Performance-based analysis of a double-receiver photovoltaic system.

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Abstract: Concentrating photovoltaic (CPV) systems with three-junction solar cells are already in the market. In the CPV market, photovoltaic systems with four cells are needed to make CPV more cost competitive. This is because systems with four cells have more yield than the existing three cell systems. Technically, making a stack of four cells imposes constrains on the choice of the materials (i.e. energy bandgap and lattice constant) and it involves complex and costly fabrication techniques. This paper suggests a design of a CPV system with two separate double-junction solar cells (i.e. four PV cells). The system proposed enables the operation of the four cells independently. It also offers high flexibility in the choice of the materials for making the solar cells. The system described in this paper involves a double-junction cell made of AlGaAs/Si; and another double-junction cell made of: InGaAsP/InGaAs. This paper presents the modeling approach and the response of the system under the standard conditions.

Keywords: *photovoltaic, beam splitting, concentrating photovoltaic system.*

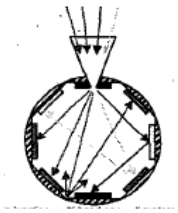
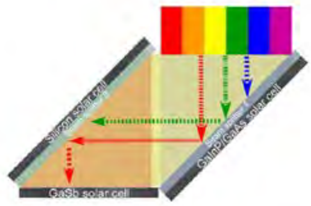
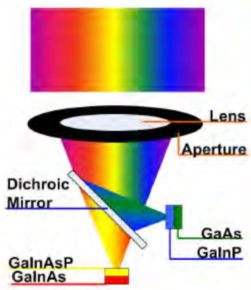
1. Introduction

Recently, efficiencies as high as 41.6 % have been measured on concentrating photovoltaic systems (CPV) with a three junction solar cell made of InGaP/InGaAs/Ge [1, 2]. Such converters are already in the PV market for terrestrial applications but with a share of less than 1%, while the other photovoltaic technologies (i.e. silicon and thin films) dominate the market [3, 4]. Though the performance of CPV systems with three cells is high, further improvements are still needed to bring down the cost of power from CPV systems and make it cost competitive with the other technologies, namely: silicon based technologies, thermal concentrating solar power and thin-films. One way to improve the response of CPV systems is to involve four-junction solar cells which are not in the market yet. As a matter of fact, the company Emcore is planning to use four-junction cells in their modules from the second quarter of 2011 to achieve 30% outdoors efficiency [5]. Theoretically, the limiting efficiency of a series connected solar cell with four sub-cells is 67.9% under the direct solar spectrum [6]. Making monolithic 4-junction solar cells is technically challenging imposes constrains on the choice of the material because the four cells need to have specific lattice constants and specific energy bandgaps for an optimum response. However, making 2-junction solar cells is relatively simple and can be made with less constrains.

In this work, we suggest a design to involve four cells to achieve a high efficiency with less constrains by using optical techniques. The idea is to design a multi-receiver system in which the cells are kept apart and the sunlight is split into different sub-beams. This type of multi-receiver systems tends to be complex shape-wise which makes wiring, mounting and cooling more complex. In the literature, many CPV systems with beam-splitting features are reported; however, three CPV systems only involve four solar cells [7-11]. United Innovations Inc. proposed a cavity receiver with four mono-junction cells coated with optical filters: InGaP, GaAs, InGaAsP and InGaAs (see configuration 1 in Table 1). The efficiency was calculated and estimated at 48.32 % under 100 suns [8]. Another receiver with four cells was demonstrated at the Fraunhofer ISE in Freiburg, Germany (see configuration 2 in Table 1) [9]. Two of the cells were made of InGaP and GaAs, and they were stacked together. The other mono-junction cells were made of Si and GaSb. An efficiency of 34% was measured [9, 11].

In configuration 3 in Table 1, a system built at the University of Delaware is shown. The system was tested under outdoors site-specific conditions and an efficiency approaching 40% was measured [10].

Table 1: Photovoltaic systems with four cells and beam-splitting features.

Configuration	Solar cells	Efficiency	Reference
 *Configuration 1*	InGaP, GaAs, InGaAsP, InGaAs	48.32 % under 100 suns (calculated)	*Ref. 8*
 *Configuration 2*	GaInP/GaAs, Si, GaSb	34 % (measured)	Ref. 9
 *Configuration 3*	InGaAsP/InGaAs, GaAs/InGaP	39.5 % under 30 suns and DNI = 360 W/m2 (not standard conditions)	Ref 10

We have looked at several systems with beam-splitting features, and based on the lessons learned from the designs proposed in the literature, we are proposing a design with four solar cells. Our system has concentration features. This is because concentration improves the response of solar cells and their yield. Also, concentrating systems use a small cells which reduces the amount of material required for making the solar cells; thus, reducing their cost. The proposed system has only two separate receivers in order to avoid multiple reflections, which is not the case in configurations 1 and 2 in Table 1. Having a system with four solar cells and two receivers imply that each receiver holds a double-junction tandem solar cell.

In this paper, the proposed system is presented. A modeling approach has been developed to estimate the response of the system under the standard conditions.

2. Description of the system

The proposed system is displayed in figure 1 and it is composed of a parabolic mirror, a plano-convex lens coated with a short-pass optical filter, and two tandem photovoltaic cells. The setup has two separate receivers: one receiver holds a double junction solar cell made of AlGaAs/Si and the other receiver holds an InGaAsP/InGaAs double-junction cell.

For the dimensions of the receiver, the diameter of the dish is 112 mm. The cells have circular shapes. The AlGaAs/Si cell has a radius of 7 mm; however, the cell at the opposite receiver has a radius of 10 mm.

The dish concentrates sunlight on the lens. The plano-convex lens is made of fused silica and it is coated with a short-pass multilayer optical filter. Ideally, the filter transmits photons with energies higher than the energy bandgap of Silicon and reflects photons with energies shorter than the energy bandgap of Silicon. We should remind that AlGaAs and Si have the following energy bandgaps of 1.817 eV and 1.124 eV. Therefore, photons with energies higher than 1.124 eV only can be absorbed and converted and those with energies lower than 1.124 eV are reflected to the InGaAsP/InGaAs solar cell. $In_{0.57}Ga_{0.43}AsP$ and InGaAs have energy bandgaps of 1.0 eV and 0.74 eV respectively. Therefore, photons with energies higher than 0.74eV and shorter than 1.124 eV can be absorbed and potentially converted.

For the sake of developing an accurate model, realistic optical properties for the reflective coating on the mirror and the short-pass coating on the lens for commercialized products were used in our model. The transmittance of the multilayer optical filter is presented in figure 2. The spectrum incident on each receiver is presented in figure 3.

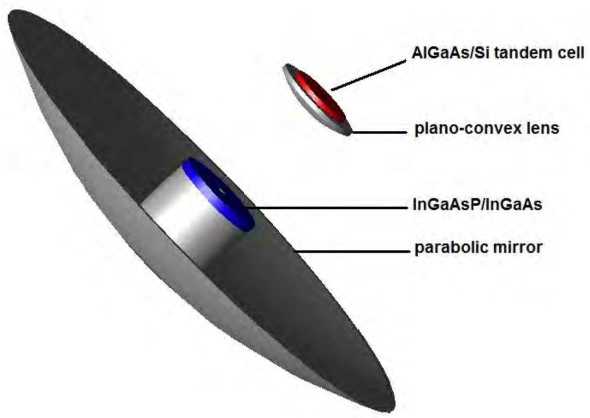


Fig. 1. Configuration of the proposed double-receiver system.

3. Modeling approach

To the best of our knowledge, there is no package dedicated to the modeling of CPV systems with multiple receivers. Therefore, we had to devise a multi-step procedure for modeling the different parts of the system: the light source, the opto-mechanical system, and the solar cells. For the details of the modeling procedure, reference [12] is recommended.

3.1. Modeling the light source:

For modeling the light source, the package SMARTS was used for generating a file for the standard solar spectrum AM1.5 D ASTM G173-03 [13, 14]. The output of the package consists of the wavelengths and the corresponding flux values in $W/m^2/nm$ in the other column. As we are modeling a concentrating photovoltaic system, only photons coming directly from the source (i.e. the sun) can be tracked. For this reason, spectrum of sunlight coming directly from the sun was generated (i.e. AM1.5D). To cover the maximum of the spectrum, we generated spectrum for wavelengths starting from 280 nm to 4000 nm. The spectrum is presented in figure 3.

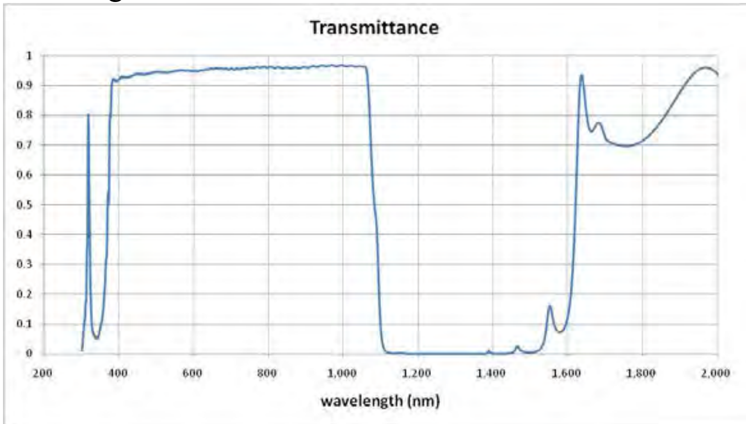


Fig. 2. Transmittance of the short-pass optical filter.

3.2. Modeling the opto-mechanical system:

The values obtained from SMARTS were used for modeling the light source in the ray tracing package TracePro Expert [15]. We used the ray tracing program to determine the flux received at the two receivers. The system presented in figure 1 was built in TracePro Expert and one million rays were launched from the source to find the power incident on each one of the two receivers. Though the acceptance angle should theoretically be 32’, in our model, we considered it to be 0^o.

3.3. Modeling the solar cells:

After determining the flux incident on the receivers and the spectrum absorbed by the two solar cells, the cells were simulated in PC1D. PC1D is a package dedicated to modeling photovoltaic solar cells [16]. That is, two PC1D models were developed: one for the AlGaAs/Si solar cell and one for the InGaAsP/InGaAs solar cell, and both are double junction tandem cells. Numerical optimization of the cells is the subject of our previous studies [17, 18].

In PC1D, two spectrum files were generated to model the two solar cells. These files were obtained by modifying the spectrum files that correspond to AM1.5D. For each wavelength in the AM1.5D file, the value of the flux was multiplied by reflectance of the reflective coating and then multiplied either by transmittance (or reflectance) to obtain the flux incident on the AlGaAs/Si cell (or the InGaAsP/InGaAs cell).

After preparing the spectrum files in PC1D and after determining the flux incident on the two solar cells by using TracePro Expert, the PC1D model was run and the final results were obtained.

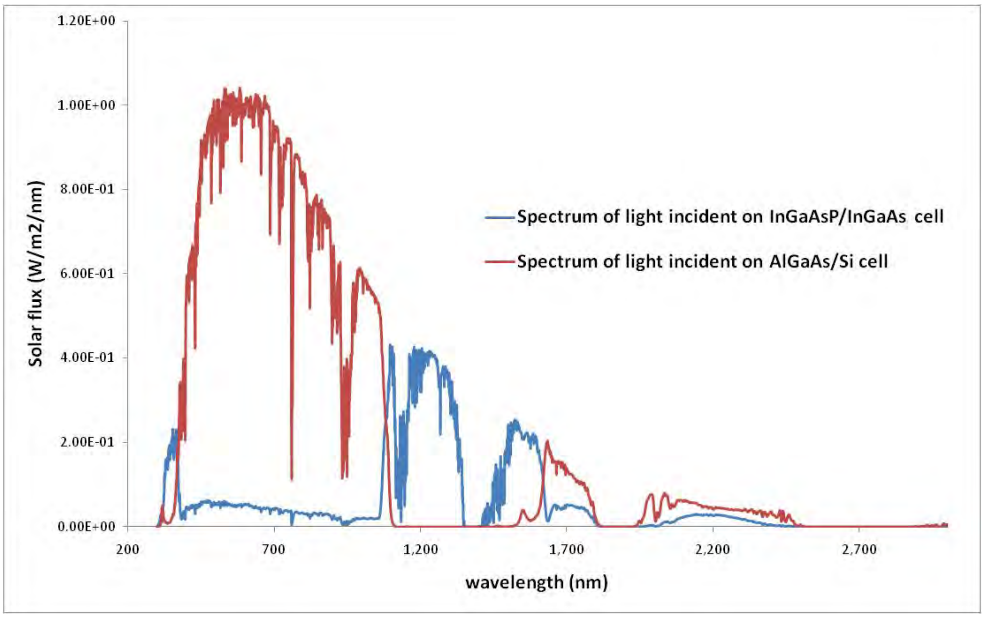


Fig. 3. Spectrum of light incident on the two receivers.

Table 2: Response of the cells in the system.

	AlGaAs	Si	InGaAsP	InGaAs
Energy bandgap (eV)	1.817	1.12	1.00	0.74
Isc (mA/cm2)	717	470	77.1	339.5
Voc (Volts)	1.352	0.752	0.624	0.425
Efficiency (%)	15.5	5.6	1.47	4.21

4. Response of the system:

After running the model, we found that under the standard conditions where the total flux incident on the dish is 850 W/m2 (i.e. a power of 8.374 W is received by the 112 mm wide receiver), 5.716 Watt of concentrated sunlight is received by the InGaAs/Si tandem cell and another 1.712 Watt of concentrated sunlight is received by the InGaAsP/InGaAs tandem cell. These values correspond to power densities of 37.13 kW /m^2 and 5.45 kW/m^2 on the AlGaAs/Si and InGaAsP/InGaAs cells, respectively. These numbers show that the optical efficiency of the system is 88.7 %. The response of the solar cells is summarized in Table 2.

The results in table 2 show that the overall efficiency of the system is 26.8 %. Under the standard conditions, this corresponds to a power density of 227.6 W/m^2. This also means that one dish generates 2.24 W under the standard conditions.

5. Conclusions

In this paper, a system with four solar cells was modeled under the standard conditions. The system involved four solar cells made of the following materials: AlGaAs (1.817 eV), Si (1.124 eV), InGaAsP (1.0 eV) and InGaAs (0.74 eV). The system has beam splitting features and an optical concentration of 63 suns. For modeling the system, we proposed a multi-step modeling procedure. The modeling results show that the efficiency of our proposed system is 26.8 % which corresponds to a power output of 2.24 W. Comparatively with systems with four solar cells reported in the literature, the efficiency of the system is low because of two reasons:

- The combination of the energy bandgaps is not optimum: changing the distribution of the energy bangaps can be done either by using other materials or by changing the composition of the materials used in this study. The optimum energy bandgaps can be determined by changing the cells.
- The optical concentration ratio: the concentration ratio of the system is 63 suns. Increasing this efficiency to very high values above 300 suns would enhance the efficiency of the system.

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