Near field radiative heat transfer between two nonlocal dielectrics

CrossMark

F. Singer, Y. Ezzahri, K. Joulain*

Institut Pprime, Univeristé de Poitiers-CNRS-ENSMA, 2, Rue Pierre Brousse, Bâtiment B25, TSA 41105, 86073 Poitiers Cedex 9, France

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 $\boldsymbol{k}$. 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.

© 2014 Elsevier Ltd. All rights reserved.

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 broad-band 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 sub-wavelength scales.

Experimental research has confirmed near field radia-tive heat transfer theoretical predictions. The thermal density of energy is much higher in the near field in

comparison to the far field, which is due to the presence of surface waves [22], whereas near field radiative heat transfer between bodies at different temperatures is increased as well as in tip-surface geometry [23–25] or in plane parallel geometry [26–30]. Moreover, the change in thermal radiation spectral content has also been observed in the near field [31–33], where a quasi-monochromatic spectral behavior has been reported above SiC and SiO$_2$.

In the work presented here, we will focus on the radiative heat transfer behavior between two heated semi-infinite parallel dielectric solid planes at small distance of separation d. In past theoretical studies, it has been shown that near field radiative heat transfer follows a $1/d^2$ law as long as the separation distance is of the order of few hundreds of nanometers [2–4,9]. Metals follow a quite different behavior due to the presence of magnetic effects which are surpassed by the $1/d^2$ law only at distances below the angstrom range [2,34]. At such low separation distances, fluctuational electrodynamics has to be questioned, in particular the fact that the material optical response is still local. Moreover, the fact that radiative heat transfer is the dominant heat transfer mode has also to be questioned. Of course, when the separation distances are going to be around the typical atomic distances in matter, quantum effects could appear especially for metals where electrons are the dominant heat carriers [35–37] but also in dielectrics for which quantum effects influence has been recently proved with molecular dynamics [38]. At these interatomic separation distances, transition to a regime where thermal conduction dominates occurs. However, it still remains an open question about whether corrections due to the nonlocal optical response of the material appear at distances larger than the one where quantum effects appear and at what distances these nonlocal effects prevail.

To the best of our knowledge, no nonlocal correction to the radiative near field heat transfer has been addressed in the past in the case of dielectrics apart from a very phenomenological description [39]. In the case of metals however, an important and complete work has been performed by Chapuis et al. [34] using the Lindhard–Mermin nonlocal dielectric permittivity model. It was shown that a deviation from the $1/d^2$ law was observed for separation distances in the angstrom range. In this case it is therefore clear that quantum effects will appear at larger distances than nonlocal effects. The goal of this paper is to pursue this work of Chapuis et al. [34] and to extend it to dielectric materials where $1/d^2$ law occurs at much larger distances typically few hundreds of nanometers, in a domain where it is very likely to observe a deviation from the local behavior at distances larger than quantum effects threshold distance.

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 6H–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.

2. Radiative heat transfer formalism

Fluctuational electrodynamics introduced by Rytov [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 correlation function (fluctuations) 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 $1/2Re$ [$\langle E(r,\omega) \times H^*(r,\omega) \rangle$], where $E(r,\omega)$ and $H(r,\omega)$ 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 $D(k,\omega) = \varepsilon(k,\omega)E(k,\omega)$. 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 $D(r,\omega) = \varepsilon(r,\omega)E(r,\omega)$. 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 ϕ 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 $(T_1 - T_2)/T_1 \ll 1$, ϕ can be linearized and written as a radiative heat transfer coefficient (RHTC) h multiplied by the temperature difference δT. The extended derivation of the RHTC has been done by many authors [2,3,6,9,42–46],
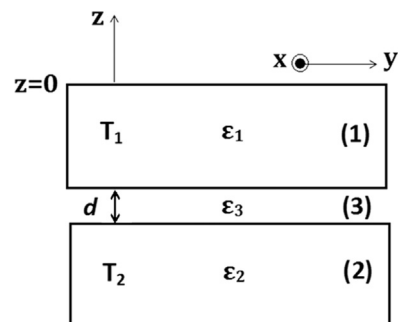

Fig. 1. Two semi-infinite parallel material planes separated by a gap distance d.