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# 12% Power Boost of 940 Suns HCPV Module by Incorporating Anti-Reflection Coated Secondary Optical Element

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**Abstract.** The efficiency of a secondary optical element (SOE) is often questioned when a real high concentrating photovoltaic (HCPV) module is considered. Three years ago Opsun Technologies Inc. introduced a new type of SOE, which increased significantly the acceptance angle of the HCPV module close to the limits predicted theoretically (1). Indeed, introducing a SOE into a HCPV module enables the increase of its acceptance angle. Furthermore, the SOE homogenizes the concentrated sun light beam's profile, which leads to an improvement of the fill factor. However, the opposite input side of the SOE introduces an additional surface, causing optical losses due to Fresnel reflections. This issue added to the cost of the SOE, discards its benefic properties. Thus, eliminating or minimizing Fresnel reflection could transform the SOE into a powerful tool to boost significantly the efficiency of the HCPV module. Silicon dioxide ($SiO_2$) nanoparticles, obtained by sol-gel technique, were used to create an antireflective coating (ARC) for the use in a high concentrating photovoltaic (HCPV) device. These ARCs have shown a transmission increase from 92% up to 99% when deposited on glass substrates. The introduction of these same ARCs, with different optical paths, in the HCPV system has shown an overall power increase with strong dependence of the HCPV module performance (based on triple junction solar cells) upon the different ARC transmission spectra. In the present work we demonstrate a combination leading to almost 12% power increase in the HCPV. Indeed, a drastic peak power increase is observed here, due to the homogenization of the concentrated sun beam by the SOE and to the incorporation of a cost effective nanoparticle based anti-reflection coating (ARC) that eliminates the Fresnel reflections.

## INTRODUCTION

There are two main types of photovoltaic (PV) devices, which convert directly the incident sun light energy into electricity. The first one is the flat-top PV, where cost-effective silicon solar cells of efficiency close to 20% are used. Here, the solar cells occupy the whole surface of the PV panel, making them easy to install and operate. The second device types are based on high concentrating PVs (HCPV), where highly efficient multi-junction (MJ) solar cells are used (2). The relatively high cost of MJ cells requires the use of concentrating optical elements to reduce their active surface, hence the cost of the final module. Although, the efficiency of MJ cells exceeds 40% (3; 1; 4; 5), the use of concentrating optics leads to a lower final efficiency of the HCPV module due to other additional losses handicapping significantly HCPVs with respect to flat-top PVs.

There are several causes of losses in the HCPV, which can be purely optical, opto-electronic, thermo-mechanical and electrical. Optical losses are related to Fresnel reflections generated at the concentrating optical element surfaces (1), to shadowing effects, observed due to manufacturing imperfections and to the absorption of optical materials used in HCPVs. Opto-electronic losses are more complex phenomena, since they do not introduce a reduction of the number of photons. They are rather related to the reaction of the solar cell to the incident light distribution at its entrance surface (5; 6). Mostly, it is referred as the fill factor (FF) reduction of the solar cell, hence, a conversion efficiency decrease. This type of loss also includes the reaction of the solar cell to spectral variations, where the total power of incident solar radiation is maintained, while the change of the spectral

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composition leads to a conversion efficiency change, due to the spectral response of the MJ solar cell. Electronic losses are mostly caused by series or shunt resistances of interconnections between solar cells. Finally, thermo-mechanical losses are generated by excessive heating of the solar cell.

In this work optical and opto-electronic losses are addressed. Namely a significant improvement of the module efficiency is demonstrated by homogenizing the beam profile with a specific SOE and by the optimal application of anti-reflection coatings (ARC), eliminating undesirable Fresnel reflections.

## HCPV STRUCTURE AND RELATED OPTICAL LOSSES

A standard HCPV module is usually composed of two main optical stages called as primary and secondary optical elements, POE and SOE, respectively. The POE is used to focus strongly the sun beam on the solar cell. This leads to a significant reduction of the required active area of MJ solar cells, resulting in a direct reduction of the HCPV module cost (7; 8). Presently, most HCPV modules are fabricated using the refractive type of POE (9), more specifically manufacturing cost considerations favor the use of Fresnel-like lenses (FL). Notice that such an approach is efficient for geometric concentration ($C_g$) ratios close to 500 Suns. Direct optical losses here are thus mostly related to Fresnel reflections occurred at both surfaces of the FL and to the manufacturing imperfections, observed at its grooves. Nevertheless, continuous cost decrease of flat top PV modules pushes to increase the $C_g$ ratio in HCPVs in order to stay competitive. However, high $C_g$ cannot be accomplished without the use of a second stage of optical element; the SOE. Indeed, there are two clear reasons (among others) making their use quite attractive and even necessary, which are the acceptance angle increase and the beam homogeneity improvement. The role of the SOE is to homogenize the beam profile, namely to change from a Gaussian beam to a flat type profile. It is well known that any optical system, where concentrating elements are used, will be sensitive to the angle at which light is incident on it. Regardless the focusing mechanisms used, the $C_g$ ratio and the acceptance angle α of the system are related by the "etendue" conservation relation given as (Eq.(1)):

$$C_g = \left( n_s \frac{\sin(\theta_{cell})}{\sin(\alpha)} \right)^2 \qquad (1)$$

where $n_s$ is the refractive index of the optical material installed on the surface of a triple junction solar cell and $\theta_{cell}$ is the incident angle on the solar cell (10).

Thus, according to the etendue conservation law, for a given $C_g$ value, there is a maximal angle at which the system can still properly operate, and this angle is decreasing when the $C_g$ value increases. For example, current commercial HCPV modules, designed without a SOE, demonstrate approximately $\alpha$~0.5-0.6deg of acceptance angle at $C_g$~400-500 Suns. Following the etendue principle, at 1000 Suns, the acceptance angle will drop to 0.35-0.42deg.

Therefore, in contrast to flat-top PV, HCPV modules need to be constantly aligned with the sun light. A HCPV module with a sensitive angular response (with respect to the misalignment angle) will require the use of a tracking system of higher precision, leading inevitably to a cost raise. Thus, there is a clear need to design concentrating modules having high values of angular response as much as possible. The ability of a SOE to uniformize (at its output) the concentrated spatial sun beam profile may help to reduce opto-electronic losses of solar cells.

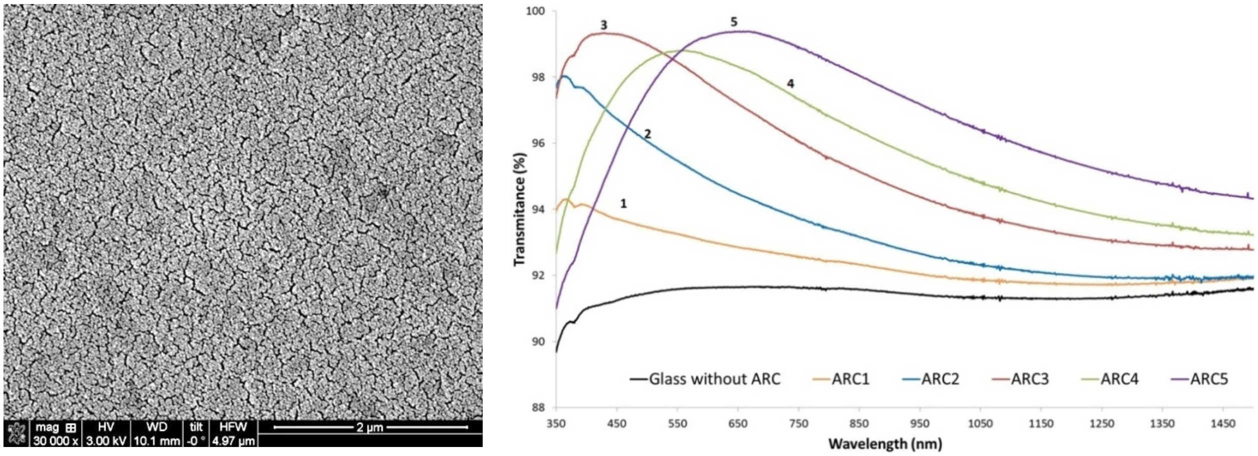
Thus, the introduction of a SOE and the development of appropriate ARCs become important to overcome the above mentioned difficulties.

## ANTI-REFLECTION COATINGS FOR HCPV

Currently, many types of ARC do exist with their specific manufacturing and deposition methods (11; 12). However, when they are considered for HCPV applications the number of possibilities narrows dramatically. Indeed, when an ARC is designed for HCPVs some specific parameters have to be taken into account, such as its capacity to resist to highly concentrated light powers, UV radiation, or wide range of operation temperatures (such as variations from10-80°C). Most importantly, it needs to have a broadband spectral response, and last but not the least: its final cost must be very low. Most standard deposition methods use the vacuum coating principle (11). However, this technique leads to an overall manufacturing cost increase that is unacceptable for HCPV module price ranges.

Recently, the use of nanoparticles in ARCs gained important interest, especially for their cost-effective manufacturing potential (11; 12). These types of coatings are based on the destructive quenching interferences principle. Optical elements transparency requirements impose on single ARC to have a refractive index small enough (e.g. 1.23) to be effective. A possible way to obtain such low refractive index, while maintaining the resistive properties of the coating is to render the coating porous. A technique is to use solid spherical nanoparticles to obtain this kind of coatings. Indeed, their shape forces them to optimize their mechanical stability by having as much contact points as possible. At the same time, the coating processes certain porosity, due to the void spaces inevitably left between solid particles (11; 13; 14; 15; 16). Hence, silica nanoparticles were rapidly considered, as they meet most of the requirements described above. ARCs made of silica nanoparticles can be produced by sol-gel processing. The silica nanoparticles here were prepared using the method described by Es'Kin et al. (15). A homemade dip coating system was used to proceed to the coatings on glass substrates.

A scanning electron microscope ((SEM) Quanta 3D FEG) and an atomic force microscope ((AFM) Veeco NanoScope V (in tapping mode)) were used to analyze the topography and roughness of the obtained coatings (see Fig.1 and 2). The optical properties of the ARCs were measured using a Cary 5000 UV-Vis-NIR spectrophotometer (Agilent Technologies).



(a) (b)

**FIGURE 1:** (a) SEM graph of a silica ARC on a glass substrate and (b) the transmission spectra of the different ARCs

Different areas on the substrates were scanned, a homogenous coating was observed everywhere similar to what one can see from Fig.1.a. The SEM graph shows that the coatings present a surface with random submicronic porosity (<100nm). The AFM measurements (about 5x5µm²), showed also a uniform coating and more importantly a surface with very small roughness. Indeed, analyzing the average surface profile showed an arithmetic roughness about 3nm, this is in good agreement with the literature (15). The figure below (Fig.1.b) shows the increase in the transmission spectra for different ARCs compared to the reference glass slide. The number of immersions (represented as ARC*X*, *X*= number of immersions) seems to have an important impact on the optical response of the coated surface. The transmission is increased between 3-8% depending on the wavelengths observed for each ARC. As expected, the increase of the ARC thickness, results in the shift of maximum transmission to higher wavelengths. Namely, one can notice that the maximum transmission for ARCs shifts from 350nm to 650nm.

## EXPERIMENTAL REALISATIONS AND RESULTS

Our experiments were performed in Quebec (Canada) region during the summer season. As a PV device, a commercial triple junction MJ solar cell (Spectrolabs WCA3000) was used, having around 0.07cm² of clear aperture and a mean conversion efficiency of about 38.5%. The solar cell was mounted on a specially designed receiver plate that was mounted on an aluminum made heat spreader. This guaranties efficient dissipation of the heat generated by the cell under highly concentrated sun beam. A Fresnel lens (FL) was used as a POE, which allowed obtaining a $C_g$ ratio around 940 Suns. The POE is an aspheric FL made of PMMA and the SOE is a glass material, whose working principle is based on the total internal reflection theory (see patent (17)). Notice that for all measurements the same POE and cell were used. Before integrating the SOE, the I-V curve of such concentrator was measured (Fig.2.a).

From the measurements an extremely low FF of such system is immediately noticed equal to 75%, which is far from the 87% announced by the cell manufacturer (for this $C_g$ ratio). This is a direct consequence of the non-uniform radiation at the focal spot of the FL, where the solar cell is placed. However, when our SOE is integrated on the solar cell, a significant power increase is observed due to the remarkable improvement of the FF, namely from 77% to 86%, almost a 12% gain. Such drastic increase is a direct result of the homogenization and color mixing of the concentrated sun light by the SOE at the input surface of the solar cell. The augmentation of the FF leads to a power generation increase as well. Indeed, without the SOE the maximal power generated was 1.56W, adding the SOE increases its values to more than 1.65W.

Thus, it becomes evident that at concentration ratios close to 1000Suns, an efficient SOE is indispensable at least to improve homogenization of the concentrated sun radiation, leading to a power increase through the FF improvement. However, the 12% of FF gain results only to 5.5% increase in maximal power ($P_{max}$), which could be more if Fresnel reflection at the entrance surface of the SOE is eliminated. The impact of reflection can be clearly seen from the variation of the short circuit current ($I_{sc}$) value of both mounting cases. Indeed, when the SOE was introduced almost 7% drop of the $I_{sc}$ was observed, its initial value was 0.68A (without SOE), while the integration of the SOE reduced the $I_{sc}$ to 0.63A.

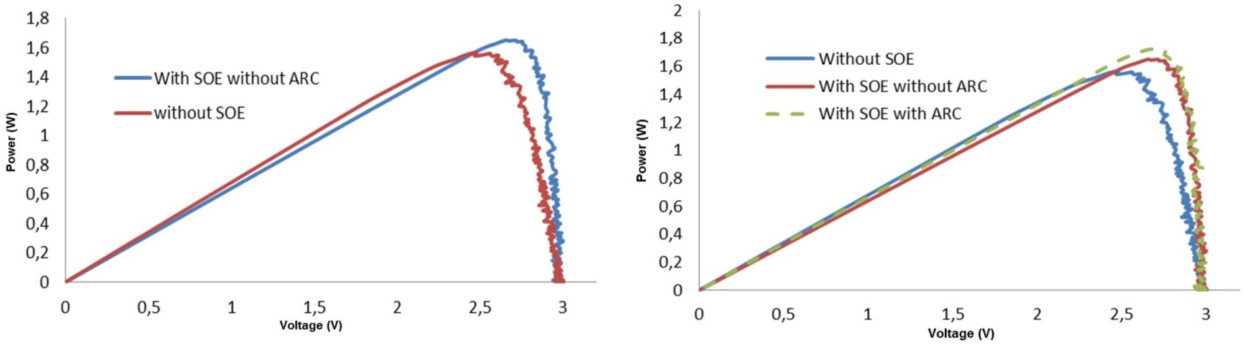
To describe the improvement of power generation due to an ARC application, following experimental set-up and procedure were developed. Normally, an ARC should be deposed directly on the SOE surface and the I-V curve measurement should detect a power improvement with respect to the uncoated case. However, such a way does not allow studying ARCs of various spectral responses and only one type of coating is tested. Therefore comparative type of measurement is done. To achieve this, the performance of the HCPV module is measured with a reference uncoated glass slide introduced between the POE and the SOE. Then, this reference slides are replaced by AR coated ones. Correctly working ARC has to lead to $I_{sc}$ and $P_{max}$ (Table 1) value gains with respect to the uncoated reference case. This cycle can be repeated several times, making possible to remove direct normal irradiance (DNI) variation as an error source.

**TABLE 1:** Performances of HCPV with AR coated and uncoated glass

| Case | HCPV | $P_{max}$ (W) | Gain in $P_{max}$ |
|---|---|---|---|
| 1 | No SOE – No ARC | 1.662 | 1.071 |
| 2 | Non AR coated SOE – Non AR coated glass | 1.551 | 1.000 |
| 3 | Non AR coated SOE – ARC1 coated glass | 1.563 | 1.008 |
| 4 | Non AR coated SOE – ARC2 coated glass | 1.593 | 1.028 |
| 5 | Non AR coated SOE – ARC3 coated glass | 1.614 | 1.041 |
| 6 | Non AR coated SOE – ARC4 coated glass | 1.637 | 1.056 |
| 7 | Non AR coated SOE – ARC5 coated glass | 1.576 | 1.016 |

*Gain in $P_{max}$ is calculated with respect to the case 2*
*All measurements have been done outdoors under the same conditions (uncertainties DNI ±0.1W/m², T ±1°C)*

An ARC was fabricated on a flat glass slide with optical properties close to our SOE. First of all, the I-V curve of the module (mounted with the SOE integrated receiver plate) was measured. Then immediately an AR coated plate was mounted at the input surface of the SOE (by means of an index matching liquid, thus eliminating reflection loss between the glass sample and the SOE). The I-V curves of this system were measured, and demonstrated a net increase in $I_{sc}$ and $P_{max}$ (Table 2). Each I-V curve measurement clearly indicated transmission and output power increase of AR coated SOEs (Fig.2.b).



(a) (b)

**FIGURE 2:** Power-Voltage curves of the HCPV (a) without and with uncoated Opsun`s SOE and (b) AR coated Opsun`s SOE integrated on a receiver plate with MJ solar cells

**TABLE 2:** Performances of HCPV without SOE, with SOE non AR coated and SOE with an ARC

| **Case** | **HCPV** | **$P_{max}$ (W)** | **FF (%)** | **Gain in FF (%)** | **Gain in $P_{max}$ (%)** |
|---|---|---|---|---|---|
| 1 | No SOE | 1.54 | 76.6 | 0.0 | 0.0 |
| 2 | Non AR coated SOE | 1.66 | 86.0 | 12.3 | 7.7 |
| 3 | AR coated SOE | 1.72 | 86.0 | 12.3 | 11.7 |
| | *All gain values are calculated with respect to case 1. In all case $C_g$ is 940 Suns. Measurements error ± 2%. All measurements have been done outdoors under the same conditions (uncertainties DNI ±0.1W/m², T ±1°C)* | | | | |

## SUMMARY AND CONCLUSION

ARCs, based on a specific combination of nanoparticles, were developed and manufactured in this work. These coatings were adapted especially for HCPV applications. Namely, particular attention was paid to the cost of manufacturing and deposition of this coating on our SOE components. Varying the thickness of ARC layers or particle dimensions, the transmission spectra of the obtained ARCs can be optimized for a certain wavelength region.

An efficient SOE is indispensable to improve homogenization of the concentrated sun radiation at concentration ratios close to 1000Suns, which leads to a power increase through the FF improvement of 12%. However, the FF gain results into a low increase in the $P_{max}$, because of Fresnel reflection at the entrance surface of the SOE. However, when ARCs were introduced in the system, its I-V curves demonstrated a net increase in $P_{max}$. Indeed, the adding ARCs allowed a maximal power gain, which was found to be about 12%.

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