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Cool Covered Sky-splitting Spectrum-splitting FK

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Abstract. Placing a plane mirror between the primary lens and the receiver in a Fresnel Köhler (*FK*) concentrator gives birth to a quite different *CPV* system where all the high-tech components sit on a common plane, that of the primary lens panels. The idea enables not only a thinner device (a half of the original) but also a low cost 1-step manufacturing process for the optics, automatic alignment of primary and secondary lenses, and cell/wiring protection. The concept is also compatible with two different techniques to increase the module efficiency: spectrum splitting between a *3J* and a *BPC* Silicon cell for better usage of *Direct Normal Irradiance DNI*, and sky splitting to harvest the energy of the diffuse radiation and higher energy production throughout the year. Simple calculations forecast the module would convert 45% of the *DNI* into electricity.

Keywords: Fresnel lens, nonimaging, Solar concentrator, Köhler integration, CPV, Multi-Junction Solar Cells, Spectrum Splitting , DNI
PACS: 42.15.Eq, 42.79.Ek, 88.40.F, 88.40.H, 88.40.jj, 88.40.fc, 88.40.jp

INTRODUCTION: THE *CCFK*

The architecture of the *FK* concentrator allows the insertion of a plane mirror half the way towards the solar cell to bounce the light back, where it could be collected later if we place the original receiver (secondary optics *SOE* and solar cell) under the primary optics (*POE*) glass cover, looking downwards.

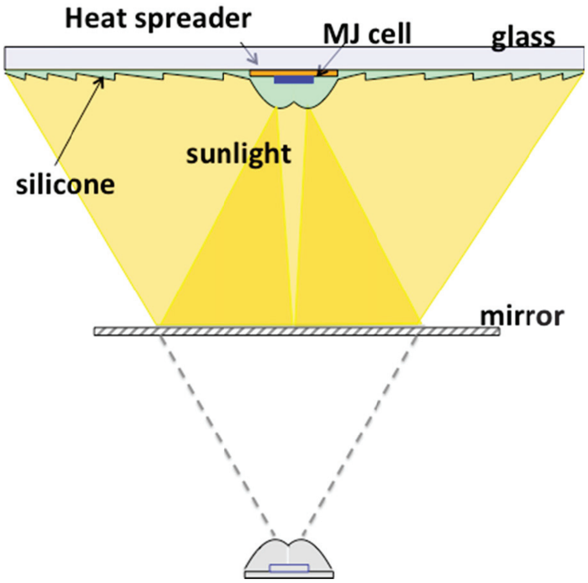

FIGURE 1. The *CCFK* concept is based in the *FK* concentrator: a plane mirror is located between the Fresnel lens and the receiver, which, thanks to the reflection properties, can be placed on the Fresnel lens panel facing downwards.

This device is called *Cover Cooled FK* (*CCFK*) and is patent pending. It device shares with the *FK* [1] a high *Concentration-Acceptance angle* product (*CAP*) and outstanding irradiance uniformity onto the solar cell, both spectral and spatial [2], yielding high performance features [3]. One novelty of this new *HCPV* concept, shown in FIGURE 1, is that the inner surface of the glass cover contains all the main components of a *CPV* system, namely: solar cells, optical primary and secondary (*POE* and *SOE*, molded in a single step Silicone-On-Glass (*SOG*)) and wiring. The over-molding of *SOEs* and *POEs* on top of the cells assemblies allows for a better protection of all electrical components, withdraws the need to invest on two different optical parts, and reduces alignment between parts to a minimum. Heat sinks can be avoided too, as long as the cell size and concentration are kept within reasonable levels (the models show 3mm-side length for the former and 500×for the latter would lead to temperatures of about 30ºC above the ambient). Only a heat spreader (screen-printed on glass, for instance) might be needed to spread the heat produced at the cell *CCA* all over the glass, where it can be removed by natural convection. The *SOE* and heat spreader cast a shadow at the entry aperture of about a 4%, so the efficiency loss is quite reasonable.

Owing to its flatness, the reflector can be a low-cost high-efficiency second-surface silver mirror, a technology that can yield reflectivity above 95%.The alignment of the front cover with the optical reflector is not necessary, only parallelism is required. The *CCFK* is very tolerant to the relative distance between

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this mirror and the top cover (relative shifts as long as the solar cell side-length are permitted).

The breakdown of elements included in the basic *CCFK* module is shown in FIGURE 2 in 3D.

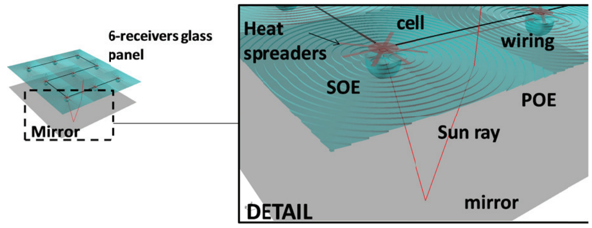

FIGURE 2.*CCFK* elements breakdown in 3D. This ultra-thin module comprises all high-tech components in one single plane substrate: that of the *SOG* lens panel. The silicone cast protects all these elements and the two optical stages are manufactured in one step and are automatically aligned with respect to each other

INCREASED ENERGY PRODUCTION: THE *CCs*^{4}*FK*

The performance of the *CCFK* can be dramatically enhanced with the addition of two technologies that are seldom utilized in practice: *Spectrum Splitting* and *Sky Splitting*. In this case, we have found a way to bring them into play in a simple and practical manner, thanks to the geometry of the *CCFK*.

Spectrum Splitting

The first one is based on "stealing" part of the *DNI* that typically produces a boost in the bottom junction photocurrent that is useless, owing to the series connection of this junction with top and middle ones (whose photocurrents are balanced by design typically, and are below that of the bottom junction). The part of the spectrum that can be split and directed to a back point contact high efficiency silicon cell (*BPC Si*) is in the near infrared, a fraction of the spectrum to which both this *BPC Si* cell and the bottom junction are sensitive. The beam split can be done by means of band-pass dichroic filter replacing the original mirror of the *CCFK* (FIGURE 3) the limited incident angles on that plane allow for a better performance of the filter and the facts that the beam is already concentrated (4×) at this stage and the filter can be evaporated on a plane substrate make its manufacture simpler and potentially cost-effective.

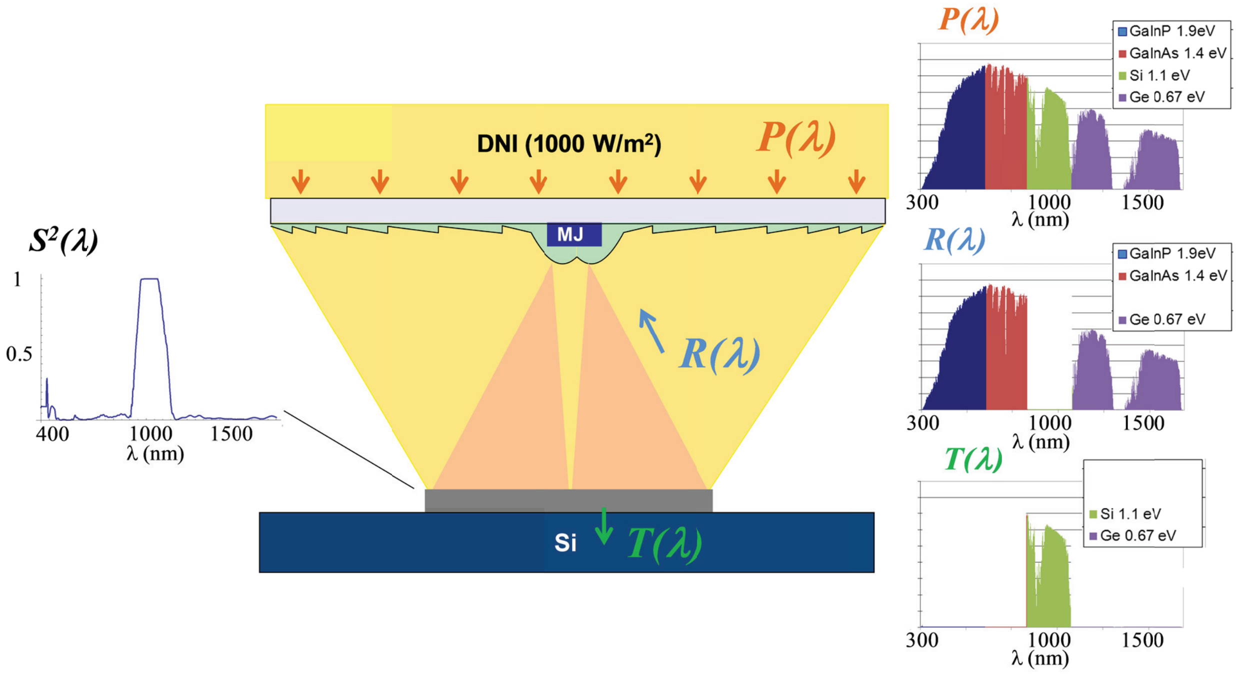

FIGURE 3. Spectrum splitting concept applied to the *CCFK* optical train. A band-pass dichroic filter $S^2(\lambda)$ reflects a part of the spectrum $R(\lambda)$ towards the *3J* cell while a fraction of the light, $T(\lambda)$ (originally producing an excess of current in the 3J cell bottom junction that is impossible to harvest) is transmitted to a silicon solar cell under the filter.

Models and preliminary prototype tests (with beams hitting the filter with 25deg) have demonstrated the potential of spectrum splitting using *3J* and *BPC Si* cells [4]. In a set up like the one shown in FIGURE 3, the two-cells (*4J*) combo can achieve a 13% boost in the efficiency (relative to the efficiency of the *3J* cell alone). Notice the thermal load of the *MJ* cell in this case is reduced due to the spectral division.

Sky Splitting

Notice there is still a sizable gap between the concentrated sunlight spots where the *BPC Si* cells are placed if the *Spectrum Splitting* concept is used. This free area can be actually filled by flat plate silicon cells that can cast the diffuse light crossing the Fresnel lens (FIGURE 4). This simple approach is called "*Sky Splitting*".

The usage of the diffuse radiation gives greater annual energy production and greater independence on the geographical location and weather conditions. The cost-effectiveness of this approach depends on these factors, electricity fees and on the price of flat *PV* modules.

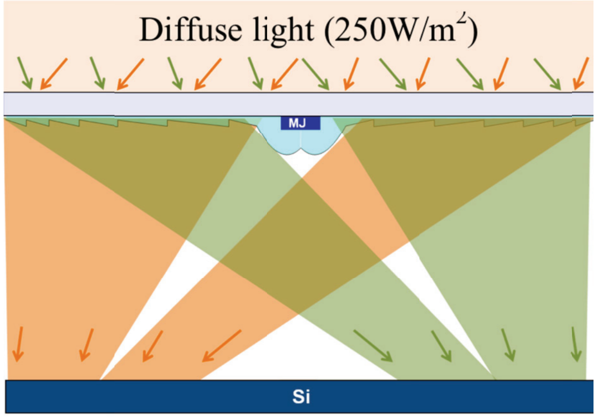

FIGURE 4. *Sky splitting* to collect diffuse radiation by means of adding flap plate cells at the bottom plane (instead of the original mirror)

Energy Production

A site like Madrid receives a yearly global radiation of about 2584 kWh/m^2 in two-axis tracking, 1880 kWh/m^2 being direct radiation and the rest diffuse. If we use *3J* and *Si* cells achieving 39.5 and 22% efficiencies, and considering the different sources of losses, we find out the *CCS^{4}FK* device can potentially deliver 859 kWh/m^2 every year. The breakdown is 635 kWh/m^2 delivered by the 3J cell, 75 kWh/m^2 by the spectrum splitting *Si* cell and 149 kWh/m^2 by the sky-splitting unit. The module would therefore turn into a 45%-equivalent *CPV* module (0.45=858/1880), i.e. it would yield the energy a 45% *CPV* module produces using only the available yearly *DNI* in Madrid.

For this calculation we have assumed the *SOE* casts a shadow of 5% of the total entry aperture area and an *AR* coating is applied to the flat entry glass surface. Additionally, the light reflected in the *3J* cell gridlines is bounced back to the *Si* back plate where a part of it is converted into electricity as well.

CONCLUSIONS

A novel *CPV* module concept has been presented. The approach offers significant performance and practical advantages while being simple at the same time. The basic *CCFK* concept already offers important practical advantages. On top of that, two techniques to increase the energy production can lead to an extremely-efficient module. The next step is demonstrating the technological feasibility of the concept with a prototype. The project will be submitted to different research programs but is also open for companies willing to invest in this module.

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