

A MIRROR-LESS DESIGN FOR MICRO-CONCENTRATOR MODULES

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ABSTRACT

We present a novel non-imaging optics design for a flat-plate concentrator PV system. The design consists of a conventional primary/secondary lens combination, but uses aspheric and TIR (Total Internal Reflection) lens components in the primary to reduce the focal length and, hence, the thickness of the whole module. Ray tracing simulations indicate that an acceptance angle in excess of $\pm 2.6^\circ$ can be achieved, which makes this design suitable for light-weight, low-cost tracking systems. The design also has the advantage of being mirror-less, avoiding all manufacturability and reliability issues associated with metallization processes as faced by previous low-profile designs.

INTRODUCTION

For a long time, concentrator photovoltaic (CPV) systems have conveyed the image of large, bulky systems, either based on Fresnel lenses or parabolic mirrors mounted on sturdy tracking mechanisms. The invention of the Simultaneous Multiple Surface design method of nonimaging optics in the early 90's has started to change this conception. New concentrator designs were proposed characterized by their compactness and an optical performance close to the thermodynamic limit.

The breakthrough was made with the RX and RXI [1] (Fig. 1) designs inspired from optoelectronic systems. These designs exploit refraction, reflection, and TIR

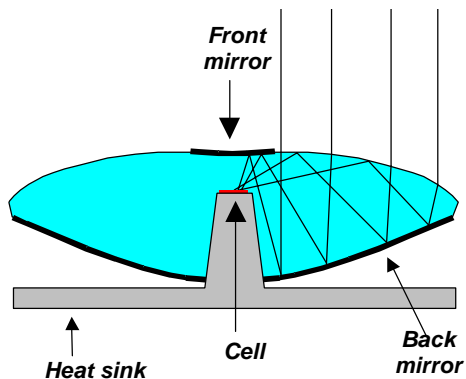


Fig. 1: RXI concentrator.

(Total Internal Reflection) phenomena on both sides of a single piece of optical material, usually PMMA (PolyMethyl MethAcrylate). The optical path is folded – twice in the case of the RXI design– in such a way that a very low profile can be achieved with a high concentration ratio. As a consequence, a flat-plate style concentrator module can be envisioned with a thickness comparable to a conventional one-sun module.

This new concept dramatically reduces the mechanical constraints on the module assembly and the tracking system. Since the RXI design can achieve a very wide acceptance angle ($\alpha = \pm 5.9^\circ$ for a 200x concentration), the module does not need to be as rigid as a Fresnel lens module. The reduced size of an individual concentrator unit means that an increased number can be packed in a single module, providing a higher voltage from a smaller volume. The lower profile and smaller size of the module provides less resistance to lateral wind. All these advantages concur to a lighter weight, less expensive tracking system.

The RXI design has a lower profile than the RX and has been studied for PV applications within the HERCULES project of the EU-JOULE program. Prototypes exhibited impressive characteristics in terms of optical efficiency and angular acceptance. However, the prototype fabrication also unearthed some shortcomings of the design. The most important one is that the front and back mirrors are difficult to evaporate. In particular, the front mirror has to be patterned and aligned on a curved surface. Reliability is also an issue since this front mirror is exposed to weathering, as is the rest of the front surface where TIR must occur. While the position of the cell inside the module was cited as an advantage of the design because it provides protection, it is also a disadvantage since it makes electrical connection and heat sinking difficult. Also, the size of the cell must be kept to a minimum because any additional edge area would cause shadowing.

In this work, we propose a new design (Figs. 2 and 3) named TIR-R that overcomes these shortcomings. It is based on a conventional primary/secondary optical element structure, but uses a primary with an aspheric section and a TIR section to obtain a very short focal length while maximizing angular acceptance.

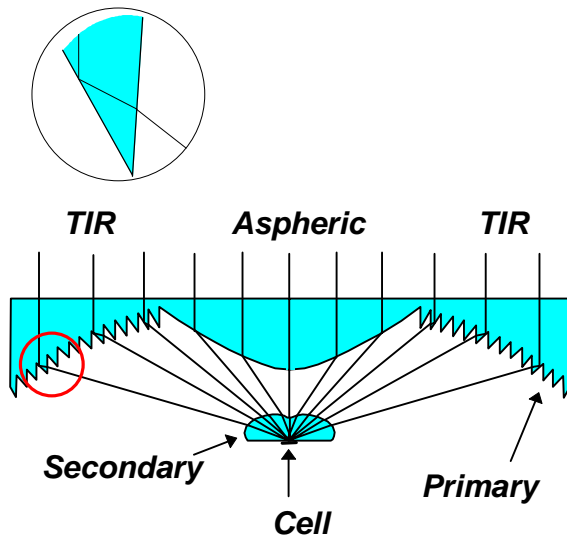


Fig. 2: TIR-R concentrator with detail of TIR lens.

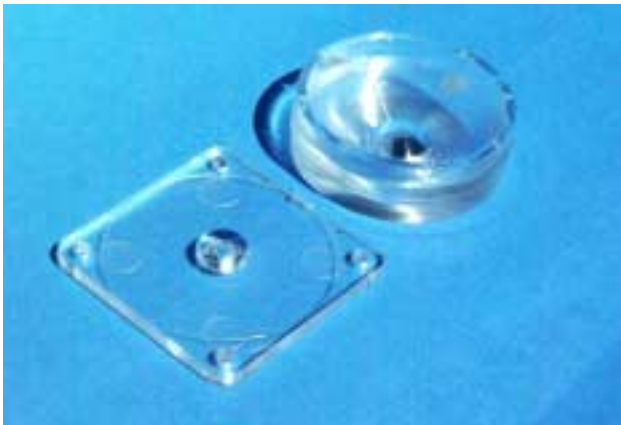


Fig. 3: First prototype of TIR-R concentrator. Left: SOE with base plate, right: Primary optics (upside-down).

DESIGN

Mirror-less design

Two approaches can be considered to reduce the thickness to diameter ratio of concentrator modules: either fold the optical path or reduce the focal length. The first approach is best obtained with mirrors. For a mirror-less design, the second approach is more appropriate. Aspheric lenses and TIR lenses are both capable of short focal lengths. They are complementary, since aspheric lenses need increasing thickness for larger diameters, while TIR lenses need sharper and smaller groves for decreasing diameters. Using an aspheric lens at the center and TIR groves on the periphery of the primary, we can combine the advantages of both systems.

An added benefit of this combination is that the two regions of the primary behave differently when the illumination source moves off-axis. This offers the

possibility to achieve better illumination uniformity on the solar cell.

Flat surface

The TIR surface in the new design has the advantage of being protected inside the module instead of being exposed on the front surface as in the RXI. Moreover, since the front surface is flat, a cover glass can be used to further protect it from scratches and dust. In the RXI design, constraining the front surface to be flat would dramatically increase the aspect ratio of the module [1], while the need for TIR prohibits the use of a cover glass.

The flat front surface makes it easier to integrate the micro-concentrator unit in a full size module [2]. A mini-module made of several micro-concentrators can be injection-molded as a single piece, then several mini-modules can be assembled onto a single cover glass and framed to be mounted on a tracker.

Cell assembly

In the TIR-R design, the cell is mounted on the back side of the secondary optical element (SOE). This makes room for more assembly options than the embedded configuration of the RXI. There is no limit on the size of the cell or the heat sink since no shadowing can occur from these elements.

The cell can be surrounded by a hemispherical cavity in the SOE, so that the highest light concentration does not occur inside the PMMA. The cavity can be filled with a material that better resists high intensity light.

SIMULATIONS

Ray tracing simulations were performed using the TracePro program from Lambda Research Corporation. All simulation results presented here were performed with a solar angular distribution and a fixed wavelength. Additional simulations performed with an AM1.5 solar spectrum gave very similar results. The design was optimized for a 250x optical concentration under normal incidence.

Acceptance angle

Fig. 4 shows the relative transmission of the lens assembly at different angles of incidence, compared to the transmission under normal incidence. It shows that an acceptance angle of about $\pm 2.6^\circ$ can be achieved. This value is somewhat lower than those published for RXI modules at similar concentration. Part of the reason is that the previous results are for a rotationally symmetric design, whereas the current design uses a square entry aperture obtained by truncating a rotational design.

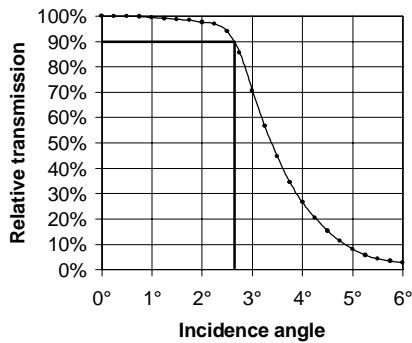
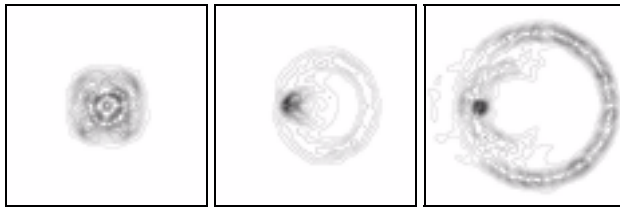
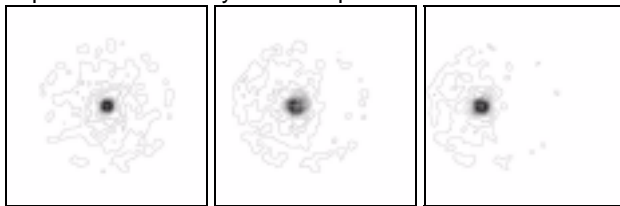


Fig. 4: Calculated relative angular transmission.

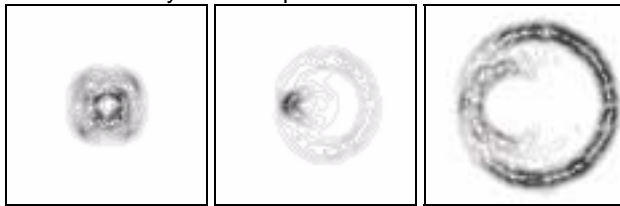
Total:



Aspheric section only with complex SOE:



TIR section only with complex SOE:



0° 1° 2°

Fig. 5: Calculated irradiance distribution on cell area under 0, 1, and 2° incidence, for the complete optical system, and separately for the aspheric and TIR sections of the primary, with a complex SOE.

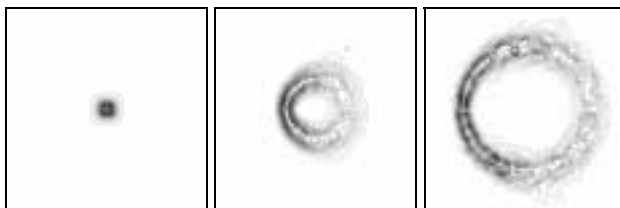


Fig. 6: Calculated irradiance distribution on cell area under 0, 1, and 2° incidence for the TIR portion of the primary and the SOE in a simple design.

Uniformity

In the RXI design, a large acceptance angle was obtained at the expense of illumination uniformity. The illuminated area was very small compared to the total cell area and moved around as the angle of incidence was modified. The limit of acceptance angle was reached when the illuminated area moved out of the cell area.

In the TIR-R design, the aspheric section of the primary lens behaves the same way but the TIR section gives a very different response to angular variations (Fig. 5). With an early design (Fig. 6), the TIR section, in combination with a simple SOE, gave a localized illuminated area on the cell under normal incidence like in the RXI design. However, under off-axis incidence, the illuminated area changed to an annular shape with a diameter increasing with the angle of incidence. This behavior, characteristic of TIR lenses greatly reduced peak illumination in off-axis condition.

With a more recent design (Fig. 5), the uniformity under normal incidence has also been improved by defocusing the image of the TIR section using a more complex shape for the SOE. In off-axis condition, the defocusing results in two annular illuminated regions instead of one, further improving uniformity.

Effect of manufacturing imperfections

When going from theoretical projections to physical realization, we naturally expect some performance degradation in terms of transmission and acceptance angle due to deviations from the ideal design.

The biggest difficulty in making these optics, as discovered while fabricating the first prototype depicted in Fig. 3, is to have a plastic injection process capable of filling the small facets of the TIR portion. If the exact correct combination of material viscosity, injection pressure and cooling speed is not found, the tip of the facets becomes rounded, leading to light loss. With a high quality mold and optimized process, we expect an edge radius of about 3 microns to be achievable.

Fig. 7 represents the simulated effect of an

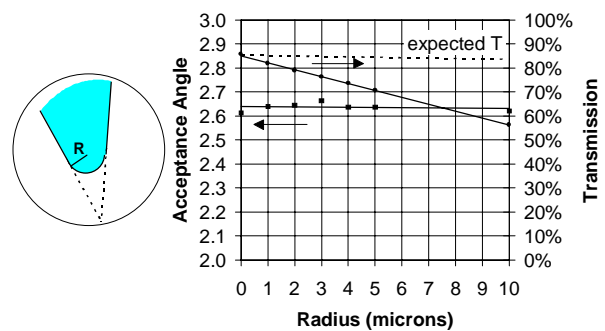


Fig. 7: Effect of edge rounding on optical performance.

increasing rounding radius on both the acceptance angle and the transmission at normal incidence. Due to the very high number of facets in this first design (around 150), the effect on the transmission is very dramatic. We are working now on a new design that would reduce the number of facets to less than 10. We expect the rounding loss to be reduced by roughly the same factor, as shown by the “expected T” line. The same figure shows that the acceptance angle is not affected by the edge rounding.

The second problem we have to face is the alignment between the three elements: the primary and secondary optics, and the cell. Simulations were performed to assess the sensitivity of the design to assembly tolerances. Each of the three elements was moved relative to the two others both in axial and radial directions.

Fig. 8 shows the results for the most sensitive alignment, which is the cell in the axial direction. A displacement of 200 microns reduces the transmission by less than a percent in one direction. In the other direction, the transmission even increases but it is at the expense of uniformity. The acceptance angle suffers more, but stays above $\pm 2.2^\circ$, still a very high value for a 250x concentration ratio. Automated assembly machines derived from microelectronics packaging are capable of achieving a much higher accuracy than 200 microns. Plastic assembly techniques may need a wider tolerance, but the alignment between primary and secondary is less critical than the cell alignment.

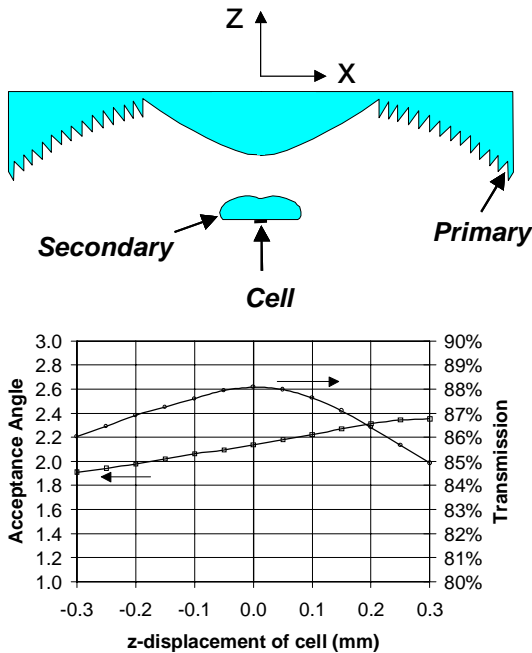


Fig. 8: Effect of cell displacement on performance.

CONCLUSIONS

We have demonstrated a novel optical element design that further exploits the flat-plate concentrator concept introduced by the RXI micro-concentrator. The new TIR-R design overcomes the most important shortcomings of the RXI design. It includes several improvements that bring it closer to a commercial product, not only in terms of manufacturability, but also as an elegant solution for module-scale assembly.

ACKNOWLEDGMENTS

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