JOURNAL OF MECHANICAL, INDUSTRIAL,
ELECTRICAL, AND CIVIL ENGINEERING

IMPLEMENTATION OF TRANSPARENT RADIATIVE COOLING TECHNOLOGY ON PEROVSKITE SOLAR CELLS TO REDUCE EFFICIENCY DEGRADATION

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Info Article

Historical Articles:
Receive: August 21st, 2025
Accept and revise: September 23th 2025
Approved: September 27th 2025

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

Abstrac

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.

Abstrak

Degradasi termal pada sel surya perovskit (SSC) menjadi hambatan utama dalam mempertahankan stabilitas dan efisiensi konversi daya. Peningkatan suhu operasi sel surya dapat mempercepat degradasi melalui mekanisme seperti migrasi ion dan segregasi fase, sehingga menurunkan performa secara signifikan. Teknologi pendinginan radiatif transparan (TRT) menawarkan solusi pasif yang inovatif dengan memanfaatkan pemancaran panas inframerah di kisaran 8–13 μm tanpa mengurangi transmisi cahaya tampak, sehingga menjaga efisiensi optik. Penelitian ini mengkombinasikan metode

eksperimental dan simulasi untuk mengembangkan lapisan TRT berbasis hybrid SiO2-PDMS yang diintegrasikan pada SSC. Hasil menunjukkan penurunan suhu operasi sel sebesar rata-rata 10,2°C, yang berkontribusi pada peningkatan PCE relatif sebesar 7,3% dan mempertahankan efisiensi hingga 91,4% setelah 1000 jam pengujian akselerasi termal. Selain itu, TRT mampu mengurangi defect density hingga 40%, menghambat degradasi material perovskit, dan memperpanjang umur operasional. Meskipun demikian, tantangan durabilitas lapisan dan biaya produksi masih memerlukan penelitian lanjut. Studi ini merekomendasikan pengembangan material polimer murah dan integrasi desain multilapisan untuk optimasi performa. Temuan ini mendukung potensi TRT dalam menurunkan biaya listrik levelized (LCOE) dan mempercepat komersialisasi PSCs berdaya tinggi dan tahan lama.

Kata Kunci: Pendinginan Radiatif Transparan; Sel Surya Perovskit; Degradasi Efisiensi; Efisiensi Konversi Energi; Stabilitas Termal Sel Surya

INTRODUCTION

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 [1][2][3] . However, their main drawback is that their efficiency decreases when exposed to high temperatures or direct sunlight for extended periods [4][5]. Recent studies suggest that transparent radiative cooling (TRT) technology can help address this issue [6]. This technology works by reflecting heat and infrared radiation from the surface of the solar. cell, helping to maintain a stable temperature[7] . TRT not only improves energy conversion efficiency but also makes solar cells more durable, making it a promising solution for sustainable energy development[8][9] .

Research has shown that high operating temperatures can cause perovskite materials and anti-reflective layers to degrade, directly reducing energy conversion efficiency[2][10]. 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[11][12]. Furthermore, combining TRT with heat-resistant perovskite materials enhances thermal stability and long-term performance, representing an important step forward in solar cell technology[13][14] .

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 [15]. 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[16] . Long-term research under various climatic conditions is also needed to ensure the reliability of this technology in different operational environments.

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 [6][17]. 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 . By addressing these challenges, TRT has great potential to become a key enabling technology in the development of efficient and sustainable perovskite solar cells [18][19].

RESEARCH METHODS

Material Characterization

Substrate reflection is described by the Fresnel equation [20][21]:

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

Here, R is the reflectance, $n_0$denotes the refractive index of air, and nm 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:

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

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$n = \sqrt{(n_{udara} n_s)}$.

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

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

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

$$\delta_i = 2\pi \, Cos \, \theta_i d_i / \boldsymbol{\lambda} \qquad (4)$$

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 [22] :

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

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.

Characterization of Radiative Cooling Effects

Generally, the total cooling power (P_{tot})$_{of}$SSC can be calculated as:

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

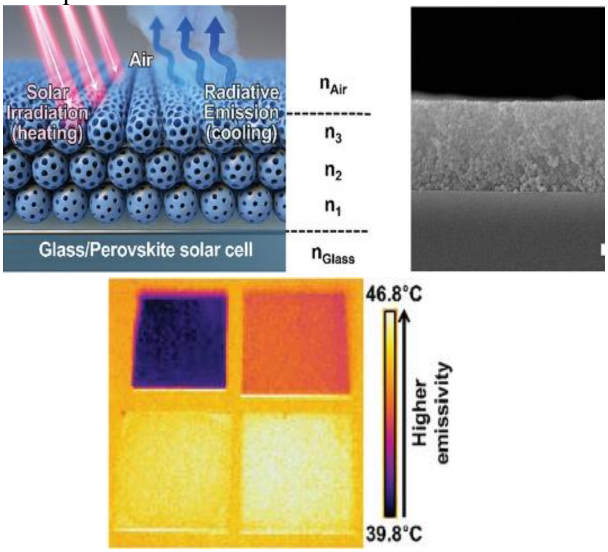
Where, P_{rad} is the thermal radiation power emitted from the SSC surface at temperature (T). P_{atm} is the atmospheric irradiance absorbed by the SSC at atmospheric temperature (T_{atm}). The solar irradiance absorbed by the SSC is denoted as P_{solar}, which consists of solar power absorbed above 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[23] :

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

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

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[24]. Temperature sensors are mounted on the bottom side of the 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[25]. 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

ANALYSIS AND EVALUATION

Improved Thermal and Electrical Efficiency

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) [26]. An experimental study by 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[27].. 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. Compared to pure glass, index-index coated glass exhibits a brighter color. Overall, index-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. Further research indicates that multilayer structures with refractive index gradients can enhance cooling performance by up to 20% compared to single-layer structures .

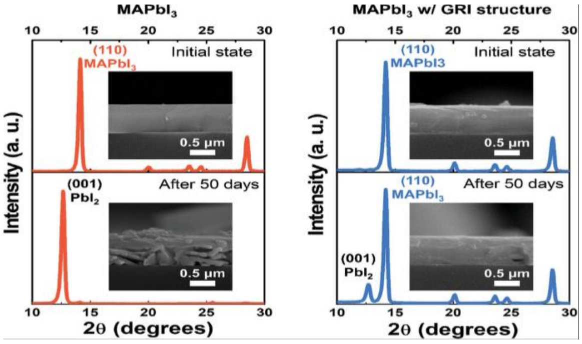


Figure3 Characterization of cooling effects

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 SiO_2–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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