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## ► To cite this version:

Yannick de Wilde, Riad Haïdar. Optical cooling achieved by tuning thermal radiation. *Nature*, 2019, 566 (7743), pp.186-187. <10.1038/d41586-019-00526-x>. <hal-02358230>

**HAL Id: hal-02358230**

**<https://hal.science/hal-02358230v1>**

Submitted on 11 Nov 2019

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# Optical cooling without lasers

Yannick De Wilde and Riad Haidar

**Radiative heat normally flows from hot to cold bodies. Inverting the direction of heat is possible by tuning the chemical potential of light in a photodiode. This provides a new way for solid-state refrigeration.**

Radiative heat transfer is interesting for applications requiring contactless cooling. It is generally taken for granted that two macroscopic bodies at different temperatures will transfer heat with a flux directed from hot to cold. When the distance between the bodies is larger than the dominant thermal wavelength (around 10  $\mu\text{m}$  at room temperature) the upper limit of this flux coincides with the fundamental blackbody limit given by Stefan-Boltzmann's law. On page 000 of this issue, Zhu et al. (1) show that a photodiode is able to cool a yet *colder* calorimeter located in the near-field, that is at a distance well below the thermal wavelength. To obtain the desired cooling effect, the photodiode, which is a directional device, must be operated in reverse voltage. The demonstration of radiative cooling using incoherent thermal light with an active device is potentially as impactful as thermoelectricity for applications in the fields of cooling and heat management.

Optical refrigeration of solids had so far only been achieved with coherent laser light, using blue-shifted fluorescence from a solid state sample to lower the thermal energy of lattice vibrations, called phonons (2). In a way similar to what was initially invented to produce ultra-cold atoms and ions, photons from a monochromatic laser source are absorbed slightly

in the red tail of an absorption line of a fluorescent sample. The absorption is followed by a fluorescence emission at a shorter wavelength, involving thus the emission of photons more energetic than the initially absorbed ones. For a solid state sample, this can only occur if vibrational energy is removed from the lattice, which causes a net refrigeration effect.

The development of the radiative cooling device by Zhu et al. (1) was motivated by a recent theoretical work by Fan's group at Stanford (3). Instead of using coherent laser radiation (2), cooling relies here on a completely new paradigm based on the direct control of the incoherent thermal radiation from a photodiode by means of a reverse voltage, combined with enhanced near-field radiative heat transfer. The first crucial ingredient to succeed in their experiment was the tuning of the chemical potential of photons, a quantity that characterizes the energy that can be absorbed or released due to a change of the photon number.

Since thermodynamic equilibrium requires to minimize the energy of a system, it is common belief that a vanishing chemical potential is a general property of photons because their number is constantly changing by absorption and emission at the walls of a blackbody radiator. However, a non-zero chemical potential of photons may occur in a system in which emission or destruction of photons goes along with a change of particle number of partners with non-vanishing chemical potentials. Such a situation is for instance obtained in semiconductor-based photodiodes under reverse (or forward) voltage conditions, where the absorption (or emission) of photons is correlated with the occupation (or vacancy) statistics of electrons, at least for photons energies larger the bandgap of the semiconductor. The peculiarity of the photon-electron interaction translates then into a chemical potential of

photons  $\mu_{ph}$  that equals the difference of chemical potentials of occupied and vacant electronic states, a quantity proportional to the voltage  $V$  applied to the photodiode (4).

By applying a reverse voltage on a photodiode ( $V < 0$ ), Zhu et al. (1) have thus modified the photon statistics of the thermal radiation from the device, producing a negative chemical potential for photon energies larger than the bandgap of the semiconductor. Since the expected value of the photon energy follows Bose-Einstein statistics, the negative chemical potential in the latter resulted in a reduced thermal radiation from the photodiode as compared to thermodynamic equilibrium (zero voltage). This effect is known as “negative luminescence” and was used in (1) to mimic a photodiode with an effective temperature  $T_{eff}$  lower than its nominal temperature  $T_{PD}$  for thermal photons emitted close to the bandgap energy. Reducing  $T_{eff}$  below the temperature of a custom-fabricated calorimetric device naturally creates a radiative heat flow from the calorimeter to the yet *hotter* reverse-voltage photodiode.

However, a second crucial step had still to be implemented before Zhu et al. (1) could detect a measurable radiative cooling effect induced by the reverse-voltage photodiode on their calorimeter. Indeed, as the emissivity of thermal bodies is less than unity, the far-field heat flow rate is bounded by the fundamental limit set by Stefan-Boltzmann’s law. Even if progresses in nanophotonics have allowed to tailor far-field thermal radiation (5,6), the maximum heat flow rate that can be achieved using a negative luminescence device operating in the optical far-field remains extremely low and practically undetectable.

Besides the tuning of the chemical potential of light by means of a negative voltage on the photodiode, the key reason why Zhu et al. (1) have been able to detect incoherent optical refrigeration is because they were also able to bring the cooling device (the reverse-voltage photodiode) and the calorimeter within each other's optical near-field using a very clever experimental set-up. It had already been observed that radiative heat transfer can be significantly increased at distances well below the thermal wavelength by the contribution of evanescent waves (7,8). This contribution, which can be viewed as energy tunneling through the gap between two surfaces, was used for enhancing the radiative cooling by negative luminescence to reach a level where it became measurable. Noticeably, the nominal temperature of the photodiode  $T_{PD}$  was higher than the calorimeter temperature at some point of their experiment, while heat was flowing from the latter to the photodiode.

Now that Zhu et al. (1) have demonstrated that photonic cooling can be achieved by controlling the chemical potential of photons, a major question to be addressed for further studies is: "What are the fundamental limits to this incoherent photonic cooling technique?" One possible direction of improvement of the cooling performances would be to cover the object to be cooled by a polar material such as hexagonal boron nitride (h-BN) or silicon carbide (SiC) that both support surface phonon-polariton resonances. The latter give rise to a strongly enhanced near-field thermal radiation with a quasi-monochromatic spectrum (9), which significantly enhances near-field thermal transfer. Recent theoretical studies have shown that the choice of a photodiode with a narrow bandgap matching the phonon-polariton resonance could produce active nanophotonic cooling with an efficiency approaching the Carnot thermodynamic limit for suitably chosen voltages, with the advantage of being contactless and faster than conventional thermoelectric coolers (3).

Another direction for further improvements would be to combine the incoherent photonic cooling technique demonstrated in (1) with infrared plasmonic nanoantennas. Such devices produce thermal radiation with well-defined resonance frequencies and concentrate the electromagnetic field in deeply subwavelength volumes (10). Moreover, recent works have shown that they could also be implemented in micron-sized active infrared photodetectors made of semiconducting materials that can be operated at room temperature (11). This suggests that with some modification, the incoherent photonic cooling device demonstrated by Zhu et al. in (1) could be reduced in size and fabricated into semiconductor devices to perform on-chip local active cooling.

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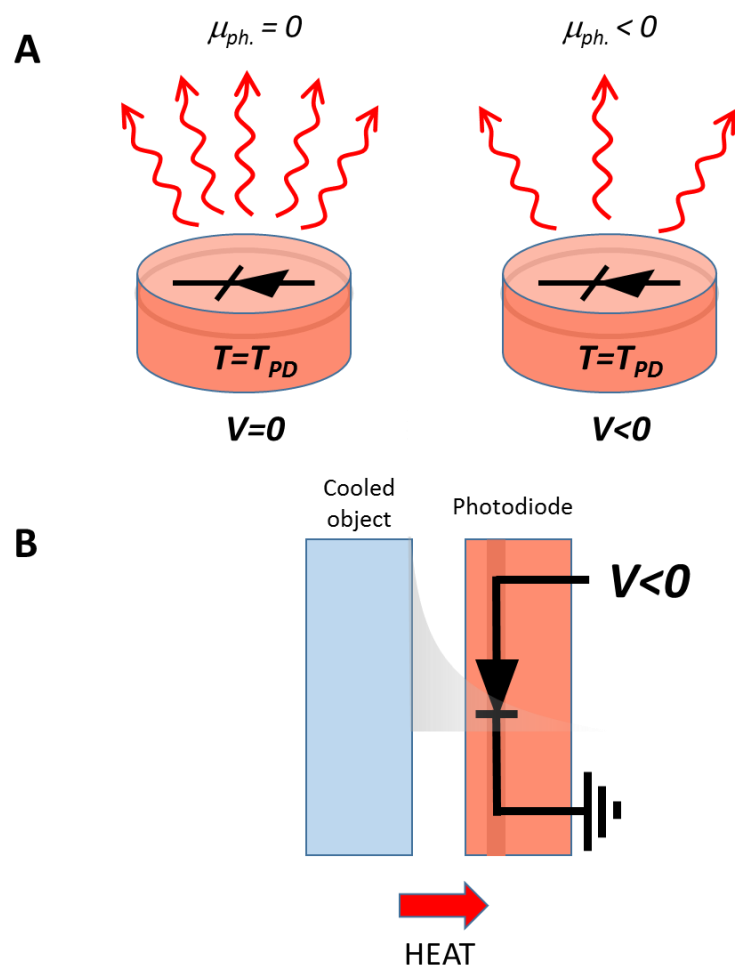
## FIGURE CAPTION

### Incoherent photonic cooling

The voltage applied on a photodiode allows one to tune the chemical potential of the photons it emits,  $\mu_{ph.}$ , and thus their statistical distribution. **(A)** As far as the thermal radiation properties of a photodiode are concerned, it emits fewer photons when a reverse voltage ( $V < 0$ ) is applied, as compared to the same device at  $V = 0$ . The negative voltage mimics thus an effective temperature of the photodiode lower than its nominal temperature,  $T_{PD}$ . **(B)** Incoherent photonic cooling of an object is obtained by Zhu *et al.* in (1) by combining the enhancement of photon transport from tunneling of evanescent waves and the suppression of thermal radiation from a photodiode when  $V < 0$ . Noticeably, the cooled object is cooler than the photodiode, because the latter removes heat from it thanks to its lower effective temperature.



**FIGURE**



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