Nighttime Radiative Cooling: Harvesting the Darkness of the Universe

Investigators

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Abstract

Radiative cooling technology, which utilizes the atmospheric transparency window (8-13 μm) to passively dissipate heat from Earth into outer space (3 K), has attracted broad interests from both fundamental sciences and real world applications. However, the temperature reduction experimentally demonstrated thus far has been relatively modest. In this GECP project, we theoretically showed that ultra large temperature reduction for as much as 60 ^{o}C from ambient is achievable, and experimentally demonstrated a temperature reduction that far exceeds previous works. Specifically, we have experimentally achieved an average temperature reduction of 37 ^{o}C from the ambient air temperature through a 24 hour day-night cycle, with a maximal reduction of 42 ^{o}C that occurs at peak solar irradiance. This result represents a record-breaking performance in radiative cooling. During daytime the performance of our radiative cooler surpasses previous record by almost an order of magnitude. The nighttime performance of our cooler, carried out in a populous area at sea level, significantly exceed previous record carried out at a mountain-top desert. Our result demonstrates significant fundamental potential for radiative cooling, and paves the way for numerous real world applications ranging from passive building cooling, renewable energy harvesting, and passive refrigeration in arid regions. In addition to passive radiative cooling, we also explored theoretical design for realizing self-adaptive radiative cooling based on phase change materials. We design a photonic structure that can self-adaptively turn 'on' and 'off' radiative cooling, depending on the ambient temperature, without any extra energy input for switching. We also explored thermophotonic circuits that can convert heat to electricity by exploring the chemical potential of photons. Our results here lead to new functionalities of using radiative cooling and thermal radiation, and can potentially be used in a wide range of applications for the thermal management of buildings, vehicles and textiles, as well as waste heat recovery.

Introduction

Fundamental thermodynamics asserts that high efficiency conversion from heat to work requires both a high temperature heat source and a low temperature heat sink. The vast majority of energy conversion processes at present use our ambient surrounding here on Earth as the heat sink. On the other hand, outer space, at a temperature of 3 K, provides a much colder heat sink. Moreover, Earth's atmosphere has a transparency window in the wavelength range from 8 to 13 μm that coincides with the peak of the blackbody spectrum of typical terrestrial temperatures around 300 K, enabling the process of radiative cooling, i.e. radiative ejection of heat from Earth to outer space, and hence the direct radiative access to this colder heat sink. Exploitation of radiative cooling therefore has the potential to drastically improve a wide range of energy conversion and utilization processes on Earth.

Background

In 2014, we reported a groundbreaking experiment on radiative cooling[1]. Using photonic design, we have achieved passive cooling of 5 ^{o}C below ambient air temperature under direct sunlight. Since then, a flurry of research on radiative cooling has been sparked on both fundamental sciences and real world applications. Some of the worldwide notable achievements include:

- We utilized the radiative cooling technique to passively cool solar cells, thus significantly enhancing their efficiency.[2]

- A research group from Columbia University reported their findings on how the Saharan silver ants keep themselves cool in hot dessert through radiative cooling.[3]

- An Australian group attempted optimizing the performance of radiative cooling using meta-materials.[4]

- Another Australian group developed novel materials to radiatively cool the roof below ambient temperature under maximum solar irradiance of mid-summer.[5]

- ARPA-E awarded muti-million dollars to fund research on radiative cooling, with a final goal to complement the air conditioning technology, thus relieving the pressure from global electrical power demand and environmental concerns.[6]

- Three groups from University of Colorado, Columbia University, and University of Maryland reported scalable manufacturing of radiative cooling materials. [7-9]

Despite the above achievements, the demonstrated performance thus far has been rather limited. For nighttime cooling, in typical populous areas the demonstrated temperature reduction from ambient air is on the order of 15-20 ^{o}C. For daytime cooling, the demonstrated temperature reduction is approximately 5 ^{o}C. An important open question then is: what is the fundamental limit of temperature reduction that can be achieved in typical populous areas on Earth?

Results

In this GECP project, we first theoretically show that ultra large temperature reductions up to 60 ^{o}C below ambient can be achieved. The key to such ultra large temperature reduction is to use highly selective thermal absorber matched to the atmospheric transparency window, and to minimize parasitic heat losses. Experimentally, we demonstrate an apparatus, which exhibits continuous passive cooling throughout both day and night. In a 24 hour day-night cycle, the cooler is maintained at a temperature that is at least 33 °C below ambient air temperature, with a maximal temperature reduction of 42 °C, which occurs during peak solar irradiance.

Theoretical predictions of ultrahigh performance radiative cooling

To illustrate the pathway towards achieving ultra-large temperature reduction, we first consider the ideal case, where the atmosphere is 100% transparent at a particular wavelength range. In such a case, an emitter that has unity emissivity within this wavelength range, and zero emissivity outside, will reach the temperature of outer space of 3 K in the absence of parasitic heat loss, since in such a case the emitter is undergoing thermal exchange only with outer space.

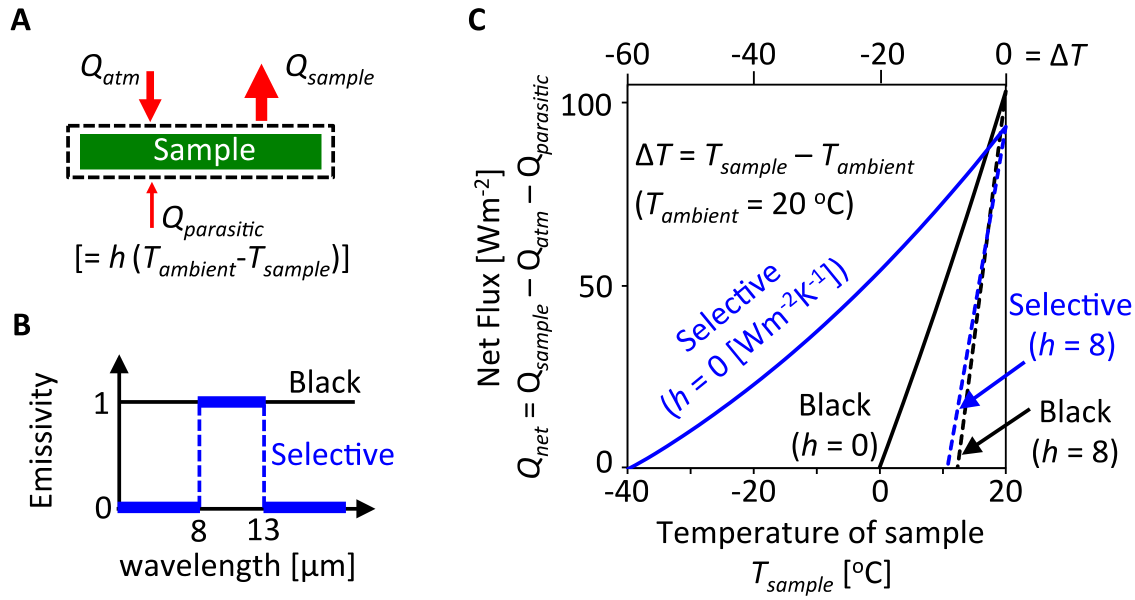

Figure 1: Theoretical predictions. (**A**) Energy balance applied to the radiative emitter (dashed line). (**B**) Two emitters are considered: a black emitter and a near-ideal selective emitter. (**C**) Net flux (Q_{net}) as a function of the temperature of the sample (T_{sample}). The analysis highlights the two key ingredients to achieve high performance radiative cooling: selectivity of the emitter and minimization of the parasitic heat loss.

For a more realistic case, we perform the theoretical analysis as illustrated in Fig. 1, where the transmittance of the atmosphere is taken to be typical of Stanford, California. Here for simplicity we analyze the performance of night-time cooling. The performance of night-time cooling provides the upper bound for the performance during daytime, an upper bound that can be reached by completely suppressing solar radiation on the cooler.

The steady-state temperature (Fig. 1A) of a radiative emitter is determined by the energy balance among three key component: the emitted thermal radiation from the sample (Q_{sample}), the absorbed thermal radiation from the atmosphere (Q_{atm}), and the parasitic heat losses ($Q_{parasitic}$) characterized by a heat transfer coefficient h. We consider two different emitters (Fig. 1B): a black emitter and a near-ideal selective emitter that has unit emissivity inside the atmospheric transparency window (8-13 μm) and zero emissivity outside. In Fig. 1C, we plot the net flux,

$$Q_{net} = Q_{sample} - Q_{atm} - Q_{parasitic}, \quad (1)$$

as a function of the temperature of the sample, T_{sample}. The steady state temperature of the sample is reached when the net flux (Q_{net}) reaches zero. Here we fix the ambient temperature ($T_{ambient}$) to be 20 °C, and use a typical atmospheric transmittance corresponding to local conditions. For each emitter, we consider two parasitic heat transfer coefficients: h = 8 $Wm^{-2}K^{-1}$ represents a typical experimental setup without sophisticated thermal design, while h = 0 $Wm^{-2}K^{-1}$ represents an ideal case with perfect thermal insulation.

Figure 1C underlines two key features. First, with a substantial parasitic heat loss (h = 8 $Wm^{-2}K^{-1}$), the difference in performance between the black and the selective emitter is relatively small. Both the black emitter and the near-ideal selective emitter are restricted to a temperature reduction $|\Delta T| \sim 10$ °C. Second, when the parasitic heat loss is completely eliminated (h = 0 $Wm^{-2}K^{-1}$), there is a very large difference in terms of performance between the black and the selective emitter. Whereas the temperature reduction of the black emitter is limited to $|\Delta T| \sim 20$ °C, the selective emitter achieves a far higher temperature reduction $|\Delta T| \sim 60$ °C. Thus, in order to approach the fundamental limit on radiative cooling, both selective emitter and ultralow parasitic heat loss are essential. These considerations, together with the need to suppress solar absorption during the daytime, motivate our design of the experimental apparatus and the selective emitter.

Experimental demonstrations of ultrahigh performance radiative cooling

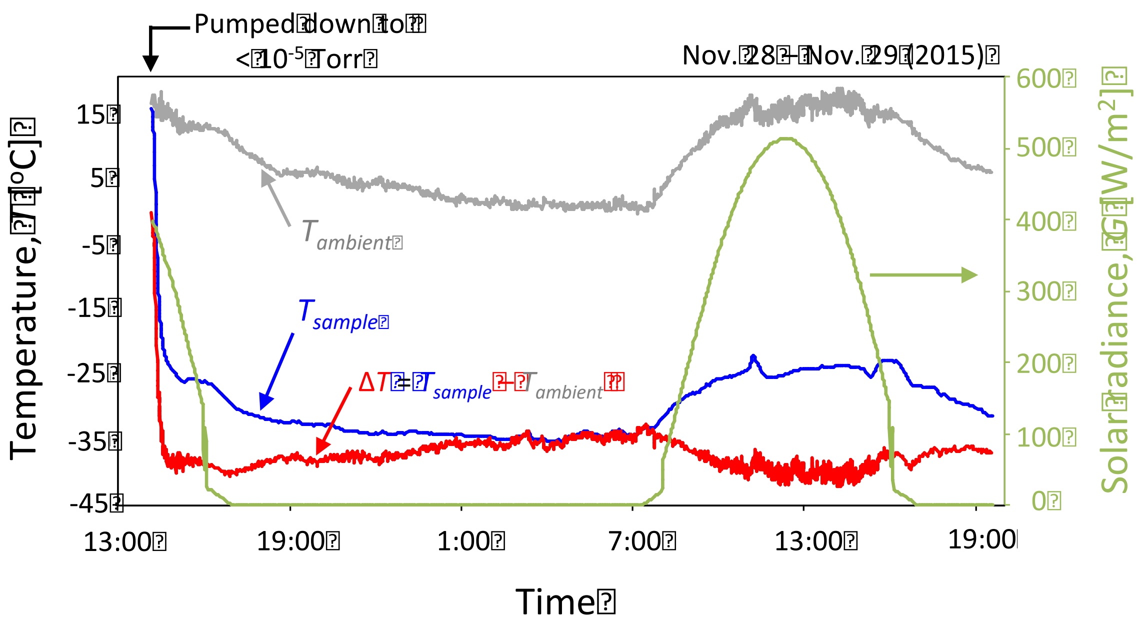

Figure 2: Experimental demonstrations of ultrahigh performance radiative cooling in a 24 hour day-night cycle. After pumping down to 10^{-5} Torr, an average temperature reduction from the ambient of 37.4 °C is achieved over a day-night cycle. The maximal cooling of 42.2 °C synchronizes the peak of the solar radiance.

We performed measurements by exposing the experimental apparatus to a clear sky throughout a 24-hour day-night cycle at Stanford, California. A typical measurement (Fig. 2) shows the temperature of the selective emitter (blue), the ambient air (gray), as well as their difference (red). The solar irradiance (green; right axis) of a typical clear day in winter is also measured for reference. A few prominent features can be clearly recognized from Fig. 2. First, the temperature of the selective emitter rapidly decreases to be ~ 40 ^{o}C below ambient air within half hour after the vacuum chamber is pumped down to ~ 10^{-5} Torr. Second, it tracks closely the trend of the temperature of the ambient air in the following 24 hours, with an average temperature reduction from the ambient of 37.4 ^{o}C. Finally, the maximal temperature reduction from ambient (42.2 ^{o}C) appears around the *peak* of the solar irradiance.

Towards large-scale deployment

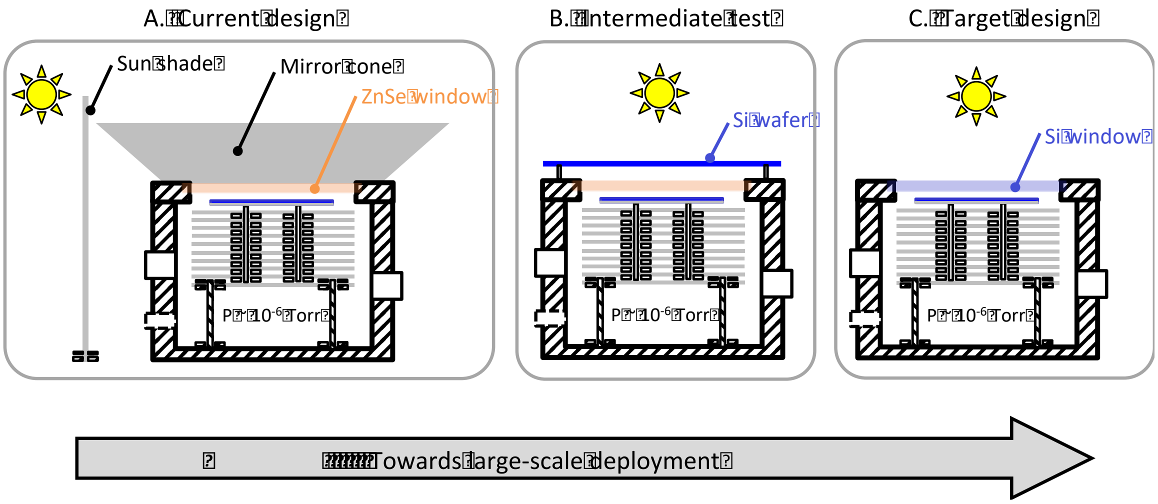

Figure 3: Modify the current setup (A) towards large-scale deployment. The key challenges are to replace the costly ZnSe window and remove the sun-shade and mirror cone. (C) A Si window could solve both of problems in (A), by sacrifice a little in performance (see Fig. 4A). (B) A sanity check on the performance of Si, by simply covering the vacuum chamber by a Si wafer.

We end by exploring the pathway towards a large industrial scale implementation of our current work. There are two major issues to scale up such high performance radiative cooling systems (Fig. 3A). First, the ZnSe window we used to equip the vacuum system for sky access in the infra-red wavelength range is too costly. Second, the shading scheme of sun-shade / mirror-cone is not robust.

These two issues could be addressed by replacing the ZnSe window and sun-shade / mirro-cone with Si or Ge window (Fig. 3C). Si and Ge are transparent in the wavelength range of 8-13 micron. Importantly, Si and Ge highly absorb in the solar wavelength range, thus they can absorb the sunlight and dissipate the heat through natural convection. This feature makes it possible to remove the sun-shade / mirror-cone.

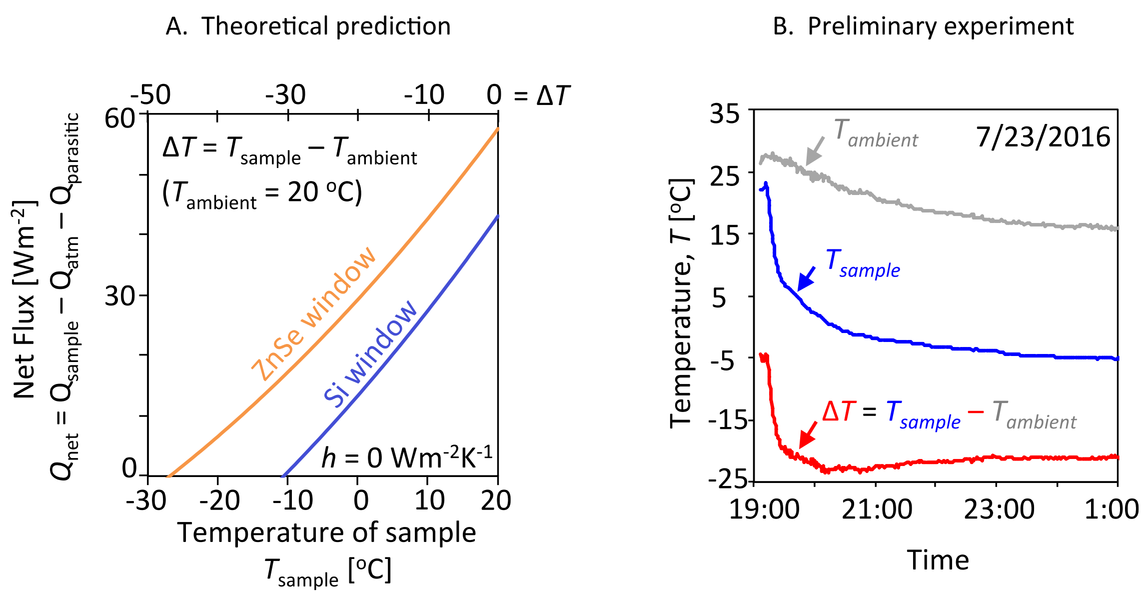

Figure 4: (**A**) Theoretical prediction on the performance of a Si window (blue), as compared to that of the ZnSe window (orange), at an ideal scenario, where the parasitic heat loss is completely compressed (h = 0 $Wm^{-2}K^{-1}$). (**B**) Experimental results on a setup as described in Fig. 3B. The experiment confirms the prediction in A.

Figure 4A shows our theoretical prediction on the performance of a Si window (blue), as compared to that of the ZnSe window (orange). At ideal scenario with no parasitic heat loss (h = 0 $Wm^{-2}K^{-1}$), the selective emitter equipped with a Si window can reach a temperature 30 °C below the ambient, while that with the ZnSe window can reach 45 °C below the ambient. Although we scarify the temperature reduction by ~ 15 °C, we save the cost by two orders of magnitude.

Figure 4B shows our experimental results on a setup as shown in Fig. 3B, which, instead of replacing the ZnSe window by a Si window, covers the vacuum chamber by a Si wafer, as a sanity check. This experiment, which reaches a temperature reduction of ~ 23 °C, is consistent with our theoretical prediction in Fig. 4A.

Photonic design for self-adaptive radiative cooling

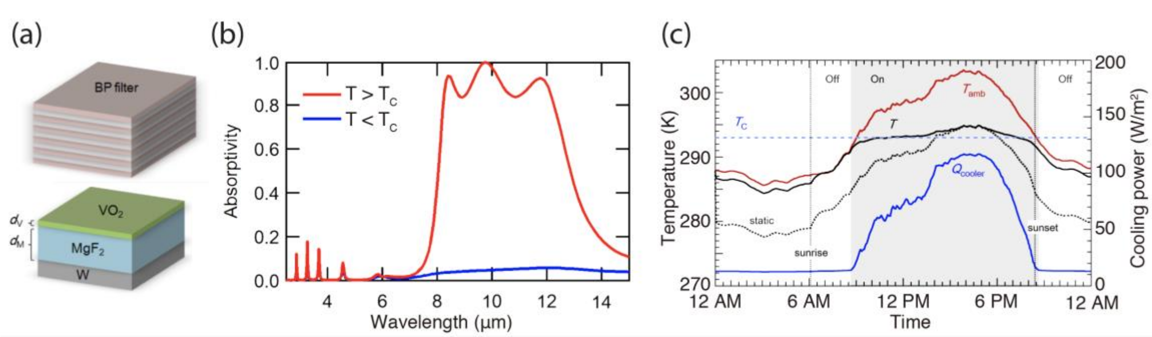

Figure 5: (a) Schematic of a photonic structure for realizing self-adaptive radiative cooling. The structure consists of a bottom radiative cooler, which is made of three layer VO2/MgF2/W structure, as well as a top spectrally-selective filter, which is made of 11 layers of Ge/MgF_2. (b) Infrared emissivity of the self-adaptive radiative cooler, when temperature is above (red) or below (blue) critical temperature. (c) Simulated thermal performance of the self-adaptive radiative cooler (black curve) over a 24h cycle with ambient temperature variation (red curve). As a comparison, the thermal performance of a static radiative cooler with the same emissivity as the 'on' state of the self-adaptive radiative cooler is also plotted (black dashed curve).

As evidenced by our previous results, radiative cooling technology is important for a broad range of applications such as passive building cooling, refrigeration, and renewable energy harvesting. However, all existing radiative cooling technologies utilize static structures, which lack the ability of self-adaptive tuning based on demand. Here we present the concept of self-adaptive radiative cooling based on phase change materials such as vanadium dioxide [10]. We design a photonic structure (Fig. 5a and b) that can adaptively turn 'on' and 'off' radiative cooling, depending on the ambient temperature, without any extra energy input for switching. The self-adaptive switching of radiative cooling performance comes from photonic engineering as well as the infrared properties changes of vanadium dioxide upon temperature change. This self-adaptive radiative cooler can perform radiative cooling when it's above a critical temperature and turn off radiative cooling when it's below the critical temperature (Fig. 5c). Our results here lead to new functionalities of radiative cooling and can potentially be used in a wide range of applications for the thermal management of buildings, vehicles and textiles.

Thermophotonic circuit for energy harvesting

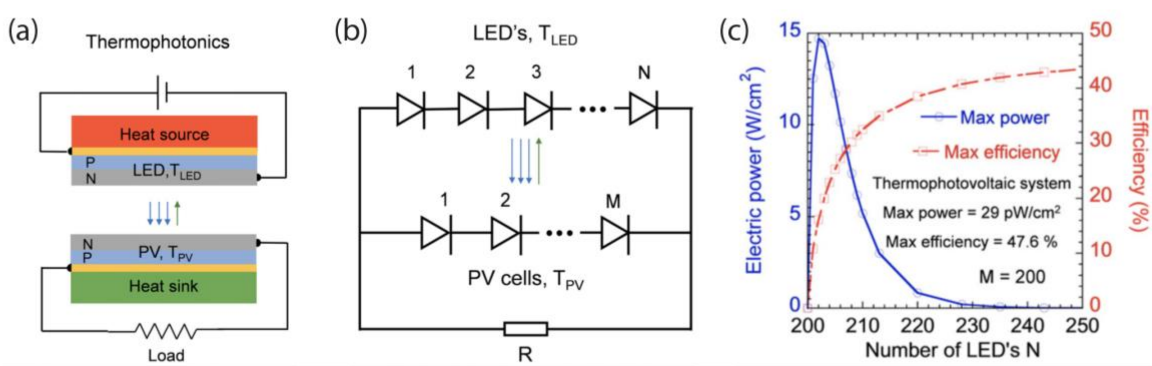

Figure 6: (a) Schematic of a thermophotonic system using batteries. The battery connected to the LED is used to drive the LED. The battery connected to the PV cell is charged by the PV cell. (b) Proposed thermophotonic circuit that uses multiple LEDs (N in total) and multiple PV cells (M in total). We assume N > M. The load is a resistor with a resistance R. (c) Maximum electric power and maximum efficiency of the proposed thermophotonic circuit, as a function of the number of LEDs. The number of PV cells is fixed at M = 200.

In addition to exploring radiative cooling where the cold universe is used as heat sink for thermal radiation, we also studied using thermal radiation and photons for energy harvesting purpose to convert heat into electricity. Photon-based systems that convert heat to electricity have been limited by low power density. Thermophotonic systems have the potential to significantly enhance the power density. This potential has not been realized in practice, due in part to the fundamental thermodynamic difficulty in designing a self- sustaining circuit that enables steady-state power generation. Current construction instead uses batteries which lower system efficiency and adds complexity (Fig. 6a). We overcome such difficulty by introducing an electronic circuit where multiple photons can be generated from a single electron (Fig. 6b) [11]. Our design enables a self- sustaining thermophotonic circuit that can achieve a steady- state power density exceeding traditional thermophotovoltaic systems by many orders of magnitude (Fig. 6c). This work highlights possibilities for constructing heat engines with light as the working medium.

Conclusions

Our results in passive radiative cooling demonstrate the possibility of reaching the fundamental limit of radiative cooling by combining photonic and thermal design. It points to an avenue for further improvement of radiative cooling systems. The selective emitter we use can be performed at large scales. There is also the possibility of applying the vacuum system on a larger scale, similar to what has already been done in the solar thermal industry. Owing to its passive nature, radiative cooling technology does not consume electrical power and emit greenhouse gas, Therefore, it could have a significant impact on greenhouse gas emission reduction. In addition, our results in self-adaptive radiative cooling and thermophotonic circuits could lead to new directions in using thermal radiation for thermal management and energy harvesting applications.

Publications and Presentations

Publications

1. Z. Chen, L. Zhu, A. Raman, and S. Fan, Radiative cooling to deep subfreezing temperatures through a 24-hour day-night cycle, *Nature Communications* **7**, 13729 (2016). DOI: 10.1038/ncomms13729
2. M, Ono, K. Chen, W. Li, and S. Fan. Self-adaptive radiative cooling based on phase change materials. Optics express **26**, A777-A787 (2018). DOI: 10.1364/OE.26.00A777
3. B. Zhao, S. Buddhiraju, P. Santhanam, K. Chen, and S. Fan. Self-sustaining thermophotonic circuits. Proceedings of the National Academy of Sciences. May (2019). DOI:10.1073/pnas.1904938116

Presentations

Plenary Talks, Keynote Talks, and Distinguished Lectures

1. S. Fan, Plenary Talk, "Nanophotonic concepts for energy applications", International Conference on Nanoscience and Nanotechnology (ICONN-2018), University of Wollongong, Australia, February 1, 2018.
2. S. Fan, Keynote Talk, "Nanophotonic Control of Thermal Radiation for Energy Applications", XXV International Summer School 'Nicolas Cabrera' on Manipulating Light and Matter at the Nanoscale, Miraflores de la Sierra, Madrid, Spain, September 13, 2018.
3. S. Fan, USTC Alumni Keynote Talk, "Nanophotonics and energy applications", 4th International Conference on Energy and Biological Materials, University of Science and Technology of China, Hefei, China, September 17, 2018.
4. S. Fan, Distinguished Lecture, "Concepts of nanophotonics and energy applications", Institute of

Molecular Engineering, University of Chicago, November 7, 2018.
5. S. Fan, Plenary Talk, "Nanophotonic concepts for thermal and energy applications", Nature Conference on Nanophotonics and Integrated Photonics, Nanjing, China, November 11, 2018.
6. S. Fan, Plenary Talk, "Nanophotonics: fundamental advances and energy applications", Smart Nanomaterials 2018: Advances, Innovations and Applications, Ecole Nationale Superieure de Chimie de Paris, Paris, December 11, 2018.

Other Invited Talks

7. S. Fan, "Theoretical limits for harvesting outgoing thermal radiation", The 49th Winter Colloquium on the Physics of Quantum Electronics (PQE), Snowbird, Utah, January 10, 2018.
8. S. Fan, "Controlling electromagnetic fields for energy applications", Physics Colloquium, Washington University at St. Louis, St. Louis, Missouri, March 21, 2018.
9. S. Fan, "Controlling electromagnetic fields for energy applications", Seminar, Department of Electrical and Computer Engineering, University of Wisconsin - Madison, March 23, 2018.
10. S.Fan,"Controllingelectromagneticfieldsforenergyapplications",inthe10thStanford University Photonics Retreat, Asilomar Conference Grounds, Pacific Grove, California, April 21, 2018.
11. S.Fan,"Nanophotoniccontrolofthermalradiationforenergyapplications",Tutorialtalk, Conference on Lasers and Eletrooptics (CLEO 2018), San Jose, California, May 17, 2018.
12. S.Fan,"Subwavelengthcontrolofelectromagneticwavesforenergyapplications",inGordon Research Conference on Solar Energy Conversion, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, June 18, 2018.
13. S.Fan,"Harvestingthecoldnessoftheuniversewithnanophotonicstructures",OSAIntegrated Photonics Research, Silicon and Nanophotonics (IPR), ETH, Zurich, Switzerland, July 2, 2018.
14. S.Fan,"Conceptsofnanophotonicsandenergyapplications",UniversityColloquium,Southeast University, Nanjing, China, November 12, 2018.
15. S.Fan,"Nanophotonics:fundamentalaspectsandenergyapplications",Colloquium,Instituteof Optics, University of Rochester, Rochester, New York, January 24, 2019.

Patent disclosures

1. Fan, S., Chen, Z., Zhu, L., and Raman, A. Ultrahigh-Performance Radiative Cooler, United States Patent Application 20180023866.

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8. J. Mandal, Y. Fu, A. Overvig, M. Jia, K. Sun, N. Shi, H. Zhou, X. Xiao, N. Yu, and Y. Yang, Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling, *Science* **362**, 315–319 (2018). DOI: 10.1126/science.aat9513
9. T. Li, Y. Zhai, S. He, W. Gan, Z. Wei, M. Heidarinejad, D. Dalgo et al. A radiative cooling structural material. *Science* **364,** 760-763 (2019). DOI: 10.1126/science.aau9101

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11. B. Zhao, S. Buddhiraju, P. Santhanam, K. Chen, and S. Fan. Self-sustaining thermophotonic circuits. *Proceedings of the National Academy of Sciences*. May (2019). DOI:10.1073/pnas.1904938116

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