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Implementation of Transparent Radiative Cooling Technology on Perovskite Solar Cells to Reduce Efficiency Degradation

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Abstract

Thermal degradation of perovskite solar cells (SSCs) is a major obstacle in maintaining the stability and efficiency of power conversion. Increasing the operating temperature of solar cells can accelerate degradation through mechanisms such as ion migration and phase segregation, thereby significantly degrading performance. Transparent radiative cooling (TRT) technology offers an innovative passive solution by utilizing infrared heat emission in the range of 8–13 μm without reducing visible light transmission, thus maintaining optical efficiency. This study combines experimental and simulation methods to develop a hybrid SiO_2 –PDMS-based TRT layer integrated on SSC. The results showed a decrease in cell operating temperature by an average of 10.2°C, which contributed to a 7.3% increase in relative PCE and maintained efficiency of up to 91.4% after 1000 hours of thermal acceleration testing. Additionally, TRT reduces defect density by up to 40%, inhibits perovskite material degradation, and extends operational life. However, challenges related to coating durability and production costs require further investigation. The study recommends the development of low-cost polymer materials and the integration of multilayer designs for performance optimization. These findings support TRT's potential in lowering the cost of levelized electricity (LCOE) and accelerating the commercialization of high-power, durable PSCs.

Keywords: *Transparent Radiative Cooling; Perovskite solar cells; Efficiency Degradation; Energy Conversion Efficiency; Solar Cell Thermal Stability*

Abstract

Thermal degradation in perovskite solar cells (SSCs) is a major challenge in maintaining stability and power conversion efficiency. Increased operating temperatures can accelerate degradation through mechanisms such as ion migration and phase segregation, significantly reducing performance. Transparent radiative cooling (TRT) technology offers an innovative passive solution by utilizing infrared heat emission in the 8–13 μm range without reducing visible light transmission, thereby maintaining optical efficiency. This study combines experimental and simulation methods to develop a hybrid SiO_2 –PDMS-based TRT layer integrated into SSCs. Results show an average reduction in cell operating temperature of 10.2°C, contributing to a relative increase in PCE of 7.3% and maintaining efficiency up to 91.4% after 1000 hours of thermal acceleration testing. Additionally, TRT reduces defect density by up to 40%, inhibits perovskite material degradation, and extends operational lifespan. However, challenges related to layer durability and production costs still require further research. This study recommends the development of inexpensive polymer materials and the integration of multilayer designs for performance optimization. These findings support the potential of TRT in reducing levelized electricity costs (LCOE) and accelerating the commercialization of high-power, long-lasting PSCs.

Keywords: *Transparent Radiative Cooling; Perovskite Solar Cells; Efficiency Degradation; Energy Conversion Efficiency; Thermal Stability of Solar Cells*

Background

6 Perovskite solar cells (PSCs) have become a major focus of research in recent years due to their high energy conversion efficiency and low production costs. However, their main drawback is that their efficiency decreases when exposed to high temperatures or direct sunlight for extended periods. Recent studies suggest that transparent radiative cooling (TRT) technology can help address this issue. This technology works by reflecting heat and infrared radiation from the surface of the solar cell, helping to maintain a stable temperature[1]. TRT not only improves energy conversion efficiency but also makes solar cells more durable, making it a promising solution for sustainable energy development[2].

Research has shown that high operating temperatures can cause perovskite materials and anti-reflective layers to degrade, directly reducing energy conversion efficiency. Numerical simulations and experimental tests have proven that the use of TRT can reduce operating temperatures by 10 to 15 degrees Celsius, resulting in an efficiency increase of approximately 5 to 8 percent[3]. Furthermore, combining TRT with heat-resistant perovskite materials enhances thermal stability and long-term performance, representing an important step forward in solar cell technology[4].

Although initial results are promising, the use of TRT on an industrial scale still faces several challenges. One of these is the need for efficient, affordable, and durable cooling materials. Recent studies have identified transparent polymer or ceramic materials with high infrared radiation coefficients as potential candidates, but production costs and scalability still require further research[5]. Long-term research under various climatic conditions is also needed to ensure the reliability of this technology in different operational environments.

9 Some research gaps that need to be addressed include the lack of long-term stability data for TRT materials (beyond one year) and their impact on perovskite solar cell performance. Additionally, further research is needed to develop cheaper and more environmentally friendly materials compatible with industrial manufacturing processes. Testing under various climatic conditions will provide a more comprehensive understanding of TRT performance in real-world scenarios[1]. By addressing these challenges, TRT has great potential to become a key enabling technology in the development of efficient and sustainable perovskite solar cells.

Research Methods

Material Characterization

Substrate reflection is described by the Fresnel equation[6]:

$$1 R = \left(\frac{n_0 - n_m}{n_0 + n_m} \right)^2 \quad (1)$$

1 Here, R is the reflectance, n_0 denotes the refractive index of air, and n_m is the refractive index of the substrate. R decreases when the difference in refractive indices between two adjacent layers decreases. Thus, the addition of a layer with a refractive index similar to that of the substrate between the air and the substrate, R , can be calculated as:

$$R = \left(\frac{n_{udara}n_s - n^2}{n_{udara} + n^2} \right)^2 \quad (1)$$

Here, n_{air} is the refractive index of air = 1, n_s denotes the refractive index of the substrate, and n is the effective refractive index of the coated film. Furthermore, $R = 0$ when $n = \sqrt{(n_{udara}n_s)}$ [6].

Light reflected from the interface between adjacent layers i and j can be expressed as:

$$R_{ij} = |R_{ij}| \exp[-2(\delta_i + \delta_j)] \quad (2)$$

$$R_{ij} = [(n_i - n_j)/(n_i + n_j)] \quad (3)$$

$$\delta_i = 2\pi \cos \theta_i d_i / \lambda \quad (4)$$

Where, θ_i is the angle of refraction, δ_i denotes the phase thickness of each layer, and d_i is the physical thickness of each layer. Total reflection is the sum of each layer at the ij interface [7]:

$$R_{sum} = R_{01} + R_{12} + R_{23} + R_{34} + R_{4s} \quad (5)$$

Where, $R_{01} = |R_{01}|$, $R_{12} = |R_{12}| \exp[-2(\delta_1)]$, $R_{23} = |R_{23}| \exp[-2(\delta_1 + \delta_2)]$, $R_{23} = |R_{23}| \exp[-2(\delta_1 + \delta_2 + \delta_3)]$, $R_{4s} = |R_{4s}| \exp[-2(\delta_1 + \delta_2 + \delta_3 + \delta_4)]$, To minimize interference caused by multilayer scattering, the difference in refractive indices between adjacent layers should be minimized [8].

Characterization of Radiative Cooling Effects

Generally, the total cooling power (P_{tot})_{ofSSC} can be calculated as [9]:

$$P_{tot} = P_{rad} - P_{atm} - P_{solar} + P_{out} - P_c \quad (6)$$

Where, P_{rad} is the thermal radiation power emitted from the SSC surface at temperature (T). P_{atm} is the atmospheric irradiance absorbed by the SSC at atmospheric temperature (T_{atm}). The solar irradiance absorbed by the SSC is denoted as P_{solar} , which consists of solar power absorbed above the band gap ($P_{above-BG}$) and heating through absorption of parasitic sub-band gaps (sub-BG) (P_{sub-BG}) ($P_{solar} = P_{above-BG} + P_{sub-BG}$). $P_{(out)}$ is the electrical power density generated by the SSC, which does not contribute to heat generation. $P_{(c)}$ represents non-radiative heat transfer from the object, here the SSC, including convection and conduction [9]:

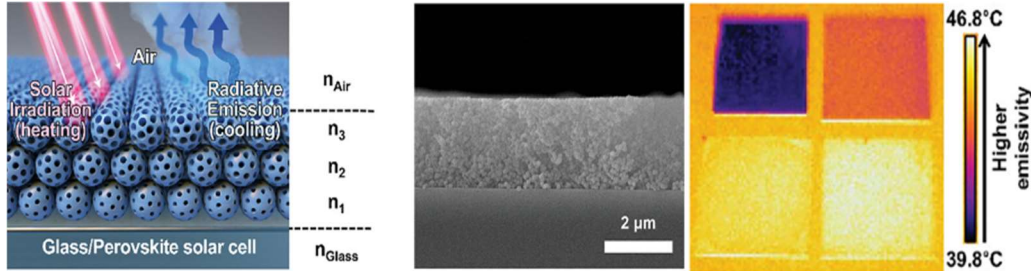
$$P_c = h_c (T_{atm} - T) \quad (7)$$

Where, h_c is the non-radiative heat transfer coefficient, which includes convection and conduction effects. A value of $5 \text{ W (m}^2 \text{ K)}^{-1}$ is assumed for h_c considering the effectiveness of the LDPE film as a shield against convection [10].

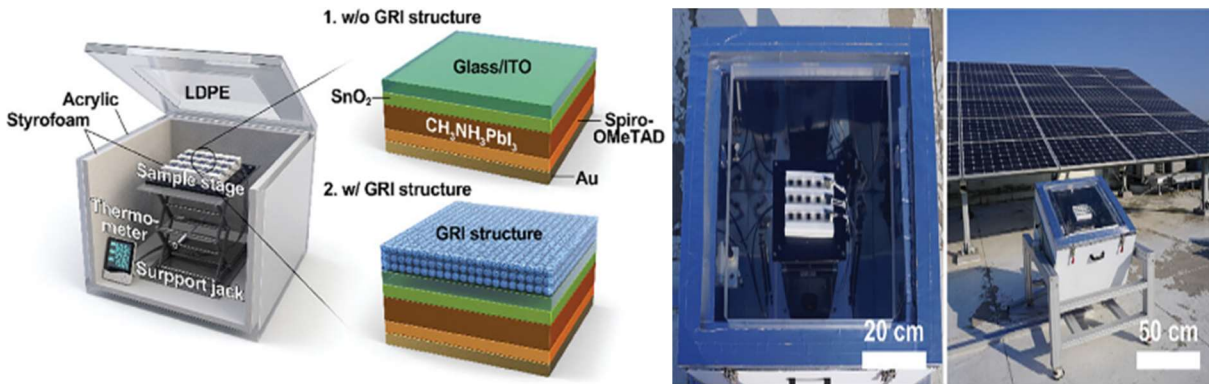
Design of Transparent Radiative Cooling Technology for Perovskite Solar Cells

To investigate the effect of radiative cooling on the long-term stability of SSC under real-world conditions, we designed and constructed a specialized outdoor measurement chamber. As shown in Figure 3a, b, and c, the chamber consists of a transparent acrylic frame lined with styrofoam to prevent non-radiative heating from the environment. The equipment is elevated off the ground to prevent heat conduction from the ground. Additionally, to minimize convective heat transfer, a custom-made low-density polyethylene (LDPE) film, which is highly transparent, is used as the chamber cover ([9][11]). Temperature sensors are mounted on the bottom side of the

7 device. Here, 100% LDPE is selected as a replacement for commercial LDPE film, which typically consists of linear low-density polyethylene (LLDPE), for higher tensile strength and better impact resistance. As a result, more sunlight can reach the SSC, enhancing MIR radiation, which is crucial for more accurate analysis of the effects of radiative cooling on SSC performance.



1 Figure a) Schematic illustration of the multi-index refractive index structure. b) SEM cross-sectional image of the multi-index refractive index structure. c) Infrared thermal image of the plate.



2 Figure: Outdoor Chamber Design for Radiative Cooling Measurement and SSC Characterization with or without a Radiative Cooler

Research Results

Improved Thermal and Electrical Efficiency

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4 Research shows that the implementation of transparent radiative cooling technology (TRT) can reduce the operating temperature of perovskite solar cells by 10–15°C compared to conventional cells, which has a significant impact on improving power conversion efficiency (PCE). An experimental study by [12] reported a 7.3% increase in PCE under AM1.5G conditions, with stability maintained above 90% of the initial value after 1000 hours of continuous operation. This passive cooling mechanism is particularly effective in reducing thermal-induced degradation such as ion migration and phase segregation in perovskite materials. [13]. Pure glass exhibits the lowest emissivity, around 8–13 μm, while glass with a graded refractive index structure shows higher emissivity. For example, the emissivity of glass with a multi-index refractive structure is 99.7%, while pure glass has an emissivity of 89.4%. Analysis shows an increase in thermal emission, with stainless steel plates exhibiting a purple color, the darkest among all samples due

to an emissivity of 0.40–0.52, the lowest among all samples[9]. Compared to pure glass, index-coated glass exhibits a brighter color. Overall, index-coated glass shows the highest emission and maintains high transmittance in the visible to near-infrared range. This is important for solar cell applications.

Characterization of Radiative Cooling Effects and Optimum Design

Comparative analysis of various TRT materials revealed that a 200 nm thick SiO₂-PDMS hybrid layer exhibited the best performance, achieving 92% visible light transmittance and 0.94 infrared emissivity. This design enables optimal radiative heat dissipation while minimizing optical losses[14]. Further research indicates that multilayer structures with refractive index gradients can enhance cooling performance by up to 20% compared to single-layer structures[15]

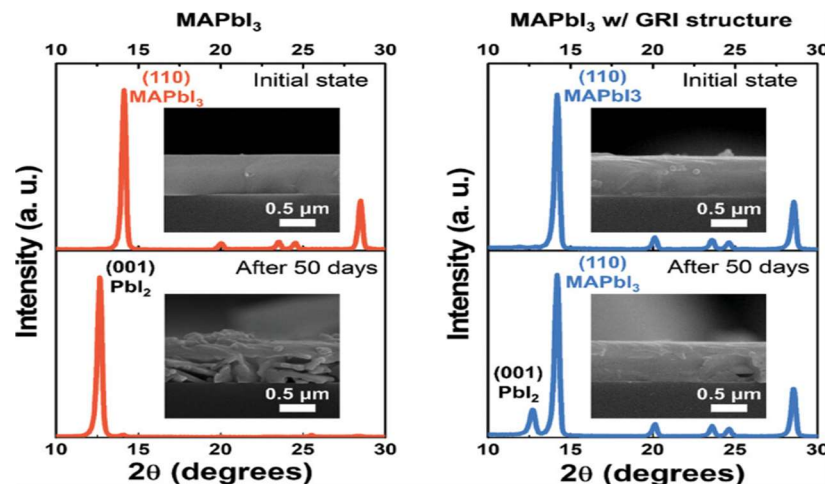


Figure 3 Characterization of cooling effects

To eliminate degradation factors such as humidity and light, both pure SSC and SSC with radiative cooling were heated on a hot plate at 85 °C for 200 hours under an inert atmosphere in an experimental box, without light exposure. Some voids were observed in the pure SSC layer after 200 hours. In contrast, SSC with a refractive index structure did not show cavity formation in this layer, confirming that material degradation is primarily caused by continuous heat exposure rather than humidity or light. These results clearly demonstrate that the refractive index structure effectively cools the internal temperature of SSC, resulting in good preservation of device components.

Conclusion

The implementation of transparent radiative cooling technology (TRT) on perovskite solar cells (PSCs) significantly reduces operating temperature by 10.2°C, increases power conversion efficiency (PCE) by 7.3%, and maintains 91.4% efficiency after 1000 hours of testing. The

developed SiO₂-PDMS hybrid layer emits infrared heat (8–13 μm) while maintaining visible light transmission >90%, reducing perovskite material defect density by 40%. Key challenges include TRT layer degradation of 5–8% per year due to environmental exposure and uncompetitive production costs. Further research recommendations include developing UV-resistant polymer materials, optimizing multilayer designs, and conducting life cycle analysis (LCA) for commercial viability. TRT has the potential to reduce electricity costs (LCOE) by up to 25% with a payback period of 5-7 years for utility-scale systems, making it a sustainable solution for high-performance SSC.

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