Simple PDMS/AlN emitter as a passive daytime radiative cooling design

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Simple PDMS/AIN emitter as a passive daytime radiative cooling design

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Abstract. Radiative cooling is a passive cooling purpose where a surface naturally cools by radiating the mid-infrared heat radiation to the cold outer space through the atmospheric window $8 - 13\mu m$. Daytime passive radiative cooling technologies can be simply provided by using a multi-layer design that emits strongly in the transparency atmospheric window, while presents high reflectance in the solar spectrum$0.3 - 2.5\mu m$. In this study, we propose a polydimethylsiloxane foil($PDMS$) coated aluminum nitride (AIN) deposed onto silver (Ag) coated glass as a radiative cooler for enhancing both daytime and nighttime radiative cooling performances. The spectral selectivity of the proposed device was obtained using matrix method. Numerical results show that our proposed design can reflect more than 96 % in the solar spectrum, while its average emissivity in the atmospheric window can reach more than 90 %.
In the absence of wind speed, the proposed device can achieve a net cooling power of $107\, W/m^2$ under direct sunlight, cooling to a $27°C$ below the ambient air temperature. At nighttime, the proposed device temperature can drop by $52°C$ below the ambient, leading to a net cooling power of$190\, W/m^2$. Therefore, the proposed radiative design can fundamentally enable new methods for exploiting solar energy harvesting and energy conservation.
Keywords: Passive cooling; sky window; multilayer design; emissivity; net power cooling; Filter.

1. Introduction

Global energy demand for space cooling in buildings is increasing spectacularly by 13% per year [1]. The radiative cooling is the best way to reduce the increasing energy consumption in buildings. Further, radiative cooling is important in the electronic industries. It has become attractive options to be alternative to the active cooling device, which can be applied in thermoelectric converters, photo-thermal (PT) technologies, Photovoltaic (PV) system, electronic heat dissipation, and power plants [2-5].

Radiative cooling or natural cooling is a passive mechanism that can cool the terrestrial objects below the ambient temperature via the atmospheric window without any external driving energy input. As opposed way, the active cooling mechanism needs the energy input. The radiator cooling process is based on the fact that the atmospheric window is transparent between 8 and $13\mu m$ which allows pumping the mid-infrared radiation from radiative cooler surface to the cold outer space. In fact, the earth emits a much energy that is received from the sun [6]. The earth's temperature does not rise consistently. At daytime, the radiative cooling cannot be achieved easily due to extremely high incident solar irradiation. Thus, to achieve radiative cooling during the day, the radiative cooler structure cools to sub-ambient temperature by reflecting the incident solar radiation, while simultaneously emitting the mid-infrared thermal radiation through the transparency atmospheric window [7-9].

In the past decade, environmentally friendly gases and different engineered structures have been developed to provide cooling effects. Passive radiative cooling can be performed with environmentally friendly gas slabs such as ammonia NH_3, ethylene oxide C_2H_4O, and ethylene C_2H_4. These gases possess high emissivity in the atmospheric transparency window, which allows them to be applied as radiative slab designs for radiative purposes [10-11]. Spectral filters, including polyvinyl fluoride plastic and silicon monoxide film on aluminium also have been proposed for radiative cooling applications [12]. In recent years, passive radiative cooling has focused on the periodic nanostructures [13-15], including metamaterials and photonic crystals.

Passive radiative cooling coolers can be classified into two main categories depending on the operating time. Passive nighttime radiative cooling purposes have been widely explored [16-18], while the peak demand for cooling generally occurs during the daytime under the direct sunlight. Thus, daytime radiative cooling has recently attracted a significant attention [13-18]. Previous studies focused on daytime radiative cooling using polymers coating have been developed [22-24]. J. L. Kou et al. [22] designed their radiative cooling device by a polymer-coated fused silica mirror to achieve high radiative cooling performance with a temperature reduction of $8.2°C$ below ambient temperature. Earlier,Yang et al. [23] demonstrated successfully daytime cooling of $11°\mathrm{C}$ below ambient temperature using polytetrafluoroethylene (PTFE) sheet on top of a silver thin film.

It is interesting to notice that a good radiative cooling device should operate at both day and night-times. In this context, we present a radiative-convective design that consists of a polydimethylsiloxane foil $(PDMS)$ coated aluminum nitride (AlN) deposed on top of the reflective silver-coated glass in order to achieve the good radiative cooling performances. The proposed design concept can be applied to a large area, which holds promise for realizing both daytime and nighttime radiative coolers. The paper is organized as follows. In the Section 2, we briefly present the theoretical cooling performance of the radiative cooler. Selectivity spectral of the proposed design as a function of the incidence angles and the thickness of layers are presented and discussed in the Section. 3. Finally, concluding remarks are summarized in Section 4.

2. Model design and modeling methods

2.1 Theoretical thermal analysis

Selective spectral optical properties of the proposed design are vital for providing high radiative cooling performance. In order to obtain the optimized optical properties of the proposed device, we use an analytical approach based on the characteristic matrix method [25]. The matrix method is numerically efficient for modeling selective optical properties of multilayer designs [26-27]. We investigate the cooling power efficiency of the selective radiative cooling device by examining the radiative energy balance of the device. It is assumed that the device of unit area at temperature T is exposed to the incident solar illumination. The ambient atmospheric temperature is denoted as $\mathrm{T_{amb}}$. The power balance of the selective device is a combination of the incident solar irradiance $\mathrm{P_{sol}}$, the incident atmospheric thermal radiation$\mathrm{P_{atm}}$, the radiative power emitted by the device $\mathrm{P_{rad}}$ and the power loss due to the conductive and convective $\mathrm{P_{cond-conv}}$. The net cooling power P_{cool} can be defined as [28-29]

$$\mathrm{P_{cool}(T) = P_{rad}(T) - P_{atm}(T_{atm}) - P_{sun} - P_{non-rad}} \quad (1)$$

where $\mathrm{P_{rad}}$ denotes the radiation power emitted of the device:

$$\mathrm{P_{rad}(T) = A \int_0^{\frac{\pi}{2}} 2\pi\, d\theta \sin\theta \cos\theta \int_0^{\infty} d\lambda\, I_{BB}(T,\lambda)\varepsilon(\lambda,\theta)} \quad (2)$$

with $\mathrm{I_{BB}}$ indicating the spectral radiation of a black body that is defined by Planck's law as:

$$\mathrm{I_{BB}(\lambda, T) = \frac{2hC^2}{\lambda^5} \frac{1}{e^{hc/\lambda K_B T} - 1}} \quad (3)$$

The absorbed power due to the incident atmospheric thermal radiation is

$$\mathrm{P_{atm}(T_{atm}) = A \int_0^{\frac{\pi}{2}} 2\pi\, d\theta \sin\theta \cos\theta \int_0^{\infty} d\lambda I_{BB}(T_{atm}\,,\lambda)\varepsilon(\lambda,\theta)\, \epsilon_{atm}(\lambda,\theta)} \quad (4)$$

The solar absorbed power by the device at angle θ is can be defined as

$$\mathrm{P_{sun} = \int_0^{\infty} d\lambda\, \varepsilon(\lambda, \theta_{sun}). I_{AM1.5}(\lambda)} \quad (5)$$

$\mathrm{P_{non+rad}}$ is the power loss due to convection and conduction, and h_c is the combined thermal coefficient.

$$P_{non+rad}(T, T_{atm}) = h_c(T_{atm} - T) \quad (6)$$

Here, K_B is the Boltzmann constant, c is the speed of light, h is the Planck constant. The solar irradiance $I_{AM1.5(\lambda)}$ is represented by $AM1.5$ spectrum [30]. $\varepsilon(\lambda,\theta)$ is the directional emissivity of the device at wavelength λ. $\varepsilon_{atm}(\lambda,\theta)$ is the emissivity of the atmosphere, which is given by

$\varepsilon_{atm}(\lambda, \theta) = 1 - (t(\lambda))^{1/\cos\theta}$. $t(\lambda)$ represents the atmospheric transmittance in the zenith direction [31].

2.2 Model design

In this study, we seek to enhance the spectral selectivity of our design in order to obtain simultaneously a high emissivity in the atmospheric window and a low emissivity elsewhere. Polydimethylsiloxane ($PDMS$) is a promising polymer for radiative cooling applications; it has been shown to manifest switching between a transparent and a light-scattering. Further, PDMS emits efficiently in the mid-infrared region [16]. The unique properties of aluminum nitride (AIN), such as low dispersion of permittivity, excellent insulator, large direct band gap, and high infrared absorption have made it useful for device cooling applications [32]. The PDMS/AIN double-layers is chosen for the anti-reflective coating leading to enhance the emissivity in the sky window. In this work, we can see how the PDMS/AIN double-layers has a striking effect on passive radiative effect. The coupling between the PDMS/AIN double-layers and the silica layer increase the emissivity peak in $8 - 13\mu m$ region and create additional emissivity peaks on large spectra. In this study, we numerically examine the radiative cooling effectiveness of the PDMS/AIN/Silica/Ag as a passive radiative cooler design. We first calculate the optimized thicknesses of each layer. The proposed design consists of an AIN thin film of $500\ nm$ thickness with $500\ nm$ thick $PDMS$ foil as a top layer and $7\mu m$ thick SiO_2/Ag miroir as a reflector back. The schematic of our design is given in Fig.1. The proposed passive radiative design serves as a key to promoting the advancement of radiative cooling technology, which is can be easily applied to a large area.

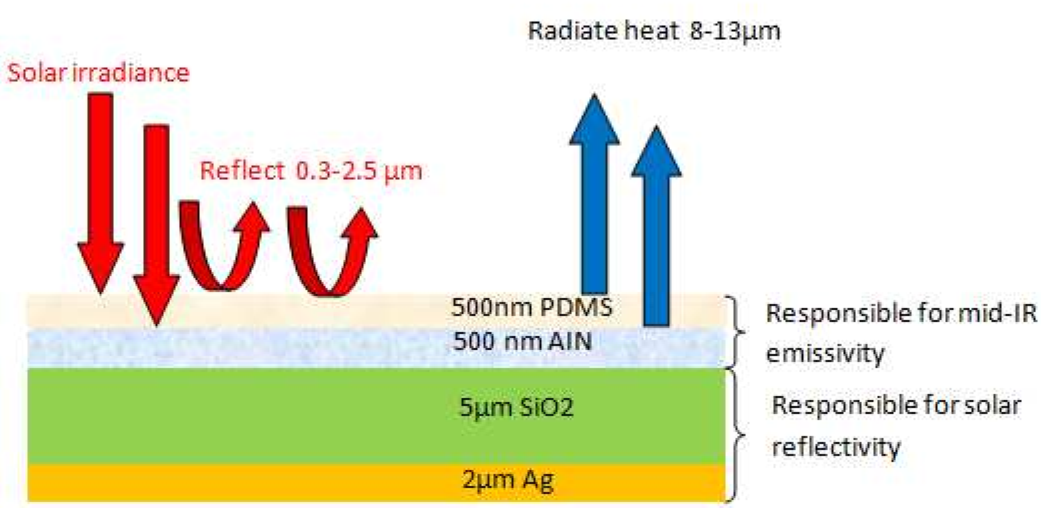


FIG.1. Schematic of the proposed device for high radiative cooling purpose.

3. RESULTS AND DISCUSSION

3.1 Optical properties of the proposed structure

The spectral optical properties of the proposed design were numerically presented in order to evaluate its potential for daytime radiative cooling effect. The air ambient temperature is set to be $300K$. The optical properties have been simulated using the transfer-matrix method [25]. Fig. 2 shows the spectral averaged emissivity over angles of the proposed selective design in $0.3 - 14\mu m$, where the spectral ideal emitter is plotted as reference. The spectral reflectivity is simply determinate by $R = 1 - A$ according to the basic Kirchoff's law leading to the absence of optical loss in the proposed design. It can be seen that the proposed design reaches the lower average absorptivity of 3% in the $0.3 - 6\mu m$ region, where approximately 97% of incident solar illumination is reflected. In addition, the proposed design exhibits a high average emissivity of 90% in the atmospheric transparency window. The high emissivity of the proposed filter in the mid-infrared region is owing to the interference effect [33]. In other way, we show that the proposed design represent also very high reflectivity in the solar region, as depicted in Fig. 3. We note that the proposed design preserve both high reflectivity in the solar spectrum and high absorpitivity in the sky window, such radiative properties values are suitable for enhancing the radiative cooling effect.

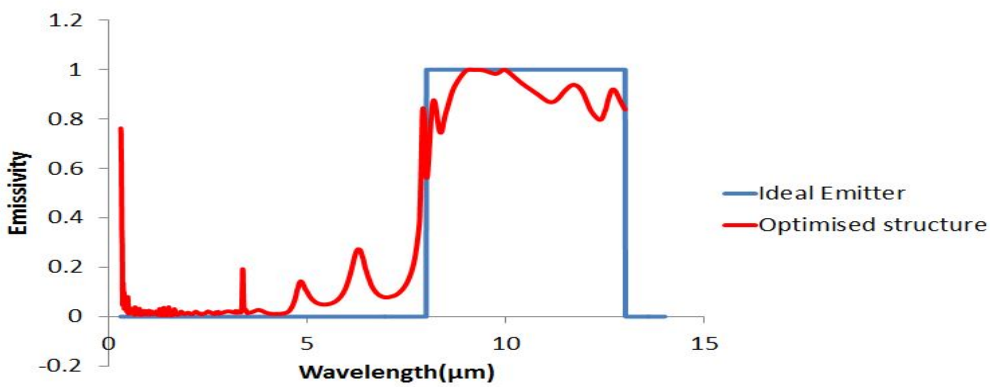


Fig. 2 Spectral emissivity of the proposed selective emitter compared with an ideal selective emitter.

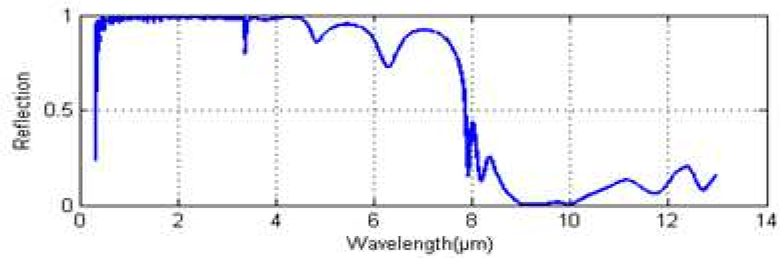


Fig.3. Reflectivity spectra of the proposed selective design from 0.3 to 14μm

It is interesting to explore the optimized design thickness (Quarter-wave stacks). Thickness of each layer in the proposed design is dependent on the optical thickness, refractive index of the layer and angle of the incident wave [19]. The optimized solar segment thickness is 7μm which has a 2μm thick Ag layer coated a 5μm thick SiO_2 layer. To understand the effect of the absorbent segment (PDMS/AIN) thickness on radiative cooling performance, the spectral selectivity of our proposed design which have the thickness of each layer of 300nm, 400nm, and 500nm in the absorbent segment are investigated, as depicted in Fig. 4. As the absorbent segment thickness increase, the emissivity design has gradually increased, particularly in the $8-13\ \mu m$ range. The table 1 presents the average absorption of the proposed design in $8-13\mu m$ range. It should be mentioned that as the thickness of layers increased from $300nm$ to $400nm$, $500nm$ average emissivity values increased from 89.29% to 90.35%, 90.82%, respectively.

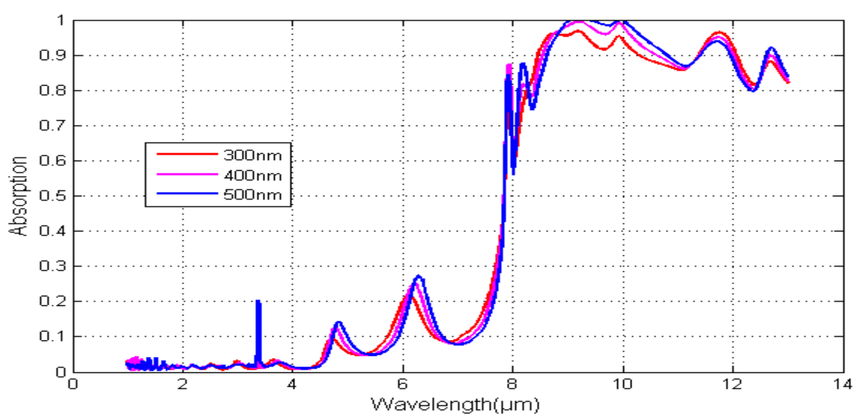
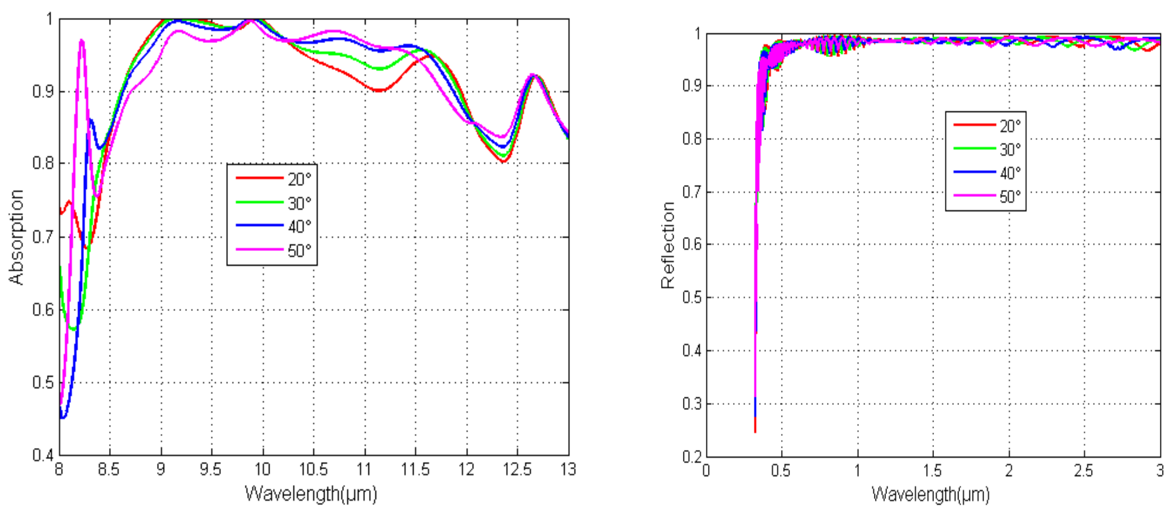


Fig.4. Spectral absorption/emissivity of the absorbent segment with different thicknesses for each layer at wavelength from 1 to 13μm.

Table 1. Average emissivity over angles in the 8-13μm spectrum with respect to absorbent layer thickness for each layer.

Thickness	**Emissivity in 8–13μm**
300 nm	89.29%
400 nm	90.35%
500 nm	90.82%

The spectral behavior of the desired coating is also dependent of the incidence angle. In Fig.5 (a, b), we present show the simulated spectral absorption and reflection of the optimized filter at four different incident angles. As shown in Fig.5 (a, b), both very high reflection in the solar spectrum and very high absorption/emissivity in the sky window is clearly observed at each of specified incident angles of $20°$, $30°$, $40°$ and $50°$. In addition, the average emissivity in the atmospheric window increases gradually as the incidence angle increases. Table 2 summarizes the specific mean absorption and reflection values at four different incident angles. It can be seen that as incidence angles increased from $20°$ to $50°$, the mean absorption values in $8-13\mu m$ range increased slightly to 89.49%, 89.76%,90.44% and 91%, respectively. We observe almost the same average solar reflectivity for all incident angles. We note that the solar spectral behavior of the proposed filter is not changed spectacularly as the angle of incidence changes.



(a) (b)

Fig. 5 (a) The mid-infrared spectral absorption of the proposed filter with different incident angles of $20°$, $30°$, $40°$, and $50°$. (b) The solar refection of the proposed filter at four different incident angles.

TABLE 2. Average reflectance and absorption values in corresponding spectrums with respect incidence angles.

Angle of incidences	Absorption 8-13µm	Reflection 0.3-3µm
20°	89,49%	97,25%
30 °	89,76%	97,14%
40 °	90,44 %	97,08%
50 °	91,00%	97,03%

3.2 Calculated cooling performance

Now we investigate the daytime cooling efficiency analysis of the proposed filter as a function of P_{sun}, P_{rad}, P_{atm} and $P_{non-rad}$ using the Eq. (1). The solar absorbed power $P_{sun}$is calculated for a wavelength ranging from 0.3 to $2.5\mu m$ with direct normal solar irradiation$I_{AM1.5}(\lambda) = 900\, W/m^2$. The atmospheric absorbed power P_{atm} and the radiative power P_{rad} are estimated in a wavelength ranging from$4 - 13\mu m$. The power loss due to convection and conduction is estimated at three different combined non-radiative heat gain coefficients $h_c = 0, 6, 12\ \mathrm{W/m^2K}$ [34]. Fig. 6 (a, b) depicts the calculated net cooling power at fdaytime and nighttime, respectively. The air ambient temperature is set to be300K. The daytime net cooling power as a function of T_{sample}(surface temperature) based on the emissivity/absorpitivity spectra is presented in Fig. 6a. For the non-radiative heat gain coefficient taken as $0\ W/m^2$ [22], the proposed design can reach a thermal equilibrium temperature (the cooling power is equal to zero) of $273K$ under direct solar irradiation. It can be seen that the proposed filter achieves a net cooling capacity of $107\, W/m^2$at ambient temperature. The proposed passive radiative cooler can reach a thermal equilibrium temperature of $293K$ and $290K$ at $h_c = 6\, W/m^2K$ and$h_c = 12\, W/m^2K$, respectively. Note that the net cooling power is decreased monotonically with the temperature of the proposed filter value declining. Fig. 6b plots the nighttime net cooling power changing versus the temperature of the proposed design. For the non-radiative heat transfer $h_c = 0\, W/m^2K$, the net cooling power is over $190\, W/m^2$ at ambient temperature, with an equilibrium temperature of $246K$. This high net cooling power is attributed to the good emissivity spectral of the proposed passive radiative cooler, which is better than our previous findings [8]. As shown in Fig. 6b, the thermal equilibrium temperature is cooled by is cooled by $-18°C$ at $h_c = 6\, W/m^2K$ and $-12°C$ at $h_c = 12\ W/m^2\, K$.

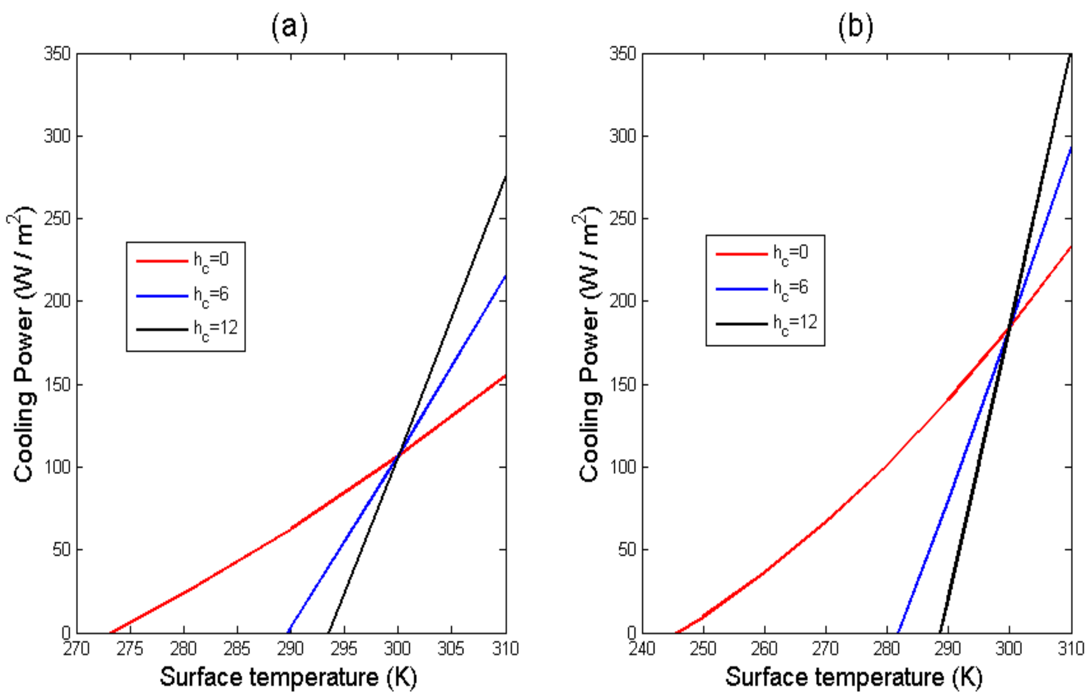


Fig. 6.Theoretical cooling power performances versus the proposed design temperature with non-radiative heat exchange. (a) Daytime cooling performance. (b) Nighttime cooling performance.

4. CONCLUSION

By combining an absorptive triple–layer $PDMS/AIN/$Silica coatings with a miroir reflector made of Ag thin film, this study demonstrates that the proposed filter can reach highly efficient daytime and nighttime passive radiative cooling performances. The proposed filter is an excellent spectral selective emitter in the atmospheric window and strongly reflective in the solar spectrum. Our proposed design may have large area practical applications due to its excellent mechanical properties to changing humidity and its good optical behaviors. The proposed design can operate even if the effect of conductive and convective heat transfer exchange is considered.

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