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Enhancing radiative cooling performance using metal-dielectric-metal metamaterials[†]

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Abstract

Thermal energy management, especially cooling, is becoming increasingly important in today's high energy consumption world. Passive cooling, which does not require additional energy consumption, could be an effective approach to thermal energy management. We analyzed spectral selective thermal emitters by investigating the performance of a type of passive cooling known as radiative cooling. Our results can be used to improve radiative cooling. As we can control the radiation characteristics of Metal-dielectric-metal (MDM) structures, we developed an MDM-based spectral selective emitter. We measured the spectral emissivity of the fabricated MDM structure in the direction of the zenith and at an incline. We also simulated structures of different sizes to determine the effect of varying the size of the structure on the emissivity. Finally, we calculated the radiative cooling performance of the selectively emissive surface. In these calculations, we considered temperature changes caused by atmospheric and surface radiation. The radiative cooling performance of our MDM-based spectral selective emitter was better than the cooling performance of a non-selective emitter. The surface temperature of the best MDM spectral selective emitter was 38 °C below the ambient temperature.

Keywords: Radiative cooling; Thermal plasmonic structure; Spectral selective emission; Atmosphere radiation

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1. Introduction

Thermal energy management directly affects the performance, efficiency, and lifetime of a device. As it becomes more important to reduce our energy consumption, thermal energy management has gained prominence [1, 2]. In particular, there is an ever-increasing demand for an effective cooling system that releases thermal energy into the atmosphere. Thermal energy is a byproduct of systems that convert energy. Passive cooling, which does not consume energy, is a good option for reducing energy waste [2].

One way to enhance passive cooling by radiative cooling is to install thermal emitters on surfaces that heat up. When designing thermal emitters, we must take into account infrared energy transmitted from the atmosphere. Thermal emitters should be designed to emit thermal radiation selectively in the 8-13 μm band. This band is the atmospheric transparency window. Emitters in this band have enhanced cooling performance as they can reflect incident atmospheric radiation from the non-transparent band. An effectively designed thermal emitter can maintain surface temperatures below the ambient air temperature [3-5].

The infrared emissivity of the radiative cooling surface must be controlled for each wavelength band. To achieve spectral selective emissivity, researchers have developed photonic crystals [6, 7], electrochromic devices [8], and plasmonic metamaterials. In this study, we developed a metal and dielectric thermal plasmonic structure [9-11]. This emitter exhibits improved radiative cooling performance.

2. Theoretical background

The temperature, T_s, of a solid surface with spectral angular-dependent emissivity, $\varepsilon_s(\lambda,\theta)$, is determined by four external heat transfer mechanisms: conduction and convection from ambient air, and thermal radiation from the sun and the atmosphere. The solid surface emits thermal radiation to balance extremal heat sources, maintaining a saturated surface temperature, T_{sat}.

We excluded conduction and convection induced by solar irradiation from our analysis. Solar irradiation is concentrated in the visible range. Surface and atmospheric radiation mainly occurs in the infrared band. Therefore, the absorbed power from solar irradiation is supposable to the radiative cooling performance only considered surface and atmosphere radiation to evaluate total radiative cooling performance [3, 4]. In addition, the absorption of solar irradiation is very sensitive to

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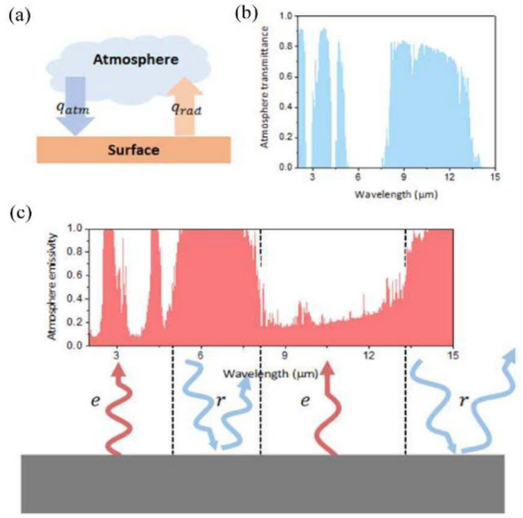


Fig. 1. (a) Schematic diagram of radiative surface cooling; (b) infrared atmospheric transmittance; (c) approach to enhancing radiative cooling performance using surfaces with spectral selective emissivity.

environmental conditions such as the time, latitude, weather, and season. The temperature gradient between a surface and the atmosphere is reduced by both convective and conductive heat transfer. It is difficult to evaluate the heat transfer coefficient quantitatively as it is affected by the surface and atmosphere temperatures in addition to the environmental conditions. We did not consider conduction and convection arising from solar irradiation as a result of these considerations. Instead, we analyzed the radiative cooling performance of solid surfaces with respect to atmospheric and surface radiation. The cooling performance is defined by Eq. (1) and explained in Fig. 1(a). The radiative cooling performance is defined as the difference between the surface radiation at a given temperature and the thermal atmospheric radiation at ambient temperature T_{atm}.

$$q_{cooling} = q_{rad} - q_{atm} . \tag{1}$$

The infrared transparency window of the atmosphere is 8-13 µm, as shown in Fig. 1(b). Passive cooling is possible in this band because surfaces that emit radiation in this window absorb low levels of atmospheric radiation. Atmospheric radiation from the non-transparent regions irradiates solid surfaces. This absorption is characterized by the absorptivity of the surface. Broadband radiation emitters have limited cooling performance as they absorb a lot of atmospheric radiation. However, spectral selective emitters, which have wavelength-dependent absorptivity and emissivity, can reflect atmospheric radiation and only produce thermal emission in the transparent region, as shown in Fig. 1(c). In other words, spectral selective emitters have better radiative cooling performance than non-selective emitters [4].

3. Experimental and numerical methods

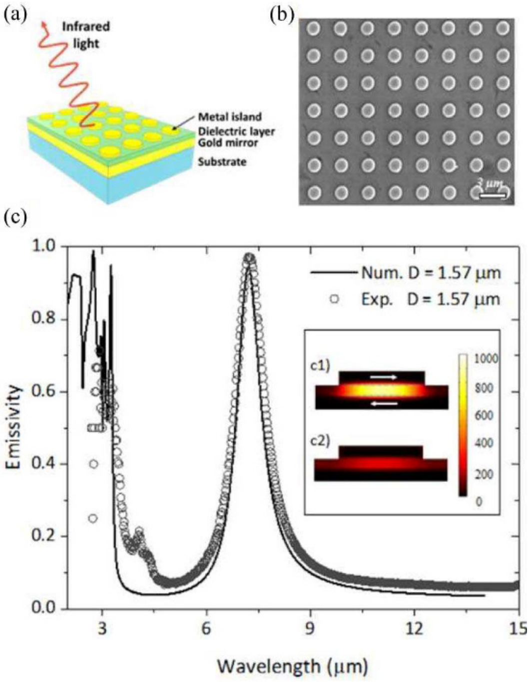


Fig. 2. Infrared selective emitter and spectral emissivity: (a) Schematic diagram of a Metal-dielectric-metal (MDM) structure with a top array composed of metal discs; (b) scanning electron microscopy image of the top view of the selective emitter; (c) spectral selective emissivity; the open circle is the measured value and the line is the simulation result. The inset contours show the amplitude of the magnetic field at wavelengths of (c1) 7 µm; (c2) 10 µm. The white arrows show the direction of the induced current.

To obtain selectively emissive surfaces, with emission matched to the atmospheric transparency window, we fabricated a plasmonic thermal emitter with a Metal-dielectric-metal (MDM) structure, as shown in Figs. 2(a) and (b). The MDM structure was made of gold (Au) with a zinc sulfide (ZnS) dielectric. We used e-beam evaporation to deposit a 100-nm layer of Au onto a cleaned silicon substrate, followed by a ZnS 200-nm layer. Then, we used photolithography to pattern a square Au disc array with a pitch of 3 µm. The surface was completed after an Au deposition and lift-off process. The upper Au disc of the MDM structure had a diameter of 1.57 µm, as shown in Fig. 2(b).

The spectral selective emissivity of the MDM structure was measured with a Fourier-transform infrared (FTIR) spectrometer (Vertex 70, Bruker, Germany) equipped with a DLaTGS detector. The base Au layer prevented infrared transmission through the MDM structure. Thus, we could determine the spectral emissivity of the MDM structure by measuring the spectral reflectance. The angular emissivity was measured by changing the angle of the incident infrared rays. To validate the value of the emissivity derived from the reflectance, we compared the radiation intensity from the heated MDM structure to the cavity blackbody radiation intensity (SR-200, Ci Systems, Israel) and found that they were identical.

We investigated the physical properties of the MDM structure and the effect of varying it numerically. We used Finite

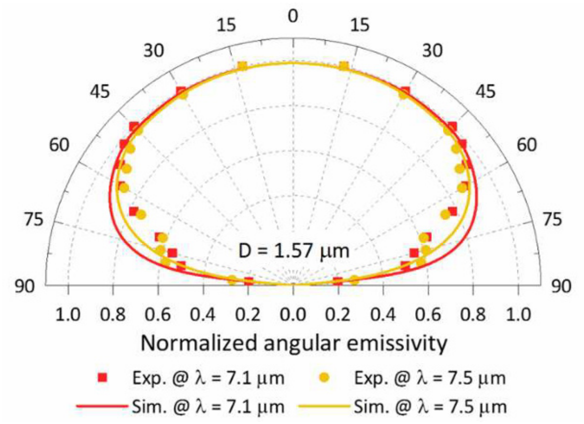


Fig. 3. Experimental and numerical simulation values of the normalized angular emissivity of a Metal-dielectric-metal (MDM) structure with a metal disc of diameter 1.57 μm at the peak emissivity wavelength (red data) and at the half-peak emissivity wavelength (yellow data). The normalized value is divided by the maximum emissivity at each wavelength.

element methods (FEM) to calculate the full differential form of Maxwell's equations for the MDM structure. These calculations were performed using commercial software (Comsol Multiphysics v5.2, Sweden). We used the Drude model to calculate the infrared properties of Au. The plasma frequency was 1.37×10^{16} [Hz] and the damping constant was 1.22×10^{14} [Hz]. In addition, we used the value of the refractive index of ZnS quoted in Debebham [12].

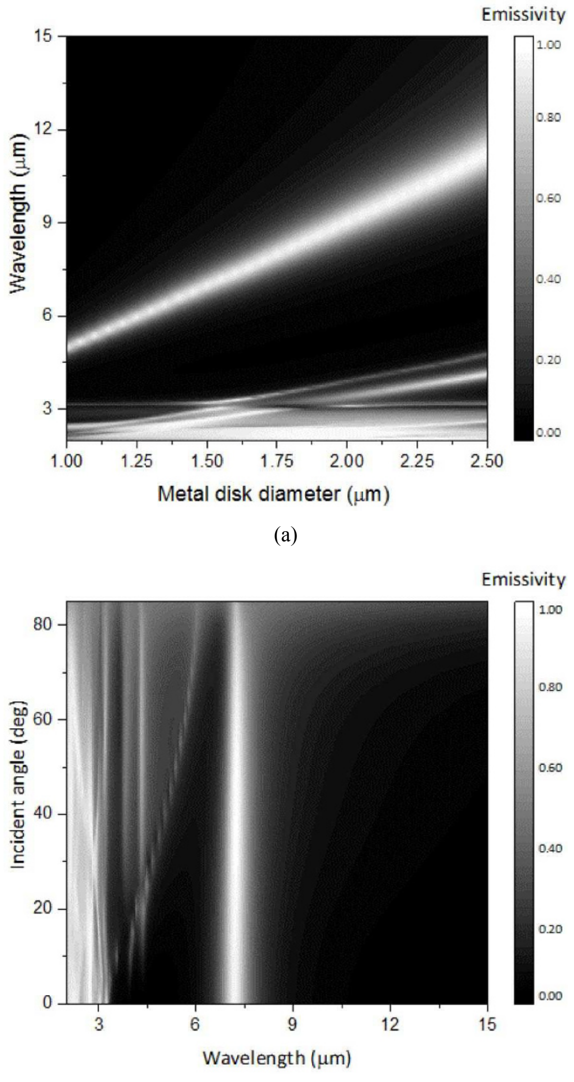
There was good agreement between the experimental and numerical results. The experimental and theoretical spectral selective emissivities of an MDM structure with an Au disc with a diameter of 1.57 μm are shown in Figs. 2(c) and 3. When the wavelength was 7.3 μm, the highest emissivity was 0.97, and a strong magnetic field was induced in the middle of the ZnS layer. The anti-parallel current between the metal disk and bottom metal layer makes the induced magnetic field in the normal direction of the current field [10]. In the non-resonating wavelength band, the emissivity dropped sharply and no magnetic field was induced.

The experimental and numerical values for the normalized angular emissivity are shown in Fig. 1. We normalized the emissivities at different angles by dividing them by the emissivity at the zenith. At wavelengths of 7.1 and 7.5 μm, the zenith emissivities were different, but the distributions of the normalized angular emissivities were the same. The angular emissivity was constant up to 60° and then gradually decreased. We then performed simulations to determine the effect of varying the shape and size of the upper Au disc on spectral selective emission and calculated the radiative cooling performance.

4. Results

4.1 Spectral selective emissivity

In our simulations, we varied the upper Au disc diameter from 1 to 2.5 μm, as shown in Fig. 4(a). The resonance wavelength continuously increased from 5.5 to 11.2 μm and the selective emission bandwidth also increased. In particular, when the diameter of the upper Au disc was 2.3 μm, resonance occurred at 10.3 μm. As radiation from this band is highly transmissible to the atmosphere, emission in this band is expected to improve radiative cooling performance.



(a)

(b)

Fig. 4. Spectral selective emissivity of Metal-dielectric-metal (MDM) structures: (a) Emissivity characteristics as the disc diameter is varied. As the diameter of the metal disc increased, the wavelength at which the peak emissivity occurred also increased; (b) angular emissivity of an MDM structure with a metal disc of diameter 1.55 μm.

The angular emissivity of an MDM structure with an Au disc with a diameter of 1.55 μm is shown in Fig. 4(b). The wavelength remained constant at 7.2 μm up to 60°. The emissivity in the wavelength band from 3 to 6 μm increased gradually as the radiation angle increased. The surface emissivity decreased as the radiation angle increased, degrading the radiative cooling performance. This is because the atmospheric radiation absorption rate increased with the radiation angle.

4.2 Radiative cooling performance

The net radiative cooling power of the surface and atmospheric radiation can be calculated using Eq. (1). The power radiated by the surface, q_{sur}, and the power absorbed by the surface from the atmosphere, q_{atm}, are calculated using Eqs. (2) and (3), respectively.

$$q_{sur} = \int_0^{\pi/2}\int_0^{\infty} 2\pi \sin\theta \cos\theta \, I_B(T_s,\lambda)\, \varepsilon_s(\lambda,\theta)\, d\lambda d\theta \tag{2}$$

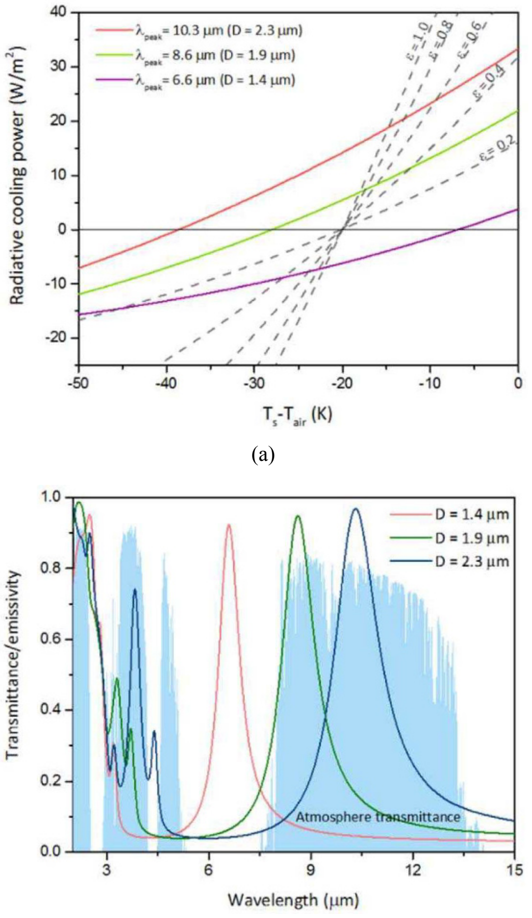
$$q_{atm} = \int_0^{\pi/2}\int_0^{\infty} 2\pi \sin\theta \cos\theta \, I_B(T_{atm},\lambda)\, \varepsilon_{atm}(\lambda,\theta)\, \varepsilon_s(\lambda,\theta)\, d\lambda d\theta \tag{3}$$

$$I_B(T,\lambda) = \frac{2hc}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_B T}}-1}. \tag{4}$$

Here, $I_B(T,\lambda)$ is the spectral radiance of a blackbody at temperature T. This is defined by Planck's law, where h is Plank's constant, k_B is Boltzmann's constant, c is the speed of light, and $\varepsilon_s(\lambda,\theta)$ and $\varepsilon_{atm}(\lambda,\theta)$ are the emissivity of the MDM structure surface and the emissivity of the atmosphere, respectively. The atmospheric spectral emissivity [13] is $\varepsilon_{atm}(\lambda,\theta) = 1 - t(\lambda)^{1/\cos\theta}$, where $t(\lambda)$ is the spectral transmittance at the zenith, which we obtained from MODTRAN (v 6.0, Spectral Sciences Inc., USA).

We calculated the net radiative cooling performance as the surface temperature varied and the atmospheric temperature remained constant at 27 °C (300 K). A positive net radiative cooling power at a given surface temperature indicates that the surface is cooling down to a lower temperature than the atmosphere, and the temperature will continue to decrease until the saturation temperature is reached. The saturation temperature is the temperature at which the net radiative cooling power is zero, so the surface radiation is balanced by the energy absorbed by the atmosphere.

The net radiative cooling power is shown in Fig. 5(a) and the saturated temperature of the surface is shown in Fig. 6. In Fig. 5(a), the dashed line represents the non-selective emissive surface. As the surface emissivity increases, the cooling performance improves until the temperatures of the surface and the atmosphere becomes same (T_s - T_{air} = 0). There is no radiative heat transfer when the surface emissivity is zero. In this case, the surface is a perfect mirror, and the result overlapped with the y-axis is zero. This is because the emissivity of the surface is constant and energy from the atmosphere is selectively absorbed to balance the energy emitted. Increasing the emissivity has a significant effect on the radiative cooling performance of surfaces in the atmospheric transparency window. However, the cooling power drops sharply as the surface temperature decreases and becomes zero on all surfaces when their temperature reaches approximately 20 °C below the ambient temperature. A typical non-selective emissive surface cannot be cooled down to 20 °C below the ambient temperature by radiative cooling.



(a)

(b)

Fig. 5. (a) Radiative cooling performance of Metal-dielectric-metal (MDM) spectral selective emitters (colored line) and non-selective emissive surfaces (dashed line); (b) infrared atmospheric transmittance and spectral emissivity of MDM structures with varied upper disc diameters.

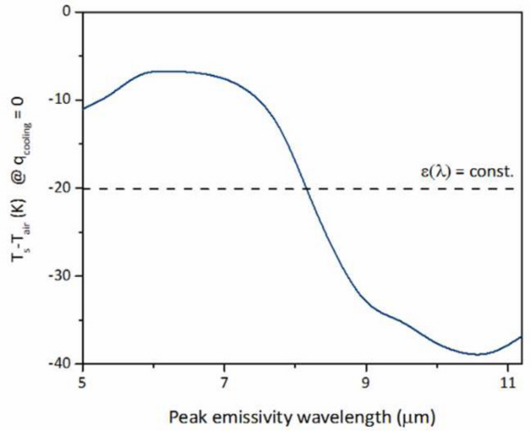


Fig. 6. Cooling performance of metal-dielectric-metal structures as a function of the peak emissivity wavelength.

The cooling performance of a spectral selective emitter is better than the cooling performance of a non-selective emitter. The level of improvement depends on the spectral emissivity. At its resonant wavelength of 10.3 μm, the MDM structure with an upper disc of diameter 2.3 μm can cool to 38 °C below the ambient temperature. This is close to twice the cooling observed with a non-selective surface. The MDM structure with an Au disc of diameter 1.4 μm had poorer cooling performance than the non-selective surface because its selective emission peak was not in the atmospheric transparency window, as shown in Fig. 5(b). To improve radiative cooling performance, it is necessary to use spectral selective emissive structures that have been designed specifically for the optical characteristics of the environment in which they are intended to operate.

5. Conclusions

Radiative cooling performance can be improved by using a spectral selective emitter that is designed to reflect atmospheric radiation and unilaterally radiate through the infrared atmosphere transparency window. Surfaces equipped with these emitters can reach temperatures 20 °C cooler than non-selective surfaces and 38 °C than atmosphere.

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Nomenclature

T : Temperature
$\varepsilon(\lambda,\theta)$: Spectral and angular emissivity
λ : Wavelength [μm]
θ : Incident angle [degree]
q : Heat flux [W/m^2]
$I_B(T,\lambda)$: Spectral radiance [W/Sc·m^3]
h : Planck's constant (6.6260693×10^{-34} Ws^2)
k_B : Boltzmann constant (1.380658×10^{-23} J/K)
c : Speed of light (2.99792458×10^{8} m/s)

Subscription

B : Black body
atm : Atmosphere
s,sur : Surface
sat : Saturation

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