Daily fill factor variation as a diagnostic probe of multijunction concentrator systems during outdoor operation

Article *in* Proceedings of SPIE - The International Society for Optical Engineering · September 2007

DOI: 10.1117/12.732604

Keith A. Emery
National Renewable Energy Laboratory

Larry Ottoson
National Renewable Energy Laboratory

James Scott Ward
National Renewable Energy Laboratory

Daily Fill Factor Variation as a Diagnostic Probe of Multijunction Concentrator Systems during Outdoor Operation

William E. McMahon, Keith E. Emery, Daniel J. Friedman, Larry Ottoson, Michelle S. Young, J. Scott Ward, Charlene M. Kramer, Anna Duda, and Sarah Kurtz
National Renewable Energy Lab, 1617 Cole Blvd, Golden, CO 80401

ABSTRACT

Optimizing a concentrator system which uses multijunction solar cells is challenging because: (a) the conditions are variable, so the solar cells rarely operate under optimal conditions and (b) the conditions are not controlled, so any design problems are difficult to characterize. Here we show how the fill factor can be used as a diagnostic tool to either verify correct system design and operation, or to help identify a problem. We give particular attention to the detection of spectral skewing by the concentrator optics, as this can reduce the performance of tandem cells and is difficult to characterize. The conclusions are equally valid for $GaInP_2$/GaAs/Ge triple-junction cells.

Keywords: multi-junction solar cell, concentrator module, current-matching, fill factor

1. INTRODUCTION

For optimal performance, monolithic (series-connected) $GaInP_2$/GaAs tandem cells [1] must be "current matched." Both the top and bottom cells must produce an equal photocurrent, or else the total current will be limited to the lower of the two values. To accomplish this in a concentrator system, both the cells and the optics must be correctly designed. In this paper, we will first discuss how the daily variation of the solar spectrum affects the design of the cells themselves, then show how the daily spectral variation can be combined with fill factor measurements to characterize any spectral skewing of the direct spectra by the concentrator optics.

In the proposed method, testing is done outdoors under natural sunlight. Our initial reason for developing an outdoor testing method was that no indoor solar simulator could mimic the spatial uniformity, collimation and spectral content of natural sunlight well enough to be useful for testing. Indoor simulators for small-aperture systems are currently being developed, but larger-scale systems pose a much greater challenge. The testing method we propose here should work equally well on systems of any size. Although outdoor testing is subject to the whims of weather, there is also a huge benefit in that systems can be field-tested in their final operating configurations, with no modifications. In fact, some conclusions can be drawn simply by plotting the fill factor versus time of day. In most cases this will require little extra effort, since fill-factor data are normally acquired during any standard testing.

2. TOP-CELL THINNING

A tandem cell is typically current-matched by thinning the $GaInP_2$ cell slightly so as to transmit some above-band-gap photons to the GaAs cell, increasing the GaAs cell's photocurrent and reducing the $GaInP_2$ cell's photocurrent until they match [2]. In terms of cell efficiency, it would be better to raise the $GaInP_2$ band gap, because this will also increase the cell voltage [3]. Within the context of this paper, thinning the top cell and raising the $GaInP_2$ band gap are equivalent. However, varying the top cell thickness allows us to easily study a wider range of parameter space. Because the solar spectrum changes throughout the day, different top-cell thicknesses (t_{top}) are optimal for different times of the day [4, 5]. To simplify tandem cell design, it is therefore useful to define a "design spectrum" to represent this ensemble of actual spectra. For the test days in this study, cells designed for either the AM1.5G (ASTM G-159GT) [6] or the ASTM G-173 direct (G-173D) [7] spectrum performed the best.

To give some background, Fig. 1 shows how performance should vary with t_{top} under several standard reference spectra [6–9]. For each spectrum, there is an optimal t_{top} for which a tandem cell's top and bottom cells are current-matched, maximizing its power. Because our model (based on Ref. [2]) is simplified to capture only the essential physics, the model t_{top} values are really just effective thicknesses. This is fine, because given all of the possible cell designs and characteristics, t_{top} cannot be a fundamental parameter anyhow. For comparison with real cells, either relative t_{top} values or the AM0 J_{sc} ratio (along the top axis of Fig. 1) should be used.

Notice that the fill factor minima in Fig. 1 basically correspond to the power maxima [10], but there are small errors. The biggest error is for the G159 spectrum, but in terms of power production even this error is negligible. If t_{top} is determined by minimizing the fill factor under the G159 direct spectrum, the resulting power will be sub-optimal by only 0.04%. It should be mentioned that this error increases as the fill factor decreases, so current-matching and fill-factor minimization are not appropriate for low-band-gap thermophotovoltaic (TPV) cells [11]. However, for high fill-factor GaAs and $GaInP_2$ solar cells, minimizing the fill factor is a good tool for maximizing power production.

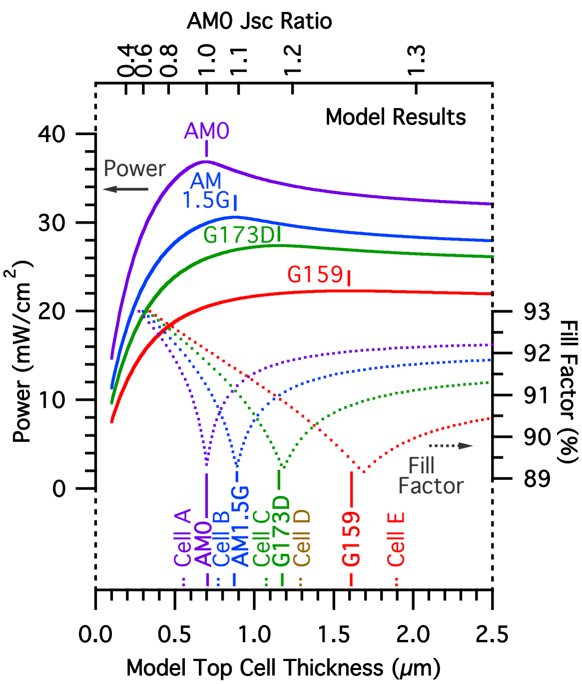

Fig. 1. Calculated power produced by an idealized $GaInP_2$/GaAs tandem cell as a function of t_{top} for AM0, AM1.5 Global (G-159GT), G-173 Direct, and G159 (E891) standard reference spectra. Approximate t_{top} values for cells A–E are indicated.

3. DAILY VARIATION IN CELL PERFORMANCE

For this study, we grew a set of tandem cells (labeled A - E) with five different top-cell thicknesses, with a t_{top} range spanning all foreseeable applications. Approximate t_{top} values for these cells are shown along the bottom axis of Fig. 1 [5]. Cell A has the thinnest t_{top} and is well suited to "blue-rich" space applications (i.e., AM0 [9]). Cell E has the thickest t_{top} and is better for "red-rich" morning and evening light. (To discuss these spectra, it is useful to divide the spectra into "blue" photons with energies above the $GaInP_2$ band gap and "red" photons with energies between the GaAs and $GaInP_2$ band gaps.) Cells B and C have intermediate t_{top} values which are compromises between midday power production and overall daily energy production. Cell B is nearly optimal for the AM1.5G spectrum, whereas Cell C is closely matched to the G-173D spectrum. As a gauge of experimental reproducibility, two cells were grown with the median t_{top} (C1 and C2).

The cells were mounted on a two-axis tracker, with the incident sunlight collimated to exclude all except the direct beam. The collimators followed the design shown in the annex of Ref. [12], with a 5° field of view. To simplify the interpretation of our results, no protective glass, antireflection coatings, nor bypass diodes were used.

The cells were actively cooled to a nominal temperature of 25° to 30° C, and I-V measurements were made for each cell throughout the day. To facilitate cell modeling, the direct solar spectrum was measured concurrently using a collimated spectrometer mounted on a two-axis tracker. Measurements were made on clear days in Golden, Colorado (40°N, 105°W, 1830m). To a first approximation, they represent the spectral variation of sunlight for a clear, high-altitude site in the southwestern United States.

The power produced by each cell on a particularly clear (blue-rich direct light) day is shown in Fig. 2. Cell B (designed for ~AM1.5G) was best for midday power production, whereas cell E performed best during the morning and evening. Cell A (designed for ~AM0) was outperformed by other cells throughout the day. Although not shown here, the measured midday power for cells B and C during slightly hazy, partly cloudy days was approximately equal. To determine each cell's daily energy, its power was integrated over the course of the test day. If cells C1 and C2 are averaged, the daily energies for cells B and C are about the same. On a slightly hazy, less blue-rich day, cell C is favored.

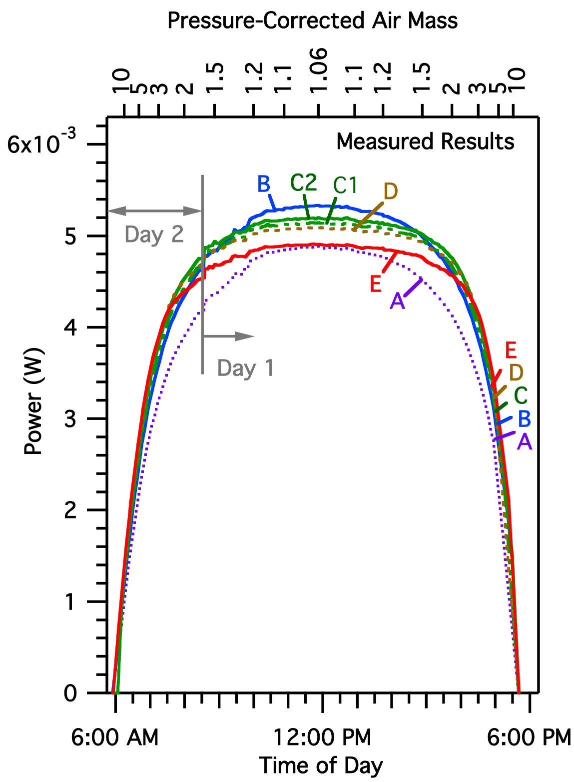

Fig. 2. Measured powers for cells A–E on Sept. 23–24, 2004, at NREL, in Golden, Colorado. This day was particularly clear. Midday turbidity at 500 nm was ~ 0.01, and midday precipitable water vapor was ~1.5 cm. Because no morning data were taken the first day, data from the morning of the second day are substituted. In subsequent figures, this will be referred to as a single "test day." Cells are labeled in the order of performance midday and during the evening. The cell area for each cell is 0.253 cm^2.

4. ON-SUN MEASUREMENT OF CURRENT MATCHING

Although power production is the ultimate goal, measuring power production is not the best way to detect and diagnose current-matching problems. In general, data from a real concentrator system will be much more difficult to interpret than the data shown in Fig. 2. The variations in Fig. 2 are small, and are visible only because great care was taken to vary only t_{top}, holding all else equal. Conclusions were drawn by comparing the performance of different cells with different t_{top} values. In a real concentrator system, only a single power curve would be obtained. Analyzing any single power curve in isolation is not so straightforward. In particular, there is no qualitative indicator for when the cell is current matched. Since current-matching is very important to the performance of series-connected multijunction cells, information about current matching is particularly valuable.

One way to obtain current-matching information is to plot the efficiency over the course of the same clear sunny day (Fig. 3a). This requires a little more effort, because both the cell power and the direct irradiance must be measured and recorded. However, any single efficiency curve gives information about current matching. To help explain how, we have calculated the ratio $J_{sc}(top)/[J_{sc}(top)+J_{sc}(bottom)]$, and plotted it as a function of time of day for each cell (Fig. 3b). A comparison between Figs. 3a and 3b shows that the pairs of efficiency maxima for cells C, D and E occur at times when the top and bottom cells are current-matched. Because cells A and B are never current-matched, only a single broad efficiency maximum is seen for each of these cells.

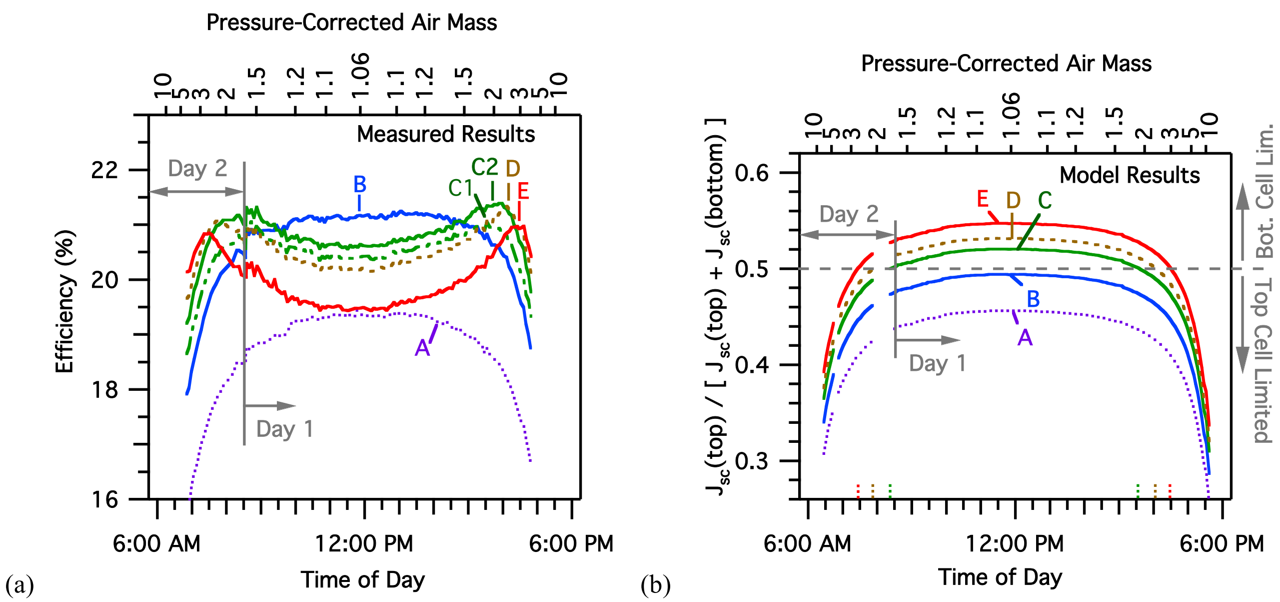

Fig. 3. (a) Measured cell efficiencies during the test day. No antireflection (AR) coatings were used on these cells, so about 30% of the incident light is reflected. With AR coatings, the efficiencies would approach 30%. (b) Modeled decoupled short-circuit currents (plotted as a ratio) during the test day. The best instantaneous power production is for a current-matched cell with a ratio of 0.5, which corresponds to $J_{sc}(top) = J_{sc}(bottom)$. Current-matched times for cells C, D, and E are indicated along the bottom axis with dashed lines. Gaps in the curves occur whenever direct spectra were not recorded. Cell C in our model corresponds to cell C2 in our measured results.

A more precise way to obtain current-matching information is to plot the fill factor over the course of the same day (Fig. 4). Because current-matching minimizes the fill factor [10] (Fig. 1), sharp minima occur when cells C, D, and E are current-matched. These minima are much sharper than the corresponding maxima in Fig. 3a, so the times of current-matching can be determined more precisely. The measurement of the fill factor is also simpler, because no direct irradiance measurement is needed. As discussed with Fig. 3, cells A and B are never current-matched, so only a single broad minimum is seen.

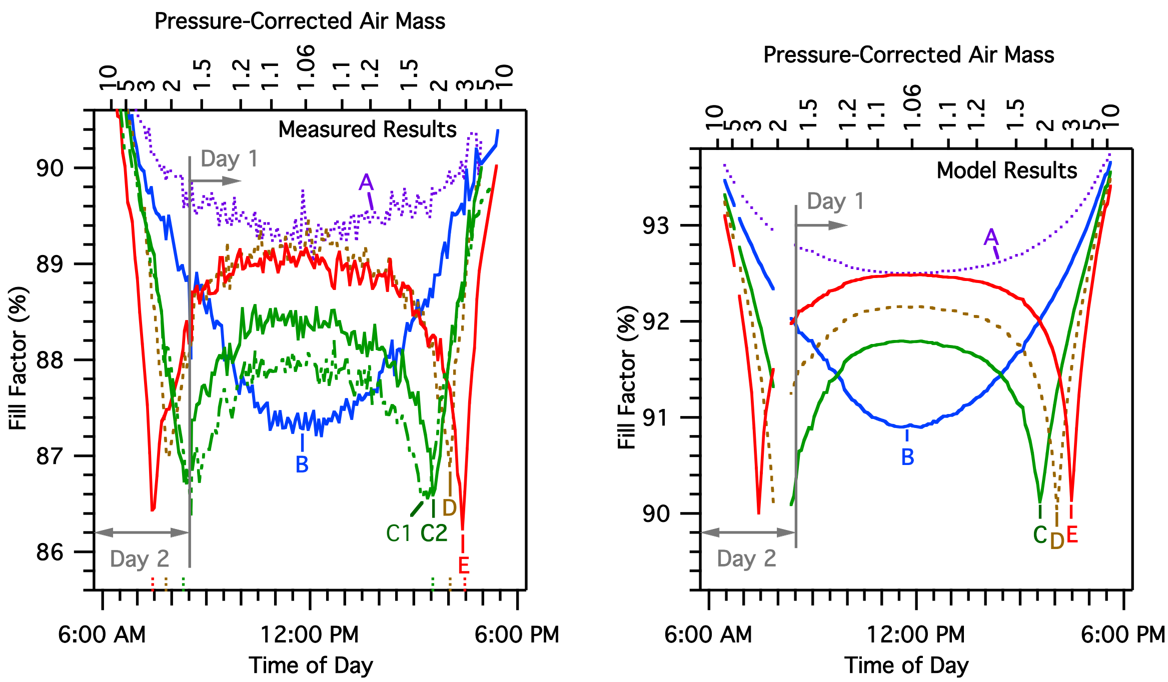

Fig. 4. Fill factor plotted versus time for cells A–E during the test day. (Left) Measured results for cells at one-sun (collimated/direct), with the cells cooled to 25°–30°C. Current-matched times for cells C, D, and E are indicated along the bottom axis with dashed lines. (Right) Model results.

5. CHARACTERIZING CONCENTRATOR OPTICS

Fill factor plots such as those shown in Fig. 4 can, in principle, be used to diagnosing any spectral skewing caused by the concentrator optics. In this paper, "spectral skewing" refers to any change in the incident spectrum which affects the current matching of a tandem cell. This could be caused by spectral dependencies in focusing, absorption, and/or reflectance. For any design using refractive optics, the effects of chromatic aberration on current-matching need to be carefully considered [13, 14]. If the concentrator optics focus and/or transmit different wavelengths of light differently, then even a correctly designed tandem cell won't be properly current-matched.

Data for a concentrator system designed to maximize daily energy should resemble the data shown in Fig. 5. Basically, the two fill factor minima seen each day indicate that the cells are top-cell limited in the morning and evening, and bottom-cell limited during the middle of the day. The exact timing of the current-matching is a subtlety which requires more careful consideration. However, once a baseline shape for a fill-factor curve has been determined for a properly functioning system, it can be used in the future to verify correct module operation and/or diagnose problems.

To be more quantitative, a matched pair of tandem cells is required: a reference cell and a test cell. When placed outdoors under direct (collimated) sunlight over the course of a clear sunny day, their fill factors should match as closely as possible. The test cell is then mounted in the concentrator system, and the reference cell is placed under one-sun collimated sunlight. (The authors of Ref. [16] use a very similar configuration.) The fill factors of these two cells can then be recorded over the course of a clear sunny day and plotted. Because cell temperature also affects current-matching [17], the temperature of the two cells must also be monitored and recorded. Ideally, direct spectra should also be recorded throughout the day, but some conclusions can be drawn even without them. The resulting data can be used in many different ways, and only a simple overview will be given here. A more detailed discussion can be found in Ref. [18].

The simplest data to interpret would be for an experiment where the reference and test cells were held at the same temperature. Current matching is essentially unaffected by changes in concentration, all else being equal, so any changes in current matching would be due to spectral skewing by the concentrator optics. For this equal-temperature example, if the test cell is current-matched closer to midday than the reference cell, then the concentrator optics are delivering a spectrum which is “red-rich” (or “blue-poor”) compared to the unaltered direct spectrum. Quantifying this spectral skewing will require knowledge of the spectral content of the direct spectra and some modeling. If the temperatures of the test and reference cells are different, then a correction for temperature will be required. In general, this will require knowledge of the spectral content of the direct spectra and some modeling.

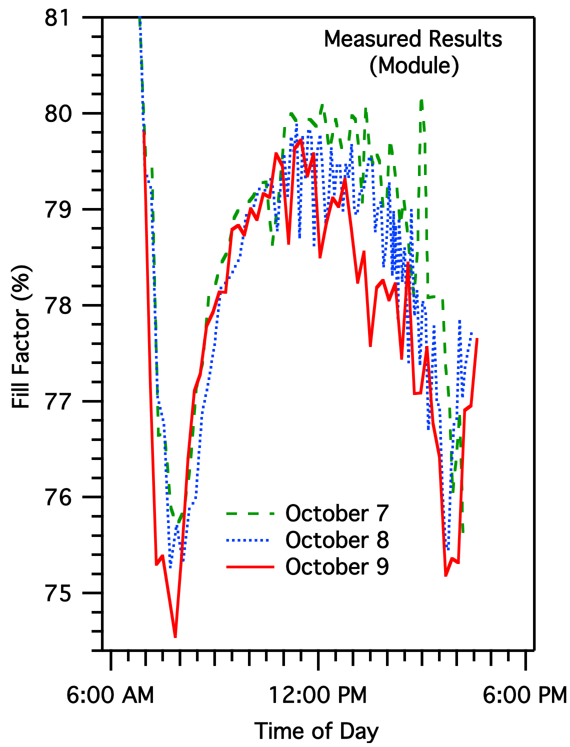

Fig. 5. Measured fill factors for a FLATCON™ concentrator module [15] populated with six series-connected $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As$ tandem cells on October 7, 8, and 9, 2004, at NREL, in Golden, Colorado. This module uses Fresnel lenses with a geometric concentration ratio of 500x. Clouds disrupted the data for the afternoon of October 7. Otherwise the sky was clear and the curves have two minima per day.

Knowing when the fill-factor minima should occur can also be important when making adjustments to a system. For example, the lens-to-cell distance for a multijunction cell can be set by minimizing the fill factor [13]. If this is done outdoors, then it is important to pick an appropriate time of day. Adjusting the focus midday will give the highest midday power production (for that particular day). For maximum daily energy production late morning and late afternoon are preferable. To eliminate uncertainties, the direct spectrum should be measured simultaneously and evaluated.

6. CONCLUSIONS

For optimal performance, multi-junction solar cells must be "current matched." Because the solar spectrum changes constantly, cells are generally designed so as to be current-matched under a representative design spectrum. If, however, the concentrator optics focus and/or transmit different wavelengths of light differently, then the spectrum seen by the cell will be “skewed”, and it won't be properly current-matched. In this paper we showed how any such spectral skewing by the concentrator optics can be characterized by combining the daily spectral variation with fill factor measurements.

REFERENCES

1. J. M. Olson, D. J. Friedman and S. R. Kurtz, "Chapter 9: High-Efficiency III-V Multijunction Solar Cells," *Handbook of Photovoltaic Science and Engineering*, Edited by A. Luque and S. Hegedus, John Wiley & Sons, Ltd (2003); ISBN: 0-471-49196-9.
2. S. R. Kurtz, P. Faine, J. M. Olson, "Modeling of Two-Junction, Series-Connected Tandem Solar Cells Using Thickness as an Adjustable Parameter," *Journal of Applied Physics* 68(4), 1890-1895 (1990).
3. J. M. Olson, W. E. McMahon, S. R. Kurtz, "Effect of Sb on the Properties of GaInP Top Cells," *Conference Record of the 4th World Conference on Photovoltaic Energy Conversion (WCPEC-4)*, Waikoloa, Hawaii, May 2006; 787-790.
4. S. R. Kurtz, J. M. Olson, P. Faine, "The Difference between Standard and Average Efficiencies of Multijunction Compared with Single-Junction Concentrator Cells," *Solar Cells* 30, 501 (1991).
5. W. E. McMahon, S. R. Kurtz, K. Emery, M. S. Young, "Criteria for the Design of GaInP/GaAs/Ge Triple-Junction Cells to Optimize their Performance Outdoors," *Proceedings of the 29th IEEE PV Specialists Conference*, New Orleans, May 2002; 931-934. Note: The t_{top}s in this paper are slightly different because fitting to the fill-factor curves in the current paper allowed us to self-consistently determine t_{top} more accurately.
6. ASTM Standard Tables for Reference Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37° Tilted Surface, Standard G159-99. *American Society for Testing and Materials*, West Conshohocken, PA, 1999.
7. G173-03 Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface. *Book of Standards Volume: 14.04, American Society for Testing and Materials*, West Conshohocken, PA, 2004.
8. K. Emery, D. Myers, S. R. Kurtz, "What is the Appropriate Spectrum for Characterizing Concentrator Cells?" *Proceedings of the 29th IEEE PV Specialists Conference*, New Orleans, May 2002; 840-843.
9. E490-00a Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables, *American Society for Testing and Materials*, West Conshohocken, PA.
10. P. Faine, S. R. Kurtz, C. Riordan, J. M. Olson, "The Influence of Spectral Solar Irradiance Variations on the Performance of Selected Single-Junction and Multijunction Solar Cells," *Solar Cells* 31, 259-278 (1991).
11. M. W. Wanlass and D. S. Albin, "A Rigorous Analysis of Seris-Connected, Multi-Bandgap, Tandem Thermophotovoltaic (TPV) Energy Converters," *Sixth Conference on Thermophotovoltaic Generation of Electricity (TPV6)*, Freiburg, Germany, June 2004, AIP Conf. Proc. 738, pp 462-470.
12. Standard ASTM E1125-99, "Standard Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Standard." *American Society for Testing and Materials*, West Conshohocken, PA.
13. H. Cotal, R. Sherif, "The Effects of Chromatic Aberration on the Performance of GaInP/GaAs/Ge Concentrator Solar Cells from Fresnel Optics," *Proceedings of the 31st IEEE PV Specialists Conference*, Lake Buena Vista, FL , January 2005; 747-750.
14. L. W. James, "Effects of Concentrator Chromatic Aberration on Multi-Junction Cells," *Proceedings of the First World Conference on Photovoltaic Energy Conversion* 1994; 1799-1804.
15. G. Siefer, A. W. Bett and K. Emery, "One Year Outdoor Evaluation of a FLATCON™ Concentrator Module," *Proceedings of the 19th European Photovoltaic Solar Energy Conference and Exhibition*, Paris France, June 7-11 2004. A. W. Bett, B. Burger, F. Dimroth, G. Siefer, H. Lerchenmüller, "High-Concentration PV using III-V Solar Cells," *Conference Record of the 4th World Conference on Photovoltaic Energy Conversion (WCPEC-4)*, Waikoloa, Hawaii, May 2006; 615-620.
16. M. Hein, M. Meusel, C. Baur, F. Dimroth, G. Lange, G. Siefer, T. N. D. Tibbits, A. W. Bett, V. M. Andreev V. D. Rumyantsev, "Characterisation of a 25% High-Efficiency Fresnel Lens Module with GaInP/GaInAs Dual-Junction Concentrator Solar Cells," *17th EU-PVSEC*, Munich, October 2001; Paper OB5.4.
17. D. J. Friedman, "Modelling of Tandem Cell Temperature Coefficients," *Proceedings of the 25th IEEE PV Specialists Conference*, Washington, DC, May 1996; 89-92.
18. W.E. McMahon, K.E. Emery, D.J. Friedman, L. Ottoson, M.S. Young,J.S. Ward, C.M. Kramer, A. Duda, and Sarah Kurtz, "Fill Factor as a Probe of Current-Matching for $GaInP_2$/GaAs Tandem Cells in a Concentrator System during Outdoor Operation," *Progress in Photovoltaics* (to be published).