# Freeform optics for Photovoltaic Concentration

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**Abstract:** Freeform surfaces are the key of the state-of-the-art nonimaging optics to solve the challenges in concentration photovoltaics. Different families (FK, XR, FRXI) will be presented, based on the SMS 3D design method and Köhler homogenization.

**Keywords:** optical design, concentrator, photovoltaic, nonimaging, Köhler illumination

## 1. Introduction

Concentration Photovoltaics (CPV) is one of the most promising areas for competitive solar electricity production. This promise relies upon the use of high-efficiency triple-junction solar cells (which already have proven efficiencies over 43%) and upon advanced optics designs, which allow for high concentration (>500) concurrent with high manufacturing tolerances, both key elements for low cost mass production of the CPV system.

Minimizing energy cost (€/kWh) is a necessary task for the success of concentrated photovoltaic energy (*CPV*). Key to minimizing this cost is an efficient and low cost optical design. These goals are best met with the fewest elements and the maximum tolerances, but always maintaining the high concentration that allows for preferential amortization of the cost of present high-efficiency triple-junction solar cells. A useful merit function for a *CPV* optic is the concentration-acceptance product [1], defined as:

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

where $C_g$ is the geometric concentration and $\alpha$ the acceptance angle, often defined as the incidence angle at which the concentrator collects 90% of the on-axis power [1]. A more practical definition says that it is the angle at which the generated photocurrent is at 90% of the maximum (often achieved at normal incidence), and this is teh one consider here. This definition gathers all the optical and electrical effects and is therefore more realistic. It is remarkable that for a given concentrator architecture, the *CAP* is practically constant.

For a given $C_g$, the acceptance angle $\alpha$ measures the total tolerance available to apportion among the different imperfections of the system: (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, (6) solar angular diameter, (7) lens warp, and (8) soiling. Each of these imperfections can be expressed as a fraction of the tolerance angle, so that, all together, they comprise a “tolerance budget”. Alternatively, for a given acceptance angle, a higher *CAP* allows a higher concentration, consequently reducing needed cell size (and cost). The actual impact of *CAP* on receiver costs has been analyzed recently in a study that compares several Fresnel-based systems [2].

## 2. The freeform advange

Classical photovoltaic concentrators relay on the use of rotational or cylindrical symmetric optical surfaces. However, in many cases, breaking the symmetry allows to achieve performance levels unattainable with the classical approach.

A good example is that situation is the design of an asymmetric CPV optics using a mirror as Primary Optical Element (POE), i.e., the one intercepting the sun light first. That asymmetric configuration is of interest to hide the solar cell receiver and heat sink behind the adjacent mirror, avoiding shading and thus maximizing the filling-factor of the aperture (see Fig.1).

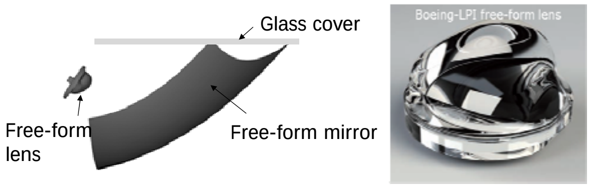

Fig. 1. XR free-form concentrator.

In order to achieve a high CAP, this extremely asymmetric problem is best solved using free-form optics. The SMS 3D design method, which designs two-free form surfaces without the need of optimization, has been used to design the high performance asymmetric mirror-lens combination shown in Fig.1 (XR, in the SMS nomenclature, where X stands for reflexion and R for refraction) [1]. The freeform lens, shown on the right of Fig.1 deviates from a rotational surface several millimeters. It was developed by LPI in collaboration with Boeing in the framework of the Solar America Initiative. Module solar-to-electrical efficiencies up to 33% have been measured (with AR coated SOE and cover glass). This XR achieves an acceptance angle of $\alpha$=±1.85º at $C_g$=1,000x, which implies a CAP ~ 1, the highest ever reported to our knowledge. A decentered rotational optics solution probably achieves a CAP < 0.4, which implies that the concentration is lowered to 1,000x0.4$^2$=160 to keep the same acceptance angle.

## 3. Freeform Köhler homogeneization

For optimum and reliable operation, the solar cell must be illuminated with suficient irradiance homogeneity and without color separation. The XR shown in Fig. 1 provides it with a prism-type kaleidoscopic homogenizer, which protrudes from the back of the free-form lens. This prism, which works by total internal reflection (TIR) is very short (~cell size) compare to others used in conventional designs, which makes is more economical, but still present some challenges, because the optical coupling of the cell and the SOE is very critical for the prisms (lateral spillage of the silicone rubber causes significant optical losses from leakage through it, and protecting the cell from moisture becomes difficult).

This has solved at LPI with a different concept, based on the design of freeform Köhler arrays [5], in which multiple functionalities are introduced in just two optical elements (POE and SOE), providing the required concentration with high tolerance and excellent light homogenization. In Köhler SOEs the silicone overflow does not affect the optical performance, greatly simplifying the joint coupling.

Different concentrator families have been developed: the XR [4], the XXR [6], the FK [3], and the F-RXI [8]). The most developed to date, the FK concentrator, consists of a Fresnel lens comprising four identical folds or quadrants, along with a free-form secondary lens, also divided in four equal sectors. Each POE + SOE pair works together as a couple. Using the Köhler illumination principle, each quadrant of the POE images the sun on its corresponding counterpart sector in the SOE, while the SOE sector images the POE ray bundle onto the cell, producing a uniform square spot onto it (see Fig. 2).

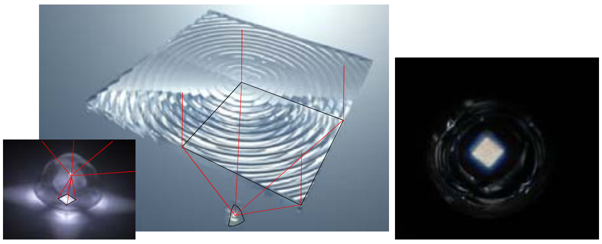

Fig. 2. On the left, rendered views of the FK concentrator. On the right, true illuminated SOE back surface.

The FK achieves a CAP up to ~0.62 ($\alpha$=±1.1° at Cg=1,000x), significatly lower than that of the XR, but still very high compared to their competing architectures using flat Fresnel lenses as POEs (which are inferior to mirrors [3]). Modules based on the FK have achieved over 32.5% solar-to-electric efficiencies [9] (corrected for 25ºC solar cell temperature) without using any AR coating, which promises to surpass 34% with AR on the SOE only.

## 4. Application to spectrum splitting systems

More sofisticated freeform optics is being used to accomadate the specral division between a triple junction cell and a silicon cell, which is an architecture that can potentially achieve over 40% efficient modules. Fig. 3 shows a design proposed by LPI and UPM recently, which is based on the F-RXI architecture using a band-pass filter.

If we consider the flat Fresnel POE, the F-RXI is the one with highest CAP reported (CAP=0.85). This is very useful because the high CAP can be spent to obtained additional efficiency gains. In this case, we have used of an external confining cavity, which occupies one hemisphere around the cell to recover the light that it reflects (sending it back to the cell). That light power is not negligible in the 5-8% range, mainly caused by the reflection of the front metal grid lines. The use of a hemisphere for the cavity reduces the etendue available at the cell by a half, and thus the CAP automatically reduces by $2^{1/2}$~0.7.

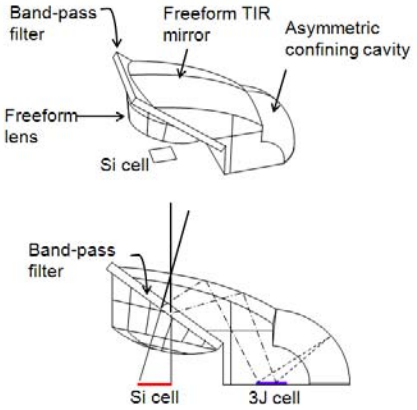

Fig. 3. Köhler RXI-RR SOE concentrator, with the band-pass filter and the 3J and BPC silicon cells, illuminated by a Fresnel lens POE (not shown).

## 5. Conclusions

Optical concentrators using freeform surfaces are improving the competitiveness of CPV via better tolerances, efficiency and manufacturability.

## 5. Acknowledgements

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