Characterization of an Aggregated Total Internal Reflection Optic

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INTRODUCTION:

Aggregated Total Internal Reflection (ATIR) is a new optics design space for solar concentration pioneered by Banyan Energy Inc. The primary advantages of ATIR are: a compact profile, wide acceptance angles, uniform energy distribution across the focal area and a direct cell mate.

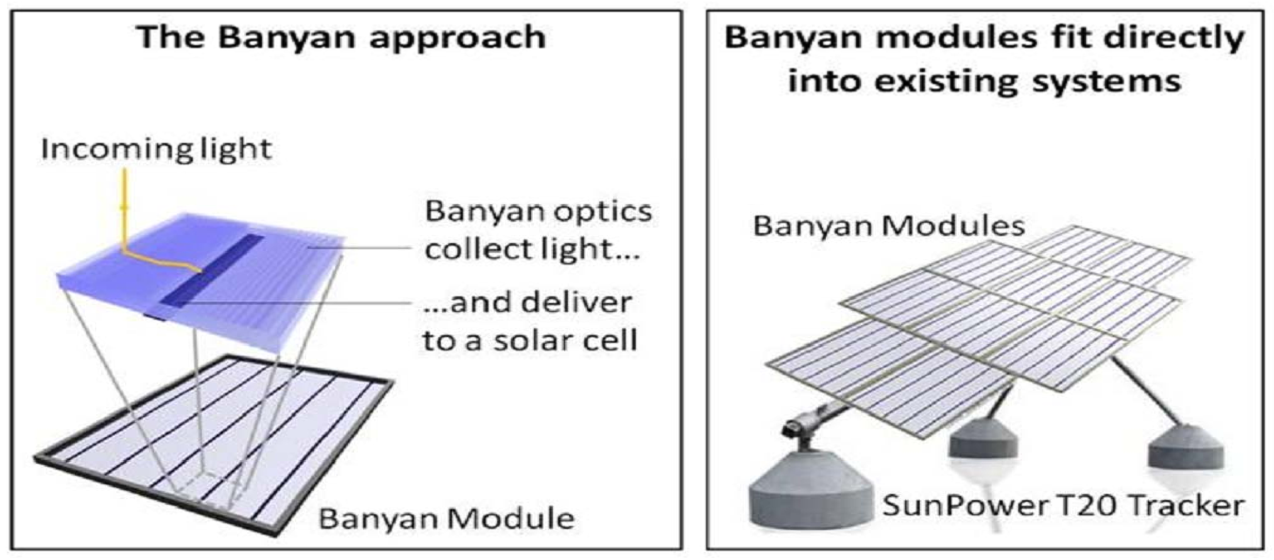


Figure 1: (Left) Rendering of a 'Banyanized' solar panel. Line-focus optics within the panel will reduce area costs and allow production to scale with fewer constraints. (Right) Existing tracking systems can be used. No downstream modification to solar infrastructure is needed.

Banyan's optics are approximately ten times flatter than conventional concentrators, and can therefore fit like a sheet within a standard module construction. This allows module mfrs. to leverage their existing silicon capacity to produce 5-10x as much product.

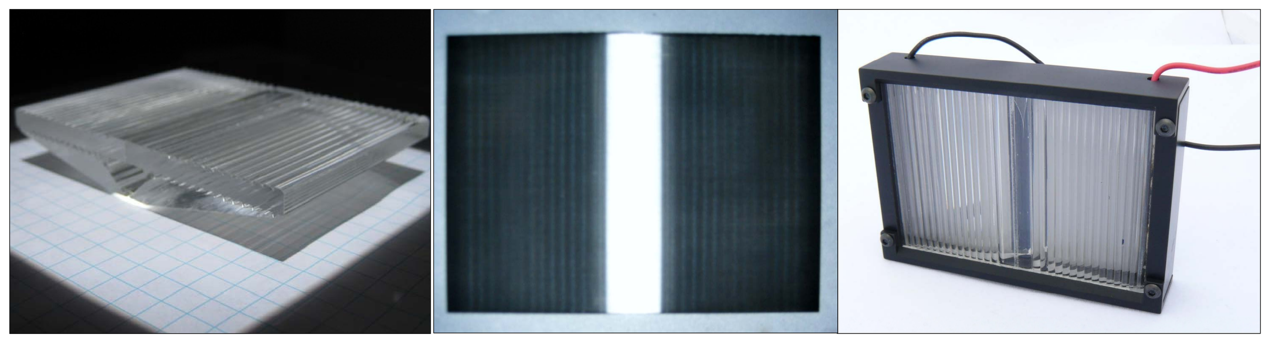


Figure 2: Isometric view of an early ATIR lens prototype (Left) that has an aspect ratio of 7:1 and produces a line-focus silhouette (Center). A single-unit module prototype demonstrates module integration and direct cell mate (Right).

ATIR SPECIFIC RELIABLITY CONSIDERATIONS:

•Cell temps ~5-10C hotter than 1-sun panel

•CTE decoupling between cell, backplane, and optic

•UV weathering performance of all optic and adhesive materials – especially with concentrated flux inside waveguide material

•ATIR design space allows (but does not require) optical features on the front surface of a module. Are any features allowable from a soiling perspective?

MEASURING OPTICAL EFFICIENCY – J_{sc} METHOD:

Short circuit current (J_{sc}) is proportional to exposed cell area and the intensity of incident light. Optical Efficiency (OE) is measured by comparing the J_{sc} of a bare cell to that of a cell coupled with an optic and controlling for the area and source intensity.

$$OE = \frac{J_{sc,final}}{J_{sc,initial}} = \frac{J_{sc,2}}{\left(J_{sc,1} * \frac{A_{optic\ input}}{A_{mask}} * \frac{DNI_2}{GNI_1}\right)} = \frac{J_{sc,2}}{J_{sc,1}} * \frac{A_1}{A_{input}} * \frac{GNI_1}{DNI_2}$$

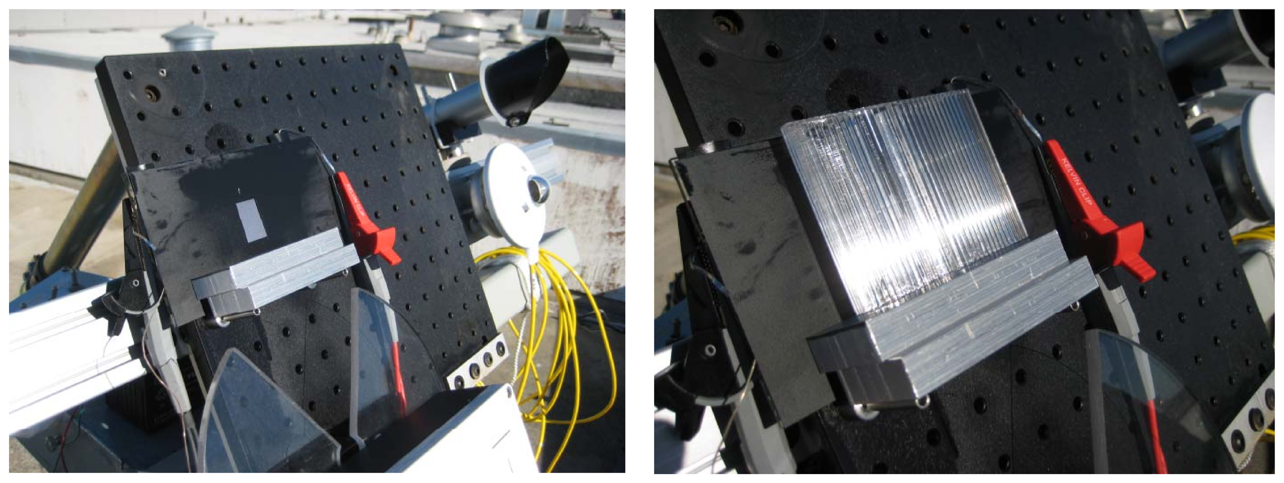


Figure 3: Detail of the outdoor test bed. (Left) Setup for input J_{sc} reading. A bare NaREC cell with precise area mask is mounted on the 2-axis tracking platform. Kipp and Zonen DNI and GNI sensors are visible. (Right) Setup for output J_{sc} reading. The Lens Step optic is coupled to the masked cell with Sylgard 184 base (n=1.42, non curing).

PREDICTED RESULTS: 84.2%

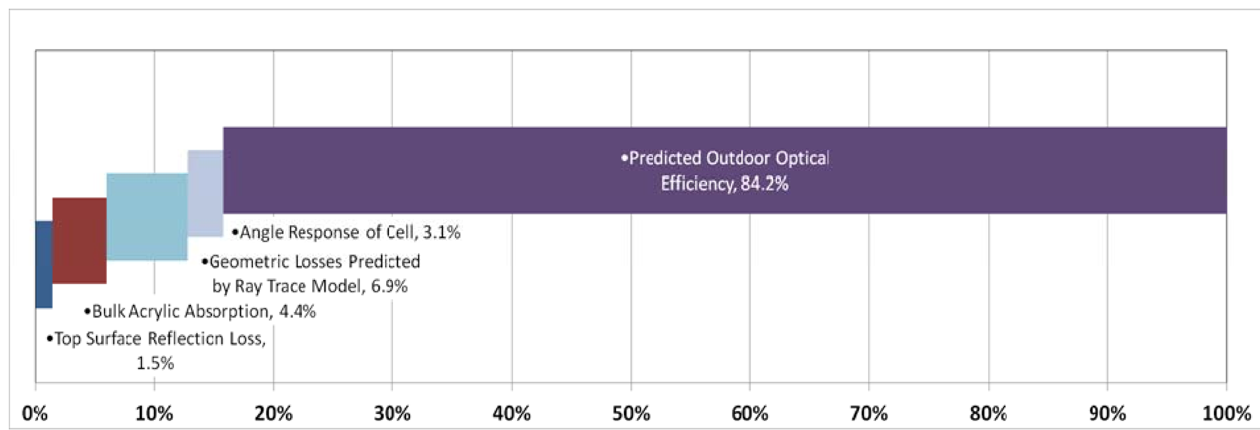
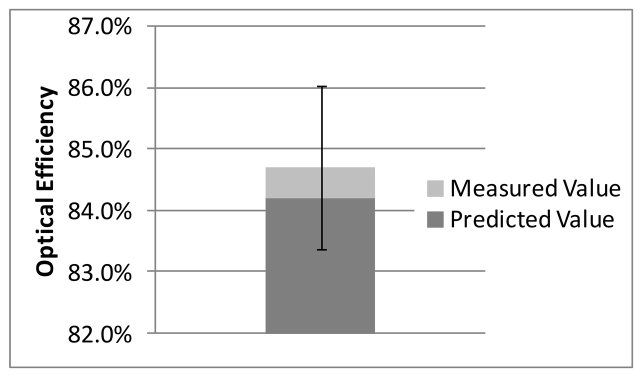


Figure 4: Predicted Optical Efficiency of prototype optic (84.2%) shown with the expected loss mechanisms. Loss mechanisms include spectral absorption by the Acrylic optic and the angular response of the cell.

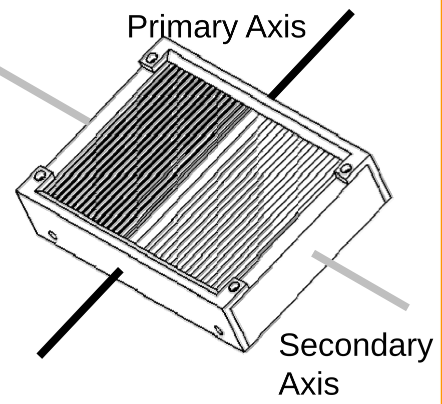
MEASURED RESULTS: 84.7%



Temperature	0.50%
Spectrum	0.50%
GNI sensor	3.60%
DNI sensor	0.54%
Mask area	0.02%
Repeatability	1.34%
Total Uncertainty (RSS)	3.94%

Figure 5: Measured optical efficiency of 84.7% is shown relative to the modeled optical efficiency of 84.2% (Left). The difference between modeled and measured performance is statistically insignificant due to the measurement uncertainty of ±3.9% (Right). Measurement uncertainty is driven largely by the large uncertainty in the GNI sensor reading. For future optical efficiency measurements, the GNI sensor is being upgraded from the Kipp and Zonnen CMP-3 to the CMP-11. This change reduces the total measurement uncertainty to ±1.8%.

ACCEPTANCE ANGLE CHARACTERIZATION:



The wide acceptance angle of ATIR optics allow a mid-concentration panel to be mounted on an existing low cost fixed tilt single axis tracker, making it a drop-in replacement for a one-sun panel.

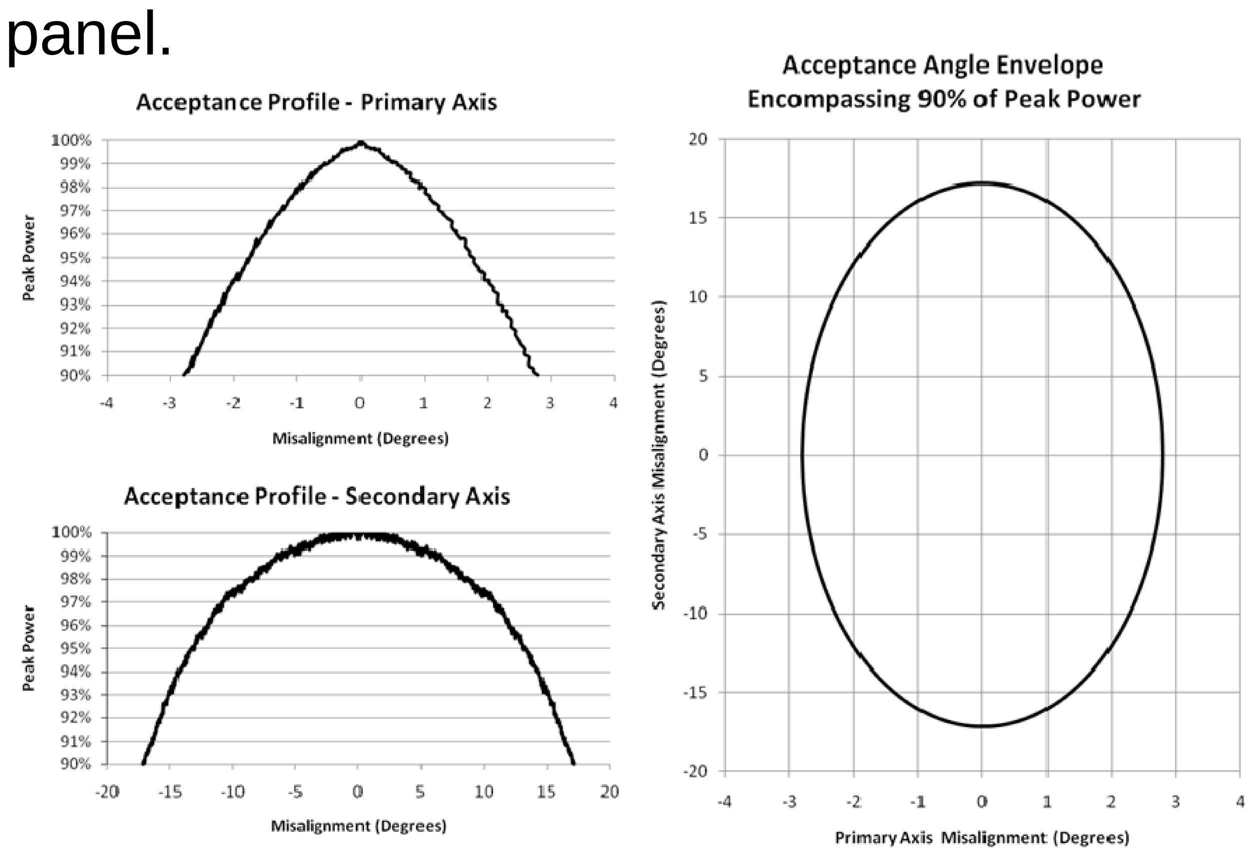


Figure 6: Acceptance Angle results. Testing performed indoors under a solar simulator with an encoder measuring degrees of misalignment. Primary axis: ±2.8˚ Secondary Axis: ±17.2˚

The measured AA's of ± 2.8˚ in the primary (tracked) axis and ± 17.2˚ in the secondary (seasonal) axis are sufficient for cost effective performance on a fixed tilt tracker. Broader AA's exceeding ± 3˚ and ± 22.5˚ are possible with greater manufacturing control and larger module sizes. Some new ATIR designs may even be effective on a horizontal axis tracker.

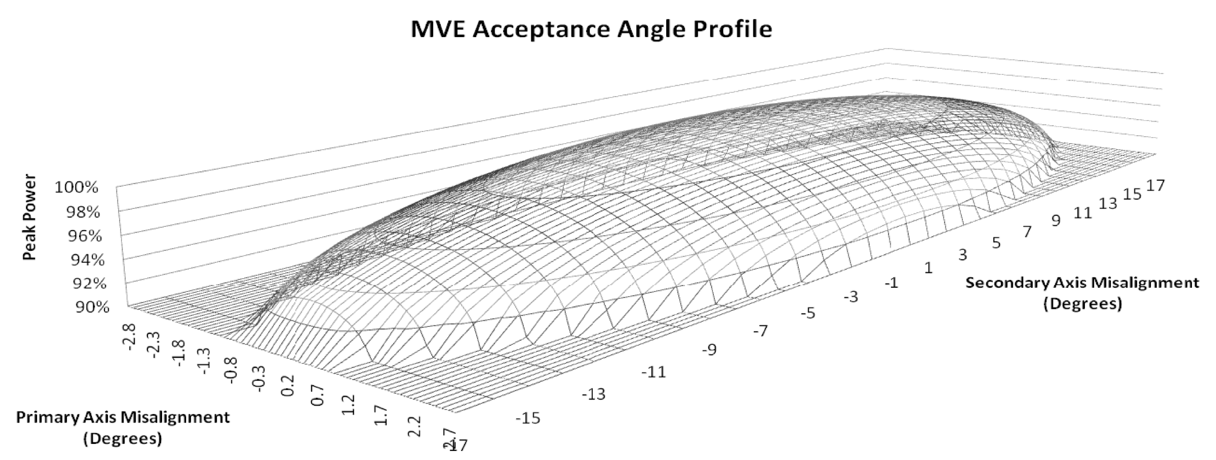


Figure 7: Minimum Volume Ellipsoid (MVE) fit to on-sun acceptance angle data illustrates expected power output given a specific misalignment

CONCLUSIONS:

Banyan's ATIR optics have demonstrated the necessary performance for effective commercialization. To reach the market successfully, proven manufacturability and reliability will be just as important.