ACS NANO

www.acsnano.org

PERSPECTIVE

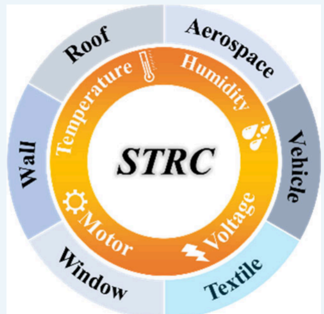
Switchable and Tunable Radiative Cooling: Mechanisms, Applications, and Perspectives

Xuzhe Zhao,[#] Jiachen Li,[#] Kaichen Dong,* and Junqiao Wu*

Cite This: *ACS Nano* 2024, 18, 18118–18128

Read Online

ABSTRACT: **The cost of annual energy consumption in buildings in the United States exceeds 430 billion dollars (*Science* 2019,** *364* (6442), 760–763), of which about 48% is used for space thermal management (https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019), revealing the urgent need for efficient thermal management of buildings and dwellings. Radiative cooling technologies, combined with the booming photonic and micro-fabrication technologies (*Nature* **2014**, *515* (7528), 540–544), enable energy-free cooling by radiative heat transfer to outer space through the atmospheric transparent window (*Nat. Commun.* **2024**, *15* (1), 815). To pursue all-season energy savings in climates with large temperature variations, switchable and tunable radiative coolers (STRC) have emerged in recent years and quickly gained broad attention. This Perspective introduces the existing STRC technologies and analyzes their benefits and challenges in future large-scale applications, suggesting ways for the development of future STRCs.



KEYWORDS: *radiative cooling, all-season energy savings, switchable and tunable radiative coolers (STRC)*

INTRODUCTION

Temperature regulation of buildings and dwellings has played a crucial role throughout the human history.[5] Technological advances in recent centuries have brought in more efficient and convenient thermal regulation approaches, such as electrical heaters,[6] gas heating,[7] and air conditioners.[8] However, these energy-consuming devices are responsible for the over-consumption of fossil fuels as well as the resultant greenhouse gas emissions.[9] According to the data by the U.S. Energy Information Administration, more than 51% of annual household site energy consumption goes to space heating and cooling.[10] Therefore, the development and deployment of eco-friendly thermal regulation technologies have become an urgent demand for our society.[11]

Among these technologies, radiative cooling is already mature enough with commercially available products and a booming global market.[1,3,12] The basis of radiative cooling technology lies in the fact that the cold outer space (~3 K) acts as a vast heat sink for the radiative cooling of terrestrial objects.[13] Radiative coolers feature materials with nearly ideal thermal emissivity for maximal outgoing thermal radiation to the cold outer space through the mid-infrared (MIR) atmospheric transparency window (8–13 μm).[14] Meanwhile, solar reflectance by the radiative coolers is maximized for minimal solar heating.[3,15]

The photonic principles and heat exchange processes in radiative coolers are illustrated in Figure 1. Taking the daytime

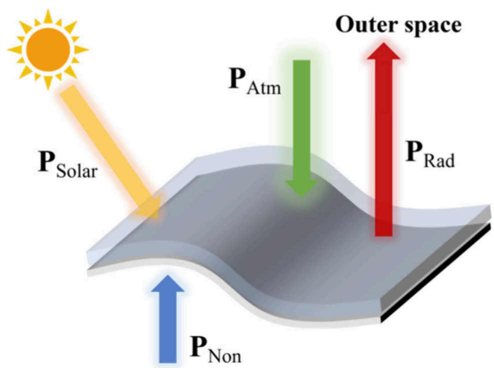
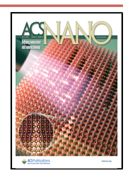


Figure 1. Schematic diagram of the daytime thermal equilibrium for radiative coolers.

as an example, the thermal equilibrium equation for the radiative cooler is as follows,

$$P_C = P_{Rad} - P_{Atm} - P_{Solar} - P_{Non} \quad (1)$$

Received: May 5, 2024
Revised: June 18, 2024
Accepted: June 18, 2024
Published: July 2, 2024



https://doi.org/10.1021/acsnano.4c05929
ACS Nano 2024, 18, 18118–18128

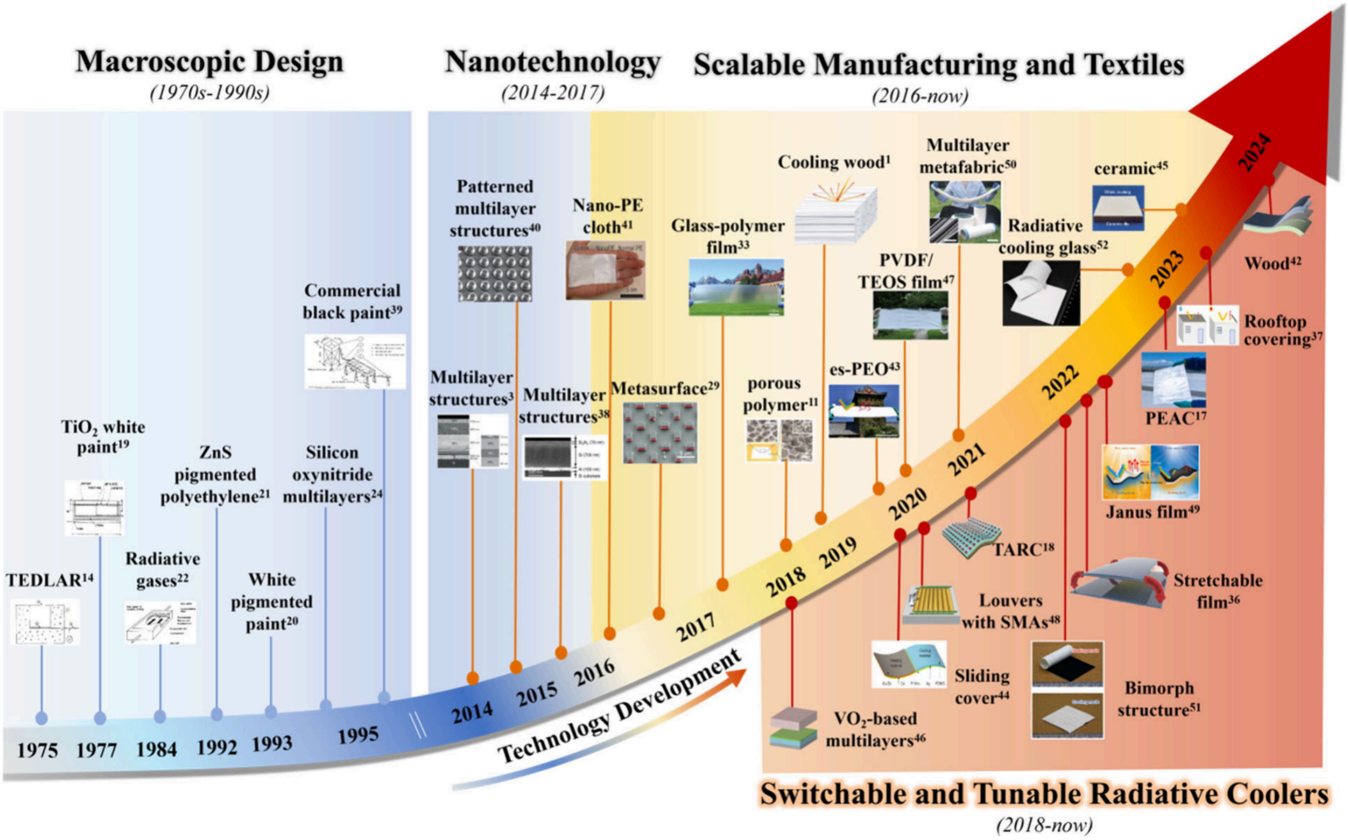


Figure 2. Timeline showing the development of radiative cooling technologies of four generations: macroscopic design, nanotechnology, scalable manufacturing and textiles, and switchable and tunable radiative coolers. Reprinted with permission from ref 1. Copyright [2019] [American Association for the Advancement of Science]. Reprinted with permission from ref 3. Copyright [2014] [Springer Nature]. Reprinted with permission from ref 11. Copyright [2018] [American Association for the Advancement of Science]. Reprinted with permission from ref 14. Copyright [1975] [Elsevier]. Reprinted with permission from ref 17. Copyright [2023] [Elsevier]. Reprinted with permission from ref 18. Copyright [2021] [American Association for the Advancement of Science]. Reprinted with permission from ref 19. Copyright [1978] [Elsevier]. Reprinted with permission from ref 20. Copyright [1993] [Elsevier]. Reprinted with permission from ref 21. Copyright [1992] [Elsevier]. Reprinted with permission from ref 22. Copyright [1984] [Optica Publishing Group]. Reprinted with permission from ref 24. Copyright [1996] [Elsevier]. Reprinted with permission from ref 29. Copyright [2017] [Wiley-VCH]. Reprinted with permission from ref 33. Copyright [2017] [American Association for the Advancement of Science]. Reprinted with permission from ref 36. Copyright [2022] [Elsevier]. Reprinted with permission from ref 37. Copyright [2023] [Elsevier]. Reprinted with permission from ref 38. Copyright [2016] [Springer Nature]. Reprinted with permission from ref 39. Copyright [1995] [Elsevier]. Reprinted with permission from ref 40. Copyright [2015] [Wiley-VCH]. Reprinted with permission from ref 41. Copyright [2016] [American Association for the Advancement of Science]. Reprinted with permission from ref 42. Copyright [2024] [American Chemical Society]. Reprinted with permission from ref 43. Copyright [2020] [Springer Nature]. Reprinted with permission from ref 44. Copyright [2020] [Springer Nature]. Reprinted with permission from ref 45. Copyright [2023] [American Association for the Advancement of Science]. Reprinted with permission from ref 46. Copyright [2018] [Optica Publishing Group]. Reprinted with permission from ref 47. Copyright [2019] [Wiley-VCH]. Reprinted with permission from ref 48. Copyright [2020] [American Chemical Society]. Reprinted with permission from ref 49. Copyright [2022] [Wiley-VCH]. Reprinted with permission from ref 50. Copyright [2021] [American Association for the Advancement of Science]. Reprinted with permission from ref 51. Copyright [2022] [Springer Nature]. Reprinted with permission from ref 52. Copyright [2023] [American Association for the Advancement of Science].

where P_C represents the net radiative cooling power of the cooler, P_{Rad} represents the thermal emission power of the cooler, P_{Atm} represents the absorbed atmospheric radiation, P_{Solar} represents the power of the solar radiation absorbed by the cooler, and P_{Non} represents all nonradiative heat exchanges.

The thermal emission power of the cooler (P_{Rad}) can be calculated by

$$P_{rad}(T) = A_{emitter} \int d\Omega \cos\theta \int_0^{\infty} I_{BB}(T, \lambda)\varepsilon(\lambda, \theta)\, d\lambda \tag{2}$$

where $A_{emitter}$ represents the surface area of the cooler, I_{BB} (T,λ) denotes the thermal radiation intensity of an ideal blackbody at a given temperature and wavelength, and $\varepsilon(\lambda,\theta)$ refers to the emissivity that is based on the wavelength and angle.

Through the analysis of power flow in a cooler under thermal equilibrium, it is imperative to enhance P_{Rad} to realize a high radiative cooling power. This requires the cooler to have a high emissivity in the 8−13 μm wavelength range because this atmospheric transparency window overlaps with the peak wavelength of blackbody radiation curve at 300 K. Concurrently, it is essential to diminish P_{Solar} and P_{Atm}. The former demands that the cooler possesses high reflectance in the solar wavelength range, while the latter necessitates a reduction in the cooler's emissivity beyond the atmospheric transparency window to mitigate the impact of atmospheric radiation.

https://doi.org/10.1021/acsnano.4c05929
ACS Nano 2024, 18, 18118−18128

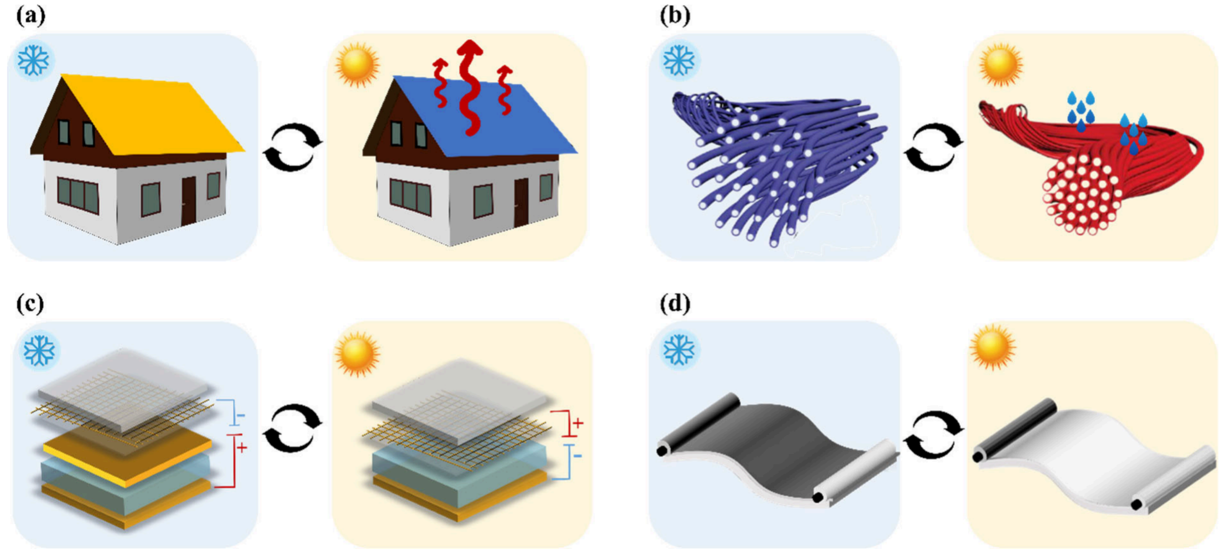


Figure 3. Schematic diagram of the four main regulation methods used in STRC. (a) Temperature-adaptive. (b) Humidity-adaptive. (c) Voltage-controlled. (d) Motor-controlled. Reprinted with permission from ref 18. Copyright [2021] [American Association for the Advancement of Science]. Reprinted with permission from ref 44. Copyright [2020] [Springer Nature]. Reprinted with permission from ref 55. Copyright [2019] [American Association for the Advancement of Science]. Reprinted with permission from ref 66. Copyright [2023] [Springer Nature].

However, these static radiative coolers can only cool objects and continue to radiative cool at cold nights or winter times, hence failing to satisfy the heat-retaining requirements in those conditions.[16] In recent years, efforts to meet the requirements of all-season passive thermal regulation have led to the invention of STRC technologies. It is worth noting that Li et al.[17] and Tang et al.[18] have conducted numerical simulations of STRCs in 15 climate zones of the United States, respectively, finding that for most climate zones, STRCs offer higher energy savings compared to static radiative cooling materials, especially in regions with significant temperature variations. However, for areas with consistently high temperatures, the energy savings of STRCs are almost comparable to those of static radiative cooling materials.

In this Perspective, we briefly summarize the mechanisms of up-to-date STRC technologies. We analyze their common technical challenges, which hinder wide commercialization and real-world deployment, and we discuss future research directions in this field. This Perspective analyzes the mechanism, benefits, challenges, and future directions of STRC that could potentially help advance the sustainability of our society and ease challenges from climate change.

HISTORY

The development of radiative cooling technologies can be divided into four stages, as shown in Figure 2.

Tremendous efforts have been made from 1970s to 1990s with experimental realization of various radiative cooling materials, including (pigmented) paints,[19,20] (pigmented) polymers,[21] radiative gases,[22] etc. Although subambient cooling could be achieved,[23] the solar reflectivity and thermal emissivity of those radiative coolers are far below unity[24] and thus their radiative cooling performance is far from satisfactory.

An revolutionary improvement of radiative cooling technologies started from 2014 which can be considered as the "renaissance" of radiative coolers.[3] In only 1−2 years, both the solar reflectivity and thermal emissivity of nanostructured radiative coolers quickly approached unity.[25] Various designs of radiative coolers with nearly perfect cooling performance were theoretically proposed and/or experimentally implemented, such as multilayer nanostructures,[26−28] metamaterials and metasurfaces.[29−34] The rapid and successful development of radiative cooling technology during that time "was standing on the shoulders of giants": advances in nanophotonics, micro/nanofabrication, and materials sciences. Nevertheless, these high-performance implementations were unable to be applied in real scenarios because they mostly rely on lithography or thin-film deposition techniques with requirements of carefully controlled micro/nanosized features.[35]

As the full cooling potential of terrestrial radiative coolers approaches saturation, research was then focused on scalable manufacturing of radiative coolers that are lithography-free with lower fabrication costs.[43] For example, Zhai et al. reported a mass-manufactured glass−polymer film with 93 W/m^2 cooling power under direct sunshine.[33] Later on, scalable radiative cooling textiles for clothes and tents were invented for the cooling of human bodies in the summer[53−55] with some success in commercialization.[41] It is worth noting that promoting the trend toward mass-production of radiative coolers would require low-cost nanostructuration approaches.

Though conventional radiative cooling technologies keep buildings and human bodies cool on hot days, the static radiative cooling power cannot be turned off, leading to undesirable "overcooling" at low temperatures,[56] thus exacerbating the heating power consumption as heating load penalties in those conditions.[57,58] To tackle this challenge, STRCs were intensively investigated since 2018.[46] Initial attempts were mostly theoretical[46,59,60] or power-consuming (active),[61,62] and several energy-free (passive) STRCs were experimentally implemented in the lab without field tests.[63,64] In 2021, Tang et al. and Wang et al. demonstrated energy-free, flexible, temperature-adaptive radiative coatings with field tests and presented year-round energy-saving simulations,[18,65] which quantitatively showed that, in areas with large daily or seasonal temperature variations, smart thermal regulation based on STRCs is preferred due to higher year-round energy savings.

https://doi.org/10.1021/acsnano.4c05929
ACS Nano 2024, 18, 18118−18128

MECHANISMS

Depending on the specific physical mechanisms and principles, STRCs can be classified into several categories (Figure 3): temperature-adaptive, humidity-adaptive, voltage-controlled, and motor-controlled. These coolers are applicable in diverse domains, encompassing roofs, windows, walls, and advanced textiles as well in the fields of electric vehicles and aerospace.

Temperature-Adaptive STRCs. Temperature-adaptive STRCs with temperature-responsive materials can dynamically adjust their infrared (IR) emissivity according to temperature changes, including dual-mode bimorph structures,[51,67] phase-change materials (PCM),[23] and shape memory alloys (SMAs).[48,51] Figure 3(a) illustrates the regulation method for temperature-adaptive STRCs. When used as a roofing material, at low temperatures, the emissivity of the temperature-adaptive STRC in the MIR band (especially the atmospheric transparent window) is rather low to effectively keep the building warm. When the temperature rises, it automatically switches to a high emissivity mode due to the dramatic refractive index change, thereby achieving strong radiative cooling and maintaining a cool indoor environment.

Dual-mode bimorph structures rely on stress changes in an additional temperature-responsive layer to achieve automatic switching between radiative cooling in high-temperature environments and solar heating in low-temperature environments.[51,67] Though the complicated design may not be conducive to large-scale production, the bimorph structure enriches the functionality of temperature-adaptive STRCs with excellent thermoregulation performance. On the other hand, PCMs (including VO_2,[68] GST,[69−71] and perovskites[72,73]) are more widely used in temperature-adaptive STRCs for their temperature-sensitive optical properties in the IR range. For example, VO_2 undergoes temperature-driven and reversible metal−insulator phase change upon heating across its transition temperature with a drastic contrast in IR refractive index.[74] Typically, photonic structures such as Fabry-Pérot cavities,[18,59] metasurfaces,[64] and optical antennas[17] are used to amplify the phase-transition properties of VO_2, resulting in various structures of VO_2-based STRCs. In addition, to enable VO_2-based STRC to undergo phase transitions at room temperatures, a variety of methods to reduce the phase-transition temperature of VO_2 could be adopted, such as metal doping,[75] ultraviolet irradiation,[76] and noncatalytic hydrogenation.[77]

Besides that, STRCs based on SMA actuators are also temperature-adaptive.[48] Xia et al. used a temperature shape memory spring (TSMS) to drive the opening angle of metal plates for adaptive radiation.[48]

Humidity-Adaptive STRCs. Humidity-adaptive, or water-absorptive is another way to achieve passive STRCs. Such radiative coolers could find applications as smart fabrics for personal thermal management as the human body secretes sweat upon temperature rises.[55,78] Figure 3(b) demonstrates the regulation method of humidity-adaptive STRCs for personal thermal management. At cold temperatures, perspiration is minimal and the STRC is in an off state. The distance between humidity-sensitive STRC fibers is large, leading to weak electromagnetic coupling with a low emissivity. Conversely, when the temperature rises, perspiration increases, and the distance between the humidity-sensitive fibers decreases, causing an enhancement in electromagnetic coupling with a high emissivity for excellent radiative cooling performance. For example, Zhang et al.[55] designed a smart fabric by coating a thin layer of cellulose triacetate bilayer fibers with carbon nanotubes, achieving over 35% IR emissivity modulation depth based on a modest humidity change. The dynamic infrared pass effect is primarily caused by the distance-sensitive electromagnetic coupling between adjacent coated fibers in the textile yarn, providing an alternative perspective for personal thermal management.

Voltage-Controlled STRCs. While passive STRCs offer energy-efficient regulation, active-control STRCs are necessary in specific application scenarios where higher control precision and faster responses are required. Though high-speed modulation of thermal emission has been proven challenging because the intensity of thermal emission from an object is typically determined by its temperature,[79] successful voltage-controlled STRCs were experimentally demonstrated. Figure 3(c) demonstrates a common modulation method and principle for voltage-controlled STRCs. During hot seasons, the top infrared-transparent electrode and the bottom high emissivity aqueous electrolyte can effectively dissipate heat through radiative cooling. On the other hand, during cold seasons, applying a reverse voltage can lead to the deposition of a metal layer on the upper surface, thereby achieving a low emissivity. For instance, electrochromic devices possess the capability of dynamically managing the optical and thermal performance of buildings with an external voltage. Hence, they find vast applications as smart windows,[66,80−82] smart roofs,[83] electro-optical camouflage,[79] or spacecraft thermal management.[84,85] Most electrochromic devices were achieved through reversible metal electrodeposition with various structures and composition materials.[66,79,80,82,83,86]

Motor-Controlled STRCs. In addition to the aforementioned approaches, mechanical braking methods are also used for the dynamic regulation of radiative coolers, with categories including flip-type,[49,87,88] pulling-type,[44] and stretch-type.[36,48] Flip-type is based on the manual flipping of Janus membranes whose two surfaces are of different IR emissivity: one for radiative cooling and the other one for solar heating.[49,87,88] Besides flipping, pulling is also effective in switching radiative coolers.[44,88] Figure 3(d) illustrates a pulling-type motor-controlled STRC. During cold seasons, the motor pulls out the low-emissivity coating to keep the mixture warm. Conversely, during hot seasons, the motor pulls out high-emissivity coating to facilitate radiative cooling.

Li et al. controlled a polymer composite sheet with a rotation brake and a wheel control system, so that the desired portion of material can be selectively exposed to the sky for heating or cooling.[44,88] As an example, Andrew et al. achieved emissivity switching by embedding patterned rectangular and cylindrical dielectric (Si_3N_4) structures into periodic wavy elastic material (PDMS) through stretching.[36]

CHALLENGES AND PERSPECTIVES

Modulation Depth of Thermal Emissivity. Modulation depth of thermal emissivity ($\Delta\varepsilon_{TE}$) upon mode-switching is another important indicator for optimizing STRCs, which determines their year-round total energy savings or thermal comfort. As an example of PCMs, VO_2 is integrated into micro/nanostructures to enhance $\Delta\varepsilon_{TE}$, leading to VO_2-based multilayer films,[105] core−shell,[106,107] and metasurfaces.[18,64,108] Nevertheless, there is still room for further improvement of $\Delta\varepsilon_{TE}$, as shown in Figure 4.

https://doi.org/10.1021/acsnano.4c05929
ACS Nano 2024, 18, 18118−18128

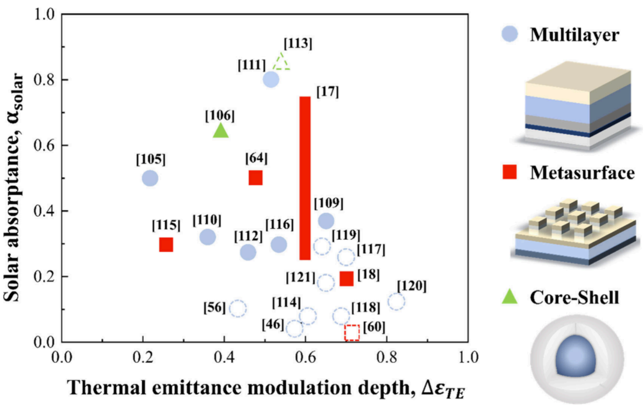


Figure 4. Typical structures of VO_2-based STRCs with their performance: multilayer, metasurface, and core–shell.[17,18,46,56,60,64,105,106,109−121] Filled symbols correspond to experimentally demonstrated STRCs while open ones indicate theoretical designs without experimental verifications.

Representative multilayer VO_2-based STRCs include VO_2/Al realized $\Delta\varepsilon_{TE}$ = 0.22 by Kruzelecky et al.[105] To better exploit the IR modulation properties of VO_2, Fabry–Perot (F–P) cavities were proposed to enhance the light–matter interaction. For example, $VO_2/SiO_2/Au$[116] and $VO_2/HfO_2/Au$[122] sandwich structures were proposed with $\Delta\varepsilon_{TE}$ = 0.49 and 0.55, respectively. Although large modulation depths can also be achieved with gradient refractive structures and core–shell structures, fabrication complexity presents a barrier to their large-scale manufacturing. In recent years, metasurfaces have been used to further enhance the $\Delta\varepsilon_{TE}$ of VO_2-based STRCs, which are favorable due to the effectively reduced solar absorptance by decreasing the VO_2 surface coverage.[108] For example, Tang et al. designed a WVO_2-based STRC metasurface with F–P cavities, achieving a record-breaking $\Delta\varepsilon_{TE}$ = 0.7 with field tests.[18]

Solar Heating and Aesthetic Requirements. Most conventional static radiative coolers are solely designed for cooling, so they are mostly white for broadband reflectance in the visible spectrum to minimize solar absorptance. However, STRCs account for both heat retaining and passive cooling, so their solar absorption should be optimized,[123] instead of simply minimized, for various climates.[18] On the other hand, white coatings are not always favored due to the aesthetic requirements of customers. Therefore, colored STRCs is becoming increasingly popular with more attention.[124]

To achieve colored STRCs, two main strategies could be adopted:[125] (1) The dye-based method directly applies IR-transparent dyes onto radiative coolers. For instance, Son et al.[126] manufactured a coating with silicon dioxide-embedded perovskite nanocrystals and applying it to emitters, leading to white, green, and red static radiative cooling materials. Peng et al.[127] encapsulated IR-transparent nanoparticles such as Prussian iron blue, iron oxide (Fe_2O_3), and silicon (Si) between polymer and Al, leading to radiative cooling films with blue, red, and yellow colors. Similarly, Li et al.[17] applied IR-transparent pigments in the design of STRCs, successfully optimizing solar albedo with aesthetic considerations. (2) The structure-based method adjusts the absorption spectrum of radiative coolers by carefully designed photonic structures.[128] Chen et al.[129] proposed a sprayable dual-layer coating that includes a thin visible light-absorbing layer on top of a nonabsorbing solar scattering base layer. The top layer absorbs specific visible wavelengths to display particular colors, while the bottom layer maximizes the reflection to reduce the level of solar heating.

Costs. Although passive STRCs do not require energy or electricity for a mode-switching operation, the high costs of material production and nanofabrication processes remain a major challenge for further large-scale applications.

To tackle this challenge, organic polymeric materials, such as TPX, PE, PVDF, and PTFE, could be used due to their well-known low costs and compatibility with large-scale manufacturing. For instance, Zhai et al.[33] proposed the combination of polymer and random metamaterials, significantly reducing the production difficulty and costs by a roll-to-roll scalable manufacturing process. While large-scale processing methods such as roll-to-roll manufacturing are adopted, it is necessary to retain the nanophotonic structures to generate strong phonon–polariton resonances. Additionally, electrospinning technologies to produce nanofiber membranes is also effective in reducing the production costs.[47]

Durability and Lifetime. Durability and lifetime are important for STRCs as they determine long-term application costs. They strongly depend on the composition materials as well as the application environments.

In addition to mechanical scratches, STRCs placed on outdoor roofs may experience reduced thermoregulation performance due to dust and precipitates accumulated on the surfaces. Therefore, self-cleaning properties may effectively improve their durability and lifetime.[89] Zhai et al.[90] and Chen et al.[91] used a particle coating method to enhance the surface hydrophobicity for excellent self-cleaning performance. The stability of the material and structure is another important factor that affects the lifetime of STRCs. For instance, ultrathin Pt films in reversible electrostatic silver deposition may form nanocracks that affect the thickness of the subsequent silver deposition.[83] Besides, polymer films are susceptible to degradation and cross-linking under the influence of common environmental factors such as light, heat, water vapor, oxygen, and their synergistic effects.[92,93] The use of polymer additives or stabilizers can be advantageous in extending the lifetime of polymers under specific application scenarios.[94]

Sustainability. The materials used in the fabrication of STRCs might have negative environmental implications, hindering their sustainable development.

SiO_2,[95] TiO_2,[96] and Al_2O_3[97] are commonly used to reflect sunlight in radiative cooling due to their low costs. However, inhaling SiO_2 nanofibers may lead to silicosis,[95] and nanoscale TiO_2 and Al_2O_3 may accumulate in mammalian reproductive organs.[96] Polymeric materials, with their low cost and high emissivity, are extensively used in radiative coolers,[97] yet they are typically easily degraded in the environment. Additionally, microplastics can easily contaminate the environment and accumulate in animal and human bodies, affecting metabolism, growth and development.[98] Therefore, biodegradable polymeric materials such as PLA (poly(lactic acid)) and PBS (polybutylene succinate) may be applicable in the field of STRCs in the future, achieving sustainability at the raw material level.[99] For example, Li et al.[100] developed a stratified radiative cooling film based on cellulose acetate (CA), with commendable biodegradability. Zhu et al.[101] applied microfabrication to process natural silk for radiative cooling fabrics. Chen et al.[102] achieved transparent radiative cooling using silk protein. It is thus expected that the use of natural materials will contribute to the sustainable development of STRC. In

https://doi.org/10.1021/acsnano.4c05929
ACS Nano 2024, 18, 18118−18128

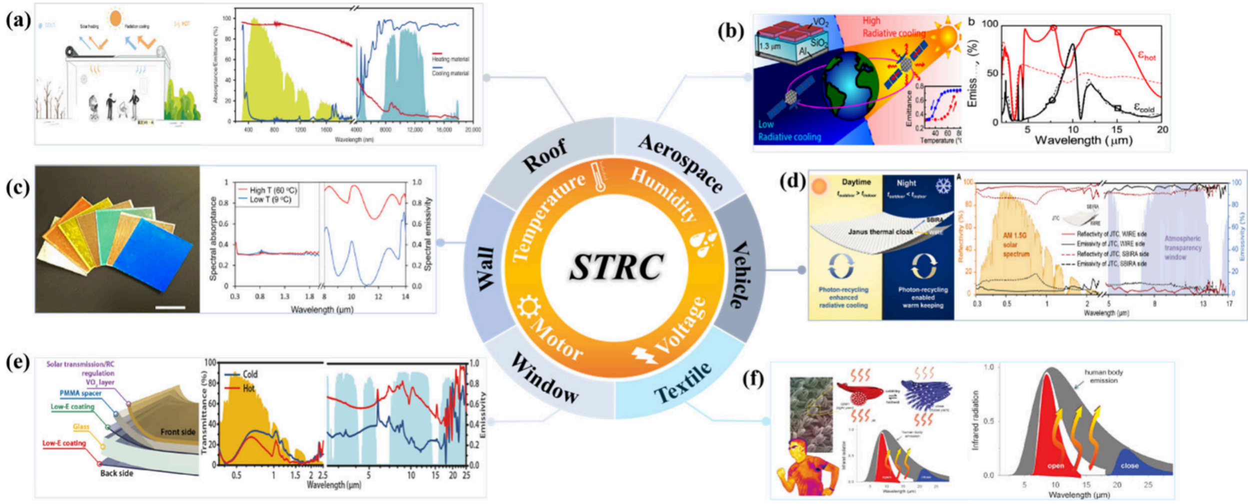


Figure 5. The mechanisms and applications of STRCs. The mechanisms include temperature adaptivity, humidity adaptivity, voltage control, and motor control. The applications range from roofs, walls, and windows to textiles, vehicles, and aerospace. (a) Motor-controlled pulling-type coatings for roof applications. (b) Temperature-adaptive VO_2 metasurfaces for aerospace applications. (c) Temperature-adaptive VO_2 metasurfaces for wall applications. (d) Flip-type Janus coatings for vehicle applications. (e) Temperature-adaptive VO_2 multilayer structures for window applications. (f) Humidity-adaptive metafibers for textile applications. Reprinted with permission from ref 17. Copyright [2023] [Elsevier]. Reprinted with permission from ref 44. Copyright [2020] [Springer Nature]. Reprinted with permission from ref 55. Copyright [2019] [American Association for the Advancement of Science]. Reprinted with permission from ref 64. Copyright [2018] [American Chemical Society]. Reprinted with permission from ref 65. Copyright [2021] [American Association for the Advancement of Science]. Reprinted with permission from ref 150. Copyright [2023] [Elsevier].

addition, it is not sufficient to focus solely on the energy savings and greenhouse gas emission reductions that STRCs bring to the environment.[103] The environmental impacts throughout the entire life cycle, or life cycle assessment (LCA), should also be considered, including the stages of raw material acquisition, production, use, and eventual disposal. Tang et al. conducted a systematic LCA assessment of MgO radiative cooling paint,[104] which provides insights for STRCs and guides researchers to assess the energy savings and sustainability of their designs by referring to the LCA.

OUTLOOKS

Application beyond Roofs. Though roofs directly facing the sky are among the most suitable applications for STRCs,[130−134] their future applications may also expand to walls,[135] windows,[65] clothes,[136] tents,[18] (electrical) vehicles,[34,137,138] and spacecrafts,[139] as shown in Figure 5.

Walls require directional emission toward the sky. Zhou et al.[135] proposed a microwedge structure with directional emissivity contrast through magnetic coupling, which has a huge potential to be applied on walls. Besides, graded epsilon near zero (ENZ) material[140−142] and Brewster metasurfaces[143,144] could also be used to realize highly directional thermal emission. It is noteworthy that STRCs intended for wall applications must also address the issue of glaring as extensive wall reflection may lead to ocular damage. Consequently, employing STRCs with the capability of color customization is imperative to significantly diminish specular optical reflection, thereby averting glaring and mitigating light pollution.

Metafabrics are of vital importance for human thermoregulation. While conventional applications of PCMs in textile materials[136,145,146] make use of their high enthalpy of fusion to effectively absorb and release heat through phase transition, STRCs with PCMs allow for personal thermal management via smart radiative cooling. Therefore, broad application prospects could be expected, such as smart blazers, jackets, and bombers. Moreover, such temperature-adaptive fabric radiators can be used to make tents to meet outdoor needs.

One fatal challenge faced by the thriving electric vehicle (EV) market is the all-season battery thermal management.[147] When the ambient temperature is lowered from 25 °C to −15 °C, the state of charge decreased by ∼23%.[148] To avoid possible overcooling issue introduced by conventional static radiative cooling technologies,[149] smart thermoregulation by STRCs have been proposed. Qiao et al.[150] proposed a Janus STRC film by using silica fiber, hexagonal boron nitride and aluminum alloy foil, which can be mass-produced, enabling year-round thermal regulation for EVs. Similarly, Heo et al.[34] introduced a Janus STRC film comprised of an Ag-polydimethylsiloxane layer on a micropatterned quartz substrate for smart thermoregulation.

In addition to terrestrial applications, STRCs may also find applications in spacecraft thermal control. With the rapid growth in spacecraft mission, using TARC as a replacement for traditional static thermal control coatings to respond to rapid changes in external thermal conditions has become essential.[139,151] Among them, Xie et al.[152] proposed a STRC based on VO_2 particles for spacecraft thermal control and Kim et al.[153] used multilayer VO_2 films to achieve smart thermal control. STRCs proposed by Tang et al.[18] and Li et al.[135] have significant potential for future aerospace thermal management due to its high modulation depth and mechanical flexibility.

Paint-Form STRCs. The current STRCs predominantly manifest in physical forms such as rigid wafers,[25] flexible membranes,[47] and bulk materials.[1] To better apply STRCs on buildings, products in the form of liquid paint are more desired, because they can then be applied to any solid surface without conformability issues.

So far, static radiative cooling paints have been demonstrated with outstanding single-layer coatings composed of SiO_2 nanoparticles[154] and paint-like porous polymer materials

https://doi.org/10.1021/acsnano.4c05929
ACS Nano 2024, 18, 18118−18128

with all-day cooling capabilities.[11] Although these coatings can achieve radiative cooling throughout the day, they are still static and lack self-regulation capabilities. Therefore, there is a pressing need for paint-form STRCs that can achieve temperature-adaptive switching and regulation throughout the seasons. This represents a crucial approach and future research direction for the large-scale application of STRCs on building surfaces.

Tunable Solar Absorption. Apart from utilizing atmospheric transparent windows for radiative cooling, daytime solar radiation power also serves as a clean heat source to harness[2,155] for thermal management. STRCs with tunable solar absorption have been proposed as a type of device that utilizes both solar absorption (smart heating) and thermal radiation (smart cooling) for high-performance heat management.[156−159]

Conventional smart materials with tunable solar absorption work in a similar way as STRCs by adjusting the absorption rate of solar irradiance in response to external stimuli.[156] This property limits their application to daytime thermoregulation, which is further constrained by low solar irradiance during certain weather conditions (especially cloudy days), seasons, and wall/window orientations. Therefore, the development of STRCs with tunable solar absorption has become a crucial avenue for future research. For example, Xiang et al.[49] proposed a Janus STRC film with one solar-absorbing surface and one thermal-emitting surface, which could be switched manually by flipping. The bimorph structure proposed by Zhang et al.[51] utilizes a temperature-sensitive actuating layer to switch between a solar heating mode and a radiative cooling mode, achieving an average heating power of 859.8 W/m^2.

Although these methods can achieve switching between solar absorbers and thermal emitters, mass-producible, passive STRCs with tunable solar absorption without mechanical moving parts are still in need owing to severe limitations on the stability of mechanical structures, the lifespan of temperature memory metals, and other factors.

CONCLUSIONS

With the rapid development in global economy and urbanization, energy consumption by buildings has surged.[160] By the emission of excess heat into outer space, radiative cooling technologies enable efficient thermal management of buildings for reduced greenhouse gas emissions. To tackle the overcooling problem of static radiative cooling at low environment temperatures, STRCs have been proposed and demonstrated as a potential and practical solution. Based on the external stimuli, STRCs are categorized into passive ones driven by environmental temperature or humidity changes as well as active ones controlled by voltages or motors. Toward commercialization and practical applications, STRCs face challenges ranging from modulation depth of thermal emissivity, solar heating optimization, and aesthetic needs to costs, lifespan, and sustainability. These factors impose high demands on the photonic design, material processing, and scalable manufacturing of STRCs. In summary, the unique advantages of STRCs promise tremendous opportunities in various thermal control applications, including buildings, electric vehicles, clothes, tents, and spacecrafts. Among them, STRCs hold substantial potential as future coating technologies for building roofs, glass windows, car glass roofs, and satellites.

AUTHOR INFORMATION

Corresponding Authors

Kaichen Dong − *Tsinghua-Berkeley Shenzhen Institute, Institute of Data and Information, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, Guangdong 518055, China; Center of Double Helix, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, Guangdong 518055, China;* orcid.org/0000-0001-5334-4243; Email: dkc22@sz.tsinghua.edu.cn

Junqiao Wu − *Department of Materials Science and Engineering, University of California, Berkeley, California 94720, United States; Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States;* orcid.org/0000-0002-1498-0148; Email: wuj@berkeley.edu

Authors

Xuzhe Zhao − *Tsinghua-Berkeley Shenzhen Institute, Institute of Data and Information, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, Guangdong 518055, China; Center of Double Helix, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, Guangdong 518055, China*

Jiachen Li − *Department of Materials Science and Engineering, University of California, Berkeley, California 94720, United States; Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsnano.4c05929

Author Contributions

#X.Z. and J.L. contributed equally to this work.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by National Key R&D Program of China grant 2023YFB3208700, National Natural Science Foundation of China grant 62375151, Start-up funding in Tsinghua Shenzhen International Graduate School, Tsinghua University.

ABBREVIATIONS

LCA, life cycle assessment; EV, electric vehicle; ENZ, epsilon near zero; IR, infrared; STRC, switchable and tunable radiative coolers; PCM, phase-change materials; SMAs, shape memory alloys; PLA, poly(lactic acid); PBS, polybutylene succinate; CA, cellulose acetate; TPX, polymethyl pentene; PE, polyethylene; PVDF, polyvinylidene fluoride; PTFE, polytetrafluoroethylene; PDMS, polydimethylsiloxane; VO_2, vanadium dioxide.

REFERENCES

(1) Li, T.; Zhai, Y.; He, S.; Gan, W.; Wei, Z.; Heidarinejad, M.; Dalgo, D.; Mi, R.; Zhao, X.; Song, J.; et al. A radiative cooling structural material. *Science* **2019**, *364* (6442), 760−763.

(2) IEA. *Global Status Report for Buildings and Construction 2019*. IEA, Paris, 2019, https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019 (accessed on January 16, 2024).

https://doi.org/10.1021/acsnano.4c05929
ACS Nano 2024, 18, 18118−18128

(3) Raman, A. P.; Anoma, M. A.; Zhu, L.; Rephaeli, E.; Fan, S. Passive radiative cooling below ambient air temperature under direct sunlight. *Nature* **2014**, *515* (7528), 540−544.
(4) Wu, X.; Li, J.; Xie, F.; Wu, X. E.; Zhao, S.; Jiang, Q.; Zhang, S.; Wang, B.; Li, Y.; Gao, D.; et al. A dual-selective thermal emitter with enhanced subambient radiative cooling performance. *Nat. Commun.* **2024**, *15* (1), 815.
(5) Subramanian, C. V.; Ramachandran, N.; Kumar, S. S. A review of passive cooling architectural design interventions for thermal comfort in residential buildings. *Indian J. Sci. Res.* **2017**, *14* (1), 163−172.
(6) Zhou, M.; Liu, H.; Peng, L.; Qin, Y.; Chen, D.; Zhang, L.; Mauzerall, D. L. Environmental benefits and household costs of clean heating options in northern China. *Nature Sustainability* **2022**, *5* (4), 329−338.
(7) Heating and Cooking by Gas. *Nature* **1886**, *34* (873) 266−269. .
(8) McLinden, M. O.; Seeton, C. J.; Pearson, A. New refrigerants and system configurations for vapor-compression refrigeration. *Science* **2020**, *370* (6518), 791−796.
(9) Zhao, D.; Aili, A.; Zhai, Y.; Xu, S.; Tan, G.; Yin, X.; Yang, R. Radiative sky cooling: Fundamental principles, materials, and applications. *Appl. Phys. Rev.* **2019**, DOI: 10.1063/1.5087281.
(10) U.S. Energy Information Administration. *Residential Energy Consumption Survey*, 2015, https://www.eia.gov/consumption/residential/ (accessed on January 13, 2024).
(11) Mandal, J.; Fu, Y.; Overvig, A. C.; Jia, M.; Sun, K.; Shi, N. N.; Zhou, H.; Xiao, X.; Yu, N.; Yang, Y. Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling. *Science* **2018**, *362* (6412), 315−319.
(12) Zhai, H.; Fan, D.; Li, Q. Scalable and paint-format colored coatings for passive radiative cooling. *Sol. Energy Mater. Sol. Cells* **2022**, *245*, 111853.
(13) Xie, W.; Xiao, C.; Sun, Y.; Fan, Y.; Zhao, B.; Zhang, D.; Fan, T.; Zhou, H. Flexible Photonic Radiative Cooling Films: Fundamentals, Fabrication and Applications. *Adv. Funct. Mater.* **2023**, DOI: 10.1002/adfm.202305734.
(14) Catalanotti, S.; Cuomo, V.; Piro, G.; Ruggi, D.; Silvestrini, V.; Troise, G. The radiative cooling of selective surfaces. *Sol. Energy* **1975**, *17* (2), 83−89.
(15) Lim, X. The super-cool materials that send heat to space. *Nature* **2020**, *577*, 18−20.
(16) So, S.; Yun, J.; Ko, B.; Lee, D.; Kim, M.; Noh, J.; Park, C.; Park, J.; Rho, J. Radiative Cooling for Energy Sustainability: From Fundamentals to Fabrication Methods Toward Commercialization. *Adv. Sci.* **2024**, DOI: 10.1002/advs.202305067.
(17) Li, J.; Dong, K.; Zhang, T.; Tseng, D.; Fang, C.; Guo, R.; Li, J.; Xu, Y.; Dun, C.; Urban, J. J.; et al. Printable, emissivity-adaptive and albedo-optimized covering for year-round energy saving. *Joule* **2023**, *7* (11), 2552−2567.
(18) Tang, K.; Dong, K.; Li, J.; Gordon, M. P.; Reichertz, F. G.; Kim, H.; Rho, Y.; Wang, Q.; Lin, C.-Y.; Grigoropoulos, C. P.; et al. Temperature-adaptive radiative coating for all-season household thermal regulation. *Science* **2021**, *374* (6574), 1504−1509.
(19) Harrison, A. W.; Walton, M. R. Radiative cooling of TiO2 white paint. *Sol. Energy* **1978**, *20* (2), 185−188.
(20) Orel, B.; Gunde, M. K.; Krainer, A. Radiative cooling efficiency of white pigmented paints. *Sol. Energy* **1993**, *50* (6), 477−482.
(21) Nilsson, T. M. J.; Niklasson, G. A.; Granqvist, C. G. A solar reflecting material for radiative cooling applications: ZnS pigmented polyethylene. *Sol. Energy Mater. Sol. Cells* **1992**, *28* (2), 175−193.
(22) Lushiku, E. M.; Granqvist, C.-G. Radiative cooling with selectively infrared-emitting gases. *Appl. Opt.* **1984**, *23* (11), 1835.
(23) Tazawa, M.; Jin, P.; Tanemura, S. Thin film used to obtain a constant temperature lower than the ambient. *Thin Solid Films* **1996**, *281-282*, 232−234.
(24) Diatezua, M. D.; Thiry, P. A.; Caudano, R. Characterization of silicon oxynitride multilayered systems for passive radiative cooling application. *Vacuum* **1995**, *46* (8−10), 1121−1124.
(25) Kou, J.-l.; Jurado, Z.; Chen, Z.; Fan, S.; Minnich, A. J. Daytime Radiative Cooling Using Near-Black Infrared Emitters. *ACS Photonics* **2017**, *4* (3), 626−630.
(26) Zhou, L.; Song, H.; Liang, J.; Singer, M.; Zhou, M.; Stegenburgs, E.; Zhang, N.; Xu, C.; Ng, T.; Yu, Z.; et al. A polydimethylsiloxane-coated metal structure for all-day radiative cooling. *Nature Sustainability* **2019**, *2* (8), 718−724.
(27) Ma, H.; Yao, K.; Dou, S.; Xiao, M.; Dai, M.; Wang, L.; Zhao, H.; Zhao, J.; Li, Y.; Zhan, Y. Multilayered SiO2/Si3N4 photonic emitter to achieve high-performance all-day radiative cooling. *Sol. Energy Mater. Sol. Cells* **2020**, *212*, 110584.
(28) Chae, D.; Kim, M.; Jung, P. H.; Son, S.; Seo, J.; Liu, Y.; Lee, B. J.; Lee, H. Spectrally Selective Inorganic-Based Multilayer Emitter for Daytime Radiative Cooling. *ACS Appl. Mater. Interfaces* **2020**, *12* (7), 8073−8081.
(29) Zou, C.; Ren, G.; Hossain, M. M.; Nirantar, S.; Withayachumnankul, W.; Ahmed, T.; Bhaskaran, M.; Sriram, S.; Gu, M.; Fumeaux, C. Metal-Loaded Dielectric Resonator Metasurfaces for Radiative Cooling. *Adv. Opt. Mater.* **2017**, DOI: 10.1002/adom.201700460.
(30) Zhang, H.; Ly, K. C. S.; Liu, X.; Chen, Z.; Yan, M.; Wu, Z.; Wang, X.; Zheng, Y.; Zhou, H.; Fan, T. Biologically inspired flexible photonic films for efficient passive radiative cooling. *Proc. Natl. Acad. Sci. U. S. A.* **2020**, *117* (26), 14657−14666.
(31) Jeong, S. Y.; Tso, C. Y.; Wong, Y. M.; Chao, C. Y. H.; Huang, B. Daytime passive radiative cooling by ultra emissive bio-inspired polymeric surface. *Sol. Energy Mater. Sol. Cells* **2020**, *206*, 110296.
(32) Shi, N. N.; Tsai, C.-C.; Camino, F.; Bernard, G. D.; Yu, N.; Wehner, R. Keeping cool: Enhanced optical reflection and radiative heat dissipation in Saharan silver ants. *Science* **2015**, *349* (6245), 298−301.
(33) Zhai, Y.; Ma, Y.; David, S. N.; Zhao, D.; Lou, R.; Tan, G.; Yang, R.; Yin, X. Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling. *Science* **2017**, *355* (6329), 1062−1066.
(34) Heo, S.-Y.; Lee, G. J.; Kim, D. H.; Kim, Y. J.; Ishii, S.; Kim, M. S.; Seok, T. J.; Lee, B. J.; Lee, H.; Song, Y. M. A Janus emitter for passive heat release from enclosures. *Sci. Adv.* **2020**, DOI: 10.1126/sciadv.abb1906.
(35) Ao, X.; Hu, M.; Zhao, B.; Chen, N.; Pei, G.; Zou, C. Preliminary experimental study of a specular and a diffuse surface for daytime radiative cooling. *Sol. Energy Mater. Sol. Cells* **2019**, *191*, 290−296.
(36) Butler, A.; Argyropoulos, C. Mechanically tunable radiative cooling for adaptive thermal control. *Appl. Therm. Eng.* **2022**, *211*, 118527.
(37) Chai, J.; Chen, J.; Kang, Z.; Lu, L.; Tang, C.-H.; Fan, J. Temperature-adaptive rooftop covering with synergetic modulation of solar and thermal radiation for maximal energy saving. *iScience* **2023**, *26* (8), 107388.
(38) Chen, Z.; Zhu, L.; Raman, A.; Fan, S. Radiative cooling to deep sub-freezing temperatures through a 24-h day-night cycle. *Nat. Commun.* **2016**, DOI: 10.1038/ncomms13729.
(39) Hamza H. Ali, A.; Taha, I. M. S.; Ismail, I. M. Cooling of water flowing through a night sky radiator. *Sol. Energy* **1995**, *55* (4), 235−253.
(40) Hossain, M. M.; Jia, B.; Gu, M. A Metamaterial Emitter for Highly Efficient Radiative Cooling. *Advanced Optical Materials* **2015**, *3* (8), 1047−1051.
(41) Hsu, P.-C.; Song, A. Y.; Catrysse, P. B.; Liu, C.; Peng, Y.; Xie, J.; Fan, S.; Cui, Y. Radiative human body cooling by nanoporous polyethylene textile. *Science* **2016**, *353* (6303), 1019−1023.
(42) Hu, X.; Cai, W.; Zhang, Y.; Shi, S.; Ming, Y.; Yu, R.; Chen, D.; Yang, M.; Wang, F.; Yang, H.; et al. Facile and Widely Applicable Route to Self-Adaptive Emissivity Modulation: Energy-Saving Demonstration with Transparent Wood. *Nano Lett.* **2024**, *24* (2), 657−666.
(43) Li, D.; Liu, X.; Li, W.; Lin, Z.; Zhu, B.; Li, Z.; Li, J.; Li, B.; Fan, S.; Xie, J.; et al. Scalable and hierarchically designed polymer film as a

selective thermal emitter for high-performance all-day radiative cooling. *Nat. Nanotechnol.* **2021**, *16* (2), 153−158.
(44) Li, X.; Sun, B.; Sui, C.; Nandi, A.; Fang, H.; Peng, Y.; Tan, G.; Hsu, P.-C. Integration of daytime radiative cooling and solar heating for year-round energy saving in buildings. *Nat. Commun.* **2020**, DOI: 10.1038/s41467-020-19790-x.
(45) Lin, K.; Chen, S.; Zeng, Y.; Ho, T. C.; Zhu, Y.; Wang, X.; Liu, F.; Huang, B.; Chao, C. Y.-H.; Wang, Z.; et al. Hierarchically structured passive radiative cooling ceramic with high solar reflectivity. *Science* **2023**, *382* (6671), 691−697.
(46) Ono, M.; Chen, K.; Li, W.; Fan, S. Self-adaptive radiative cooling based on phase change materials. *Opt. Express* **2018**, *26* (18), A777.
(47) Wang, X.; Liu, X.; Li, Z.; Zhang, H.; Yang, Z.; Zhou, H.; Fan, T. Scalable Flexible Hybrid Membranes with Photonic Structures for Daytime Radiative Cooling. *Adv. Funct. Mater.* **2020**, DOI: 10.1002/adfm.201907562.
(48) Xia, Z.; Fang, Z.; Zhang, Z.; Shi, K.; Meng, Z. Easy Way to Achieve Self-Adaptive Cooling of Passive Radiative Materials. *ACS Appl. Mater. Interfaces* **2020**, *12* (24), 27241−27248.
(49) Xiang, B.; Zhang, R.; Zeng, X.; Luo, Y.; Luo, Z. An Easy-to-Prepare Flexible Dual-Mode Fiber Membrane for Daytime Outdoor Thermal Management. *Advanced Fiber Materials* **2022**, *4* (5), 1058−1068.
(50) Zeng, S.; Pian, S.; Su, M.; Wang, Z.; Wu, M.; Liu, X.; Chen, M.; Xiang, Y.; Wu, J.; Zhang, M.; et al. Hierarchical-morphology metafabric for scalable passive daytime radiative cooling. *Science* **2021**, *373* (6555), 692−696.
(51) Zhang, Q.; Lv, Y.; Wang, Y.; Yu, S.; Li, C.; Ma, R.; Chen, Y. Temperature-dependent dual-mode thermal management device with net zero energy for year-round energy saving. *Nat. Commun.* **2022**, DOI: 10.1038/s41467-022-32528-1.
(52) Zhao, X.; Li, T.; Xie, H.; Liu, H.; Wang, L.; Qu, Y.; Li, S. C.; Liu, S.; Brozena, A. H.; Yu, Z.; et al. A solution-processed radiative cooling glass. *Science* **2023**, *382* (6671), 684−691.
(53) Zhou, Z.; Fang, Y.; Wang, X.; Yang, E.; Liu, R.; Zhou, X.; Huang, Z.; Yin, H.; Zhou, J.; Hu, B. Synergistic modulation of solar and thermal radiation in dynamic energy-efficient windows. *Nano Energy* **2022**, *93*, 106865.
(54) Pan, S.; Peng, H. Making Passive Daytime Radiative Cooling Metafabrics on a Large Scale. *Advanced Fiber Materials* **2022**, *4* (1), 3−4.
(55) Zhang, X. A.; Yu, S.; Xu, B.; Li, M.; Peng, Z.; Wang, Y.; Deng, S.; Wu, X.; Wu, Z.; Ouyang, M.; et al. Dynamic gating of infrared radiation in a textile. *Science* **2019**, *363* (6427), 619−623.
(56) Xu, X.; Gu, J.; Zhao, H.; Zhang, X.; Dou, S.; Li, Y.; Zhao, J.; Zhan, Y.; Li, X. Passive and Dynamic Phase-Change-Based Radiative Cooling in Outdoor Weather. *ACS Appl. Mater. Interfaces* **2022**, *14* (12), 14313−14320.
(57) Gao, Y.; Xu, J.; Yang, S.; Tang, X.; Zhou, Q.; Ge, J.; Xu, T.; Levinson, R. Cool roofs in China: Policy review, building simulations, and proof-of-concept experiments. *Energy Policy* **2014**, *74*, 190−214.
(58) Ulpiani, G.; Ranzi, G.; Shah, K. W.; Feng, J.; Santamouris, M. On the energy modulation of daytime radiative coolers: A review on infrared emissivity dynamic switch against overcooling. *Sol. Energy* **2020**, *209*, 278−301.
(59) Taylor, S.; Yang, Y.; Wang, L. Vanadium dioxide based Fabry-Perot emitter for dynamic radiative cooling applications. *Journal of Quantitative Spectroscopy and Radiative Transfer* **2017**, *197*, 76−83.
(60) Zhang, W.-W.; Qi, H.; Sun, A.-T.; Ren, Y.-T.; Shi, J.-W. Periodic trapezoidal VO2-Ge multilayer absorber for dynamic radiative cooling. *Opt. Express* **2020**, *28* (14), 20609.
(61) Lashley, C. H.; Krein, S. J.; Barcomb, P. Deployable Radiators - A Multi-Discipline Approach. *SAE Technical Paper* **1998**, 981691.
(62) Goncharov, K. A.; Orlov, A. A.; Tarabrin, A.; Gottero, M.; Perotto, V.; Tavera, S.; Zoppo, G. P. 1500 W Deployable Radiator with Loop Heat Pipe. *SAE Technical Paper* **2001**, 2001−01−2194.
(63) Taylor, S.; Long, L.; McBurney, R.; Sabbaghi, P.; Chao, J.; Wang, L. Spectrally-selective vanadium dioxide based tunable metafilm emitter for dynamic radiative cooling. *Sol. Energy Mater. Sol. Cells* **2020**, *217*, 110739.
(64) Sun, K.; Riedel, C. A.; Urbani, A.; Simeoni, M.; Mengali, S.; Zalkovskij, M.; Bilenberg, B.; de Groot, C. H.; Muskens, O. L. VO_2 Thermochromic Metamaterial-Based Smart Optical Solar Reflector. *ACS Photonics* **2018**, *5* (6), 2280−2286.
(65) Wang, S.; Jiang, T.; Meng, Y.; Yang, R.; Tan, G.; Long, Y. Scalable thermochromic smart windows with passive radiative cooling regulation. *Science* **2021**, *374* (6574), 1501−1504.
(66) Sui, C.; Pu, J.; Chen, T.-H.; Liang, J.; Lai, Y.-T.; Rao, Y.; Wu, R.; Han, Y.; Wang, K.; Li, X.; et al. Dynamic electrochromism for all-season radiative thermoregulation. *Nature Sustainability* **2023**, *6* (4), 428−437.
(67) Zhang, Q.; Wang, Y.; Lv, Y.; Yu, S.; Ma, R. Bioinspired zero-energy thermal-management device based on visible and infrared thermochromism for all-season energy saving. *Proc. Natl. Acad. Sci. U. S. A.* **2022**, DOI: 10.1073/pnas.2207353119.
(68) Fu, D.; Liu, K.; Tao, T.; Lo, K.; Cheng, C.; Liu, B.; Zhang, R.; Bechtel, H. A.; Wu, J. Comprehensive study of the metal-insulator transition in pulsed laser deposited epitaxial VO2 thin films. *J. Appl. Phys.* **2013**, DOI: 10.1063/1.4788804.
(69) Qu, Y.; Li, Q.; Du, K.; Cai, L.; Lu, J.; Qiu, M. Dynamic Thermal Emission Control Based on Ultrathin Plasmonic Metamaterials Including Phase-Changing Material GST. *Laser Photon. Rev.* **2017**, DOI: 10.1002/lpor.201700091.
(70) Qu, Y.; Cai, L.; Luo, H.; Lu, J.; Qiu, M.; Li, Q. Tunable dual-band thermal emitter consisting of single-sized phase-changing GST nanodisks. *Opt. Express* **2018**, *26* (4), 4279.
(71) Du, K.-K.; Li, Q.; Lyu, Y.-B.; Ding, J.-C.; Lu, Y.; Cheng, Z.-Y.; Qiu, M. Control over emissivity of zero-static-power thermal emitters based on phase-changing material GST. *Light: Sci. Appl.* **2017**, *6* (1), No. e16194.
(72) Fan, D.; Sun, S.-Y.; Guo, L. Thermal Emittance of $La_{0.7}Ca_{0.3-x}K_xMnO_3$ Coatings on Aluminum Substrate. *Int. J. Thermophys.* **2018**, *39*, 67.
(73) Tachikawa, S.; Ohnishi, A.; Shimakawa, Y.; Ochi, A.; Okamoto, A.; Nakamura, Y. Development of a Variable Emittance Radiator Based on a Perovskite Manganese Oxide. *Journal of Thermophysics and Heat Transfer* **2003**, *17* (2), 264−268.
(74) Long, L.; Taylor, S.; Ying, X.; Wang, L. Thermally-switchable spectrally-selective infrared metamaterial absorber/emitter by tuning magnetic polariton with a phase-change VO2 layer. *Materials Today Energy* **2019**, *13*, 214−220.
(75) Ling, C.; Zhao, Z.; Hu, X.; Li, J.; Zhao, X.; Wang, Z.; Zhao, Y.; Jin, H. W Doping and Voltage Driven Metal-Insulator Transition in VO2 Nano-Films for Smart Switching Devices. *ACS Appl. Nano Mater.* **2019**, *2* (10), 6738−6746.
(76) Li, G.; Xie, D.; Zhong, H.; Zhang, Z.; Fu, X.; Zhou, Q.; Li, Q.; Ni, H.; Wang, J.; Guo, E.-j. Photo-induced non-volatile VO2 phase transition for neuromorphic ultraviolet sensors. *Nat. Commun.* **2022**, DOI: 10.1038/s41467-022-29456-5.
(77) Chen, Y.; Wang, Z.; Chen, S.; Ren, H.; Wang, L.; Zhang, G.; Lu, Y.; Jiang, J.; Zou, C.; Luo, Y. Non-catalytic hydrogenation of VO2 in acid solution. *Nat. Commun.* **2018**, DOI: 10.1038/s41467-018-03292-y.
(78) Mandal, J.; Jia, M.; Overvig, A.; Fu, Y.; Che, E.; Yu, N.; Yang, Y. Porous Polymers with Switchable Optical Transmittance for Optical and Thermal Regulation. *Joule* **2019**, *3* (12), 3088−3099.
(79) Inoue, T.; Zoysa, M. D.; Asano, T.; Noda, S. Realization of dynamic thermal emission control. *Nat. Mater.* **2014**, *13* (10), 928−931.
(80) Zhao, X.; Aili, A.; Zhao, D.; Xu, D.; Yin, X.; Yang, R. Dynamic glazing with switchable solar reflectance for radiative cooling and solar heating. *Cell Rep. Phys. Sci.* **2022**, *3* (4), 100853.
(81) Browne, M. P.; Nolan, H.; Berner, N. C.; Duesberg, G. S.; Colavita, P. E.; Lyons, M. E. G. Electrochromic Nickel Oxide Films for Smart Window Applications. *Int. J. Electrochem. Sci.* **2016**, *11* (8), 6636−6647.

(82) Zhang, H.; Zhang, X.; Sun, W.; Chen, M.; Xiao, Y.; Ding, Z.; Yan, D.; Deng, J.; Li, Z.; Zhao, J.; et al. All-Solid-State Transparent Variable Infrared Emissivity Devices for Multi-Mode Smart Windows. *Adv. Funct. Mater.* **2024**, DOI: 10.1002/adfm.202307356.
(83) Tao, X.; Liu, D.; Liu, T.; Meng, Z.; Yu, J.; Cheng, H. A Bistable Variable Infrared Emissivity Device Based on Reversible Silver Electrodeposition. *Adv. Funct. Mater.* **2022**, DOI: 10.1002/adfm.202202661.
(84) Niu, J.; Wang, Y.; Zou, X.; Tan, Y.; Jia, C.; Weng, X.; Deng, L. Infrared electrochromic materials, devices and applications. *Appl. Mater. Today* **2021**, *24*, 101073.
(85) Demiryont, H.; Moorehead, D. Electrochromic emissivity modulator for spacecraft thermal management. *Sol. Energy Mater. Sol. Cells* **2009**, *93* (12), 2075−2078.
(86) Ergoktas, M. S.; Bakan, G.; Kovalska, E.; Le Fevre, L. W.; Fields, R. P.; Steiner, P.; Yu, X.; Salihoglu, O.; Balci, S.; Fal'ko, V. I.; et al. Multispectral graphene-based electro-optical surfaces with reversible tunability from visible to microwave wavelengths. *Nat. Photonics* **2021**, *15* (7), 493−498.
(87) Hu, M.; Zhao, B.; Suhendri, S.; Cao, J.; Wang, Q.; Riffat, S.; Yang, R.; Su, Y.; Pei, G. Experimental study on a hybrid solar photothermic and radiative cooling collector equipped with a rotatable absorber/emitter plate. *Appl. Energy* **2022**, *306*, 118096.
(88) Ke, Y.; Li, Y.; Wu, L.; Wang, S.; Yang, R.; Yin, J.; Tan, G.; Long, Y. On-Demand Solar and Thermal Radiation Management Based on Switchable Interwoven Surfaces. *ACS Energy Lett.* **2022**, *7* (5), 1758−1763.
(89) Ding, S.; Xiang, T.; Li, C.; Zheng, S.; Wang, J.; Zhang, M.; Dong, C.; Chan, W. Fabrication of self-cleaning super-hydrophobic nickel/graphene hybrid film with improved corrosion resistance on mild steel. *Materials & Design* **2017**, *117*, 280−288.
(90) Zhai, Q.; Zhu, Q. Radiative cooling film with self-cleaning function. *Sol. Energy Mater. Sol. Cells* **2021**, *228*, 111117.
(91) Chen, G.; Wang, Y.; Qiu, J.; Cao, J.; Zou, Y.; Wang, S.; Ouyang, J.; Jia, D.; Zhou, Y. A visibly transparent radiative cooling film with self-cleaning function produced by solution processing. *Journal of Materials Science & Technology* **2021**, *90*, 76−84.
(92) Qiao, R.-M.; Zhao, C.-P.; Liu, J.-L.; Zhang, M.-L.; He, W.-Q. Synthesis of Novel Ultraviolet Absorbers and Preparation and Field Application of Anti-Ultraviolet Aging PBAT/UVA Films. *Polymers* **2022**, *14* (7), 1434.
(93) Zhang, F.; Yang, R.; Lu, D. Investigation of Polymer Aging Mechanisms Using Molecular Simulations: A Review. *Polymers* **2023**, *15* (8), 1928.
(94) Chenoweth, K.; Cheung, S.; van Duin, A. C. T.; Goddard, W. A.; Kober, E. M. Simulations on the Thermal Decomposition of a Poly(dimethylsiloxane) Polymer Using the ReaxFF Reactive Force Field. *J. Am. Chem. Soc.* **2005**, *127* (19), 7192−7202.
(95) Li, T.; Yang, X.; Xu, H.; Liu, H. Early Identification, Accurate Diagnosis, and Treatment of Silicosis. *Can. Respir. J.* **2022**, *2022*, 1−6.
(96) Minghui, F.; Ran, S.; Yuxue, J.; Minjia, S. Toxic effects of titanium dioxide nanoparticles on reproduction in mammals. *Front. Bioeng. Biotechnol.* **2023**, DOI: 10.3389/fbioe.2023.1183592.
(97) Liu, Y.; Tian, Y.; Liu, X.; Chen, F.; Caratenuto, A.; Zheng, Y. Intelligent regulation of VO2-PDMS-driven radiative cooling. *Appl. Phys. Lett.* **2022**, DOI: 10.1063/5.0089353.
(98) Thompson, R. C.; Moore, C. J.; vom Saal, F. S.; Swan, S. H. Plastics, the environment and human health: current consensus and future trends. *Philosophical Transactions of the Royal Society B: Biological Sciences* **2009**, *364* (1526), 2153−2166.
(99) La Fuente, C. I. A.; Maniglia, B. C.; Tadini, C. C. Biodegradable polymers: A review about biodegradation and its implications and applications. *Packaging Technology and Science* **2023**, *36* (2), 81−95.
(100) Li, J.; Liang, Y.; Li, W.; Xu, N.; Zhu, B.; Wu, Z.; Wang, X.; Fan, S.; Wang, M.; Zhu, J. Protecting ice from melting under sunlight via radiative cooling. *Sci. Adv.* **2022**, DOI: 10.1126/sciadv.abj9756.
(101) Zhu, B.; Li, W.; Zhang, Q.; Li, D.; Liu, X.; Wang, Y.; Xu, N.; Wu, Z.; Li, J.; Li, X.; et al. Subambient daytime radiative cooling textile based on nanoprocessed silk. *Nat. Nanotechnol.* **2021**, *16* (12), 1342−1348.
(102) Chen, Y. H.; Hwang, C. W.; Chang, S. W.; Tsai, M. T.; Jayakumaran, K. N.; Yang, L. C.; Lo, Y. C.; Ko, F. H.; Wang, H. C.; Chen, H. L. Eco-Friendly Transparent Silk Fibroin Radiative Cooling Film for Thermal Management of Optoelectronics. *Adv. Funct. Mater.* **2023**, DOI: 10.1002/adfm.202301924.
(103) Zhao, D.; Tang, H. Staying stably cool in the sunlight. *Science* **2023**, *382* (6671), 644−645.
(104) Tang, H.; Li, S.; Zhang, Y.; Na, Y.; Sun, C.; Zhao, D.; Liu, J.; Zhou, Z. Radiative cooling performance and life-cycle assessment of a scalable MgO paint for building applications. *J. Cleaner Prod.* **2022**, *380*, 135035.
(105) Haddad, E.; Kruzelecky, R. V.; Hendaoui, A.; Chaker, M.; Jamroz, W.; Poinas, P. Large Tuneability IR Emittance Thermal Control Coating for Space Applications. In *43rd International Conference on Environmental Systems*, 2013.
(106) Wu, X.; Yuan, L.; Weng, X.; Qi, L.; Wei, B.; He, W. Passive Smart Thermal Control Coatings Incorporating CaF_2/VO_2 Core-Shell Microsphere Structures. *Nano Lett.* **2021**, *21* (9), 3908−3914.
(107) Chen, M.; Morsy, A. M.; Povinelli, M. L. Design of VO(2)-coated silicon microspheres for thermally-regulating paint. *Opt Express* **2019**, *27* (15), 21787−21793.
(108) Ito, K.; Watari, T.; Nishikawa, K.; Yoshimoto, H.; Iizuka, H. Inverting the thermal radiative contrast of vanadium dioxide by metasurfaces based on localized gap-plasmons. *APL Photon.* **2018**, DOI: 10.1063/1.5025947.
(109) Beaini, R.; Baloukas, B.; Loquai, S.; Klemberg-Sapieha, J. E.; Martinu, L. Thermochromic VO2-based smart radiator devices with ultralow refractive index cavities for increased performance. *Sol. Energy Mater. Sol. Cells* **2020**, *205*, 110260.
(110) BenKahoul, M.; Haddad, E.; Kruzelecky, R.; Wong, B.; Jamroz, W.; Soltani, M.; Chaker, M.; Poinas, P. Multilayer Tuneable Emittance Coatings, with Higher Emittance for Improved Smart Thermal Control in Space Applications. In *40th International Conference on Environmental Systems*, 2010.
(111) Du, Z.; Li, M.; Xu, S.; Li, K.; Zou, F.; Zhang, R.; Li, G. VO_2-based intelligent thermal control coating for spacecraft by regulating infrared emittance. *J. Alloys Compd.* **2022**, *895*, 162679.
(112) Hendaoui, A. Low Solar Absorptance, High Emittance Performance Thermochromic VO_2-Based Smart Radiator Device. *Nanomaterials* **2022**, *12* (24), 4422.
(113) Huang, J.; Zhang, X.-k.; Yu, X.; Tang, G. H.; Wang, X.; Du, M. Scalable self-adaptive radiative cooling film through VO2-based switchable core-shell particles. *Renewable Energy* **2024**, *224*, 120208.
(114) Kim, M.; Lee, D.; Yang, Y.; Rho, J. Switchable diurnal radiative cooling by doped VO_2. *Opto-Electronic Advances* **2021**, *4* (5), 200006−200006.
(115) Sun, K.; Xiao, W.; Wheeler, C.; Simeoni, M.; Urbani, A.; Gaspari, M.; Mengali, S.; de Groot, C. H.; Muskens, O. L. VO2 metasurface smart thermal emitter with high visual transparency for passive radiative cooling regulation in space and terrestrial applications. *Nanophotonics* **2022**, *11* (17), 4101−4114.
(116) Wang, X.; Jin, H.; Wang, B.; Ling, C.; Yang, J.; Li, D.; Li, J. Thermochromic VO2 based sandwich structure Ag/Al2O3/VO2 with low solar absorption and tunable emittance for spacecraft. *J. Appl. Phys.* **2022**, DOI: 10.1063/5.0084341.
(117) Wang, X.; Yang, J.; Li, D.; Ye, H.; Ling, C.; Li, J.; Jin, H. Design of highly reflective film for smart radiation device. *Vibroengineering PROCEDIA* **2022**, *40*, 132−138.
(118) Wu, B.; Mao, Q.; Li, H.; Liu, H.; Wu, X.; Huang, X. Spacecraft smart radiation device with near-zero solar absorption based on cascaded photonic crystals. *Case Stud. Thermal Eng.* **2023**, *50*, 103473.
(119) Wu, B.; Wu, X.; Liu, H.; Li, H.; Huang, X. An efficient optimization strategy applied to spacecraft smart radiation devices design. *International J. Thermal Sci.* **2024**, *195*, 108635.
(120) Xie, B.; Zhang, W.; Zhao, J.; Zheng, C.; Liu, L. Design of VO2-based spacecraft smart radiator with low solar absorptance. *Appl. Thermal Eng.* **2024**, *236*, 121751.

(121) Zhang, K.; Lv, Y.; Wu, B.; Yu, K.; Liu, Y.; Wu, X. A theoretical study on the effect of protective layer on the solar absorption and infrared emittance of spacecraft smart thermal control devices. *Opt. Laser Technol.* **2024**, *169*, 110087.
(122) Wang, X.; Cao, Y.; Zhang, Y.; Yan, L.; Li, Y. Fabrication of VO2-based multilayer structure with variable emittance. *Appl. Surf. Sci.* **2015**, *344*, 230−235.
(123) Liu, P.; Bae, S.; Noh, J.; Kim, M.; Heo, J. W.; Son, D.; Kang, J.; Rho, J.; So, S.; Kang, J. G.; et al. Functional Radiative Cooling: Basic Concepts, Materials, and Best Practices in Measurements. *ACS Appl. Electron. Mater.* **2023**, *5* (11), 5755−5776.
(124) Xi, W.; Liu, Y.; Zhao, W.; Hu, R.; Luo, X. Colored radiative cooling: How to balance color display and radiative cooling performance. *Int. J. Thermal Sci.* **2021**, *170*, 107172.
(125) Srinivasarao, M. Nano-Optics in the Biological World: Beetles, Butterflies, Birds, and Moths. *Chem. Rev.* **1999**, *99*, 1935−1962.
(126) Son, S.; Jeon, S.; Chae, D.; Lee, S. Y.; Liu, Y.; Lim, H.; Oh, S. J.; Lee, H. Colored emitters with silica-embedded perovskite nanocrystals for efficient daytime radiative cooling. *Nano Energy* **2021**, *79*, 105461.
(127) Peng, Y.; Fan, L.; Jin, W.; Ye, Y.; Huang, Z.; Zhai, S.; Luo, X.; Ma, Y.; Tang, J.; Zhou, J.; et al. Coloured low-emissivity films for building envelopes for year-round energy savings. *Nature Sustainability* **2022**, *5* (4), 339−347.
(128) Yalçın, R. A.; Blandre, E.; Joulain, K.; Drévillon, J. Colored Radiative Cooling Coatings with Nanoparticles. *ACS Photonics* **2020**, *7* (5), 1312−1322.
(129) Chen, Y.; Mandal, J.; Li, W.; Smith-Washington, A.; Tsai, C.-C.; Huang, W.; Shrestha, S.; Yu, N.; Han, R. P. S.; Cao, A. Colored and paintable bilayer coatings with high solar-infrared reflectance for efficient cooling. *Sci. Adv.* **2020**, DOI: 10.1126/sciadv.aaz5413.
(130) Ma, M.; Zhang, K.; Chen, L.; Tang, S. Analysis of the impact of a novel cool roof on cooling performance for a low-rise prefabricated building in China. *Building Services Engineering Research and Technology* **2021**, *42* (1), 26−44.
(131) Chen, J.; Lu, L. Comprehensive evaluation of thermal and energy performance of radiative roof cooling in buildings. *J. Building Eng.* **2021**, *33*, 101631.
(132) Baniassadi, A.; Sailor, D. J.; Ban-Weiss, G. A. Potential energy and climate benefits of super-cool materials as a rooftop strategy. *Urban Climate* **2019**, *29*, 100495.
(133) Lu, X.; Xu, P.; Wang, H.; Yang, T.; Hou, J. Cooling potential and applications prospects of passive radiative cooling in buildings: The current state-of-the-art. *Renewable and Sustainable Energy Reviews* **2016**, *65*, 1079−1097.
(134) An, Y.; Fu, Y.; Dai, J.-G.; Yin, X.; Lei, D. Switchable radiative cooling technologies for smart thermal management. *Cell Rep. Phys. Sci.* **2022**, *3* (10), 101098.
(135) Zhou, J.; Chen, T. G.; Tsurimaki, Y.; Hajj-Ahmad, A.; Fan, L.; Peng, Y.; Xu, R.; Wu, Y.; Assawaworrarit, S.; Fan, S.; et al. Angle-selective thermal emitter for directional radiative cooling and heating. *Joule* **2023**, *7* (12), 2830−2844.
(136) Peng, Y.; Cui, Y. Advanced Textiles for Personal Thermal Management and Energy. *Joule* **2020**, *4* (4), 724−742.
(137) Kim, D. H.; Lee, G. J.; Heo, S.-Y.; Kang, I.-S.; Song, Y. M. Thermostat property of Janus emitter in enclosures. *Sol. Energy Mater. Sol. Cells* **2021**, *230*, 111173.
(138) Zhang, C.; Huang, J.; Sun, W.; Xu, X.; Li, C.; Li, Y. Research on liquid preheating performance for battery thermal management of electric vehicles at low temperature. *J. Energy Storage* **2022**, *55*, 105497.
(139) Dong, K.; Tseng, D.; Li, J.; Warkander, S.; Yao, J.; Wu, J. Reducing temperature swing of space objects with temperature-adaptive solar or radiative coating. *Cell Rep. Phys. Sci.* **2022**, *3* (10), 101066.
(140) Ying, Y.; Ma, B.; Yu, J.; Huang, Y.; Ghosh, P.; Shen, W.; Qiu, M.; Li, Q. Whole LWIR Directional Thermal Emission Based on ENZ Thin Films. *Laser Photon. Rev.* **2022**, DOI: 10.1002/lpor.202200018.
(141) Chamoli, S. K.; Li, W. Visibly transparent multifunctional camouflage coating with efficient thermal management. *Opt. Lett.* **2023**, *48* (16), 4340−4343.
(142) Xu, J.; Mandal, J.; Raman, A. P. Broadband directional control of thermal emission. *Science* **2021**, *372* (6540), 393−397.
(143) Fan, H.; Li, J.; Lai, Y.; Luo, J. Optical Brewster Metasurfaces Exhibiting Ultrabroadband Reflectionless Absorption and Extreme Angular Asymmetry. *Phys. Rev. Appl.* **2021**, DOI: 10.1103/PhysRevApplied.16.044064.
(144) Fan, H.; Chu, H.; Luo, H.; Lai, Y.; Gao, L.; Luo, J. Brewster metasurfaces for ultrabroadband reflectionless absorption at grazing incidence. *Optica* **2022**, *9* (10), 1138.
(145) Rathod, M. K.; Banerjee, J. Thermal stability of phase change materials used in latent heat energy storage systems: A review. *Renewable and Sustainable Energy Reviews* **2013**, *18*, 246−258.
(146) Mondal, S. Phase change materials for smart textiles - An overview. *Applied Thermal Engineering* **2008**, *28* (11−12), 1536−1550.
(147) Longchamps, R. S.; Yang, X.-G.; Wang, C.-Y. Fundamental Insights into Battery Thermal Management and Safety. *ACS Energy Lett.* **2022**, *7* (3), 1103−1111.
(148) Nagasubramanian, G. Electrical characteristics of 18650 Li-ion cells at low temperatures. *J. Appl. Electrochem.* **2001**, *31*, 99−104.
(149) Li, J.; Dong, K. Scalable and durable temperature-stabilizing Janus thermal cloak. *Joule* **2023**, *7* (7), 1402−1405.
(150) Qiao, H.; Huang, Z.; Wu, J.; Shen, J.; Zhang, H.; Wang, Q.; Shang, W.; Tang, W.; Deng, T.; Xu, H. Scalable and durable Janus thermal cloak for all-season passive thermal regulation. *Device* **2023**, *1* (1), 100008.
(151) Grob, L. M.; Swanson, T. D. Parametric study of variable emissivity radiator surfaces. *AIP Conf. Proc.* **2000**, *504* (1), 809−814.
(152) Xie, B.; Dong, J.; Zhao, J.; Liu, L.; Fu, X.; Zhai, Z. VO(2) particle-based intelligent metasurface with perfect infrared emission for the spacecraft thermal control. *Appl. Opt.* **2022**, *61* (35), 10538−10547.
(153) Kim, H.; Cheung, K.; Auyeung, R. C. Y.; Wilson, D. E.; Charipar, K. M.; Pique, A.; Charipar, N. A. VO(2)-based switchable radiator for spacecraft thermal control. *Sci. Rep* **2019**, *9* (1), 11329.
(154) Atiganyanun, S.; Plumley, J. B.; Han, S. J.; Hsu, K.; Cytrynbaum, J.; Peng, T. L.; Han, S. M.; Han, S. E. Effective Radiative Cooling by Paint-Format Microsphere-Based Photonic Random Media. *ACS Photonics* **2018**, *5* (4), 1181−1187.
(155) Zhao, B.; Hu, M.; Ao, X.; Chen, N.; Pei, G. Radiative cooling: A review of fundamentals, materials, applications, and prospects. *Applied Energy* **2019**, *236*, 489−513.
(156) Mei, X.; Wang, T.; Chen, M.; Wu, L. A self-adaptive film for passive radiative cooling and solar heating regulation. *Journal of Materials Chemistry A* **2022**, *10* (20), 11092−11100.
(157) Wang, J.; Xie, M.; An, Y.; Tao, Y.; Sun, J.; Ji, C. All-season thermal regulation with thermochromic temperature-adaptive radiative cooling coatings. *Sol. Energy Mater. Sol. Cells* **2022**, *246*, 111883.
(158) Wang, S.; Zhou, Y.; Jiang, T.; Yang, R.; Tan, G.; Long, Y. Thermochromic smart windows with highly regulated radiative cooling and solar transmission. *Nano Energy* **2021**, *89*, 106440.
(159) Liu, M.; Li, X.; Li, L.; Li, L.; Zhao, S.; Lu, K.; Chen, K.; Zhu, J.; Zhou, T.; Hu, C.; et al. Continuous Photothermal and Radiative Cooling Energy Harvesting by VO2 Smart Coatings with Switchable Broadband Infrared Emission. *ACS Nano* **2023**, *17* (10), 9501−9509.
(160) Hernández-Pérez, I.; Álvarez, G.; Xamán, J.; Zavala-Guillén, I.; Arce, J.; Simá, E. Thermal performance of reflective materials applied to exterior building components—A review. *Energy and Buildings* **2014**, *80*, 81−105.

https://doi.org/10.1021/acsnano.4c05929
ACS Nano 2024, 18, 18118−18128