# DUAL FOCUS CASSEGRAINIAN MODULE CAN ACHIEVE >45% EFFICIENCY

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## ABSTRACT

Various types of multijunction solar cells have now been demonstrated with energy conversion efficiencies over 40%. Higher cell efficiencies are still possible. NREL, Fraunhoffer and others have announced >40% Inverted metamorphic triple-junction (IMMTJ) InGaP/GaAs/GaInAs cells. One key feature of these cells is that the lowest bandgap cell is no longer a Ge cell. The IMMTJ lowest cell bandgap now allows for a 4th junction cell either integrated or separate. Herein, it is observed that the dual focus Cassegrainian (DFC) module can be fitted with a InGaP/GaAsP/InGaAs triple junction cell at its primary focus and with a GaSb or other IR sensitive cell at its secondary focus. This can allow a straight forward rapid path to a combined cell efficiency of >44%. The potential advantages of this configuration are, first, a rapid path to a combined cell efficiency of 44%, and second, given the fact that the heat load is divided into two locations, both cells will run cooler giving a higher module efficiency.

## DUAL-FOCUS CASSEGRAIN (DFC) MODULE CONCEPT

Maximizing conversion efficiency in solar photovoltaic systems is a current focus of leading cell manufacturers [1] and [2]. The reasons are obvious: a cost effective 50% efficient solar ***system*** would radically change the renewable energy production landscape in the United States and the world. While recent work on improving the cell efficiencies to over 40% in the lab (which can result in up to 30% at the system level in actual use) shows promise to improve overall concentrated solar PV systems, no group has proposed or defined a truly ground breaking system design that can shatter previous conversion records and holds the potential to be economically viable in the very near term. The path by which a DFC enables higher conversion efficiency is by the addition of a fourth solar cell at a separate location that then converts a previously unused portion of the solar spectrum into electricity.

The fourth cell adds to the system conversion efficiency by converting long wave infra-red light that would otherwise not be converted by the triple junction (TJ) cell. There are two choices for the fourth IR sensitive cell. Either the simple GaSb diffused junction IR cell or the epitaxial InGaAs/InP IR cell can be used as the fourth cell. Figure 1 shows the spectral response of a current state of the art IMMTJ cell [1], with an additional InGaAs TPV cell [3], and figures 2 and 3 show how the addition of a TPV cell to a best in class National Renewable Energy Lab IMMTJ can result in up to 46% conversion efficiency.

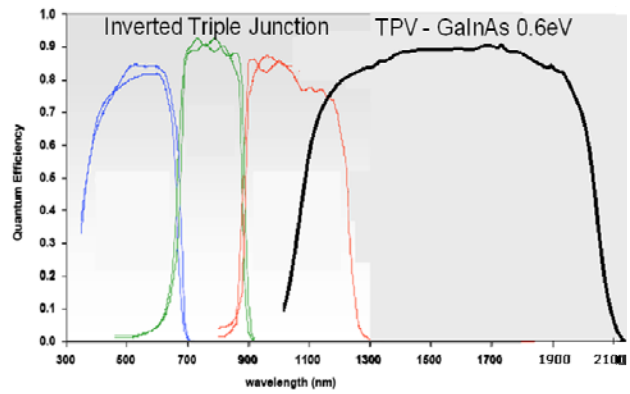


Figure 1: Spectral Response of an Emcore [1] Inverted Metamorphic Triple Junction Solar Cell and a 0.6 eV InGaAs TPV Cell.

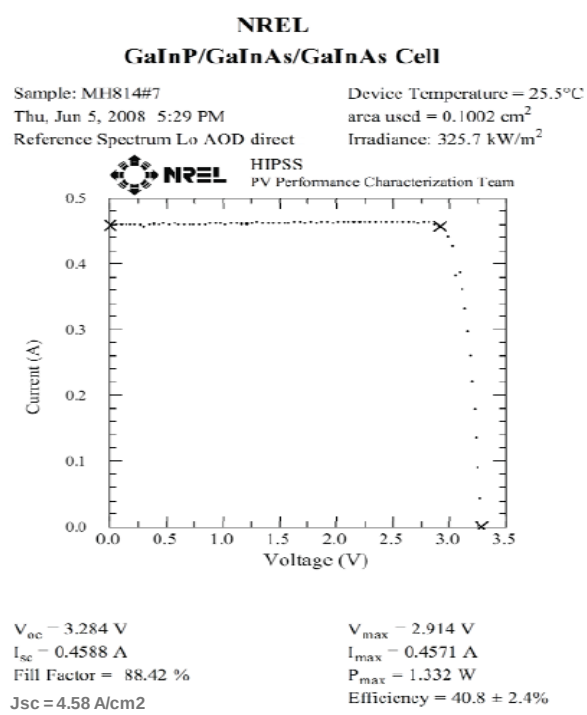


Figure 2: NREL [2] has demonstrated a IMM TJ cell with a measured efficiency of 40.8%.

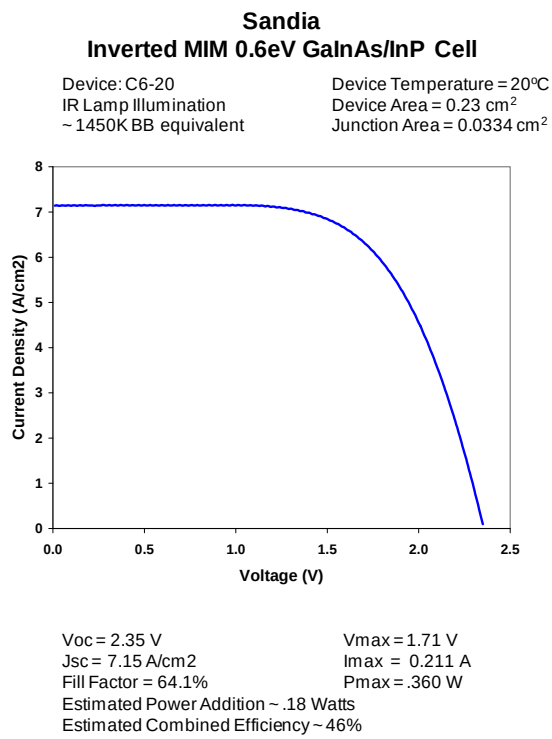


Figure 3: Sandia has demonstrated [3] an InGaAs/InP IR cell that can potentially be used as a 4th junction cell in a DFC module to produce a combined cell efficiency of 46%.

How can these cell efficiencies be affectively added? The Dual-Focus Cassegrainian module shown in Figure 4, with an already demonstrated first iteration cell set, provides the answer. The DFC solar concentrator module concept uses a primary mirror to collect the sunlight and direct it to a secondary mirror. The dichroic secondary mirror then splits the solar spectrum into two parts and directs the infrared and near visible portions of the spectrum to two separate cell locations. As shown in figure 4, in the first embodiment, a GaSb infrared cell was located behind the dichroic secondary and an InGaP/GaAs dual junction cell was located under a homogenizing prism in the center of the primary. The cell efficiencies used in this first embodiment were 32% and 6% respectively for a combined cell efficiency of 38%.

Now, with the improved cell combination shown in figures 1, 2, and 3, a 46% efficient cell combination is possible. In addition to providing a means to effectively obtain a 4 junction 46% efficient cell combination, this configuration removes considerable heat load from the TJ cell, further increasing its efficiency. Dividing the heat load allows both cells to run cooler increasing the real world system efficiency.

The Dual Focus Cassegrain dish concentrator system, combined with the recent cell advances, improved optical filter coatings and thermal design can lead to greater system conversion efficiency than ever achieved. Furthermore, the DFC has a clear path to a competitively priced deployment that favors large scale utility generation use, which could change the renewable energy production landscape. A background and chronology of the current state of the art of this type of system follows.

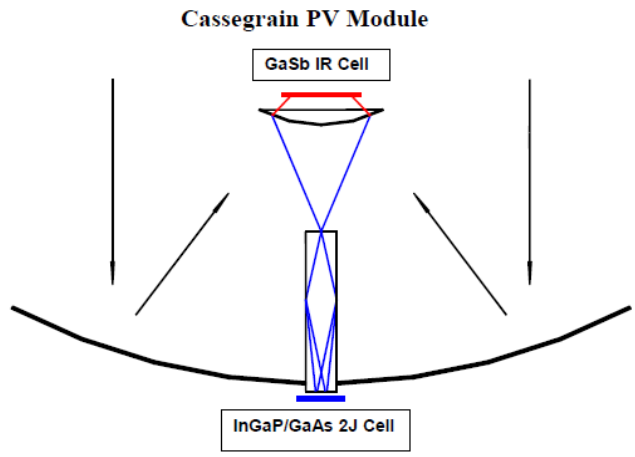


Figure 4: Dual-Focus Cassegrainian module concept shown with first iteration InGaP/GaAs and GaSb cell set.

## DUAL-FOCUS CASSEGRAIN MODULE BACKGROUND

In 1978, Fraas and Kinechtli first proposed the monolithic InGaP/GaInAs/Ge triple junction (TJ) concentrator solar cell predicting a cell efficiency of 40% at 300 suns [4]. Then in 1990, Fraas, Avery, et al invented, demonstrated, and reported a 35% efficient GaAs/GaSb 2J mechanically stacked cell for use with Fresnel lenses and concentrated sunlight [5]. Subsequently in May of 2005, Fraas and Shifman invented, demonstrated, and reported on the use of multijunction cells in a Dual-Focus Cassegrain (DFC) mirror module [6]. The DFC Module concept is shown above in Figure 4. In November of 2005, SolFocus was formed to make a module resembling the Cassegrain mirror module using InGaP/GaInAs/Ge 3J cells. The founders of SolFocus then received an Innovation Award from NREL. Then in April of 2006 as shown in Figure 5 and Table 1, Fraas, Avery, Shifman, et al demonstrated the DFC concentrator module with a measured outdoor efficiency of 31% [7]. Additionally in December of 2006, R.R.King et al demonstrated InGaP/GaInAs/Ge TJ concentrator cell with a 40% efficiency measured at 300 suns [8].

Still higher cell and module efficiencies are possible as described here. The DFC solar concentrator module concept has two very significant benefits. First, the DFC module design now allows a larger portion of the solar spectrum to be converted by distinct cell pairs, and second, since the solar heat load is now divided into two separate cell locations, both cells will run cooler leading to higher real world module conversion efficiency.

We have already demonstrated these advantages for this DFC configuration in a breadboard prototype [7] with non optimized components as shown in Figure 5.

(a)

(b)

Figure 5: (a) 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.
(b) A close up photograph of one Dual-Focus Cassegrainian module.

Table 1 shows that higher combined module efficiencies can result by simply replacing the Ge cell with a GaSb IR cell. Since the Ge cell in the triple-junction cell produces current in excess of that available to the InGaP and GaAs cells, a GaSb cell with a higher bandgap can increase the 3J cell combined voltage without a loss in current leading to higher module efficiency. The GaSb cell can produce a higher voltage relative to a Ge cell by at least 0.2 V if all cells are operated at 25 C. However, because the DFC cell configuration splits the heat loads, there is an additional advantage for the DFC cell configuration. If the cells in the DFC panel operate 30 C cooler than in a traditional concentrator system, there is an additional voltage advantage for the DFC case of 3 x 30 x 2 mV = 0.18 V. Combining these 2 effects gives a voltage increase of 0.38 V and that translates to a 4 percentage-point advantage in higher conversion efficiency for the DFC configuration given this set of cells. This has already led to the 31% world record module efficiency (pending independent validation by measurement laboratory). Note that this 31% module efficiency is a real world efficiency including optical losses and measured at cell operating temperature.

More sophisticated cell choices are now possible for incorporation into this DFC configuration. Various types of multijunction solar cells have now been demonstrated with energy conversion efficiencies above or near 40%. Higher cell efficiencies are still possible. Spectrolab, NREL with EMCORE and Fraunhoffer have recently announced Inverted MetaMorphic triple-junction (IMMTJ) InGaP/GaAs/GaInAs cells that approach and exceed 40% efficiency in a flash test, and are also actively pursuing 4J and 5J technology. A DFC allows the addition of a 4th cell in a much more economical fashion, with the previously described thermal advantages as well. MicroLink Devices is also working on an IMMTJ cell. The lowest cell bandgap can now hypothetically be tuned to 1.1eV, which is optimum for a 4$^{th}$ junction TPV cell's bandgap.

**Table 1: Performance Summary [7]**

| | Packaged Cells at STC | Projected STC with 90% Optical Effic | Measure at Operate Temp (April 28, 2006) | Measure Module at STC (April 28, 2006) |
|---|---|---|---|---|
| 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

Herein, it is observed that the DFC module shown in Figure 5 can be fitted with a InGaP/GaAsP/InGaAs triple junction cell at its primary focus and with a GaSb or InGaAs/InP IR sensitive cell at its secondary focus. As summarized in Table 2, this can allow a straight forward rapid path to a combined cell efficiency of 44% near term with a real world module system efficiency approaching

40% in the longer term. Given production IMMTJ cells, the only requirement to demonstrate 44%+ conversion efficiency in a flash test is funding and system engineering.

**Table 2: Projected DFC Cell and Module Efficiencies.**

| Cell Type | Demonstrated | Near Term | Mid Term |
|---|---|---|---|
| Dual Junction | 31.5% | | |
| IMM TJ | | 39% | 41% |
| GaSb IR | 6.6% | 5% | 6% |
| Combined Cell Total | 38% | 44% | 47% |
| Module Effic | 31% | 37% | 40% |

## DISCUSSION

What are the potential advantages and disadvantages of this configuration? A first advantage is the rapid path to a combined cell efficiency of 44% as soon as the TJ and the GaSb cells become available. A prototype Cassegrainian module and the GaSb cell are already available. The TJ cell is still under development as the FF needs to be improved for operation at over 500 suns. Given this TJ cell FF improvement, the only requirement to demonstrate 44% will be funding and cell packaging. So, what is the longer term benefit of this configuration? The fact that the heat load is divided into two locations is a second significant advantage of this configuration. This means that not only do the separate cells combine to give a predicted efficiency of >44% at a cell temperature of 25 C but that in practical operation, both cells will run cooler giving a higher real world module efficiency.

There are two legitimate questions that need to be addressed. Is circuit wiring too complex and what about the cost of the 2 separate cells? Figure 6 addresses the circuit wiring question. By measuring the performance of the triple junction cell appropriately, the current generated in the triple junction cell can be matched by the current generated in the IR cell such that all cells in a module can be wired in series. Alternatively, GaSb and InGaAs IR cells can be made so that they are either voltage or current matched for the maximum amount of irradiance conditions.

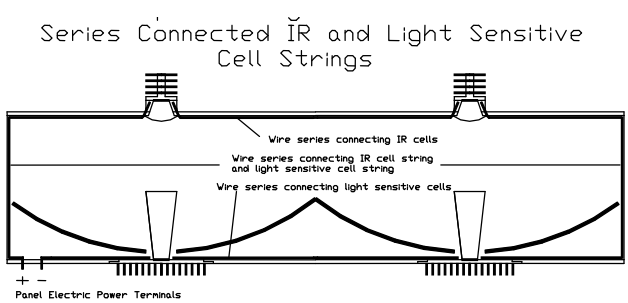


Figure 6: Example Cassegrain PV Panel with Series Connected IR and Light Sensitive Cell strings.

Preliminary calculations for the Dual Focus Cassegrain module, assuming an Inverted MetaMorphic TJ cell with InGaP/GaAsP/GaInAs with a lower cell bandgap of 1.1 eV and a GaSb cell as the 4th junction, have been made. In a high concentrating solar system, we assume 3.5 V, and 0.85 A for the TJ cell and 0.5 V and 0.8 A for the GaSb cell. We calculate current densities at 1-sun AM1.5d of 13 mA/cm2 for the TJ cell, and 14 mA/cm2 for the GaSb cell. At high concentration, these assumptions lead to a TJ efficiency of 38.7% and a GaSb cell efficiency of 5.2% for a combined efficiency of 43.9%. Assuming 600 cm2 active primary lens area, the Isc for both cells is 7.8 A. The power produced by each cell is then 23 W for the TJ and 3.1 W for the GaSb cell. All of the above assumes 1 kW/m2 incident light flux.

Now what about the additional cost of the GaSb cell? The good news is that if the complete system is already justified and paid for with the TJ cell, then the GaSb cell will add benefit if its additional incremental cost is less than the system cost. So what is the projected cost of the GaSb cell? The good news again is that it is a simple diffused junction cell [9]. Assuming $150 per processed 76 mm GaSb wafer and using 0.5 cm2 GaSb cells generating 3 W each, then the add-on cost for the GaSb cell will be $0.75/W.

The conclusion is that if the HCPV system total cost is $1.5 per W or more, it is economically attractive to add the GaSb cell.

It is possible that a higher performance system can be achieved with an InGaAs/InP IR cell because epitaxy allows more device optimization relative to simple diffusions. This approach can be used to develop a 46% efficient cell combination by adjusting the InGaAs IR cell bandgap to 0.7 to 0.74 eV and also adjust the number of junctions (InGaAs IR cells stack junctions horizontally to build up voltage on chip) to change the cell's voltage, and/or the cell's area to adjust its current. Although much more expensive, and perhaps not currently practical for a production system, it is this flexibility that allows the highest possible conversion efficiency and matching to IMMTJ cells.

While our goal here is to simply improve performance, we are aware that there will be additional considerations in the longer term when considering costs at the system level. For example, a positive attribute for the IMM TJ cell relative to the established TJ cell on a Ge substrate is the elimination of the Ge substrate as Ge is much less abundant that Ga [10]. A negative for the InGaAs/InP cell would be Indium availability and the higher cost of higher pressure InP crystal growth relative to GaSb crystal growth. These considerations warrant a multi pronged approach to this novel high efficiency module development: one that combines the best of all available resources to set a combined cell efficiency record of 47% or higher, and another that provides a cost effective production path in a much higher conversion efficiency system than anything currently out there, and at lower cost.

## CONCLUSIONS

In summary, a Dual Focus Cassegrain module design that can break current module and system efficiency records has been described. This design leverages recent developments in high efficiency triple junction cells and provides a cost effective approach to adding a 4th cell. The benefit of adding a 4th cell that converts IR light is increased efficiency in a lab test, but more importantly, even greater real world operating efficiency due to the IR heat load being directed away from the TJ cell.

More generally, the DFC module concept is interesting in itself because it allows a larger choice of potential cell designs. In the future, there may be lower cost alternatives to the IMMTJ cell. Lower cost cells may allow lower concentration modules saving costs in the optics and tracker systems. This research will answer some of the more complex questions and establish a new standard in concentrated solar conversion efficiency performance.

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