Free-form Fresnel RXI-RR Köhler design with spectrum-splitting for photovoltaics

M. Buljan[a], P. Benítez[a,c], R. Mohedano[b], J.C. Miñano[a,c] , Y. Sun[c], W. Falicoff[c], J. Vilaplana[b], J. Chaves[b], G. Biot[a], J. López[a]

[a] E.T.S.I.T. Universidad Politécnica de Madrid, Avenida Complutense Nº 30, Ciudad Universitaria, 28040 Madrid, Spain
[b] LPI Europe, S.L., Edif. CeDInt Campus Montegancedo UPM 28223 Pozuelo, Madrid, Spain
[c] LPI-LLC, 2400 Lincoln Ave., Altadena, CA 91001

ABSTRACT

The development of a novel optical design for the high concentration photovoltaics (HPCV) nonimaging concentrator (>500x) that utilizes a built-in spectrum splitting concept is presented. The primary optical element (POE) is a flat Fresnel lens and the secondary optical element (SOE) is a free-form RXI-type concentrator with a band-pass filter embedded in it. The POE and SOE perform Köhler integration to produce light homogenization on the receiver. The system uses a combination of a commercial concentration GaInP/GaInAs/Ge 3J cell and a concentration Back-Point-Contact (BPC) silicon cell for efficient spectral utilization, and an external confinement technique for recovering the 3J cell's reflection. A design target of an "equivalent" cell efficiency ~46% is predicted using commercial 39% 3J and 26% Si cells. A projected CPV module efficiency of greater than 38% is achievable at a concentration level greater than 500X with a wide acceptance angle of ±1º. A first proof-of concept receiver prototype has been manufactured using a simpler optical architecture (with a lower concentration, ~100x and lower simulated added efficiency), and experimental measurements have shown up to 39.8% 4J receiver efficiency using a 3J cell with a peak efficiency of 36.9%.

Keywords: Concentrator, free-form, spectrum splitting, high concentration, Köhler integration.

1. INTRODUCTION

At this time, the high concentration PV industry (HCPV) is focused on commercializing products based on triple-junction (GaInP/GaInAs/Ge) solar cells, to take advantage of the high efficiency these cells provide. Increasing the cell efficiency is a clear path for reducing the energy cost (€/kWh) of concentrated photovoltaic energy (CPV). Commercial cells from a variety of suppliers are close to 40% average efficiency, not far from the present world record 41.6% (see [3]). Even though competition between manufactures has resulted in a lowered triple-junction cell and assembly cost, these costs are still high requiring high concentration (>500) for the systems to be competitive in terrestrial applications.

Two main sources of conversion losses are present in HCPV triple-junction cells: (a) they do not fully utilize parts of the solar spectrum above 900nm, and (b) there are reflection losses off the face of concentrator cells, mainly due to grid line shading. Here we propose the development of a novel HCPV module with high concentration (>500) and wide acceptance angle ($\alpha > \pm 1^{\circ}$) that aims to reduce both sources of losses. The novel approach [20] uses the combined four junctions of a concentration (GaInP/GaInAs/Ge) cell and a Back-Point-Contact (BPC) concentration silicon cell for efficient spectral utilization, as well as an external confinement technique for recovering the reflected light from the cell. The silicon bandgap is nearly ideal for combining with the other three gaps (with a theoretical limit of 57% for two terminal devices (see [4]), which makes the combination very attractive.

At present, the External Quantum Efficiency (EQE) of 3J cells is handicapped by the reflection losses from its face. These losses are very significant and severely limit the performance of the devices. In the case of GaInP/GaInAs/Ge solar cells, the front grid design is optimized to keep the series resistance joule losses low while minimizing the front metal grid shading factor. Reflection losses are produced by the reflection on the metallic front gridlines and the Fresnel reflection on the semiconductor surface. One of the strategies to recover light reflected by the 3J cells has been referred to as External Confinement [11] is compatible with high concentration optical systems. It consists of a mirror cavity that retro-reflects the reflected light from the cell back to the cell.

One of the most promising strategies for improving the utilization of the solar spectrum in multi-junction cells is the use of four or more p-n junctions. Different strategies have been followed to increase the number of junctions built into a solar cell such as: conventional epitaxial growth over a substrate (lattice matched and metamorphic), wafer bonding/ layer transfer process layer, and inverted metamorphic cells. The jury is still out on these approaches and other alternative ones. And it is still not known if the new devices can be built affordably and have the reliability and capacity to work efficiently under high concentration.

An alternative approach consists of using separate cells and dichroic optical filters. Compared to single cell solutions, this approach has the possibility of avoiding the current-mismatch losses through the use of multiple terminal configurations, thereby eliminating the lattice matching prerequisites of monolithic growth. However, the development of a commercially viable product based on this approach is very challenging due to probable increased material cost and system complexity. Even so, in the last few years, the dichroic beam-splitting approach has captured renewed interest [5][6][7][8][9].

The need for competitive HCPV systems requires that the optical concentrator is designed not only to provide high concentration but also sufficient tolerances in order to keep the cost manufacturing low. A useful merit function for a CPV optic is the concentration-acceptance product [12], defined as:

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

where, Cg is the geometric concentration and α the acceptance angle, often defined as the incidence angle at which the concentrator collects 90% of the on-axis power [13]. A more practical definition states it is the angle at which the generated photocurrent is 90% of the maximum (often achieved at normal incidence). This definition gathers all optical and electrical effects and is therefore more realistic. The acceptance angle (α) measures the total tolerance available in the system for a given Cg. 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, the 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 ensure that their operating in the tunneling region [14]. This is especially important in high concentration designs as is the the case for those 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 [15]) due to local current mismatch between the top and middle cells.

Good irradiance uniformity on the solar cell can potentially be obtained using two well-known methods in classical optics: kaleidoscope homogenization and Köhler integration. With a kaleidoscope homogenizer the solar cell is bonded to one end of the kaleidescope and the light reaches the cell after bouncing on its walls. The light distribution on the cell can be uniform with a 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 now being investigated and applied to PV concentrators.

We have incorporated the aforementioned novel approaches into a new type of HCPV nonimaging concentrator. The system consists of a novel Fresnel RXI-RR Köhler concentrator that achieves a high concentration (>500x) with a built-in spectrum splitting feature. The system has a primary optical element (POE) that is a flat Fresnel lens, and a secondary optical element (SOE) that consists of a monolithic free-form Köhler RXI-RR concentrator and an embedded cost-effective high-performance band-pass filter that reflects or refracts the light rays while crossing the device. The Fresnel RXI-RR concentrator performs Köhler integration and is designed using 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 [1], which is the branch of optics that provides solutions that achieve theoretical maximum efficiency light transfer.

A proof-of-concept prototype that is based on a simpler optical concept has been manufactured by LPI and UPM-CeDInt. The prototype (seen in Figure 1) is comprised of an RXI prism, with a 41-layer stop-band dichroic filter (deposited on the long right angle prism leg proximate to the 3J cell), a GaInP/GaInAs/Ge cell and a BPC concentration silicon cell. The entry aperture (hypotenuse of the prism) is AR coated with a proprietary design by LPI. The short side of the right triangle leg of the prism also has the same AR coating, which ensures high transmission of the prism to the silicon cell, which has an air gap between itself and the prism. The filter was designed to reflect the light whose wavelengths range between 900-1150nm to the silicon cell, transmitting the light whose wavelengths are outside this range to the 3J cell. This prototype doesn't include confining cavity, so reflected radiation of the semiconductor and grid-lines is sent back through the filter to the silicon cell. Although, this prototype still illustrates the high potential of the spectrum splitting concept.

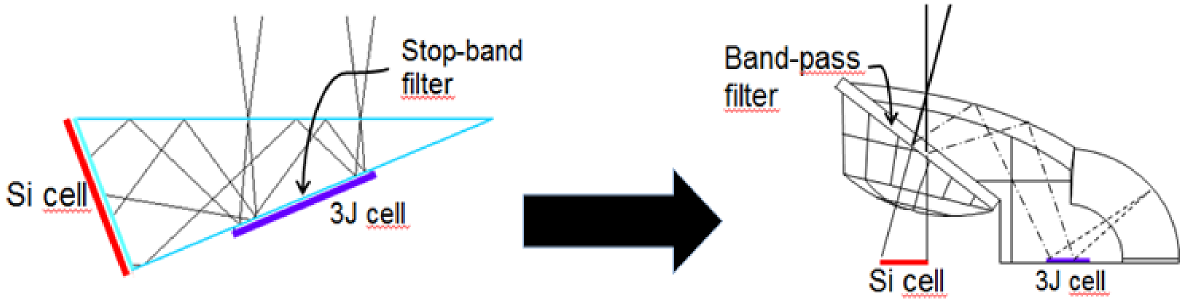

Figure 1 Design principle: proof-of concept model and new optical design RXI-RR, respectively.

The results we have achieved to date are very significant and promising, especially taking into account the problems found in the coatings manufactured in this first iteration. Optical transmission measurements of the manufactured filter coating have shown important deviations from the design values. From measured values we could predict that there is a higher reflection of photons below 900nm to the silicon cell. The measurement of the manufactured AR coating showed that it produces a transmission ~96% over 900 nm, instead of the designed 98%. In first phase we were using 100x concentrator rig to measure the prototype and have obtained a +8% efficiency gain. In the next phase we plan to use a concentrator rig with higher concentrations (~300x). Commercial 3J cell and BPC Si cells will operate at higher efficiencies in this new configuration as the concentration ratio will be closer to optimum levels.

2. FRESNEL-RXI KÖHLER CONCENTRATOR DESIGN

The concept of the Fresnel RXI-RR Köhler concentrator is shown on Figure 2. The primary optical element (POE) is a flat Fresnel-Köhler lens, and the secondary optical element (SOE) (a monolithic free-form Köhler RXI-RR concentrator), includess an embedded band-pass filter and an external confining cavity. The letters naming the device originate from the usual nomenclature of the SMS method [1], and refer to the type of surface (R=refraction, X=reflection, I=Total Internal Reflection) that reflects or refracts the light rays while crossing the device. RXI-RR free-form surfaces are calculated with the SMS method using an iterative process in three dimensions.

In the RXI-RR SOE concentrator, the RR illuminates the BPC silicon cell, while the RXI illuminates the 3J cell (see Figure 2). The triple junction cell is asymmetrically illuminated from one hemisphere, allowing the use of a confining cavity in the other hemisphere which efficiently collects the light reflected by the grid lines and the semiconductor surface of the triple junction cell.

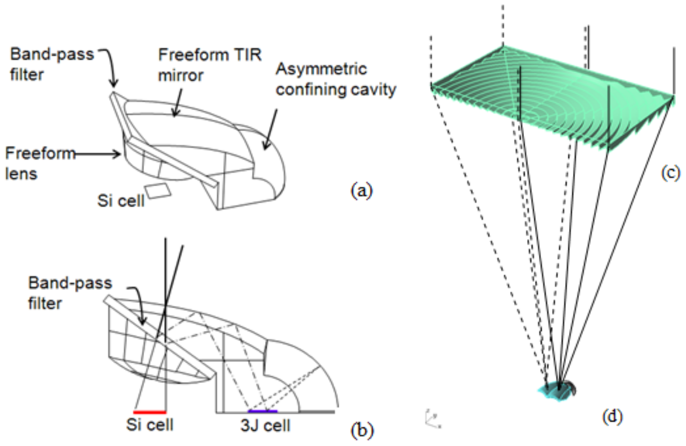

Figure 2 (a) & (b) 1-fold Köhler RXI-RR SOE concentrator, including the flat band-pass filter and the GaInP/GaInAs/Ge and BPC silicon cells. (c)Asymmetric 2-fold Köhler Fresnel lens illuminating the corresponding 2-fold RXI-RR SOE (d) (extracted from [10]).

Optical design description

This design presented here is based on the previously developed free-form 4-fold design RXI recently introduced as a Köhler secondary for HCPV [16]. This Köhler-based CPV optical device has a Fresnel lens used as primary element (POE) with an RXI as a secondary element whose surfaces are calculated using the SMS design method in three dimensions.

In the RXI-type, secondary rays undergo a refraction (R), reflection (X) and total internal reflection (I), so the SMS nomenclature for this device is RXI, assigning letters to each surface that deflects rays (see Figure 3). The goal is to design optics that produce the desired light concentration with a high tolerance (high acceptance angle) as well as an excellent light homogenization (through the use of Köhler integration).

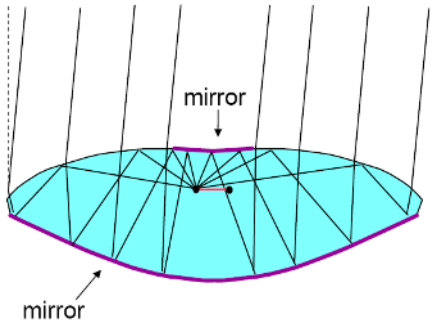

Figure 3 RXI concentrator geometry. (Primary Fresnel lens not shown.)

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 [1] and later with free-form surfaces [2]. The free-form RXI was originally developed for Solid State Lighting in the automotive industry, and it has been recently designed for HCPV applications.

Calculation of the free/form surfaces is performed using free-form wavefronts at the RXI entrance and focusing those wavefronts to the corresponding points of the cell's active area. It is important to ensure that a source at infinity (the sun) is imaged on these points on the cell.

The RXI design in general 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 is deduced from the circumstance that two distinct optical surfaces, the chosen surface R and the calculated surface I, must be the same physical surface.

In the design of Köhler concentrators, we select the number, N, which indicates the number of paired Köhler sectors in the POE and SOE. The design is then referred to as an N-fold design, and N usually ranges between 1 and 4. In first Fresnel RXI 3D Köhler design carried out by the group we developed [16] a 4-fold design (see Figure 4), while for the Köhler RXI-RR design we limited our research to 1-fold and 2-fold options.

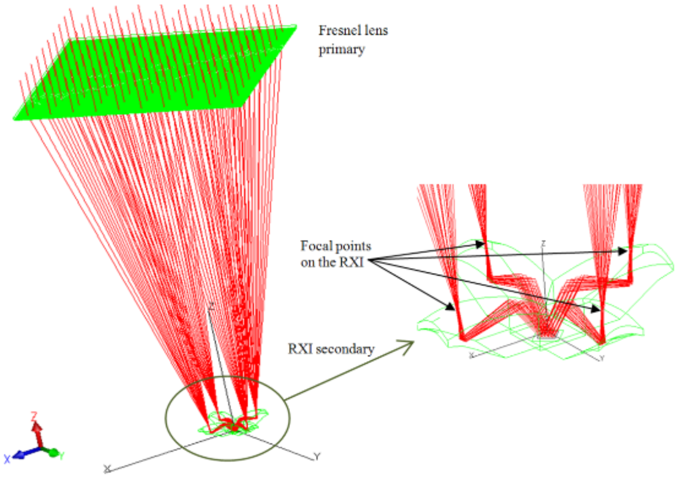

Figure 4 Ray tracing on the SOE of a 4-fold Fresnel-RXI Köhler showing performance of the 3D Köhler free-form FRXI concentrator. Light that enters is focused by the Fresnel lens on the corresponding SOE's lenticulations in order to obtain an uniform irradiance on the cell (extracted from [16]).

Two previously designed systems are FRXI with small metalized frontal area and FRXI without frontal metallization (FRXI**). We would like to point out that the free-form 4-fold RXI has the highest "CAP budget" among concentrators with a refractive POE (see Figure 5). This high "CAP budget" is actually the tolerance budget that we can invest in an additional element (external cavity in FRXI-RR design) in order to reduce 3J reflective losses and still achieve the necessarily high concentration and acceptance angle.

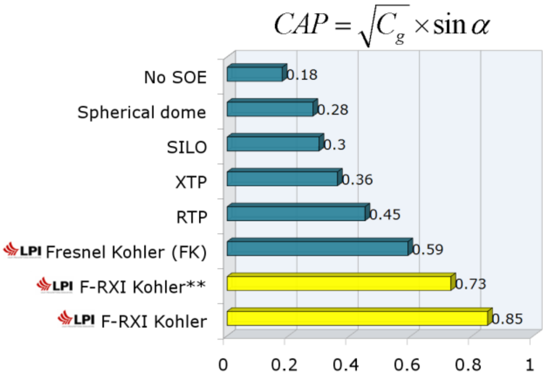

Figure 5 The Fresnel-RXI Köhler concentrator surpasses the Concentration Acceptance angle product (CAP) of all the existing commercial concentrators using a flat Fresnel lens as a POE (extracted from [16]).

There are various advantages of the RXI-RR design over prior beam splitting systems such as a reduction in complexity. First, the filter, the SOE for the BPC silicon cell (i.e., the RR) and the SOE for the triple-junction cell (i.e., the RXI) form a single piece of dielectric, which simplifies its mounting. Secondly, the two cells are located on the same plane, simplifying the heat management and wiring. Thirdly, there are no optical surfaces in contact with the cell rim, which differs from other traditional HCPV secondary optics (such as prism homogenizers). This makes the encapsulation of the cells much easier and more robust, since there is no threat of light loss due to meniscus effects by the silicone rubber coupler, making it more suitable for high-yield in mass production [18].

There are alternative SOE's architectures that have been considered. Freeform RXI-RI^2 configuration allows the Silicon and 3J cell to be located not only coplanar but also closer than in the RXI-RR, so they can share the receiver substrate. This design, with a geometrical concentration of 625x for the 3J cell and 560x for the Si cell, has a modeled optical efficiency of 85% for both the 3J and silicon cells (no AR coating considered). In addition it exhibits a well-balanced acceptance angle of ±0.9º for both cells as well as achieving uniform irradiance distribution on 3J and Si cells as evident in Figure 6. The Köhler integration technique guarantees in this design, as well as in other previously presented ones, uniform illumination on both cells, free from spatial chromatic aberration.

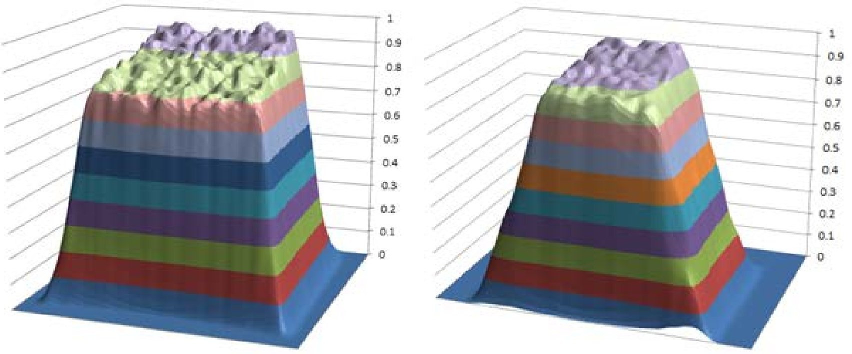

Figure 6 Irradiance distributions on the 3J and Si cells (a.u.), respectively.

Confining cavity

Apart from possibility to increase efficiency by improving solar spectrum utilization through the use of dichroic filter spectrum splitting, the new approach adds an external confining cavity to recover the lost reflected light from the 3J cell. As already mentioned, this feature consists of a mirror cavity that collects the light reflected by the cell either by the gridlines or by the semiconductor surface and sends it back to the cell. (Light absorbed on the grid lines is not recovered.)

For present triple-junction cells, the light reflected on the semiconductor surface is specular (the cell surface roughness is very small, similar to good optical mirrors), while the light reflected on the grid lines has a significant diffuse component caused by the grid line geometry and roughness. However, the roughness and imperfections of the grid line surface still keep the same cylindrical symmetry, as a good approximation (see Figure 7). Therefore, the direction of the scattered light conserves the vector component along the grid line, and a light ray is scattered inside the surface of a reasonably narrow cone. This is important for the design of the concentrator and the external cavity (which traditionally has assumed random Lambertian scattering). As was stated before in this approach the illumination of the cell must be done from one hemisphere, while the cavity occupies the other (asymmetric cavity).

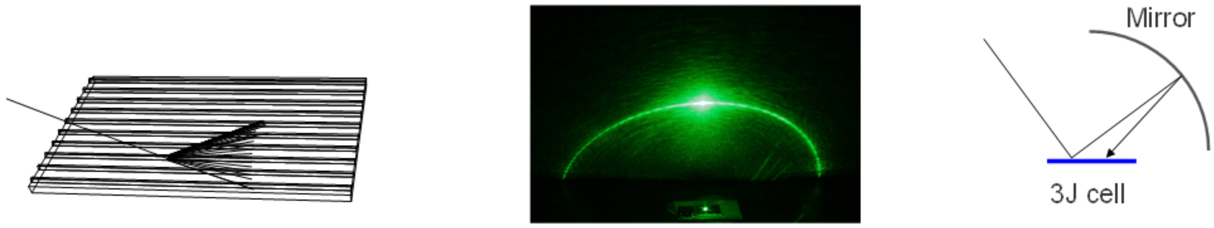

Figure 7 The irregularities and roughness of the gridlines of a commercial concentration triple-junction cell has approximately cylindrical symmetry, which allows efficient external confinement with an asymmetric cavity.

In case of our design we are investing a half of the system to enhance the overall efficiency by means of external confining cavity. Having sufficient tolerance budget in our optical design, we are in a position to do it as it was already explained in previous subsection.

Band-pass filter

The performance specification of filter embedded in RXI-RR SOE is limited by costs constraints. In order to achieve the price target we have restricted our concentrator design to operate using a flat filter. On one hand we would like the light to reach the filter with high concentration in order to lower the size and thereby cost (€/m2) of the filter (that are meant to be deposited on large plane substrates), but on the other hand high concentration means wide incident angles α_F, that smoothen the filter transmission curve, which compromises the current balance.

The necessity to moderate values of α_F suggests limiting the concentration on the filter to the minimum that is cost effective (~40-50x). That is why an SOE is utilized after the filtering, which provides an additional 10-12x concentration on the cells. We have selected $\beta_F > 25^{\circ}$ and $\alpha_F > 5^{\circ}$, when the surrounding media is a dielectric material ($n \approx 1.5$).

The EQE of the four junctions and its aggregation curve for the four-terminal case are shown in Figure 8a. The dip in the aggregation curve near the silicon band-gap corresponds to photons which are sent to the silicon cell but not efficiently absorbed by it. The effectiveness of the external confinement cavity is clear in Figure 8b by the comparison of this curve with the original EQE's of the triple-junction cell.

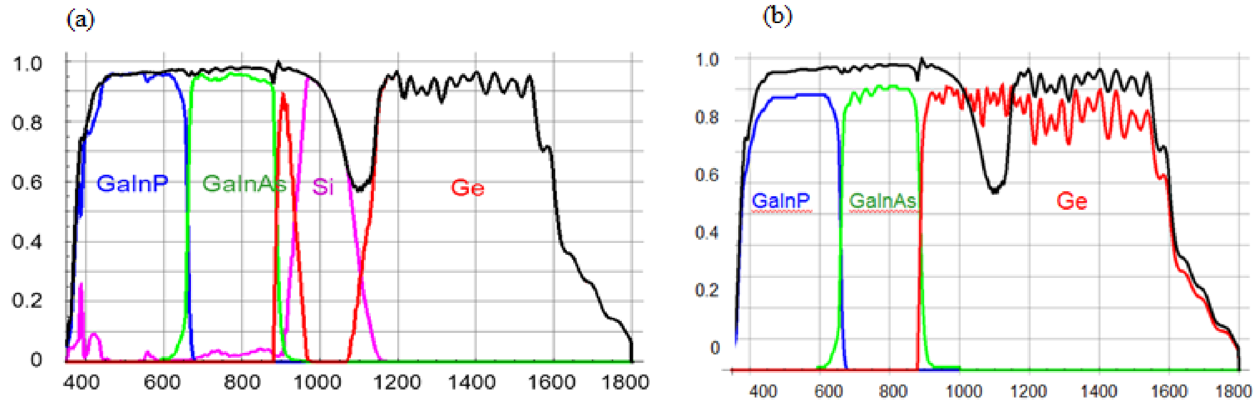

Figure 8 (a) EQE of the four junctions of an RXI-RR design for four terminals, and its aggregation. Our modeling indicates that this design should achieve about 46% efficiency under AM1.5d with 39% 3J cell and 26% silicon cell. (b) The same aggregation overlapped with the original EQE of the triple-junction cell where the increase of the EQE due to the external confining cavity can be appreciated.

3. CONCLUSIONS

The main objective of this work is to increase the overall system efficiency and reliability of CPV system through the use of solar spectrum division thereby reducing lifetime energy cost (€/kWh). Our approach was guided by an analysis of the causes of receiver/optics losses and resulting improvements in the optical system design through more efficient use of the available energy in the bottom cell of a 3J cell.

The type of solar concentrator described herein was designed using the most advanced design method in the field of the Nonimaging Optics. This approach allows one to obtain devices with acceptance-concentration products approaching the maximum value as derived from the étendue conservation theorem. We have presented a novel high-concentration Köhler SOE concept with an integrated dichroic flat filter for coplanar commercial 3J cell and BPC Si cells, with expected equivalent cell efficiency of 46% from 39% 3J cells (+17% gain). The first simple prototype showed an +8% efficiency gain, and the next iteration (with an improved filter) targets a +13% gain and 43% efficiency at 300x (see Table 1). Future efficiencies of over 50% could be attainable with custom designed 3J (with better Ge sub-cells) and Si cells (with better IR response).

	Measured	Expected
Reference 3J	36.9%	37.4%
4J prism	39.7%	42.5%
Gain	**+8%**	**+13%**

Table 1 Measured efficiencies of the 3J reference cell and 4J prism receiver in 4T operation (corrected for Tcells=25ºC).

4. AKNOWLEDGMENTS

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