A Janus emitter for passive heat release from enclosures

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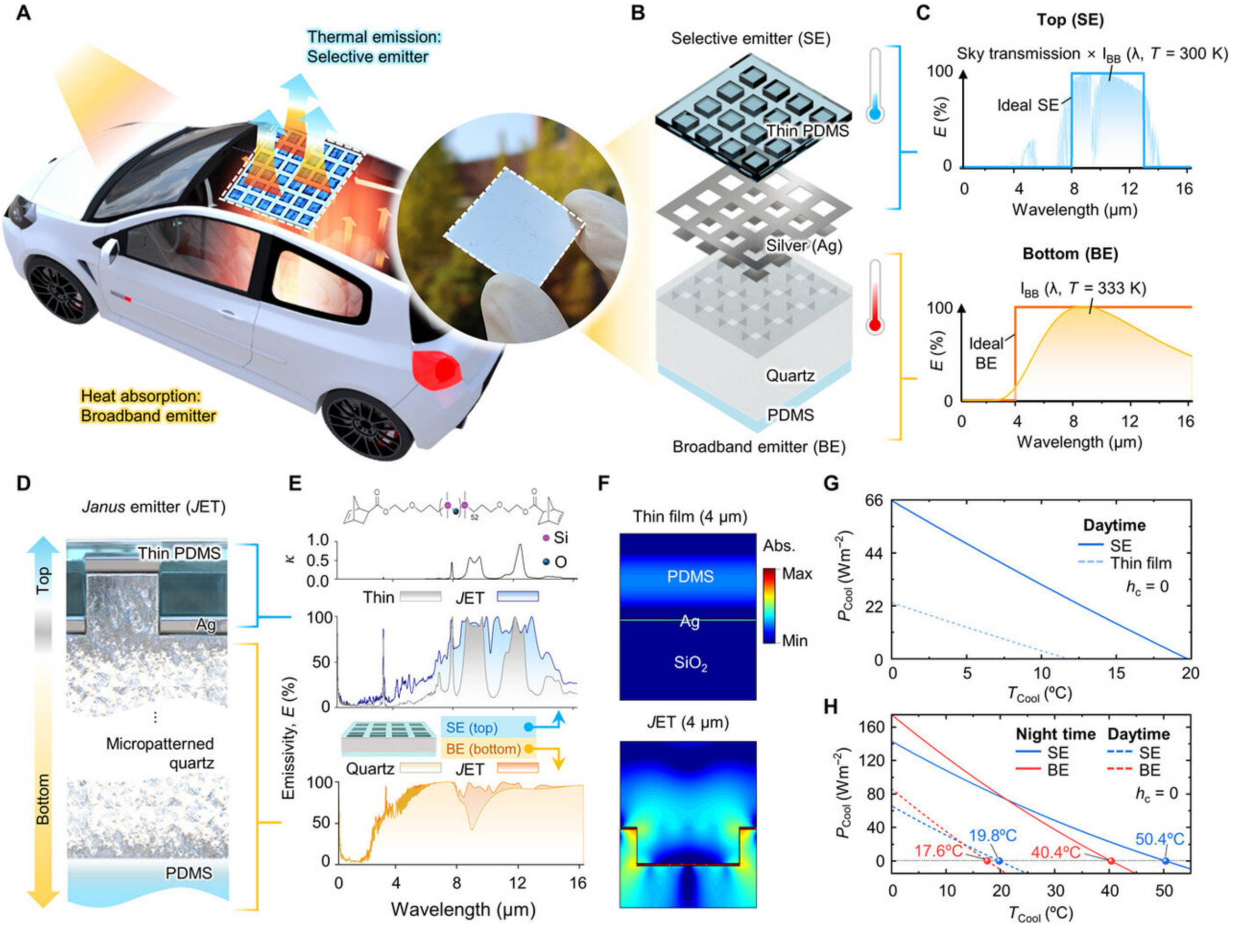
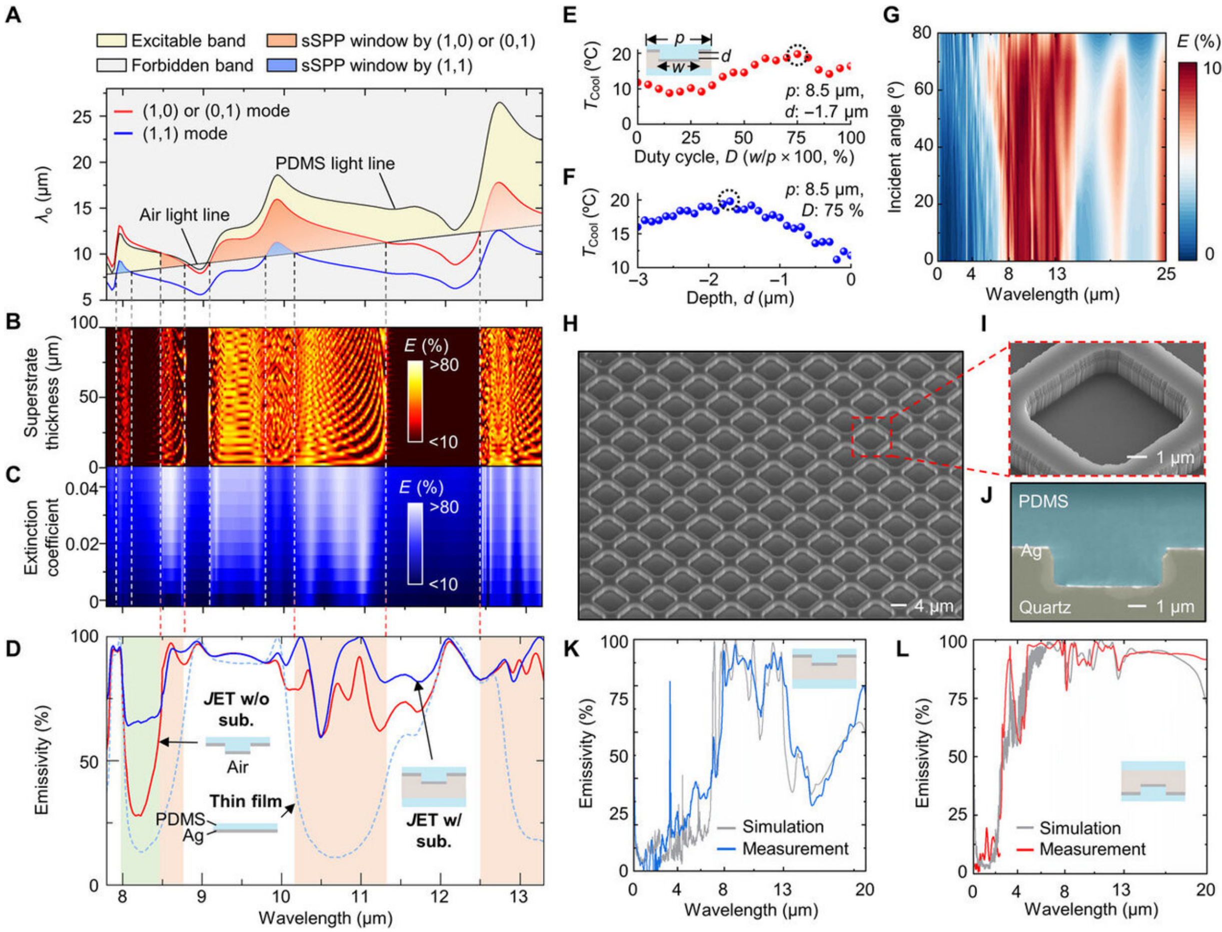


Janue emitter (JET) for cooling enclosed space. (A) Schematic of JET applied to a stationary automobile under direct sunlight, where heat is trapped by the greenhouse effect. The Janus thermal radiation property allows broadband absorption of IR waves from the enclosure and selective emission to the ultracold space. Inset photograph: Fabricated JET exhibiting strong reflection in the visible range. Photo credit: Yeong Jae Kim, GIST. (B) Magnified structural view. From top to bottom: 4-µm PDMS, silver, micropatterned quartz, and 10-µm PDMS. (C) Emission spectra of the ideal JET with broadband emission (BE) on the bottom and selective emission (SE) on the top. BB, blackbody radiation. (D) Cross-sectional schematic view of JET. (E) Top: Polymer structure and extinction coefficient of PDMS. Simulated FIR emission spectra of JET for the SE (middle) and BE (bottom) in the 0- to 16-µm wavelength region. (F) Absorption profiles of thin PDMS (top) and JET (bottom) at 10.75-µm wavelength, where the largest emission loss occurs in thin PDMS. (G and H) Calculated cooling powers (Pcool) and cooling temperatures (Tcool) under AM1.5G solar radiation for (G) PDMS thin film versus SE in daytime and (H) SE versus BE in daytime (dashed lines) and nighttime (solid lines). Credit: Science Advances, doi: 10.1126/sciadv.abb1906

It is presently challenging to efficiently cool enclosed spaces such as stationary automobiles that trap heat via the greenhouse effect. In a new report in *Science Advances*, Se-Yeon Heo and a team of scientists in materials science, engineering and nanoarchitectonics in Japan and the Republic of Korea, presented a Janus emitter (JET) for surface cooling. They used a silver (Ag)-polydimethylsiloxane (PDMS) layer on a micropatterned quartz substrate and the material allowed them to cool the space even when the JET was attached within an enclosure. As a result, the JET (Janus emitter) could passively mitigate the greenhouse effect in enclosures and offer surface cooling performance comparable to conventional radiative coolers.

Cooling technologies

Present-day cooling technologies depend on vapor compression and fluid-cooled systems, but they consume approximately 10 percent of the global energy, while accelerating the depletion of fossil fuels. Between 1990 and 2018, the amount of carbon dioxide (CO_2) emissions from space cooling have more than tripled to reach 1130 million tons, alongside escalating issues of ozone depletion and air pollution. The Earth can cool itself via radiative cooling a passive thermal management strategy to emit unwanted heat to outer space without energy consumption, and passive radiative coolers have shown sub-ambient cooling when attached to exterior materials such as the roof or even human skin to draw heat through convection or conduction in the daytime. However, such strategies can be ineffective during extreme heat accumulation in stationary vehicles, where extremely high temperatures can develop under the greenhouse effect due to transparent windows that allow solar radiation to enter, while being opaque to the exiting long-wave thermal radiation. In this work, Heo et al. proposed a Janus thermal emitter to act as a selective emitter (SE) on the top and as a broadband emitter (BE) on the bottom. The design efficiently drew heat from the inner space and surface, while the top emitted heat to space without disturbing the ambient radiation.

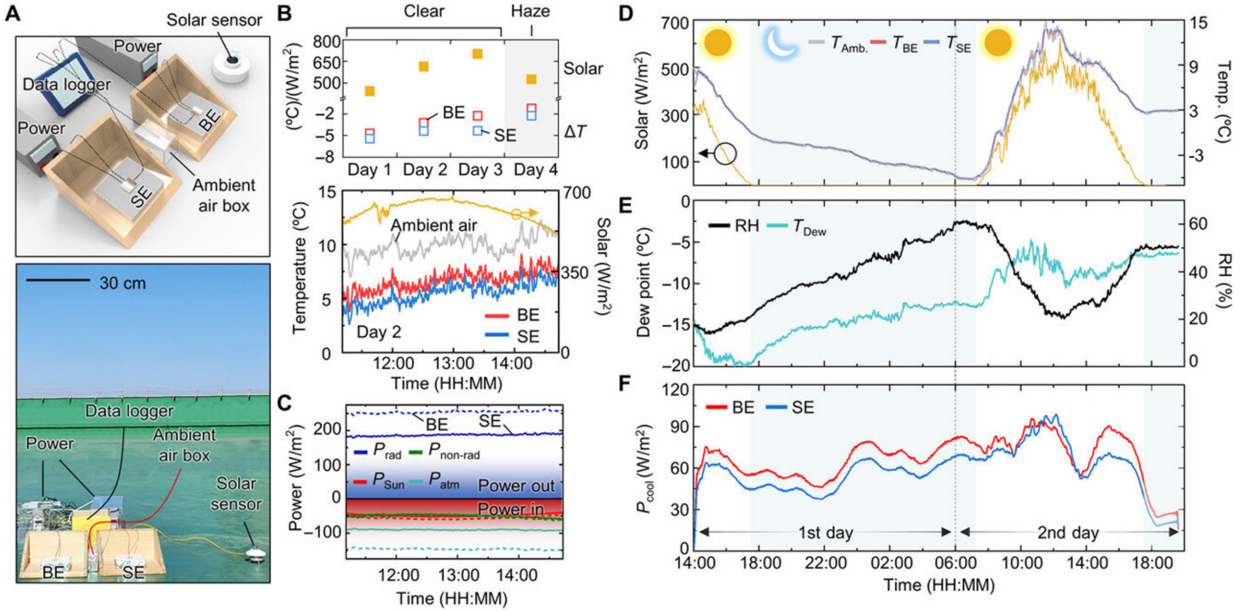


Theoretical analyses, optimization, and characterization of JET. (A) Dispersion curve of sSPP for the superstrate with the refractive index of PDMS. Yellow and gray shaded areas: Excitable band and forbidden band of sSPP determined by air and PDMS light lines, respectively. Orange and bluish shaded regions: sSPP windows from the (1,0)/(0,1) and (1,1) modes, respectively. (B and C) Emissivity spectra as a function of (B) thickness of a non-absorbing superstrate and (C) extinction coefficient of superstrate. These results show that emission enhancements depending on the superstrate thickness and extinction coefficient only occur in sSPP windows, particularly the sSPP window from the (1,0)/(0,1) modes. (D) Emissivity spectra of thin-film PDMS (sky blue dashed line) and JET without and with SiO2 substrate (red and blue lines, respectively). Orange boxes: Areas with enhanced emissivity by sSPP windows. White boxes: Regions with inherently strong emissivity by PDMS owing to high extinction coefficient. Greenish box: SiO2 substrate reinforces the emissivity dip that is uncovered by the sSPP window and strong emissivity region. (E and F) Optimizations of duty cycle and depth. (G) Calculated angular response of JET, showing maintained selective emission feature up to the incident angle of 80°. (H to J) SEM images of optimized JET (H and I) without Ag or PDMS coating and (J) with Ag and PDMS coating. (K and L) Measured and simulated emissivity spectra for the (K) SE and (L) BE of fabricated JET. Credit: Science Advances, doi: 10.1126/sciadv.abb1906

JET for cooling enclosed spaces and sSPP resonance for near-ideal selective emitters

The scientists first designed a polymer-based selective emitter (SE) incorporating spoof surface plasmon polariton (sSPP) to achieve near-ideal selectivity. Then they theoretically and experimentally showed the cooling performances of the Janus emitter (JET) on both sides, much like state-of-the-art radiative coolers. The JET functioned as an effective heat channel to absorb broadband thermal radiation from the interior and bottom, while using the top-side to radiate heat as infrared (IR) waves to outer-space, much like a cold sink. The sample contained a polydimethylsiloxane (PDMS) layer, a 100 nm thick silver layer and a micropatterned quartz layer coated with 10 µm-thick PDMS on the bottom. The JET minimized the disturbance from solar energy and ambient radiation, where the bottom-side broadly adsorbed inner thermal radiation. The team calculated the cooling powers and cooling temperatures for the selective emitter (SE) and broadband emitter (BE) during the study.

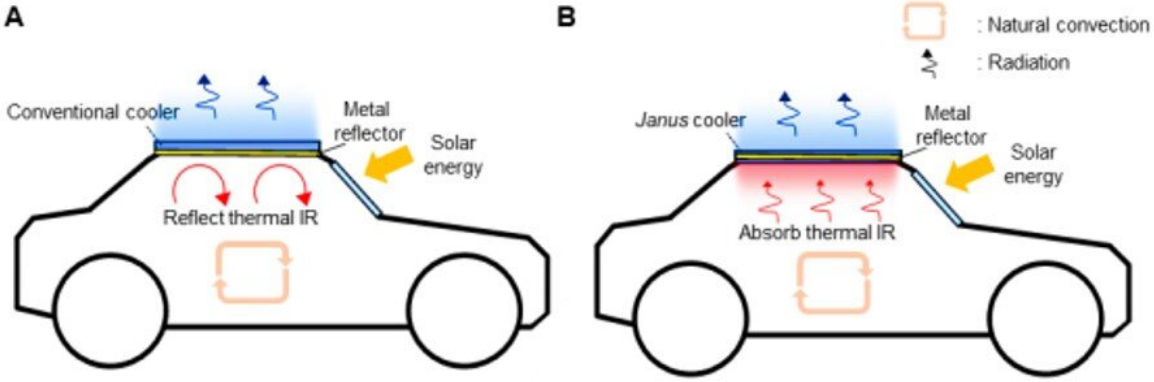
Heo et al. analyzed the effects of spoof surface plasmon polariton (sSPP) resonances on JET emissivity and the simulation showed strong resonant absorption peaks excited between the two sSPP modes, due to the Fabry–Pérot cavity resonance of the setup. The JET showed angle-robust emissivity near the atmospheric window. Using scanning electron microscopy (SEM) images they observed the micropatterned quartz with or without PDMS coating. The measured and simulated emissivity spectra indicated near-ideal features in both selective emitters (SE) and broadband emitters (BE) of the fabricated JET system.



Surface cooling performances of two emitters in JET. (A) (Top) Schematic illustration and (bottom) photograph of the radiative cooler in rooftop test configuration. Ambient air box, which prevents self-heating of air sensor, is shown in fig. S5 (A and B) in detail. Photo credit: Gil Ju Lee, GIST. (B) (Top) Average solar intensity and average cooling temperature (ΔT) of SE and BE in clear and haze days. All data demonstrate that SE has better subambient cooling performance. (Bottom) Detailed logged temperature measured of the result for day 2. (C) Calculated power components in the thermal equilibrium equation (Prad, PSun, Pnon-rad, and Patm) over time, using data in (B). The dashed line indicates BE, and solid line is SE. (D to F) Thirty-hour continuous measurements for (D) solar intensity and temperatures of SE, BE, and ambient air; (E) relative humidity (RH) and dew point; and (F) the cooling power (PCool) of SE and BE. The heating power is generated by the power supply output when the sample temperature matches ambient air. Credit: Science Advances, doi: 10.1126/sciadv.abb1906

Proof-of-concept: Surface cooling performance of JET in SE and BE

To examine the cooling power and cooling temperature of both selective emitters and broadband emitters (SE and BE) in the device, the scientists accessed an outdoor rooftop at the Gwangju Institute of Science (GIST). The team prevented self-heating of the ambient air sensor by using an ambient air box to shade the solar spectrum and provided continuous air flow to the setup. They tested the temperature sensors for reliability and did not use a convection shield due to imperfect transmittance. The results showed sub-ambient cooling under different weather conditions, where haze and humidity inhibited heat transfer to the atmosphere. Heo et al. classified the steady-state energy balance equation into four power terms, including the (1) power emitted by the sample, (2) power absorbed by atmospheric emission, (3) absorbed power of solar irradiation and (4) non-irradiation heat transfer, which included conduction and convection. The SE was more effective during sub-ambient cooling compared to BE. The team measured the cooling power alongside climate conditions during the experiments.

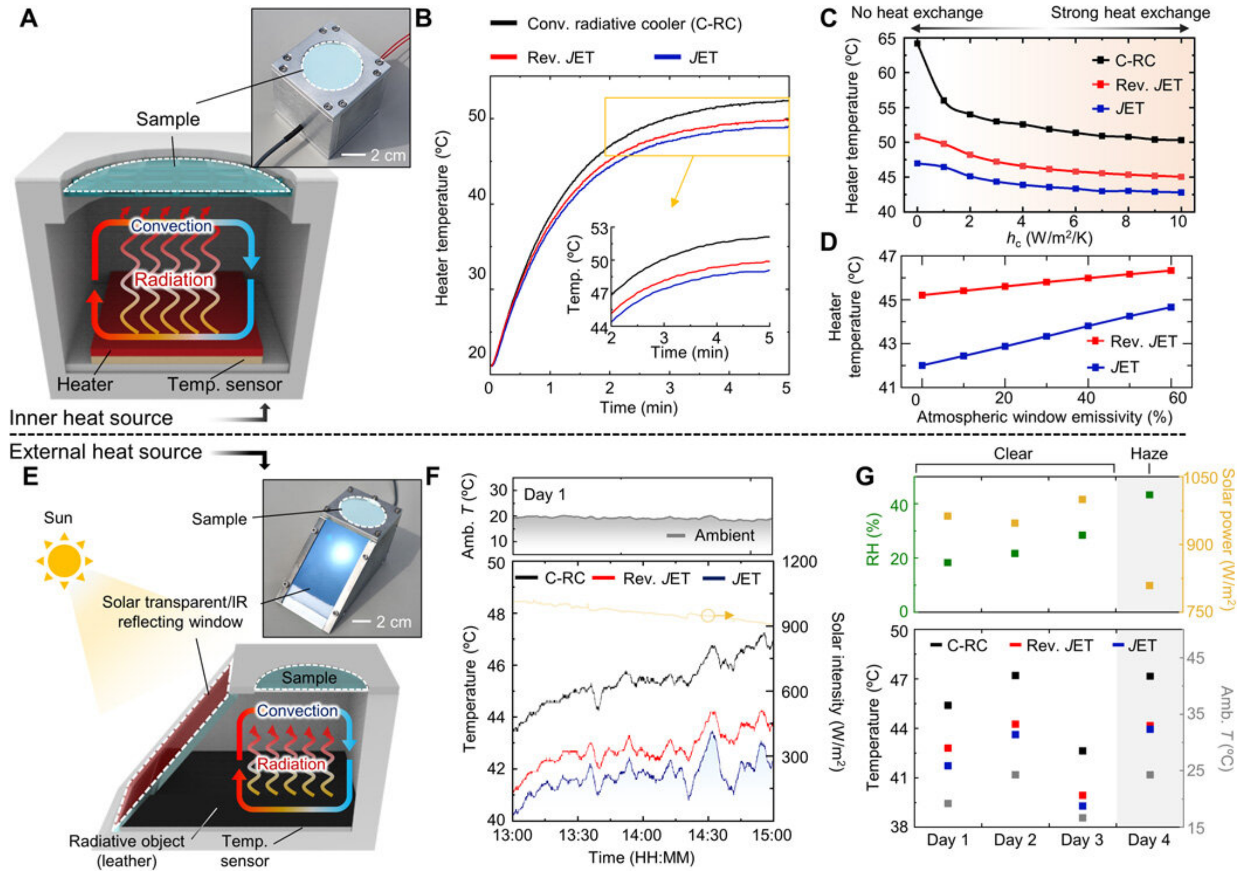


Heat release by JET in stationary vehicles. Schematic comparison of conventional radiative cooler and our Janus emitter for a stationary vehicle. The stationary vehicle accumulates solar energy and becomes extremely heated. (A) The conventional cooler worsens the heating by reflecting the inner radiation and causing the greenhouse effect. (B) The Janus cooler cools the car by broadly absorbing the inner trapped heat and selectively emitting it to the outer space. Credit: Science Advances, doi: 10.1126/sciadv.abb1906

Cooling capability of JET in an enclosed space

Although heat transfer mainly occurs via convection in open areas, the mechanism can differ in an enclosed space with a heating source. For example, an automobile parked under the sun can heat from 60 degrees up to 80 degrees Celsius, although the ambient temperature is only 21 degrees Celsius, causing hyperthermia in occupant children. During Janus thermal radiation, the JET (Janus emitters) can function as a heat channel to draw heat from the enclosure and significantly alter temperature distribution in the inner region. The JET is highly efficient in dropping temperature from the shielded area via broadband absorption and allowing selective thermal emission through the atmospheric window.

The team developed an experimental model using aluminum metal and black leather to mimic a stationary vehicle interior and floor, parked under the sun. They performed the experiment on a rooftop and noted the exceptional cooling performance of JET in the enclosed space repetitively on four different days under different weather conditions. Based on the outcomes, the team proposed replacing the material used here with other polymers for a variety of optimized benefits, including an enhanced overall cooling capacity by minimizing solar power and increasing thermal radiation. The surface properties of the JET also provided water-proofing and self-cleaning effects.



Demonstration of enclosure cooling using the Janus mode of JET. (A) Measurement setup using an inner heater. Photo credit: Gil Ju Lee, GIST. (B) Measured steady-state heater temperature with C-RC, Rev. JET, and JET. The supplied voltage and current to the heater were fixed as 7.5 V and 0.105 A, respectively, for 5 min. The averaged ambient temperatures were 11.6°, 11.3°, and 11.0°C during the measurements of C-RC, Rev. JET, and JET, respectively. Photo credit: Gil Ju Lee, GIST. (C) Simulated heater temperatures considering heat exchange with ambient air for the three radiative coolers. hc = 0 W/m2 per K refers to no heat exchange between the enclosure and ambient air. The conditions of simulations are as follows: heat flux = 4 W, Tamb = 25°C, and atmospheric window emissivity in 8- to 13-µm wavelength = 30%. (D) Simulated heater temperature depending on the atmospheric window emissivity in 8- to 13-µm wavelength for the radiative coolers. Lower emissivity indicates more transparent atmospheric window. The simulation parameters are as follows: heat flux = 4 W, Tamb = 25°C, and hc = 4 W/m2 per K. The detailed emissivity spectra of coolers and atmospheric window are shown in fig. S6C. (E) Schematic setup with heating by external solar radiation in a molded shape of a car. The hole on top of the Al housing is covered by the sample, while the front side is covered by a solar-transparent and IR-reflecting window. (F) Temperatures of the radiative object for different groups of cover materials: C-RC (black), Rev. JET (red), and JET (blue). (G) Measurements for 4 days with different weather conditions of clear and haze. The weather conditions are estimated in terms of solar power (yellow), RH (green), and ambient air temperature (gray). Black, red, and blue respectively mark the temperatures of three coolers. Credit: Science Advances, doi: 10.1126/sciadv.abb1906

In this way, Se-Yeon Heo and colleagues showed how Janus emitters provided a passive strategy for selective emission to outer space, alongside broadband absorption on the opposing side of the enclosure. To accomplish this, they developed an almost-ideal selective emitter (SE) with spoof surface plasmon polariton (sSPP) within a PDMS polymer clad on a silver-coated micropatterned quartz frame for the experiments. They examined the capability of JET to cool enclosures, where it drew heat away compared to other materials. Using the bidirectional emission characteristics of Janus emitters, the team lowered the temperature of a radiative object in an enclosure which simulated a stationary automobile environment. The superior capability to passively cool both top and bottom surfaces as well as enclosed spaces can allow the development of advanced designs to minimize the greenhouse effect in enclosed spaces such as stationary automobiles.

More information: 1. Heo S. et al. A Janus emitter for passive heat release from enclosures, *Science Advances*, 10.1126/sciadv.abb1906

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