

Moreover, for future works, ray tracing simulations should include some other non-idealities like scattering on the surfaces or any possible light leakage [11] through the optical adhesive between SOE and solar cell.

ACKNOWLEDGMENTS

European Regional Development Fund (ERDF) and Spanish Economy Ministry (ENE2013-45242-R and ENE2016-78251-R); Universidad de Jaén (UJA) and Caja Rural de Jaén (UJA2015/07/01). Financial support provided by the Universidad de Jaén Doctoral School. The authors also thank Lambda Research Corporation for its donation of TracePro optical software.

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