DESIGN AND PERFORMANCE OF A TRIPLE SOURCE AIR MASS ZERO SOLAR SIMULATOR

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Simulating the sun in a laboratory for the purpose of measuring solar cells has long been a challenge for engineers and scientists.[1,2,3] Multi-junction cells demand higher fidelity of a solar simulator than do single junction cells, due to a need for close spectral matching as well as AM0 intensity. A GaInP/GaAs/Ge solar cell for example, requires spectral matching in three distinct spectral bands (**figure 1**). A commercial single source high-pressure xenon arc solar simulator such as the Spectrolab X-25 at NASA Glenn Research Center, can match the top two junctions of a GaInP/GaAs/Ge cell to within 1.3% mismatch, with the GaAs cell receiving slightly more current than required. The Ge bottom cell however, is mismatched +8.8%. Multi source simulators are designed to match the current for all junctions but typically have small illuminated areas, less uniformity and less beam collimation compared to an X-25 simulator. It was our intent when designing a multi source simulator to preserve as many aspects of the X-25 while adding multi-source capability.

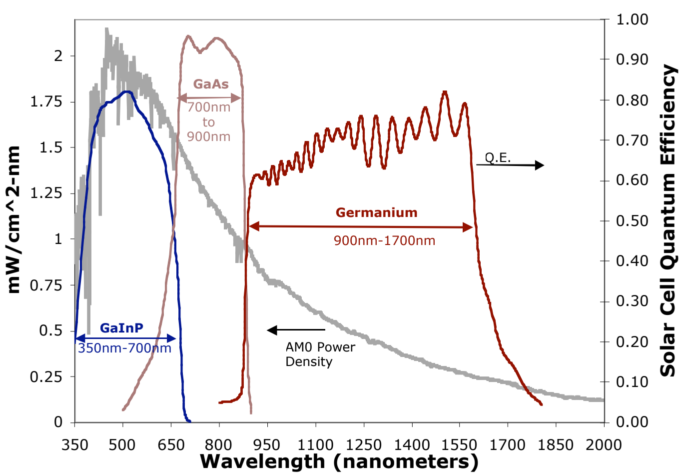

Figure 1) The quantum efficiency of a GaInP/GaAs/Ge solar cell plotted with the AM0 spectrum.

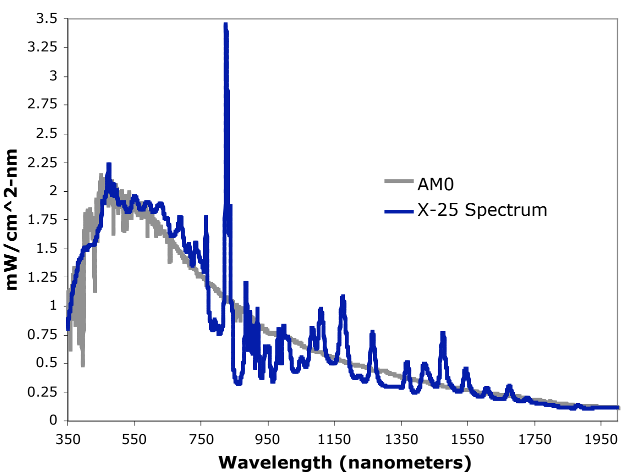

Figure 2) Spectrum of the Spectrolab X-25 solar simulator5 compared to AM0.

The X-25 faithfully reproduces the AM0 spectrum from approximately 350-nm to 750-nm but beyond that region the spectrum quickly diverges from AM0 (**figure 2**). This multi-source simulator takes advantage of this property and uses the X-25 to provide the bulk of the UV and visible light. A non-absorbing dichroic mirror (designed and fabricated by Displays and Optical Technologies, of Round Rock, Texas) is used as a beam splitter to reflect the blue portion of the spectrum and transmit the infrared. The transmission and reflection curves of the filter (**figure 3**) show that there is a fairly good cutoff transition at 700-nm but that the reflection band pass is limited to approximately one octave and begins to transmit excessively at wavelengths shorter than 450nm. This behavior

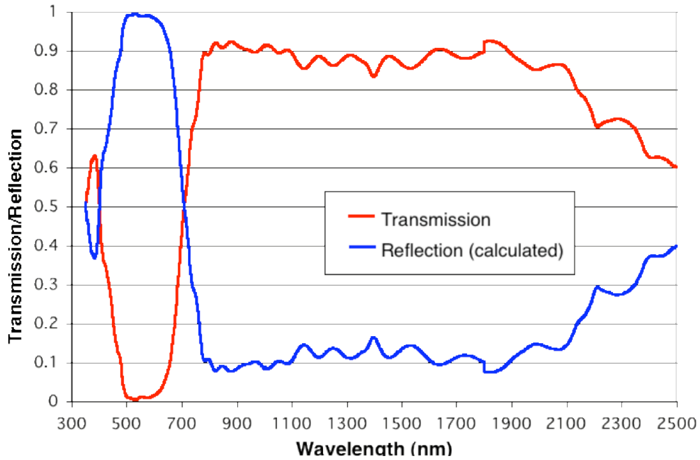

Figure 3) Transmission and reflection of dichroic mirror.

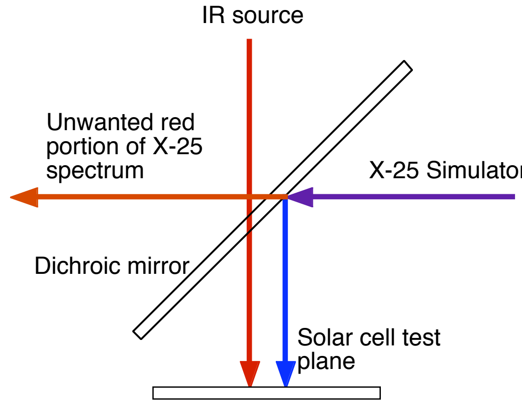

Figure 4) Optical path for combining the IR source with the X-25 beam.

is typical for high efficiency, thin-film dielectric stack filters. Although not ideal, the filtered beam provides sufficient UV and visible light for solar cells and excellent IR transmission for adding in the balance of the AM0 spectrum. With the cell test plane and the X-25 simulator mounted 90° to each other, the dichroic mirror is mounted at a 45° angle to reflect the blue portion of the X-25 beam onto the cell and allow for additional lights sources from above the cell plane (**figure 4**).

The initial design strategy for the IR source was to pack as many lamps into as small an area as possible and mount the lamps as far from the test plane as practical. This philosophy (in principle) will yield the best collimation angle and beam uniformity. The lamps used are tungsten filament bulbs mounted in a gold reflector. The lamps operate at 12 Volts with an output of 75 Watts and have an average life expectancy of 4,000 hours. The vendor is Gilway Technical Lamp in Woburn, MA. The reflector has a nominal beam angle of 14°. The attempt to pack as many lamps into as small a space as possible, was a rectangular array of 40 lamps. Although a round lamp should pack more tightly in a hexagonal pattern, the lamp holders have a rectangular base and thus the best packing is achieved using a rectangular pattern. This lamp arrangement had one major shortcoming; it required that each lamp have two degrees of pointing control in order to achieve acceptable uniformity. Without this control, the beam had a significant center hot spot. A second design, which capitalizes on the natural radial symmetry of the beam pattern, was designed. Here, the lamps required only one degree of freedom of pointing to achieve acceptable beam uniformity. In this design, 36 lamps are oriented in a radial pattern and each lamp can be pointed along a line that sweeps from center to edge along a radius of the beam. Pointing of each lamp is achieved by mounting the lamp holder to a aluminum block with four spring-loaded screws. The blocks are fastened normal to the lamp mounting plate. The four screws can be adjusted to tilt the lamp housing approximately ±5°. This is enough movement to sweep the beam from center to the outside edge of the test plane. **Figure 5** shows the mounting arrangement for a single lamp. In practice, all the lamps are splayed away from the center to decrease the center beam hot spot.

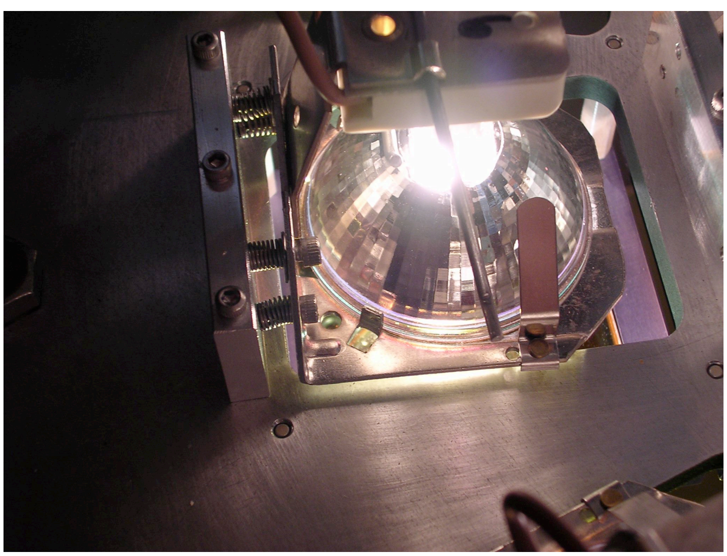

Figure 5) Each IR lamp is mounted on an aluminum block with 4 spring-loaded adjustment screws.

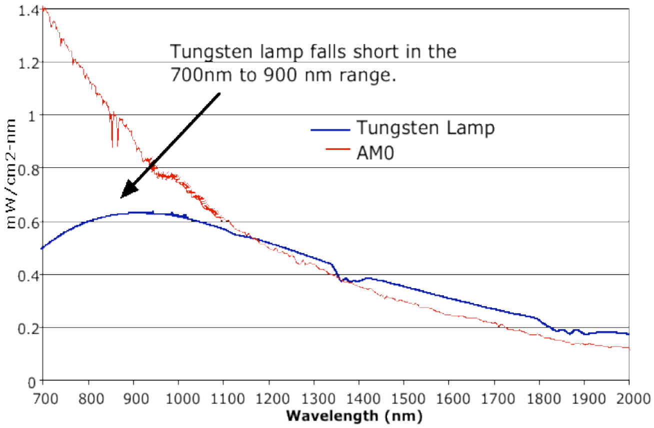

Figure 6) Spectrum of the tungsten lamp compared to AM0.

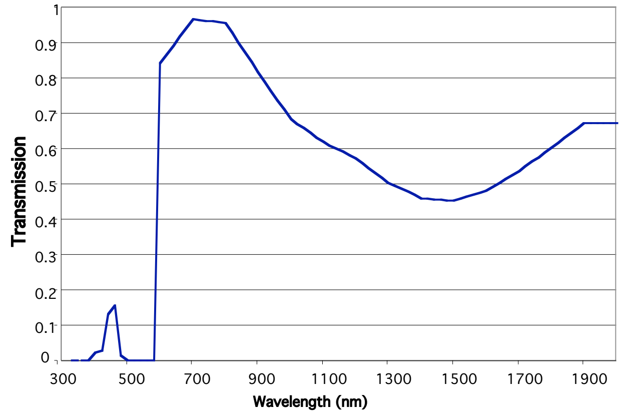

Figure 7) Design of the filter to shape the IR lamp spectrum to match AM0.

The spectrum of an unfiltered tungsten lamp does not adequately simulate the IR portion of AM0. **Figure 6** shows the spectrum of an unfiltered tungsten lamp versus AM0 in the infrared. Note that below 1000-nm the power density of the tungsten lamp drops compared to AM0. This is a critical region of the spectrum for the GaAs junction of a GaAlnP/GaAs/Ge cell. When the intensity of the tungsten lamps is raised to match the GaAs middle cell current, then the Ge cell has 40% excess current! Another filter was designed to shape the tungsten lamps to match AM0. **Figure 7** shows the (calculated) transmission of this filter. The filter is placed between the tungsten lamps and the dichroic mirror. The resulting spectrum is close to AM0, but still needs an additional degree of freedom to perfectly match all three junctions.

A third light source was created by filtering a subset of the 36 tungsten lamps. A non-absorbing filter was designed to transmit only in the region of 700-900-nm. This filtration is optimized for adjusting the current of a GaAs middle cell separate from the germanium or GaInP cell. The filters are placed in front of 6-12 lamps depending on the amount of spectral mismatch of a particular cell (**figure 8**). The filtered lamps are put on a separate power supply and their intensity is controlled independently of the 24 remaining lamps. For the 12 700-900-nm filtered lamps, the lamps are connected as 4 parallel strings of 3 lamps each for a nominal operating voltage of 36 Vdc at 25 Amps. The remaining 24 lamps are wired as 4 parallel strings of 6 lamps, and operate at 72 Vdc at 25 Amps. Using all three light sources, the short circuit current of each reference cell of a GaInP/GaAs/Ge multijunction cell, can be simultaneously matched to their reference values to better than 0.5% in less than 30 minutes set up time. The spectrum of the simulator is shown in **figure 9**.

Figure 8) Photograph showing the 12 filtered lamps of the 36 lamp IR source.

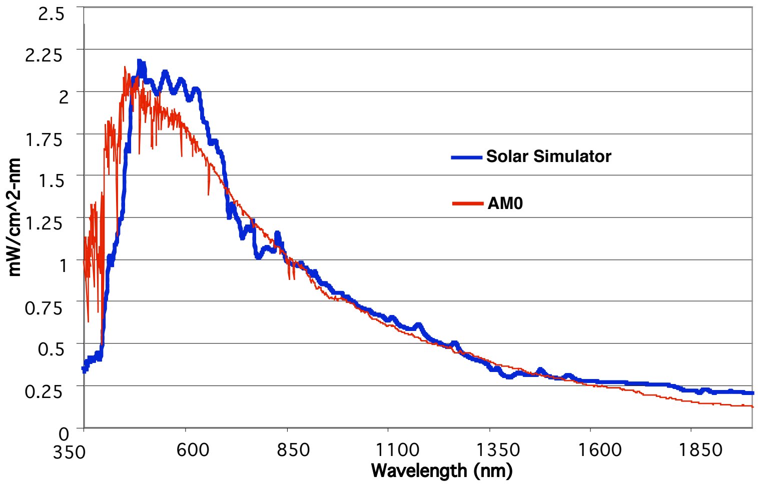

Figure 9) Spectrum of the solar simulator when all three junctions of a GaInP/GaAs/Ge solar cell are properly illuminate, compared to AM0.

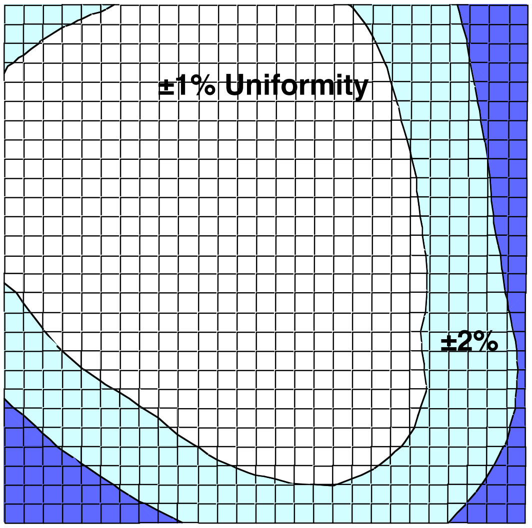

Figure 10) Uniformity of the long IR light source over a 20-cm x 20-cm area. The light blue contour represents the additional area where the uniformity is at least ±2%.

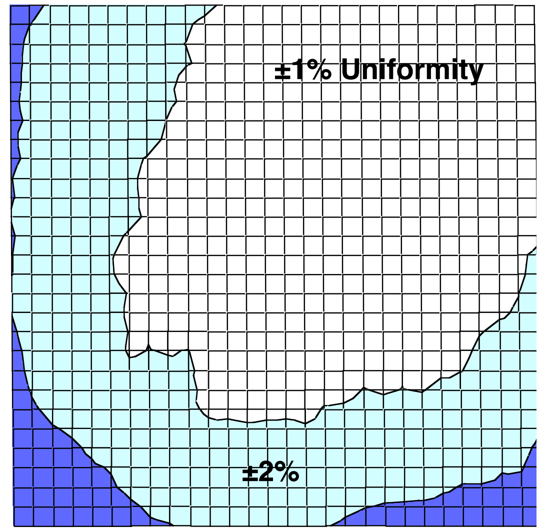

Figure 11) Uniformity of the X-25 Simulator over a 20-cm x 20-cm area.

The collimation half-angle is determined by the angle formed by the radius of the IR lamp cluster and the distance the lamps are located above the test plane. This angle is 7.6 degrees. The uniformity of light intensity in the test plane is most strongly affected by the number of individual lamps that can be articulated to reduce “hot or cold” spots in the beam. All of the lamps contribute to the 700-900-nm portion of the spectrum and therefore the number of lamps is effectively 36 in the 700-900-nm region. The intensity changes made with the 700-900-nm filtered lamps are small (<5%) compared to the overall intensity in the 700-900-nm range and have little affect on the uniformity. In the long IR region (900-1700-nm) the number of lamps is effectively 24. The intensity uniformity of these lamps is ±1% over a large area of a 20-cm X 20-cm test plane as shown in **figure 10**. The uniformity of the X-25 is similar to the IR lamps and is shown in **figure 11**. The intensity maps were made using an X-Y plotter fitted with a photodiode. The method is similar to that used by Spectrolab to characterize the X-25 (X-25 documentation) and at other labs such as National Renewable Energy Laboratory (NREL). The stability of the lamps has not been quantitatively characterized at this time but after an initial 30 minute warm-up period there is no perceptible drift while making measurements over a 4 hour period. The IR lamps are also flicker free, due to the nature of the IR lamp optics and the DC power used.

A schematic figure of the entire system is shown in **figure 12**. For many applications the single source X-25 is all that is required. In such cases, the system can be quickly reconfigured by exchanging the dichroic mirror for a simple aluminized first surface mirror. This also helped preserve the X-25 capability while the new system was being built.

The cost of all the hardware (excluding the X-25 simulator) was 25,000 USD (in 2002). Operating the simulator offers many challenges. There are a number ways to set up the intensity and spectrum of a multi-source simulator. The easiest method is to have separate calibrated reference cells for each sub junction of the test cell. If such cells are not available, then one must either apply spectral correction to existing reference cells that are close in spectral response, or calculate the required spectral intensity from measurements of the spectral response of the test cell and measurements of the simulator’s spectral intensity.

We have successfully converted a Spectrolab X-25 solar simulator into a multi-source simulator capable of precisely matching the required currents in a triple junction GaInP/GaAs/Ge solar cell. The system is relatively inexpensive to impliment and preserves the original functionality of the X-25 as well. It has excellent uniformity as well as good stability and a collimation angle better than ±8°. Future plans for improving the performance, include the addition of another xenon light filtered to provide a boost in the blue region of the spectrum to more closely match AM0.

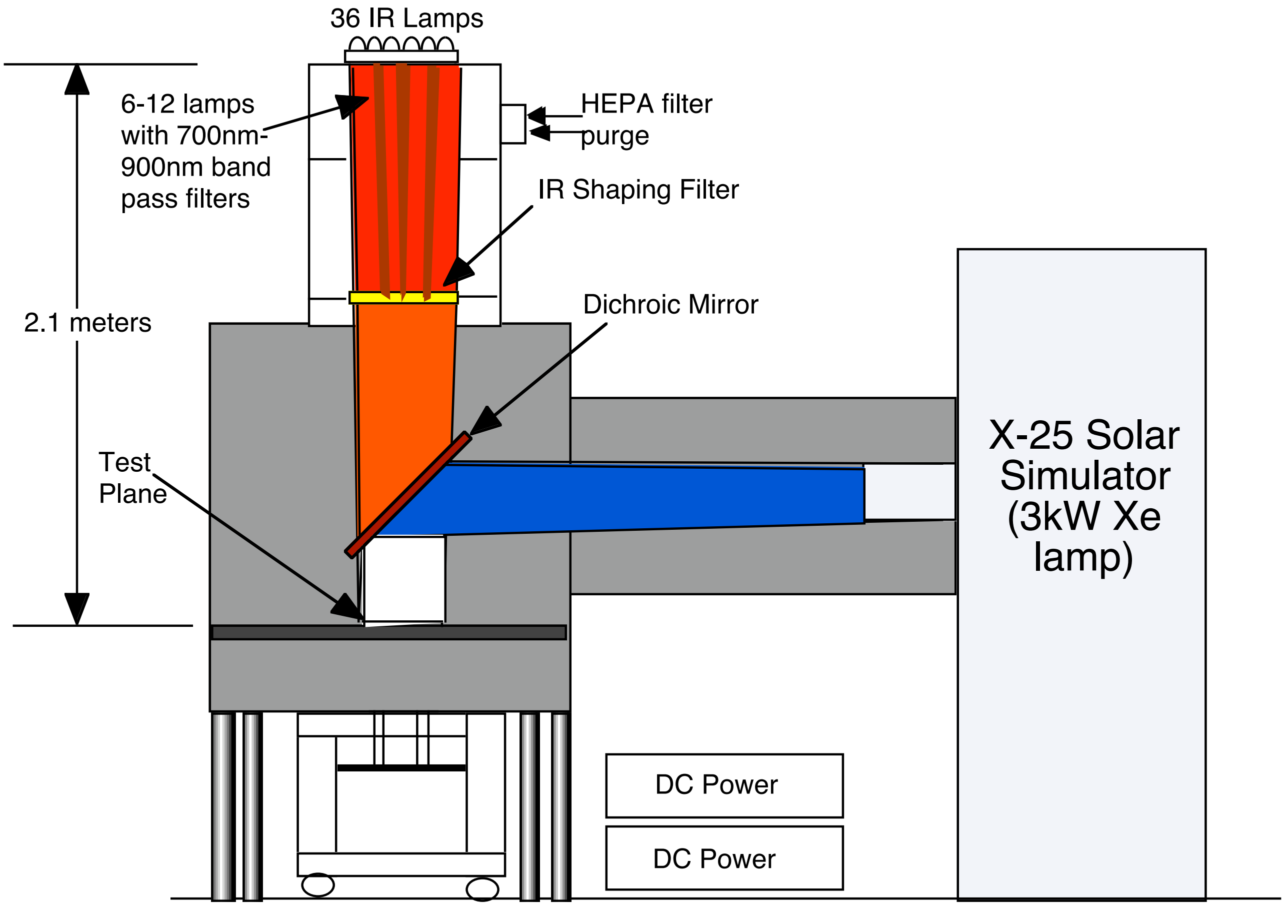

Figure 12) Schematic representation of the multi-source simulator.

References

[1] Solar Cell Standards Group, Energy Conversion Task Group, West Coast Solid State Devices, "Photovoltaic Solar Simulator Specification, American Institute of Electrical Engineers, June 7, 1961, Revised September 5, 1961.

[2] D.B. Bickler, "The Hoffman Solar Simulator," Proceedings of the Solar Working Group Conference (2nd PVSC), Volume II, 6-1 to 6-21, Held, in Washington D.C., Feb. 27 and 28, 1962.

[3] Joseph H. Apfel and Alfred J. Thelen, "A Solar Simulator," Proceedings of the Solar Working Group Conference (2nd PVSC), Volume II, 7-1 to 7-21, PIC-SOL 209/2.1, Held, in Washington D.C., Feb. 27 and 28, 1962.