DEMONSTRATION OF A 33% EFFICIENT CASSEGRAINIAN SOLAR MODULE

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ABSTRACT

The Cassegrainian solar concentrator module concept we shall describe here uses a primary and a dichroic secondary mirror to split the solar spectrum into two parts and direct the infrared and near visible portions of the spectrum to two separate cell locations. An efficiency of 32.9% (STC) is reported measured outdoors for a solar concentrator PV module using InGaP/GaAs dual junction (DJ) cells located at the near-visible focus at the center of the primary and GaSb infrared solar cells located behind the secondary.

CASSEGRAIN MODULE CONCEPT

High efficiency monolithic InGaP/GaAs/Ge multijunction (MJ) solar cells have been used in space for powering satellites. These monolithic MJ cells are grown on thin germanium wafers in order to be lightweight because launch costs dominate the hardware costs for space. However, lightweight is not the criterion for terrestrial applications. These monolithic MJ cells are very difficult to fabricate and the lattice match constraint for growing all junction materials in succession on germanium is quite restrictive. Using two separate cells relaxes this constraint and potentially allows even higher conversion efficiency. It has been previously noted that the theoretical limit efficiency for the InGaP/GaInAs cell in combination with a separate GaSb IR cell is as high as 59.5% [1].

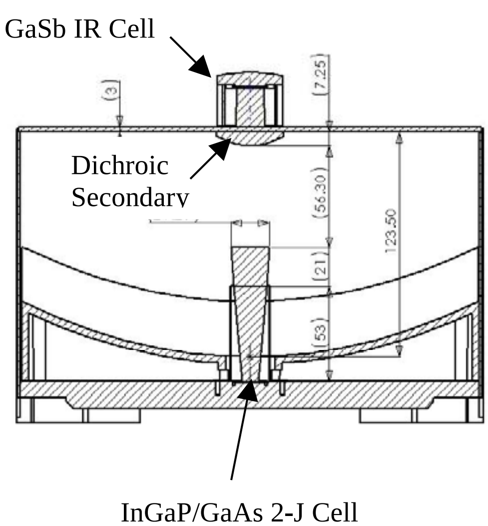

Figure 1: Cassegrain PV module with dichroic secondary for use with separate multijunction solar cells.

The Cassegrainian solar concentrator module concept shown in figures 1 and 2 uses a 25 cm x 25 cm primary and a dichroic secondary mirror to split the solar spectrum into two parts and direct the infrared and near visible portions of the spectrum to two separate cell locations. Herein, we report the fabrication and outdoor testing of prototype solar concentrator PV module using InGaP/GaAs dual junction (DJ) cells located at the near-visible focus at the center of the primary and GaSb infrared solar cells located behind the secondary.

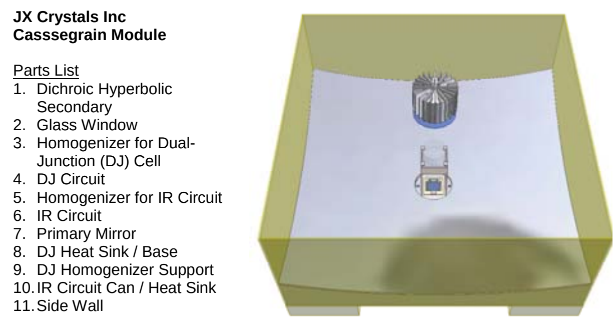

Figure 2: Cassegrain module shown in perspective view along with a parts list.

COMPONENT CELL FABRICATION & TEST RESULTS

Under an NREL contract, we have previously described the fabrication of our first prototype Cassegrainian module and opportunities for improvement [2, 3]. In our earlier unit, we used InGaP/GaAs cells from Spectrolab with a 1 cm^2 aperture area operating at a geometric concentration ratio of 600 suns. Since these cells operated outdoors at only 3.5 C above ambient, we decided to decrease the InGaP/GaAs cell aperture area to 0.5 cm^2. We ordered and obtained 50 DJ cells from Spectrolab and we were very pleased with the results. Nineteen of the cells had measured efficiencies over 31.5%. Table I shows the reported performances at the chip level for a representative group of these cells.

A group of GaSb IR cells was also designed and fabricated in house at JX Crystals Inc. The aperture area for the IR cells is 1 cm^2.

Both types of cells were then mounted onto alumina substrates as shown in figure 3. A bypass diode is mounted near the DJ cell to protect it against back bias if shaded. A single cell is used at each focus with the plan being to eventually current match and series connect both types of cells in a Cassegrainian panel.

Table I: Spectrolab InGaP/GaAs Cell Test Data
1000x (HIPSS)
Incident Power Density (ASTM G173): 0.09 W/cm^2
Concentration: 1030 (mean value)
Aperture Area: 0.5476 cm^2

Cell ID	Isc One Sun (X-25)	Isc	Voc	Pmax	FF	Aperture Area Efficiency (1030x)
JX15	0.0067	6.96	2.780	16.01	0.83	31.5%
JX17	0.0068	6.98	2.780	16.09	0.83	31.7%
JX26	0.0069	7.05	2.785	16.29	0.83	32.1%
JX27	0.0067	6.89	2.765	15.94	0.84	31.4%
JX28	0.0068	7.03	2.784	16.24	0.83	32.0%
JX36	0.0067	7.01	2.775	16.19	0.83	31.9%
JX37	0.0068	7.03	2.771	16.02	0.82	31.6%
JX38	0.0068	7.08	2.775	16.38	0.83	32.3%
JX40	0.0068	7.03	2.775	16.24	0.83	32.0%
JX46	0.0068	7.05	2.770	16.31	0.84	32.1%
JX48	0.0068	7.03	2.769	16.25	0.83	32.0%

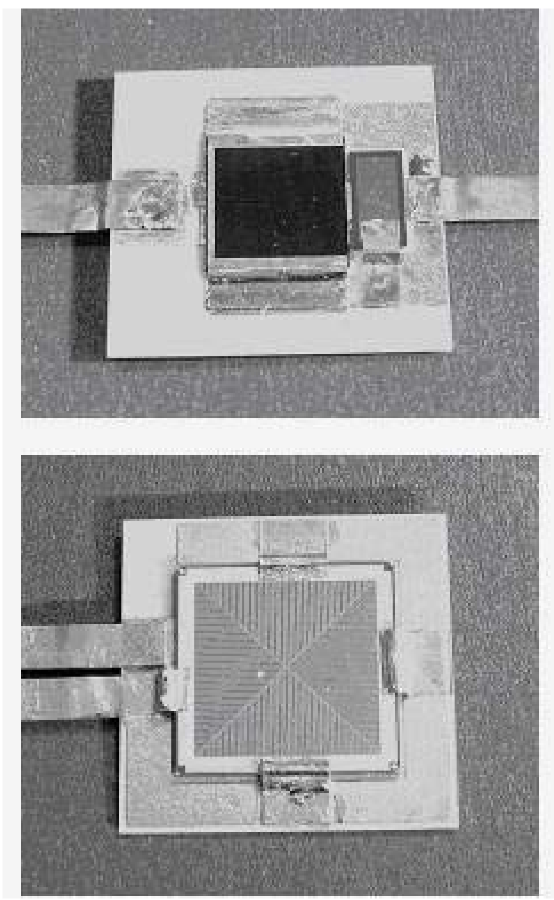

Figure 3: Photographs of DJ and IR cell packages.

Both types of cell packages were then flash tested at high current levels and the results were positive as shown in table II.

Table II: Flash test results for DJ and IR packages showing good fill factors at high short circuit currents.

Cell	ID2	FF	Voc	Isc	Imax	Vmax	Pmax
IR	*1-2	0.69	0.507	8.06	7.27	0.39	2.80
IR	*2-5	0.69	0.507	8.02	7.27	0.39	2.80
IR	*3-2	0.69	0.513	8.04	7.46	0.38	2.86
IR	*3-5	0.70	0.511	8.07	7.29	0.39	2.86
IR	*4-1	0.72	0.518	8	7.28	0.41	2.98
IR	*4-2	0.73	0.518	8.05	7.37	0.41	3.02
IR	*4-3	0.73	0.518	8.04	7.37	0.41	3.04
IR	*4-4	0.72	0.516	8.03	7.29	0.41	2.97
IR	*4-5	0.71	0.515	8.03	7.51	0.39	2.95
DJ	11	0.83	2.765	7.06	6.76	2.4	16.24
DJ	15	0.84	2.761	7	6.75	2.39	16.16
DJ	17	0.83	2.763	7.01	6.63	2.43	16.12
DJ	21	0.83	2.776	7.02	6.76	2.39	16.16
DJ	27	0.83	2.751	7.01	6.75	2.37	16.01

Figure 4 shows the illuminated current vs voltage curve for a packaged IR cell.

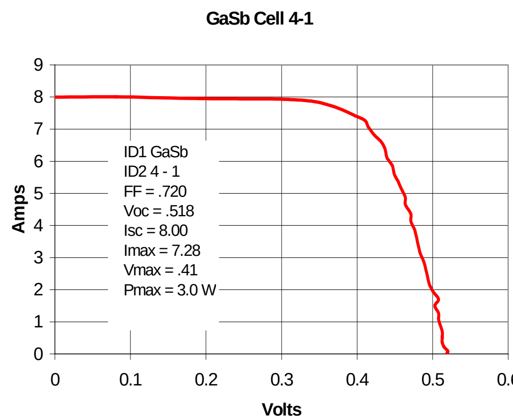

Figure 4: IR cell package produces 3 W at a current density of 8 Amps.

OPTICAL EFFICIENCY MEASUREMENTS

Making a PV concentrating module requires good optical components in addition to good solar cells. While we have specified and ordered all of the required optical components, we do not know if as built, they meet the design specifications. As an example, is the dichroic reflection-to-transmission wavelength just below the GaAs cell bandgap wavelength? As a second example, is the focal length of the primary mirror correct, as specified for the module design? In order to address these questions, we did some indoor testing with a lamp at a distance with and without the window and secondary in place. We measured the current ratio at the DJ cell with and without the window reasoning that this ratio should be nearly equal to the ratio of the window area to the secondary area. The difference in these ratios should then give us a measure of the optical efficiency. We then did this with both a silver coated secondary and a dichroic secondary.

This procedure gave us a tentative optical efficiency of 91% with the silver coated secondary and 89% for the dichroic secondary.

OUTDOOR TEST RESULTS

Cassegrainian modules using first and second iteration cells were mounted on an Array Technologies 2-axis tracker and measured in outdoor sunlight as shown in figure 5. The results for the first iteration have been reported previously [3]. The results for the second iteration cells are reported here. Note in figure 5 that instruments for measuring the direct and global solar flux are also mounted on this tracker.

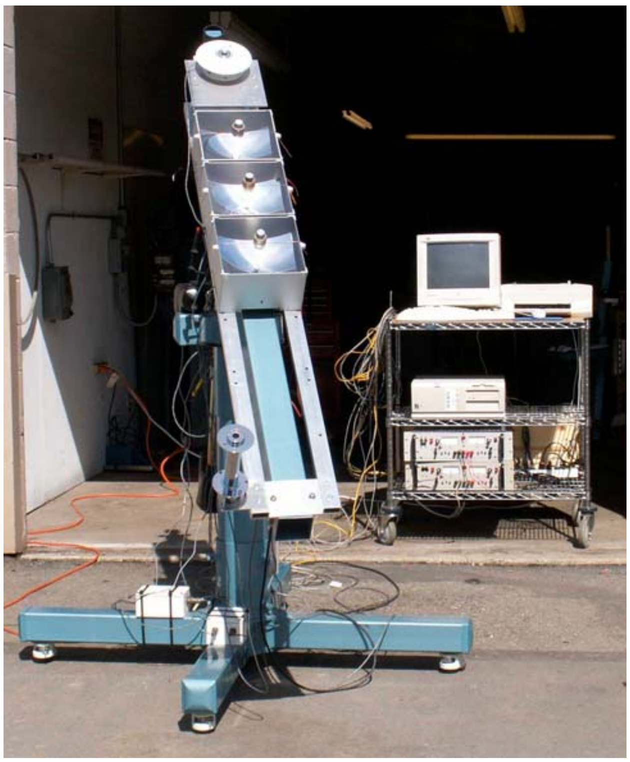

Figure 5: Photograph of 3 Cassegrainian modules mounted on a 2-axis solar tracker with associated illuminated current vs voltage measurement equipment and direct and global solar intensity monitors.

Measurements were recorded over a 2 hour period on a sunny blue sky day (April 28 2006). Typical results are summarized in Table III. Figure 6 shows a measured illuminated current vs voltage curve for the DJ cell.

Referring to column 3 in table III, at actual operating temperature, the power produced by the DJ cell was 14.4 W and the power produced by the IR cell was 2.6 W for a combined electrical output power of 17 W. The direct solar intensity reading was 919 W / m2. So for the module area of 600 cm2, the input power was 55.2 W. These numbers translate to a module efficiency of 30.8%. From the Voc readings for the two cells, we can also determine the individual cell temperatures. The DJ cell was operating at 12.5 C above ambient and the IR cell was operating at 30 C above ambient. The DJ cell temperature is really remarkable given that it was operating at a geometric concentration ratio of 1200 suns. While the IR cell operating temperature is acceptable, there is room for improvement in the IR heat sink fin design to decrease that cells operating temperature still further. Column 4 in table III shows the cell efficiencies when corrected back to 25 C for a sum STC module efficiency of 32.9%.

While we are quite pleased with this outdoor module efficiency, there is still room for improvement as shown in column 2 in table III. Column 2 shows the DJ and IR cell power and efficiencies obtained by multiplying the packaged cell powers and efficiencies summarized in column 1 by an optical efficiency of 90%. Note that an efficiency of 34.3% might have been expected. Further future component characterization will be required.

Table III: Performance Summary

	Packaged Cells at STC	Projected STC with 90% Optical Effic	Measure at Operate Temp (April 28)	Measure Module at STC (April 28)
DJ Cell Power	17.4 W	15.7 W	14.4 W	15.1 W
DJ Cell Effic.	31.5%	28.4%	26.1%	27.3%
IR Cell Power	3.64 W	3.28 W	2.6 W	3.1 W
IR Cell Effic.	6.6%	5.9%	4.7%	5.6%
Sum Power	21 W	19 W	17 W	18.7 W
Sum Effic.	38.1%	34.3%	30.8%	32.9%

NIP DNI = 0.92; Area = 600 cm2; Input Power = 55.2 W

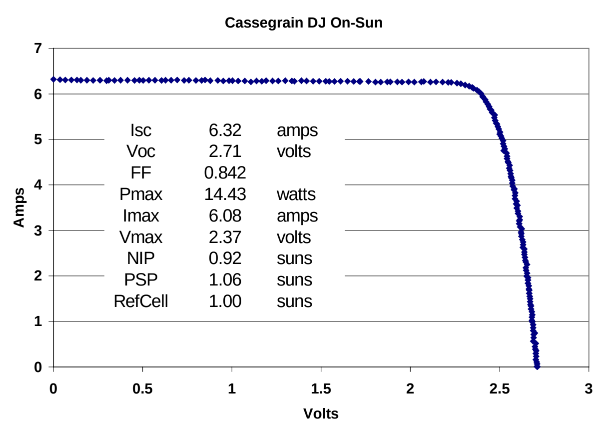

Figure 6: Illuminated current vs voltage curve for DJ cell on sun on 2-axis tracker.

PANEL DESIGN

Having now demonstrated a respectable Cassegrainian module, we are now moving on to a full size panel. Here, we define a module as a complete set of unique cell and optical components and a panel as an array of modules. Figure 7 shows a Cassegrainian panel consisting of a 3 by 6 array of modules. As this figure shows, this panel consists of a metal back sheet with an array of holes where DJ cell packages complete with heat sinks are mounted. The panel also comprises a glass front sheet with holes where IR cell packages complete with heat sinks and the dichroic secondary mirror are mounted. An array of primary mirrors is then mounted on posts extending up from the back sheet and then these 3 arrays are captured by side-wall aluminum extrusions.

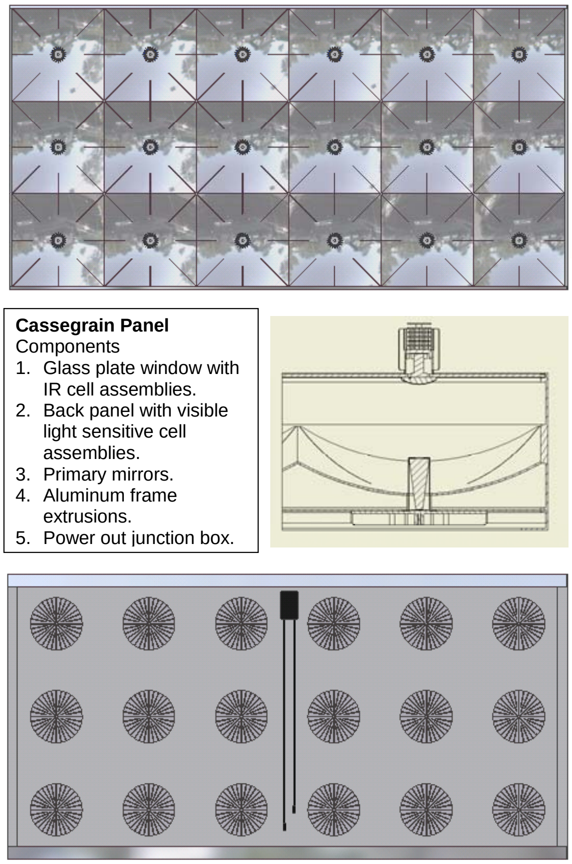

Figure 7: Cassegrainian panel design. This particular panel is a 3 x 6 array with dimensions of 750 mm x 1500 mm, about the same size as a silicon 180 W panel. However, extrapolating from column 2 in table III, this panel should produce 340 W.

Our wiring plan for this module is to interconnect all of the cells of both types in series. With this in mind and referring to column 3 in table III, more work on the visible light sensitive cell is required.

We see 2 possible options. For low cell cost, we can use a simple GaAs(0.95)P)0.05) single junction cell array series connected with the GaSb IR cell array with all cells operating at about 10 Amps [4]. This option should allow a panel efficiency of over 30%. Alternately for still higher panel efficiency, indium can be added in both junctions in an In(0.6)Ga(0.4)P / Ga(0.9)In(0.1)As DJ cell and a cell array of this type can then be series connected with the GaSb IR cell array operating at a current of about 7 Amps [4]. This option should allow a panel efficiency of over 35%.

CONCLUSIONS

We have reported here for the first time the outdoor measurement of a module efficiency approaching 33% for a Cassegrainian PV module. This Cassegrainian module is unique in that it has a dichroic secondary mirror that allows for two separate cell locations dividing the heat load and allowing for both cells to be operated at very high concentration ratios. In the module demonstrated here, the geometric concentration ratio for the DJ cell is 1200 suns and for the IR cell, it is 600 suns. An additional advantage of the two separate cell locations is a much larger set of choices for the individual cells. This allows for example:

1.) More optimal cells such as the higher voltage GaSb IR cell vs the Ge IR cell,
2.) Less expensive simpler cells such as a single junction GaAs cell vs a DJ cell, or
3.) A higher performance cell combination such as the InGaP/GaInAs cell in combination with a separate GaSb IR cell with a combined theoretical limit efficiency as high as 59.5%.

High efficiency concentrated sunlight PV systems now offer a path to affordable solar electric power on a large scale in sunny locations [5].

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[3] L. Fraas, J. Avery, H. Huang, Leonid Minkin, She Hui, Eli Shifman, "Towards a 33% Efficient Cassegrainian Solar Module", Shanghai, October 2005.

[4] Lewis M. Fraas, Patent pending.

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