# IMPROVING PERFORMANCES OF FRESNEL CPV SYSTEM: FRESNEL-RXI KÖHLER CONCENTRATOR

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ABSTRACT: A novel and advanced photovoltaic concentrator optic is presented comprising a Fresnel lens and a dielectric solid RXI as a secondary optical element, both with free-form surfaces (i.e. neither rotational nor linear symmetry). The RXI secondary is designed with the Simultaneous Multiple Surface (SMS) design method of Nonimaging Optics. In the secondary optics rays undergo refraction (R), reflection (X) and total internal reflection (I), so SMS nomenclature [2] for the device is RXI assigning letters to each surface that deflects rays. This is the first time the RXI-type geometry has been applied to design a photovoltaic secondary element. The LPI patented Fresnel-RXI Köhler concentrator [1] produces both the desired light concentration with high tolerance (high acceptance angle) as well as high irradiance uniformity on the solar cell achieved by Köhler integration method. The optical performance of the FRXI device (F denotes a Fresnel lens surface) will be presented as well as comparison with other conventional Fresnel-based CPV concentrators and application of the designed system.

Keywords: High efficiency concentrators, Fresnel lens, Köhler integration

## 1 INTRODUCTION

An optical PV concentrator must achieve various goals in order to minimize the energy cost. Two important parameters in evaluation of the performance of an PV concentrator are high concentration (>500) that offsets the cost of expensive high-efficiency multi-junction solar cell and maximum acceptance angle traduced into the tolerances of the system. Acceptance angle (formally defined as angle at which transmission drops to 90% of maximum) is a measure of the total tolerance of the system. The tolerance budget is distributed between (1) shape errors and roughness of the optical surfaces, (2) concentrator module assembly, (3) array installation, (4) tracker structure finite stiffness, (5) sun-tracking accuracy and (6) solar angular diameter.

Besides concentration and acceptance angle, irradiance uniformity on the cell has great importance. The cell efficiency depends on it, as well as long term solar cell and concentrator reliability. High local differences in flux over the solar cell surface can cause series resistance losses, although this has less impact in multi-junction cells than in silicon cells. In case of multi-junction cells, we have to assure their operating in the tunneling region [5]. This is especially important in a high concentration designs as the ones presented here. Also, the cell efficiency can be significantly affected if different wavelengths have a different irradiance distribution (which has been referred to as chromatic aberration [6]) due to local current mismatch between top and middle cells.

Good irradiance uniformity on the solar cell can be potentially obtained using two well known methods in the classical optics: a kaleidoscope homogenizer and the Köhler integrator. With the kaleidoscope homogenizer the solar cell is glued to one end of it and the light reaches the cell after bouncing on the kaleidoscope walls. The light distribution on the cell can be uniform with sufficiently long homogenizer. The use of kaleidoscope homogenizer in the CPV field has various manufacturing drawbacks and that´s why the concept of the Köhler integration is investigated and applied in PV concentrators.

The Fresnel RXI concentrator performs Köhler integration and was designed with the Simultaneous Multiple Surface optical design method in three dimensions (SMS3D), which leads to free-form devices (i.e. neither rotational nor linear symmetry). This method is the most advanced design method in Nonimaging Optics [2], which is the branch of Optics dealing with maximum efficiency light transfer problems.

There are two main groups of design problems in Nonimaging Optics. The first group is called "bundle-coupling" and has as objective to maximize the light power transferred from the source to the receiver. The second group of design problems is focused to obtain a desired pattern at a certain target surface and is called "prescribed irradiance".

In bundle-coupling, the design problem consists in coupling two ray bundles Mi and Mo, called the input and the output bundles respectively. This literally means that any ray entering into the optical system as a ray of the input bundle Mi exits as a ray of the output bundle Mo. Having the same rays inside of the input and output bundles Mi and Mo, we refer to it as the same bundle of rays Mc where, in general, Mc= Mi ∩ Mo. In the prescribed irradiance problem, it is necessary that one ray bundle must be included in the other, Mi in Mo (Mi and Mc will coincide). Additionally, the ray bundle Mc produces prescribed irradiance pattern on the target. As Mc is not fully specified, the design problem is less restrictive than bundle coupling one.

The photovoltaic concentrator (CPV) design is a good example of a design problem which contains both the bundle coupling problem for obtaining maximum acceptance-concentration product (CAP) as well as the prescribed irradiance in order to obtain uniform irradiance distribution on the solar cell active area. This is a very difficult task and therefore only partial solutions have been found.

## 2 THE KÖHLER INTEGRATOR CONCEPT

### 2.1 Statement of the problem

An elemental Köhler integrator is shown in Fig. 1 consisting of a solid piece of refractive index n>1 bounded by two symmetrical lenslet arrays, separated by their focal length (T). Any light intensity distribution inside ±α angle on the upper lenslet array will be transformed into constant intensity for a ±α bundle of rays after the lower lenslet. The optical system couples all the rays impinging on the array from top forming a half-angle:

$$\alpha = \arctan(\frac{p/2}{T})$$

The input and output bundles are the same, but the integrator changes the ray assignations from input to output. This ray assignation exchanges angular and spatial features, and this is why the integrator can produce angularly uniform output radiation from input spatially uniform illumination which is angularly non-uniform.

For instance, Fig. 1 shows the input surface uniformly illuminated with vertical incident rays (α=0º) that are focused onto the center of each lenslet of the output array, and the intensity at the exit will be uniform within ±α. In the Fig. 1 later on is shown the same integrator but with a tilted impinging parallel ray fan. Modification of the incident angle of the parallel ray fan from normal incidence up to angle α does not affect the far field of the exit rays, but only the emission points at the bottom array are shifted. Therefore, the optical integrator can produce an intensity pattern that can be quite insensitive to lateral source-position errors of a point source.

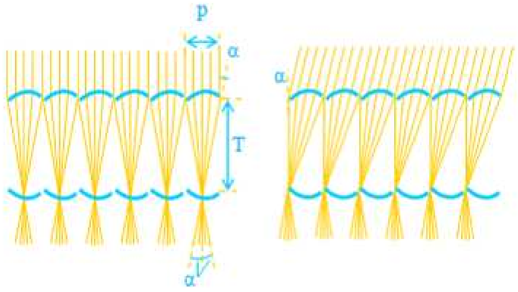

**Figure 1:** Operation principle of a basic integrator array

### 2.2 State of the art

The first photovoltaic integrating concentrator (SILO) was proposed in the late 80's [11] by Sandia Labs, and it was commercialized later by Alpha Solarco [20]. This photovoltaic Köhler concentrator is composed of a Fresnel lens as the primary optical element and a single-surface imaging lens as a secondary, which encapsulates the cell. In this concentrator the primary images the sun onto the secondary aperture. As primary is uniformly illuminated by the sun, the irradiance distribution on the cell is also uniform, and it will remain unchanged when the sun moves within the acceptance angle (equivalently when the sun image moves within the secondary aperture). The concentration-acceptance angle product that can be attained with this configuration is very limited, because the numerical aperture on the cell is small. As the system uses the single Köhler integration element and the optic is refractive, the whole system cannot be compact and also such imaging secondary cannot achieve high illumination angles on the cell so low acceptance angles are reached. Despite the simplicity and high uniform illumination on the cell of this concept, their application is limited to low concentrations because it has low acceptance-concentration product (±1deg at 300x).

Another approach has also been proposed in the past, using four surfaces and obtaining a photovoltaic concentrator for maximum acceptance angle and uniform irradiance distribution on the solar cell [7]. The primary of this concentrator should be an element that images the sun on the aperture of secondary, for example a double aspheric imaging lens. As secondary optical element, the SMS designed RX concentrator can be used, which is an imaging element that works near thermodynamic limit of concentration. [2][12][13]

Recently was presented a novel Fresnel-R Köhler system (FK) [4] comprising a flat Fresnel lens as the primary optical element (POE), and a single refractive surface as the secondary optical element (SOE) where Köhler integration process was performed between the lower surface of the Fresnel lens and upper surface of the secondary lens. Optical surfaces are designed as the free-form Köhler integrating arrays. The irradiance uniformity obtained by the FK concentrator is excellent, without the chromatic aberration so typical for other Fresnel concentrators.

An advanced novel PV concentrator Fresnel-RXI presented here has optical surfaces designed as free-form Köhler integrating arrays as well as the previously mentioned FK. It has the highest value of CAP (the concentration acceptance angle product) among the values reported in the designs of this type of geometry with a Fresnel lens as the primary element.

## 3 FRESNEL-RXI 3D KÖHLER CONCENTRATOR

In this section we will present an academic example of a 3D design, a Köhler integrator that performs the integration in two directions. First variant of the system comprises a Fresnel lens as the primary element and a dielectric solid RXI as the secondary, both with free-form surfaces. Fresnel lens and dielectric RXI are split into 4 doublets: each Fresnel lens unit focuses incoming rays from the sun on the corresponding unit of the secondary, and each of the four units of the secondary focuses back traced rays from the photovoltaic (PV) cell on the corresponding one of the four Fresnel lens units.

Fig. 2 shows the scheme of the normal incidence rays passing through one quarter of a Fresnel POE and focusing on the corresponding RI surface of the SOE where complete SOE and a section along the diagonal of a quarter of a Fresnel lens are shown.

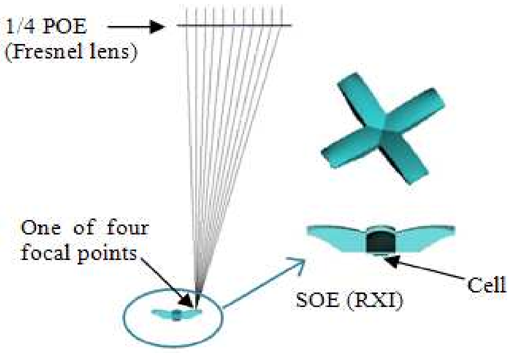

**Figure 2:** Scheme of the normal incidence rays passing through quarter of POE (Fresnel lens) and focusing on the corresponding RI surface of SOE (RXI).

Fig. 3 illustrates normal incidence ray tracing and shows a free-form Fresnel-RXI Köhler design (Cg=2,300x, square solar cell). A plane wavefront emulating the sun center point has been traced in order to show how this beam is split and focused on the four SOE facets to be spread afterwards to produce uniform irradiance on the solar cell. Nevertheless, this will be valid for every ray within a design acceptance angle ±α.

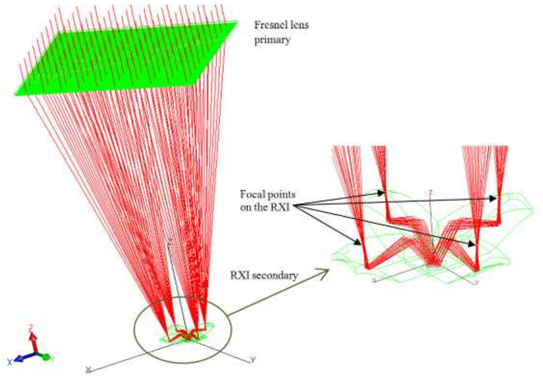

**Figure 3:** Performance of the 3D Köhler free-form FRXI concentrator. Light that enters is focused by the Fresnel lens on the corresponding SOE's lenticulations in order to obtain an uniform irradiance on the cell.

To prove the relevance of this novel design, it is necessary to refer to the concentration acceptance angle product, CAP, which is a merit function usually employed to compare PV concentrator designs. It is defined as $CAP=\sqrt{Cg}\cdot\sin(\alpha)$, where Cg is the geometrical concentration and α the acceptance angle, defined as the incidence angle at which the concentrator collects 90% of the on-axis power.

Three variants of the concentrators comprising RXI as a secondary optical element are going to be considered. First variant of the designed concentrator optics is before mentioned concentrator with Fresnel lens as primary and RXI secondary with small frontal area metalized (Fig. 4). It has a value for CAP of 0.85. In second variant we changed 4-fold Fresnel primary lens for 4-fold primary mirror in order to increase the angular acceptance of the system. CAP of this model has a value of 1.02 and it is CPV Köhler concentrator with highest reported CAP value. Third variant of the system is Fresnel-RXI without frontal metallization (Fig. 4) done in order to make the design cheaper and easier to manufacture. It reaches the value for CAP of 0.73. Up to our knowledge, two variants with Fresnel lens as primary have the highest reported values for CAP among the concentrators based on flat Fresnel lenses.

### 3.1 Design description

This Köhler-based CPV optical device has a Fresnel lens used as primary element (POE) with RXI as a secondary element whose surfaces are calculated using SMS design method in three dimensions.

In the secondary rays undergo refraction (R), reflection (X) and total internal reflection (I), so SMS nomenclature for device is RXI assigning letters to each surface that deflects rays (Fig. 4). The goal is to design optics producing both the desired light concentration with high tolerance (high acceptance angle) as well as an excellent light homogenization by Köhler integration.

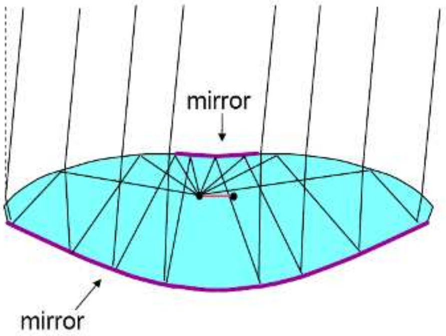

**Figure 4:** RXI concentrator geometry (Primary Fresnel lens not shown.)

The RXI is a dielectric solid that has a small metalized surface on the front (optional) and larger metalized surfaces on the back side that act as mirrors. The RXI is a well-known device in the field of Nonimaging Optics. It was first designed with rotational symmetry [2] and later with free-form surfaces for automotive applications [3].

The design presented herein is done using certain approximations in 3D compared to the procedure conventionally used for Köhler integrators in solar concentrators. Calculation is performed using free-form wavefronts at the RXI entrance and focusing those wavefronts to the corresponding points of the active cell area. Attention is paid to ensure that a source at infinity (the sun) is imaged on the cell points.

The RXI design uses an iterative process in which the R and I surfaces are considered as if they were two separate surfaces. An initial shape for the surface R is chosen ($R_0$) and the SMS 3D method is applied to calculate surfaces X and I. Next, the calculated surface I is considered as a new R surface ($R_1$) and the design is done again to recalculate new surfaces X and I. The process is repeated until the sequence of surfaces $R_n$ converges towards the final design surface. This iterative process is peculiar to the RXI when compared to other SMS devices, and arises from the circumstance that two distinct optical surfaces, the chosen surface R and the calculated surface I, must be the same physical surface.

### 3.2 Simulation results

In this section we will present the simulation results of the three variants of the 3D Köhler systems before mentioned that perform the integration in two directions. First system we have designed is a FRXI with an f-number f/1.4 (calling f-number the ratio of the distance between the cell and Fresnel lens to the Fresnel lens diagonal, i.e. a purely geometrical definition, without the usual optical meaning) and a geometrical concentration (ratio of entry aperture area to cell area, being both square shaped) of Cg=2,300x. Secondary optical element RXI has a small frontal metallization area.

The relative transmission curve is shown in Fig. 5 with dashed lines highlighting a key point (90% relative efficiency) at 1.02° angle, which may be used to define the nominal acceptance angle. Curves for transmission in a plane parallel to the sides of the square Fresnel primary lens (referred to as "parallel") and in a plane parallel to the diagonal of the square Fresnel primary lens (referred to as "diagonal") are provided. A CAP=0.85 is reached.

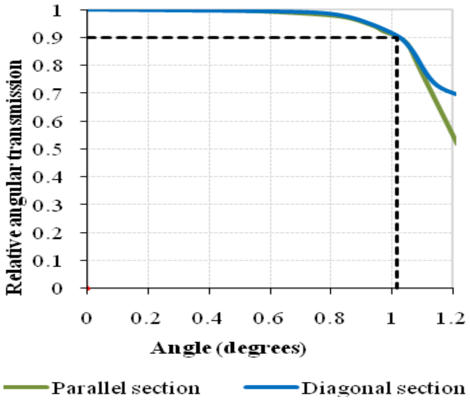

**Figure 5:** Computer simulation of the 2,300x 3D free-form FRXI Köhler concentrator. Relative optical efficiency versus incidence angle. Acceptance angle α = ±1.02º.

This model FRXI has the following parameters:

(i) Fresnel lens: area=852.64 cm2, made of PMMA (n≈1.49), facet draft angle=2º;

(ii) Dielectric SOE: BK7 glass (n≈1.51872) with mirror reflectivity 0.97.

Small part of the upper RXI surface is metalized (Fig. 4). The SOE area is below 4% the Fresnel lens area. SOE size is reduced for smaller f-numbers.

The optical efficiency (power on the cell surface over the power of a perfectly-tracked sun beam considering Fresnel losses, absorption losses and RXI mirror reflectivity) is simulated as 82.5%, which can be increased up to 85% with AR coating on the RXI front face.

The FRXI concentrator produces excellent irradiance uniformity on the cell. Fig. 6 shows the irradiance distribution on the cell of the FRXI concentrator of Cg=2,300x, f/1.4, when the sun is on-axis with Direct Normal Irradiance (DNI) of 850W/m2. Absorption in dielectric materials and Fresnel losses are considered. It will be probably somewhat lower in practice, however, (this ray-trace model does not include scattering and optical manufacturing errors) but is instructive to compare the FRXI concentrator with an irradiance plateau of ≈ 1,700 suns (@DNI=850 W/m2) with other concentrators of the same Cg=2,300x.

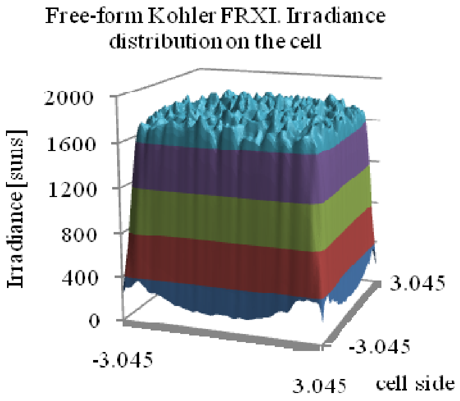

**Figure 6:** Computer simulation of the 2,300x 3D Köhler free-form FRXI concentrator (RXI with small frontal metalized area). Irradiance distribution on the cell for a perfectly-tracked sun (@DNI=850W/m2).

Changing the 4-fold primary Fresnel lens for a 4-fold primary mirror increases the angular acceptance of the system. Incident rays in this new design undergo reflection first, at the POE, and then enter the RXI secondary element. In this manner we obtain a design with strong theoretical importance. Concentration acceptance product of this model is one of two highest ever obtained in a CPV, and among Köhler designs is the highest.

Parameters of the XRXI concentrator are shown in Table I together with the parameters of other two variants with Fresnel lens as primary. The optical efficiency of the XRXI is simulated as 88.8% (the same simulation conditions as previously mentioned). This concentrator produces excellent irradiance uniformity on the cell as well.

Another embodiment is an FRXI system with a secondary RXI w/o frontal metalized area, with an f-number f/1.4 and a geometrical concentration of 2,330x. The simulation results show the acceptance angle of ±0.87 deg to be compared, which imply a CAP=0.73 is reached (see Table I). The highest CAP value among the concentrators based on flat Fresnel lenses is maintained.

The optical efficiency (considered Fresnel losses, absorption losses and RXI back mirror reflectivity) is simulated as 83.5%, which additionally can be increased with AR coating on the RXI front face.

**Table I:** Comparison of three described systems (FRXI with small frontal metalized area, XRXI with mirror as primary element, FRXI** without frontal metalization)

| | Cg | α | CAP |
|---|---|---|---|
| FRXI | 2,300 | 1.02º | 0.85 |
| XRXI | 2,230 | 1.24º | 1.02 |
| FRXI** | 2,330 | 0.87º | 0.73 |

The FRXI concentrators produce excellent irradiance uniformity on the cell, with negligible chromatic aberration of that irradiance. Conventional Fresnel lens has considerable chromatic aberration. We are not explicitly presenting irradiance diagrams for the top and middle subcells of multi-junction cell, but as well as in the case of FK concentrator [4] in the FRXI the chromatic aberration of the Fresnel lens barely affects the irradiance, thanks to its Köhler integration basis. White light that is split by the Fresnel lens into a range of different focal points will be refocused at the same point of the cell, after passing through the SOE.

## 4 COMPARISON

Comparing the FRXI concentrators with other six more conventional CPV concentrators designs that use flat Fresnel lens as a primary is presented. All the concentrators will have the same POE entry aperture area (625 cm2), and concentration ratio will be varied (and thus cell size will vary accordingly). Both the Fresnel lens and the solar cell are square. First there is a Fresnel lens concentrator with no secondary, which is a type of system being used for instance by Concentrix Solar [18]. Second is a hemispherical glass dome centered on the cell surface and in optical contact with it. This type of dome concentrator has been considered as a candidate for improving the CAP of Concentrix design [19]. Third, we selected for the comparison the SILO secondary (previously described in the section 2.2). The fourth SOE is a hollow reflective truncated pyramid (XTP), which is the type of SOE being used by Amonix [21] and Guascor Foton [22]. The fifth is the dielectric-filled truncated pyramid (RTP), which works by total internal reflection. This type of SOE is used in several commercial products [23]. Finally, last design to compare with is before mentioned a novel Fresnel-R Köhler system (FK) [4]. Our two systems are FRXI with small metalized frontal area and FRXI without frontal metallization (FRXI**). With the exception of SILO, we have selected concentrators that are being used in current commercial products, or that have been considered as next-generation designs. We have included the SILO because it is conceptually related to FK and FRXI concentrators.

**Table II:** The f-number and geometrical concentration of the selected Fresnel-based concentrators under comparison

| | f-number | Cg |
|---|---|---|
| No SOE | 1.5 | 104 |
| Spherical dome | 1.5 | 257 |
| SILO | 1.2 | 248 |
| XTP | 1.3 | 425 |
| RTP | 0.85 | 677 |
| FK | 1.0 | 1,057 |
| FRXI | 1.4 | 2,300 |
| FRXI** | 1.4 | 1,750 |

The concentrator ratio of system height to POE diagonal (f-number) are listed together with the geometrical concentration of the different configurations (see Table II). All these concentrators have the same POE entry aperture area (625 cm2) and the same acceptance angle (α = ± 1°). That's why it is safe to assume that cost savings will come only from reduced cell area and reduced SOE costs. The true-scale relative size comparison among the different SOE's can be seen in the crosssectional drawings of Fig. 7. We can observe that our FRXI concentrators use solar cells with the smallest area in chosen geometry.

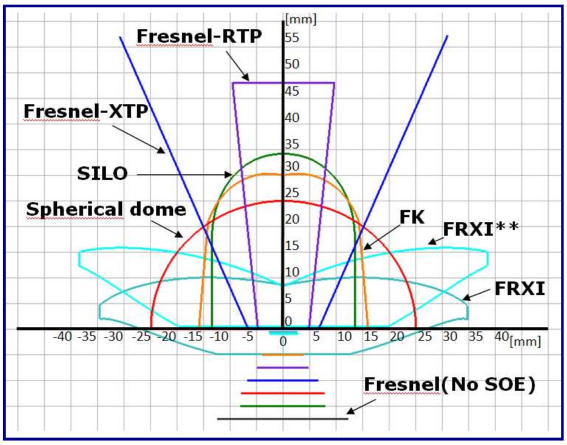

**Figure 7:** Cross section of the Secondary Optical Elements of the Fresnel-based concentrators to compare. All these concentrators have the same POE entry aperture area (625 cm2) and the same acceptance angle (α = ± 1º). The cross section of their corresponding cells, which should be centered at the origin, are shown displaced downward to make them visible.

Comparison of the concentration-acceptance angle product (CAP) for the selected concentrators is shown in Fig. 8. We can see that the FRXI concentrator is superior to all of the Fresnel-based concentrators described. To interpret well the Fig. 8 note that, for instance, using values for FK and RTP, $(0.59/0.45)^2=1.7$, the FK 1,000x is equivalent a 580x RTP.

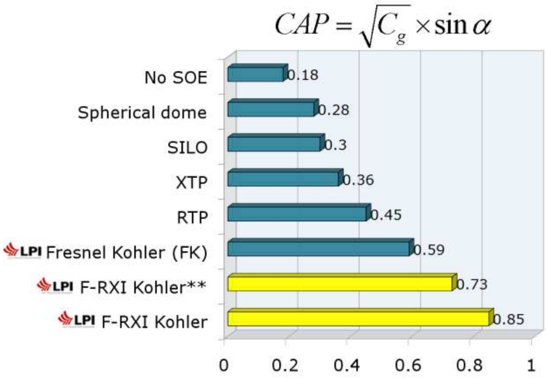

**Figure 8:** Concentration acceptance angle product (CAP) for the concentrators under comparison.

## 5 APPLICATION: RXI WITH EXTERNAL CONFINING CAVITY

Light confinement in solar cells is commonly used for maximization of the photon path inside the cell for maximum absorption. However, the light reflected by the grid lines (about 10% at present) is not captured in present commercial CPV systems. Although prismatic covers have been proposed, their low compatibility with the use secondary optics (needed for high concentration and high tolerance) has kept them out of the market.

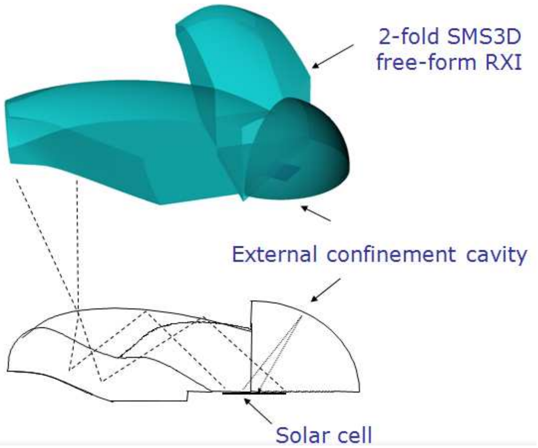

**Figure 9:** A perspective view and a side view of another embodiment of an SMS 3D RXI SOE.

Fig. 9 shows an embodiment using a different approach, based on the use of light-confining external cavities integrated with Köhler-type secondary optics. External cavities have been proposed in the past, but they had also difficulties of integration with classical secondary optical elements using kaleidoscopic homogenization. However, the recent invention of high-performance Köhler concentrators, fully compatible with the use of external cavities, will allow for this practical integration. It must be remarked that external confinement allows the use of more dense grid-lines, which minimizes Joule losses and permits the use of higher concentrations.

Although flat Fresnel lenses have a smaller concentration capability than mirrors or curved Fresnel lenses, the use of an advanced secondary as the RXI can compensate for that limitation. The FRXI Köhler optics has recently theoretically proven the highest concentration capability among all flat Fresnel based systems, and it is specially suitable for self-supporting systems, that is to say, designs sufficiently deep and stiff that the module housing serves as a structural component of the array. Such a design has been proposed by Amonix and Guascor Foton. The superior optical capability of the FRXI allows developing the external cavity for recovering not only the grid-line reflections but also the cell AR coating reflections.

## 6 CONCLUSIONS

The optical performance of a free-form Fresnel-RXI Köhler solar concentrator, using a high efficiency multi-junction solar cell, is presented. This type of solar concentrator is designed using the most advanced design method of the Nonimaging Optics which allows obtaining devices with acceptance-concentration products approaching the maximum value as derived from the étendue conservation theorem.

Light homogenization on the cell is important for proper behavior and durability of the system, minimizing risks associated to high local concentrations, as well as obtaining high values of tolerance for PV concentrators because manufacturing process always implies some accuracy errors.

The FRXI concentration-acceptance angle product, CAP, is the highest among the concentrators based on flat Fresnel lenses, and is also superior respect to other designs reported in [14]. However, two designs using mirrors as POE have been announced with a higher CAP than the FRXI together with the XRXI design [15][16]. The irradiance uniformity obtained by the FRXI concentrator is excellent, without the chromatic aberration typical of other Fresnel concentrators.

The optical surfaces of the FRXI, from the manufacturing point of view, are very similar to a conventional flat Fresnel lens and a secondary optics. This means that they can be manufactured with the same techniques and that their production cost is essentially the same, but their optical performance (CAP) is much better. Techniques like continuous roll embossing, hot embossing, compression molding, etc. are used for the POE. For SOE manufacturing can be used methods widely known in automotive industry for headlamps such as plastic injection and glass molding. Glass molded mirrored SOE's are already being used in commercial CPV products [17]. Here they are used for back surface RXI and small area of the front surface that is optional considering possibility of different variants of SOE.

The true innovation in these new designs (as well as in [4]) is that they are free-form Köhler integrating arrays. This degree of freedom enables the design of optical surfaces that can perform different functions at the same time (improving the device performance without affecting its cost). This allows good irradiance uniformity and high tolerance angle at high concentration values.

## 7 REFERENCES

[1] International Patent Pending
[2] R.Winston, J.C. Miñano, P.Benítez, "Nonimaging Optics", Chapter 8, Elsevier-Academic Press, New York (2005).
[3] J.C. Miñano et al., "Free-form integrator array optics", in Nonimaging Optics and Efficient Illumination Systems II, SPIE Proc., R. Winston & T.J. Koshel ed. (2005), Vol. 5942-12.
[4] P. Benítez et al. "High performance Fresnel-based photovoltaic concentrator", Optics Express, Vol. 18, Issue S1 (2010), pp. A25-A40.
[5] A. Braun, B. Hirsch, E. A. Katz, J. M. Gordon, W. Guter, and A. W. Bett, "Localized radiation effects on tunnel diode transitions in multi-junction concentrator solar cells," Sol. Energy Mater. Sol. Cells 93(9) (2009) 1692–1695.
[6] S. Kurtz, and M. J. O'Neill, "Estimating and controlling chromatic aberration losses for two-junction, two terminal devices in refractive concentrator systems", 25th PVSC (1996), pp.361–367.
[7] A. Martí, A. Luque, "Next Generation Photovoltaic", Chapter 13th, Taylor & Francis, CRC Press (2003).
[8] P. Benítez, J. C. Miñano, J. Blen, R. Mohedano, J. Chaves, O. Dross, M. Hernández, and W. Falicoff, "Simultaneous multiple surface optical design method in three dimensions," Opt. Eng. 43(7), (2004), 1489–1502.
[9] J. C. Miñano, M. Hernandez, P. Benítez, J. Blen, O. Dross, R. Mohedano, and A. Santamaría, "Free-form integrator array optics", in Nonimaging Optics and Efficient Illumination Systems II, SPIE Proc., R. Winston & T.J. Koshel ed. Vol. 5942–12, (2005).
[10] R. Leutz, and A. Suzuki, Nonimaging Fresnel Lenses, (Springer-Verlag, Berlin, 2001).
[11] L.W. James, "Use of imaging refractive secondaries in photovoltaic concentrators", SAND89-7029, Alburquerque, New Mexico, (1989).
[12] J.C. Miñano, P. Benítez, J.C. González, "RX: a nonimaging concentrator", Appl. Opt. 34(1995), pp. 2226-2235.
[13] P. Benítez, J. C. Miñano, "Ultrahigh-numerical-aperture imaging concentrator", J. Opt. Soc. Am. A, 14 (1997) , pp. 1988-1997.
[14] M. Victoria, C. Domínguez, I. Antón, G. Sala, "Comparative analysis of different secondary optical elements for aspheric primary lenses," Opt. Express 17 (2009) , 6487–6492.
[15] P. Zamora, A. Cvetkovic, M. Buljan, M. Hernández, P. Benítez, J.C. Miñano, O. Dross, R. Alvarez, A. Santamaría, "Advanced PV Concentrators", 34th IEEE PVSC, (2009).
[16] M. Hernandez, A.Cvetkovic, P.Benítez, J.C.Miñano, J. Chaves, "CPV and illumination systems based on XR-Köhler devices", SPIE, Optics and Photonics, Proc. SPIE 7785, 77850A (2010)
[17] Gen 1 of http://www.solfocus.com/
[18]http://www.concentrixsolar.de/fileadmin/user_upload/Download/Technical_Data_Sheets_Q3-2009.pdf.

[19] G. Peharz, J. Jaus, P. Nitz, T. Schmidt, T. Schult, and A. W. Bett, "Development of refractive secondary opticsfor flatcon® modules", 23rd European Photovoltaic Solar Energy Conference, 1DV.3.34, (2008).
[20] D. Anderson, B. Bailor, D. Carroll, E. Schmidt, P. Tyjewski, M. Uroshevich, "Alpha Solarco's Photovoltaic Development Concentrator Program", Contractor report SAND95–1557, (1995).
[21] http://www.amonix.com/technology/index.html.
[22] http://www.guascorfoton.com/home_en.php.
[23] See, for instance: www.sol3g.com, http://www.solfocus.com/ and K. Araki et al., "Development of a new 550X concentrator module with 3J cells-Performance and. Reliability-", Proc. 31st IEEE PVSC, (2005).