Near field radiative heat transfer between two nonlocal dielectrics

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ABSTRACT

We explore in the present work the near-field radiative heat transfer between two semi-infinite parallel nonlocal dielectric planes by means of fluctuational electrodynamics. We use a theory for the nonlocal dielectric permittivity function proposed by Halevi and Fuchs. This theory has the advantage to include different models performed in the literature. According to this theory, the nonlocal dielectric function is described by a Lorenz-Drude like single oscillator model, in which the spatial dispersion effects are represented by an additional term depending on the square of the total wavevector \( k \). The theory takes into account the scattering of the electromagnetic excitation at the surface of the dielectric material, which leads to the need of additional boundary conditions in order to solve Maxwell’s equations and treat the electromagnetic transmission problem. The additional boundary conditions appear as additional surface scattering parameters in the expressions of the surface impedances. It is shown that the nonlocal modeling deviates from the classical \( 1/d^2 \) law in the nanometer range at distances still larger than the ones where quantum effects are expected to come into play.

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1. Introduction

In the last two decades, a growing theoretical and experimental research has been devoted to the study of radiative heat transfer at distances much smaller than the typical wavelength of thermal radiation [1–7]. This so-called near field radiative heat transfer follows physical laws that are different from the ones governing classical radiative heat transfer, i.e. the laws of geometrical optics. At subwavelength distances, the wave behavior of light has to be considered and phenomena such as tunneling or interferences dominate the radiative heat transfer. These phenomena completely change the usual behavior of radiative heat transfer which is classically seen as a broadband signal limited in intensity to the exchanges between blackbodies. In the near-field, radiative heat transfer which is ruled by the density of electromagnetic states can be strongly changed due the presence of additional modes at certain frequencies: radiative heat transfer can surpass classical radiation due to the presence of modes close to the surface able to tunnel between heated bodies [8–10]. These new features have open the way to the search of very promising energetics applications such as near field thermophotovoltaics. Indeed, the control of the near-field thermal radiation could lead to a quasi-monochromatic transfer enhanced by several orders of magnitude from the far field values and potentially leading to high conversion ratios [11–17]. Other applications such as cooling [18], nanolithography [19,20] or subwavelength sources [21] are concerned with these physics laws changes at subwavelength scales.

Experimental research has confirmed near field radiative heat transfer theoretical predictions. The thermal density of energy is much higher in the near field in
effects which are surpassed by the quite different behavior due to the presence of magnetic quantum effects. The threshold distance of few hundreds of nanometers [2]–[33] is considered. The paper is dedicated to the conclusions and future outlooks.

2. Radiative heat transfer formalism

Fluctuational electrodynamics introduced by Rylov [8,41] states that a body at a temperature $T$ radiates thermal energy due to the fluctuations of random currents generated by electrons in metals or ions in polar crystals. The properties of these currents are given by the fluctuation-dissipation theorem relating the currents to the medium radiative losses (dissipation). These currents radiate an electromagnetic (EM) field related to the currents by Green’s tensors of the system. The emitted surface density of the radiative heat flux (in W m$^{-2}$) is given by the Poynting vector $1/2\text{Re} [\mathbf{D}(\mathbf{r},\omega) \times \mathbf{H}^*(\mathbf{r},\omega)]$, where $\mathbf{E}(\mathbf{r},\omega)$ and $\mathbf{H}(\mathbf{r},\omega)$ are the electric field and the magnetic field, respectively.

In the most general sense, constitutive relations in a medium that relate bound charges to the electric field depend on the wavevector and the frequency so that for example

$$\mathbf{D}(\mathbf{r},\omega) = \varepsilon(\mathbf{r},\omega) \mathbf{E}(\mathbf{r},\omega).$$

When the EM field varies on a spatial scale larger than the microscopic characteristic lengths of the propagation medium, the medium is usually considered to be local so that $\mathbf{D}(\mathbf{r},\omega) = \varepsilon(\mathbf{r},\omega) \mathbf{E}(\mathbf{r},\omega)$. When it is not the case, the medium is nonlocal i.e. the optical properties depend on the wavevector of the EM field [6,18].

As mentioned earlier, the surface density of the radiative heat flux $\phi$ between two semi-infinite parallel planes in local thermodynamic equilibrium, maintained at temperatures $T_1$ and $T_2$ and separated by a gap distance $d$ (Fig. 1), can be calculated by means of fluctuational electrodynamics. When the temperature difference is small $(T_1 - T_2)/T_1 \ll 1$, $\phi$ can be linearized and written as a radiative heat transfer coefficient (RHTC) $h$ multiplied by the temperature difference $\Delta T$. The extended derivation of the RHTC has been done by many authors [2,3,6,9,42–46].

![Fig. 1. Two semi-infinite parallel material planes separated by a gap distance $d$.](image)

As already suggested, we study in this paper the radiative heat transfer between two semi-infinite parallel dielectric solid planes as the gap distance $d$ between them tends to zero. We will carry on this study using a macroscopic nonlocal dielectric permittivity model suggested by Halevi and Fuchs [40] in which spatial dispersion is considered. The paper is organized as follows: in Section 2, we briefly review the near field radiative heat transfer calculation obtained in the framework of fluctuational electrodynamics formalism for a local modeling of the material optical response. In Section 3, we present the nonlocal modeling of the dielectric optical properties using the theory developed by Halevi and Fuchs. This theory is then used to calculate the radiative heat transfer coefficient between two SiC–SiC semi-infinite parallel planes. In Section 4, we present the results obtained and discuss them by comparing both local and nonlocal optical properties. Section 5 will be dedicated to the conclusions and future outlooks.
