All-day radiative cooling with beam-controlled architecture for urban area

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Abstract: Here we report an inexpensive planar polydimethylsiloxane (PDMS)/metal thermal emitter for all-day radiative cooling. In addition, a spectral-selective architecture was designed to suppress solar irradiation and taper the thermal emission.

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Cooling is one of the major energy consumer nowadays and such demand is growing rapidly. For instance, air conditioning consumes ~15 % of the primary energy used by buildings in the United States [1]. Thus, developing an alternative cooling system is one of the most critical issues among the novel energy topic. In recent years, an ancient cooling technology was brought onto the stage due to its non-energy consuming characteristic. The so-called technology, radiative cooling, has been exploited for decades. However, since the solar heating will dominate during the daytime, it is of great challenge to engineer the material's optical characteristics. In 2014, researchers at Stanford University first reported such a photonic structure that can function well during both daytime and nighttime [2]. Several strategies were also reported followed by this pioneering work [3, 4]. In this report, we propose and experimentally demonstrate a PDMS/metal thermal emitter for all-day radiative cooling. A spectral-selective architecture is also implemented to suppress the solar input and taper the thermal radiation. Outdoor experiments were performed in Buffalo, NY, realizing an average 6 °C temperature reduction through 48 hours.

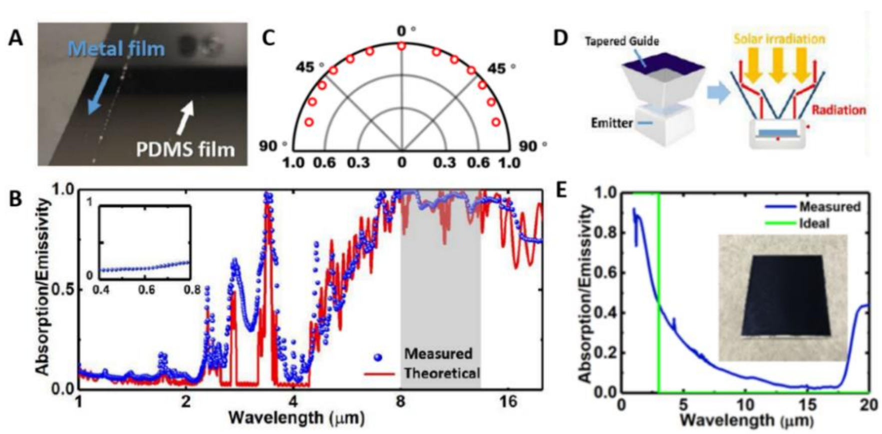

Figure 1. (A) The photo of the planar emitter; (B) The measured (blue dot) and the modeled (red line) absorption spectrum of the planar emitter; (C) The measured angular absorption of planar emitter at 10 μm; (D) The schematic of the beaming structure; (E) The absorption of the selective material in tapered guide.

The earth's atmosphere has a transparent window within the wavelength range from 8 μm to 13 μm, which coincidentally corresponds to the peak thermal radiation spectral range of terrestrial objects at a typical ambient temperature (e.g. ~ 25 °C). Through this window, thermal energy can be transferred from the thermal body to cold outer space. On the other hand, significant energy is brought onto the earth surface by the solar illumination. To achieve daytime radiative cooling, it is essential to engineer the absorption spectrum of the emitter. In this article, we report a planar PDMS/metal thermal emitter that is useful for efficient radiative cooling over large areas. As illustrated in **Fig. 1A**, the emitter is composed of a 150-μm-thick PDMS film on aluminum plate. Both measured and modeled absorption spectrum domain is given in **Fig. 1B**, which exhibit strong absorption in mid-infrared wavelength range and weak absorption in visible-to-near infrared wavelength range. However, even for this relative weak absorption in solar wavelength range, it is still too large due to the high density of the solar irradiation (~1000 W/m^2). In addition, to reveal the angular-dependence of the absorption, the absorption at 10 μm was also measured, as shown in **Fig. 1C**. As one can see, the absorption/emissivity is almost omnidirectional. This angular independence requires an open testing area so that the surroundings won't block the pathway to the outer space. To summarize, not only the solar irradiation will affect the cooling performance, the testing landscape will too. To address this issue, we introduce a selectively absorbing architecture in the cooling system, as shown in **Fig. 1D**. The absorption spectrum of the material is given in **Fig. 1E**, showing a high absorption in visible-to-near infrared wavelength range and weak absorption in mid infrared wavelength range. Ideally, such tapered structure can block all downwards solar irradiation while reflect the thermal emission from the thermal emitter. Moreover, due to the geometric design of the structure, the output radiation can be confined within a certain angle range, showing a better tolerance to the complicated environment. By employing this spectral-selective architecture, it is possible to implement radiative cooling systems in a very complicated environment, for example the urban area where the demand for cooling is significant. Such a discussion has never been made before, since most of the groups are focused on optimizing the material. In next section, we will experimentally demonstrate the beaming effect on radiative cooling.

To illustrate the critical impact of the environment, we measured the temperature reduction of two groups at two different locations in Buffalo, respectively. The test locations' photos are taken by the fisheye camera and given in the inset of **Fig. 2A**, indicating the complexity of the test environment. The temperature was measured in the system that with and without the beaming structure. As one can see, for the group without the beaming structure, the emitter's temperature reduction varied from 2.5 °C to 11 °C as the test environment changed. Meanwhile, for the group with the beaming structure, the temperature reduction was reasonable steady no matter how complicated environment was. These results show that the beaming structure could efficiently eliminate the environmental effects. The weaker performance in open area compared to the other group was caused by the imperfect optical characteristic of the tapered guide, whose further optimization is under investigation but beyond the scope of this work. At last, a 48-hours cooling test was performed in a typical America neighborhood, as shown in **Fig. 2B-C**. Remarkably, the temperature of the beaming structure was always lower than ambient temperature, while the temperature of the control group will increase dramatically above the ambient temperature when exposed to the sun. In general, the beaming group can achieve an average 6 °C cooling performance through the day, which corresponds to ~80 W/m^2 cooling power.

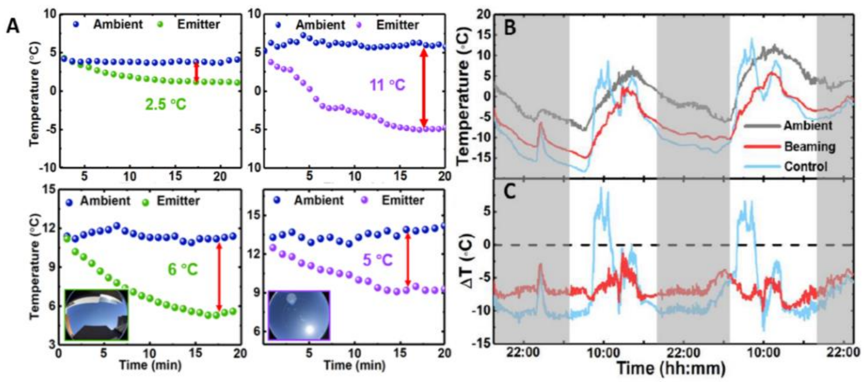

Figure 2. The outdoor cooling test in Buffalo. (A) The cooling at different locations. The upper panel was tested without beaming structure, the lower panel was tested with beaming structure; (B) The 48-hours continuous cooling test. (C) The corresponding temperature reduction in (B).

In summary, we developed a passive cooling technology by exploiting the sky as a cold source. The proposed PDMS/metal emitter is low-cost and suitable for massive production, which is of great value if one intend to implement such kind of technology. In addition, a spectral-selective beaming structure was introduced to improve the sensitivity of the environment. All-day continuous test was performed, demonstrating an effective cooling effect even under the solar illumination. Compared to the traditional cooling technology (e.g. air conditioning), the proposed technology is totally energy-free and operates at a reasonably low cost, showing a great potential in commercial applications.

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