ACHROMATIC LENS CASTING NEARLY UNIFORM IRRADIANCE OVER MJ SOLAR CELLS

Marta Victoria*, Guido Vallerotto, Stephen Askins, Ignacio Antón, Gabriel Sala
Instituto de Energía Solar, Universidad Politécnica de Madrid
*marta.victoria@ies.upm.es

ABSTRACT: The Achromatic Doublet on Glass (ADG) Fresnel lens is a novel concentrator that combines a low-dispersion elastomer and a high-dispersion plastic to obtain a Fresnel lens with reduced chromatic aberration, and consequently, increased concentration capability. This article summarizes the outcomes of the ray-tracing simulations as well as the experimental results obtained within the past two years. In addition, the uniformity of the irradiance profile cast by the lens onto Multi-Junction solar cells is analyzed and compared to that of a classic Silicone on Glass (SoG) Fresnel lens used as a benchmark. The more uniform profile cast by the achromatic lens requires lower horizontal current transportation across the MJ solar cell since the photocurrent distributions for the top and middle subcells are similar. It has been experimentally shown that, although the Fill Factor (FF) of the solar cell illuminated by the SoG Fresnel lens strongly depends on the lens-to-cell distance (showing a characteristic W-shaped curve), for the ADG Fresnel lens, the FF remains high at every position. This implies a higher tolerance not only to errors in the module assembly but also to variations in the temperature of the primary lens.
Keywords: Concentrators, Characterization, Multijunction Solar Cell

1 INTRODUCTION

CPVMatch is a Horizon 2020-funded project that aims to attain 40% efficient concentrating photovoltaic (CPV) modules using monolithic Multi-Junction (MJ) solar cells and improved concentrating optics [1]. Within this framework, the IES-UPM is developing a novel achromatic lens design and manufacturing method. The Achromatic Doublet on Glass (ADG) Fresnel lens benefits from the usual advantages of refractive concentrators (high efficiency, ease of parquet assembly and low cost) while simultaneously reducing their main drawbacks (limited attainable concentration due to chromatic aberration and high thermal sensitivity).

The ADG Fresnel lens is composed of glass, plastic and elastomeric materials. The lens design takes advantage of the different dispersion of the materials to reduce chromatic aberration at the wavelengths range converted by the MJ solar cells. First, a 'bi-Fresnel' lens is obtained by plastic injection, compression molding or hot-embossing. Then, it is laminated together with the elastomer over a glass substrate (Fig. 1). The manufacturing method, completely different to previous approaches [2], is based on standard industrial processes and it is one of the key innovations of the project. In summary, the proposed process enables, for the first time, an achromatic lens affordable for the CPV market.

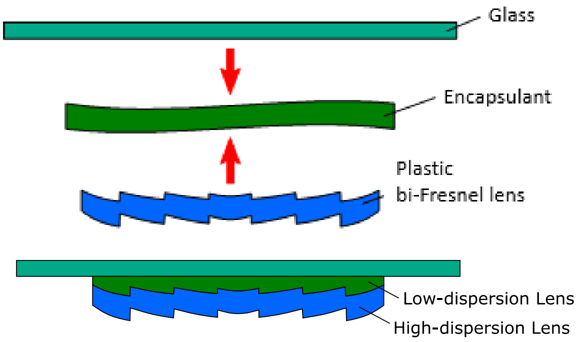

Figure 1: Conceptual drawing of the Achromat Doublet on Glass (ADG) Fresnel lens: (top) the components prior to the lamination process, (bottom) the laminated doublet.

The paper is organized as follows. The main simulation and experimental results obtained within the past two years are summarized in section 2. Then, section 3 focuses on the analysis of the irradiance profiles cast by the ADG and SoG Fresnel lenses and their impact on the performance of a MJ solar cell. Finally, the main conclusions are summarized in section 4.

2 SIMULATED AND EXPERIMENTAL RESULTS

The first step in the development of this novel concentrator comprised an extensive set of ray-tracing simulations to assess the performance of the ADG Fresnel lens that we have designed. The attainable concentration, acceptance angle, efficiency, irradiance profile cast by the lens, as well as the impact of real-world constraints (draft angles, tip rounding) and manufacturing error have been reported elsewhere [3]. In both cases, for the ray-tracing and for the experimental tests, a classic Silicone on Glass (SoG) Fresnel lens [4] with the same optical aperture (40 x 40 mm) and focal distance (approximately 75 mm) is used as a reference against which the results are evaluated.

The ray-tracing simulations showed that the reduced chromatic aberration increases the concentration-acceptance product (CAP) of the lens. Hence, either a higher concentration or a wider acceptance angle can be achieved. For example, operating at the same optical efficiently, the concentration attained by the ADG Fresnel lens is 722X while that achieved by the SoG is 267X [3].

The ray-tracing also showed that the best pair of materials was polycarbonate (PC) and ethylene-vinyl acetate (EVA) so they were chosen for the first prototypes. The rigid bifacial Fresnel lens was manufactured out of PC by Fresnel Optics GmbH according to our design. We used a custom laminator to encapsulate these lenses to small pieces of low-iron glass. After several weeks of fine-tuning the process, we were able of producing the elementary unit prototype shown in Fig. 1 which has very good transparency and it is air bubble free. Furthermore, we had also been able of obtaining arrays of lenses by one-single lamination (Fig. 2). We believe the ease with which we could proceed with lamination bodes well for the manufacturability prospects of this lens.

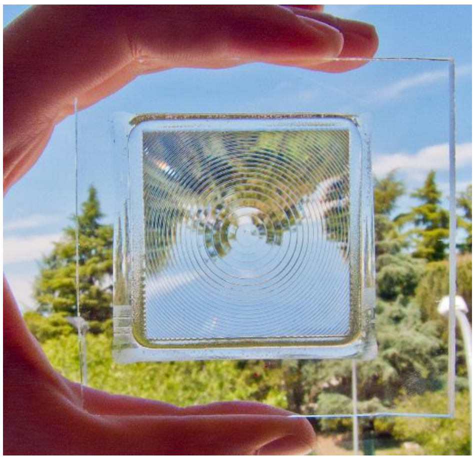

Figure 2: A PC-EVA ADG Fresnel lens prototype laminated at the IES-UPM.

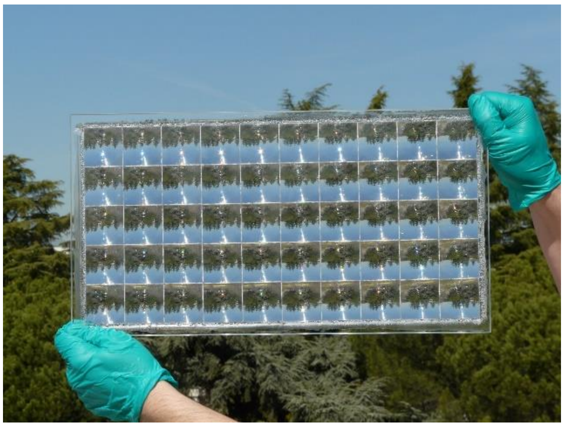

Figure 3: Photograph of the parquet composed of ADG Fresnel lenses. The PC bi-Fresnel lenses were first manufactured by plastic injection, and then, encapsulated to EVA and a glass substrate in a single lamination at the IES-UPM.

The achromatic behavior of the ADG Fresnel lens was experimentally proven by measuring the size of the spot cast by the lens using a charge-coupled device (CCD) camera. This is one of the techniques usually employed at IES-UPM to characterize CPV primary optics and a detailed description can be found in [5]. In summary, the lens is illuminated with a flash solar simulator for CPV modules [6] and high-pass or low-pass filters are added to the CCD camera. This allows to discriminate between the spots of light that can be converted into electricity by the different subcells within a MJ solar cell. By measuring the evolution of the 'blue' and 'red' spots as the lens-to-cell distance is varied, the achromatic behavior of the lens was proven [7]. The measurements were repeated at different lens temperatures proving that the thermal sensitivity of the ADG Fresnel lens is lower than that of the reference SoG Fresnel lens. We believe that two effects are the main responsible for the reduced thermal sensitivity. First, refractive index variation as a function of temperature is lower for the plastic and elastomeric materials comprising the ADG lens than for the silicone. Second, the difference in the coefficient of thermal expansion (CTE) of the materials comprising the lens is particularly adverse in the glass-silicone pair, causing the deformation of the silicone and the change in the optics profile [8]. Conversely, the materials comprising the ADG show a more similar CTE which implies a reduced deformation of the optically active surfaces. This is a significant result since SoG Fresnel lens are known to be highly impacted by changes in the temperature of the lens [8], [9] which can reduce the energy harvested by the CPV system throughout a year [10].

The tolerance of the ADG Fresnel lens to variation in the lens-to-cell distance has also been experimentally characterized using solar cells of different sizes [11]. Additionally, the spectrally-resolved optical efficiency of the ADG Fresnel lens has been measured by using a recently introduced experimental technique described in [12]. In this experiment, the efficiency at different narrow spectral bands is measured using a MJ solar cell as light sensor and a series of band-pass filters. Additional bias light is provided to saturate the subcells whose spectral response is out of the transmittance of every band-pass filter.

3 IRRADIANCE CAST ON MULTI-JUNTION SOLAR CELLS

The chromatic aberration suffered by a SoG Fresnel lens causes an irradiance profile over the MJ solar cell that is neither spatially nor spectrally uniform. This may worsen the performance of the solar cell due to an increased effective series resistance. If the distributions of photogenerated currents are very different for the top and middle subcells, the current needs to flow horizontally across the device which increases the effective series resistance and decrease the solar cell fill factor (FF) [13], [14]. For SoG Fresnel lenses, due to the high sensitivity of silicone refractive index with temperature, the irradiance profile significantly varies during the lens outdoor operation (see Fig. 4). On the top of that, the variation in the spectral content of the incident light as a function of the time of the year does not counterbalance this effect but exacerbates it. Thus, in winter, as the temperature decreases, the silicone refractive index increases, the lens becomes more converging and 'red' light (converted by the middle subcell) is focused on the MJ solar cell entrance. At the same time, since air mass (AM) values are higher during summer, the 'blue' light is absorbed and a red-shifted spectral distribution is found at the entrance of the optical system. The opposite situation is found in summer. High temperatures reduce silicone refractive index focusing 'blue' light on the cell. Simultaneously, lower AM values found in summer also increase the 'blue' content of the input spectrum [15].

One quick approach to analyze this effect consists in recording the IV curve of a MJ solar cell illuminated by a primary lens as the lens-to-cell distance is varied. For SoG Fresnel lenses, this measurement has been previously reported by several authors [16]–[18]. When plotted against the lens-to-cell distance, the FF of the solar cell, shows a characteristic W-shaped signature. This is known to be caused by the evolution of two combined effects: the spatial concentration and the mismatch among the subcell within the MJ device [18].

As a general rule, the extent to which non-uniformity reduces the FF of a solar cell depends on both, the characteristics of the non-uniform irradiance distribution produced by a certain optics and the ability of the solar cell to smooth the uneven profile. This capability depends on the cell size and its technological characteristics (which determines the effective series resistance for the horizontal current transportation).

In our case, the outdoor measurements of the IV curve of a lattice-matched Ge-based MJ solar cell illuminated by the reference SoG Fresnel lens unveil the typical W-shaped evolution of the FF (see Fig. 6). However, when the cell is illuminated by the ADG Fresnel lens and the lens-to-cell distance is modified, the FF remains almost constant for every position. This results can be predicted by observing the evolution of the photocurrent distributions for the top and middle subcells of a Lattice Matched Germanium-based (LM-Ge) obtained from ray-tracing (Fig. 5). Details for the ray-tracing simulations are included in [3]. In the first place, the photocurrent distributions for top and middle subcells are more similar, reducing the horizontal current flow. In the second place, the ADG Fresnel lens is less sensitive to temperature changes (which are to some extent, equivalent to variations in the lens-to-cell distance).

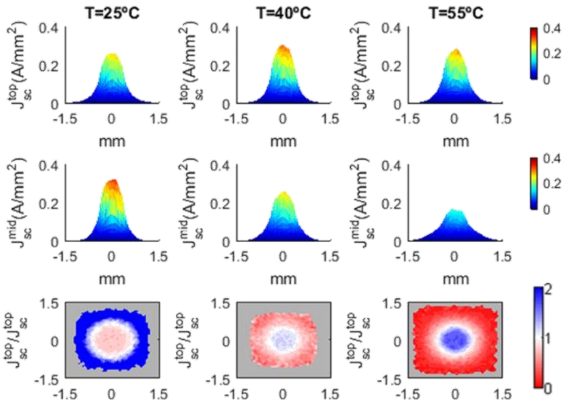

Figure 4: Results for the SoG Fresnel lens used as a benchmark. Spatial distribution of the photogenerated current for the top (first row) and middle (second row) subcells of a LM-Ge MJ solar cell at different temperatures predicted by ray-trace simulations. Contour plots (third row) show the ratio between top and middle photocurrents. Blue areas represent cell regions where there is an excess of top photogenerated current (middle limited) while red areas represent an excess of middle photogenerated current (top limited). Regions where both subcell photocurrents are matched are shown in white. Gray areas represent regions where both photocurrent values are below 0.1% of the maximum, that is, dark areas.

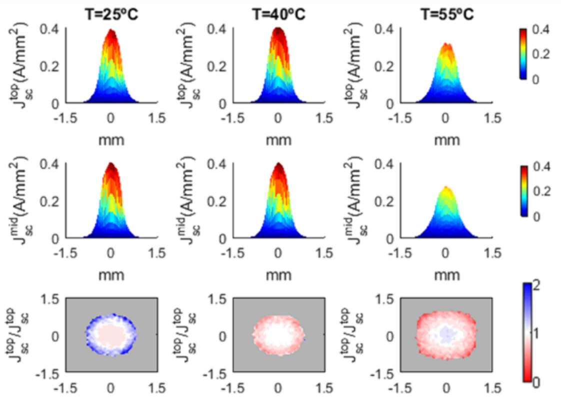

Figure 5: Results for the ADG Fresnel lens. Spatial distribution of the photogenerated current for the top (first row) and middle (second row) subcells of a LM-Ge MJ solar cell at different temperatures predicted by ray-trace simulations. Contour plots (third row) show the ratio between top and middle photocurrents. Blue areas represent cell regions where there is an excess of top photogenerated current (middle limited) while red areas represent an excess of middle photogenerated current (top limited). Regions where both subcell photocurrents are matched are shown in white. Gray areas represent regions where both photocurrent values are below 0.1% of the maximum, that is, dark areas.

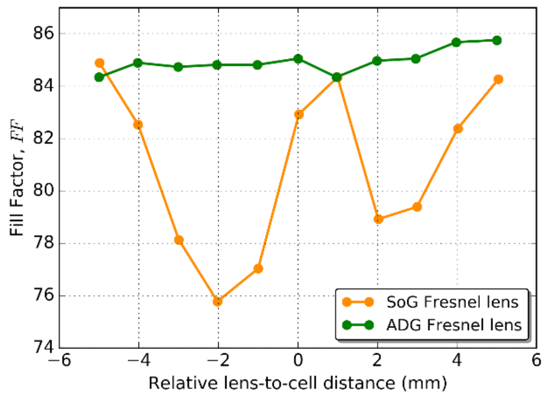

Figure 6: Fill factor *FF*, of the solar cell illuminated by the ADG Fresnel lens as a function of the relative lens-to-cell distance. The measurement was performed outdoors at Fraunhofer-ISE. For comparison, a SoG Fresnel lens with the same optical aperture and focal distance was also characterized.

4 CONCLUSIONS

The Achromatic Doublet on Glass (ADG) Fresnel lens is the first achromatic lens affordable for Concentrating Photovoltaics (CPV) thanks to the proposed manufacturing method in which a low-dispersion elastomer and a high-dispersion plastic are combined in a low-cost lamination process. Reducing the chromatic aberration allows increasing the concentration-acceptance angle product (CAP) of the ADG Fresnel lens when compared to the values attained by a classic Silicone on Glass (SoG) Fresnel lens. Elementary unit and parquet of lenses prototypes have been manufactured showing good transparency and no bubbles. The achromatic behavior of the ADG has been experimentally demonstrated in previous works.

This paper focuses on the analysis of the irradiance distribution cast by the ADG Fresnel lens onto a MJ solar cell and its effect on the cell performance. The ADG Fresnel lens produces similar photocurrent distributions for the top and middle subcells, and consequently, reduces the effective series resistance, and increases the Fill Factor (FF) of the MJ solar cell. The FF has been experimentally measured as a function of the lens-to-cell distance. While the FF corresponding to the SoG Fresnel lens used a benchmark shows a characteristic W shape, the FF for the ADG Fresnel remains constantly high for different positions proving the advantages of a more uniform illumination. Moreover, the sensitivity to changes in temperatures is lower for the ADG Fresnel lens.

5 ACKNOWLEDGEMENTS

This work has been partially supported by the Spanish

Ministry of Economy and Competitiveness under the Acromalens project (ENE2013-45229-P) and it has received funding from the European Union's Horizon 2020 research and innovation program within the project CPVMatch under grant agreement No 640873. The authors thank Maike Weisenfarth at Fraunhofer-IES for the outdoor measurements of the ADG Fresnel lens.

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