Advancements in solar simulators for Terrestrial solar cells at high concentration (500 to 5000 Suns) levels

Doug Jungwirth, Lynne C. Eigler and Steve Espiritu

Spectrolab, Inc., 12500 Gladstone Avenue, Sylmar, CA 91342, USA

ABSTRACT

Testing requirements for high concentration solar cell systems have changed dramatically in the recent past, therefore a new generation of solar cell testers need to be developed to fulfill these testing requirements. This paper reports on one of those new solar cell illuminators. Spectrolab has completed initial evaluation of a Terrestrial-High Intensity Pulsed Solar Simulator (T-HIPSS) [3]. This pulsed illuminator produces up to 5000 Suns of raw Xe flash lamp spectrum over an area of 10 cm by 10 cm with very good uniformity. This complete, tabletop size system has the capability to be spectrally tuned to produce any of the AM1.5 spectral distributions and can be actively or passively adjusted to deliver the spectrum required. The illumination levels for these various spectral distributions are still well over 2000 Sun with spatial uniformity of better than 1% across the 10 cm by 10 cm area. The spectral balancing technique utilized in this system allows for the independent adjustment of at least 6 different wavelength bands from 250nm to 1800 nm. Included diagnostics allow for pulse to pulse monitoring of the spectral content and the possibility for computer controlled feedback for spectral balance/adjustment.

Introduction

Testing requirements for modern solar cells have changed dramatically in the recent past due to the emphasis on testing of terrestrial solar cells and the advent of new cell designs such as the multi-junction cell (3 thru 6 junctions), hybrid cells, quantum technology, etc.

The operational regime of these new terrestrial solar systems is significantly different from both the space cells and the older generation 1 Sun silicon systems. Not only is the optical spectrum different from the space environment, it changes from location to location on the earth. To optimize performance of large solar farms with these new technologies, solar cells may need to be custom designed to take full advantage of the local spectral environment. But even more generally, many of the standard operational parameters are different. Instead of a uniform AM0 spectrum anywhere in earth local space, terrestrial systems have to deal with anything from AM1 to over AM2. For economic and efficiency reasons, high concentrators are the design being exploited for terrestrial systems. Concentrations anywhere from a few hundred Suns to several thousand Suns are being designed. These systems require testing at, and above these concentrations for both development and reliability purposes. Although the reliability requirements for terrestrial components are not as stringent as space systems, a reasonable level of reliability testing is usually required from a purely economic point of view.

Probably the biggest driver in the terrestrial market is cost. In this highly competitive market, to compete with fossil fuels, wind, hydroelectric, nuclear, etc. the cost of the solar cell needs to be as low are possible. To keep costs down, 'touch' labor must be kept to a minimum. This means minimizing the number of steps that are needed to produce and assembly a solar cell assembly and automating those steps that are required. To that end, new solar illumination and testing systems needed to be developed. These new systems need to be able to 1) test at levels of 200 to ~2000 suns, 2) have a spectral distribution of ~AM1.5 and adjustable around that level, 3) illuminating an area which is large enough to test as many cells as possible in a single test, 3) be a flashed illumination system to eliminate long term thermal effects on the measurements, 4) have fast enough electronics to test the performance of those individual cells in the flash duration, 5) testing techniques that will provide the required data, at the required accuracy in a single pulse and 6) be automated such that the entire process can be computer controlled in a continuous manufacturing environment. These tests also have to be completed at a fast enough pace to keep up with production rates and within a reasonable cost for both development and manufacturing implementation.

Spectrolab has developed a new, pulsed solar simulator which provides testing capabilities meeting these testing parameters. This new solar simulator uses a single, linear, high pressure Xe flash lamp and various flat and cylindrical optics to generate 19 different images of that lamp. This system can obtain an optical collection efficiency of up to 6.3% of all light emitted from the lamp into a uniform, usable illumination area of ~10 cm by 10 cm. At its highest illumination levels, it can produce over 5000 Suns (at the raw Xe flash lamp spectrum).

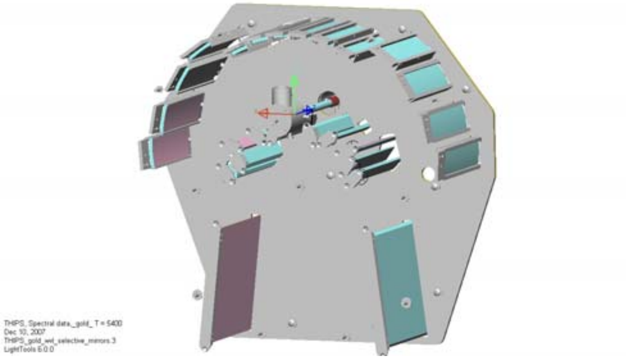


Figure 1a. Internal mirror configuration for the T-HIPSS Solar Simulator
(Front and side panels removed for clarity)

Spectral Balancing

Spectral filtering is needed to tune the spectral output of the Xe flash lamp to the desired spectrum (typically AM1.5G). This is done using a large spectral matching filter for coarse corrections and wavelength specific mirrors for fine adjustments which allow up and down adjustment of up to 6 specific wavelength bands. These wavelength specific mirrors are used in balanced pairs to maintain very good spatial uniformity across the useable test area. Even with the losses associated with these filtering techniques, illumination levels of over 2000 Suns are still achievable. Adjustments to the illumination level can be achieved using either Neutral Density (ND) filters, wire grid attenuators or lamp current adjustments.

In this design there are 19 different paths for light to get to the image plane. One path goes directly from the lamp to the image plane. 7 pairs of beam paths reflect off of a cylindrical mirror and get re-imaged at a point in space that is approximately the same distance (25”) as the direct path from the lamp to the image plane. Those beams are directed to overlap at that specified point in space defined as 25” from the lamp. Some of these beams are folded using flat mirrors to appear closely packed near the image of the central lamp. This is to minimize the overall angle of the incoming beam to more accurately duplicate the incoming light that most solar cells might encounter. These beam paths are configured in ”pairs” to maintain spatial uniformity at the image plane. 6 of these 7 pairs are used to provide the capability to spectrally balance the light that is incident on the image plane. If raw power is required for any particular optical tests, all of the mirrors in the system would be aluminum coated with no spectral filtering. This will give the maximum amount of light at the test plane with the spectrum of the Xe lamp. In this configuration, over 5000 Suns can be achieved at the highest setting on the power supply. If a particular spectrum is required, specially selected absorbing optical filters can be inserted in front of specific cylindrical mirrors (inserted in balance pairs to maintain spatial balance) which will selectively filter the light associated to those two beam paths. Judicious selection of filters will allow any spectrum to be generated at the test plane. In some instances, if the spectrum is significantly different from the Xe spectrum, a change in the ‘coarse” filter will be required. This configuration of the T-HIPSS is usually chosen for test environments where a specific spectrum is needed for extended periods of time. Once set, the filters do not need to be adjusted or changed for weeks or months.

For test configurations where the spectrum needs to be changed often or where it is desired for the cut-on and cut-off wavelengths to be picked specifically for the devices being tested, or where absorbing optical filters (with the required spectral shape is not available) are not available, a different optical configuration should be employed. The more advances version of the T-HIPSS incorporates selectively reflective mirror coating on pairs of cylindrical mirrors. These selective mirrors reflect certain wavelengths of light while transmitting the rest. The reflected light continues on in the system to eventually hit the test plane, while the transmitted light goes out to the walls to be absorbed. Blocking apertures can be introduced into each of those wavelength specific beam paths which blocks that light from getting to the mirror all together thus reducing that wavelength of light from getting to the test plane. This approach sacrifices overall intensity of the light that can be applied to the test plane, but allows better spectral balancing of the light that does get to the test plane. Figure 1b shows an example of the first mirror configuration using the absorbing filter. Figure 1c. shows an example of the wavelength selective reflector.

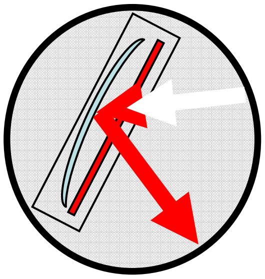


Figure 1b. Cylindrical mirror with absorbing filter

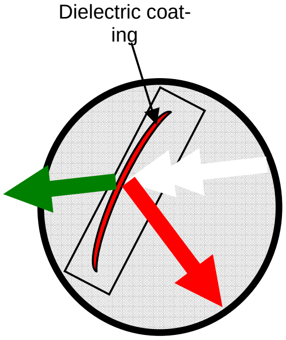


Figure 1c. Cylindrical mirror with wavelength selective coating

These particular pairs of mirrors only reflect light in that wavelength band to the image plane which allows the system to selectively increase or decrease one particular wavelength band of light while still maintaining good spatial distribution. This “increasing or decreasing” of the amount of light reflected from those particular beam paths is accomplished by the use of obscuring plates that block the cylinder mirror from seeing the light from the lamp. Depending on the composition of the other remaining lamps, this adjustment range can be up to +/- 10% of any particular wave band. The present configuration allows for 6 separate wavelength bands to be chosen and independently adjusted. Figure 1d. shows the mirror mount with the wavelength selective reflector with the shutters partially closed.

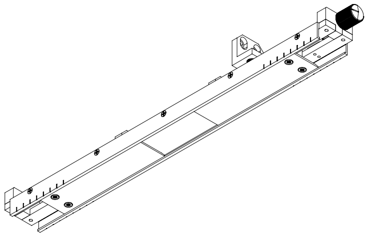


Figure 1d. Mirror mount for wavelength selective mirror with shutter mechanism.

One advantage of this configuration is that the adjustable wavelength bands edges can be chosen to match the existing absorption bands of multi-junction devices, which allows very easy, direct adjustment of the magnitude of optical power hitting each individual layer of the cell. Using individual isotypes or a spectrometer, it is now possible to adjust the current in each isotype without disturbing the current generated in the other isotypes. This dramatically decreases the set up time for a testing system. It also allows the possibility of a closed loop system for a shot by shot monitoring of the spectral content of each shot and the capability of simple computer spectral balancing feedback. There are 2 other pairs of beam paths that direct light from the lamp to the image plane but do not involve cylindrical mirrors and which utilize only aluminum flat mirrors. This means that there are a total of 12 wavelength ‘narrowed’ beam paths and 7 ‘full’ wavelength beam paths that hit the image plane. Figure 4 shows the orientation and the distribution of those beam paths.

Figure 2.
Right hand set of individual beam paths for the T-HIPSS

Figure 3 shows the spectral distribution of the 6 individual beam paths. Notice how the combination of these 6 separate wavelength ‘narrowed’ beams add up to duplicate the desired spectrum, typically AM1.5G.

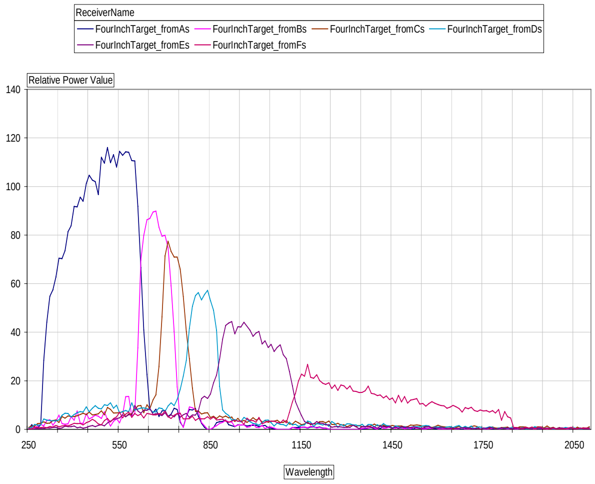


Figure 3.
Six individual spectral plots representing the six different spectral beam paths. These beams are used to fine tune the spectral balance of the illuminating beam.

The large (coarse) spectral filter is fabricated by taking the spectrum of the Xe lamp and comparing it to the desired spectrum for measurement (usually AM1.5G) [1]. We mathematically divide those two spectra and from that design a dielectric filter that will achieve roughly that transmission curve. We optimize that design to be for the average angle of incidence of the photons that will hit the area of interest at the image plane.

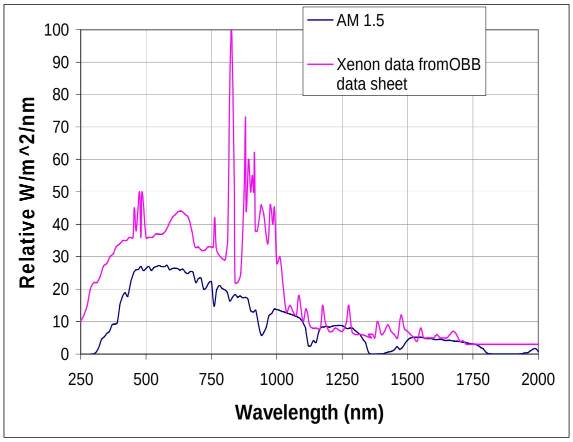


Figure 4
Plot of the spectral output of the Xe lamp and the desired spectral distribution. This ratio is used to develop the transmission of the coarse spectral filter

Pulsed Measurements

A large Pulse Forming Network (PFN) is used to supply electrical power to the lamp during the pulse. This provides a stable, 2.5 mS long optical pulse with ~+/- 1.5% amplitude fluctuations. Measurements are taken during a 2 mS measurement window using a LabView based control algorithm with 16 bit, multi-MHz A/D converters. Reference optical detectors are used to automatically correct for pulse to pulse variations. Various data input configurations allow for I-V curve measurements for both Isotypes and full cells to be made in this 2mS optical pulse window. Shunt resistor measurements can be performed providing simultaneous time histories for both Isotype and full cell devices. Present pulse rate for PFN is one pulse every 15 seconds. Current plans call for achieving pulse rates of >1 pulse per 7.5 seconds.

Figures 5a and 5b are plots of the current through shunt resistors from 3 isotypes. They plot out the current as a function of time for each of the individual isotypes of a typical c-ITJ (concentrator Triple Junction) cell. These cells are side by side in the image plane of the illuminator so they all get the same level of intensity and the same spectral content. The difference between the two pulses is that Figure 5a was made with the matched set of filters for the top isotype not installed and the figure 5b was made with the filter set for the top isotype installed. It shows that the current from one isotype can be manipulated a significant amount while not disturbing the current from the other isotypes. This allows a method to accurately and predictably adjust the spectrum to balance the outputs of all the individual isotypes independently, or use closed loop feedback to monitor the spectrum on an ongoing basis during testing.

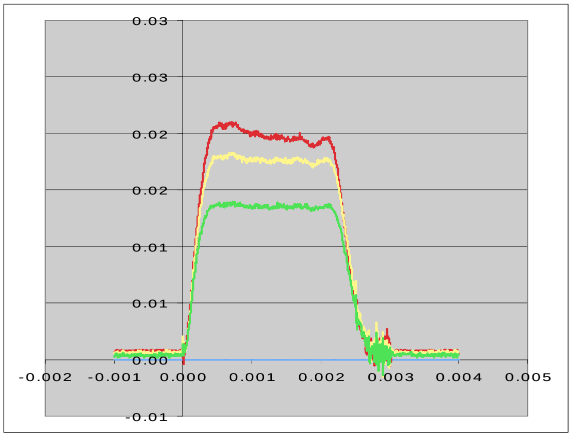


Figure 5a.
Current across shunt resistors with no “red” filters in.
Red curve (highest) is current from “top” Isotype
Yellow curve (middle) is current from “middle” Isotype

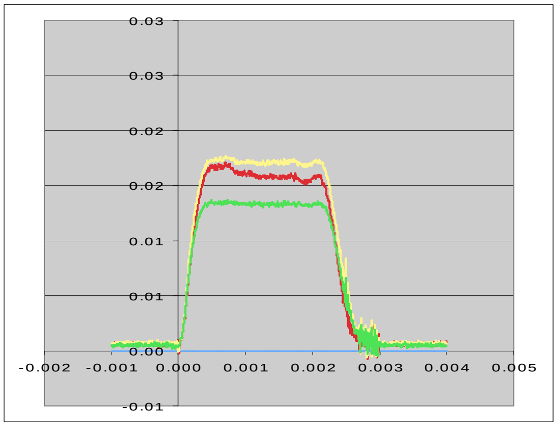


Figure 5b.
Current across shunt resistors with pair of “red” filters in.
Red curve is current from “top” Isotype
Yellow curve is current from “middle” Isotype

Figure 5c is an I-V curve generated by the Spectrolab LAPSS software [2] which shows the characteristic current vs. voltage relationship for a generic c-ITJ isotype under 555 Suns of illumination. Isc, Voc and fill factor can be calculated from this plot. This data was taken within the 2.5 mSec optical pulse of the solar simulator. A 34% transmitting neutral density screen was needed to bring the illumination power level down to 555 Suns for this test.

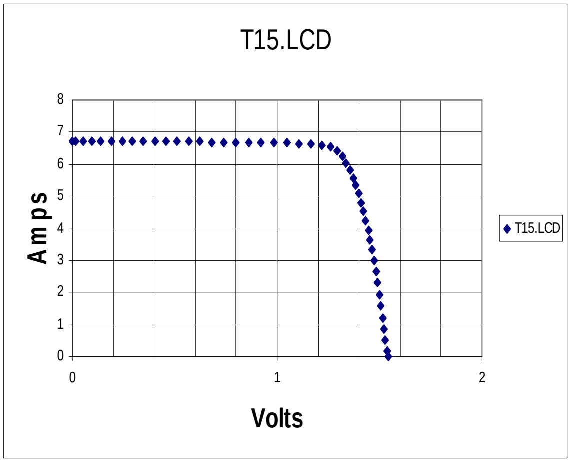


Figure 5c
I-V curve for generic c-ITJ middle cell Isotype at 555 Suns illuminated with AM 1.5G

Spatial Uniformity

Spatial uniformity across the illuminated area is critical to assure the reliability and accuracy of the tests performed within that area. If large numbers of cells are to be tested simultaneously, then the illumination beam must be uniform over that area or at least well defined across the area of testing. The design of this illuminator maintains the apparent spacing of the various lamp images to be within a small, confined angular space (+/- 20 degrees) above the illuminated area and all at a distance of approximately 25 inches distant. There is complete left/right symmetry in both the lamp positioning and the filter placement. A non-sequential optical model was used to predict the intensity distribution of the T-HIPSS system at the image plane. The central 4” by 4” region was investigated. Figure 6a shows the predicted intensity distribution over the 4 by 4 inch central area. The initial power of the lamp was scaled at one watt of optical power out of the lamp.

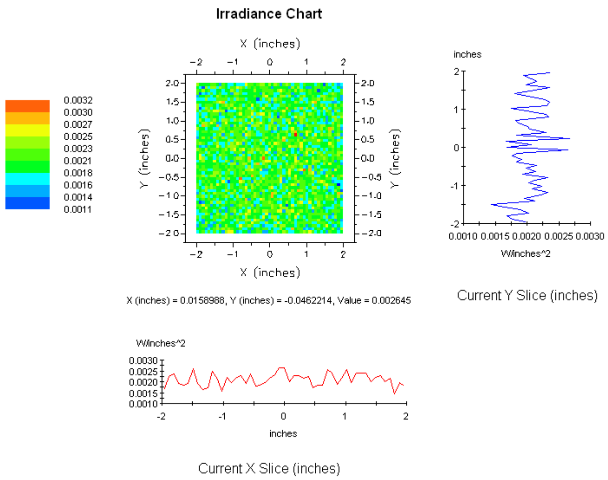


Figure 6a.
Projected intensity distribution for T-HIPSS over a 4” by 4” illuminated area. One Watt of input optical power Light Tools output -- noisy due to limited number of rays

Figure 6b shows the theoretical and measured intensity profile along the transverse direction of the test plane (transverse: perpendicular to the lamp direction)

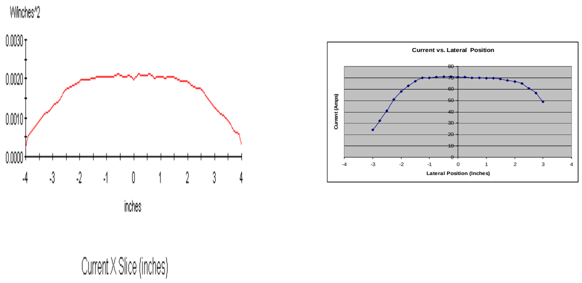


Figure 6b. Theoretical and measured intensity profile at the test plane in the transverse direction.

Figure 6c shows the theoretical and measured intensity profile along the longitudinal direction of the test plane (longitudinal: along the lamp direction)

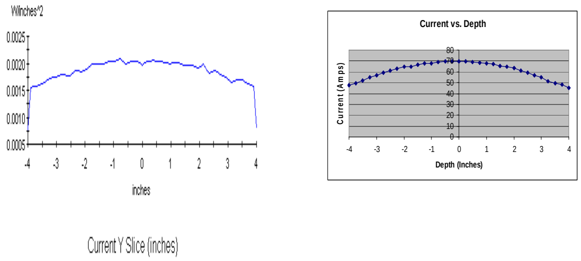


Figure 6c. Theoretical and measured intensity profile at the test plane in the longitudinal direction.

Spectral Uniformity

Once the spectrum is tuned to the profile that is required, it is important that the shot to shot variation in the spectral content of the flash stays within the required margins. Figure 7 shows a plot of 10 consecutive reading from a Si based spectrophotometer on a production T-HIPSS balanced for AM 1.5G at 555 Suns. For the 10 consecutive shots, the plots are one on top of the other.

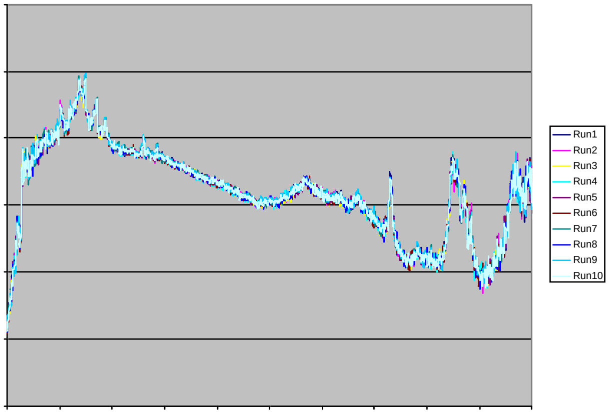
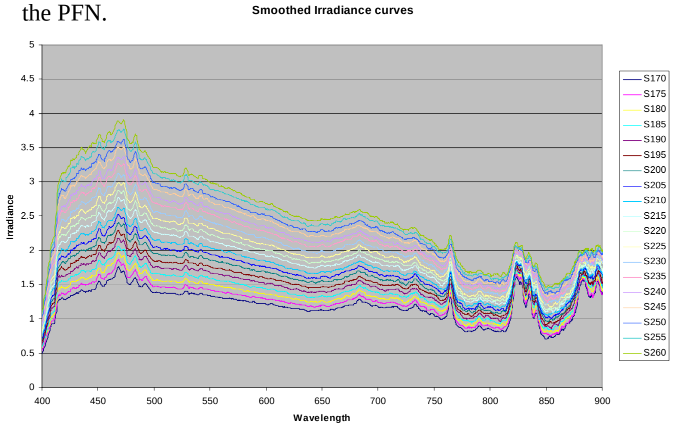


Figure 7 Spectral repeatability. 10 consecutive spectrophotometer curve at the same settings for a 555 Sun system balanced for AM 1.5G.

One important and commonly used method of changing the magnitude of the light at the test plane is increasing or decreasing the setting on the PFN, which increases or decreases the voltage and current applied to the lamp. These voltage and current changes alter the plasma temperature of the lamp discharge, and this changes the spectrum emitted from the lamp. Figure 8a shows 19 different irradiance curves at 19 steadily increasing settings on the PFN.



This figure indicates that the spectral distribution is changing with PFN settings. To determine the percent change at any wavelength or wavelength band, we can divide any spectrum with a normalizing spectrum. In Figure 8b, all the spectra are divided by the spectrum at a setting of 170. This figure clearly shows that the percentage change varied as a function of wavelength. This is to be expected if the plasma temperature changed depending on the voltage and current applied. This plot also shows you can increase the overall power by approximated a factor of 2 with a change of settings from 170 to 260. It also shows that there is a noticeable, systematic differences in the percentage change at the shorter wavelengths than at the longer wavelengths. From this plot too, you can determine the amount of "fine" tuning that would be required to adjust the spectrum back to an original profile if the PFN settings were changed.

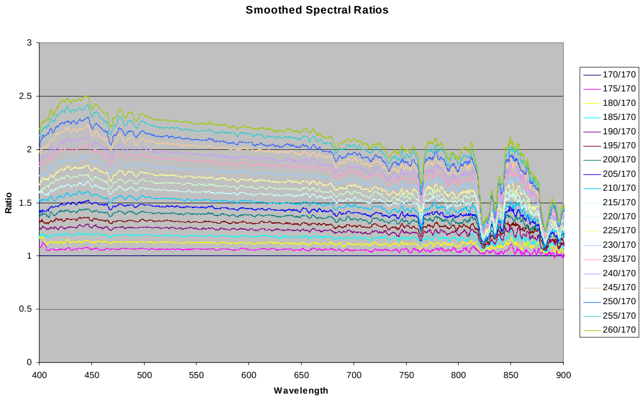


Figure 8b. Ratio of spectra for 19 different settings on the PFN

Diagnostics

Diagnostics include visible and IR (optional) pulsed spectrometers, which can provide pulse to pulse spectral measurements of the optical illuminating beam. These diagnostics collect pulse to pulse spectra and display them for user monitoring. This can significantly aid in spectral fine tuning due to current adjustments, ageing of the lamp or other physical phenomenon that naturally change the spectral content of the illuminating beam. Advanced systems include computer controlled monitoring of spectral content (vie spectrometers) with automatic fine tuning of the wavelength specific mirrors (motorized) to maintain any desired spectral waveform.

Summary

The T-HIPSS system is described as an operational pulsed solar simulator for terrestrial solar cell testing which has the capability to produce a very uniform (+/-1%) spatially homogeneous beam, with high concentration level (>2000 Suns spectrally balanced) with the capability to actively fine tune the spectral balance over at least 6 independent, user defined wavelength bands. Diagnostics are included which allow active monitoring of spectral content and intensity.

Acknowledgments

The authors wish to thank Kent Barbour for his help in the testing of the solar cells. We also wish to thank Dmitri Krut for his insights in the designs of the previous lamp houses and Xe flash lamps. The authors wish to thank Greg Campbell and Emilio Quezada for their encouragement and support in the development of this system and their knowledge of the testing processes for multi-junction solar cells. We also wish to thank Nasser Karam for his assistance in the editing and formatting of this paper. This work was funded from Spectrolab Illuminations IR&D.

References

[1] ASTM standard G173-03, Standard Tables for reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface, American Society of Testing and Materials, 1916 Race St., Philadelphia, PA.

[2] K.E.Barbour, *LAPSS II Manual*, Spectrolab, Sylmar, CA (1994)

[3] Patent Pending, Submission 06-1013, Douglas Jungwirth, 2006