Moth-eye photonic cooler for efficient daytime radiative cooling

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Introduction

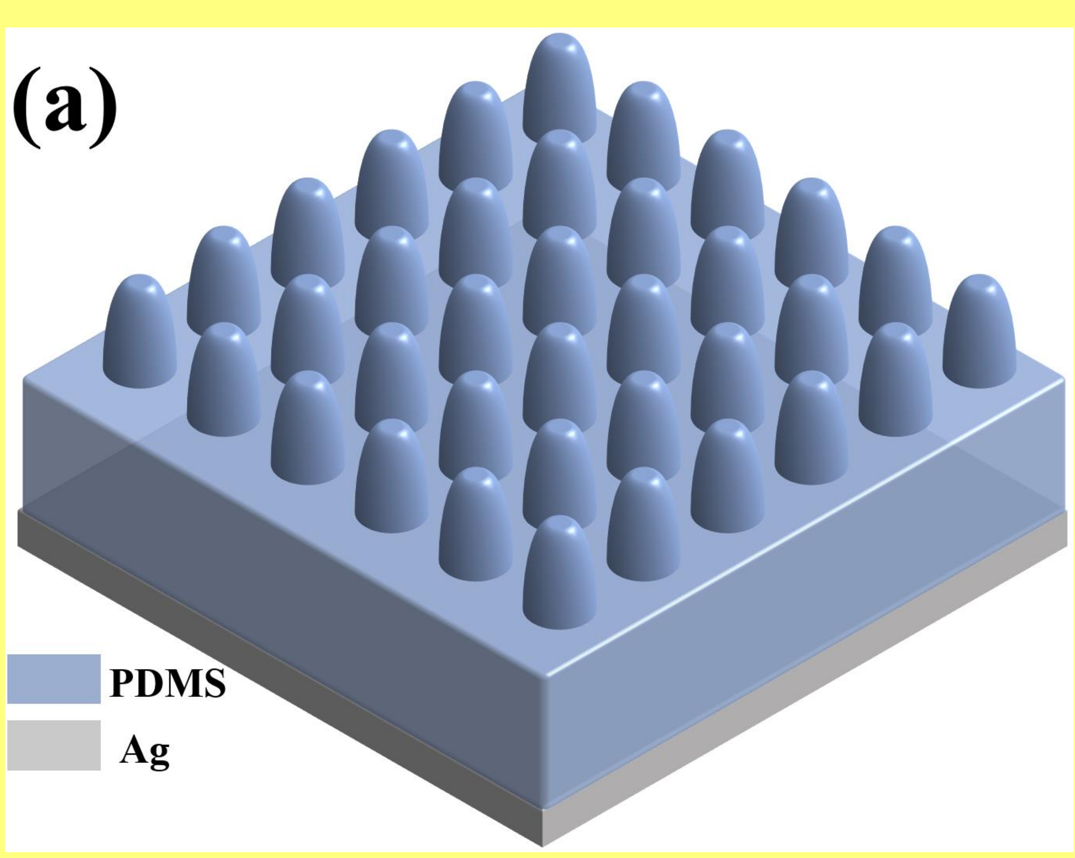
Radiative cooling is a passive cooling method, which can achieve sub-ambient cooling phenomenon by radiating the waste heat of the earth to the cold universe. In the recent decade, radiative cooling has aroused much attention in the field of renewable energy harvesting due to its passive cooling characteristics [1].

In the past, radiative cooling was applied during the night when sunlight was absent, and this is because strong sunlight heating would counteract the passive cooling effect. So, materials with high emissivity within the atmospheric window (i.e., 8-13) can achieve passive cooling at night when exposed to clear sky. However, daytime radiative cooling is more desired since cooling is required during the day. With the development of material science, daytime radiative cooling was experimentally demonstrated in 2014 based on a photonic multilayer film [2]. This film has a high solar reflectivity of nearly 97% and simultaneously exhibits high emissivity within the atmospheric window, which makes the film 4.9 temperature below the ambient air. Since then, much effort has been devoted to cooler development, and various daytime radiative coolers have been proposed, such as paint (particles + polymer) [3], porous structure [4], and photonic coolers [5]. During these designs, photonic cooler has been regarded as one of the promising candidates since it can control the interaction of light and matter using the interface structures via spectrum engineering.

In this work, a PDMS/Ag photonic cooler has been proposed by introducing moth-eye nanostructures into the planar PDMS film. Optical optimization and simulation have been conducted, and the results show the moth-eye photonic cooler has high solar reflection and strong mid-infrared emissivity, showing great potential for daytime radiative cooling.

Optical Simulation

The schematic diagram of the moth-eye photonic cooler is shown in Fig. 1(a). The hybrid structure comprises bioinspired moth-eye nanostructures integrated with double-layer planar films. The upper section consists of ellipsoidal moth-eye structures and their substrate fabricated using polydimethylsiloxane (PDMS), while the bottom layer employs silver (Ag) as the solar reflective layer. Side view of the moth-eye photonic cooler is shown in Fig. 1(b). The subwavelength-scale moth-eye array (period P=20 μm, height h_1=20 μm, duty cycle 0.7) combined with a 180-μm-thick PDMS substrate (h_2) functions as the thermal radiative layer. This configuration is complemented by a 300-nm-thick Ag film (h_3) that serves as the reflection layer for enhanced thermal management.



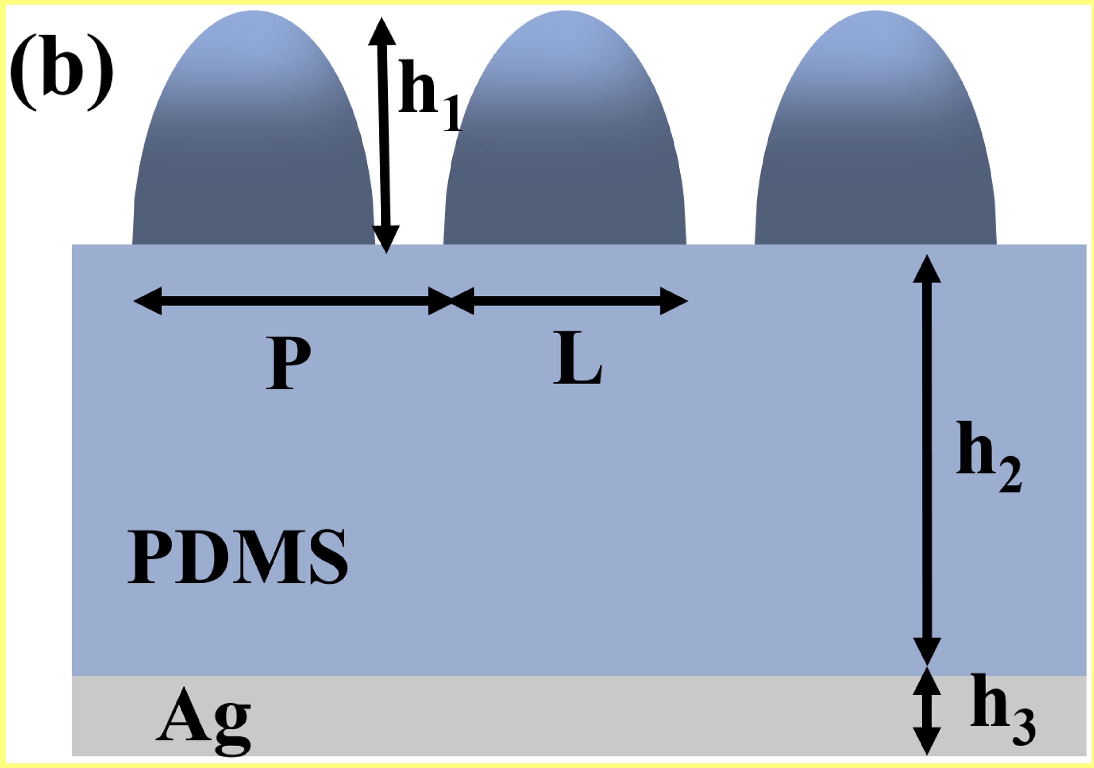


Fig. 1. (a) The schematic illustration of the moth-eye photonic cooler. (b) Side view of the moth-eye photonic cooler.

To investigate the spectral properties of the proposed photonic cooler, an optical simulation is conducted using the S4 code that is established based on the rigorous coupled-wave analysis (RCWA) method[6]. During the simulation, the complex refractive index of the PDMS and Ag are obtained from the optical handbook[7] and database[8].

Fig. 2 shows the simulated spectral solar reflectivity of the moth-eye photonic cooler. It can be found that the cooler has a high solar reflectivity with an AM 1.5 weighted solar reflectivity of over 90%, which is responsible for reflecting incident sunlight during the daytime radiative cooling process and ensuring net heat dissipation. This is mainly because PDMS material is an optically non-destructive material in the solar light band. Moreover, the feature sizes of periodic moth-eye photonic structures are orders of magnitude larger than the wavelengths of visible and near-infrared light, consequently, these structures do not introduce additional diffraction or scattering within the solar band, and light traverses the PDMS layer without significant deviation. Therefore, the primary mechanism governing solar reflectivity in such cooler is the underlying metallic reflector—in this case, a silver film—which provides high reflectance (>90%) across the solar spectrum.

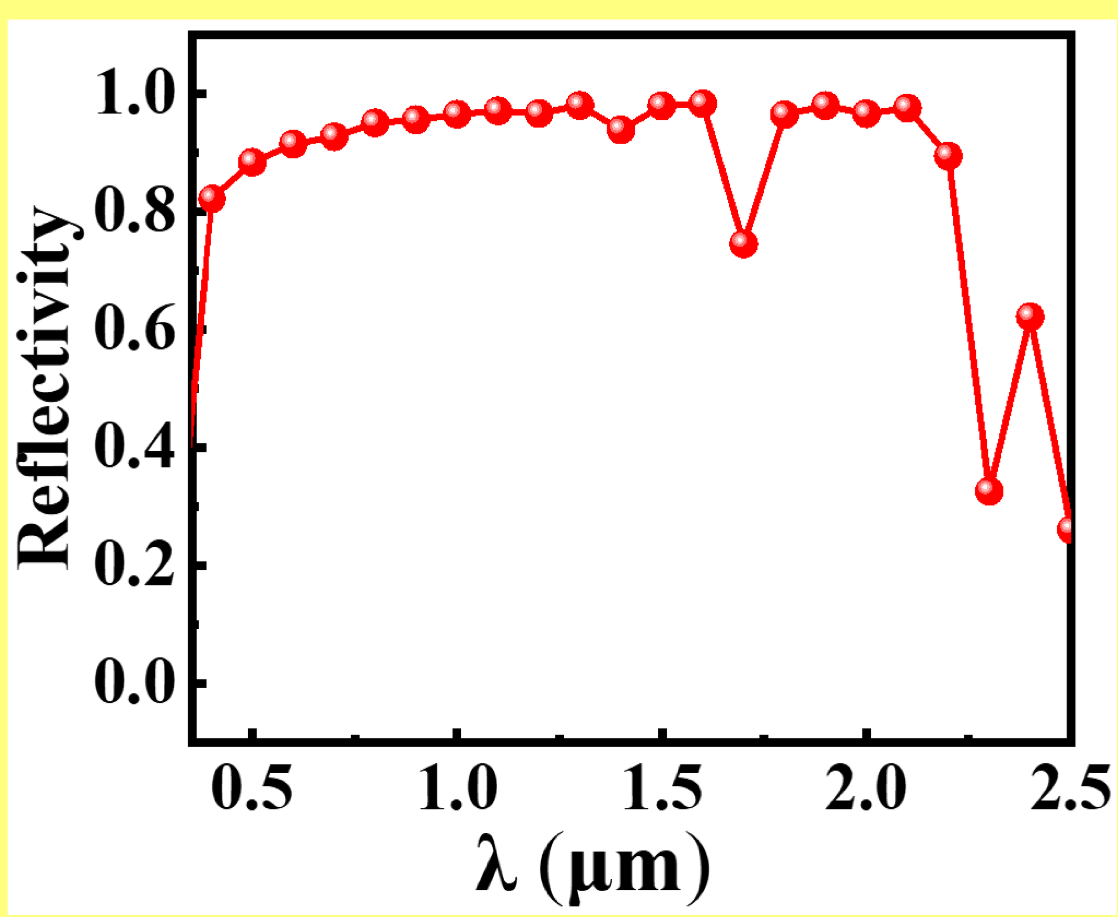


Fig. 2. Simulated solar reflectivity of the moth-eye photonic cooler.

Fig. 3 presents the simulated spectral emissivity of the photonic cooler across the mid-infrared region. The data reveal that the cooler exhibits an emissivity approaching 100 % throughout the entire mid-infrared band, effectively behaving as an ideal blackbody. This remarkable performance stems from the incorporation of a "moth-eye" three-dimensional microstructure on the surface of the PDMS layer: by establishing a graded refractive index, this architecture substantially reduces reflection losses at the air–PDMS interface, enabling a smooth transition of the effective refractive index and thereby dramatically enhancing the PDMS's emissivity in the mid-infrared. Consequently, the moth-eye photonic cooler functions as a highly efficient mid-infrared radiator, maximizing thermal emission toward the cold sink of outer space.

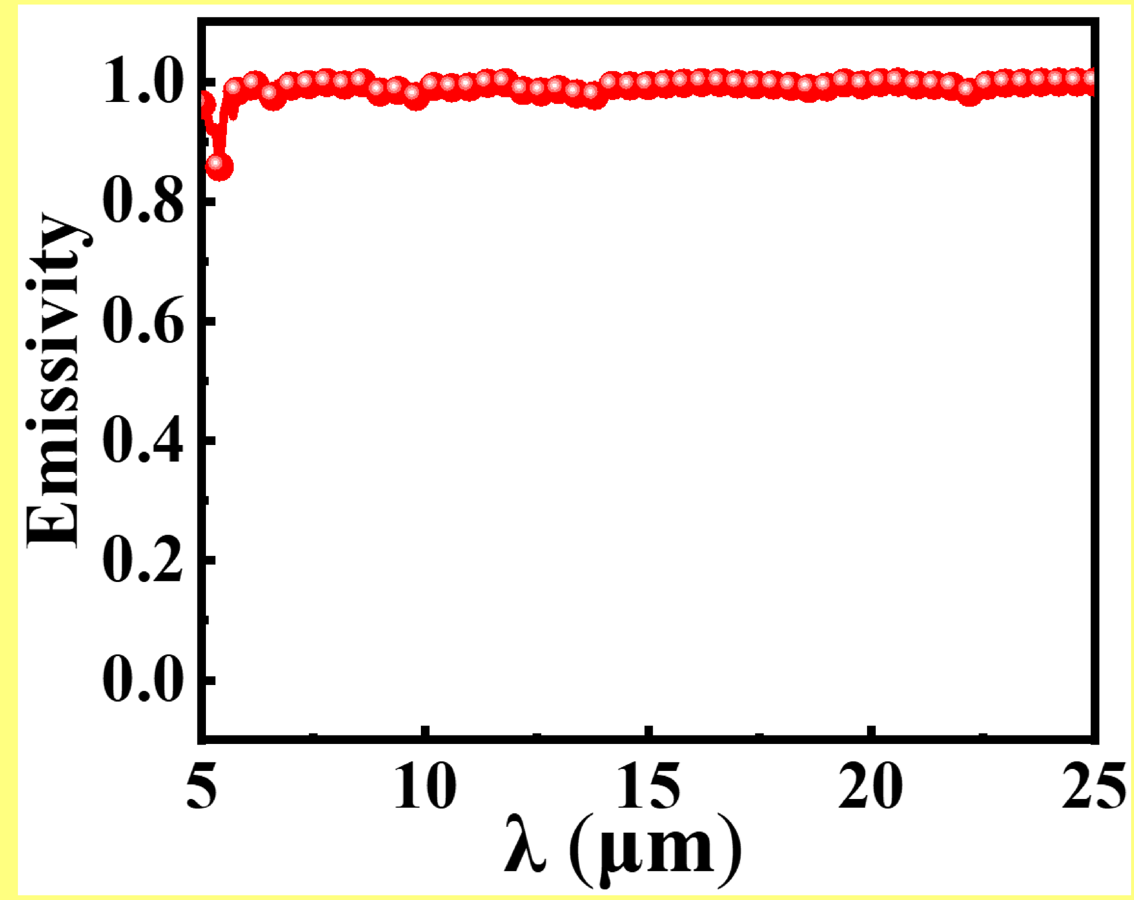


Fig. 3. Simulated infrared emissivity of the moth-eye photonic cooler.

Results

The proposed moth-eye photonic cooler achieves over 90 % reflectivity across the solar spectrum, thereby markedly suppressing incident solar irradiance, while its emissivity in the mid-infrared approaches 100 %, enabling exceptionally efficient thermal radiation. By combining high solar reflectivity with outstanding mid-infrared emissivity, the PDMS/Ag moth-eye photonic cooler demonstrates significant potential for daytime radiative cooling. Moreover, this photonic cooler can be fabricated at low cost using straightforward processing techniques and readily scaled to large areas, offering a practical route to implement passive daytime radiative heat rejection.

Conclusions

This work proposed a high-efficiency daytime radiative cooler by integrating a moth-eye microstructured PDMS layer with an underlying Ag film. Optical simulations demonstrated that the moth-eye photonic cooler exhibited near-unity reflectance across the solar spectrum and approaches ideal blackbody emissivity throughout the mid-infrared band, thereby revealing substantial potential for daytime radiative cooling. In future implementations, such a cooler could be applied over large areas—e.g., building roofs, vehicle roofs, and outdoor equipment housings—to achieve passive thermal management, significantly reducing cooling energy demand and mitigating urban heat island effects.

References

[1] Zhao B, Hu M, Ao X, Chen N, Pei G. Radiative cooling: A review of fundamentals, materials, applications, and prospects. Appl Energy 2019;236:489–513.
[2] Raman AP, Anoma MA, Zhu L, Rephaeli E, Fan S. Passive radiative cooling below ambient air temperature under direct sunlight. Nature 2014;515:540–4.
[3] Mandal J, Yang Y, Yu N, Raman AP. Paints as a Scalable and Effective Radiative Cooling Technology for Buildings. Joule 2020;4:1350–6.
[4] Mandal J, Fu Y, Overvig AC, Jia M, Sun K, Shi NN, et al. Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling. Science (80-) 2018;362:315–9.
[5] Hossain MM, Jia B, Gu M. A Metamaterial Emitter for Highly Efficient Radiative Cooling. Adv Opt Mater 2015;3:1047–51.
[6] Liu V, Fan S. S4 : A free electromagnetic solver for layered periodic structures. Comput Phys Commun 2012;183:2233–44.
[7] Palik ED. Handbook of Optical Constants of Solids Volume I. Handb. Opt. Constants Solids, Elsevier Inc.; 1985.
[8] Refractive Index Data base n.d. https://refractiveindex.info/?shelf=main&book=Ag&page=Hagemann.