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Photon Entropy Control and Near-Field Radiative Coupling Improve Efficiency of Thermoradiative Cells

Wei-Chun Hsu, Jonathan K. Tong, Bolin Liao, Yi Huang, Svetlana V. Boriskina, and Gang Chen
Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA
sborisk@mit.edu , gchen2@mit.edu

Abstract. Efficiency of thermoradiative cells can be increased by spectrally selecting high-entropy long-wavelength infrared photons for radiative energy exchange. Furthermore, near-field coupling to phonon polaritons in the heat sink increases both conversion efficiency and power density.
OCIS codes: (260.3060) Infrared; (290.6815) Thermal emission; (260.2160) Energy transfer; (350.5340) Photothermal effects; (040.5350) Photovoltaic.

Photon entropy is an important thermodynamic characteristic of light [1]. Understanding the entropy of photons helps to establish the fundamental upper limits for the processes involving conversion of light energy into work and vice versa, including photovoltaics, light generation, and optical refrigeration [2,3]. Our calculations of the entropy content of light (i.e., a ratio of the entropy flux to the power flux) reveal that the entropy content of blackbody emission is higher than that of heat conduction. Furthermore, long-wavelength infrared photons carry more entropy per energy unit than more energetic photons of the visible light. In turn, heat conduction or high frequency photon radiation carry the lowest entropy content per unit energy, and thus are the most favorable forms of energy for an input to an energy-conversion engine.

A p-n junction maintained at above ambient temperature can work as a heat engine, converting some of the supplied heat into electricity and rejecting entropy by interband emission [4]. Such an engine is knows as the thermoradiative (TR) cell, and it has potential to harvest low-grade heat into electricity. As work carries zero entropy, the entropy supplied to the TR cell by heat conduction and the entropy generated in the engine must be rejected to the heat sink. We predict that the best form of energy to maximize the entropy removal from the engine is low-frequency infrared photon emission, which is characterized by the high entropy flux per unit energy [2,5].

Furthermore, we predict that the near-field radiation extraction [6,7] by coupling photons generated from interband electronic transition to phonon polariton modes on the surface of a heat sink can increase the TR cell energy conversion efficiency as well as the power generation density, providing more opportunities to efficiently utilize terrestrial emission for clean energy.

The effect of the proposed improvements is illustrated in Fig. 1, which compares the performance of the TR cell emitting a broadband photon spectrum in the form of the far-field radiation and its counterpart that dumps entropy via narrowband near-field emission into the phonon-polariton mode in the heat sink. It can be seen that an ideal InSb thermoradiative cell can achieve a maximum efficiency and power density up to 20.4 % and 327 Wm^{-2}, respectively, between a hot source at 500K and a cold sink at 300K. However, sub-bandgap and non-radiative losses will significantly degrade the cell performance.

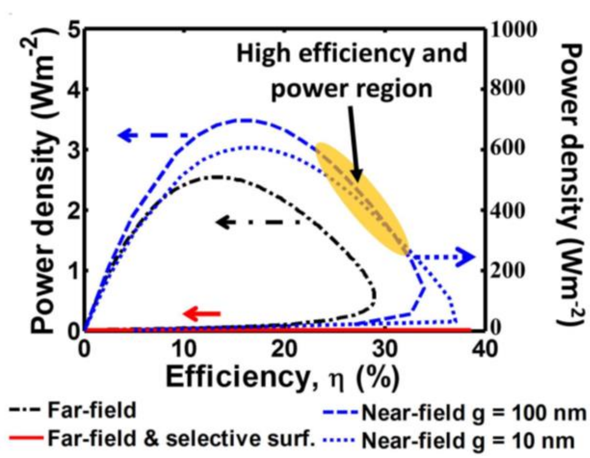

Figure 1. The performance of the 50-nm-thick InSb TR cells operating between a hot source at 500 K and a cold environment at 300 K, calculated for various scenarios of the radiative energy extraction. These include: a far-field infrared emission from a thin-film InSb cell, a far-field narrowband ($\Delta\hbar\omega$=0.01eV) emission from a thin-film InSb cell with a selective surface, and a near-field phonon-polariton-enhanced energy transfer from a thin-film InSb to a bulk $CaCO_3$ across 10nm and 100nm-wide vacuum gaps.

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References

1. L. Landau, "On the thermodynamics of photoluminescence," J. Phys. **10**, 503–506 (1946).
2. S. V. Boriskina, J. K. Tong, W.-C. Hsu, B. Liao, Y. Huang, V. Chiloyan, and G. Chen, "Heat meets light on the nanoscale," Nanophotonics, DOI 10.1515/nanoph-2016-0010. (2016).
3. S. V. Boriskina, M. A. Green, K. Catchpole, E. Yablonovitch, M. C. Beard, Y. Okada, S. Lany, T. Gershon, A. Zakutayev, M. Tahersima, V. J. Sorger, M. J. Naughton, K. Kempa, M. Dagenais, Y. Yao, L. Xu, X. Sheng, N. D. Bronstein, J. A. Rogers, A. P. Alivisatos, R. G. Nuzzo, D. M. Wu, M. D. Wisser, A. Salleo, J. Dionne, J. M. Gordon, P. Bermel, J.-J. Greffet, I. Celanovic, M. Soljacic, A. Manor, C. Rotschild, A. Raman, L. Zhu, S. Fan, and G. Chen, "Roadmap on optical energy conversion," J. Opt. Press (2016).
4. R. Strandberg, "Theoretical efficiency limits for thermoradiative energy conversion," J. Appl. Phys. **117**, 055105 (2015).
5. W.-C. Hsu, J. K. Tong, B. Liao, Y. Huang, S. V. Boriskina, and G. Chen, "Entropic and near-field improvements of thermoradiative cells," submitted (2016).
6. L. Hu, A. Narayanaswamy, X. Chen, and G. Chen, "Near-field thermal radiation between two closely spaced glass plates exceeding Planck's blackbody radiation law," Appl. Phys. Lett. **92**, 133106 (2008).
7. S. Boriskina, J. Tong, Y. Huang, J. Zhou, V. Chiloyan, and G. Chen, "Enhancement and tunability of near-field radiative heat transfer mediated by surface plasmon polaritons in thin plasmonic films," Photonics **2**, 659–683 (2015).