Self-Adaptive Radiative Cooler for Maximizing Year-Round Energy Saving of households

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Abstract: We present an approach to household thermal regulation and energy saving from an all-season perspective by developing a mechanically flexible and energy-free coating that automatically adapts its thermal emittance to different ambient temperatures.

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1. Introduction

Using sky as a natural heat sink for passive radiative cooling of households roofs has been extensively investigated for decades. Past experimental works focused on using static, cooling-optimized material properties to maximize the radiative cooling power of roof coating in hot daytime [1, 2]. However, in cold night or winter times, especially in climates where heating dominates energy consumption, the resultant overcooling exacerbates the heating cost and further increases the total energy consumption in thermal regulation. While this issue is well-acknowledged by the community and mitigation of overcooling is a timely demand [3], most existing efforts are either purely theoretical, require external activation [4], or involve mechanically moving parts [5, 6]. Thus, practical household applications dealing with over-cooling challenges are limited.

Here we present a different, holistic approach to thermal regulation by designing and fabricating a mechanically flexible and energy-free temperature-adaptive radiative coating (TARC) to minimize total energy consumption through the entire year [7].

2. Experiments and simulations

The TARC is based on the metal-insulator transition (MIT) of W-doped vanadium oxide ($W_xV_{1-x}O_2$), combined with photonic amplification by a metamaterials design [8]. The transition temperature (T_{MIT}) is tailored to the desired household temperature of ~22 ºC by setting the tungsten composition x to 1.5%. We embedded a two-dimensional array of thin $W_xV_{1-x}O_2$ blocks on a BaF2 dielectric layer that sits on top of an Ag film (Fig. 1b). The whole structure is supported by a layer of cellophane tape. In the insulating (I) state of $W_xV_{1-x}O_2$ at $T<T_{MIT}$, $W_xV_{1-x}O_2$ is largely transparent to the infrared radiation in the 8-13 μm sky spectral window, so the sky-window infrared absorptance is minimized. In contrast, metallic $W_xV_{1-x}O_2$ is highly absorptive in the sky-window when $T>T_{MIT}$, which is further amplified by the photonic resonance with adjacent $W_xV_{1-x}O_2$ blocks as well as with the bottom Ag layer via the 1/4-wavelength cavity. According to Kirchhoff's law of radiation [9], the sky-window emittance equals the sky-window absorptance. Consequently, the TARC serves as a passive radiative cooler exclusively at high temperatures, leaving the system in the solar-heating or heat-retaining mode at low temperatures (Fig. 1a).

Fig. 1c shows spectral properties of the TARC, measured by a UV-visible-NIR spectrometer and Fourier transform infrared spectroscopy (FTIR). The integrated sky-window emittance ε_w is 0.20 in the I state and 0.90 in the M state. The solar absorption A of the TARC is also optimized to 0.25 for all-season energy saving in major US cities. We performed extensive numerical simulations to analyze the household energy saving performance of the TARC for major US cities from an all-season perspective. We used past simulations of cool-roof energy savings to predict potential space conditioning source energy saving (SCSES) per unit roof area attainable by using the TARC in place of roofing materials that have static values of solar absorptance and thermal emittance. Fig. 1d is a minimal SCSES map for cities representing all the 15 US climate zones, which shows that TARC provides clear, positive annual SCSES relative to existing roof coating materials in most major cities. For cities with significant seasonal variations, the TARC can yield a significant cut in annual source energy consumption for a typical single-family home.

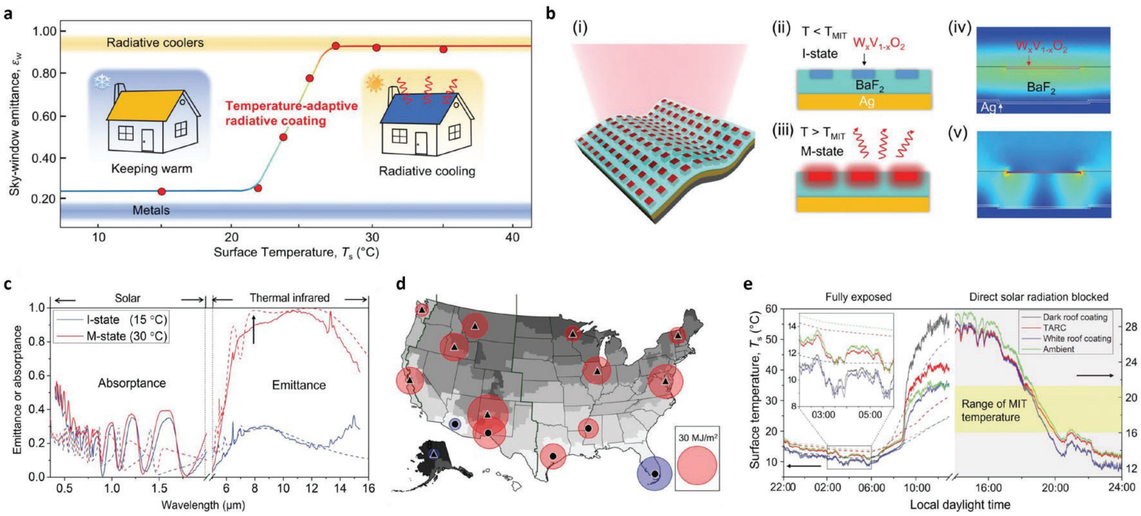

Fig. 1. **a**. Basic properties of the TARC in sky-window emittance modulation and schematics of temperature regulation when used as a household roof coating. **b**. Schematic of the structure (i), material composition and working mechanism (ii, iii) of the TARC. (iv, v) show the simulated distribution of electric-field intensity below and above the transition temperature, respectively. **c**. Solar spectral absorptance and thermal spectral emittance of the TARC at a low temperature and a high temperature. **d.** $SCSES_{min}$ of the TARC compared with other existing roof-coating materials for cities in the United States. Red and blue circles indicate positive and negative $SCSES_{min}$ values, respectively. The values are scaled to the area of circles. **e.** Surface temperatures of the TARC, a commercial dark roof coating (A = 0.70, ε_w = 0.90), and a commercial white roof coating (A = 0.15, ε_w = 0.90) in an open-space outdoor environment recorded over a day-night cycle.

We demonstrated actual outdoor performance of the TARC by recording the surface temperatures (T_s) of the TARC, a commercial dark roof coating product and a commercial white cool-roof coating product over 24 hours on a cloudless summer day on a rooftop in Berkeley, California, with a careful design of the measurement system to minimize artifacts (Fig. 1e). The TARC regulates the roof temperature closer to ~22 ^oC than the cool-roof coating in most conditions. From an all-year-round perspective, the TARC demonstrates superiority compared to regular roof coatings in terms of source energy saving.

We are now working on improving the scalability and lowering the cost by developing a mass production method, as well as using alternative materials for the dielectric layer, the metal mirror and the mechanical supporting layer. Our preliminary results support broad applications of the TARC technology.

3. Conclusion

In conclusion, we developed a mechanically flexible, energy-free TARC for smart regulation of household temperatures. Our system features a thermally driven metal-insulator transition in cooperation with photonic resonance, and experimentally demonstrates self-switching in sky-window thermal emittance. Simulations show that our TARC has great potential in cutting energy consumption for households. Moreover, the TARC can be applied for other advanced applications such as spacecraft and consumer electronics thermal regulation.

4. References

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