Nanophotonic control of thermal radiation: maximal violation of detailed balance, and experimental demonstration of daytime radiative cooling

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The use of nanophotonic structure opens significant new possibilities to control thermal radiation, both in enabling new thermal physics effects, and in creating new application opportunities. In this talk, we will review some of our recent efforts in nanophotonics-enabled thermal radiation control. In particular, we will discuss the possibility of using non-reciprocal nanophotonic structures to maximally violate detailed balance. We will also report some of our recent experimental efforts in the successful demonstration of passive radiative cooling under direct sunlight.

1. Maximal violation of detailed balance in non-reciprocal nanophotonic structures

For thermal radiation, the principle of detailed balance leads to the general form of the Kirchhoff's law which states that

$$e(\omega,\theta,\phi) = \alpha(\omega,\theta,\phi) \quad (1)$$

where $e(\omega,\theta,\phi)$ is the directional spectral emissivity, $\alpha(\omega,\theta,\phi)$ is the directional spectral absorptivity, Microscopically, Eq. 1 can be proven using the fluctuation-dissipation theorem, but only for emitters consisting of materials satisfying Lorentz reciprocity [1]. It has been noted theoretically that non-reciprocal materials, such as magneto-optical materials, may not obey detailed balance [2] and hence may not satisfy Eq. 1, without violating the second law of thermodynamics. However, there has not been any direct experimental measurement or theoretical design of actual physical structures that violate detailed balance.

In recent years, significant recent efforts have been devoted to the use of engineered photonic structures, including photonic crystals, optical antennas, and meta-materials, for the control of thermal radiation properties. Photonic structures can exhibit thermal radiation properties that are significantly different from naturally occurring materials. Notable examples include the creation of thermal emitters with narrow spectrum or enhanced coherence. All previous works on the thermal radiation properties of photonic structures, however, consider only reciprocal materials. Here, using the formalism of fluctuational electrodynamics, we present a direct numerical calculation of thermal emission from non-reciprocal photonic structures, and introduce the theoretical conditions for such structures to maximally violate detailed balance, i.e. to achieve a unity difference between directional spectral emissivity and absorptivity [3].

Non-reciprocal photonic structures represent an important emerging direction for the control of thermal radiation. From a fundamental point of view, significant numbers of theoretical approaches for the calculations of far-field thermal radiation use the Kirchhoff's law of Eq. 1 by computing the absorption properties. Such an approach is no longer applicable for non-reciprocal thermal emitters, and direct calculations using the formalism of fluctuational electrodynamics become essential. From a practical point of view, creating non-reciprocal thermal emitters can have important implications for the enhancement of the efficiency for solar cells [4] and thermophotovoltaic systems.

2. Experimental demonstration of daytime radiative cooling

Cooling is a significant end-use of energy globally and a major driver of peak electricity demand. Air conditioning of buildings, for example, accounts for 15% of the primary energy used to generate electricity in the United States. A passive cooling strategy that cools without any electricity input could therefore have a significant impact on global energy consumption.

To achieve cooling one needs to be able to reach and maintain a temperature below the ambient air. At night, passive cooling below ambient air temperature has been demonstrated using a technique known as radiative cooling, where one uses a device exposed to the sky to radiatively emit heat to outer space through a transparency window in the atmosphere between 8-13 μm [5][6]. Peak cooling demand however occurs during the daytime. Daytime radiative cooling below ambient under direct sunlight [7][8] was never achieved, because sky access during the day results in heating of the radiative cooler by the sun.

Here, using a thermal nanophotonic approach [9], we introduce an integrated nanophotonic solar reflector and thermal emitter that reflects 97% of incident sunlight while emitting strongly and selectively in the atmospheric transparency window. When exposed to direct solar irradiance of greater than 850 W/m^2 on a rooftop, the nanophotonic radiative cooler achieves 4.9^{o}C below ambient air temperature, and has a cooling power of 40.1 W/m^2 at ambient. These results demonstrate that a tailored, nanophotonic approach can fundamentally enable new technological possibilities for energy efficiency, and further indicate that the cold darkness of the universe can be used as a renewable thermodynamic resource, even during the hottest hours of the day.

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