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The influence of surface roughness on nanoscale radiative heat flux between two objects

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ABSTRACT

Radiative heat transfer between two closely located plates can exceed black body limit due to the near-field effects. The surface roughness is not considered in the investigation of the enhancement of the near-field radiative heat transfer. In this paper, a computational model based on the finite-difference time-domain (FDTD) method and the Wiener Chaos Expansion (WCE) method is established to calculate the near-field radiative heat transfer between two plates with Gaussian type rough surfaces. The effect of the surface roughness on the near-field radiative heat transfer is analyzed. The numerical results show that the surface roughness has an obvious impact on the spectral radiative heat flux between two plates and the near-field radiative heat transfer may be decreased by the very small surface roughness. This indicates that the surface roughness needs to be considered in order to precisely evaluate the near-field radiative heat transfer between two plates.

1. Introduction

When two plates are located at sub-wavelength distances (in the nano/micron scale), the radiative heat transfer can be enhanced to exceed the black body limit by several orders of magnitude [1,2] due to the excitation of evanescent wave and other near-field effects, such as surface plasmon polaritons (SPP) [3] and surface phonon polaritons (SPhP) [4]. This phenomenon has been intriguing during the past decades and drives researchers to devote themselves into the investigation and application of the thermal radiation heat transfer at nanoscale dimensions.

In order to verify the near-field effects on the radiative heat transfer enhancement, which can exceed the black body limit, many experimental researches were carried out to measure the radiative heat transfer between two closely placed objects. Various devices were set up by different groups during the past decades. Kittel et al. [5] presented the measurement method for the near-field radiative heat transfer between sensor tip and planar surface in the vacuum. The experimental results could be applied to the interpretation of signals obtained by the near-field thermal scanning systems. Narayanaswamy et al. [2] studied the radiative heat transfer between two planar glass plates where the polystyrene spheres were used to control the gap distance between the two plates. The results clearly showed that the radiative heat transfer through the vacuum gap of nano/micron scale exceeds the black body limit. In 2011, Ottens et al. [6] also studied the near-field radiative heat transfer between two macroscopic sapphire plates at the room temperature. The results revealed that the evanescent wave could be utilized to enhance the near-field radiative heat transfer. These experiments have confirmed the phenomenon of the enhancement of the near-field radiative heat transfer.

The traditional method based on the Planck blackbody radiation law fails to predict the near-field radiative heat

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Nomenclature

a	scale-invariant factor, $a=1$ μm
$\vec{B}$	magnetic induction, N s C^{-1} m^{-1}
$C(r)$	correlation function
c	light speed, m s^{-1}
$\vec{D}$	electric displacement, C m^{-2}
D	plate thickness, μm
d	vacuum gap distance, μm
$dW(\vec{r})$	white noise function
$\vec{E}$	electric field vector, V m^{-1}
$\overline{\overline{G}}$	dyadic Green's function, m^{-1}
$\vec{H}$	magnetic field vector, A m^{-1}
$\vec{J}$	current source, A m^{-2}
j	symbol for complex number, $j=\sqrt{-1}$
$\vec{j}_n$	normalized current source
k	wave number, rad m^{-1}
l	correlation length, μm
L	periods of x and y directions, μm
$\vec{S}$	Poynting vector, W m^{-2}
T	temperature, K
$W(k), W(k_x, k_y)$	power spectral density function
x, y, z	directions of coordinates

Greek symbols

δ	root mean square height, μm
$\delta_{nn'}$	Kronecker delta function
$\delta(r-r')$	Dirac delta function
ε_0	permittivity, C^2 N^{-1} m
ε_r	relative permittivity
ε''	imaginary part of, ε_r
ξ_n	standard Gaussian number
μ_0	permeability, N m^{-2}
Θ	average energy of Planck oscillator, J
$\Phi_n(\vec{r})$	orthonormal basis
ω	angular frequency, rad s^{-1}

Superscripts/subscripts

*	complex conjugate
(norm)	normalized variable
n, n'	the number of different series
p,q,g,n_k,m_k	integers
x,y,z	coordinate directions

transfer because the evanescent mode dominates the radiation transfer. Considering the electromagnetic wave nature of the thermal radiation the near-field thermal radiative heat transfer can be calculated directly by solving Maxwell equations [7]. For example, the dyadic Green's function method is a widely-used analytical technique to deal with the electromagnetic propagating problems. In 2009, Basu et al. [8] gave a review about the near-field thermal radiation calculation and its application for energy conversion. In their work, the dyadic Green's function method was introduced and the near-field thermophotovoltaic (TPV) system was investigated. Francoeur et al. [9] discussed the detailed solution of the near-field radiative heat transfer in 1D layered media based on the dyadic Green's function method and the scattering matrix method. Their work is valuable for optimizing the design of radiator performance in nano-gap TPV power generators. In 2011, Zheng and Xuan [10] further studied the near-field radiative heat transfer in layered media and the metamaterial with its relative permeability greater than 1 was considered. The results revealed that the SPP can be excited under both TE mode and TM mode of the electromagnetic waves.

The theoretical investigations discussed above are focused on the near-field radiative heat transfer without considering the surface roughness. Therefore, it is necessary to establish more common methods to predict the effects of the surface roughness on the near-field radiative heat transfer. Biehs et al. [11] demonstrated the near-field radiative heat transfer between two rough bulk materials by means of the second-order perturbation theory based on the dyadic Green's function method. Their work revealed that the proximity approximation for describing rough surfaces is valid for the distance much smaller than the correlation length of the rough surface. However, for arbitrary complex structures, the exact expressions of the near-field radiation transfer method can hardly be given by means of the dyadic Green's function method. As a more commonly used approach, numerical method is an alternative way to solve the near-field thermal radiation problems. A number of numerical methods are existed, such as the finite-difference time-domain (FDTD) [12,13], the discrete dipole approximation (DDA) [14,15], the finite element method (FEM) [16] and the boundary element method (BEM) [17].

According to the fluctuating dissipation theory (FDT), frequency domain expression of the statistical average describes the uncorrelated fluctuating current source. To modeling the statistical behavior of the thermal emitting source, two normal approaches can be employed. One is the Monte Carlo (MC) simulation, which adopts the Langevin approach to simulate the random property of current source in an emitting body [12,18]. Its natural superiority is that it satisfies the original definition of the current source while the simulation is a little time consuming because lots of simulations need to be run to cancel the random effects. It also depends on a good random number generator. Another method is the Wiener Chaos Expansion (WCE) method [13,19], which is utilized to convert the statistical expression of the FDT into the summation of different series. The WCE method does not require any mode expansion of the wave vector. The published papers [13,19] showed that the results obtained by means of the WCE method can well coincide with the analytical results.

In this paper, the normalized Maxwell equations are applied to analyze the radiative heat flux between two closely placed plates of the Drude material. The effect of