Simultaneous energy harvesting from the hot sun and the cold universe

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Abstract

The sun and the universe are the two most important fundamental thermodynamics resources for human beings on Earth. The capability for harvesting solar energy has been of central importance throughout the history of human civilization. Harvesting the coldness of the universe using radiative cooling technology also has a long history and has received renewed interest recently. However, simultaneously and synergistically harvesting energy from these two thermodynamics resources has never been realized. In this GCEP project, we report the first experimental demonstration of such simultaneous energy harvesting using a configuration where a solar absorber that is transparent in mid-infrared is placed above a radiative cooler[1]. The solar absorber is heated to 24°C above the ambient temperature and provides a shading mechanism that enables the radiative cooler to reach 29°C below the ambient temperature. Our work points to a new avenue for harvesting of renewable energy resources.

Introduction

The objectives of this research project are to identify new opportunities for renewable energy harvesting by simultaneously utilizing the hot sun and the cold universe.

Background

A significant portion of current renewable energy research has been focusing on harvesting energy from the sun. Examples include solar thermal panels that convert solar energy to thermal energy, and photovoltaics that convert solar energy to electricity. Recently, energy harvesting from cold universe has also been proposed, which can be achieved using radiative cooling technology[2]. This technology utilizes cold universe as a heat sink. The heat from Earth in the form of thermal radiation is dissipated to the cold universe through the wavelength range from 8 to 13 μm, where the atmosphere is highly transparent. This wavelength range is commonly referred to as the atmospheric transparency window.

Considering the fact that both the sun and the universe can be simultaneously accessed through radiation at daytime, it is certainly desirable to have the capability for harvesting energy from both resources at the same time. Such a capability however has not been realized before. Solar cells and solar thermal panels operate at a temperature above ambient and cannot be used for cooling purposes. Existing experimental structures for daytime radiative cooling reflect and hence do not utilize the sunlight[2,3,4]. While as a practical approach one can place a solar thermal panel and a cooling panel side by side, in this approach a given physical area can only be used for either purposes but not for both. To maximize the capability for harvesting both the sun and the universe as renewable energy resources, it is important to develop an approach through the same physical area can be used simultaneously for both purposes.

Results

In this GCEP project, we report the first experimental demonstration of such simultaneous energy harvesting using a configuration where a solar absorber that is transparent in mid-infrared is placed above a radiative cooler. The solar absorber is heated to 24°C above the ambient temperature and provides a shading mechanism that enables the radiative cooler to reach 29°C below the ambient temperature.

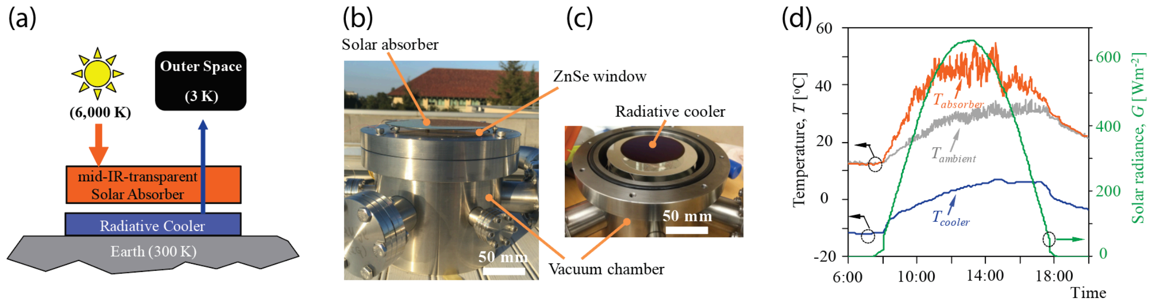

Figure 1: (a) Our approach of harvesting energy from both the sun and the universe simultaneously using the same physical area. The solar absorber above the radiative cooler is mid-infrared transparent, so that it allows unhindered energy dissipation from the radiative cooler to the universe. (b) Our experimental setup: a solar absorber is placed above a radiative cooler which is enclosed in a vacuum chamber equipped with a ZnSe window. (c) Inside view of the vacuum chamber, highlighting the radiative cooler. (d) Experimental results. The orange line is the temperature of the germanium solar absorber, $T_{absorber}$. The grey line isthe ambient temperature, $T_{ambient}$. The green line is the G_{solar}.

Figure 1a-c shows the experimental setup. We use a radiative cooler consisting of a 70 nm thick silicon nitride layer, a 700 nm thick amorphous silicon layer, and a 150 nm thick aluminum layer from top to bottom[5]. The cooler is enclosed in a vacuum chamber equipped with a mid-infrared-transparent ZnSe window. A solar absorber, which consists of a 500 μm thick intrinsic germanium wafer with double-side antireflection coatings for the mid-infrared wavelength range, is placed above the ZnSe window. This solar absorber is highly transparent in the 8-13 μm wavelength range, which, together with the ZnSe window, ensures the unhindered thermal radiation exchange between the universe and the radiative cooler inside the vacuum chamber.

Figure 1d shows a typical measurement by exposing the experimental setup to direct sunlight under a clear sky in a late autumn day at Stanford. The temperature of the germanium solar absorber ($T_{absorber}$), the radiative cooler (T_{cooler}), and the ambient ($T_{ambient}$) was measured from sunrise to sunset over a total period of 14 hours. The solar irradiance, G_{solar} (green; right axis), was also measured.

We first examine the temperature of the germanium solar absorber $T_{absorber}$ (orange line in Figure 1d). Before the sunrise, $T_{absorber}$ is approximately the same as the ambient temperature $T_{ambient}$. After sunrise, the two temperatures, $T_{absorber}$ and $T_{ambient}$, gradually deviate from one another, with a maximal difference, $T_{absorber}$ - $T_{ambient}$ = 24.4 °C, reached around the peak of the solar irradiance, demonstrating the harvesting of solar energy. At sunset, $T_{absorber}$ again approaches $T_{ambient}$.

We next examine the temperature of the radiative cooler, T_{cooler} (blue line in Figure 1d). The radiative cooler has a temperature that is significantly below the ambient air temperature. The temperature difference $T_{ambient}$ - T_{cooler} has a maxima of 28.9 ^oC at around 4:30pm, indicating the significant effect of radiative cooling.

Conclusions

Our experiments represent the first demonstration of harvesting energy simultaneously and synergistically from the sun and the universe, with an important feature that the solar absorber and the radiative cooler occupy the same physical area. The use of the mid-infrared-transparent solar absorber simplifies the design of the radiative cooler. Our work indicates the potential for simultaneously harvesting both solar radiation and the coldness of the universe all passively, without any energy inputs and CO_2 emissions. The concept can be deployed over a substantially larger scale[3,4,6], therefore could have a significant impact on greenhouse gas emission reduction.

Publications and Presentations

Publications

1. Z. Chen, L. Zhu, W. Li, and S. Fan, Simultaneously and synergistically harvest energy from the sun and outer space, *Joule* **3**, 101-110 (2019). DOI: 10.1016/j.joule.2018.10.009

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, "Controlling electromagnetic fields for energy applications", in the 10th Stanford University Photonics Retreat, Asilomar Conference Grounds, Pacific Grove, California, April 21, 2018.
11. S. Fan, "Nanophotonic control of thermal radiation for energy applications", Tutorial talk, Conference on Lasers and Eletrooptics (CLEO 2018), San Jose, California, May 17, 2018.

12. S. Fan, "Subwavelength control of electromagnetic waves for energy applications", in Gordon 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, "Harvesting the coldness of the universe with nanophotonic structures", OSA Integrated Photonics Research, Silicon and Nanophotonics (IPR), ETH, Zurich, Switzerland, July 2, 2018.
14. S. Fan, "Concepts of nanophotonics and energy applications", University Colloquium, Southeast University, Nanjing, China, November 12, 2018.
15. S. Fan, "Nanophotonics: fundamental aspects and energy applications", Colloquium, Institute of Optics, University of Rochester, Rochester, New York, January 24, 2019.

References

1. Z. Chen, L. Zhu, W. Li, and S. Fan, Simultaneously and synergistically harvest energy from the sun and outer space, *Joule* **3**, 101-110 (2019). DOI: 10.1016/j.joule.2018.10.009
2. A. Raman, M. Anoma, L. Zhu, E. Rephaeli, and S. Fan, Passive radiative cooling below ambient air temperature under direct sunlight, *Nature* **515**, 540–544 (2014). DOI: 10.1038/nature13883
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5. 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
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