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NEAR-FIELD THERMAL RADIATION AND POTENTIAL APPLICATION FOR CLEAN ENERGY PRODUCTION

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Near-field effects of thermal radiation

Radiant energy exchanges between closely spaced bodies can exceed by several orders of magnitude the values predicted for blackbodies due to near-field effects. Bodies at temperature greater than 0 K induce oscillating dipoles emitting far- and near-field components. Far-field components are propagating waves taken into account in the classical theory of thermal radiation; near-field components are evanescent (non-propagating) waves decaying exponentially (over a distance of about a wavelength) normal to the surface of an emitting body. When bodies exchanging thermal radiation are spaced in such a way that their surfaces lay in the evanescent field of their opposite bodies, radiative heat transfer due to evanescent waves occur (radiation tunneling).

To account for near-field effects of thermal radiation (**wave interference** and **radiation tunneling**), Maxwell's equations need to be solved in conjunction with the fluctuational electrodynamics (to model the emission process).

Fluctuational electrodynamics

Thermal agitation in a body at temperature greater than 0 K causes a chaotic motion of charges. These random fluctuations of charges induce oscillating dipoles generating an electromagnetic field (thermal radiation field). The **fluctuational electrodynamics (FE)** is based on a macroscopic level, where an extraneous stochastic current density term $\mathbf{J}^r$ (due to thermal agitation of charges) is added on the right-hand side of Ampère's law (the mean value of this current density term is zero). Fourier components of the electric and magnetic fields induced by the random current are given by:

$$\mathbf{E}(\mathbf{r},\omega) = i\omega\mu_0 \int_V dV' \overline{\overline{\mathbf{G}}}^e(\mathbf{r},\mathbf{r}',\omega)\cdot\mathbf{J}^r(\mathbf{r}',\omega)$$

$$\mathbf{H}(\mathbf{r},\omega) = \int_V dV' \overline{\overline{\mathbf{G}}}^h(\mathbf{r},\mathbf{r}',\omega)\cdot\mathbf{J}^r(\mathbf{r}',\omega)$$

Computation of the Poynting vector (radiative heat flux) involves calculation of terms $\langle E_i H_j^* \rangle$:

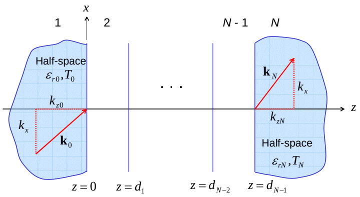
$$\langle E_i(\mathbf{r},\omega) H_j^*(\mathbf{r},\omega)\rangle = i\omega\mu_0 \int_V dV' \int_V dV'' G_{in}^e(\mathbf{r},\mathbf{r}',\omega) G_{jm}^{h*}(\mathbf{r},\mathbf{r}',\omega) \langle J_n^r(\mathbf{r}',\omega) J_m^{r*}(\mathbf{r}'',\omega)\rangle$$

The link between the ensemble average of the spatial correlation function of fluctuating currents and the local temperature of the emitting medium is given by the **fluctuation-dissipation theorem (FDT)**:

$$\langle J_n^r(\mathbf{r}',\omega) J_m^{r*}(\mathbf{r}'',\omega)\rangle = \frac{\omega\varepsilon_0}{\pi}\varepsilon_r''(\omega)\Theta(\omega,T)\delta_{nm}\delta(\mathbf{r}'-\mathbf{r}'')$$

The FE/FDT is applicable to media in local thermodynamic equilibrium, where a temperature can be defined at any points.

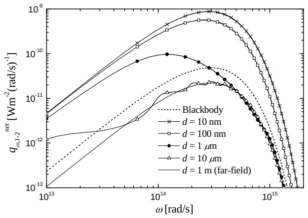
Near-field radiative heat transfer in 1D layered media

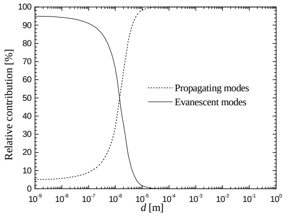


The net radiative heat flux between half-spaces 0 and *N* is found from the solution of the dyadic Green's function for 1D layered media:

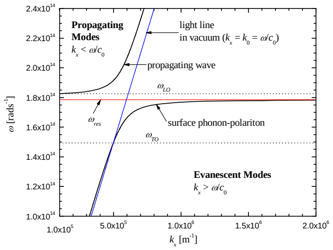
$$q_{0N}^{net} = \frac{1}{4\pi^2}\int_{\omega=0}^{\infty}[\Theta(\omega,T_0)-\Theta(\omega,T_N)]d\omega \int_{k_x=0}^{\infty} k_x dk_x \times \left[\frac{\mathrm{Re}(k_{z0})\mathrm{Re}(k_{zN})}{|k_{z0}|^2}|t_{0N}^s|^2 + \frac{\mathrm{Re}(\varepsilon_{r0}k_{z0}^*)\mathrm{Re}(\varepsilon_{rN}k_{zN}^*)}{|n_0|^2|n_N|^2|k_{z0}|^2}|t_{0N}^p|^2\right]$$

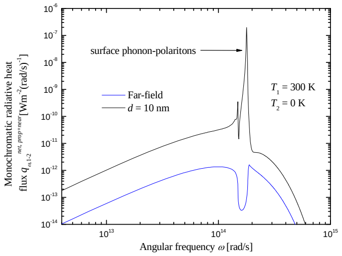
We analyzed radiative heat transfer between two half-spaces (denoted 1 and 2) spaced by a vacuum gap (medium 0) of thickness *d*. Both half-spaces are dielectric materials with frequency-independent dielectric constants (20 + *i*0.0001) maintained at 800 and 200 K.

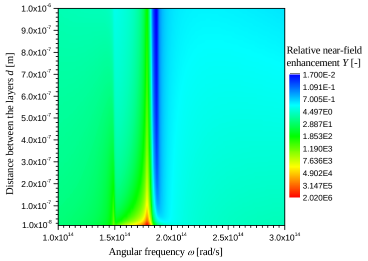




Quasi-monochromatic radiant energy exchanges can occur in the near-field when **surface phonon-** (polar crystals) **or plasmon-polaritons** (metals or doped semiconductors) are resonantly excited. SiC is a material supporting surface phonon-polaritons with resonance at 178.6×10^{12} rad/s (where $k_x \to \infty$ in the dispersion relation. Note that the part of the dispersion relation right to the light line in vacuum corresponds to evanescent waves contributing to radiative heat transfer only in the near-field.



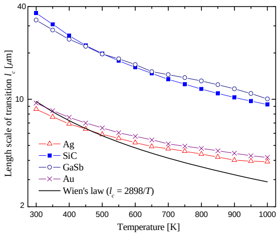




The monochromatic ratio *Y* of the radiative heat flux due to evanescent waves and propagating waves, as a function of *d*, shows that most of the energy is transferred around the resonant frequency at small *d*.

Length scales of transition

We studied the length scales of transition from near- to far-field radiative heat transfer regimes. We have shown that this critical length scale is about three times larger than Wien's law for dielectric materials [1].



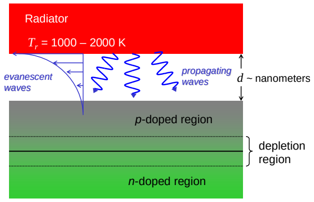
We are currently investigating the length scales of transition for real materials that can support surface polaritons [2].

These results show that the length scales of transition are function of the temperature of the emitting body, and the materials.

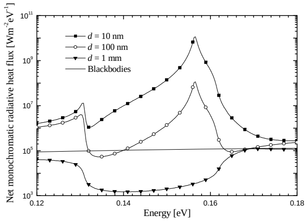
Nano-thermophotovoltaic devices

Near-field radiative heat transfer can potentially be applied to thermophotovoltaic (TPV) power generators.

TPV devices are similar to conventional photovoltaic (PV) systems, except that the source of photons is a radiator maintained at temperature between 1000 and 2000 K. By spacing the radiator and layer of PV cells by few nanometers, more photons are exchanged due to tunneling of evanescent waves.



By using materials supporting surface polaritons, it is possible to achieve quasi-monochromatic radiative heat exchanges between the radiator and the PV cells. If the resonant frequency of the materials matches the bandgap of the PV cells, it is possible to increase the efficiency of TPV devices.



Radiative heat transfer between two half-spaces of cBN spaced by vacuum shows that almost 99% of the energy is exchanged around 0.157 eV for a gap *d* of 10 nm.

We are in the process of developing an extensive numerical model to compute efficiencies of nano-TPV devices, and eventually built a prototype. Note that the model accounts for thermal transport in the PV cells, which has not been studied so far for nano-TPV devices.

References: [1] M. Francoeur, and M.P. Mengüç, "Role of fluctuational electrodynamics in near-field radiative heat transfer", *Journal of Quantitative Spectroscopy and Radiative Transfer*, **109**, 280-293 (2008).
[2] M. Francoeur, M.P. Mengüç, and R. Vaillon, "Length scales of transition from near- to far-field radiative heat transfer regime for materials supporting surface polaritons", To be submitted to *ASME Journal of Heat Transfer* (2008).

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