Perspective

Thermal Photonics and Energy Applications

Shanhui Fan[1,*]

The ability to control thermal radiation plays a fundamentally important role in a wide range of energy technology. Here I review the development of thermal photonics, which utilizes structures where at least one of the structural features is at a wavelength or subwavelength scale, for the control of thermal radiation. Thermal photonic structures have emission properties that are drastically different from those of conventional thermal radiators. These properties lead to new application opportunities in energy technologies, such as daytime radiative cooling.

Context & Scale

Thermal radiation represents a ubiquitous aspect of nature. All thermodynamic resources emit or absorb thermal radiation. For example, the sun, at the temperature of 6,000 K, represents the most important renewable energy resource. Every object that we encounter in everyday life emits thermal radiation. Finally, the universe, at a temperature of 2.7 K, represents the ultimate heat sink. In our quest to utilize various thermodynamic resources, therefore, the ability to control thermal radiation plays a fundamentally important role.

In the past few decades, the field of thermal photonics has emerged; this utilizes thermal photonic structures with characteristics that are drastically different from those of the conventional thermal radiators. A defining aspect of these thermal photonic structures is that at least one of the structural features of the radiator is comparable with or even smaller than the thermal wavelength. The development of these thermal photonic structures, in turn, provides exciting opportunities for new energy applications. This Perspective provides a short review of some of the fundamental properties of thermal photonic structures and highlights a few examples of potential applications such as daytime radiative cooling.

Introduction

Thermal radiation represents a ubiquitous aspect of nature. All thermodynamic resources emit or absorb thermal radiation. Here I highlight a few examples of such thermodynamic resources that are important for energy applications: The sun, at the temperature of 6,000 K, represents the most important renewable energy resource. Every object that we encounter in everyday life, ranging from an incandescent light bulb where the filaments are heated to 3,000 K, to our own human body at a temperature near 310 K, emits thermal radiation. I also note that the universe, at a temperature 2.7 K, represents the ultimate heat sink in terms of both its temperature and its capacity. Moreover, from the Earth's surface, the coldness of the universe is accessible by thermal radiation through the atmosphere. In our quest to utilize various thermodynamic resources, therefore, the ability to control thermal radiation plays a fundamentally important role.

Conventional thermal radiators have typical characteristics including a broad frequency bandwidth and a near-isotropic emission pattern.[1] Also, they are subject to a set of fundamental constraints.[2] For example, the spectral density of the thermal emission per unit emitter area is upper bounded by Planck's law of thermal radiation. In addition, thermal radiators are typically subject to Kirchhoff's law, which states that the angular spectral absorptivity and emissivity must be equal to each other. These characteristics and constraints impose strong restrictions on the capability for controlling thermal radiation with conventional structures.

In the past few decades, in close connection with the development of nanophotonics, the field of thermal photonics has emerged, which utilizes thermal photonic structures with characteristics that are drastically different from those of conventional thermal radiators. A defining aspect of these thermal photonic structures is that at least one of the structural features of the radiator is comparable with or even smaller than the thermal wavelength. The development of these thermal photonic structures, in turn, provides exciting opportunities for new energy applications. In this Perspective I provide a short review of some of the fundamental properties of thermal photonic structures, and highlight a few examples of potential applications.

Aspects of Thermal Photonic Structures

I start by providing a brief review of thermal photonic structures designed for the purpose of controlling thermal radiation. In particular, I will focus on structures where the emitting area is macroscopic, i.e., the dimension of the emitting area is much larger compared with the relevant thermal wavelength. For a thermal emitter, the total emitted power is proportional to the emitting area. To achieve total power that is sufficient for typical energy applications, the required area is typically macroscopic in dimension. To make this article compact, I will limit it largely to the control of far-field thermal radiation, i.e., I will be primarily concerned with the thermal electromagnetic fields generated by these emitters at a distance that is at least several wavelengths away from the emitter. Many exciting applications of near-field thermal radiation can be found in reviews such as that by Basu et al.[3]

The key quantities characterizing thermal emitters are the angular spectral absorptivity $\alpha(\omega, \hat{n}, \hat{p})$, and the angular spectral emissivity $e(\omega, \hat{n}, \hat{p})$. The angular spectral absorptivity represents the absorption coefficient of the structure for incident light at a frequency ω and direction $\hat{n}$ with a polarization vector $\hat{p}$, and is typically measured by taking the ratio between the incident power density and the absorbed power per unit area. The angular spectral emissivity $e(\omega, \hat{n}, \hat{p})$ measures the spectral emission power per unit area at the frequency ω, to a plane wave propagating at the direction $\hat{n}$, with a polarization vector $\hat{p}$, normalized against the spectral emission power per unit area at the same frequency to the same direction, of a blackbody emitter of the same area.

The vast majority of thermal emitters are made of reciprocal materials, i.e., materials characterized by symmetric permittivity and permeability tensors, including isotropic materials that are characterized by a scalar permittivity and permeability. Reciprocal emitters satisfy Kirchhoff's law, which states that:

$$\alpha\left(\omega, \hat{n}, \ \hat{p}\right) = e\left(\omega, \hat{n}, \hat{p}^*\right). \qquad \text{(Equation 1)}$$

Here the asterisk on the polarization vector denotes complex conjugate as required by a time-reversal operation. For such reciprocal thermal emitters, to control its emissivity it is sufficient to consider its absorptivity.

Spectral Control

In thermal photonic structures where the feature sizes are comparable with the wavelength of light, the wave interference effects lead to numerous possibilities for tailoring their spectral responses. One can create structures for which the emissivity is drastically different from that of the underlying materials.

Firstly, one can strongly suppress the emissivity of a material, over a range of spectral region, with the use of a photonic crystal structure that supports a photonic band gap. The gap corresponds to a frequency range where a structure has very little density of states. Within the gap the structure strongly reflects incident light. Such high reflectivity translates into a strongly suppressed thermal emissivity in the band gap. Strong suppression of thermal emissivity has been proposed and demonstrated in dielectric and metallic photonic crystal structures.[4–7] As an example, Yeng et al. considered an array of air holes in metal film (Figure 1A). Each air hole can be considered as a metallic waveguide with a cutoff frequency that is inversely proportional to the diameter of the holes. The array supports a band gap in the frequency range below the cutoff. The resulting structure therefore exhibits a strong suppression of thermal emissivity over a broad frequency range from near-zero frequency to the cutoff frequency.[8]

Alternatively, one can also strongly enhance the emissivity of a material with a variety of photonic resonators. A lossy resonator can be used to create a sharp spectral peak

[1]Ginzton Laboratory, Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA
*Correspondence: shanhui@stanford.edu
http://dx.doi.org/10.1016/j.joule.2017.07.012

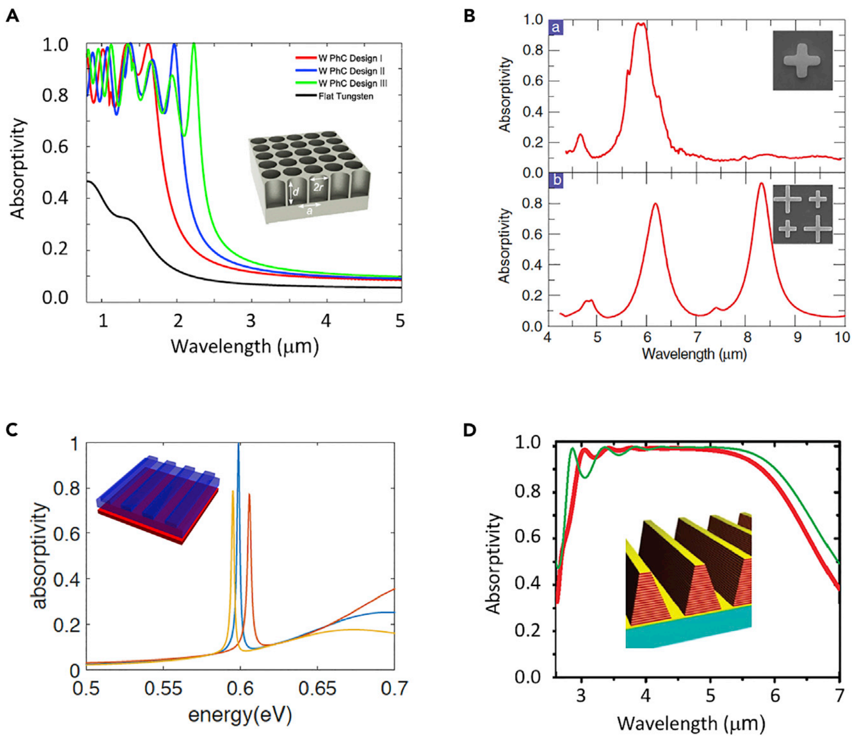

Figure 1. Thermal Photonic Structures for the Spectral Control of Thermal Radiation

Each figure shows the absorptivity spectrum for the structure shown in the inset.

(A) Periodic array of air holes in a tungsten layer for broad-band suppression of thermal radiation. Adapted from Yeng et al.[8]

(B) Gold antenna structures for the generation of narrow-band thermal radiation. Adapted from Liu et al.[9] Copyright the American Physical Society.

(C) A dielectric photonic crystal (blue region), separated by a vacuum spacing from a flat tungsten surface (red region), for the generation of narrow-band thermal radiation. As the size of the spacing increases, the system tunes from the under coupling regime (yellow curve), through the critical coupling regime (blue curve) where the peak emissivity approaches unity, to the over coupling regime (red curve). Adapted from Guo and Fan.[12] Copyright the Optical Society of America.

(D) Tapered metamaterial structures for broad-band enhancement of thermal radiation. Adapted from Cui et al.[20] Copyright the American Chemical Society.

in the absorption spectrum. Consequently, such a resonator can be used to create a narrow-band thermal emitter. A wide variety of resonant systems have been applied for this purpose. These include, for example, arrays of metallic antennas (Figure 1B),[9,10] guided resonances in photonic crystal slabs (Figure 1C),[11,12] surface plasmons,[13] Fabry-Perot cavities,[14,15] dielectric microcavities,[16] and metamaterials.[17]

In understanding the absorption and emission of a single resonator, the concept of critical coupling plays a significant role.[12,18] For a single resonance coupling to a single channel of externally incident wave, its absorptivity spectrum from that channel, and as a result its emissivity spectrum to that channel, has a Lorentzian lineshape,

$$\alpha(\omega) = e(\omega) = \frac{4\gamma_e\gamma_i}{(\omega-\omega_0)^2 + (\gamma_e+\gamma_i)^2}, \qquad \text{(Equation 2)}$$

where ω_0 is the resonant frequency, γ_e is the external radiative leakage rate of the resonance to the channel, and γ_i is the intrinsic loss rate of the resonance due to material absorption. Remarkably, no matter how small is the material absorption, i.e., no matter how small is γ_i, it is in principle always possible to achieve 100% absorption, at the resonant frequency ω_0, by satisfying the critical coupling condition

$$\gamma_e = \gamma_i. \quad \text{(Equation 3)}$$

Figure 1C illustrates the condition of the critical coupling.[12] The structure consists of a dielectric photonic crystal, assumed to be lossless, evanescently coupled to a uniform tungsten slab, which is lossy. As the spacing between the photonic crystal and the tungsten slab varies, the intrinsic loss rate γ_i of the resonance varies, while the external leakage rate γ_e largely remains constant. The variation of the spacing therefore allows one to tune through the critical coupling point, resulting in narrow-band thermal emission with a unity emissivity peak.

By introducing multiple resonances into the emitter structure, the thermal emission can exhibit physical effects associated with resonant interactions. For example, an analog of super-radiance can arise in thermal radiation when multiple resonances with the same resonant frequencies are placed together in a subwavelength volume.[19] Alternatively, broad-band enhancement of thermal radiation can be achieved by introducing multiple resonances into the emitter, each of the resonances having a different resonant frequency (Figure 1D).[20] In general, the understanding of resonances and resonant interactions provide a versatile conceptual framework for engineering the thermal emissivity spectrum.

Many thermal photonic structures have absorption spectra that are strongly polarization dependent. As a result, their thermal emission can be strongly polarized. This is in contrast to a conventional blackbody or gray-body thermal emitter from which the thermal emission is typically unpolarized.

Angular Control

Closely related to the capability for controlling the frequency dependency of the emissivity, one can also consider the possibility for tailoring the direction dependency of the emissivity. As an example, Greffet et al. considered thermal emission from an SiC grating structure, and demonstrated strong angular dependency of emissivity.[21] Similar directional thermal emission can be seen using a tungsten grating structure[22] and a one-dimensional photonic crystal.[23] In addition, photonic structures that have been designed to achieve strong angular response, such as multi-layer coating[24] or an angular coupler,[25] may also be combined with a thermal emitter to produce strong angular-selective thermal emission.

For a resonant thermal emitter, the angular dependency of its emissivity can be understood by analyzing the underlying photonic band structure. As an illustration,[12] Figure 2 shows the emissivity dependency on both the frequency ω and the wavevector component k_x that is parallel to the structure, for the photonic crystal-guided resonance structure, as shown in Figure 1C. The emissivity clearly peaks along bands in the $\omega - k_x$ plane. These bands coincide with the photonic band structure of system. At a given frequency ω, resonant emission occurs at the angle $\theta = \sin^{-1}(ck_x(\omega)/\omega)$, where $k_x(\omega)$ is determined from the band structure. Designing the photonic band structure thus enables one to design the angular dependency of thermal emission.

Both the spectral and angular control of thermal emission changes the coherent properties of thermal emitters. A narrow-band thermal emitter results in enhanced temporal coherence and a directional thermal emitter results in enhanced spatial coherence, as compared with the standard blackbody radiator.

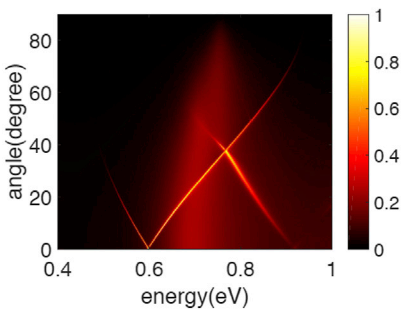

Figure 2. Photonic Band Structure Underlies the Angular Dependency of Narrow-Band Thermal Emitter

Shown here is the emissivity spectrum as a function of angle and energy, for the structure shown in Figure 1C, when the critical coupling condition is satisfied at normal incidence. Strong enhancement of thermal emissivity is seen along narrow bands that correspond to the photonic band of the system. Adapted from Guo and Fan.[12] Copyright the Optical Society of America.

Beyond Planck's Radiation Law: Thermal Extraction

Since the absorptivity $\alpha(\omega, \hat{n}) \leq 1$, it follows from Equation 1 that the emissivity $e(\omega, \hat{n}) \leq 1$. Since the ideal blackbody has an emissivity of $e(\omega, \hat{n}) = 1$, it follows that when directly emitting into free space, a thermal emitter with an area A cannot emit more than a corresponding blackbody emitter with the same area. When integrated over all emission angles $\hat{n}$, the spectral density of the total emission power P of the emitter with an area A must satisfy

$$P \leq P_0 = A \cdot \frac{\omega^2}{4\pi^2 c^2} \cdot \frac{\hbar\omega}{e^{\hbar\omega/k_B T} - 1}. \quad \text{(Equation 4)}$$

Here, ω is the angular frequency of the emission. $\hbar$ and k_B are the reduced Planck constant and the Boltzmann constant, respectively. T represents the temperature of the emitter. c is the speed of light in vacuum. The formula for P_0 in Equation 4, which describes the emission power of a blackbody emitter, is Planck's radiation law.

I note that when using Equation 4 to determine the upper bound of thermal emission power, the area A in fact needs to be taken as the absorption cross-section rather than the geometrical cross-section of the emitter. For an object with sizes comparable with the wavelength, its absorption cross-section can significantly exceed that of its geometrical cross-section, and its emission can then exceed the constraint set by the Planck radiation law of Equation 4 if A in Equation 4 is taken to be the geometrical cross-section of the emitter. Such a super-Planckian thermal radiation was observed for a thermal antenna structure.[26] On the other hand, for an emitter with a macroscopic emitting area, when it is directly surrounded by free space, its absorption cross-section cannot significantly exceed its physical cross-section. As a result, independent of the internal structure within the emitter, the overall emission cannot exceed Planck's radiation law.[27] This result has been explicitly demonstrated numerically in a direct calculation of thermal emission from a photonic crystal using the formalism of fluctuational electrodynamics. The computed thermal emission of the photonic crystal falls below what is required by Planck's law despite the significant modification of the density of states within the structure.[28]

For a blackbody emitter emitting into a transparent dielectric material with a refractive index n instead of vacuum, the speed of light c in Equation 4 needs to be replaced by c/n, and consequently the emission is enhanced by a factor of n^2. Exploiting this fact, Yu et al. developed a thermal extraction scheme that results in a far-field macroscopic super-Planckian emitter by placing a thermal emitter in near-field radiative contact with a transparent semispherical dome (Figure 3).[29] The emission into the dome is higher than the emission into vacuum due to the fact that the dome has a refractive index exceeding unity. The area of the dome is

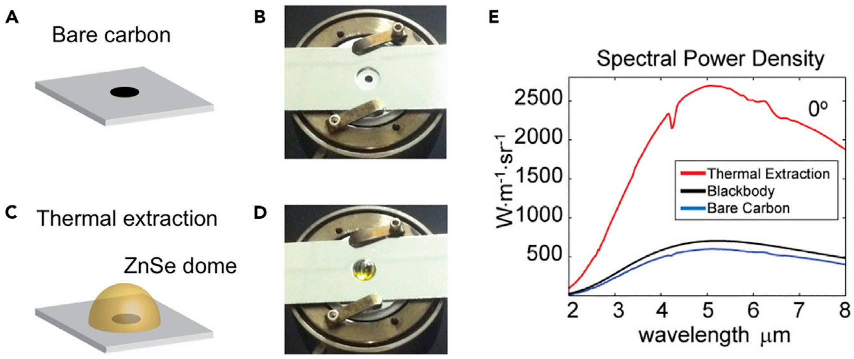

Figure 3. Thermal Extraction

(A and B) Schematic (A) and experimental configuration (B) of a bare carbon emitter on a reflecting substrate.

(C and D) Schematic (C) and experimental configuration (D) of a ZnSe semispherical dome directly placed on the carbon emitter.

(E) Measured spectral power density showing enhancement of the setup in (C) has emission power significantly exceeding that of the blackbody with the same physical area.

Adapted from Yu et al.[29]

chosen to be significantly larger than the physical area of the emitter, which ensures that all power emitted into the dome can be extracted to far field. In this case, the use of the dome results in the enhancement of the absorption cross-section of a macroscopic emitter beyond its geometrical cross-section, which results in the total emission exceeding P_0 in Equation 4 when the area A in Equation 4 is taken to be the physical area of the emitter.

Beyond Kirchhoff's Law: Non-reciprocal Thermal Radiation

While Kirchhoff's law plays a very significant role in the understanding of thermal radiation, it is important to note that it is not the requirement of the Second Law of Thermodynamics, but rather is a constraint that arises from reciprocity. Its practical importance arises because most emitters are constructed out of reciprocal materials described by an electric permittivity and a magnetic permeability function that are scalar or symmetric tensors. Kirchhoff's law does not apply if the emitter instead is made of gyrotropic materials that break reciprocity.

The ability to break Kirchhoff's law is of fundamental importance in thermal radiation harvesting. For example, to convert solar radiation to electricity, one would need to design an efficient solar absorber. However, by Kirchhoff's law an efficient absorber will also be an efficient emitter. Thus such an absorber must radiate part of the energy back to the sun, which represents an intrinsic loss mechanism. It is in fact known that the Landsberg limit,[30] which represents the upper limit of the efficiency for solar energy harvesting, can only be achieved with the use of non-reciprocal systems.[31,32]

While the possibility for breaking Kirchhoff's law has been known for some time, earlier works showed only a very small difference in the angular spectral absorptivity and emissivity.[33] Recently, Zhu et al. numerically proposed a design based on magneto-optical photonic crystals, where near-complete violation of Kirchhoff's law was achieved.[34] For a given frequency and angle of incidence, the spectral angular absorptivity can reach unity, while the corresponding emissivity vanishes (Figure 4). Miller et al. developed a generalized form of Kirchhoff's law that is applicable for both reciprocal and non-reciprocal thermal emitters.[35]

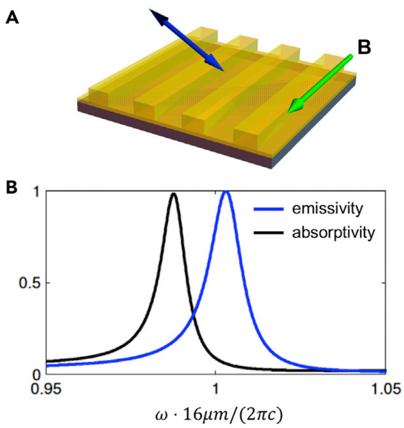

Figure 4. Non-reciprocal Thermal Radiation
(A) The structure consists of an InAs grating structure placed on top of a reflection substrate, subjected to a magnetic field (labelled as "B" and represented as the green arrow) parallel to the substrate.
(B) For the direction as indicated by the blue arrow in (A), the spectral absorptivity and emissivity significantly differ, indicating strong violation of Kirchhoff's law.
Adapted from Zhu and Fan.[34] Copyright the American Physical Society.

Daytime Radiative Cooling

The fundamental advances in controlling thermal radiation have led to many new possibilities for energy applications. A few examples of recent experimental developments include demonstrations of an improved incandescent light source,[36] a thermophotovoltaic system incorporating a thermal photonic emitter,[37] and a textile for indoor cooling applications.[38] Here, I focus on the example of daytime radiative cooling to illustrate the potential of thermal photonic structures for practical applications.

The motivation of radiative cooling is to seek to exploit the coldness of the universe as a thermodynamic resource (Figure 5A). The universe, at a temperature of 2.7 K, represents the ultimate heat sink in terms of both its temperature and its capacity. Moreover, the Earth's atmosphere is highly transparent in the wavelength range of 8–13 μm. This transparency window coincides with the peak of blackbody radiation spectrum at typical ambient temperature near 300 K. Thus any object on earth, given sky access, can radiate heat out to the universe and thus lower its temperature. As a result, night-time radiative cooling has been studied for decades.[39–41]

For cooling purposes, however, it would be more interesting to operate during the daytime under direct sunlight when typical objects become hot. For this purpose, then, one will need a structure that reflects the entire solar spectrum while generating strong thermal radiation in the wavelength range of 8–13 μm (Figure 5B).[42] Raman et al. have designed and fabricated a multi-layer photonic structure, which consists of seven dielectric layers deposited on top of a silver mirror (Figure 5C).[43] These layers are designed using a systematic optimization process taking into account fabrication constraints. The top three layers, with thickness on the order of hundreds of nanometers, are responsible generating strong thermal radiation. The bottom four layers, with thicknesses on the order of tens of nanometers, are used to enhance the reflectivity of silver mirror especially in the UV wavelength range. This sample, when placed in a roof-top measurement setup (Figure 5D), was able to reach a temperature that is 5°C below the ambient air temperature, despite having about 900 W/m^2 of sunlight directly impinging upon it (Figure 5E). Subsequently, by placing an emitter in a vacuum chamber, Chen et al. demonstrated more than 40°C reduction from the ambient air temperature during the daytime.[44] Daytime radiative cooling have now been considered in various material systems and structures.[45–47] In particular, significant experimental progress has been made in the scaling up of such coolers,[48,49] and in the integration of such coolers into

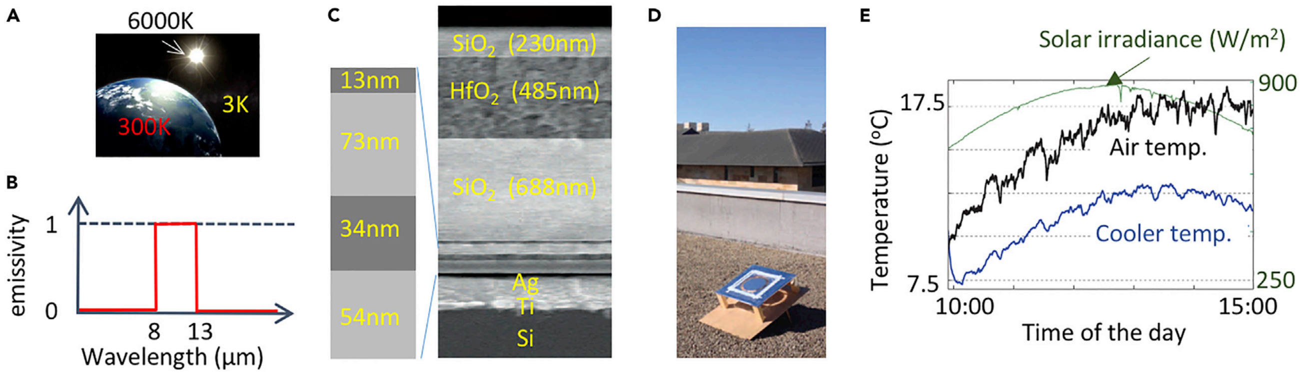

Figure 5. Daytime Radiative Cooling

(A) Major thermodynamic resources around the Earth.

(B) To achieve daytime radiative cooling, one needs to create a structure that achieves broad-band reflection of sunlight and strong thermal emission in the transparency window of the atmosphere.

(C) A multi-layer structure deposited on a silicon wafer that functions as a daytime radiative cooler. The four layers with nanoscale thickness are illustrated on the left panel. The dark and light regions correspond to HfO_2 and SiO_2, respectively.

(D) Roof-top measurement setup.

(E) The blue curve shows the temperature of the radiative cooler structure as shown in (C), when placed in the setup as shown in (D). The cooler reaches a temperature of 5°C below the ambient air under direct peak sunlight.

Adapted from Raman et al.[43]

air-conditioning systems.[49] The concepts of daytime radiative cooling can also be generalized toward cooling of solar absorbers[50] and solar cells.[51]

While the spectrum as shown in Figure 5B, which is required for daytime radiative cooling, may appear simple, no naturally occurring material in fact has such a spectrum that meets the specification required for reaching subambient temperature under direct sunlight. As an example, there is an intriguing observation of the possibility of daytime radiative cooling in silver ants that live in deserts. The spectrum of the ant body, however, is not sufficient to reach a subambient temperature under sunlight.[52] The key to daytime radiative cooling is the capability of a thermal photonic structure to control the radiation property over a very broad-band wavelength range spanning from UV to mid-wave infrared. The success in demonstrating the technology of daytime radiative cooling highlights the importance of making fundamental advances in the field of thermal photonics.

Concluding Remarks and Future Perspectives

I end this Perspective with a few remarks. The advances in thermal photonic structures builds upon the exciting developments made in the past several decades on designing photonic structures for the control of light. As evidenced in this brief review, all major conceptual developments in nanophotonics, such as photonic crystals, plasmonics, and metamaterials, have found significant applications in the control of thermal radiation. The emerging new concepts in nanophotonics, including for example the concept of parity-time symmetry, the exploration of aperiodic and random structures, and the introduction of new material systems into photonics,[53] will also have a substantial impact on the development of thermal photonics.

Unlike many photonic applications in which minimizing loss is a central issue, thermal photonic structures require a judicious management of loss: a structure that is completely lossless does not generate thermal radiation. The developments of thermal photonic structures therefore significantly enrich the field of nanophotonics.

While most thermal photonic structures considered up to now are at local thermal equilibrium, there are significant opportunities in considering the thermodynamic properties of non-equilibrium systems, such as semiconductors under external bias.[54] The efforts along this direction may lead to the exciting opportunities of thermal optoelectronics for the active manipulation of heat.

For thermal photonic structures to make an impact in practical applications, it is important to be able to scale these structures up. In addition, it is of crucial importance to be able to integrate these thermal photonic structures into practical thermal systems. The field of thermal photonics lies at the interface between thermodynamics and photonics, with significant potential for both fundamental advances and practical energy applications.

ACKNOWLEDGMENTS

I acknowledge current support from the Global Climate and Energy Project at Stanford University, the Department of Energy (DOE) Office of Basic Energy Sciences (grant no. DE-FG02-07ER46426), the DOE Advanced Project Research Agency-Energy (APRA-E) (grant nos. DE-AR0000316, DE-AR0000533, DE-AR0000731), the DOE ''Light-Material Interactions in Energy Conversion'' Energy Frontier Research Center (grant no. DE-SC0001293), and the National Science Foundation (CMMI-1562204). I also would like to acknowledge the current and former students, postdocs, and research staff in my group, as well as many collaborators, who contributed to the works cited here.

REFERENCES

1. Howell, J.R., Menguc, M.P., and Siegel, R. (2011). Thermal Radiation Heat Transfer (CRC Press).
2. Kittel, C., and Kroemer, H. (2000). Thermal Physics (W. H. Freeman and Company).
3. Basu, S., Zhang, Z.M., and Fu, C.J. (2009). Review of near-field thermal radiation and its application to energy conversion. Int. J. Energ. Res. *33*, 1203.
4. Cornelius, C.M., and Dowling, J.P. (1999). Modification of Planck blackbody radiation by photonic band-gap structures. Phys. Rev. A *59*, 4736.
5. Lin, S.-Y., Fleming, J.G., Chow, E., Bur, J., Choi, K.K., and Goldberg, A. (2000). Enhancement and suppression of thermal emission by a three-dimensional photonic crystal. Phys. Rev. B *62*, R2243–R2246.
6. Arpin, K.A., Losego, M.D., Cloud, A.N., Ning, H.L., Mallek, J., Sergeant, N.P., Zhu, L.X., Yu, Z.F., Kalanyan, B., Parsons, G.N., et al. (2013). Three-dimensional self-assembled photonic crystals with high temperature stability for thermal emission modification. Nat. Commun. *4*, 2630.
7. Rinnerbauer, V., Lenert, A., Bierman, D.M., Yeng, Y.X., Chan, W.R., Geil, R.D., Senkevich, J.J., Joannopoulos, J.D., Wang, E.N., Soljačić, M., and Celanovic, I. (2014). Metallic photonic crystal absorber-emitter for efficient spectral control in high-temperature solar thermophotovoltaics. Adv. Energy Mater. *4*, 1400334.
8. Yeng, Y.X., Ghebrebrhan, M., Bermel, P., Chan, W.R., Joannopoulos, J.D., Soljačić, M., and Celanovic, I. (2012). Enabling high-temperature nanophotonics for energy applications. Proc. Natl. Acad. Sci. USA *109*, 2280–2285.
9. Liu, X., Tyler, T., Starr, T., Starr, A.F., Jokerst, N.M., and Padilla, W.J. (2011). Taming the blackbody with infrared metamaterials as selective thermal emitters. Phys. Rev. Lett. *107*, 045901.
10. Liu, B., Gong, W., Yu, B., Li, P., and Shen, S. (2017). Perfect thermal emission by nanoscale transmission line resonators. Nano Lett. *17*, 666–672.
11. De Zoysa, M., Asano, T., Mochizuki, K., Oskooi, A., Inoue, T., and Noda, S. (2012). Conversion of broadband to narrowband thermal emission through energy recycling. Nat. Photon. *6*, 535–539.
12. Guo, Y., and Fan, S. (2016). Narrowband thermal emission from a uniform tungsten surface critically coupled with a photonic crystal guided resonance. Opt. Express *24*, 29896–29907.
13. Pralle, M., Moelders, N., McNeal, M., Puscasu, I., Greenwald, A., Daly, J., Johnson, E., George, T., Choi, D., and El-Kady, I. (2002). Photonic crystal enhanced narrow-band infrared emitters. Appl. Phys. Lett. *81*, 4685–4687.
14. Celanovic, I., Perreault, D., and Kassakian, J. (2005). Resonant-cavity enhanced thermal emission. Phys. Rev. B *72*, 075127.
15. Rephaeli, E., and Fan, S.H. (2009). Absorber and emitter for solar thermophotovoltaic systems to achieve efficiency exceeding the Shockley-Queisser limit. Opt. Express *17*, 15145–15159.
16. Maruyama, S., Kashiwa, T., Yugami, H., and Esashi, M. (2001). Thermal radiation from two-dimensionally confined modes in microcavities. Appl. Phys. Lett. *79*, 1393–1395.
17. Molesky, S., Dewalt, C.J., and Jacob, Z. (2013). High temperature epsilon-near-zero and epsilon-near-pole metamaterial emitters for thermophotovoltaics. Opt. Express *21*, A96–A110.
18. Zhu, L.X., Sandhu, S., Otey, C., Fan, S.H., Sinclair, M.B., and Luk, T.S. (2013). Temporal coupled mode theory for thermal emission from a single thermal emitter supporting either a single mode or an orthogonal set of modes. Appl. Phys. Lett. *102*, 103104.
19. Zhou, M., Yi, S., Luk, T.S., Gan, Q., Fan, S., and Yu, Z. (2015). Analog of superradiant emission in thermal emitters. Phys. Rev. B *92*, 024302.
20. Cui, Y., Fung, K.H., Xu, J., Ma, H., Jin, Y., He, S., and Fang, N.X. (2012). Ultrabroadband light absorption by a sawtooth anisotropic metamaterial slab. Nano Lett. *12*, 1443–1447.
21. Greffet, J.-J., Carminati, R., Joulain, K., Mulet, J.-P., Mainguy, S., and Chen, Y. (2002). Coherent emission of light by thermal sources. Nature *416*, 61.
22. Laroche, M., Arnold, C., Marquier, F., Carminati, R., Greffet, J.-J., Collin, S., Bardou, N., and Pelouard, J.-L. (2005). Highly directional radiation generated by a tungsten thermal source. Opt. Lett. *30*, 2623–2625.
23. Lee, B., Fu, C., and Zhang, Z. (2005). Coherent thermal emission from one-dimensional photonic crystals. Appl. Phys. Lett. *87*, 071904.

24. Shen, Y., Ye, D., Celanovic, I., Johnson, S.G., Joannopoulos, J.D., and Soljačić, M. (2014). Optical broadband angular selectivity. Science *343*, 1499–1501.

25. Kosten, E.D., Atwater, J.H., Parsons, J., Polman, A., and Atwater, H.A. (2013). Highly efficient GaAs solar cells by limiting light emission angle. Light Sci. Appl. *2*, e45.

26. Schuller, J.A., Taubner, T., and Brongersma, M. (2009). Optical antenna thermal emitters. Nat. Photon. *3*, 658.

27. Trupke, T., Würfel, P., and Green, M.A. (2004). Comment on "Three-dimensional photonic-crystal emitter for thermal photovoltaic power generation" [Appl. Phys. Lett. 83, 380 (2003)]. Appl. Phys. Lett. *84*, 1997–1998.

28. Luo, C., Narayanaswamy, A., Chen, G., and Joannopoulos, J.D. (2004). Thermal radiation from photonic crystals: a direct calculation. Phys. Rev. Lett. *93*, 213905.

29. Yu, Z., Sergeant, N.P., Skauli, T., Zhang, G., Wang, H., and Fan, S. (2013). Enhancing far-field thermal emission with thermal extraction. Nat. Commun. *4*, 1730.

30. Landsberg, P.T., and Tonge, G. (1980). Thermodynamic energy conversion efficiencies. J. Appl. Phys. *51*, R1.

31. Ries, H. (1983). Complete and reversible absorption of radiation. Appl. Phys. B *32*, 153–156.

32. Green, M.A. (2012). Time-asymmetric photovoltaics. Nano Lett. *12*, 5985–5988.

33. Snyder, W.C., Wan, Z., and Li, X. (1995). Thermodynamic constraints on reflectance reciprocity and Kirchhoff's law. Appl. Opt. *37*, 3464.

34. Zhu, L., and Fan, S. (2014). Near-complete violation of detailed balance in thermal radiation. Phys. Rev. B *90*, 220301.

35. Miller, D.A.B., Zhu, L., and Fan, S. (2017). Universal modal radiation laws for all thermal emitters. Proc. Natl. Acad. Sci. USA *114*, 4336–4341.

36. Ilic, O., Bermel, P., Chen, G., Joannopoulos, J.D., Celanovic, I., and Soljačić, M. (2016). Tailoring high-temperature radiation and the resurrection of the incandescent source. Nat. Nanotechnol. *11*, 320–324.

37. Lenert, A., Bierman, D.M., Nam, Y., Chan, W.R., Celanovic, I., Soljacic, M., and Wang, E.N. (2014). A nanophotonic solar thermophotovoltaic device. Nat. Nanotechnol. *9*, 126–130.

38. Hsu, P.-C., Song, A.Y., Catrysse, P.B., Liu, C., Peng, Y., Xie, J., Fan, S., and Cui, Y. (2016). Radiative human body cooling by nanoporous polyethylene textile. Science *353*, 1019–1023.

39. Catalanotti, S., Cuomo, V., Piro, G., Ruggi, D., Silvestrini, V., and Troise, G. (1975). The radiative cooling of selective surfaces. Solar Energy *17*, 83–89.

40. Granqvist, C.G., and Hjortsberg, A. (1981). Radiative cooling to low temperatures: general considerations and application to selectively emitting SiO films. J. Appl. Phys. *52*, 4205–4220.

41. Gentle, A.R., and Smith, G.B. (2010). Radiative heat pumping from the earth using surface phonon resonant nanoparticles. Nano Lett. *10*, 373–379.

42. Rephaeli, E., Raman, A., and Fan, S. (2013). Ultra-broadband photonic structures to achieve high-performance daytime radiative cooling. Nano Lett. *13*, 1457–1461.

43. Raman, A.P., Anoma, M.A., Zhu, L., Rephaeli, E., and Fan, S. (2014). Passive radiative cooling below ambient air temperature under direct sunlight. Nature *515*, 540–544.

44. Chen, Z., Zhu, L., Raman, A., and Fan, S. (2016). Radiative cooling to deep sub-freezing temperatures through a 24-h day-night cycle. Nat. Commun. *7*, 13729.

45. Kou, J.-l., Jurado, Z., Chen, Z., Fan, S., and Minnich, A.J. (2017). Daytime radiative cooling using near-black infrared emitters. ACS Photon. *4*, 626–630.

46. Gentle, A.R., and Smith, G.B. (2015). A subambient open roof surface under the mid-Summer sun,. Adv. Sci. *2*, 1500119.

47. Hossain, M.M., Jia, B., and Gu, M. (2015). A metamaterial emitter for highly efficient radiative cooling. Adv. Opt. Mater. *3*, 1047–1051.

48. Zhai, Y., Ma, Y., David, S.N., Zhao, D., Lou, R., Tan, G., Yang, R., and Yin, X. (2017). Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling. Science *355*, 1062–1066.

49. Goldstein, E.A., Raman, A.P., and Fan, S. (2017). Subambient non-evaporative fluid cooling with the sky. Nature Energy *2*, 17143.

50. Zhu, L., Raman, A.P., and Fan, S. (2015). Radiative cooling of solar absorbers using a visibly transparent photonic crystal thermal blackbody. Proc. Natl. Acad. Sci. USA *112*, 12282–12287.

51. Zhu, L., Raman, A., Wang, K.X., Anoma, M.A., and Fan, S. (2014). Radiative cooling of solar cells. Optica *1*, 32–38.

52. Shi, N.N., Tsai, C.-C., Camino, F., Bernard, G.D., Yu, N., and Wehner, R. (2015). Keeping cool: enhanced optical reflection and radiative heat dissipation in Saharan silver ants. Science *349*, 298–301.

53. Guler, U., Boltasseva, A., and Shalaev, V.M. (2014). Refractory plasmonics. Science *344*, 263–264.

54. Chen, K., Santhanam, P., Sandhu, S., Zhu, L., and Fan, S. (2015). Heat-flux control and solid-state cooling by regulating chemical potential of photons in near-field electromagnetic heat transfer. Phys. Rev. B *91*, 134301.