CHARACTERIZATION OF FRESNEL-KÖHLER CONCENTRATOR

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ABSTRACT: Getting a lower energy cost has always been a challenge for concentrated photovoltaic. The FK concentrator enhances the performance (efficiency, acceptance angle and manufacturing tolerances) of the conventional CPV system based on a Fresnel primary stage and a secondary lens, while keeping its simplicity and potentially low-cost manufacturing. This work presents some measured performance features of a FK prototype that show its skills and potential for the achievement of competitive electricity generation costs. First prototype was built and characterized, and efficiency higher than 30% has been demonstrated.
Keywords: Fresnel lens, concentrated photovoltaics, Köhler integration

1 INTRODUCTION

Minimizing energy cost (€/kWh) is necessary for the success of concentrated photovoltaic energy (CPV). Key to minimizing this cost is an efficient and low cost optical design, what can be get with concentrator of the fewest elements and the maximum tolerances, but always maintaining the high concentration (>500) that offsets the cost of expensive high-efficiency multi-junction solar cells. A useful merit function for a CPV optic is the concentration-acceptance product [1], which we define as:

$$CAP = \sqrt{C_g}\,\sin\alpha \qquad (1)$$

Where Cg is the geometric concentration and α the acceptance angle, defined as the incidence angle at which the concentrator collects 90% of the on-axis power. It is remarkable that for a given concentrator architecture, the CAP is rather constant with Cg, which means that if we know the CAP for a concentrator architecture that we want to redesign for a higher concentration, the resulting acceptance angle will be close to that of Eq. (1).

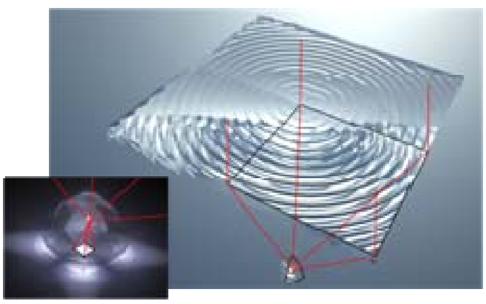

Figure 1: Rendered views of the *FK* two optical stages showing the working principle of the *FK* concentrator: Each pair of *POE-SOE* sectors form reciprocal images according to the Köhler principle- and attain a perfectly uniform square sun spot on the solar cell. The Fresnel facets are exaggerated, for clarity purposes

For a certain Cg value, a high value of tolerance (which means a high acceptance angle) for the system is really important for several reasons: optic surfaces require high accuracy; assembling is expensive because of fine adjustments; efficiency decreases significantly from single unit to array; electricity production waves in moderate windy conditions; soiling decreases efficiency more strongly than in flat modules. Another important issue in PV concentrator is irradiance distribution on the cell, since it directly affects the cell efficiency and long term system reliability. [2]

LPI-patented Fresnel Kohler [3] system uses the principles of optical integration [4][5] and nonimaging optics [6] to reach unique performance features, such as compactness, perfect irradiance uniformity over the solar cell, and a very good CAP (away from the thermodynamic upper bound but still beyond conventional Fresnel concentrators). Additionally, the FK is free of chromatic effects (if different wavelengths produce different irradiance distribution on the cell - chromatic aberration of the irradiance [7], the cell efficiency can be significantly affected, due to local current mismatch between the top and middle junctions).

FK concentrator consists of a Fresnel lens comprising four identical folds, along with a free-form secondary lens, also divided in four sectors. The POE and SOE sectors work in couples, where each pair of POE-SOE folds form image onto each other and the integration effect produces a perfectly uniform square spot onto the solar cell (see Figure 1).

2. SIMULATION RESULTS FOR THE FK CONCENTRATOR

The FK concentrator design and its ray-tracing simulations have been done with the following features: (i) Fresnel lens: made of PMMA (n≈1.49), facet draft angle=2º, vertex radius=3 μm, facet height<250 μm; (ii) SOE: made of B270 glass (n≈1.52) coupled to the cell with a transparent silicone rubber of n≈1.41 (e.g., Sylgard 182 of Dow Corning); (iii) high efficiency (≈38%) commercial triple-junction cell. Absorption in dielectric materials and Fresnel reflections are considered, but surface scattering is neglected. The f-number of the FK concentrator is 0.85, as defined to be the ratio of the distance between the cell and Fresnel lens to the Fresnel lens diagonal (therefore, it is a purely geometrical value, without the usual optical meaning).

2.1 Optical efficiency

The optical efficiency for a FK concentrator with Cg=625x and f/0.85, calculated at a single wavelength (555 nm), is 84%, without an AR coating on the SOE. In order to estimate the performance limit when there is an AR coating, the optical efficiency for a perfect AR coating (i.e., zero Fresnel reflection by the SOE) is 88% for f/0.85 at 555 nm. An effective polychromatic optical efficiency can be defined as:

$$\eta_{opt,polychrom} = \frac{I_{sc}^{conc}}{C_g I_{sc}^{1\,sun}} = \frac{\min\left\{I_{sc,top}^{conc}, I_{sc,middle}^{conc}, I_{sc,bottom}^{conc}\right\}}{C_g \min\left\{I_{sc,top}^{1\,sun}, I_{sc,middle}^{1\,sun}, I_{sc,bottom}^{1\,sun}\right\}} \quad (2)$$

Eq. (2) is computed by integrating over the wavelength using the curves shown in Figure 2: the optical efficiency versus wavelength of that FK design, and the lossless spectral photocurrent densities (calculated as the product of Cg, the AM1.5d ASMT G173 spectrum, and the EQE of the sub-cells). The ratio of the currents Isc,top/Isc in that FK concentrator under that standard spectrum is nearly the same (1% variation) as that ratio without the concentrator losses. These calculations also show that the difference between the two optical efficiencies (monochromatic @ 555 nm and polychromatic) is negligible (<0.1%) for both the uncoated and perfect AR coated case of that FK concentrator. Therefore, we conclude that the for the FK concentrator the monochromatic calculation satisfactorily estimates the optical efficiency.

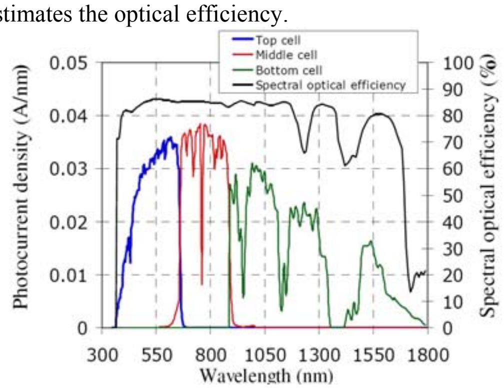

Figure 2: Lossless spectral photocurrent densities and spectral optical efficiency of an FK concentrator with Cg=625x and f/0.85

From this spectral transmission curve we can deduce photocurrent generated in the solar cell. In the case of the current FK, considering standard AM1.5d ASMT G173 spectrum, the generated Isc is 7.15A DNI@1000W/m2 or 7.4A DNI @1000W/m2, depending on whether we apply an AR coating or not.

2.2 Concentration-acceptance angle product (CAP)

Figure 3 shows the variation of photocurrent produced in the MJ cell (limiting junction) with the sun beam incident angle. From this simulated curve we can estimate the effective acceptance angle, α* (defined as the aim-error angle when the generated photocurrent drops to 90% of its nominal value). The simulation takes into account the finite size of the sun and the comparison of the products of the solar spectrum and the EQE of the three subcells to find which one is limiting, and it considers the DNI of 900W/m^2. Resulting effective acceptance angle is 1.25º.

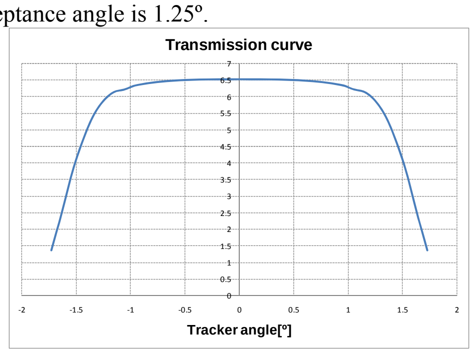

Figure 3: Variation of generated photocurrent with tracker angle. Effective acceptance angle is 1.25º

We can define a further merit function that we call effective *CAP* (or *CAP**), which is defined by substituting in Eq. (1) for the acceptance angle α by an aim-error angle α*. The utility of the CAP* is that it can be experimentally measured. In the previous work [8] have been shown that both CAP and CAP* are maintained constant for the same concentrator architecture.

For f/0.85 the FK concentrator with no AR coating on the SOE has C_g = 625x and α^*=±1.25º (which corresponds to the values *CAP**≈0.55 mentioned before). If the FK concentrator is designed for C_g = 1000x, the resulting acceptance angle can be well estimated to be α=±1.25º$(625/1000)^{1/2}$=±1º.

2.3 Irradiance on the cell

Non-uniformity on solar cells irradiance reduces the I-V curve fill factor, due to higher series resistance losses and to current density being limited by a tunnel junction. Moreover, chromatic non-uniformity of cell irradiance can produce an additional fill factor loss [7] due to a local current mismatch between top and middle junctions. For these two important reasons, FK concentrator is designed to produce excellent irradiance uniformity on the cell, with negligible chromatic aberration of that irradiance. Figure 4 shows two irradiance distributions (top and middle subcells) of an FK concentrator of Cg=625x, f/0.85, no AR coating of SOE, when the sun is on-axis with Direct Normal Irradiance (DNI) of 850W/m2. In the FK concentrator the chromatic aberration of the Fresnel lens barely affects the irradiance spatial distribution thanks to its Köhler integration basis.

2.4 Manufacturing tolerances

Broadly speaking, the acceptance angle describes how some optics performs angularly. For instance, for a perfectly manufactured CPV system, it tells the maximum tracking error allowable if we want to assure a 90% of the maximum achievable power output (which occurs at normal incidence, perfect sun-aim).

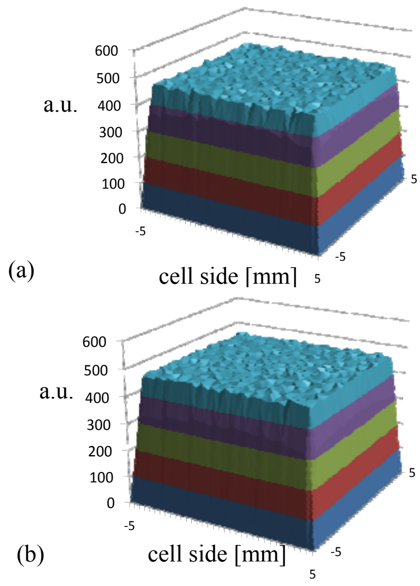

Figure 4: Irradiance distribution on the cell for the FK concentrator with parameters C_g=625x, f/0.85, no AR coating on SOE, when the sun is on axis and the solar spectrum is restricted to: (a) the top-subcell range (360-690 nm), and (b) the middle-subcell range (690-900 nm)

However, these values do not fully describe how sensitive is the system to manufacturing errors, such as misalignment between optical parts or between optical parts and receiver. Indeed, although such sensitivity is partly linked to the acceptance characteristic, the manufacturing tolerances cannot be deduced from the latter right away. Moreover, depending on the optical approach (geometry, number and type –mirrors, lenses, total internal reflection TIR- of surfaces…) a concentrator might be less sensitive to manufacturing inaccuracies even having lower acceptance values. The reasons behind the actual sensitivity of each system are not so clear in other cases, and the actual tolerances should be analyzed through ray tracing.

A simple tolerance analysis defining maximum shifts allowable in three directions has been carried out for the FK concentrator, fixing minimum acceptance and/or efficiency levels, and analyzing which one limits in each case. The study includes:

- Lateral shifts (perpendicular to the optical axis Z, and parallel to the X and Y axes) of receivers (SOE+cell) with respect to the POE Fresnel lens.
- Longitudinal shifts (along the optical axis) of receivers both away from/towards the POE Fresnel lens.
- Lens warp (spherical shape) effects on performance, to analyze one of the major concerns in CPV industry based on PMMA Fresnel lenses

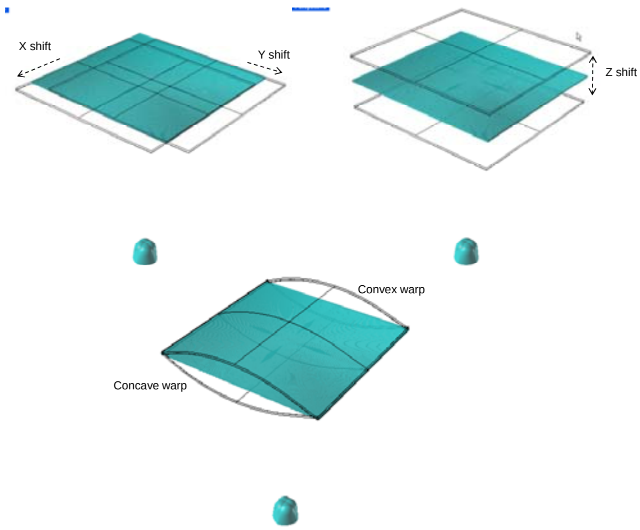

Figure 5 This work analyzes the effect of lateral and longitudinal shifts between the optical parts of the FK system, along with the effect of lens warp**.**

The following table shows the maximum shifts the FK can bear when we fix different acceptability criteria. The figures are referred to the cell size or the lens equivalent focal distance f and have been calculated with a FK of equivalent f-number = 0.85 (system optical depth f/lens diagonal) and Cg=625×.

Table I: FK concentrator tolerances are limited by the loss of acceptance angle, rather than efficiency. According to the results gathered in this table, for a 250mm side-length lens and 1cm^2 solar cell, 1.5mm and 7.7mm lateral and vertical shifts are allowed, with no efficiency loss and still maintaining a ±1deg acceptance angle.

Criteria	Maximum lateral shift	Maximum vertical shift
10% efficiency drop	0.8 *l*	0.08 *f* (or 2.7 *l*)
20% efficiency drop	0.95 *l*	0.09 *f* (or 3.3 *l*)
10% acceptance drop	0.13 *l*	0.018 *f* (or 0.65 *l*)
1deg acceptance	0.15 *l*	0.021% *f* (or 0.77 *l*)

We have found it is the acceptance angle criteria that limits in all cases. In fact, the FK concentrator maintains the original efficiency for longitudinal shifts more than twice the side of the cell. Notice the system is more sensitive to lateral shifts, which is logical if we think on the FK design principles: in this system, the loose of performance occurs due to cross-talk between sectors. However, an error of 15% the side-length of the cell is affordable still keeping ±1deg acceptance angle and no losses at normal incidence.

PMMA Fresnel lenses are low-weight, efficient and potentially inexpensive (continuous roll embossing produce large area array of lenses facilitating assembling and alignment). Although this technology seemed free of competitors for some time, the lens warp noticed (which is probably linked to moisture absorption of the acrylic, and typically shows a equivalent curvature radius of 10m, is encouraging some manufacturers to try alternatives such as those based on Silicon on Glass (SOG), since such warp implies important light leakage in systems of scarce acceptance.

We have analyzed the effect on FK performance warp (curvature radius = 10m), and found out the system is quite insensitive to such warp, as Table 1 shows.

Table 1 A 10m-curvature warp on the Fresnel lenses imply a slight drop in the FK actual acceptance angle achievable, but does not compromise efficiency.

Type of warp (10m)	Acceptance
Concave	±1.12º
Convex	±1.15º

This is a very important result, since SOG is nowadays more expensive than PMMA. And its potential to reach competitive costs is an unknown.

Some of the benefits of having loose tolerances are easy to anticipate. In general, if we fix the maximum admissible manufacturing costs, the systems can be built with lower risks and the production yield (number of nice performance systems per year) increases, or we can exhaust the tolerance "budget" reducing the accuracy and costs needed at each manufacturing step.

These are some performance enhancements we can achieve by using high acceptance angle solutions:

- Array performance (low series connection mismatch)
- Efficient energy production under wind loads
- Collection of circumsolar
- Lower sensitiveness to soiling –dirt-.
- Insensitivity to lens war.

And these, some of the different aspects we can act on aiming at a cost reduction.

- Optical components manufacturing (shape and roughness)
- Module assembling
- Tracker structure stiffness
- Tracking accuracy

3. OUTDOOR MEASUREMENTS OF THE FK CONCENTRATOR

The FK prototype consists of 4 stage Fresnel lens, with active area of 625cm2, made of PMMA (n≈1.49), B270 glass molded SOE without anti-reflexive coating (Figure 6) coupled to the cell with a transparent silicone rubber of n≈1.41 (Sylgard 182 of Dow Corning) and high efficiency (≈38%) 1cm^2 commercial triple-junction cell mounted on aluminium heatsink. FK prototype, shown in Figure 7, was designed for f-number of 0.85.

Figure 6: FK SOE

Figure 7: FK prototype

In the Figure 8 is shown a measured IV-curve of such mounted FK prototype. Measurement shown is not temperature corrected (so is somewhat pessimistic) and is preformed under the DNI of 835W/m2. The power produced by this module was 15.75W what corresponds to the efficiency of 30.24% (see Table 3).

Table 3 Outdoor measurement results

Isc	Voc	Pmp	FF	DNI	Eff.
6.05A	3.06V	15.75W	85%	835W/m^2	**30.24%**

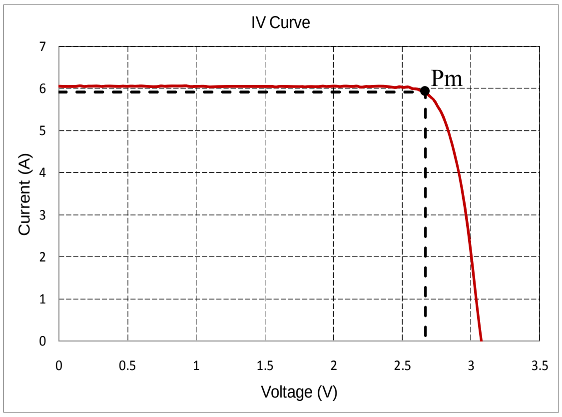

Figure 8: Measured IV-curve

The modules show maximum power with the sun irradiance perpendicular to the surface which is the principal axis of the system. With increasing deviation between principal axis and sun irradiation the focus points of Fresnel lenticulations move on the SOE surface, what results in a power loss defined by the acceptance angle measurement.

For the acceptance angle measurement the tracker is fixed in a position which the sun will reach within a certain time. Then the electric performance is measured continuously while the sun is passing the optimal position. By establishing a relationship between the electrical measurement and the angle arising from the position the sun takes compared to the optimal position a transmission curve is achieved (Figure 7). Measurements have been done under the DNI of 975W/m^2.

With the sun incidence of 1.24º the FK efficiency drops off to the 90% of its nominal value, what is just 0.01º less than the simulated result (see comparative curves in Figure 7). It can be seen that simulated and measured curves apart of close acceptance angle, have the same pill-box shape.

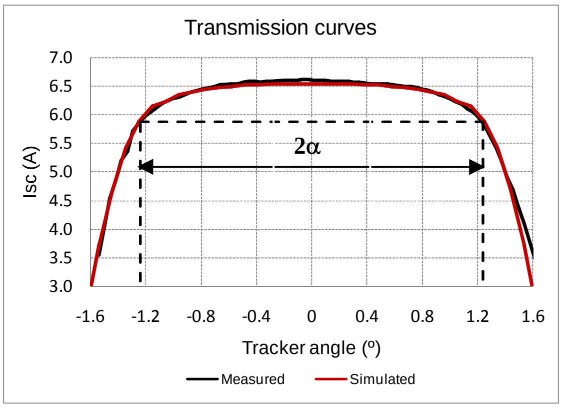

Figure 9: Simulated and measured transmission curves (α_{sim}=1.25º and α_m=1.24º)

Another important issue for system durability is the irradiance distribution on the cell. It can be measured by taking and analyzing picture of SOE back surface without solar cell, as the one shown in Figure 10.

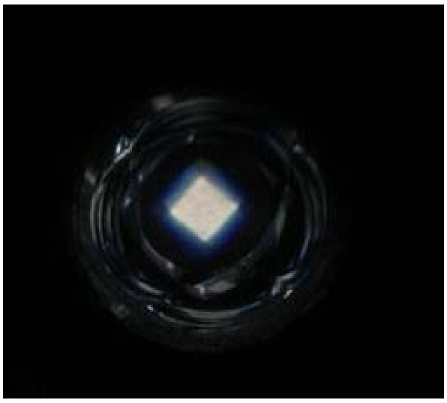

Figure 10: Illuminated SOE back surface

Analyzing the picture, the irradiance distribution on the cell can be obtained (Figure 11). The maximum irradiance values are maintained below 650 suns for DNI values of 850W/m^2 (same conditions as assumed for simulations shown in previous section).

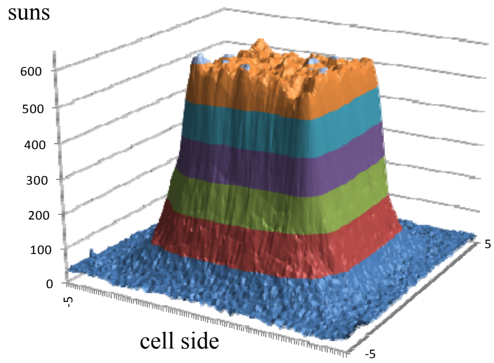

Figure 11: Measured FK irradiance distribution

4. CONCLUSIONS

The FK concentrator is a highly-tolerant technologically-simple system. Apart from attaining medium-high concentration-acceptance angle product (CAP) is capable of providing perfect irradiance uniformity on the solar cell, which is one of the factors to make a system durable. The large acceptance angle relaxes the manufacturing tolerances of all the optical and mechanical components of the system included the concentrator itself and is one of the keys to get a cost competitive photovoltaic generator. The proof of concept presented here, is technologically very similar to the traditional Fresnel-based systems, but at the same time more reliable and able to facilitate a more relaxed fabrication, which makes it suitable for the array level.

The characterization of FK prototype has been presented. This is the first step of demonstrating a novel concept that can significantly cut off the cost of CPV system, thanks to its excellent performance, low aspect ratio, high efficiency and CAP and at the same time excellent manufacturing tolerances.

4.3 References

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