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Review

Fluctuational electrodynamics calculations of near-field heat transfer in non-planar geometries: A brief overview

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ABSTRACT

Near-field electromagnetic heat transfer is of interest for a variety of applications, including energy conversion, and precision heating, cooling and imaging of nano-structures. This past decade has seen considerable progress in the study of near-field electromagnetic heat transfer, but it is only very recently that numerically exact methods have been developed for treating near-field heat transfer in the fluctuational electro-dynamics formalism for non-trivial geometries. In this paper we provide a tutorial review of these exact methods, with an emphasis on the computational aspects of three important methods, which we compare in the context of a canonical example, the coupled dielectric sphere problem.

Contents

1. Introduction

Heat will flow between bodies at different temperatures. Among the mechanisms of heat transfer, radiative electromagnetic heat transfer is special in that it may

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transmit heat through vacuum. When certain classes of dielectric bodies are in close proximity, so that their separation falls below the characteristic thermal wavelength $\lambda_T = hc/k_B T$, we observe the near-field regime, where the heat flow can be enhanced beyond the constraint of the Planck law that governs far-field heat transfer. Such an enhancement has been demonstrated in a number of recent experiments [1–4], leading to the prospect of applying near-field heat transfer in areas including non-contact radiative cooling [5], thermal imaging [6,7], thermal circuit elements [8–11], as well as energy conversion and thermo-photo-voltaics [12–16].

These experimental developments have in turn motivated theoretical studies of the mathematical and computational underpinnings of near-field heat transfer. What has emerged is a clear need for exact methods to calculate electromagnetic heat transfer in the fluctuational electrodynamics formalism [17]. It is important to state up front that the quantum electrodynamics formalism yields the same results, provided the thermodynamic interpretation is appropriate; in particular it must be assumed that the sources are in local equilibrium with a thermal reservoir [18].

Using the fluctuational electrodynamics formalism, we can calculate heat flux between two bodies separated by a vacuum gap, as shown in Fig. 1a. The problem is completely specified by the temperature distribution $T(\mathbf{r})$ and relative dielectric function of the materials, $\epsilon(\mathbf{r},\omega) = \epsilon'(\mathbf{r},\omega) + i\epsilon''(\mathbf{r},\omega)$. We work with the time-harmonic form of Maxwell's equations, with implicit $\propto e^{-i\omega t}$ time-dependent factors, so a positive imaginary part of the dielectric functions, $\epsilon''(\mathbf{r},\omega)$, corresponds to material loss. We limit our discussion to the case of homogenous dielectric bodies, so that $\epsilon(\mathbf{r},\omega) = \epsilon_n(\omega)$ in the various regions $n \in 0,1,2$. Free space corresponds to $n=0$, and is spatially unbounded, with $\epsilon_0 = \lim_{\delta\to 0} 1 + \delta i$. The dielectric constants are typically assumed to be local, i.e. depends on the frequency but not the wave vector of the excitation. One expects that such a local dielectric function should be applicable unless one is in the deep near-field regime where the size of the vacuum gap is reduced to a few nanometers [7,19]. We note that in this regime, other mechanisms of heat transfer may come into play, such as phonon transport [20], but we do not consider these mechanisms in this review. Regarding the temperature distribution, we assume that the temperature is uniform in each region; we label these temperatures T_n.

The sources of electromagnetic heat transfer are thermally fluctuating current density distributions $J_i(\mathbf{r},\omega)$ within the bodies; see Fig. 1b. For the purpose of calculating ensemble-averaged heat transfer in a stationary system, it suffices to know the two-point spectral correlation function of the current densities, which for a system in local thermal equilibrium is given by the fluctuation–dissipation theorem [21–23]. We use the time-harmonic form of the theorem, and thus we already assume a stationary process. Here and throughout, an overbar will denote an ensemble average. The theorem holds in general for dissipative linear systems. In the present case, the dissipation is due to dielectric losses, and we write

$$\overline{J_i(\mathbf{r},\omega)J_k^*(\mathbf{r}',\omega)} = \frac{4}{\pi}\omega\Theta(\omega,T)\delta(\mathbf{r}-\mathbf{r}')\mathrm{Im}[\epsilon(\mathbf{r},\omega)]\epsilon_0\delta_{ik} \tag{1}$$

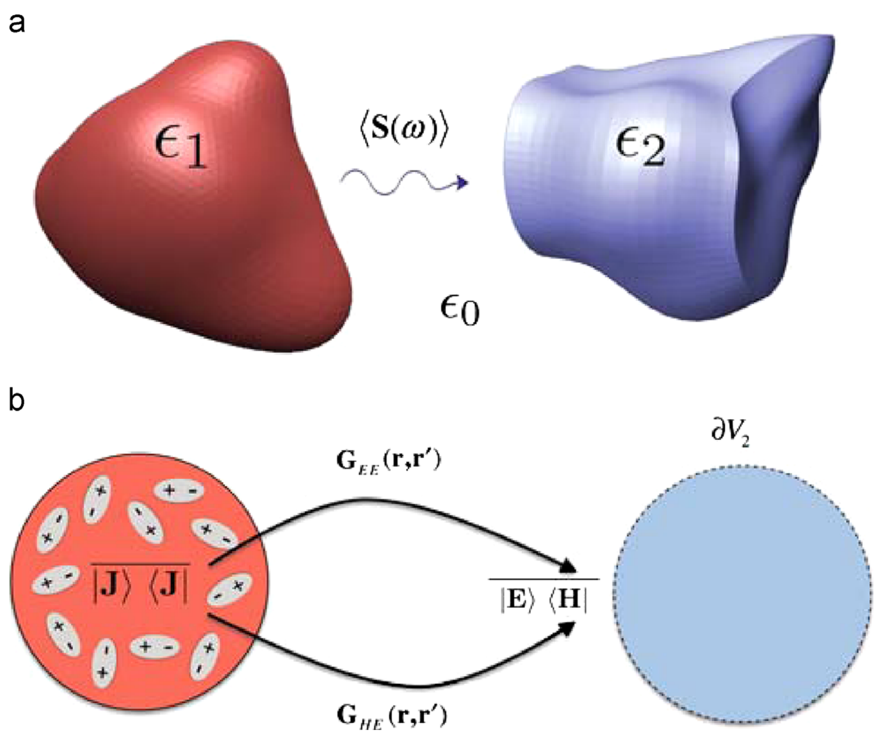

Fig. 1. (a) Near-field heat transfer between two non-planar bodies V_1 and V_2 with dielectric functions ϵ_1 and ϵ_2, separated by vacuum and maintained at temperatures T_1 and T_2, respectively. (b) Schematic of a fluctuational electrodynamics calculation in the Green function picture. The current–current correlations in V_1 are specified by the fluctuation–dissipation theorem, and are related via the dyadic Green functions $\mathbf{G}_{EE}$ and $\mathbf{G}_{HE}$ to the field–field correlations, and thus the ensemble-averaged Poynting vector on the boundary of V_2.