Diurnal cooling for continuous thermal sources under direct subtropical sunlight produced by quasi-Cantor structure*

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In this paper, an optical radiative cooler with quasi-Cantor structure is theoretically proposed and analyzed. This simple and symmetrically designed optical structure operates upon continuous thermal sources in diurnal subtropical conditions, and its efficiency is much higher than natural cooling, for instance, when operating upon a typical 323.15 K continuous thermal source with a wind speed at 3 m·s^{-1}, it can generate a net cooling power of 363.68 W·m^{-2}, which is 18.26% higher than that of non-radiative heat exchange (natural cooling) under the same conditions. Additionally, several aspects are considered in its design to ensure a low cost in application, which is of great economical and environmental significance.

Keywords: thin film, photonic quasicrystal, photonic crystal, nanophotonics, radiative cooling

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1. Introduction

Radiative cooling devices are revealed to possess the potential of providing energy-saving air conditioning without external energy input. They were first designed to be used in nocturnal conditions. The structures, practical application and performance of nocturnal radiative coolers were discussed several decades ago.[1–11] It was demonstrated recently that, by utilizing advanced nanophotonic technologies, high solar reflection and high infrared emission within the atmospheric transparency window can be processed simultaneously to realize radiative cooling below ambient air temperature in mid-latitude areas.[12–15] At the same period, above-ambient cooling for heat sources like solar absorbers is also realized,[16–18] new kinds of materials of high infrared (IR) emission for radiative cooling is proved to be high-efficient,[19] and radiative cooling to deep sub-freezing temperature is experimentally demonstrated.[20]

However, the radiative cooler is not geographically universal.[21] The differences in the concentration of certain molecules like H_2O, CO_2, O_3, CH_4, and N_2O within the atmosphere,[22,23] and other aspects of climatic and seasonal difference can highly affect overall value and bandwidth of the atmospheric transparency window within 8 μm–13 μm, which is a crucial factor that influences the radiative cooler's performance. An efficient above-ambient broadband radiative cooler for mid-latitude areas may suffer from significant heat gain from atmospheric radiation and high ambient temperature in subtropical regions, where atmospheric transmission is low and radiative cooling is hard to achieve. This limitation makes the densely populated subtropical regions a rare topic in the scope of radiative cooling studies. In addition, the reported models are composed of complicated optical structures demanding high precision in their production and manufacturing, and therefore, are expensive in actual application.

The prior studies focused on the radiative cooling in mid-latitude regions for passive heat emitters, yet subtropical daytime radiative cooling for continuous thermal sources has not been discussed. In this paper, a selective quasi-Cantor radiative cooler with simple and symmetric structure is proposed to operate upon continuous thermal sources under direct subtropical sunlight. It features a higher efficiency than non-radiative natrual cooling, with a simple design and a lower cost. For a 323.15-K continuous thermal source, the radiative cooler is capable of generating a net cooling power of 363.68 W·m^{-2} at 3 m·s^{-1} of wind speed, which is 18.26% more efficient than the cooling power of natural non-radiative heat exchange. Such design will be greatly useful in protecting active heat-emitting machines that exposed to direct sunlight from aging and failure due to thermal causes.

The following contents of this paper are arranged as follows. In Section 2, the model of continuous thermal sources, the principles of the radiative cooling and the design of the optical structure are explained in detail. In Section 3, the performance of the cooler is demonstrated and analyzed. Finally, the further application of the radiative cooler is discussed.

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2. Principles and design

To achieve above-ambient radiative cooling in previous mid-latitude studies, a broadband cooler is usually considered a first choice,[16–18] for it can produce high IR emission which can compensate the heat gain caused by atmospheric radiation outside the transparency window and outperform a selective cooler greatly.[21] Nevertheless, the atmospheric transmittance is very low in subtropical areas in summer with a clear sky. This makes the heat gain outside the transparency window a heavy burden for broadband coolers, and a selective cooler design is useful in such scenario. From simulations and analysis discussed in Section 3, one can discover that a selective quasi-Cantor radiative cooler can produce a cooling power very close to that of an ideal broadband cooler whose IR emission is 1.00 across the IR regime from 6 μm to 20 μm.

Additionally, the object being cooled in this model is totally different from previous researches. The model of "continuous thermal sources" is an abstraction of "active" heat emitting objects, such as the external unit of air conditioners, combustion engines, diurnal street lamps, etc. By this concept, these objects are usually powered by external energy supply and their heat emission is large, constant and stable, which may be or may not be a function of temperature T. Therefore, the heating power of a temperature-dependent continuous thermal sources can be expressed as

$$P_{\text{source}} = P_{\text{source}}(P_{\text{input}}, T_{\text{air}}, T_{\text{source}}), \tag{1}$$

where P_{input} is the power of energy input, T_{air} is the temperature of ambient air, and T_{source} is the temperature of the source itself. Likewise, the heating power of a temperature-irrelevant continuous thermal sources is

$$P_{\text{source}} = P_{\text{source}}(P_{\text{input}}). \tag{2}$$

To evaluate the optical design, all heat exchange processes should be taken into account, including gross power emitted by the radiative cooler P_{cooler}, the heating power of the continuous thermal source P_{source}, the power of atmospheric radiation $P_{\text{atmsphere}}$ outside the atmospheric transparency window of 8 μm–13 μm, the power of conductive and convective heat exchange $P_{\text{nonradiative}}$ and the power of sunlight absorption P_{solar}. Thus, the actual cooling power for an above-ambient cooler should be

$$\begin{aligned} P_{\text{actual}} = {} & P_{\text{cooler}} + P_{\text{nonradiative}} \\ & - P_{\text{atmosphere}} - P_{\text{solar}} - P_{\text{source}}. \end{aligned} \tag{3}$$

However, based on the "continuous thermal source" model, the P_{source} is usually not analytical. Therefore, the assessment method using "the maximum temperature reduced" (ΔT) in previous above-ambient cooler studies[16–18] is inapplicable and the properties of this radiative cooler should be analyzed by means of the net cooling power P_{net}, with P_{source} treated as a cooling-target-dependent constant. In a unit area A, the net cooling power is defined as follows:

$$P_{\text{net}} = P_{\text{cooler}} + P_{\text{nonradiative}} - P_{\text{atmosphere}} - P_{\text{solar}}. \tag{4}$$

The variables in the above equation are defined by the following expressions[21]

$$\begin{cases} P_{\text{cooler}} = 2\pi \displaystyle\int_0^{\pi/2} \sin\theta\cos\theta\,\mathrm{d}\theta \int_0^{\infty} I_{\text{blackbody}}(T_{\text{cooler}}, \lambda)\varepsilon_{\text{cooler}}(\lambda,\theta)\,\mathrm{d}\lambda, \\ P_{\text{atmosphere}} = 2\pi \displaystyle\int_0^{\pi/2} \sin\theta\cos\theta\,\mathrm{d}\theta \int_0^{\infty} I_{\text{blackbody}}(T_{\text{air}}, \lambda)\varepsilon_{\text{cooler}}(\lambda,\theta)\varepsilon_{\text{atmosphere}}(\lambda,\theta)\,\mathrm{d}\lambda, \\ P_{\text{nonradiative}} = (q_{\text{cond}} + q_{\text{conv}})(T_{\text{cooler}} - T_{\text{air}}) = q(T_{\text{cooler}} - T_{\text{air}}), \\ P_{\text{solar}} = \displaystyle\int_0^{\infty} I_{\text{AM1.5}}(\lambda)\varepsilon_{\text{cooler}}(\lambda,\theta_{\text{solar}})\,\mathrm{d}\lambda. \end{cases} \tag{5}$$

Here, $I_{\text{blackbody}}(T,\lambda) = \left(2hc^2\right) / \left\{\lambda^5\left[\exp(hc/\lambda k_{\text{B}}T) - 1\right]\right\}$ is the spectral radiance of blackbody by Planck's law at temperature T, where h is the Planck's constant, c is the speed of light in vacuum, k_{B} is the Boltzmann constant, and λ is the wavelength. $\varepsilon_{\text{cooler}}(\lambda,\theta)$ is the emissivity of the radiative cooler defined by Kirchhoff's law, and $\varepsilon_{\text{atmosphere}}(\lambda,\theta) = 1 - t(\lambda)^{1/\cos\theta}$ is the angle-dependent atmospheric emissivity,[9] where $t(\lambda)$ is the atmospheric transmittance, which in our simulation, is acquired by MODTRAN$^{\text{TM}}$ model.[24] T_{cooler} and T_{air} are the temperature of the radiative cooler and the temperature of the ambient air, separately. q is the combined non-radiative heat coefficient, which is estimated in several reports,[5,13,18,21,25] to have a value ranging from 2 W·m^{-2}·K^{-1} to 12 W·m^{-2}·K^{-1} according to wind speed for radiative coolers in experimental conditions. And $I_{\text{AM1.5}}(\lambda)$ is the AM1.5 reference solar irradiance spectrum.[26]

There are several factors that affect the net cooling power P_{net} of the radiative cooler. One can see from Eq. (4) and Eq. (5) that, for above-ambient cooling, the presence of P_{cooler} and $P_{\text{nonradiative}}$ is beneficial, while $P_{\text{atmosphere}}$ and P_{solar} should be minimized. Although ideal blackbody has strong emissivity across the entire IR regime, when operating outdoors under direct sunlight, the IR emission outside the atmospheric transparency window increases $P_{\text{atmosphere}}$ which lowers the

total P_{net}. Therefore, the optical structure should emit selectively and strongly inside the atmospheric transparency window within 8 μm–13 μm. Nevertheless, by use of the atmospheric transmission model MODTRAN^{TM} (shown in Fig. 3(b) in the next section), one can discover that besides the absence of the secondary window, the overall atmospheric transmittance of the primary window in subtropical areas is much lower than that in the previous mid-latitude researches, which lowers the efficiency of radiative cooling. Additionally, the solar irradiance distribution varies in different latitudes, for instance, a typical value of cumulative solar irradiance in subtropical area is 1000 W·m^{-2} while that of mid-latitude area is about 800 W·m^{-2} to 840 W·m^{-2}. Combining these geographical factors and the model differences, subtropical radiative cooling for continuous thermal source under direct solar radiation is another distinctive aspect of radiative cooling, besides the previous researches.

In this study, a quasi-Cantor structure is proposed and optimized to realized low-cost high-efficient diurnal radiative cooling in subtropical regions. It is well known that the Cantor set is a typical fractal structure that is extensively discussed in photonic quasicrystal studies. The advantage of adopting Cantor set in the design of the radiative cooler is that, its structure is mirror symmetric, simple and brief, which has the potential of lowering the difficulty in manufacturing. This simple structure unveils the radiative cooling ability of simple one-dimensional optical structure other than complex disordered structures and two-dimensional metamaterials, which may enable wider application of radiative coolers with lower cost.

In order to achieve better performance without complicating the optical structure, a "symmetric needle method" is used to optimize the parameters: two 1 nm–5 nm layers are inserted symmetrically into the corresponding layer pairs of a standard Cantor model at a time until the P_{net} reaches its peak. As a result, the final design with a balance between structural complexity and heat-load reduction is illustrated in Fig. 1, which has 4.5% improvement on solar reflection over the standard Cantor model and the goals of our radiative cooling model are achieved by fulfilling the demands listed below.

Firstly, the radiative cooler can emit selectively in the subtropical atmospheric transparency window within 8 μm–13 μm and reflect strongly in the AM1.5 spectrum. SiO_2 is chosen in the quasi-Cantor structure as the low-index material to utilize its omni-directionality in emissivity spectrum and high absorption caused by phonon-polariton resonance. One can see from Fig. 2 that electromagnetic (EM) wave within the AM1.5 spectrum is reflected by the optical structure of quasi-Cantor cooler and EM wave within the atmospheric transparency window is absorbed within the altering layers, which results in high emissivity inside the window and energy emission into the cold outer space.

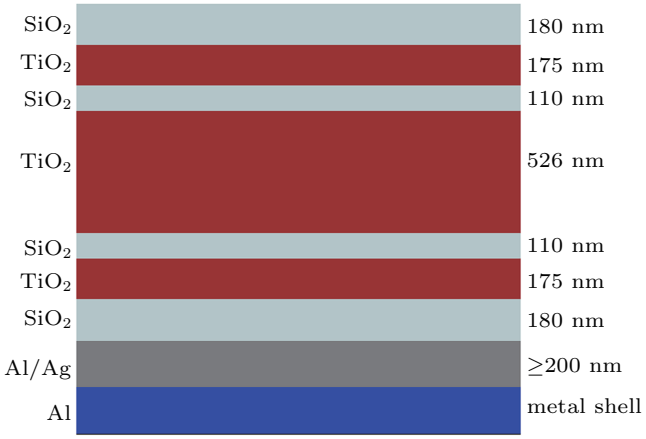


Fig. 1. (color online) The schematic diagram of the optical structure of the quasi-Cantor radiative cooler. It has seven altering layers of SiO_2 and TiO_2 that are arranged in a symmetric pattern. The thickness of the silver (Ag) layer should exceed 200 nm to obtain a high efficiency in cooling. Aluminum (Al) in this figure is to illustrate the base material in practical use, which in some cases, can be the shell of continuous thermal source. The presence of the Al layer does not affect the performance of the cooler.

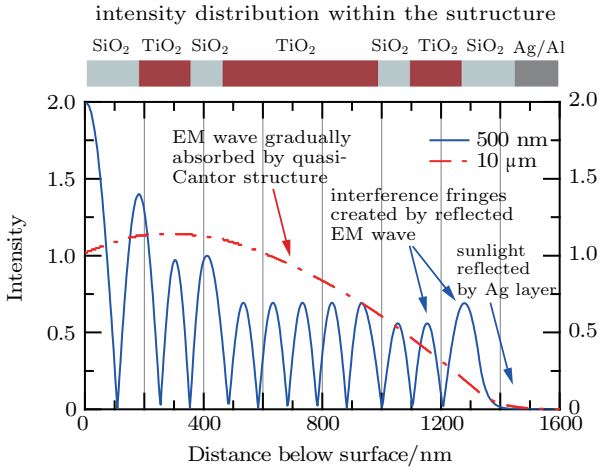


Fig. 2. (color online) The steady state of intensity distribution within the layers of the quasi-Cantor radiative cooler in solar spectrum range and in the atmospheric transparency window range. The 500-nm EM wave within solar spectrum range is reflected and the 10-μm EM wave within the atmospheric window range is gradually absorbed by the quasi-Cantor structure.

Secondly, the optimization of heat conductivity for continuous thermal source cooling is taken into consideration. The bottom layer of the radiative cooler which contacts with the heat source is designed to be metallic. Other kinds of metals and alloys can be added beneath the silver/aluminum layer in Fig. 1 to increase the efficiency of heat conductivity without affecting the cooling performance.

Thirdly, the structure is cost oriented. The thicknesses of layers of the radiative cooler are of hundreds of nanometers, which requires far less precision in manufacturing than the complicated radiative cooler designs reported recently with structural thicknesses of tens of nanometers. As for the design pattern, the structure of quasi-Cantor radiative cooler is simple and symmetric. It is shown in Fig. 1 that, the silver (Ag) layer can be replaced by aluminum (Al) layer to lower the cost without significantly reducing the overall performance. Combining

these advantages mentioned above, the quasi-Cantor radiative cooler design can ensure a low cost.

In this paper, the target of the radiative cooler is to reduce the heat load of the continuous thermal source at a high efficiency, while preserving the other benefits from its design. Its performance and properties are discussed and analyzed in the next section.

3. Properties and performance

In the simulation by using transfer matrix method (TMM)[27] based program with inorganic solid material (n,k) databases,[28–30] under the subtropical summer atmosphere and solar radiation conditions, the quasi-Cantor radiative cooler can strongly reflect the solar radiation and emit selectively within the atmospheric transparency window of subtropical region simultaneously, as shown in Fig. 3. It is well known that, the standard reference solar irradiance distribution is usually higher than the values measured by experiments, and the overall atmospheric transmittance in subtropical regions shown in Fig. 3(b) is low comparing with mid-latitude models.

In order to numerically demonstrate the efficiency of heat dissipation with and without the radiative cooler, several assumptions should be made to simplify the comparison. First, for radiative cooling and natrual cooling without coolers, the objects being cooled are the same (including size, materials, surface area) and they satisfy the model of continuous thermal source, which means they should be compared using P_{net}. Second, the amount of heat gain from the sunlight exposure without the cooler is approximately 5%, which is a typical value for commercial white paint for cooling. Third, the conditions of conductive and convective heat exchange near the surface are the same, and the experimental values of non-radiative heat exchange coefficient[12–15,18–20] are considered to be 2 $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ with no wind, 6 $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ with wind speed at approximately 1 $\text{m}\cdot\text{s}^{-1}$, and 12 $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ with wind speed at approximately 3 $\text{m}\cdot\text{s}^{-1}$.

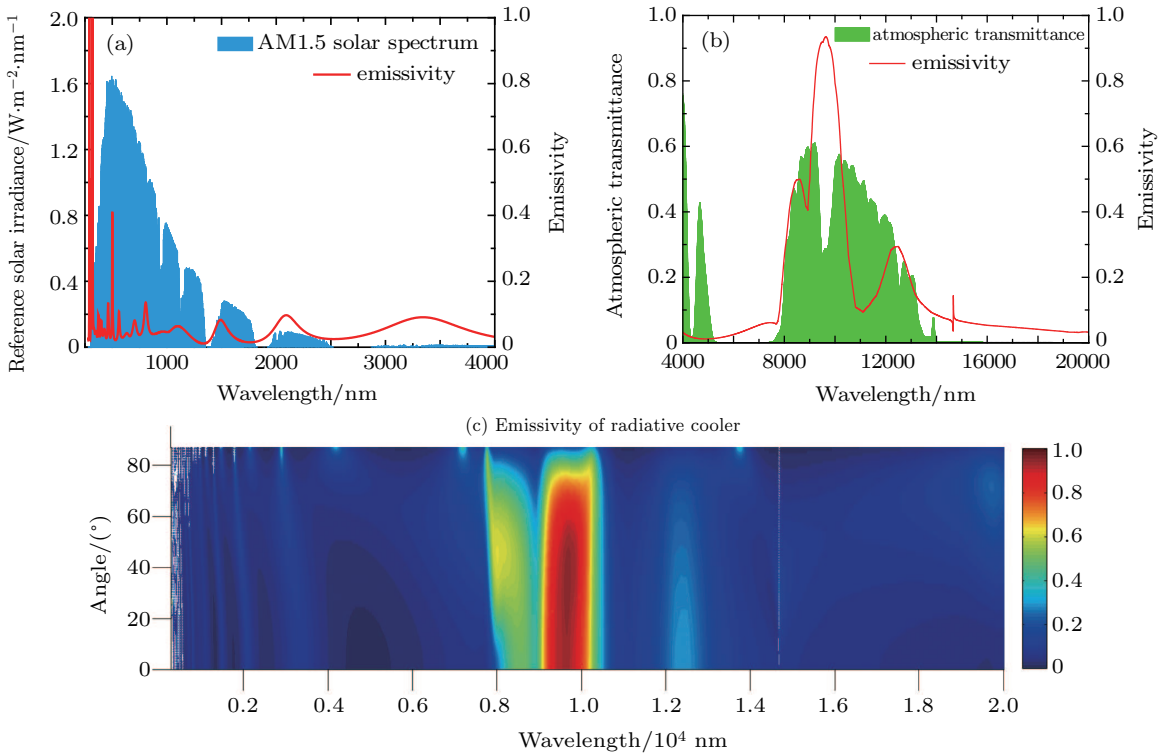


Fig. 3. (color online) The emissivity of the radiative cooler at near-normal incidence. Panel (a) shows the emissivity within solar spectrum range, which presents a low absorption of the total 1000 $\text{W}\cdot\text{m}^{-2}$ solar radiation; panel (b) indicates high emissivity within the atmospheric transparency window of hot summer in subtropical region (Guangzhou, Guangdong, China, with moderate air pollution and ambient air temperature of 30° celsius). Panel (c) illustrates the emissivity of the radiative cooler from normal incidence to grazing incidence.

It is common phenomenon that, although natural cooling power is greater than zero when the temperature of the object T_{object} is slightly higher than ambient T_{air}, due to the strong solar radiation and atmospheric radiation in subtropical regions, a positive net cooling power does not exist unless the T_{object} is above the "balance point" of natural cooling and heat gain caused by sunlight absorption. Therefore, objects exposed to direct sunlight are usually hotter than the temperature of ambient air, which can be easily observed in daily life. One can see from Fig. 4 that, the heat load of an object without radiative cooler starts to be reduced by natural cooling at a temperature higher than that with the radiative cooler. The quasi-Cantor

radiative cooler can help reduce the "balance point" to near-ambient temperature in the hot summer of Guangzhou, China. When there is no wind, the quasi-Cantor cooler can greatly reduce the "balance point" by about 15 K. When operating on a continuous thermal source at 323.15 K, the radiative cooler is 18.26% more efficient than natural heat dissipation, with hotter the thermal source is, the greater net cooling power the radiative cooler would generate, and the higher efficiency the cooler would reach.

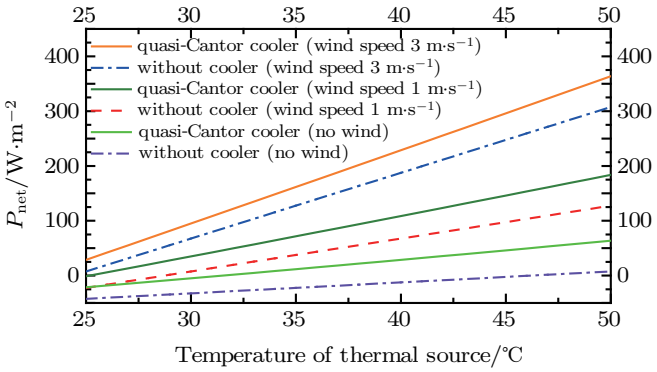


Fig. 4. (color online) The comparison between the cooling power of quasi-Cantor radiative cooler and natural non-radiative heat exchange cooling without radiative cooler (with ambient air temperature at 20° celsius in Guangzhou, China). The cooling power of natural cooling without radiative coolers are illustrated under the same heat dissipation conditions as the radiative cooler with wind speed at 3 m·s^{-1}, 1 m·s^{-1}, and 0 m·s^{-1} separately.

In reality, in order to achieve powerful radiative cooling, the structure should not be sealed. That means the actual non-radiative heat exchange coefficient of the quasi-Cantor radiative cooler is much higher than the demonstration in Fig. 4, which indicates a lower "balance point", a higher efficiency and a better performance. In addition, the heat conductivity of the object (as continuous thermal source without radiative cooler) is usually not optimized, which may result in a worse natural cooling performance. As a result, the quasi-Cantor radiative cooler is useful and high-efficient under direct subtropical sunlight.

Finally, consider an above-ambient oriented ideal broadband radiative cooler model with the same heat absorption as the quasi-Cantor cooler within the solar radiation range, and a high IR emission of 1.00 across a range from 6 μm to 20 μm. By calculation one can discover that, at 298.15 K, the ideal broadband cooler produces 30.0093 W·m^{-2} of cooling power while the quasi-Cantor cooler produces 28.6318 W·m^{-2}, which is 4.6% lower; at 323.15 K, the ideal broadband cooler produces a cooling power of 367.7203 W·m^{-2} while the quasi-Cantor cooler at 363.6806 W·m^{-2}, which is 1.09% lower. The higher the operation temperature is, the closer the performance of the quasi-Cantor cooler is to the ideal broadband cooler. In fact, the ideal cooler can hardly be achieved and broadband radiative cooler for above-ambient cooling is not as efficient as it is in mid-latitude areas. It can be concluded from this numerical comparison that, the quasi-Cantor is well optimized in subtropical environment.

4. Further application of the radiative cooler

In practical consideration, several alterations can be made to lower the cost and optimize the performance. The thickness of the silver layer of the structure is adjustable according to actual situation like cost, industrial requirements, local climatic pattern, and so on, as long as it exceeds 200 nm, which will not significantly affect the performance. The base material is also adjustable from silicon (Si), silicon dioxide (SiO_2), titanium (Ti) to aluminum (Al), and so on, as the user sees fit, for it does not involve in radiation processing. However, materials with high thermal conductivity is highly recommended, so as to increase the efficiency in heat conducting from the continuous thermal source.

In further application, certain parameters should be tuned in manufacturing. To some extent, a few differences between the performance of the simulation and the final product may occur due to the perfection of the theory and inevitable industrial flaws,[27] thus, adjustment should be made to meet the actual demands. As for the target of cooling, the "continuous thermal source", or "heat-producing object" can be referred to machines that operate outdoors within direct sunlight exposure, for instance, the external unit of air conditioners, the combustion engines, the diurnal street lamps, etc. The low efficiency of natural heat dissipation may do damage to the internal electronic circuits, causing thermal-related aging and failure. Additionally, the shells of those machines, especially plastic, may be destroyed due to exceeding amount of sunlight exposure, and after they are broken down, the inner parts of the machines remain unprotected. Conventional approaches like painting light-reflecting white paints and applying electric fans have been used to protect those machines. However, the paints may not be high efficient within AM1.5 spectrum[6] and electricity consumed by radiator fans can be enormous. The quasi-Cantor radiative cooler for continuous thermal source can be applied on these machines to help reduce the cost on maintenance and electricity bill. Most importantly, this kind of radiative cooler is less geographically limited, for it can operate efficiently in poor atmospheric conditions in subtropical regions, a better performance is expected in high transmittance clear skies of areas outside the subtropical zone.

References

[1] Catalanotti S, Cuomo V, Piro G, Ruggi D, Silvestrini V and Troise G 1975 *Sol. Energy* **17** 83

[2] Head A K (U.S. Patent) US3043112 [1962]
[3] Johnson T E 1975 *Sol. Energy* **17** 173
[4] Givoni B 1977 *Energ. Buildings* **1** 141
[5] Bartoli B, Catalanotti S, Coluzzi B, Cuomo V, Silvestrini V and Troise G 1977 *Appl. Energy* **3** 267
[6] Harrison A W and Walton M R 1978 *Sol. Energy* **20** 185
[7] Michell D and Biggs K L 1979 *Appl. Energy* **5** 263
[8] Granqvist C G 1981 *Appl. Opt.* **20** 2606
[9] Granqvist C G and Hjortsberg A 1981 *J. Appl. Phys.* **52** 4205
[10] Granqvist C G and Hjortsberg A 1980 *Appl. Phys. Lett.* **36** 139
[11] Addeo A, Nicolais L and Romeo G 1980 *Sol. Energy* **24** 93
[12] Rephaeli E, Raman A and Fan S 2013 *Nano Lett.* **13** 1457
[13] Raman A P, Anoma M A, Zhu L, Rephaeli E and Fan S 2014 *Nature* **515** 540
[14] Gentle A R and Smith G B 2015 *Adv. Sci.* **2** 1500119
[15] Zhu L, Raman A and Fan S 2013 *Appl. Phys. Lett.* **103** 223902
[16] Wu S H and Povinelli M L 2015 *Opt. Express* **23** A1363
[17] Zhu L, Raman A P and Fan S 2015 *Proc. Natl. Acad. Sci. USA* **112** 12282
[18] Zhu L, Raman A, Wang K X, Anoma M A and Fan S 2014 *Optica* **1** 32
[19] Hossain M M, Jia B and Gu M 2015 *Adv. Opt. Mater.* **3** 1047
[20] Chen Z, Zhu L, Raman A and Fan S 2016 *Nat. Commun.* **7** 13729
[21] Hossain M and Gu M 2016 *Adv. Sci.* **2** 1500360
[22] Harrison A W 1981 *Sol. Energy* **26** 243
[23] Berdahl P and Fromberg R 1982 *Sol. Energy* **29** 299
[24] Berk A, Conforti P, Kennett R, Perkins T, Hawes F and van den Bosch J 2014 *SPIE* **90880H**
[25] Gentle A R and Smith G B 2010 *Nano Lett.* **10** 373
[26] IEC-60904-3-2008 International Standard 2008 IEC
[27] Yeh P 1988 *Optical Waves in Layered Media* (New York: John Wiley & Sons)
[28] Palik E 1998 *Handbook of Optical Constants of Solids* (Orlando: Academic Press)
[29] Rakić A D, Djurišić A B, Elazar J M and Majewski M L 1998 *Appl. Opt.* **37** 5271
[30] Wood D L, Nassau K, Kometani T Y and Nash D L 1990 *Appl. Opt.* **29** 604