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Developing a Highly Integrated Receiverless Low Concentration Module with III-V Multijunction Cells

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Abstract. Concentrator photovoltaic (CPV) modules are composed of many components and interfaces and require complex fabrication processes, which in turn may cause lack of reliability. The presented work tackles these considerations, proposing an innovative highly integrated low concentration photovoltaic (LCPV) concept. The purpose is to develop a module with a high level of integration by lowering the number of components and interfaces. At first, the linear parabolic mirror, used as concentrator optics, can be considered as multifunctional, combining thermal, structural and optical functionalities. On this basis, the proposed CPV prototype design features a receiverless configuration, where the cells are directly arranged on the rear side of each mirror. Moreover, such implementation claims to demonstrate the applicability of reliable flat PV fabrication processes (such as lamination and cell interconnection) for the manufacturing of this LCPV module. Geometrical considerations, together with thermal and optical analyses are presented, in order to validate the concentrator design. Then, further prototyping aspects are discussed, including an overview of the manufacturing processes, materials selection and proposed procedures for the CPV module qualification and characterization.

PRESENTATION OF THE CONCEPT

CPV technology takes advantage of low cost concentrator optics in order to increase the irradiance on reduced-area high efficiency multijunction solar cells (MJSC). In comparison with flat PV, CPV modules are composed of many components and interfaces. The involved optical and thermal constraints require high assembly accuracy and relatively complex fabrication processes which have a significant impact on the fabrication cost of such modules. Given these considerations, this study proposes the implementation of an innovative low cost concentrator, with a high level of integration, including high efficiency, low CPV (LCPV) and cost effective cells, such as thin film III-V solar cells [1]. The purpose of this concept is based on lowering the number of components and interfaces and simplifying the CPV assembly process. The architecture of the LCPV concept, sketched in Fig. 1, is based on a parabolic trough reflective concentrator [2] that concentrates the solar radiation on a focus line located on the rear of the (following) adjacent aluminum (Al) mirror.

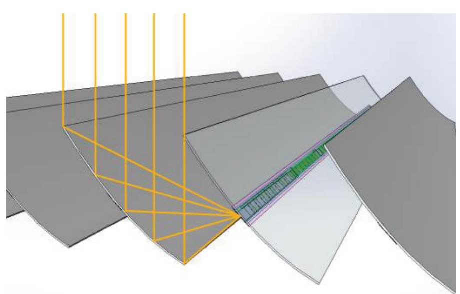

FIGURE 1. Sketch of the LCPV highly integrated receiverless concept.

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Although such mirrors arrangement, generically known as parabolic trough, has been already studied in past design studies [3], the cell array was placed on a receiver including aluminum fins as heat sink and the mirrors were usually made of coated glass. Here, the innovation remains in the multi-functionality of the concentrator mirror acting as primary optical element (POE), which, in addition to the optical function, becomes the mechanical support of the cell arrays and the heat sink in charge of the cell cooling. By doing so, we get rid of the CPV receiver element, including the dedicated heat sink, which represent a significant part of the CPV module cost [2]. Similar design efforts were developed and demonstrated by Whitfield et al. [4]; however, here, the goal is to optimize a MJSC based concentrator and its associated fabrication processes. Moreover, the proposed concept relies on high-throughput, reliable and cost-effective techniques, well-established for flat-plate PV manufacturing, such as lamination, used for assembling the cell array with the rear of the POE. In this work, the main actions leading to the design and fabrication of the first highly integrated LCPV module prototypes will be presented, e.g. encapsulant material characterization, optical and thermal simulation, cell array manufacturing, lamination processing, dielectric testing, etc. The electrical performance of these prototypes have been evaluated indoors, through their I-V characteristics, obtained using collimated light flashes, by means of a Helios 3198 CPV module characterization system.

GEOMETRICAL CONSIDERATIONS

The presented concept is based on a parabolic trough mirror, concentrating the solar flux on the back of the following mirror. The design method proposed by Luque et al. in [5] for optimizing the acceptance angle of a parabolic trough system cannot be applied here as the position and the tilt of the cell are imposed by the mirror on which it is placed. Fig. 2(a) shows a 2-dimensional (2D) geometrical representation, where *M1* and *M2* mirrors are identical. The mirror *M1* is a portion of the parabola *P* which origin *O* is centered in the system O*xy*. The parameter *a* is the aperture length of the mirror, i.e. the projection of the mirror on a plane perpendicular to the incident solar flux. If we want *M1* mirror to focus on mirror *M2*, the focal *f* of the parabola *P* has to be equal to *a*/2. With this single condition, each mirror focuses on the back of the following. For a given aperture *a*, the mirrors focal is thus fixed, but we can adjust the limits of the portion of parabola. In Fig. 2(b), still in the system O*xy*, the limits of the mirrors are shifted to the left and the *x* position of the limit x_1 is lowered. The mirrors still have the same aperture and focal, however the relative position of *C* and *M2* is altered, with the cell *C* being placed now on the upper part of the mirror *M2*. Therefore, moving the limits of the portion of parabola directly impacts the position of the cell. Looking at these representations, it seems that the former design (a), with a centered cell is better for thermal spreading, while the latter design (b) seems to be better optically, as the mirror faces the cell in a more perpendicular way, thus reducing the reflectivity. Moreover, such design seems to offer a better acceptance angle.

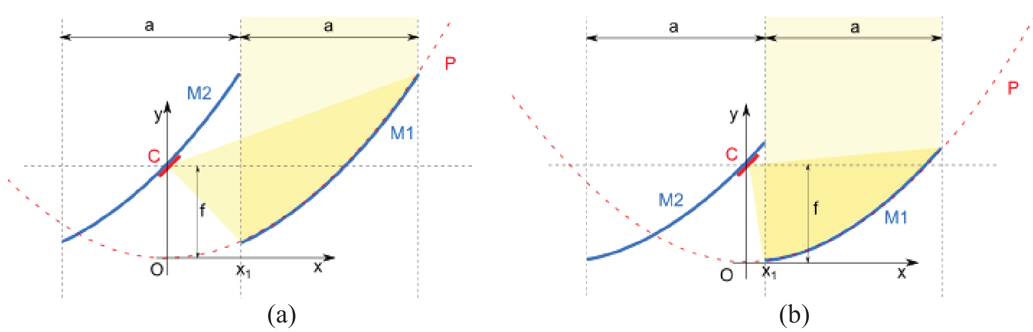


FIGURE 2. Schemes of two different geometrical dispositions (a, b) of the concept.

THERMAL DIMENSIONING

In a first approach, the thermal ability of the mirror to dissipate the heat has been chosen as the dimensioning driver that maximizes cell efficiency and minimizes performance losses and subsequent end-of-life failures due to heating. A first analytical thermal model has allowed calculating the cell temperature as a function of the mirror surface available for convection. It shows that the temperature distribution has to be homogenous through the mirror surface, in order to feature maximum thermal efficiency, in terms of convection. On this basis, the cell array has been placed in the middle of the mirror's back side, equidistantly from the top and bottom edges. A complementary model calculates the relative temperature gradient between the mirror edge and the cell, versus mirror thickness and width

(Fig. 3). This model allows defining dimensions that ensure a good thermal spreading throughout the mirror by means of conduction. Given the results, a mirror thickness of 2mm and a width of 20cm were chosen, considering the cell array across the mirror median line. As Fig. 3 shows, these dimensions guarantee a maximal temperature gradient of 90% relative to the maximum value.

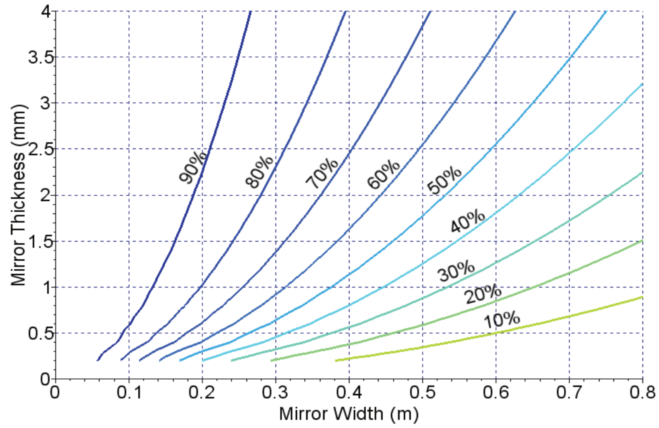


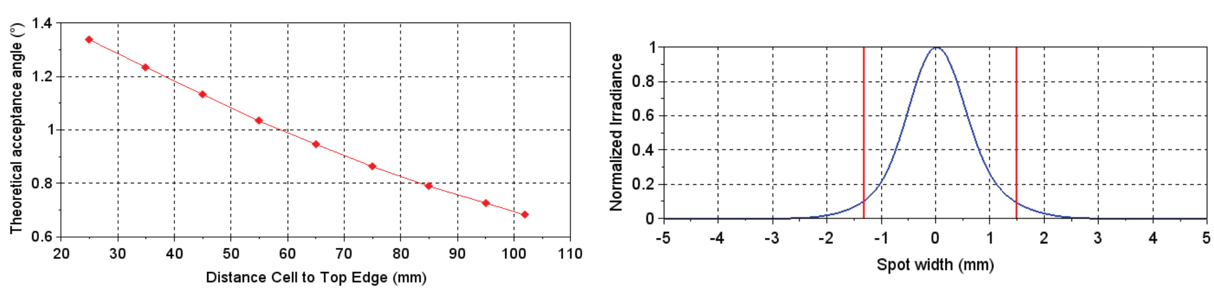
FIGURE 3. Thermal modeling results. Maximum temperature gradient within the mirror (in % relative to the maximum value) versus width and thickness

Considering 1cm² commercial MJSC, the 20cm width mirror matches typical concentrations (10-50suns), based on prior parabolic trough LCPV experiences. The thermal model has been upgraded with finite element simulation, implementing thermal interfaces under worst case convection conditions (no wind effects). The temperature increases ΔT_{cell}= 57°C for a simple plain Al sheet used as mirror and matches the temperature increase calculated with the simpler previous model.

This thermal analysis of the considered system allowed defining dimensions of the system which will be prototyped and characterized. Looking at the geometrical study, an aperture a=15cm matches the 20.5cm long mirror profile. The mirror will be then a portion of a 75mm focal parabola with an appropriate limit x_1 for which the cell position is equidistant from the edges of the mirror.

OPTICAL STUDY

The obtained design has been simulated by ray-tracing, implementing a source of sunrays within a 0.27° cone angular solar distribution and different deviation angles (reproducing misalignment) with respect to the plane perpendicular to the sunrays. Looking at the conclusion of the geometrical study, the influence of the relative position of *C* and *M2* will be studied. The simulations have been carried out as a function of the height of the 10mm wide cell array on the rear-side of the mirror, i.e. centered or next to the top edge, moving the x_1 parameter, which imposes another optical (and thermal) design constraint. The simulations were implemented assuming a perfect parabolic mirror, with the aforementioned dimensions.



(a) (b)

FIGURE 4. (a) Theoretical acceptance angle calculated from ray tracing simulation for different cell array locations. (b) Normalized theoretical irradiance profile for a cell array centered on the rear of the mirror M2, the red bars delimit 95% of the flux. The cell array is 10mm wide.

The flux reaching the cell has been calculated for misalignments from -2° to 2°, relative to the maximum flux for 0° (no misalignment) with ray-tracing simulation. This function has been plotted for different cell positions on the back of the mirror. This cell position is defined by the distance between the center of the cell and the top edge of the mirror (i.e. from 25mm to 102mm for a centered position). Fig. 4(a) shows the acceptance angle corresponding to each cell position. It provides a worst case theoretical acceptance angle of +/-0.65º, above typical one-axis tracking errors.

Besides, the theoretical distribution of the irradiance profile on the cell for 0° misalignment for a centered cell configuration is shown on Fig.4 (b). It shows that 95% of the flux is within a 3.8mm wide area. The peak to average ratio is 3.

PROTOTYPING OF THE HIGHLY INTEGRATED LCPV MODULE USING LAMINATION PROCESSES

The first prototypes have been manufactured with a cell array centered on the mirror back to maximize heat dissipation and, thus, optimize thermal management, as we have verified that acceptance angles for most commercial one-axis trackers are tolerant enough, even for such design. Given that the cells are positioned directly on the back surface of the Al mirror, also acting as a heat sink, the cell string will be laminated using a conventional flat-plate PV mass production laminator. We have demonstrated the compatibility of the lamination process on Al mirrors with commercial 1cm² MJSC. The lamination stack is composed of a front sheet, an encapsulant underneath, then the cell array and a thermal conductive and electrical insulating pad as interface with the mirror. Dark I-V testing showed no degradation of the cell array during the process. Moreover, the resulting laminated mirror was bended in the shape of the parabola without damaging the cell string, while the lamination stack has passed normative thermal fatigue test without showing any delamination. The device has passed normative insulation test from IEC62108. Different encapsulation materials have been optically characterized in order to select materials for appropriate MJSC spectral response. The results are presented in Fig. 5. We have chosen encapsulant type 2 and front sheet type 1 for the prototype realization, they have the larger transmission ranges.

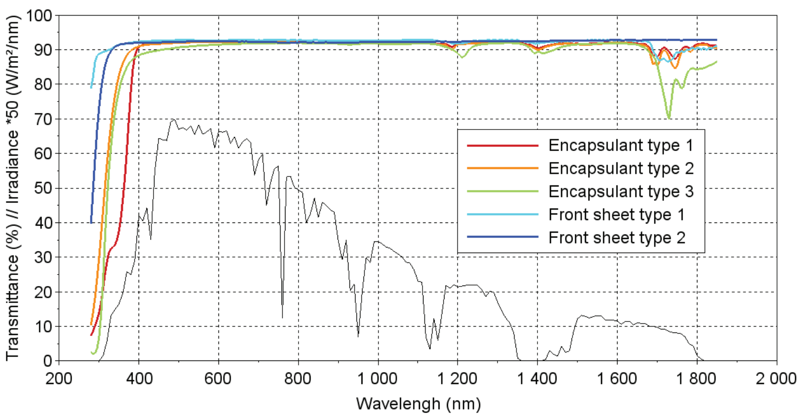
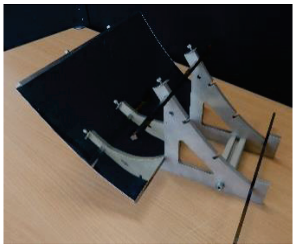
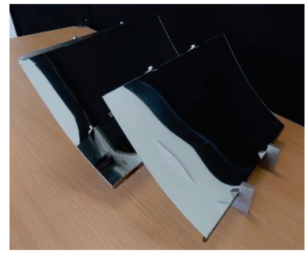


FIGURE 5. Transmittance of different encapsulant materials. The AM1.5d spectrum is plotted in black for information

With a 2mm thickness the resulting mirror is rigid and has to be shaped with a forming process. Several fabrication techniques have been identified compatible with the mirror requirements in terms of surface finishing, mirror dimensioning and cost. Finally, a first prototype has been realized with a standard reflective Al sheet 0.5mm thin (Fig. 6). This first prototype version (V1) has allowed developing the lamination process and testing a first functional prototype prior to the rigid 2mm thick mirror manufacturing. With such thickness, this sheet is flexible and can adopt the curvature of a numerically controlled (NC) machined profile fabricated in purpose. This method is widely used for large thermal and PV parabolic trough concentrators with Al mirrors. The mirror edges are held by rigid screwed clamps.



(a)



(b)

FIGURE 6. Prototype version V1. (a) View of the mirror M1 mounted and bare parabolic rib support prior to mounting mirror M2. (b) Full mounted V1 prototype.

The resultant focus line on the rear of mirror M2 (Fig. 7) presents a bow in the center and a really clear focus next to the parabolic holders. This divergence is due to mechanical strength in the center of the Al mirror, which is deformed within the elastic domain.

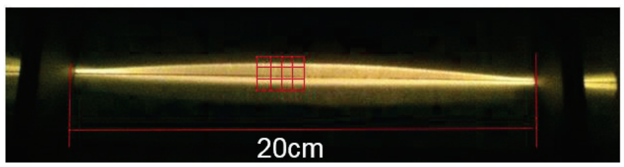
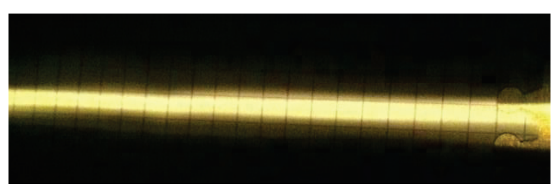


FIGURE 7. Focus line at the rear of the mirror M2 for the prototype V1. On the reference grid a red square is $5*5mm^2$

The spot in the center is wider than 10mm, which is the size of the cell. Therefore, for the fabrication of this first functional prototype, the gap between the holders (i.e. metallic ribs) was reduced to 10cm in the aim to minimize the spot width. A linear cell array has been manufactured using commercial triple junction cells, in the aim to perform electrical characterization of the prototype. The 4 cell receiver has been characterized under concentrated light before being integrated in the module.

Different fabrication processes have been considered, for bringing a rigid 2mm thick mirror to the expected dimensions. NC rolling has been identified as ideal, but no supplier has guaranteed enough precision in the parabolic profile. Therefore, another process has been explored, called pre-bending. In particular, the parabolic longitudinal profile is obtained by bending the Al sheet step by step, with wide angles. The fabrication is made with a traditional folding press, with a bending step of 5mm, resulting in a linear formed mirror with “faceted” aspect. A second prototype (V2) has thus been manufactured using such mirrors (Fig. 8(a)). For this prototype, the mirror reflective coating has been realized by laminating an Al coated reflective polymer sheet. The polymer film will not be kept as a long term choice for reliability reasons, but will be used for proof check of the concept. Other techniques such as physical vapor deposition or polishing will be explored in future works.

(a)

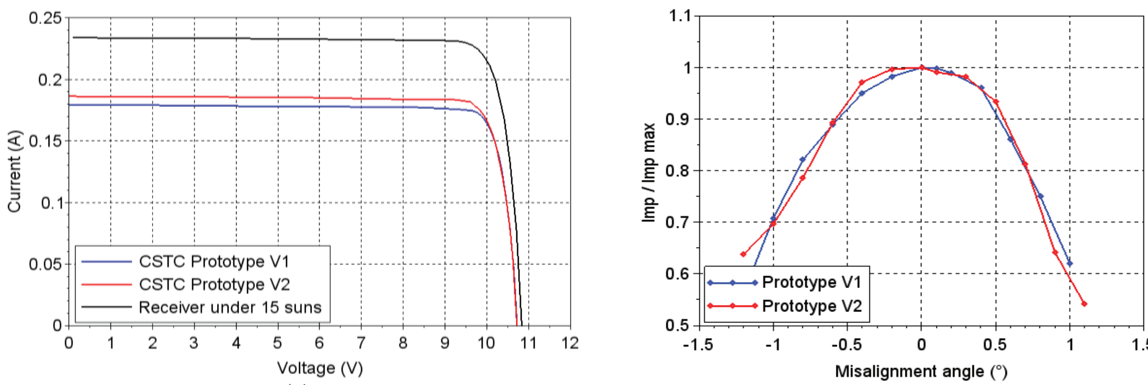


(b)

FIGURE 8. (a) Picture of the prototype V2. The rigid 2mm thick Al mirrors are self-supporting, being fixed by only 4 points. (b) Picture of the focus line at the rear of the mirror M2 for the prototype V2. The grid on the paper has a 5mm pitch

An image of the focus line in Fig. 8(b) shows a continuous and longitudinal concentrated spot within a 5mm wide area. The longitudinal symmetry of the focused line was expected considering the forming process of the mirror. The shaping accuracy is not optimized in the first version but the longitudinal symmetry guarantees a uniform flux on the cells and thus an optimum current matching.

Both prototypes presented above were characterized indoors, by means of a solar simulator, type Helios 3198. This CPV module sun simulator fulfils the concentrator standard test conditions (CSTC) requirements (1000W/m², 25°C and AM 1.5d spectrum), generating a homogeneous irradiance, with a collimated ray bundle. Fig. 9(a) shows the I-V characteristics of the two prototypes, with the 4-cell string integrated in the modules, which were also characterized under concentrated light at 15suns, using a Xenon multi-flash cell simulator which also provides CSTC conditions. Efficiencies have been calculated for 4-cell string on both concentrator prototypes and under the flash cell tester, for an aperture area of 60.9cm² in the case of the prototypes and 4.06cm² for the case of the cell string.



(a) (b)

FIGURE 9 (a) I-V measurements of prototypes V1 and V2 and associated cell string under 15 suns illumination for an aperture area of 60.9cm², (b) Measurement of the normalized maximum power point current (I_{mpp}) for different misalignment angles. The acceptance angle is defined as the angle for which the I_{mpp} is 90% of the maximum value (at 0° misalignment).

The prototype V2 reaches an encouraging 28.7% efficiency, one percent above the first prototype. The comparison with the I-V measurement of the cell array shows a cell-to-module absolute loss of 7.4% providing a global optical efficiency of around 80% for the POE. The acceptance angle for each prototype was measured and the results are shown in fig 9(b). The acceptance angle is 0.55° for the two designs, compared to the 0.65° theoretical acceptance angle for the selected design.

CONCLUSION

The innovative concept presented above intends to cut down the CPV price per watt-peak by limiting the number of interfaces, components, and materials used for its manufacture, compared to the standard parabolic trough designs using a CPV receiver that hosts the cells and evacuates the generated heat. This novel CPV module has been designed for new high efficiency low cost cells upcoming on the market, such as thin film cells or other multijunction inexpensive technologies. The heat sinking has allowed defining typical dimensions of the POE and lamination of the cell string on Al mirrors that have been successfully used for the manufacturing of these first prototypes. Alternative manufacturing processes for mirror forming are being studied and will be further characterized.

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