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Design and modeling of a cost-effective achromatic Fresnel lens for concentrating photovoltaics

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Abstract: This paper presents a novel Fresnel lens capable of significantly reducing chromatic aberration in solar applications. The optical performance of this achromatic lens has been analyzed through ray-tracing simulations, showing a concentration factor three times higher than that attained by a classic silicone on glass (SOG) Fresnel lens while maintaining the same acceptance angle. This should avoid the need for a secondary optical element, reducing the cost associated with its manufacturing and assembly and increasing the module reliability. The achromatic lens is made of inexpensive plastic and elastomer which allows a highly scalable and cost-competitive manufacturing process similar to the one currently used for the fabrication of SOG Fresnel lenses.

OCIS codes: (350.6050) Solar energy; (220.1770) Concentrators; (220.1000) Aberration compensation.

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1. Introduction

High-concentration photovoltaic (HCPV) systems have the capacity to reduce the cost of solar-based electricity because they can take advantage of the rapid increment in the efficiency of advanced multijunction (MJ) solar cells. Every subcell within a MJ solar cell is made of a different semiconductor compound, has a different bandgap and consequently converts into electricity a distinct part of the solar spectrum making MJ solar cell the most efficient among the existing photovoltaic devices. Currently, MJ solar cells reach efficiencies higher than 46% under concentrated light doubling that of conventional silicon solar cells [1]. Since the cost of MJ devices is high, optical systems are used to concentrate the irradiance on them, reducing its impact on the final system cost.

Currently, most of the commercially available HCPV systems are based on Silicone On Glass (SOG) hybrid Fresnel lenses [2]. The injection-molded SOG process features a rigid glass substrate to which a Fresnel lens structure composed of optical silicone rubber is directly molded. A mold is pressed against the glass, the uncured silicone is injected and the silicone is allowed to cure at elevated temperatures. This process has proven to be cost effective and highly scalable, allowing the production of large parquets of lenses. The maximum concentration attainable by a Fresnel lens is considerably lower than that of an ideal system, i.e., one that conserves light étendue. The most significant factors that limit the attainable concentration are the sun angular size (γ_{sun}), the chromatic aberration, and, if the facets have been designed to be flat, their width [3]. In classic SOG Fresnel lenses, the chromatic aberration is the main effect that enlarges the size of the irradiance spot Imposing the collection of every ray, considering the silicone dispersion across the bandwidth converted by MJ solar cells and assuming a maximum groove width of 0.4 mm (if 40 mm lens diameter), the maximum concentration is limited to 226X for the real sun angular size, $\gamma_{sun} = \pm 0.265°$. If an extended light source with $\gamma_{sun} = \pm 1°$ is considered to account for some tolerance when tracking the sun, the achievable concentration decreases to 63X.

Fresnel lenses are typically coupled with secondary optical elements (SOE) [4] in order to achieve one or several of the following objectives: to increase geometrical concentration for reducing the influence of the solar cell on the system cost, to widen the acceptance angle increasing tolerance to errors in module assembly and tracking and to reduce optical losses introduced by the thermal sensitivity of systems including SOG Fresnel lenses [5].

This paper introduces a new concept for manufacturing a Fresnel lens for solar applications composed of two materials coupled in such a way that the chromatic aberration is minimized. The novel achromatic lens architecture, named Achromatic Doublet on Glass (ADG), is able to increase the maximum theoretical concentration value with respect to the equivalent SOG Fresnel lens. Since the manufacturing process envisaged to obtain the ADG is very similar to the one employed to fabricate SOG lenses the increase in concentration will be obtained without increasing significantly the cost. Section 2 of this article includes an overview of the ADG Fresnel lens concept and its manufacturing process. In section 3, the design method is explained. Section 4 gathers all the results obtained with ray-tracing simulation based on Monte Carlo method including the attainable concentration, acceptance angle, optical efficiency and photogenerated current distribution for the bandwidth corresponding to every subcell within the triple junction (3J) solar cell, and tolerances to manufacturing errors. Finally, section 5 summarizes the main conclusions.

2. A cost-effective laminated achromatic Fresnel lens architecture

The design of achromatic lenses using two materials with distinct dispersion is well-known since the 18th century. The classic achromatic doublet is composed of a crown glass whose dispersion is low and a flint glass with high dispersion. However, the cost of this architecture makes it unaffordable for HCPV systems. Languy and associates [6] proposed an achromatic doublet for CPV composed of two plastics: poly(methyl methacrylate) (PMMA) and polycarbonate (PC). They did a comparative analysis on the different configurations and their advantages but they did not describe a manufacturing process that can be scalable at high production level at low cost. In this article we propose for the first time a low-cost achromatic lens that can be manufactured using lamination processes. As shown in Fig. 1 the proposed architecture includes an elastomer with low dispersion, a rigid plastic with high dispersion, and a rigid substrate (glass or plastic). The plastic piece operates as a mold, shaping the geometry of the elastomeric lens; the elastomer, in turn, acts as a glue coupling the plastic lens and the rigid substrate. Other simpler structures avoiding the thin glass are also being studied.

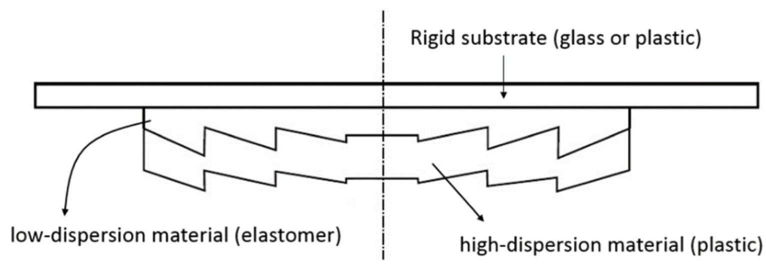

Fig. 1. Schematic representation of the materials comprising the ADG Fresnel lens.

The ADG Fresnel lens manufacturing process is basically divided into two steps. In the first one, a lens whose geometry includes Fresnel facets in both surfaces is fabricated by standard plastic injection molding, compression molding or hot embossing processes, each one of them is inexpensive, reliable and commonly used in high volume industry. In the second step, the materials sandwich (glass/elastomer/plastic) is laminated to obtain the final ADG. During the lamination, the elastomer reaches the liquid condition and fills the volume between the plastic lens and the rigid substrate, which act as mold and counter mold, respectively. Then the elastomer is allowed to solidify to its final shape, thus creating a stable sandwich. Depending on the chosen elastomer, its transition from liquid to solid state happens as a consequence to a heating process, a pressure process, or a combination of both.

A comprehensive research was carried out to identify suitable material candidates. The requirements used to evaluate those materials are based on their optical and physical properties. Candidates, both plastic and elastomer, must show high transmittance across the bandwidth of wavelengths that are converted into electricity by MJ solar cells, i.e., 350-1700 nm typically. Then, plastic candidates need to show high dispersion whereas low-dispersion elastomers are preferred. Regarding physical properties, they need to allow compatibility between the elastomer and the plastic during the previously described manufacturing process. Basically, the temperature at which the elastomer solidifies (or cures if it is a thermosetting) has to be lower than the maximum operating temperature of the plastic. In addition, we also paid attention to the coefficient of thermal expansion (CTE) of the materials. Large differences may cause thermal stresses that could damage the lens once laminated. Currently, the selected materials are PMMA and PC as rigid thermoplastics and ethylene-vinyl acetate (EVA) and silicone (polydimethylsiloxane) as elastomers.

3. Design of the achromatic Fresnel lens

The classic design of an achromatic doublet is based on coupling two lenses: a converging one with high-dispersion index (focal distance F_1) and a diverging one with low-dispersion index (F_2). The focal distance of the doublet ($F_{doublet}$) is determined by Eq. (1).

$$\frac{1}{F_{doublet}} = \frac{1}{F_1} + \frac{1}{F_2} \tag{1}$$

Then, the “achromaticity condition” is imposed, that is, the focal distance of the doublet is set the same for two representative wavelengths. In the classic doublet, two wavelengths at the edges of the visible spectrum are selected to reduce chromatic aberration in the visible region. The Abbe number υ_d used to quantify dispersion in the visible region is defined as

$$\upsilon_d = \frac{n_d - 1}{n_F - n_C} \tag{2}$$

where d, F, and C stand for the Fraunhofer lines at the visible region, that is, 587.6, 486.1 and 656.3 nm respectively. However, in this case it seems better to select two wavelengths at the edges of the bandwidth converted by MJ solar cell: a ‘blue’ or shorter wavelength λ_b (e.g., 350 nm) and a ‘red’ or longer wavelength λ_r (e.g., 1800 nm). For every material under study the solar Abbe number υ_{solar} is defined using the refractive index for those values n_b and n_r, and for an intermediate wavelength (λ_m) [6].

$$\upsilon_{solar} = \frac{n_m - 1}{n_b - n_r} \tag{3}$$

The achromaticity condition leads to the following relation

$$\frac{F_1}{F_2} = -\frac{\upsilon_2}{\upsilon_1} \tag{4}$$

where the focal distances of the converging and diverging lenses are related to the solar Abbe numbers of the material composing the lenses, υ_1 and υ_2. The designing process is described in detail elsewhere [7]. Figure 2 shows the focal distance variation as a function of wavelength for a classic SOG Fresnel lens and the ADG Fresnel lens made of PC and EVA, whose difference in Abbe number are suitable for achieving achromaticity.

Since Fresnel lenses do not require the optical surface to be continuous, every groove can be independently designed. It is important to remark that the lenses analyzed in this work, both achromatic and classic, were designed with flat facets in order to ease the manufacturing. Hence, the ray passing through the middle of the groove determines the facet slope. For every groove, the slopes of both interfaces (elastomer-plastic and plastic-air) are determined by imposing the condition that rays with ‘blue’ and ‘red’ wavelengths λ_b and λ_r, reach the same focal point.

The next section includes a comparative analysis of an ADG Fresnel lens design and the equivalent classic SOG Fresnel lens. Both designs have a square optical aperture of 40 x 40 mm and a nominal focal distance of 75 mm, that is, their f-number or focal ratio is 1.33 (calculated using the diagonal between two lens corners as clear aperture).

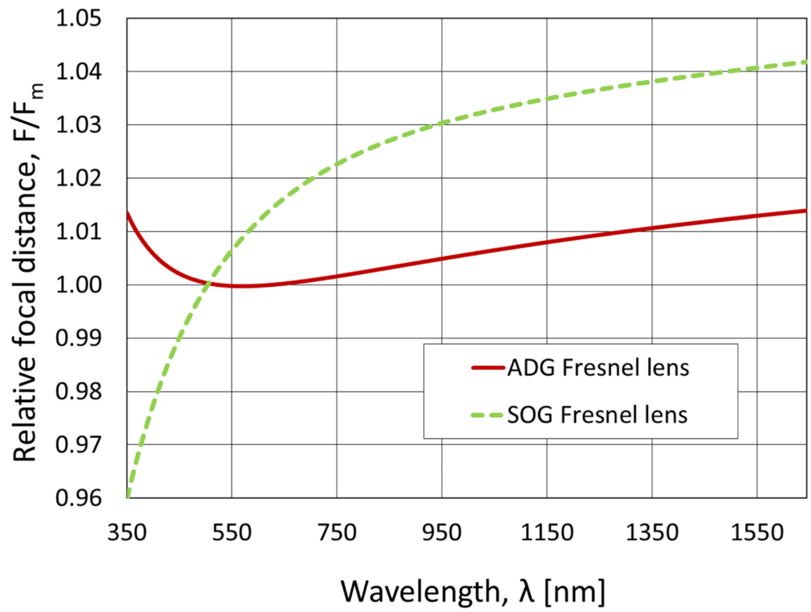

Fig. 2. Relative focal distance (focal distance normalized by the nominal value) as a function of wavelength for both the EVA/PC Achromatic Doublet on Glass (ADG) (solid line) and a classic Silicone On Glass (SOG) (dashed line). The nominal focal distance F_m correspond to the intermediate wavelength λ_m that is about 550 nm.

On top of design requirements, manufacturing imposes additional constrains that are also included in the simulations. The manufacturing of the rigid lens by plastic injection limits the grove width and height to 1.5 mm and 0.5 mm respectively. Draft angles varies from 2° for central groves to 5° for most exterior ones. The tip rounding is assumed to be 5 µm. Although the manufacturing process is slightly different, the same parameters are considered for the SOG Fresnel lens used as benchmark. The only exception is in the case of the tip rounding. Since the silicone is expected to attain sharper tips a more realistic value of 3 µm has been assumed for the SOG Fresnel lens.

4. Comparative analysis based on ray-tracing simulations

A comprehensive set of ray-tracing simulations was performed in order to predict and analyze the performance of the ADG Fresnel lens previously described. The subsections hereafter reproduce the main results including optical efficiency, profile of the irradiance spot, acceptance angle and photocurrent distribution on every subcell within the MJ solar cell. The following assumptions are made in every simulation:

- the real sun angular size (± 0.27°) and the reference spectrum AM1.5D for Direct Normal Irradiance (DNI) is assumed [8]
- the receiver at the focal plane is considered to be ideal, i.e., it absorbs every ray impinging its surface
- for every material involved (glass, silicone, PC and EVA), spectrally-resolved values for transmittance and refractive index are used. Data has been provided by the manufacturer or found in the literature [6,9,10]
- Ideal surfaces with no losses due to surface roughness (scattering), waviness or shape errors are assumed

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- The number of elements comprising the receiver's mesh and the number of traced rays are selected as a trade-off that takes into consideration accuracy, resolution and computational time. Then, for every simulation two million rays are used and the receiver's mesh is composed of 40 x 40 nodes, leading to an estimated error below 2% in every bin.

4.1. Lens optical efficiency

The optical efficiency is defined as the fraction of radiant power at its input aperture P_{in} which reaches a designated receiver area P_{out} [11,12].

$$\eta_{op} = \frac{P_{out}}{P_{in}} \tag{5}$$

For the results included in this subsection the size of the receiver is large enough to capture every ray refracted by the useful region of the facets. In this way the computed efficiency takes into account only those phenomena which lower the throughput of radiant power through the lens: absorption in the materials, reflections at any of the lens faces, geometrical losses caused by draft angles and round tips, etc.

Table 1 summarizes the results for the SOG Fresnel lens and the glass-EVA-PC ADG Fresnel lens. For every lens the first line shows the efficiency when only geometrical losses related to draft angles and round tips are considered, that is, materials are assumed to be ideal and neither absorption nor Fresnel reflection in any surface are taken into account. Since the ADG includes two Fresnel surfaces with larger tip rounding, the geometrical losses associated to rounding at valleys and corners cause a lower optical efficiency. It should be remarked here that the value assumed for round tips was that estimated by the manufacturer but if sharper tips are obtained in the fabrication the optical efficiency values predicted for both lenses would be closer. For every lens, the second line in Table 1 reproduces the optical efficiency estimated for a more realistic situation, that is, including not only geometrical losses but also materials absorption and Fresnel reflection. When compared to 'ideal materials' the realistic values of efficiency are degraded in a similar way for both lenses. Put simply, what is causing a lower efficiency for the ADG is mainly geometrical differences.

Table 1. Optical efficiency predicted by ray-tracing for the ADG Fresnel lens composed of glass, EVA, and PC and the equivalent SOG Fresnel lens used as benchmark.

Simulations	*Optical efficiency*	
	SOG	ADG
Ideal materials (only draft angles and round tips: 3 μm for SOG, 5 μm for ADG)	97.6%	93.5%
Realistic simulation (materials absorption, Fresnel reflection added)	88.5%	83.0%

4.2. Attainable concentration

In order to make a fair comparison regarding the concentration attainable by both lenses it is convenient to plot the efficiency of the lens as a function of the size of the receiver considered, in other words, as a function of the geometric concentration at which the lens will be operated (Fig. 3). A circular receiver area is considered. Both curves intersect at a value of 1.38 mm for the irradiance spot which corresponds to a geometrical concentration of 267X. Then, maintaining the same optical efficiency, the ADG design allows reducing the size of the irradiance spot to 0.84 mm radius for a geometric concentration of 722X.

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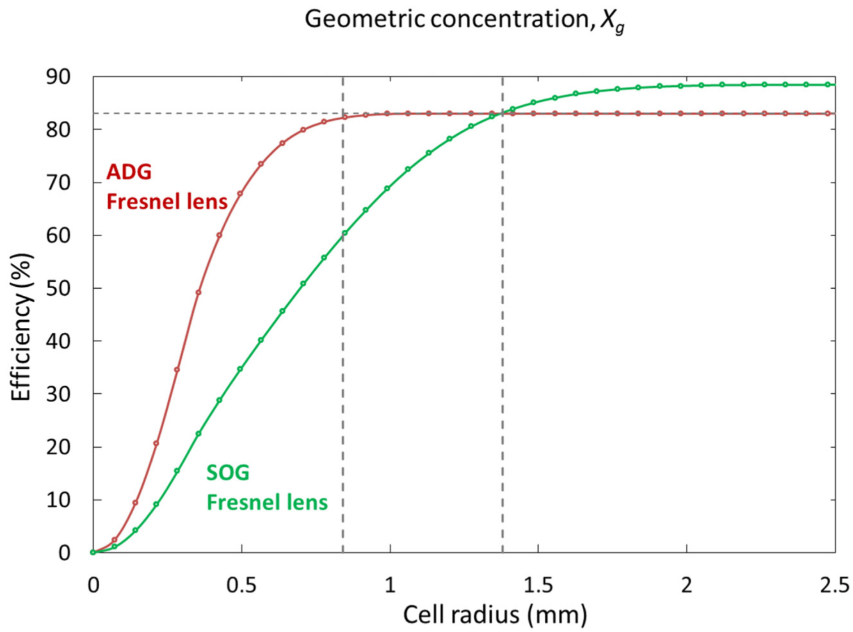

Fig. 3. Optical efficiency of the lens vs. radius of the receiver for the EVA-PC ADG Fresnel lens design and the SOG Fresnel lens, both with a 75 mm focal distance and entrance aperture of 40x40 mm^2. Top x-axis indicates the geometric concentration X_{geo} corresponding to the radius of the receiver selected (bottom x-axis).

4.3. Concentration – acceptance angle product (CAP)

The most adequate figure of merit for CPV is the concentration-acceptance angle product (CAP). The CAP indicates the similarity of a certain concentrating optics to an ideal system that conserves light étendue. CAP is calculated according to Eq. (6):

$$CAP = \sqrt{X_g} \cdot \sin\theta \tag{6}$$

where X_g is the geometric concentration and θ is the acceptance angle. The geometric concentration X_g is defined as the ratio of the input area A_{in} to the output area, that is, the receiver area, A_{out}.

$$X_g = \frac{A_{in}}{A_{out}} \tag{7}$$

The acceptance angle θ is defined as the deviation angle such that the optical efficiency is 90% of its maximum. Put simply, the higher the CAP the better the optical performance.

Figure 4 depicts the different combinations of X_g and θ achievable by the ADG Fresnel lens and the SOG Fresnel lens. Since the ADG CAP is higher, one can choose either to increase the concentration maintaining the same acceptance angle or to keep the same concentration and use the ADG to widen the acceptance angle, thus increasing the tolerance to assembly positioning, tracking errors and lens temperature variations.

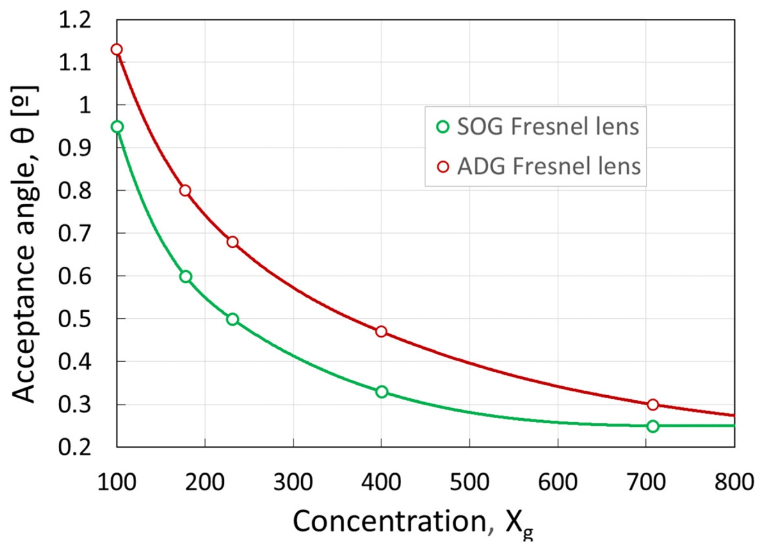

Fig. 4. Acceptance angle θ vs geometrical concentration Xg predicted by ray-tracing simulation for the ADG Fresnel lens and the equivalent classic SOG Fresnel lens. Acceptance angle is defined as the deviation angle such that the optical efficiency is 90% of the maximum.

4.4. Photocurrent distribution produced by the ADG Fresnel lens and the equivalent SOG Fresnel lens

In this subsection the distribution of photogenerated current for the different subcells and the impact of lens temperature on them is analyzed. To estimate photocurrent instead of light power, the emitting source of the ray-tracing simulations is modified. Instead of using the reference spectrum $B(\lambda)$ for the emitting source, it is multiplied by the MJ solar cells spectral response $SR_{i\text{-}subcell}(\lambda)$ to obtain a wavelength-dependent electrical response $S_{i\text{-}subcell}(\lambda)$.

$$S_{i-subcell}(\lambda) = B(\lambda) SR_{i-subcell}(\lambda) \tag{8}$$

$S(\lambda)$ weights every wavelength by its capacity to generate an electron-hole pair in the solar cell, avoiding the usual overestimation of 'blue' light which, due to the shorter wavelengths, has lower conversion efficiency. Therefore, instead of predicting irradiance distribution over the cell, the simulation output represents the photogenerated-current distribution for every subcell, making it possible to determine which subcell produces the least current at any part of the cell. The sensitivity to lens temperature has been investigated by taking into account the dependence of refractive index on temperature for the different materials involved. Simulations were run at 25 °C, 40 °C and 55 °C lens temperatures, representative of cold, warm and hot environmental conditions.

Non-uniformities, where the spectral content of the flux varies across the cell, are inherent to refractive CPV systems because of the optical transfer function and chromatic aberration in the optics. When the photogenerated current distribution are such that there are different regions over the cell either limited by the top or the middle subcell, the limiting subcell will be determined by the resistance of the layers connecting the subcells [13,14]. As it can be observed in Fig. 5, the ADG Fresnel lens does not only cast a smaller irradiance spot but it provides two significant benefits compared to classic SOG Fresnel lens. First of all, the photogenerated current distribution for top and middle subcells are much more similar reducing the losses associated to lateral current flows. Second of all, the irradiance distribution is less sensitive to the temperature of the primary lens. This thermal sensitivity is one of the main drawbacks of SOG Fresnel lens [5,15,16] and reducing its impact on the irradiance distribution over the cell is expected to increase the energy harvested throughout the year [17]. The refractive index variation with temperature for the involved materials can be found in references [18,19]. The significant deformations experienced by the SOG lens [5,15,16] have not been taken into account, though, which might further worsen its temperature sensitivity.

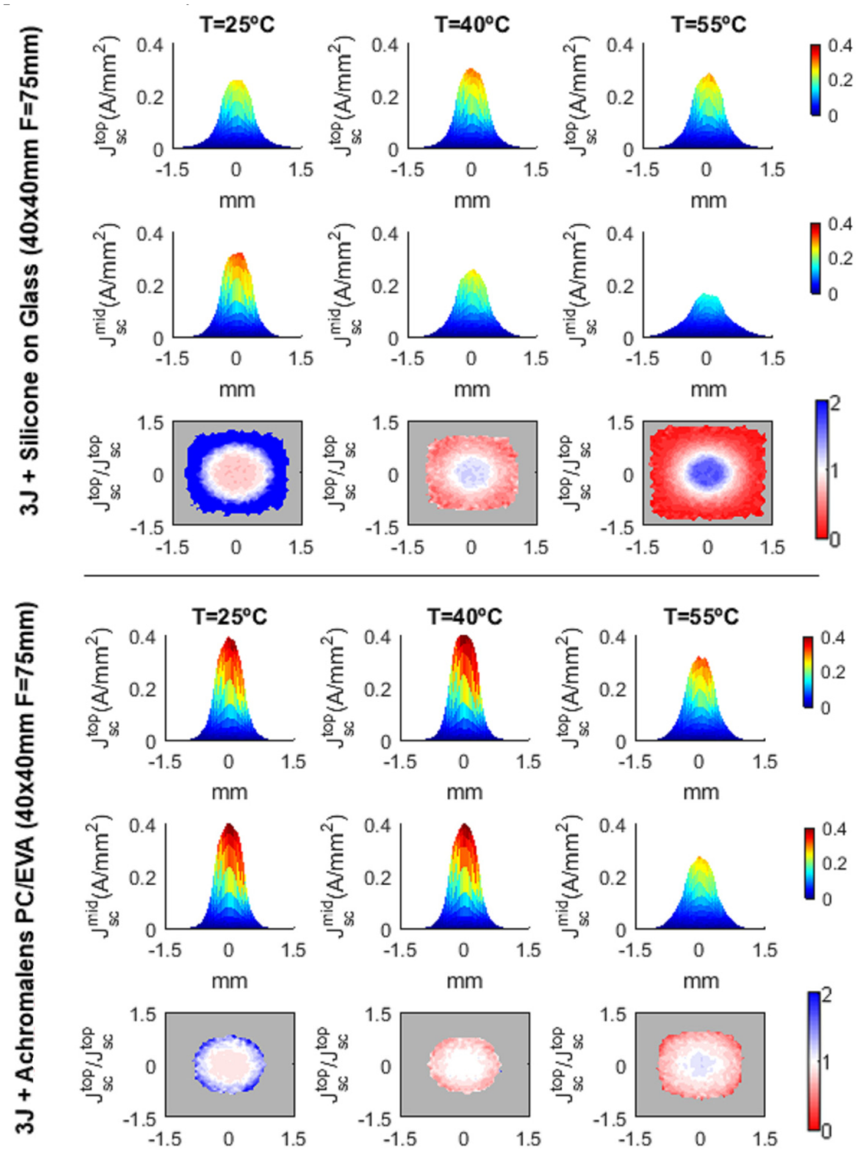

Fig. 5. Spatial distribution of the photogenerated current for the top J_{sc}^{top} (upper half graphs) and middle J_{sc}^{mid} (lower half) subcells at different temperatures predicted by ray-tracing simulations. Contour plots (third line) show the ratio between top and middle photocurrents $J_{sc}^{top} / J_{sc}^{mid}$. 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.

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It should be remarked here that, for the sake of clarity, the irradiance distribution over the bottom subcell was obviated in the previous discussion. Two facts justify this decision. Firstly, for the majority of optical materials, dispersion is far more significant at shorter wavelengths than at longer ones, hence the bottom subcell irradiance profile is expected to be very similar to that of the middle subcell. Secondly, in classic Germanium-based triple junction solar cells the bottom subcell generates an excess of current and consequently the current flowing throughout the device is limited by any of the other subcells.

4.5. Geometrical and manufacturing tolerances

Ray-tracing simulations have been used to analyze the effects of manufacturing errors, such as draft angles and tip rounding values, on the system performance. Figure 6 depicts the impact of draft angle and tip rounding on the optical efficiency of the EVA-PC ADG Fresnel lens. For every dot in the plot, the ADG with the corresponding geometrical parameters was generated and a 2 million rays simulation was conducted. Based on the previous experience of the plastic injector, the most probable values for average draft angle and tip rounding are 3.5° and 5µm respectively (indicated in Fig. 6 with a black circle). The first result that can be observed is that, since the ADG includes two Fresnel surfaces, if wider draft angles were necessary the losses caused by optically inactive surfaces will decrease the optical efficiency to unbearable values. The second result is related to tip rounding at valleys and corners. Currently, a conservative value (5µm tip) has been assumed for this figure. Sharpness of injected PC is expected to be worse than that attained by silicone in SOG Fresnel lenses (3µm tip). Nevertheless, according to Fig. 6, if the optimization of the injection process allows a better tip rounding value than initially expected an increase in the optical efficiency of 1-2% may be obtained.

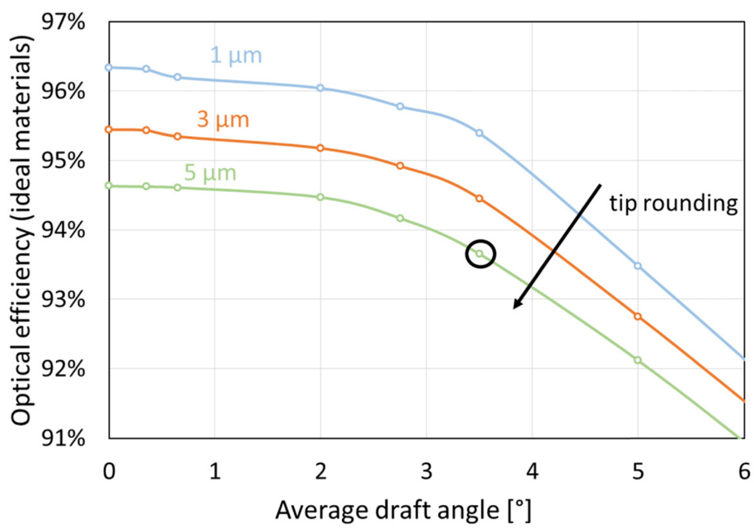

Fig. 6. Optical efficiency of the EVA-PC ADG Fresnel lens as a function of the average draft angle and tip rounding values. Simulations include neither materials absorption nor Fresnel reflection losses. An 'average draft angle' is used since the draft angle varies along the lens profile in order to ease the manufacturing of the plastic injected piece. The black circle marks the simulation assuming the most probable geometry according to the manufacturer. Consequently, those values are included in the simulation in Table 1.

Concentricity of the two optical inserts including the Fresnel pattern (both sides of the plastic piece) has been identified as one of the most critical requirement to ensure the correct performance of the lens. Figure 7 shows the efficiency drop as a consequence of errors in concentricity when the ADG Fresnel lens is operated at different concentration ratios. For

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higher concentration values (>700X) concentricity tolerance should be below 100 µm to avoid a significant efficiency reduction.

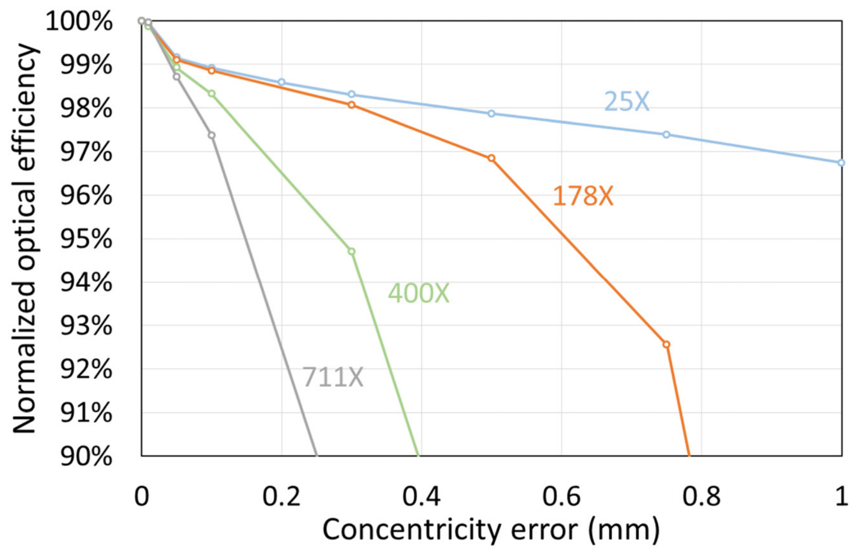

Fig. 7. Normalized efficiency vs. manufacturing error affecting concentricity of the two Fresnel faces of the plastic piece when the ADG is used at different concentration ratios. The efficiency values have been normalized using the value attained when perfect concentricity is assumed.

Conversely, tolerance in the total thickness of the plastic piece (from peaks on the first surface to valleys on the second) does not seem to be that critical. Ray-tracing simulations predict that the optical efficiency value is kept constant for variations of ± 250 µm around the nominal value of 2 mm.

5. Conclusions

A novel achromatic lens concept for application as the primary optics in a Concentrated Photovoltaic (CPV) system has been presented. The ADG comprises a bifacial Fresnel lens manufactured by plastic injection and an elastomer filling the space between the plastic and a rigid glass substrate. The procedure described in this work allows a highly scalable and cost-competitive manufacturing process. The candidate materials to fabricate the lens are poly(methyl methacrylate) (PMMA) or polycarbonate (PC) as plastic together with silicone or ethylene-vinyl acetate (EVA) as elastomers. Due to their distinct dispersion, the pair showing the best performance among the materials explored is EVA with PC.

An extensive set of simulations was carried out to predict the optical performance of the Achromatic Doublet on Glass (ADG) in comparison to the current state of the art, that is, an equivalent Silicone On Glass (SOG) Fresnel lens. Considering two lenses with the same optical aperture, 40x40 mm, focal distance of 75 mm and operating at the same efficiency, the ray-tracing predicts that the concentration attained by the EVA-PC ADG is 722X while that achieved by the SOG is 267X. The reduction of the irradiance spot size due to a reduced chromatic aberration can be used to either increase the concentration ratio or to improve acceptance angle and hence tolerance to assembly or tracking error. One of the main advantages of the ADG concept presented here is that it allows high concentration thereby eliminating the need for a Secondary Optical Element (SOE). This avoids the cost associated with the fabrication of the SOE and its assembly over the solar cell and improves the reliability of the module. Furthermore, ray tracing also predicted a reduced thermal sensitivity of the ADG Fresnel lens when compared to classic SOG Fresnel lenses, as well as

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better spectral uniformity throughout the solar cell, which would reduce series resistance losses. Future investigations will include the fabrication of ADG prototypes and their optical characterization to analyze experimentally their spectral transmittance and concentrating capability.

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