Impact of Radiative Cooling on Multi-Junction Solar Cells Under Unconcentrated and Low-Concentrated Light

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Abstract **— Multi-junction solar cells are a key technology for high efficiency photovoltaics. Since their performance and reliability are strongly influenced by the operating temperature, their effective thermal management is an important concern, especially in concentrating photovoltaics. Radiative cooling is a cost-effective, passive, and scalable solution for thermal management of solar cells. This technique can effectively expel a large amount of heat by radiating it into outer space through the atmospheric transparency window between 8 and 13 µm. In this work, we analyze the impact of this cooling strategy on multi-junction solar cells under different illumination conditions by means of a detailed balance model for the cell/cooler system. We show that the increase in efficiency resulting from reduced operating temperature is more significant for multi-junction architectures in comparison to single-junction ones, because of their more negative temperature coefficient. Furthermore, we explore two viable approaches for successfully utilizing the radiative cooler in low-concentration photovoltaic systems. The first method involves increasing the size of the radiative cooler area, while the second entails combining it with a nonradiative cooling system.**

Keywords **— Multi-junction solar cells, radiative cooling, concentrating photovoltaics**

I. Introduction

Multi-junction (MJ) solar cells are the most mature technology for high-efficiency photovoltaics (PV) systems. They use junctions with increasing band gaps stacked one on top of each other to circumvent the trade-off between transmission and thermalization losses of single-gap cells, optimizing solar energy conversion. Despite the mitigation of thermalization, they undergo significant self-heating, which results in degraded performance and reduced lifetime. Therefore, proper thermal management is crucial, especially for concentrating photovoltaics (CPV) that face high heat loads.

To this end, several cooling systems have been investigated, primarily based on nonradiative heat transfer mechanisms. However, they are expensive and complex, limiting their use to CPV only [1]. In 2014, Raman et al. demonstrated experimentally that a body can radiatively cool down below ambient temperature by emitting thermal radiation through the atmospheric transparency window between 8 and 13 µm [2]. This work sparked numerous studies by both industrial and academic researchers on the application of radiative cooling to solar cells, which is an attractive approach because it is integrable, requires no energy input, and performs well [3], [4].

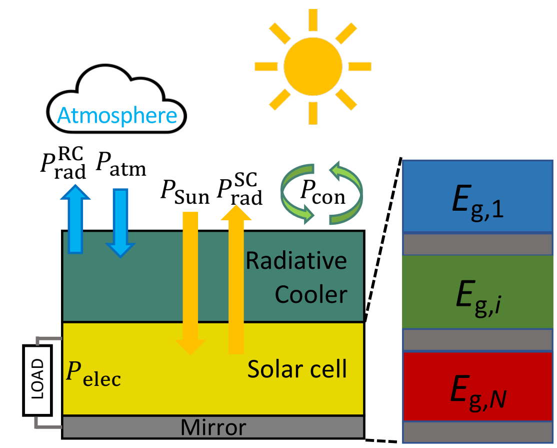

Fig. 1 Schematic of the system made by multi-junction solar cell and radiative cooler, and energy flows involved in the detailed balance model.

However, most studies have been focused on single-junction cells and unconcentrated systems. We could find only one study on MJ solar cells [5] and a couple on low-gap single-junction CPV systems [6], [7]. As the performance-to-cost ratio of MJ solar cells is increasingly improved and novel low-cost technologies emerge [8], such as the Si/perovskite tandem solar cell, further research must be conducted to determine the impact of radiative cooling in both concentrating and non-concentrating photovoltaics systems.

In this work, we assess the effectiveness of an ideal radiative cooler on the performance of multi-junction solar cells, with a focus on low-concentration PV. We describe a device made by solar cell coupled with a radiative cooler by means of the detailed balance model shown in Fig. 1. Here, the solar cell efficiency is analyzed in the radiative limit via the Shockley-Queisser (SQ) model for MJ solar cells [9]. The developed model is simple and general, making it applicable to various radiative coolers and different solar cells. We used it to examine the performance enhancement provided by radiative cooling for different numbers of junctions under unconcentrated illumination. Then, we studied the device operating under sunlight concentration up to 10-sun. The steady state temperature becomes far from acceptable even at low concentration ratios. To address this issue, we propose two potential methods to enhance the cooling capacity of the device. The first aims at improving the radiative and nonradiative heat transfer mechanisms by enlarging the area of the radiative cooler compared to that of the solar cell. The second combines radiative and nonradiative cooling approaches.

II. Methods

The structure used to evaluate the radiative cooling performance consists of three components arranged from top to bottom: a radiative cooler, a bare solar cell, and a perfect and insulating mirror. Assuming that the temperature is uniform through the device, it can be determined by finding its value at thermal equilibrium, which occurs when the net power balance of the system is zero.

$$P_{net} = P_{rad}^{RC} - P_{atm} + P_{con} + P_{rad}^{SC} + P_{elec} - P_{Sun} = 0 \qquad (1)$$

P_{rad}^{RC} and P_{atm} are the power density radiated and absorbed from the atmosphere by the radiative cooler. P_{con} corresponds to the power exchanged with the surroundings by nonradiative heat transfer mechanisms. P_{rad}^{SC}, P_{elec}, and P_{Sun} are the power radiated, delivered to the load, and absorbed from the Sun by the solar cell. We used the SQ model for multi-junction solar cells to calculate these terms, considering the series connected architecture shown in Fig. 1. For this model, we made the following assumptions: 1) Each sub-cell has unit absorbance for energies greater than its band gap, according to the SQ model. 2) Selective mirrors are interposed between the sub-cells to limit the radiative recombination and obtain the highest efficiencies, as demonstrated by Araùjo and Martì [10]. 3) For simplicity, an insulating mirror is placed on the back to limit nonradiative power exchanges to the top of the device; this also reduces radiative recombination of the bottom cell. Based on these assumptions and the current-matching configuration, the last three terms of Equation (1) are given by:

$$P_{rad}^{BB} = \pi \int_0^{hc/E_{g,1}} d\lambda \, L_{e,\Omega,\lambda}^{BB}(\lambda, T, V_{1,MPP}) + \pi \sum_{i=2}^{N} \int_{hc/E_{g,i-1}}^{hc/E_{g,i}} d\lambda \, L_{e,\Omega,\lambda}^{BB}(\lambda, T, V_{i,MPP}) \qquad (2)$$

$$P_{elec} = \min\{J_{i,MPP}\}_{i=1}^{N} \cdot \sum_{i=1}^{N} V_{i,MPP} \qquad (3)$$

$$P_{Sun} = X \int_0^{hc/E_{g,N}} d\lambda \, E_{e,\lambda}^{Sun}(\lambda) \qquad (4)$$

$L_{e,\Omega,\lambda}^{BB}$ is the generalized Plank's law, T is the device temperature, X is the concentration ratio, and $E_{e,\lambda}^{Sun}$ corresponds to the AM1.5g or AM1.5d spectra depending on the applications. Computation of the current and voltage follows [9].

Since the radiative cooler is deployed for cooling a solar cell, whose operating temperatures are well above the ambient one, it is designed to emit as a black body above the sunlight wavelengths, so as to optimize the removal of excess heat produced during solar energy conversion [11]. We considered an ideal radiative cooler with unit emissivity above 4 µm and completely transparent elsewhere. Overall background conduction/convection is modeled as $P_{con} = h_c(T - T_0)$, with $h_c = 10.6$ W/m²/K. Finally, to assess the performance of radiative coolers with larger area than the solar cell, we multiplied the radiative cooler-related terms, P_{rad}^{RC} and P_{atm}, and the nonradiative term P_{con} by a factor equivalent to the ratio between the cooler and solar cell areas, $f_A = A_{RC} / A_{SC}$.

III. Results

We compared the temperatures obtained by solving $P_{net} = 0$ with and without P_{rad}^{RC} and P_{atm} to evaluate the impact of radiative cooling on the performance of solar cells. Fig. 2 depicts the results that we obtained for the unconcentrated case. The temperature reduction provided by the radiative cooler grows with temperature, which increases for lower band gaps and numbers of junctions. The efficiency increase follows the same trend, as shown in the inset of Fig. 2. The colored triangles in the figure identify the most efficient energy gap configurations for MJ cells, while for the single junction cell we adopted the c-Si case as a benchmark. The cooler's impact on performance is more significant for the MJ solar cells because of their higher temperature coefficient, which leads to greater efficiency gains despite the smaller temperature reduction.

As for CPV systems, we considered a triple junction cell with optimum gaps under AM1.5d (0.70/1.18/1.75 eV) as a case study. The heat removal by radiative cooling is significant, but not enough to achieve acceptable temperature values. Consequently, the solar cells are less efficient under concentration than at 1-sun, as can be observed in Fig. 3 considering the case of equal area of solar cell and radiative cooler ($f_A = 1$). However, radiative and nonradiative heat transfer mechanisms can be improved by enlarging the size of the radiative cooler compared to that of the solar cell. With this approach, demonstrated experimentally by Wang et al [7], the temperature is significantly reduced (Fig. 3a), and the efficiency under concentration overcomes that at 1-sun with

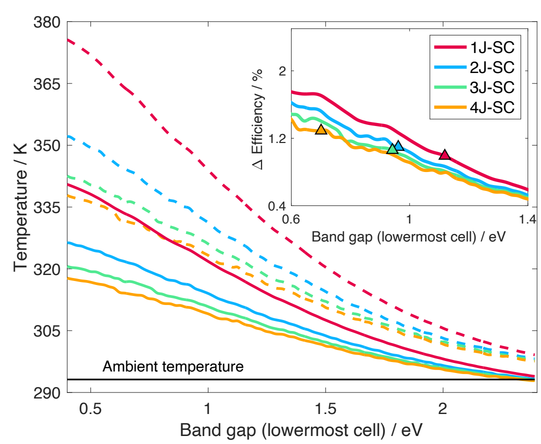

Fig. 2 Operating temperature of MJSCs with (solid lines) and without (dashed lines) an ideal radiative cooler as a function of the lowermost cell band gap. In the inset, the efficiency gain enabled by the radiative cooler.

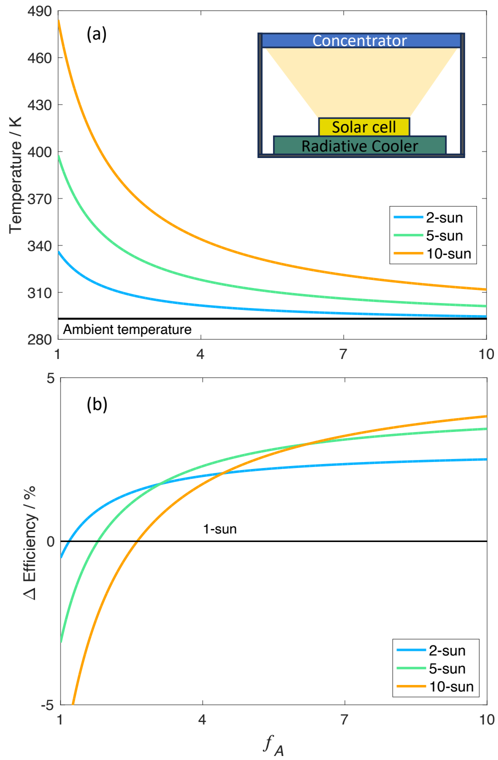

Fig.3 Triple-junction solar cell coupled with a radiative cooler. (a) Operating temperature as a function of the area ratio (f_A) at various concentration ratios. The inset shows a possible set-up in a CPV system. (b) Difference between the efficiency as a function of f_A at various concentration ratios >1 and the efficiency at 1-sun, $f_A = 1$.

just a small increase of the area of the cooler, as shown in Fig. 3b.

This method is particularly suitable for concentrating photovoltaics where the radiative cooler area is limited only by the concentrator lens area, provided that the radiative cooler thermal diffusion length is large enough. Another viable approach, not shown here for the sake of brevity, involves combining the device with a nonradiative cooling system. Although this method reduces the relative impact of the radiative cooler due to the increased conductive and convective heat transfer mechanisms, we found that the radiative cooler still significantly contributes to the temperature reduction, relaxing the requirements for the nonradiative cooling system.

III. Conclusions

This work presents a first analysis of the impact of radiative cooling in multi-junction solar cells by means of detailed balance modeling. The study shows that at 1-sun multiple-junction cells benefit more than single-gap ones from radiative heat transfer because their efficiency is more sensitive to temperature. Under concentration, the size of the radiative cooler must be larger than that of the solar cell to decrease the device temperature enough to achieve higher efficiency than the unconcentrated case. Alternatively, the device can be paired with a nonradiative cooling system, which can have relaxed design requirements thanks to the additional temperature reduction provided by the radiative cooler. These results demonstrate the significance of radiative cooling in the thermal management of multi junction solar cells, and its attractive potential in low-concentration systems [11].

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