

MIRROR BASED SPECTRAL SPLITTING CPV SYSTEM

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ABSTRACT: CPower Srl has been designing and developing different Mirror Based Spectrum Splitting Systems (MBS³), partially supported in the framework of European APOLLON Project, mainly to minimize the cost/performance ratio.

The concentrators employ dichroic dielectric filters working for light interference, that is an alternative respect to other spectral splitting concepts based on the refraction of the light, to spatially spread the wavelength of the spectrum. The dichroic mirrors are introduced in an intermediate plane between primary optics and the receivers. This design permits two different levels of geometrical concentration (40x and 600x), suiting well with the requirements of Si cells (primary receiver) and III-V cells, in term of economics and electrical performances.

The optimization of CPower spectrum splitting systems goes through the optimization of optics components, the complete automation of receivers assembly and the designing of a dedicated tracking system. The new module design also allows a better thermal management without shadowing due to heat dissipation elements.

Keywords: Concentrators, Spectral splitting

1 INTRODUCTION

The dichroic approach for concentrators have been recognized for long time as an effective way for high efficiency PV conversion, however it has not been employed till now in commercial products because of its complexity for the consequent related costs.

The so called Mirror Based Spectrum Splitting Systems (MBS³) development is partially supported in the framework of European APOLLON Project, a multi-approach project concerning the optimization and development of concentrating systems. The main goals for the MBS³ approach in the project are the optimization of high efficiency fully industrialized systems minimizing the cost/performance ratio [1].

CPower Srl are developing Mirror Based Spectrum Splitting Systems, where the light is concentrated using geometrical optical solutions based on reflection and the splitting of the spectrum is obtained using the interference of the light (dichroism) that is an alternative respect to other spectral splitting concepts based on the refraction of the light to spatially spread the wavelength of the light.

After the first experimental modules, proofs of concept of the basic schemes, optimized design and manufacturing processes are thought with a commercial purpose: this needs significant innovations to achieve competitive performances, reliability and safety for in-field installations.

The optimization of CPower spectrum splitting systems goes through the size reduction of the optical units in order to have shorter modules profile and an innovative design for the secondary optics allowing for a higher optical acceptance, low optical losses and the direct connection of receivers of the two different cells with the rear side of the module.

2 THE SPECTRAL SPLITTING APPROACH

The spectral splitting of the concentrated light gives some important advantages; it permits to use different kinds of cells in a module without suffering of the current

limitation produced by a series connection like in the monolithic multi-junction solar cells; it permits to use different levels of concentration on different materials and to distribute the heat on two different regions.

On the other hand, the system presents a certain complexity due to the many parts to be assembled and to the many optical interfaces which could give significant optical losses and additional costs.

The dichroic filter can be obtained using stacks of nanometrical layers of dielectrics on a glass substrate; these components are already objects of industrial production in the field of illumination

3 DICHROIC CONCENTRATOR DESIGNS

CPower has been working on CPV since its initial formation, following two main routes: one related to low concentration with Si solar cells [2] and another one related to high concentration; regarding this second application, CPower has focused its activity on the design of concentrators in which it's possible to employ a spectral splitting of the sunlight to get improved performances.

The first module using the dichroism effect developed by CPower is sketched in fig.1; it is an open structure composed of six sub-modules. Each sub-module has a concentrating optics of metalized, mould plastics, a first receiver with a dense array of silicon cells covered with a flat dichroic mirror which reflects back the concentrated light onto an homogenizer which guides the light on a dense array of InGaP solar cells.

This design permits two different levels of geometrical concentration (100x and 400x), suiting well with the requirements of Si cells (primary receiver) and III-V cells, in term of economics and electrical performances. To cool down the receivers, dedicated passive heat sinks have been realized.



Fig.1: Starting technology of dichroic module developed by CPower Srl

This first design presented some significant problems, both related to fabrication and design issues. On the manufacturing side, the mechanical deformations of the primary concentrator deliver a not uniform light distribution on the primary receiver leading to current mismatch on the cells in the dense array of the Si receiver and to significant optical losses at the secondary optics. The design was then changed to mitigate these effects, to improve the thermal management, to get the module in a closed and sealed box, improving the optical efficiency and the angular acceptance; moreover, the concentrating factors have been changed for economic reasons. The concentration on the primary receiver has been reduced, while it has been increased onto the second cell (40x and 600x respectively). This new design (Patent Pending) works using different optical effects like reflection, refraction, dichroism and TIR.

Regarding the optical efficiency improvement, the new design avoids the shadowing of the primary receiver shifting it behind the closest primary concentrator; with ideal surfaces and materials, i.e. with ideal ARC coating on the interfaces between perfectly transparent materials and with perfect reflectors, the optical efficiency achieves the 98.5% on the secondary receiver. In fig.2 a ray-trace cross section of the design is showed.

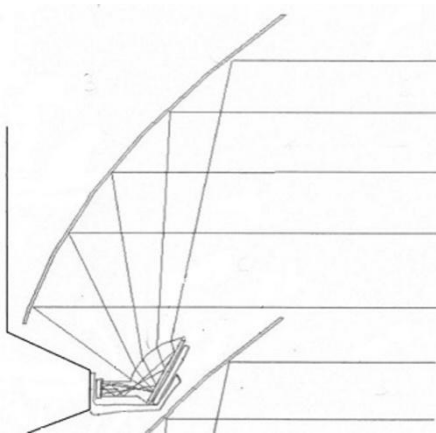


Fig.2: Cross section of a schematic raytrace for the new dichroic concentrator of CPower

With this configuration, the lens and the light guide act improving the angular tolerance of the optics and permit to make a compact structure with a uniform

irradiation on the secondary cell. The short distance between the two receivers under different concentration level allows to mechanically join both of them to the rear side of the module. This gives very good heat sinking from both the PV cells; from numerical simulations carried out by Robotiker/Tecnalia, partner in the Apollon project, the temperature of the cells achieves 55°C in the conditions of $DNI=850W/m^2$, 35 °C of air temperature and absence of wind.

The designed module has 15 concentrating units, as represented in fig.3.

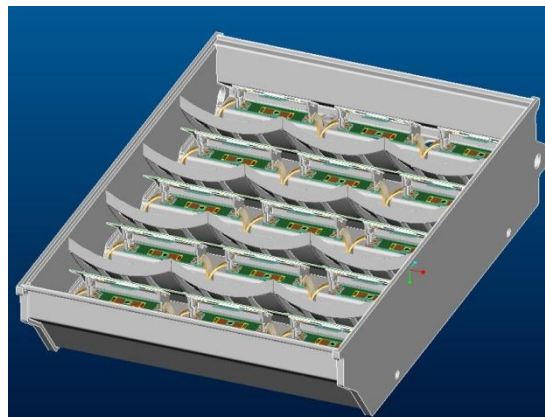


Fig.3: Dichroic module design with 15 units

The first experimental steps to validate the assembling solutions and the material choices have been carried out on a single unit fabricated with rapid prototyping processes; this element is sketched in fig.4. Both cells are mounted on their substrates using automatic technologies for electronic assembling; the optics of this first prototype has been fabricated by direct machining of aluminum (primary optics) and transparent plastic (secondary optics).

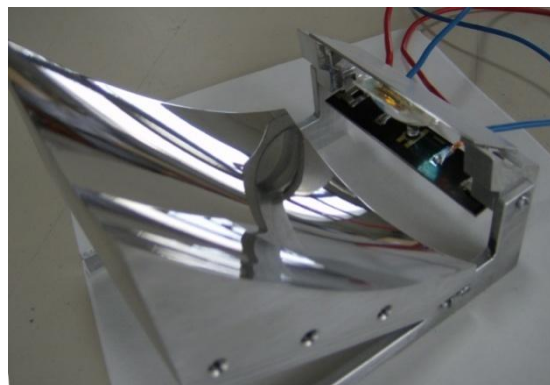


Fig.4: Prototype of a single unit of concentrator

4 EXPERIMENTAL RESULTS

The prototype has been tested in Sun during the Summer 2010 in Ferrara. The performances have been measured using the I-V curve tracer MP-160 EKO and the DNI has been measured using a Sun Tracker with double arm and pyrliometer from EKO as well.

The silicon cells are delivered by Narec and are designed to work under the requested concentration with an efficiency of 19% over the whole Sun spectrum. With the used dichroic filter, the silicon should deliver the 66% of its current generated under full AM1.5 spectrum. This

result has been confirmed by the test in Sun. With a DNI of 807W/m^2 , the cell delivered a I_{sc} of 2A, $V_{oc}=630\text{V}$ and $FF=71\%$. Considering an optical area of 120cm^2 , the resulting optical efficiency on the Si receiver is of 84%. The receivers are not mounted on the mechanical structure considered for the complete module, so the cells have achieved an higher temperature than that expected for the final module. The low FF is probably due to the non uniform irradiation on the cell, as appears from the picture in fig.6. However, this part of the sub-module delivers the 9.2% of efficiency on the full spectrum. Correcting it to 25°C the efficiency would achieve an efficiency of 10.4%; this value is perfectly aligned with the theoretical calculation with the used materials.



Fig.6: Receiver under the Sun

The measured angular acceptance of the Si receiver is in good agreement with the modeled results obtained by optical simulations. The angular tolerance for this part of the module is of 3° , with the characteristics shown in fig. 7.

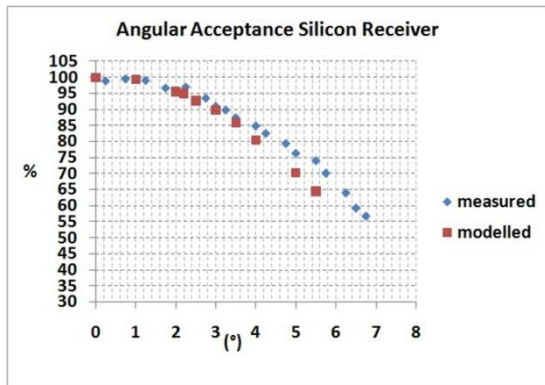


Fig.7: Measured (blue dots) and modeled angular tolerance (red dots) at the Si receiver of the prototype

On the second part of the sub-module the performances are not so good as for the first receiver. In this prototype a light-guide with diameter of 4.5mm has been used instead of 5mm; this means a geometrical concentration factor of 750x. This smaller diameter has been used to allow for a easier centering of the optics onto the InGaP cell. The theoretical angular acceptance with this secondary optics is reduced up to 1.2° . On this high concentration optics the results are significantly lower than the expected, with the InGaP cells delivering a 5.8% of efficiency on the global spectrum with DNI of 812W/m^2 instead of the forecasted 11%. The reduced efficiency is not due to solar cell limitations, but to

optical losses in the concentrator, which have led the optical efficiency on the secondary cell to the 44%. The InGaP cells were delivered by ENE and have been measured with an efficiency of 15% at the considered concentrated irradiation, with 25°C . The main optical losses for the prototype have been identified in the scarce adequateness of some employed manufacturing steps, which caused an enlarged focus at the inlet region of the light-guide. In particular, two fabrication effects have been assumed as principal reasons: long wavelength roughness of the machined aluminum reflector and long wavelength roughness on the plastic machined lens. In addition, potting errors on the InGaP cells could have led to light losses near the exit surface of the secondary optics. An optical evidence of the deviation of the light-rays respect to their ideal directions is observed looking at the Si cell through a partial optical magnification of the lens and of the primary optic: an optical, unwanted image deformation is evidenced in an unreal periodic zigzag of fingers of the Si cell, probably due to a long wavelength roughness due to the used machining tools.

A consequence of this focus enlargement is an increased angular tolerance for the InGaP circuit; a tolerance of 1.8° has been measured instead of 1.2° which is the expected value from the optical simulation of the designed concentrator, as reported in fig.8.

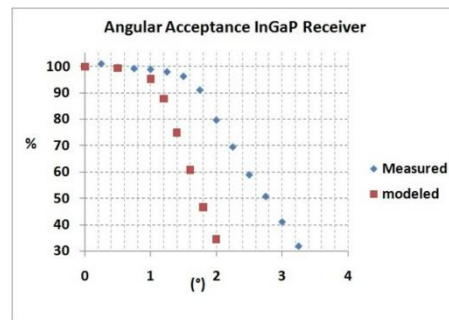


Fig.8: Measured (blue dots) and modeled angular tolerance (red dots) at the secondary receiver of the prototype

This effect produces important losses on the secondary cell and not on the Silicon circuit, because the magnification of the light deviations in the primary receiver is very lower.

Globally, the electrical measured efficiency of this sub-module has been of 16% ($9.2+5.8$), without corrections for temperature effects.

5 MODULE EFFICIENCY IMPROVEMENTS

As further system optimization a more efficient photovoltaic conversion of the solar light can be achieved increasing the number of photovoltaic junctions. Following the spectral splitting concept already developed by CPower, a dichroic concentrator suitable for using high efficiency Multi Junction (MJ) cells in the high concentration sub-receivers could be considered assuming that technology improvements will make them cost effective.

A properly designed filter with high transmission in the 900 -1100 nm wavelength range (CWL at about 1000 nm) could allow the use of DJ InGaP/GaAs cells, which are currently available with an efficiency of 30-31%, in

combination with Si cells. In the fig.9 the Spectral Responses of the different photovoltaics devices are reported with the transmission curve of the hypothetical pass-band filter.

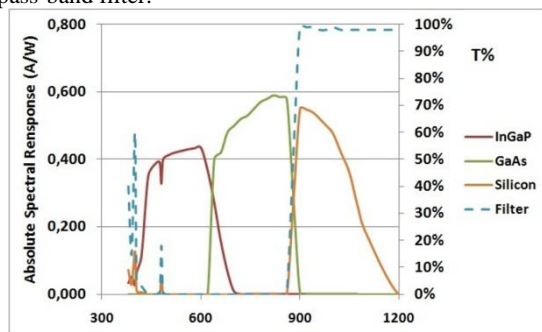


Fig.9: Spectral response of the sub-cells of a MJ solar cells with the addition of a silicon SC, using a dedicated optical filter; the transmittance characteristics of the filter is represented with the dotted line

In the range of wavelength transmitted through the filter (about 900–1200nm), a Silicon cell produces about the 27% of its current; that means, assuming a Si cell efficiency of 20% under the full solar spectrum, about 5.4% points of efficiency. Considering an optical efficiency of about 83%, it gives about 4.5% of its absolute efficiency.

A DJ InGaP /GaAs solar cell with $\eta = 31\%$ under 500x and an optical efficiency of 79% contributes to the module efficiency with about 24.5% .

Globally, the module could achieve an efficiency of about 29%, with currently available technology.

The use of a triple junction solar cell with $\eta = 39\%$ (commercially available [3,4]) could deliver a module efficiency of 34%, considering the previously indicated optical efficiencies. Further studies to determine the optical materials suitable for this purpose are under investigation.

4 TRACKER

In the HCPV systems, the solar tracker requires a high degree of accuracy in order to ensure a low acceptance tracking angle: inaccurate sun tracking introduces appreciable losses in the system efficiency value and energy production. Since the commercial trackers are usually not suitable for CPV systems, a properly designed tracking system has been developed paying a particular attention both to accuracy & reliability and to the cost.

Mechanical structure, actuators and electronic control must be well-integrated to reach this goal.

After examining different solutions for the mechanical tracking system, CPower identified the “equatorial” configuration as the best choice. This configuration seems to be more cost-effective also for small-scale production and assures more stiffness using the same amount of steel. A tracker dimensioned for mounting 1.5 kW of the optimized dichroic modules of fig.4 has been designed and optimized.

The electronic control, designed and integrated by Tecnia, allows the system to track the sun with an error lower than the acceptance angle of the CPower dichroic modules using the information provided by installed sensors. After designing and integrating the electronic

control on one CPower tracker in its facilities in Bilbao, as shown in fig.10, Tecnia measured an accuracy of $\pm 0.2^\circ$.

The cost of this tracker is less than 1 €/W for 1 MW production.



Fig.10: Tracker designed by CPower and electronic control unit developed by Tecnia, in the site of Tecnia, in Bilbao (ES).

7 CONCLUSIONS

A new dichroic mirror based spectral slitting system has been developed by CPower Srl, in collaboration with the partners of the Apollon Project. A module with potentially high optical efficiency, good thermal properties and good angular acceptance has been designed (Patent Pending). Experimental tests in Sun of the first prototype have delivered an efficiency of 16%, without temperature corrections. With better manufacturing processes allowing for a more precise fabrication of the surfaces, an efficiency higher than 21% is expected using a receiver with InGaP and Si cells of efficiency 15% and 20% respectively and a global optical efficiency of 80%. Using Si cells and high efficiency TJ cells a module of 34% is feasible.

A tracker suitable for these modules with pointing precision even better than 0.2° has been realized, using an electronic control developed by Tecnia.

8 ACKNOWLEDGMENTS

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