Improving Temperature-Dependent Energy Output of Concentrator Photovoltaic Systems using Nanotextured Surfaces

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***Abstract*- We optimize a nanostructured surface derived from glass microbeads to stabilize the power output of concentrator photovoltaic (CPV) systems over a wide range of lens temperatures. Rigorous coupled wave analysis computes the transmission/scattering of the sub-wavelength structure, which we then couple to a ray tracing analysis to simulate the entire CPV system. We find that beads with diameters 300-400 nm demonstrate the highest temperature-dependent improvement with a short-circuit current gain of up to 4% relative to not using beads. Our results show that nanotextured surfaces integrated into CPV systems can improve its competitiveness versus silicon-based solar cells over a wider range of locations.**

I. INTRODUCTION

Concentrator photovoltaic (CPV) systems have demonstrated the highest efficiency for the conversion of solar to electrical energy. They are based on optical systems that concentrate sunlight by hundreds of times onto highly efficient III-V photovoltaic cells (typically ≥40% efficient), which are installed on trackers that follow the sun. The cell efficiency increases with concentration; however, higher concentration demands higher tracking precision. The acceptance angle of the system quantifies its tolerance to tracking errors; it is defined as the angle at which the power generated by the module is reduced by 10%. Wide acceptance angles relax the manufacturing design constraints for CPV systems and trackers. Silicone-on-glass Fresnel lenses provide a cost efficient yet high-performance platform for solar concentration. However, they can suffer from focusing errors resulting from the sizeable difference in thermal coefficients of expansion of the basic materials [1]. The focal length of the lens decreases with temperature, increasing the angle of incidence of rays reaching the solar cell. It thereby decreases the transmission of light into the solar cell. Nanostructured surfaces can increase the transmission of light, especially for rays incident at large angles. Researchers at CEA-LITEN (France) have developed a technique, called BooStream, to form ordered micro/nanostructured front surfaces on solar cells by depositing glass microbeads which sink halfway into a silicone layer [2]. In this paper, we introduce our model which incorporates nanostructured surfaces in a CPV sub-module. We use this model to study the effects the microbeads have on the energy output of the CPV system for various lens temperatures.

II. MODEL

Fig. 1 introduces the model used to simulate the effects of these microbeads on concentrated sunlight in a CPV module with 500X geometric concentration. We used a 4 mm thick silicone-on-glass Fresnel lens with size 60.5X60.5 mm^2 and a focal length of 93 mm. Placed at the focal length is a GaInP/InGaAs/Ge triple junction solar cell with a 1 mm thick silicone encapsulant. We employ the commercial software package Zemax for ray-tracing through the system [3], and the open-source rigorous coupled wave analysis (RCWA) code RETICOLO for the sub-wavelength nanostructured surface above the solar cell. The wavelength-dependent transmission and scattering of the microbeads (calculated by RCWA) are incorporated into Zemax as a custom air-silicone interface atop the solar cell. The optical properties of the solar cell are simulated using the transfer matrix method (TMM) and are also incorporated

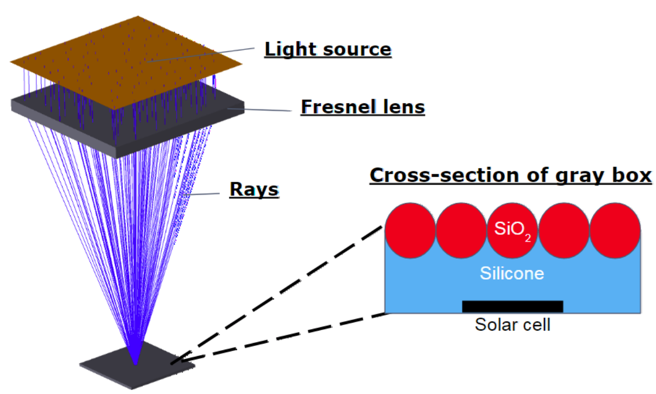

Fig. 1. Schematic diagram of the modelled CPV submodule. Ray tracing simulates the large optical components where the orange square represents the starting point of the rays. The optical spectrum transmitting through the microbead surface is modelled with rigorous coupled wave analysis (RCWA), and the transfer matrix method (TMM) is used to simulate components of light reaching the solar cell.

into Zemax. The effects of temperature variations for the silicone-on-glass Fresnel lens are simulated by controlling the focal length of the lens. We assume 0.11 mm/ºC as the linear coefficient that relates the change of the lens temperature to the change of the lens focal length from their ideal values (25 ºC and 93 mm) [4].

III. RESULTS

The simulation results shown in both Figs. 2 and 3 compare a CPV system with and without a nanostructured surface. The short-circuit current is calculated by weighting the light absorbed in the solar cell by both the AM1.5d solar spectrum and the internal quantum efficiency (IQE) of the triple junction solar cell. The 300-400 nm diameter beads provide the highest short-circuit current gain at low lens temperatures (more than 4% increase relative to no beads). This bead size also increases the acceptance angle by up to 2.5% at high lens temperatures (relative to no beads). The highest acceptance angle gain is reached by the 500-nm diameter beads at ideal lens temperatures (more than 6% relative improvement), which can also increase the short circuit current by up to 3% relative increase at low lens temperatures. Fig. 2 shows an increasing gain of the short circuit current as the lens temperature decreases from its ideal 25ºC working temperature.

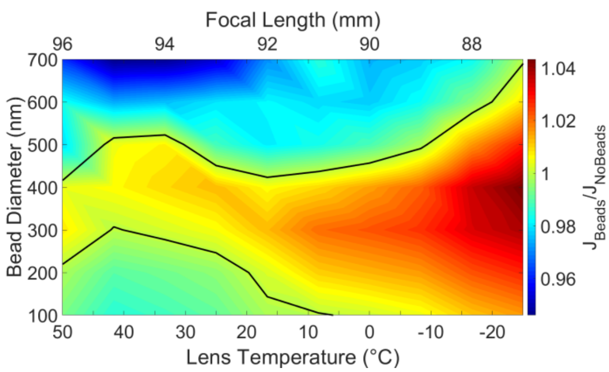

Fig. 2. Short-circuit current improvement for beads of various sizes and lenses with differing focal lengths. The Fresnel lens has focal lengths of 96 mm and 87 mm at temperatures of 50°C and -25°C, respectively. The black contour outlines the frontier between the short-circuit current gain and loss.

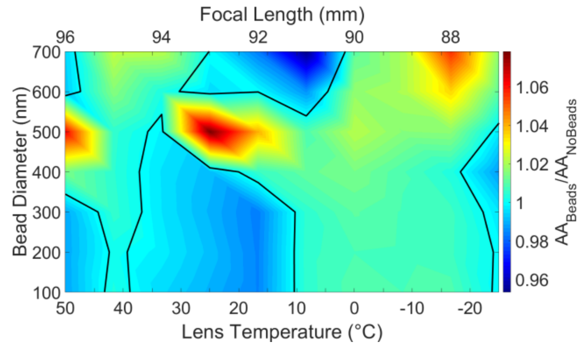

Fig. 3. Acceptance angle (AA) improvement for beads of varying diameters and for a wide range of lens temperatures. The black contour outlines the frontier between the acceptance angle gain and loss.

But, Fig. 3 shows no clear trend relating the acceptance angle gain to bead diameter. This suggests the need to optimize the bead diameter such that the annualized improvement balances gains and losses to obtain an overall benefit. Ultimately, these results show that integrating nanostructured surfaces into CPV systems can improve their stability in regions with a high temperature operating range, such as Canada and other temperate or northern regions.

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