Simple Double-Layer Coating for Efficient Daytime and Nighttime Radiative Cooling

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Abstract: The passive radiative cooling approach refers to the physical process that pumps heat into outer space via the atmospheric window (8–13 µm) without energy input. The ability to continuously adjust the emissivity of thermal emitters in the sky window while maintaining high reflectivity in the solar spectrum remains a challenge. In order to achieve this task, a novel design referred to as double-layer nanoparticle-based coating is proposed. Our proposed emitter is appropriate for both high solar reflection and strong mid-infrared emissivity. The bottom and top layers are Al2O3 embedded with Ni nanoparticles and a super-hydrophilic TiO2-SiO2 layer. The bottom layer is designed to achieve high emissivity in “the atmospheric transparency window”. The top layer is designed to block solar illumination and to favor an enhanced cleanability of the coated design. Our double-layer coating as an optical solar reflector has excellent solar irradiation (0.96) and is strongly emissive (0.97) across the “full sky window” at room temperature. Furthermore, a detailed numerical energy study has been performed, evaluating the temperature reduction and the radiative cooling performance under different conditions. The proposed simple coating can be used as an efficient radiative cooler on a large scale for energy conservation and thermoelectric devices.

Keywords: radiative cooling; nanoparticle embedded coating; emissivity; transfer matrix method; net cooling power; Al2O3; TiO2-SiO2

1. Introduction

Radiative heat dissipating from Earth to outer space is a universal research topic that can have a vital impact on global energy consumption. Passive daytime radiative phenomena have become an important topic recently because of their potential application in space technology, architecture, vehicle-making, and so on. Passive radiative cooling is a promising mechanism to maintain the temperature of Earth’s surface, which can usually be applied to spacecraft thermal control, thermal management of buildings, thermoelectric cooling, and cooling of solar cells [1−5]. While two other transparency windows exist, 4–5 µm and 16–26 µm, the atmosphere transmits about 87% of the outgoing mid-infrared thermal radiation from the Earth in the “famous” window (8–13 µm) [6]. While the passive radiative cooling process is generally present in nature, the natural radiative materials usually provide a low potential pathway to approach cooling abilities. Most of these radiative materials are not able to achieve both high solar reflection and strong mid-infrared thermal radiation emissivity only in the atmospheric window to avoid exchanging the thermal radiation with the atmosphere [7]. Scientific research on passive radiative cooling can be separated into two main modes: radiative cooling during nighttime and radiative cooling during daytime. The first one has been studied widely and extensively and can be traced back several centuries [8−10]. The second mode has received great attention in recent years [11−13]. The nighttime radiative, or nocturnal, cooling process neglects solar radiation. However, daytime radiative cooling has been achieved under direct sunlight and...
is more useful as cooling demand peaks during daytime hours. Currently, the strategy of radiative sky cooling occurs by backscattering solar radiation and pumping mid-infrared thermal radiation from the radiative, resulting in continuous sub-ambient cooling during both day and night.

Recently, a radiative cooling design has been proposed by Kong et al. [14]. Great efforts have been made to achieve a high cooling performance by enhancing the solar radiation reflectance and emitting strongly mid-infrared thermal energy via the famous atmospheric transparency window. Their daytime passive radiative cooler consisted of porous anodic aluminum oxide deposited on the Al substrate back reflector, resulting in 99% reflectance of solar illumination and an average emissivity of about 95% in the mid-infrared atmospheric window. This composite structure shows a potential cooling power density of 64 W/m² at ambient air temperature and experimentally provides a potential of cooling 2.6 °C below the ambient. By using a cost-effective double-layer coating embedded with nanoparticles that is shielded from direct sunlight, Huang et al. [15] combined more than 90% of the solar illumination with a strong emissivity in the atmospheric transparency window larger than 90%. A daytime net cooling power of 100 Wm⁻² was obtained. In 2014, Raman et al. first experimentally demonstrated that a photonic device consisting of seven layers of HfO₂ and SiO₂ on top of the Ag substrate reflector can emit 65% in the atmospheric window and reflect 97% solar irradiance. Raman et al. obtained a 5 °C reduction below the ambient temperature under direct solar illumination irradiance and achieved a 40 Wm⁻² net cooling power. In addition, J. Kou et al. [13] numerically demonstrated that a polymer-coated fused silica mirror, as a near-ideal emitter in the mid-infrared, achieves 8.4 °C below the ambient temperature at daytime and 8.2 °C at nighttime. In addition, Zhai et al. [16] demonstrate effective daytime radiative cooling, with a silver substrate covered by a kind of metamaterial consisting of TPX coatings for passive daytime radiative sky cooling. A solar reflectance of 96% and 93 W/m² net cooling power were reported for this glass-polymer hybrid metamaterial. Even if the photonic and plasmonic surface technologies can enhance high emissivity, it is still quite challenging to widely apply such surfaces in real applications [17,18]. For practice, the photonic and plasmonic surface technologies may have cost and efficiency issues.

In this paper, to achieve the daytime cooling performance with high solar reflection and strong infrared emissivity within the two atmospheric transparency windows, a double-layer nanoparticle-based coating is presented and numerically investigated. The TiO₂ - SiO₂ top layer serves as low-cost, anti-reflective, and self-cleaning coating (hydrophobia). Overall, the high absorption of our radiative cooler can be attributed to the highly absorbent nickel–alumina layer. The Ni - Al₂O₃ layer is responsible for the high mid-IR emissivity in the transparency atmospheric widow. When placed on an aluminum substrate, this double-layer coating has a strong solar reflection while maintaining a desired emissive property across the famous “sky window” region. The spectral radiative properties of our proposed cooler are calculated using the transfer matrix formulation, considering the effect of the filling ratios, incidence angles, and the coating thicknesses.

2. Computational Method

In our numerical modeling, the design and optimization of double-layer nanoparticle-based coating was carried out using the characteristic matrix method [19,20]. It is a powerful tool in the analysis of light propagation via multilayered thin films [21,22] and is often referred to as thin-film optics. The optical properties of multilayer thin films depend not only on the optical properties of each material but also on their electromagnetic behavior. The fundamental idea lies in the fact that the components of electric or magnetic fields in the position of first boundary can be related to those in the next one or others via the transfer matrix.
According to the boundary conditions, the characteristic matrix of \( j \) layers is defined as:

\[
\begin{pmatrix}
  E \\
  H 
\end{pmatrix} = \left\{ \prod_{r=1}^{j} \begin{bmatrix}
  \cos \varphi_r & \frac{i}{\sqrt{q_s}} \sin \varphi_r \\
  i q_r \sin \varphi_r & \cos \varphi_r 
\end{bmatrix} \right\} \begin{bmatrix}
  1 \\
  q_s
\end{bmatrix},
\]

(1)

where \( \varphi_r = 2\pi N_r d_r \cos \theta / \lambda \) is the phase factor, \( \theta \) is the incident angle, \( d_r \) is the thickness of the \( r \)-th layer, \( N_r \) is the refractive index of the \( r \)-th layer, and \( \lambda \) is the wavelength.

Here, \( E \) and \( H \) are the normalized electric and magnetic fields across the boundary respectively. Optical admittance \( q_r \) of the \( r \)-th layer is defined as:

\[
q_r = N_r q_0 \cos \theta, \quad \text{For } s \text{ polarized light}
\]

(2)

\[
q_r = N_r q_0 / \cos \theta, \quad \text{For } p \text{ polarized light}
\]

(3)

where \( q_0 \) is the optical admittance in free space. \( q_s \) is the substrate admittance, which can be expressed by:

\[
q_s = N_s q_0 \cos \theta, \quad \text{For } s \text{ polarized light}
\]

(4)

\[
q_s = N_s q_0 / \cos \theta, \quad \text{For } p \text{ polarized light}
\]

(5)

When the normalized electric and magnetic fields, \( E \) and \( H \), are derived by iterative procedure, the reflectance and absorbance are calculated as:

\[
R = \frac{q_0 E \cdot H}{q_0 E + H} \left( \frac{q_0 E - H}{q_0 E + H} \right)^* \quad \text{(6)}
\]

\[
A = \frac{4q_0 \text{Re}(EH^* - q_r)}{(q_0 E + H)(q_0 E + H)} \quad \text{(7)}
\]

where \((\cdot)^*\) denotes a complex conjugate.

### 3. Structure Design

The schematic of the investigated double-layer coating design is shown in Figure 1. On the top, we find the super-hydrophilic TiO\(_2\)-SiO\(_2\) composite. The self-cleaning layer TiO\(_2\)-SiO\(_2\) is expected to reject visible and near-IR spectra. At the same time, the self-cleaning layer exhibits extremely low mid-infrared reflectance in order to reject the thermal radiation emitted by the top layer. The super-hydrophilic TiO\(_2\)-SiO\(_2\) sol-gel is not absorptive in most of the solar spectra because of their intrinsic mid-infrared thermal emission properties [23]. The radiative cooling in our proposed cooler is assisted by the optical Tamm resonance structure (Ni-Al\(_2\)O\(_3\)) [24]. The Al\(_2\)O\(_3\) embedded with a Ni nanoparticle at the bottom is designed to enhance high emissivity in the “atmospheric window” in order to evacuate mid-infrared radiation from the structure. High emissivity is reached for nickel–alumina composites with a nickel content varying from 60 to 80% [25]. The addition of Ni is known to stabilize Al\(_2\)O\(_3\) for high-temperature applications and was also found to improve high mechanical resistance [26]. Transmission electron microscopy (TEM) study has shown that the Ni particle size is of the order of 5–10 nm [27,28]. The aggregate sizes are thus much smaller than the wavelength of the radiation in the solar and mid-infrared regions (0.3 \(\mu\)m–14 \(\mu\)m).

The dielectric functions of composite films such as Ni-Al$_2$O$_3$ and TiO$_2$-SiO$_2$ layers are usually derived from models such as Bruggeman theory effective medium approximations [24]. The distribution of Ni particles was randomly in the alumina (Al$_2$O$_3$) layer, and the Bruggeman approximation was applied to estimate the effective refractive index.

$$f_{\text{Ni}} \frac{\varepsilon_{\text{Ni}} - \varepsilon_{\text{eff1}}}{\varepsilon_{\text{Ni}}} + 2\varepsilon_{\text{eff1}} = (1 - f_{\text{Ni}}) \frac{\varepsilon_{\text{Al}_2\text{O}_3} - \varepsilon_{\text{eff1}}}{\varepsilon_{\text{Al}_2\text{O}_3} + 2\varepsilon_{\text{eff1}}}$$ \hspace{1cm} (8)

where $\varepsilon_{\text{Ni}}$ is the complex dielectric function for Ni [29], and $\varepsilon_{\text{Al}_2\text{O}_3}$ is the complex dielectric function for alumina. The effective medium dielectric function of Ni-Al$_2$O$_3$ composite is denoted $\varepsilon_{\text{eff1}}$, and the filling fraction (volume fraction) of c is denoted $f_{\text{Ni}}$(FF). On the other hand, the TiO$_2$ and SiO$_2$ composite layer could also, consequently, be considered as an effective medium component according to the Bruggeman model based on the following equation:

$$f_{\text{TiO}_2} \frac{\varepsilon_{\text{TiO}_2} - \varepsilon_{\text{eff2}}}{\varepsilon_{\text{TiO}_2}} + 2\varepsilon_{\text{eff2}} = (1 - f_{\text{TiO}_2}) \frac{\varepsilon_{\text{SiO}_2} - \varepsilon_{\text{eff2}}}{\varepsilon_{\text{SiO}_2} + 2\varepsilon_{\text{eff2}}}$$ \hspace{1cm} (9)

where $\varepsilon_{\text{TiO}_2}$, $\varepsilon_{\text{SiO}_2}$, and $\varepsilon_{\text{eff2}}$ represent the dielectric function of TiO$_2$, SiO$_2$ and effective medium $\varepsilon_{\text{eff2}}$ respectively. $f_{\text{TiO}_2}$(FF) is the filling fraction of TiO$_2$.

The real part $\varepsilon_{\text{eff1}}$ and imaginary part $\varepsilon_{\text{eff2}}$ of the dielectric constant $\varepsilon_{\text{eff1}}$ of Ni-Al$_2$O$_3$ are shown in Figure 2. We note that the Nickel–alumina composite has phonon-polariton resonance optical absorptions at the far-IR window [30]. We observe that the second loss peak at 17.5 micron is out of the primary far-IR atmosphere widow. The real part $\varepsilon_{\text{eff1}}$ and imaginary part $\varepsilon_{\text{eff2}}$ of the effective medium dielectric function $\varepsilon_{\text{eff1}}$ of TiO$_2$ - SiO$_2$ composite is shown in Figure 3. As shown in Figure 3, the real part $\varepsilon_{\text{eff2}}$ and imaginary part $\varepsilon_{\text{eff2}}$ decrease with decreasing wavelength from 0.3 to 9 $\mu$m, implying dielectric behavior. We can observe an absorption bulge at 9 $\mu$m due to O - Si - O bending vibration.
4. Optimize the Filling Ratio of a Nanoparticle-Based Double-Layer Coating

4.1. Effect of Filling Fraction of TiO$_2$-SiO$_2$

Although the goal of this section is to enhance the passive radiative cooling ability of the proposed design, the optimization of spectral properties at different filling ratios seems to be absolutely necessary, especially for designs with many layers. Thus, the optimized spectral emissivities of the double-layer nanoparticle-based coating are mainly related to the filling fraction and thickness of each layer. According to Kirchhoff’s law of thermal radiation [31], the spectral absorption equals the spectral emissivity at thermodynamic equilibrium. In order to investigate the filling ratio effect of TiO$_2$-SiO$_2$, we first fix the filling fraction of Ni-Al$_2$O$_3$ as FF = 0.8. Figure 4 shows the emissivity/absorptivity spectrum at filling ratios from 0.6 to 0.9 of TiO$_2$-SiO$_2$ with a fixed filling ratio (FF = 0.8) of Ni-Al$_2$O$_3$ for normal and oblique incidences. It is evident that a clear relationship between the spectral emissivity profile and filling ratio of TiO$_2$-SiO$_2$ is observed. Notably, the low spectral emissivity profile in the wavelength from 0.3 to 6 µm does not change, while the intensity...
of the emissivity in the range from 8 to 13 µm changes with the increase in filling ratios for both normal and oblique incidences.

Figure 4. Effect of filling ratios for the selective emitter: Spectral averaged emissivity at filling ratios from 0.6 to 0.9 of TiO$_2$-SiO$_2$ with a filling ratio (FF = 0.8) of Ni-Al$_2$O$_3$. (a) Left-hand side of column indicates a normal incidence and (b) right-hand side of column indicates an oblique incidence.

4.2. Effect of Filling Fraction of Ni-Al$_2$O$_3$

Figure 5 provides the absorptivity/emissivity spectrum of filling ratios from 0.6 to 0.9 of Ni-Al$_2$O$_3$ with a fixed filling ratio (FF = 0.8) of TiO$_2$-SiO$_2$ for normal and oblique incidences. It can be seen that the absorptivity in the wavelength from 0.3 to 6 µm is low enough (high reflectivity) when the filling fraction reaches 0.8 for both normal and oblique incidences, while the emissivity/absorptivity profile in the range from 8 to 13 µm does not change with the increase in filling ratios for both normal and oblique incidences. The Ni-Al$_2$O$_3$ layer not only provides high emissivity within the atmospheric window spectrum, it also guarantees a low solar absorptivity. At FF = 0.8, the double-layer coating has nearly blackbody-like unit emissivity from 8 to 13 µm, and that can exhibit high reflectivity (low emissivity) at short wavelengths, especially for normal incidence. It has been demonstrated that the optimal filling fraction (FF = 0.8 for both layers) will correspond to a good cooling performance.

Figure 5. Effect of filling ratios for a double-layer selective emitter: (a) Spectral averaged emissivity at filling ratio from 0.6 to 0.9 of Ni-Al$_2$O$_3$ with a filling ratio (FF = 0.8) of TiO$_2$-SiO$_2$. (a) Left-hand side of column indicates a normal incidence (b) and right-hand side of column indicates an oblique incidence.
5. Optical Properties of the Proposed Cooler Structure

Figure 6 shows a contour plot of the spectral averaged emissivity for a simple coating selective emitter as a function of incident angle, wavelength, and thickness. As shown in Figure 6b, the maximum area can be 3.5–5 µm for the first cermet layer (SiO$_2$-TiO$_2$), and a range of 6–8 µm for the second layer (Ni-Al$_2$O$_3$). In the same way, the calculation allowed us to obtain the optimized thickness layer of 7.5 µm and 4.5 µm for the Ni-Al$_2$O$_3$ and SiO$_2$-TiO$_2$, respectively. By using these optimized thicknesses, the angle-dependent emissivity spectral versus the wavelength are plotted in Figure 6a, which reveals that the steady-state emissivity remains higher even at a large incident angle of up to 75°. Therefore, the spectral emissivity of the proposed emitter shows a relatively broadband high emissivity of 8–13 µm, which covers the whole transparency atmospheric window.

The spectral emittance, reflectance, and transmittance of the proposed emitter are shown in Figure 7. We note that the absorbed solar power of our structure remains well below 10%. The proposed selective emitter is appropriate for both high solar reflectance and strong mid-infrared emissivity. The high reflectance of the simple coating emitter in the 0.3–5 µm band is mainly due to the strong scattering effect of TiO$_2$ particles, which disappears progressively with the increase in wavelength. It was found that our proposed emitter exhibits good spectral selectivity from the solar region to mid-infrared spectrum. The high broadband emissivity achieved is mainly caused by the combination of the optical properties of each layer and interference effects.
6. Principles of Passive Radiative Cooling Performance

In general, all objects emit and absorb radiation continuously. The solar radiation on a body is partially reflected, absorbed, or transmitted. The temperature-dependent emissivity is given by Planck’s law of blackbody radiation. A body that fully absorbs the radiation it receives is a black body; the spectral radiance of a black body is defined by Planck’s law at any temperature T:

\[
I_{BB}(\lambda, T) = \frac{2hC^2}{\lambda^5} \frac{1}{e^{\frac{hC}{k\lambda T}} - 1}
\]

where \( h \) is Planck’s constant, \( c \) is the speed of light in a vacuum, \( k \) is Boltzmann’s constant, and \( \lambda \) is the wavelength. The effect of solar irradiance is important for the evaluation of radiative cooling performance. \( I_{AM1.5}(\lambda) \) is the \( AM_{1.5} \) spectrum distribution of solar irradiance. A solar spectral irradiance \( AM_{1.5} \) (ASTM-173) spectrum profile is shown in Figure 8 [32].
Figure 8. (ASTMG173) solar spectrum and irradiance of a blackbody at 5800 K.

The atmospheric transmittance is a consequence of the vibration of its molecules, such as nitrogen, oxygen, carbon dioxide, water vapor, etc. On the other hand, the transparency of the atmospheric window is quite sensitive to the water vapor concentration. The angle-dependent emissivity of the atmosphere is given by:

\[ \varepsilon_{atm} = 1 - \left( t(\lambda) \right) \cos \theta \]  

where \( \theta \) is the angle emission and \( t(\lambda) \) is the atmospheric transmittance in the zenith direction, which is obtained from atmospheric modeling Modtran/PcModWin [33].

The atmospheric spectral distribution of the sky window (8–13 \( \mu \)m) is quite similar to that of a black body at 300 K, as depicted in Figure 9b. This part of the spectrum known as the “atmospheric transparency window”, provides extremely high mid-infrared transmittivity. It can be seen from the above that the spectral atmospheric transmittance has two transparency windows in the region of 7–14 \( \mu \)m and 16–26 \( \mu \)m. However, only the first transparency window can be utilized for pumping mid-infrared radiation due to the spectral irradiance broadband profile of the black body.

Figure 9. (a) The computed atmospheric transmittance spectrum, computed using Modtran/PcModWin model (shaded blue) and (b) the computed spectral irradiance of a black body at 300 K (shaded black).
In the following, the fundamental principles of passive radiative cooling, including theoretical models, calculations, and corresponding discussions, are detailed. The net cooling power density $P_{\text{Net}}$ per unit radiative surface area at temperature $T$ with the ambient temperature $T_{\text{amb}}$ is expressed by [34]:

$$P_{\text{Net}}(T) = P_{\text{Rad}}(T) - P_{\text{Atm}}(T_{\text{atm}}) - P_{\text{Sun}} - P_{\text{Nonrad}}$$ (12)

in Equation (13)

$$P_{\text{rad}}(T) = A \int_0^{\frac{\pi}{2}} 2 \sin \theta \cos \theta \ d\theta \int_0^\infty d\lambda I_{BB}(T, \lambda) \epsilon(\lambda, \theta)$$ (13)

is the radiative power emitted by the proposed cooler.

$$P_{\text{Atm}}(T_{\text{atm}}) = A \int_0^{\frac{\pi}{2}} 2\pi \ d\theta \ \sin \theta \cos \theta \ \int_0^\infty d\lambda I_{BB}(T_{\text{atm}}, \lambda) \epsilon(\lambda, \theta) \epsilon_{\text{atm}}(\lambda, \theta)$$ (14)

is the atmospheric power radiation absorbed by the proposed cooler.

$$P_{\text{sun}} = \int_0^\infty d\lambda c(\lambda, \theta_{\text{sun}}) \cdot I_{\text{AM1.5}}(\lambda)$$ (15)

is the power density of solar radiation absorbed by the proposed cooler.

$$P_{\text{Nonrad}} = q_c (T_{\text{amb}} - T_{\text{sample}})$$ (16)

is the power density of non-radiative heat exchange from the sample.

Here, $q_c$ is the combined non-radiative heat transfer coefficient of convection and conduction. $\epsilon(\lambda, \theta)$ is the directional emissivity of the proposed emitter at the wavelength $\lambda$.

At night, the proposed cooler cannot be affected by solar irradiance. Thus, the net cooling power can be expressed as:

$$P_{\text{Net}}(T) = P_{\text{Rad}}(T) - P_{\text{Atm}}(T_{\text{atm}}) - P_{\text{Nonrad}}$$ (17)

The mid-infrared emissivity of the proposed cooler design is dependent on the amount of water vapor in the atmospheric transparency window. In this paper, the water vapor is taken as 1 mm, and the air mass is assumed to be AM1.5 illumination. The validity of our transfer matrix method code is tested in the published study [35].

The calculated net cooling performance of the optimized proposed cooler is studied by taking non-radiative heat exchange, such as conduction and convection, into account [35,36]. Figures 10 and 11 present the net-cooling power performances at daytime and nighttime versus radiative cooler temperature, respectively. The heat coefficient $q_c = 0$ means that the effect of conductive and/or convective heat exchange is negligible. The presence of 1 m/s and 3 m/s wind speed indicates that the heat coefficient is about 6 and 12 W/m²·K, respectively [37].
Figure 10. Calculated net daytime cooling performance of the proposed cooler design versus radiative cooler temperature with different thermal coefficients $q_c = 0$, $q_c = 6$ and $q_c = 12 \text{ W/m}^2\cdot\text{K}$. 

Figure 11. Calculated net nighttime cooling performance of the proposed cooler structure as a function of device temperature with different thermal coefficients $q_c = 0$, $q_c = 6$ and $q_c = 12 \text{ W/m}^2\cdot\text{K}$. 
The net daytime cooling performance versus temperature sample with and without the influence of the non-radiative cooling is depicted in Figure 10. By eliminating the non-radiative exchange \( q_c = 0 \) at ambient temperature \((300 \text{ K})\) and under direct solar illumination, Figure 10 shows that the proposed cooler design can achieve a net-cooling power over 75 W/m\(^2\) compared to that of porous alumina \((64 \text{ W/m}^2)\) [38]. In addition, the daytime cooling performance can attain a very low equilibrium temperature of 270 K, which leads to a maximum temperature cooling reduction of 30 \(^\circ\text{C}\). For two other different coefficients of conduction and convection \( q_c = 6 \) or 12 W/m\(^2\)·K, a significant temperature reduction can still be achieved. The proposed cooler design can reach an equilibrium temperature of 291.5 K and 295 K at \( q_c = 6 \text{ W/m}^2\cdot\text{K} \) and \( q_c = 12 \text{ W/m}^2\cdot\text{K} \) respectively.

Figure 11 depicts the computed net nighttime cooling performance versus radiative cooler temperature for \( q_c = 0 \), \( q_c = 6 \), and \( q_c = 12 \text{ W/m}^2\cdot\text{K} \). When the proposed cooler design is exposed to the night environment, the incident solar power absorbed by the radiative cooler design is null \((P_{\text{sun}} = 0)\). On one hand, the proposed cooler design can achieve a net cooling power over 129 W/m\(^2\) at ambient temperature. The computed cooling power line (black) leads to a maximum temperature cooling reduction of 62.3 \(^\circ\text{C}\) at the thermal equilibrium temperature \((P_{\text{net}} = 0)\). On the other hand, the non-radiative heat exchange can hamper radiative cooling performance when the proposed cooler design is applied to achieve cooling performance at a thermal equilibrium temperature. For \( q_c = 6 \) and \( q_c = 12 \text{ W/m}^2\cdot\text{K} \) heat transfer coefficients, the net nighttime cooling performance can achieve a thermal equilibrium temperature of 285.2 K and 291.3 K, respectively. As compared to the previous nighttime radiative coolers [39–42], our proposed cooler design has a high temperature reduction and suits the passive cooling of hot objects on a large scale.

7. Concluding Remarks

In summary, we have numerically demonstrated a new design emitter for switching both high-performance daytime and nighttime radiative cooling devices. The influence of the layers’ thicknesses, incidence angle, and filling factors on optical selective properties has been investigated. The proposed design behaves as a mirror for solar irradiation and as an atmospheric transparency window selective thermal emitter. The spectral properties of our radiative cooler indicate close-to-near unity reflectivity in the solar region and high emissivity in the atmospheric window 8–13 \(\mu\text{m}\). The proposed structure TiO\(_2\)-SiO\(_2\)/Ni - Al\(_2\)O\(_3\) with the optimized structure of TiO\(_2\)-SiO\(_2\) (4.5 \(\mu\text{m}\))/Ni - Al\(_2\)O\(_3\) (7.5 \(\mu\text{m}\)) show good spectral selectivity.

The simple nanoparticle-based coating can achieve a potential cooling power density of 75 W/m\(^2\) at the ambient temperature, resulting in a temperature reduction of 30 \(^\circ\text{C}\). At nighttime, the net radiative cooling power is greater than 129 W/m\(^2\), leading to a temperature reduction of 62.3 \(^\circ\text{C}\). Even assuming a non-radiative heat transfer coefficient, the designed cooler has the ability to cool down 8.7 \(^\circ\text{C}\) below the ambient temperature at daytime and 14.78 \(^\circ\text{C}\) below the ambient at nighttime, respectively. The nanoparticle-based multilayer coatings approach provides a promising way of producing low-cost passive radiative coolers that can be explored for feasible energy conservation.

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Nomenclature

- $\text{Al}_2\text{O}_3$: Aluminium oxide (alumina)
- $\text{TiO}_2 - \text{SiO}_2$: silica titania
- $\varphi_r$: phase factor
- $\theta$: incident angle
- $N_r$: refractive index of the r-th layer
- $\lambda$: wavelength
- $q_r$: optical admittance of the r-th layer
- $q_s$: substrate admittance
- $q_0$: optical admittance in free space
- $E$: normalized electric field
- $H$: normalized magnetic field
- $R$: reflectance
- $A$: absorbance
- $\varepsilon_{\text{Ni}}$: complex dielectric function for Ni
- $\varepsilon_{\text{Al}_2\text{O}_3}$: complex dielectric function for alumina
- $\varepsilon_{\text{eff}}$: effective medium dielectric function
- $f_{\text{Ni}}(\text{FF})$: effective medium dielectric function of nickel
- $P_{\text{net}}$: thermal equilibrium temperature
- $P_{\text{rad}}$: radiative power
- $P_{\text{Atm}}$: atmospheric power radiation
- $P_{\text{sun}}$: power density of solar radiation
- $P_{\text{Nonrad}}$: power density of non-radiative heat exchange
- $P_{\text{Net}}$: net cooling power
- $q_c$: combined non-radiative heat exchange coefficient
- $q_s$: substrate admittance

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