Radiative Cooling and Metalens for Advanced Micro-Concentrating Photovoltaic Systems

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Abstract

Aiming to advance next-generation photovoltaic architectures, we explore radiative cooling as a cooling system for multi-junction solar cells under high concentration. Additionally, we investigate the feasibility of metalenses for micro-concentrating photovoltaics, offering high design flexibility and compactness to enhance system efficiency.

To achieve high-efficiency photovoltaic systems, beyond improving the solar cells at the device level, two key approaches are better thermal management and concentrated photovoltaics (CPV). In this work, we investigate the potential of radiative cooling in high-concentration multi-junction (MJ) solar cells and the feasibility of a metalens-based micro-concentration system (μ-CPV). Radiative cooling, which relies on heat dissipation via infrared radiation through the atmospheric transparency window (8–13 μm), offers a cost-effective, passive approach for cooling solar cells [1]. Building on our previous findings on radiative cooling for MJ solar cells [2], we now focus on high-concentration scenarios. We demonstrate that placing a larger radiative cooler beneath the solar cell improves thermal management, achieving acceptable temperatures without the need for additional non-radiative systems. This approach is especially well-suited for CPV, where solar cells are significantly smaller than the system itself.

μ-CPV aims to enable compact, high-efficiency photovoltaic systems by miniaturizing CPV components, enhancing both performance and commercial viability [3]. However, such systems remain complex, particularly due to the need for multiple optical elements and the associated manufacturing challenges. Metalenses, with their design flexibility and compactness, offer a promising solution by integrating essential CPV requirements—such as uniform intensity and aberration correction—into a single optical component. Research in this area is still in its early stages, with some review papers addressing related aspects but not covering the practical realization of these metalenses, such as component dimensions [4]. To bridge this knowledge gap, we discuss the feasibility and challenges of developing metalens-based solar concentrators for μ-CPV, presenting preliminary results.

Figure 1a presents a schematic of our system, illustrating the detailed balance model for the solar cell/radiative cooler stack. The temperature is assumed to be uniform throughout the system and determined by the thermal equilibrium condition, set by zero net power exchange:

$$P_{\mathrm{net}} = P_{\mathrm{rad}}^{\mathrm{RC}} \in P_{\mathrm{atm}} + P_{\mathrm{con}} + P_{\mathrm{rad}}^{\mathrm{SC}} + P_{\mathrm{elec}} \in P_{\mathrm{Sun}} = 0 \tag{1}$$

The terms related to the solar cell are calculated using the Shockley-Queisser model for series-connected MJ solar cells. The first three terms are scaled by the area ratio factor, $f_{\mathrm{A}} = A_{\mathrm{RC}}/A_{\mathrm{SC}}$, to account for the radiative cooler larger area. More details are provided in [2]. Figure 1b shows the temperature of a three-junction (3J) solar cell, composed of GaP/GaAs/Ge (1.87/1.4/0.67 eV), for different concentration factors and area ratios, calculated by solving Equation 1. The solar cell temperature can be reduced to acceptable values ($T < 350$ K)

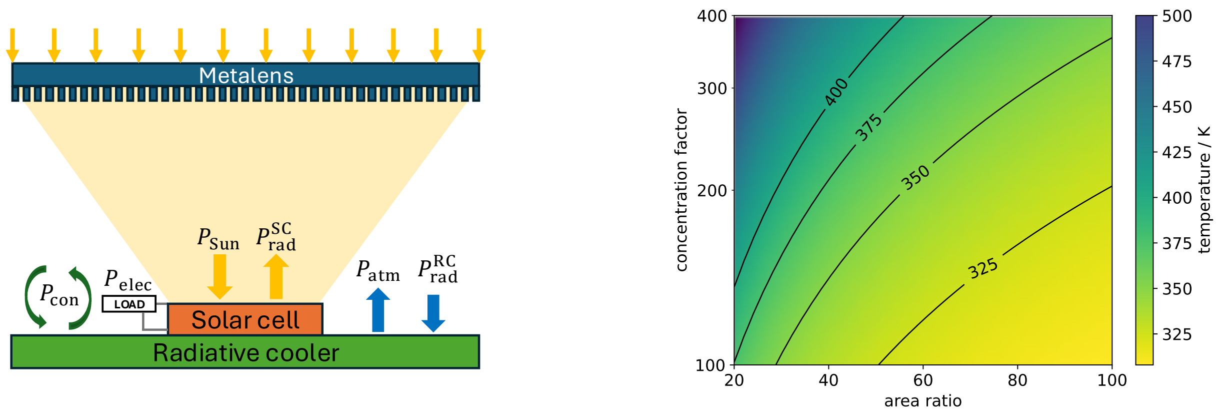

Figure 1: (a) Schematic of the system, illustrating the detailed balance model. (b) Temperature of the 3J solar cell for different concentration factors as a function of the area ratio.

for high concentration factors by simply increasing the radiative cooler's area in typical wind conditions ($h_c = 10.6\,\mathrm{W m^{-2} K^{-1}}$) [1], as experimentally shown for a single junction solar cell in [5].

The metalens in Figure 1a acts as the concentrator in our system. Designing metalenses for μ-CPV requires satisfying key criteria such as broad bandwidth, uniform intensity, and achromatic performance. The achievable dimensions of an achromatic metalens are constrained by the group delay, as discussed in the literature [6]. We compute the geometric concentration factor, $C_g = A_{\text{metalens}}/A_{\text{solar cell}}$, and calculate the required group delay for various metalens sizes and numerical apertures. Using a non-imaging optics approach, we derive the phase profile and assess feasibility by comparing the calculated group delay with the maximum achievable values reported in the literature [7]. Given the small size of miniaturized solar cells [3], our results suggest that high concentration is theoretically achievable with metalenses for μ-CPV. In conclusion, the combination of radiative cooling and a metalens-based micro-concentration system shows strong potential for advancing next-generation photovoltaic systems.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 Research and Innovation Program under grant agreement no. 964450.

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