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Thermal Emission Shaping and Radiative Cooling with Thermal Wells, Wires and Dots

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Abstract: We discuss radiative heat extraction and spectral shaping via engineering of the density of confined photon states in low-dimensional potential traps, including wells, wires, and dots. Applications include thermophotovoltaics, radiative cooling, energy up- and down-conversion.

OCIS codes: (310.6628) Subwavelength structures; (260.2160) Energy transfer; (350.5340) Photothermal effects

We explore a new approach to radiatively extract heat from the near into the far field via morphology-mediated thermal emission (Fig. 1). Morphology-mediated engineering of optical density of states (DOS) in photonic structures has already been successfully used to manipulate light absorption, fluorescent emission rates, Raman scattering efficiency, etc. However, the broadband nature of thermal emission and the temperature dependence of the occupancy of available states make engineering the electromagnetic potential for heat extraction much more challenging.

We will show how thermal emission can be shaped via engineering of the emitter local optical potential, and will discuss limits of thermal radiation from micro- and nano-scale structures. We will also discuss opportunities for up- and down-conversion of photon energy with low-dimensional thermal absorbers/emitters. Below we highlight two examples of the low-dimensional absorbers and emitters for potential applications in energy conversion and radiative cooling.

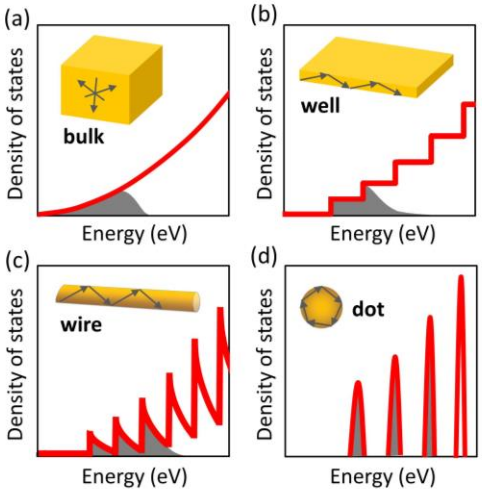

Figure 1. Spatial confinement concentrates photon states enhancing thermal emission at select frequencies. Red lines: density of optical states in the light-confining structures of various configurations; Shaded areas: thermal distribution of photons in (a) bulk material, (b) wells, (c) wires, and (d) dots.

As the first example, radiative heat transfer between thin films in both the near and the far field has been investigated. Thin film 'thermal well' structures act as photonic analogs to quantum wells and thus exhibit a photonic dispersion that deviates strongly from bulk systems as shown in Fig. 2a. When the thicknesses of both the emitter and the absorber are reduced to the sub-wavelength size, coupling between trapped waveguide modes leads to resonant enhancement of the radiative transfer of high-energy photons. At the same time, emission and absorption of low-energy photons is suppressed by modal cut-offs, yielding strong spectral shaping of radiative transfer between thermal wells (Fig. 2b).

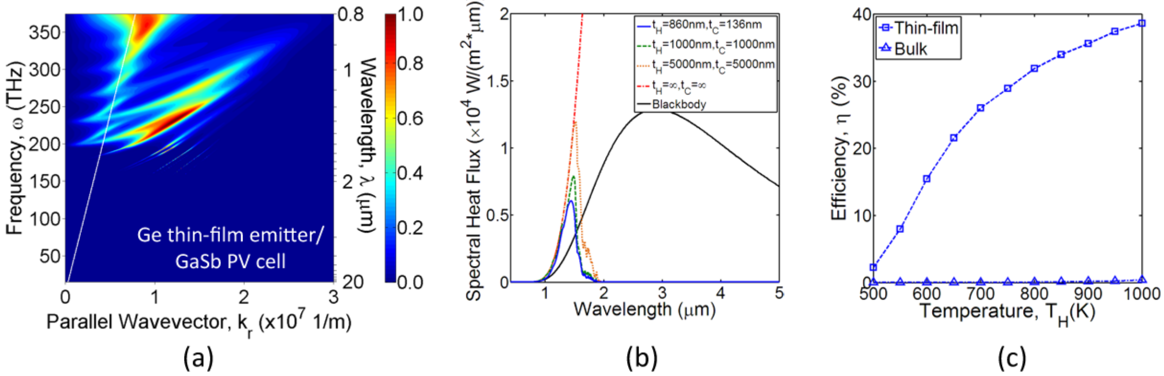

Figure 2. (a) The transfer function describing radiative exchange between two thermal wells (Ge emitter and GaSb absorber) in the energy-momentum domain. (b) Spectral radiative heat flux as a function of varying thicknesses of thermal wells on both hot and cold sides. (c) The predicted TPV energy conversion efficiency comparing a thermal well system and a bulk system.

Such efficient spectral shaping of thermal emission shows great promise for thermophotovoltaics (TPV). We theoretically predict an order-of-magnitude efficiency enhancement of thermal well TPV platforms versus their bulk counterparts [1]. The calculated thermal-well TPV efficiency can reach 38.7% in the near-field regime (for 100 nm gap between the emitter and the photovoltaic cell) and 31.5% in the far-field regime for a Ge thermal emitter at 1000K and a GaSb thin-film cell at 300K (Fig. 2c).

We will also discuss opportunities provided by thermal dots (i.e., wavelength-scale microcavities supporting trapped photon states) for photon energy down-conversion, emission spectral shaping, and radiative cooling of plasmonic nanostructures. In particular, optically coupling plasmonic nanoantennas to thermal dots may simultaneously provide intensity enhancement at the operating wavelength in the visible (e.g., for imaging or spectroscopy) [2] and avoid overheating via a combination of reduced absorption and radiative cooling. We will show that hybrid nanoantenna-thermal-dot structures enable two orders of magnitude enhancement of localized electric fields. At the same time, thermal-dot-mediated radiative cooling lowers antenna temperature by several hundred degrees for the irradiance of 10^5-10^6 W/m^2 (Fig. 3).

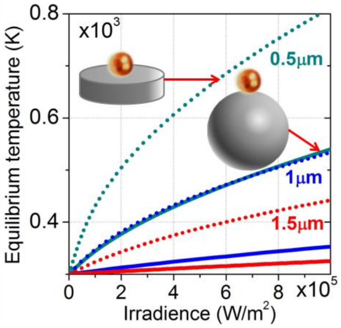

Figure 3. Thermal dots coupled to nanoantennas enhance light intensity by an order of magnitude and reduce temperature by several hundred degrees. Equilibrium temperature is shown for steady-state illumination with varied photon flux.

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