Compound Parabolic Concentrator Cross-Sections and 3D-Printed Designs for Solar Thermophotovoltaic Systems

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Background

The Shockley–Queisser limit predicts the theoretical maximum efficiency of single-junction solar cells to be approximately 31% due to the mismatch between the Sun's broadband spectrum and the silicon bandgap. [1] Solar Thermophotovoltaic systems (STPVs) use an intermediate absorber and emitter that allow the emission spectrum to be tuned, enabling theoretical efficiency levels approaching 85% under ideal conditions. Laboratory STPV systems have achieved efficiencies as high as 42% using III–V photovoltaic cells and selective emitters but these systems can be impractical and expensive due to low availability of materials. The STPV system includes a concentrator, an absorber, an emitter, and a PV cell. To prevent thermal damage on the PV cell, we have attached a heat sink on the back allowing it to cool through convection.

Research Objectives

In this study, we investigate the role of various components, specifically a compound parabolic concentrator (CPC) and the absorber/emitter material in the STPV system, and their impact on system performance under practical operating conditions.

Methods

Traditionally, concentrators are primarily Fresnel lenses, parabolic dishes, or CPCs, commercially available but often prohibitively expensive. We chose to work with the CPC as it offered more design flexibility than other concentrators and fabricated custom CPCs through 3D printing. We conducted a parameter sweep over the shape of the concentrator cross-section: circle, ellipse, rectangle as explored in [2]; acceptance angle; and relevant dimensions (radius of the circle, major and minor diameter for the ellipse; length and width for the rectangle). Notably, we introduced the parameter split, which allowed larger concentrators to be fabricated as an attachment of two separately printed components (in regard to CAD, not the print bed). Two concentrators were fabricated for testing: a circular CPC with radius 74.265 mm and an acceptance angle of 20º, and an elliptical CPC (split) with major and minor radii of 100.64 mm and 98.14 mm, and an acceptance angle of 15º and 10º along the major and minor axes, respectively. These concentrators were tested outdoors on a 1 cm x 1 cm one-sided anodized (blackened) aluminum sheet against each other.

Indoors, we evaluated the use of different absorber/emitter materials including a 3 in x 3 in silicon carbide (SiC) sheet, a 3 in x 3 in SiC sheet painted black on the absorber side, a 1 cm x 1 cm SiC sheet, a 1 cm x 1 cm SiC sheet painted black, and a 1 cm x 1 cm one-sided anodized aluminum sheet.

For each of these scenarios, system efficiency is calculated as the ratio of power output to power input. We connected the PV cell to a circuit that measures the current and voltage through a range of load resistance and determined the system's maximum power. Because the weather was partly cloudy on the day of outside measurement, the solar irradiance was estimated from the measurements obtained with the PV cell and manufacturer specifications regarding efficiency.

Results

The 3 in × 3 in SiC absorbers produced no measurable electrical output. Among the 1 cm × 1 cm samples, the painted SiC achieved the highest efficiency (4.06%) and maximum power (4.48 mW), followed by the unpainted SiC (3.85%, 4.25 mW) and anodized aluminum (3.68%, 4.06 mW).

Using the PV cell directly with the sunlight, and accounting for its efficiency information from the manufacturer, I calculated the solar irradiance to be 502.5 W/m^2. With the anodized aluminum and the 2 mm cavity distance, the circular CPC had an efficiency of 0.35% and a maximum observed power output of 30.1 mW. If the load resistance was optimized, the system could theoretically produce 31.63 mW of power. The elliptical CPC performed slightly better, with an efficiency of 0.496% and an observed power output of 14.4 mW. However, it had a greater potential for an improved performance, with a theoretical efficiency of 2.1% and a maximum power output of 43.25 mW, assuming optimized load resistance under the measured irradiance conditions.

Conclusions/Implications

This work demonstrates a practical split-and-join fabrication approach for 3D-printed CPCs. Comparing two designs, a split-elliptical CPC and a circular CPC, we find the elliptical design to show more potential for growth in terms of power output and efficiency. Future research could investigate split-and-join, specifically elliptical designs for cheap and quick fabrication in STPVs.

References

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