FIBER OPTICAL SOLAR SIMULATOR

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ABSTRACT

This paper describes a new solar simulator whose output closely matches a desired solar spectrum for testing photovoltaic cells. The accurate simulation of the spectrum is attained by combining three light beams, each tailored to have suitable spectral content. The three light beams, derived from two sources, are filtered, and "mixed" by means of a trifurcated, randomized fiber cable so that when superimposed they add up to the desired solar spectrum. The Fiber Optic Solar Simulator (FOSS) simplifies solar cell testing by greatly reducing measurement time, obviating need for spectral mismatch corrections, and improving the accuracy of measurement. Other applications of FOSS are also described.

INTRODUCTION

During the past decade advances in the design and fabrication of solar cells have resulted in complex device designs capable of yielding very high efficiencies — approaching theoretical values. Today, an accurate measurement of the solar cell performance is a time-consuming, tedious, elaborate, and expensive process. The measurement problems arise because the solar simulators, based on a single xenon arc lamp, have an output spectrum that has significant deviations from a standard solar spectrum (1,2). These deviations are due to: mismatch in the envelopes of the standard and the actual output from a xenon lamp, presence of sharp emission lines from xenon lamp, and the absence of atmospheric absorption such as that arising from water vapor and CO_2. Although the current simulators employ some subtractive filtering, an accurate solar cell testing still requires elaborate procedures necessitating: (i) use of calibrated reference cells(s) fabricated on the same material and closely matching the performance of the test cell, (ii) measurement of the spectral response of the test cell, and (iii) measurement of the spectrum of the simulator and the current-voltage (I-V) characteristics of the test cell under this spectrum. After acquiring these data, a correction to the device short circuit current is made to compensate for the mismatch in the desired and the actual spectra. The current technique works well with single junction cells for which reference cells are available.

However, the technique for spectral mismatch corrections can only correct for the short circuit current; the cell parameters such as the open circuit voltage (V_{oc}) and the fill factor (FF) cannot be corrected. This can result in serious measurement errors in multijunction cells where a minor deviation in the current matching conditions between the design spectrum and the test spectrum can produce large effects on the FF of the cell (3). These problems can be circumvented if the measurements are done under a light source that can accurately reproduce the desired spectrum (4 - 8). Hence, we have developed the Fiber Optic Solar Simulator (FOSS), which produces an output beam that accurately replicates the solar spectra, Global AM1.5 or AM0, as desired (9,10). This paper describes the instrument and compares the results of test data on a variety of cells obtained by FOSS and conventional procedures used at NREL.

PRINCIPLE OF FOSS

Our approach is to synthesize a broad-band solar spectrum by superposing a number of light beams, each covering a different part of the spectrum. We have determined that a solar spectrum can be accurately synthesized by three broad-band beams covering UV, visible, and the IR regions of the solar spectrum. In order to ensure the lateral uniformity of the spectral content in the output beam, the intensity distribution of each individual beam must be uniform in the test plane. FOSS uses three suitably-filtered light beams which are superposed axially. This is accomplished by mixing the three optical beams by means of a randomized optical fiber. Each fiber acts as an element of an optical integrator. The randomized nature of the fiber cable and the large number of the elements of the optical integrator lead to a highly uniform spatial distribution of the intensity of each beam.

SYSTEM CONFIGURATION

Figure 1 is a schematic of the FOSS illustrating use of two light sources - a xenon arc lamp and a tungsten filament lamp. The xenon arc lamp is configured to produce two beams which serve as UV and visible (Vis) beams. The arrangement, shown in Figure 1, for extracting two beams from a single source can capture nearly all the light emanating from the xenon arc lamp and , hence, results in a much more efficient operation of the lamp as compared to the conventional use in a solar simulator. The output beams from the xenon arc lamp are modified by a suitable lens system and passed through low pass filters F1 and F2 that block the region of sharp emission lines and provide a smooth roll-off of the transmission beyond the cut-off wavelength. The tungsten lamp has no filter.

The output from the filters F1 and F2 and the direct output from the IR source are passed through individual apertures A1, A2, and A3, respectively. These apertures are used to control the power contained in each beam and hence allow adjustment of the ratio of three beam intensities in the output beam. The output from each aperture is focused by individual lenses, L1, L2, L3, onto to the corresponding ends of the trifurcated optical fiber cable. Two legs of fiber cable, the Vis and the IR legs, are made of glass fibers, whereas the UV leg is made of quartz fibers. Each input leg of the fiber cable has about 2000 fibers, and the numerical apertures of the quartz and the glass fibers are about the same. The output beam is collimated by a quartz lens to produce a highly uniform beam whose spectrum can be adjusted by changing the intensity-ratio of the three beams. This allows an accurate production of the envelope of the solar spectrum.

The necessary characteristics of the various elements of FOSS are determined by a computer program that takes the spectrum of each source and determines the modified spectrum due to the transmittance of filters, lenses, and the optical fiber, and arrives at the combined spectrum at the output. This program can determine the optimum filter combination for the best fit to the spectrum required at the test plane. Although use of all-quartz optics can significantly reduce design effort, such a system would be quite expensive. Concomitantly, we have employed quartz optics only in the UV path. It should be pointed out that since our system can independently control power and the spectral distribution in each beam, there are many possible combinations of filters that can produce the same output spectrum.

One of the criterion for filter selection is to suppress the emission lines from the xenon arc in the UV and Visible beams; this establishes a cutoff around 0.7-0.8 μm for these filters. The fiber cable is designed to achieve the following features:

1. High coupling efficiency at each input end to ensure a minimum loss of optical power. Clearly, this is related to the optical design of the source, the focusing optics, and the

numerical aperture of the optical fibers. In our current fiber, a coupling efficiency of 60%-65% can be achieved.

2. The loss within the fiber should be minimized to avoid undesired dissipation.
3. The effective output (optical) diameter of the cable and the size of each fiber should be compatible with the requirements of the size and the uniformity of the output beam in the test plane.
4. The distribution of fibers in the output end of the cable should be random in order to produce a spatially uniform superposition of each input beam.

It is instructive to track the spectral changes that each beam develops as they propagate, and produce the combined output. Figure 2a shows the spectral contents of the UV beam at the input and the output of filter F_1. The corresponding spectra for the Vis beam are shown in Figure 2b. Figure 3 shows the spectra of the individual UV, Vis and IR beams in the test plane; the total output spectrum corresponding to these individual beams is also shown. Figure 4 shows a comparison of the spectrum from the fiber optic simulator and the standard Global AM1.5 spectrum. It is clear that a very close match of AM1.5 envelope can be produced by the fiber optic simulator. Figure 5 shows the typical distributions of the intensities of each beam in the test plane for a 4-in diameter of the output beam. The uniformity within the central 3-in spot is better than ± 2%. This high degree of the spatial uniformity of each beam ensures a corresponding high degree of the spectral uniformity in the output beam.

Due to ease of adjusting the output spectrum of FOSS, we can also produce AM0 solar spectrum by simply changing the ratio of the beams. Figure 6 shows a comparison of standard AM0 and the corresponding spectrum from FOSS.

TEST RESULTS

As a result of its highly uniform beam, with a spectrum closely matched to the solar spectrum, a measurement of the solar cell performance can be done under FOSS in only about 5 minutes, even on a multijunction cell. We have made measurements on a variety of solar cells fabricated on different materials and with single and multijunction devices. Tables 1 and 2 summarize the test results of single and multijunction cells, respectively. Also shown in these tables are test results from conventional procedures. The test results are in very close agreement with standard cell test measurements done by the National Renewable Energy Laboratory.

Cell Type/ID	I_{sc}(mA)		V_{oc}(Volts)		Fill Factor (%)		Area (cm^2)
	A	B	A	B	A	B	
GaAs/G361-42	2.25	2.24	0.89	0.89	79.2	79.7	0.25
Si/S1	35.9	36.1	0.65	0.65	74.8	74.8	1.00
a-Si/L3574-10	3.84	3.92	0.91	0.91	60.0	61.2	0.25
InGaP/G433-4	1.32	1.40	1.35	1.35	86.1	87.8	0.25
CIS/I182-1	31.7	31.2	0.54	0.54	49.3	49.6	1.00

Table 1: Comparison of single junction solar cell parameters measured with the Fiber Optic Simulator and with NREL standard.

A: Fiber Optic Simulator
B:Standrad NREL measurement

Cell Type/ID	I_{sc}(mA)		V_{oc}(Volts)		Fill Factor (%)		Area (cm^2)
	A	B	A	B	A	B	
GaInP on GaAs/G423-4	2.10	2.0*	2.35	2.34*	82.2	84.0*	0.25
Tandem α-Si/α-Si/L3079-8	1.83	1.97	1.83	1.85	70.6	71.2	0.27

Table 2: Comparison of multijunction solar cell parameters measured with the Fiber Optic Simulator and with NREL standard.

A: Fiber Optic Simulator
B:Standrad NREL measurement
*:These values were not verified by NREL.

The other advantages of the FOSS are

- It is a compact, table-top system that is convenient to use at laboratory test facilities and is considerably less expensive than conventional systems
- It has a high optical throughput
- Each source is maintained at a constant color temperature, which minimizes the variations in the spectrum
- The output spectrum can be easily corrected to accommodate for changes in the optical elements, such as those due to aging of lamps and filters.

OTHER APPLICATIONS OF FOSS

Although FOSS was designed primarily for testing solar cells, this system can be easily modified for a number of other applications. These applications include:

- Reflectometer for accurate measurement of solar reflectance of solar materials, paints, and textiles.
- Medical applications that require a controlled broad-band spectrum
- A system for solar cell testing that includes measurement of the spectral response of the cell under actual operating conditions.

CONCLUSION/MARKET POTENTIAL

A fiber-optic solar simulator has been developed that can be adjusted to produce an output beam to match either AM0 or AM1.5. The initial tests on single- and multi-junction cells show a good agreement between the cell parameters measured with the fiber optic simulator and by standard procedures. The measurements made with the fiber optic simulator did not incorporate any spectral mismatch corrections and did not use a reference cell. Further improvements are being incorporated that will allow individual cells of a multijunction device to be characterized.

The market potential of FOSS appears to be quite high. Photovoltaic energy is one of the most promising energy technologies for the future. The market for photovoltaics has been growing at a rate of 25% per year over the last 4 years and is expected to grow at an accelerated pace in the future. With markets that may soon be toping several billions of dollars per year, and with an increasing number of PV products coming into the market, the need for measurement standards and quality control will be imperative. Researchers and the industry will need a quick, easy, and accurate method for testing devices. The FOSS and its progeny are the instruments that will provide that service. The FOSS offers the expanding number of researchers who are developing new complex solar cell designs a unique opportunity that no other instruments can match—experimental adjustment of the cell design parameters such as doping profiles, material composition, antireflection coatings, and window layers. A fine-tuning of such design parameters on an experimental basis, using an accurate simulator spectrum, is essential for advanced devices that use spectral splitting and current matching to achieve very high conversion efficiencies.

The FOSS can be used in other applications that require a tight control of the light spectrum. Such application include measurement of the solar relectance of materials for color matching, medical research, and characterization of solar materials and devices.

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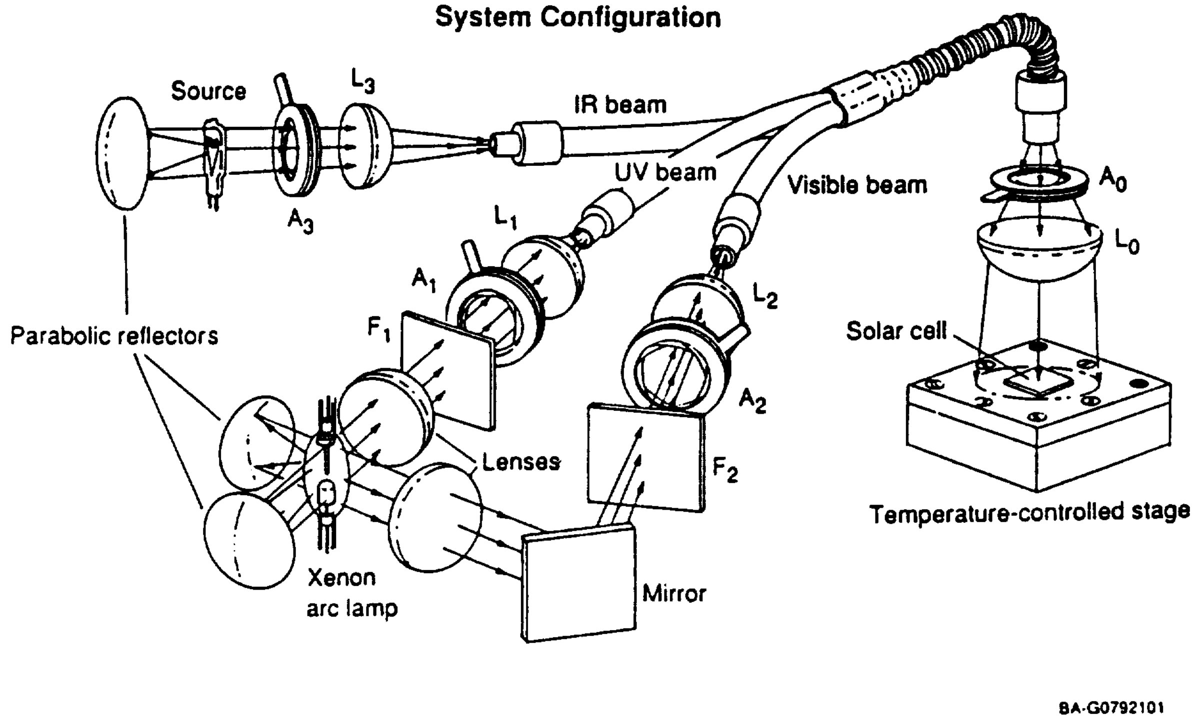

Figure 1. A schematic of the Fiber Optic solar simulator showing major elements of the system

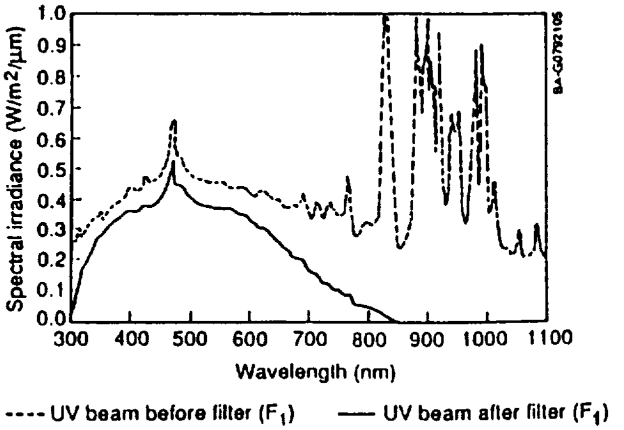

Figure 2a. Comparison of the spectral contents of the UV beam before and after the filter F_1

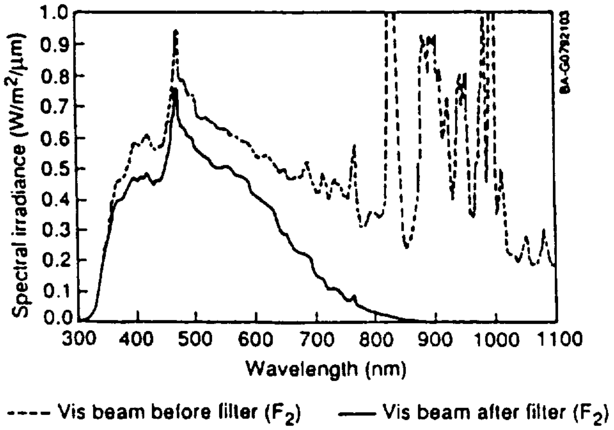

Figure 2b. Comparison of the spectral contents of the Vis beam before and after filter F_2

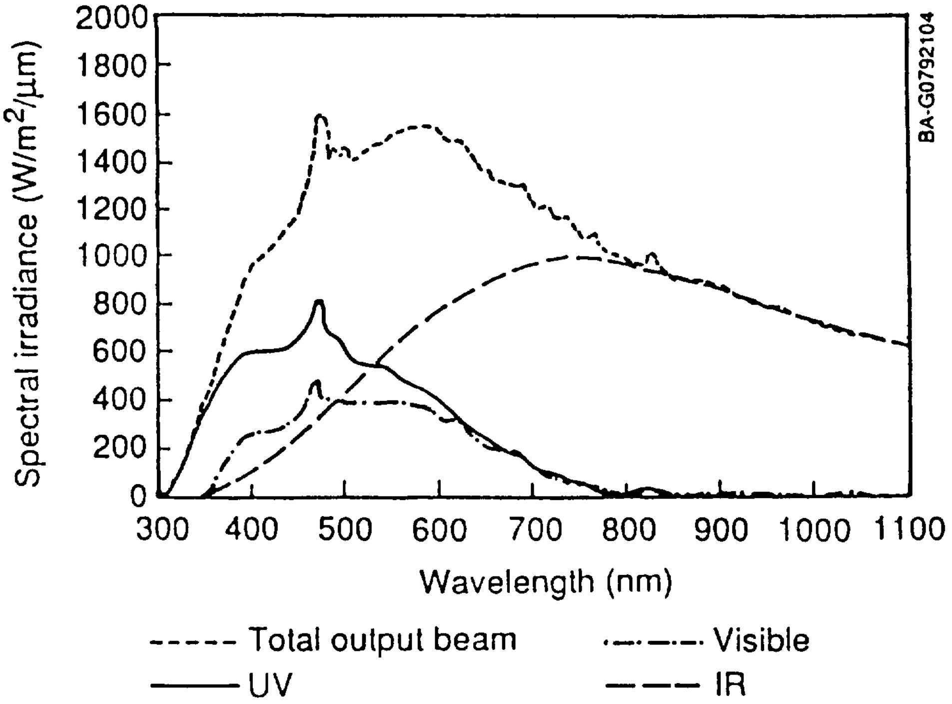

Figure 3. Spectra of individual UV, Vis and IR beams and the total output beam in the test plane

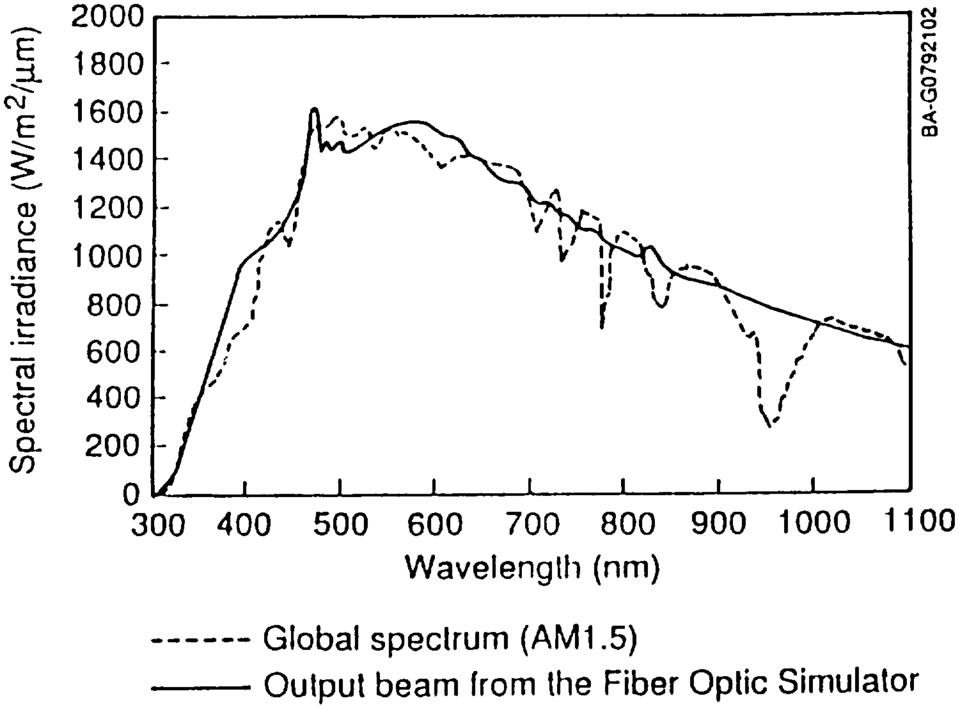

Figure 4. A comparison of the spectrum of the output beam from the fiber optic simulator with AM1.5 Global spectrum

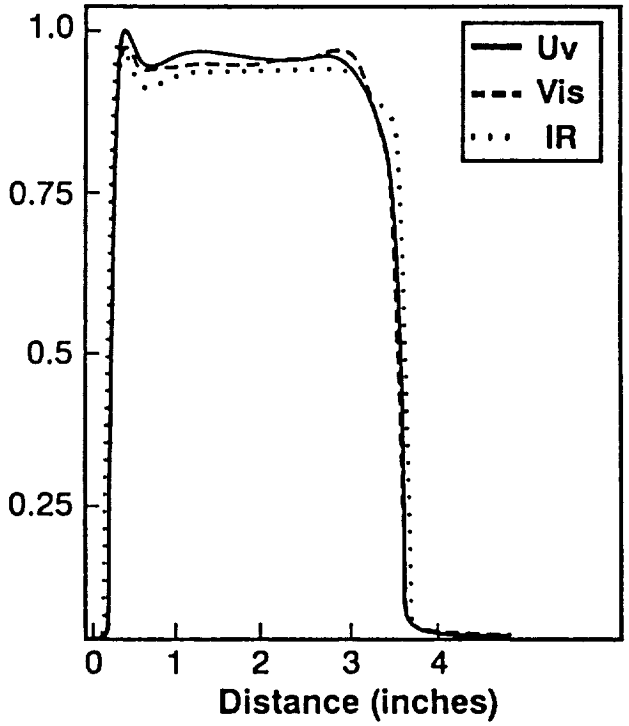

Figure 5. Normalized intensity distributions of UV, Vis, and IR beams in the test plane

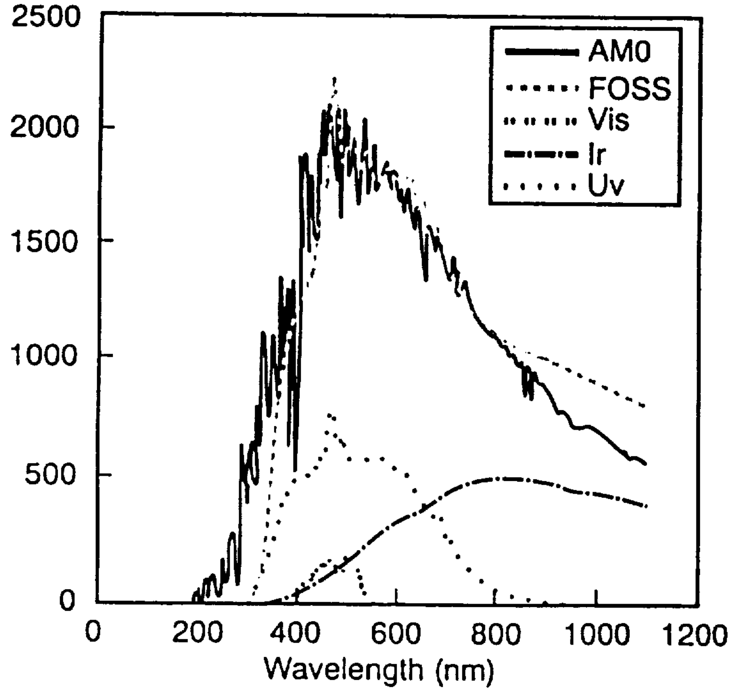

Figure 6. Comparison of the standard AM0 and the output from FOSS

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