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Solution of near-field thermal radiation in one-dimensional layered media using dyadic Green's functions and the scattering matrix method

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ABSTRACT

A general algorithm is introduced for the analysis of near-field radiative heat transfer in one-dimensional multi-layered structures. The method is based on the solution of dyadic Green's functions, where the amplitude of the fields in each layer is calculated via a scattering matrix approach. Several tests are presented where cubic boron nitride is used in the simulations. It is shown that a film emitter thicker than 1 μm provides the same spectral distribution of near-field radiative flux as obtained from a bulk emitter. Further simulations have pointed out that the presence of a body in close proximity to an emitter can alter the near-field spectrum emitted. This algorithm can be employed to study thermal one-dimensional layered media and photonic crystals in the near-field in order to design radiators optimizing the performances of nanoscale-gap thermophotovoltaic power generators.

1. Introduction

Thermal agitation of charges inside a body at a finite temperature ($T>0$ K) generates propagating and evanescent radiation fields. Propagating waves travel to the far-field, while evanescent waves are confined on the surface of the emitting body, and decay exponentially over a distance of about a wavelength. In the classical theory of thermal radiation based on the Planck blackbody distribution, only the propagating modes are accounted for in the analyses [1,2].

If a body is brought within the evanescent field of an emitter, radiative energy is also transferred through evanescent modes, due to a mechanism referred as radiation tunneling. As a first order approximation, it can be assumed that bodies separated by a distance less than the dominant wavelength emitted, as predicted by the Wien law, experience near-field effects of thermal radiation, which also includes wave interference. Due to contributions from both propagating and evanescent waves, radiative heat transfer in the near-field can exceed the values predicted by the Planck blackbody distribution by a few orders of magnitude.

Near-field thermal radiation has only recently attracted attention due to applications in nanoscale-gap thermophotovoltaic (TPV) power generation [3–5], in near-field thermal microscopy [6–8], and far-field control of thermal

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Nomenclature

A, B, C, D	field amplitude coefficients
$\mathbf{E}$	electric field vector, V m^{-1}
$\bar{\bar{\mathbf{g}}}$	Weyl component of the dyadic Green's function, m
$\bar{\bar{\mathbf{G}}}$	dyadic Green's function, m^{-1}
$\mathbf{H}$	magnetic field vector, A m^{-1}
i	complex constant, $(-1)^{1/2}$
Im	imaginary part
$\mathbf{J}^r$	random current density vector, A m^{-2}
k	wavevector ($= k' + ik''$), rad m^{-1}
n	complex refractive index ($= n' + in''$)
$\hat{\mathbf{p}}$	TM-polarized unit vector
P_i	propagation matrix in layer i
q	radiative heat flux, W m^{-2}
r_{ij}	Fresnel reflection coefficients at interface i–j
$\mathbf{r}$	position vector, m
Re	real part
$\hat{\mathbf{s}}$	TE-polarized unit vector
$\mathbf{S}$	Poynting vector, W m^{-2}
$S^{+,-}$	amplitude of source propagating in forward/backward direction
$S(i, j)$	scattering matrix between layers i and j
t	time, s or film thickness, m
t_{ij}	Fresnel transmission coefficients at interface i–j
T	temperature, K
V	volume, m^3
V_{ij}	transmission matrix at interface i–j
x, y, z	Cartesian coordinates
$\hat{\mathbf{x}}, \hat{\mathbf{y}}, \hat{\mathbf{z}}$	unit vectors oriented in orthogonal directions (Cartesian coordinate system)
z_c	location where the radiative flux is calculated, m

Greek symbols

δ	penetration depth of evanescent waves, m
ε	electric permittivity, C^2 N^{-1} m
ε_r	dielectric constant ($= \varepsilon_r' + i\varepsilon_r''$)
ε_∞	high frequency dielectric constant
γ	damping factor, s^{-1}
λ	wavelength, m
μ	magnetic permeability, N A^{-2}
Θ	mean energy of a Planck oscillator, J
ρ, θ, z	polar coordinates
$\hat{\boldsymbol{\rho}}, \hat{\boldsymbol{\theta}}, \hat{\mathbf{z}}$	unit vectors oriented in orthogonal directions (polar coordinate system)
ω	angular frequency, rad s^{-1}

Subscripts/Superscripts

$*$	complex conjugate
$'$	source point
E	electric
H	magnetic
l	layer where the radiative flux is calculated
P	primary wave
s	source layer
v	vacuum
ω	monochromatic
evan	evanescent wave
LO	longitudinal optical
prop	propagating wave
tot	total
TE	transverse electric
TM	transverse magnetic
TO	transverse optical

emission [9–12]. Understanding and predicting radiation transfer in the near-field is also fundamental for thermal management of micro and nanoscale devices, and in selective melting of nanoparticles for bottom-up nanofabrication processes [13,14].

Near-field radiative heat transfer predictions are performed by solving the Maxwell equations combined with fluctuational electrodynamics (FE), where the source of thermal radiation is modeled as an extraneous stochastic current density [15]. During 1960s, Tien's group studied near-field thermal radiation [16,17], but Polder and Van Hove [18] were the first to tackle the problem within the FE framework. Since then, numerical predictions of near-field radiative heat transfer between parallel surfaces with bulk emitters [19,20] and film emitter [21–23], between a dipole and a surface [24], between two dipoles [25–27], in a cylindrical cavity [28], between two large spheres [29], and between a dipole and a structured surface [30], have been reported. In all these cases, the combined Maxwell's equations and FE, sometimes referred as stochastic Maxwell's equations, are solved using dyadic Green's functions (DGFs).

Accurate predictions of near-field radiant energy exchanges in one-dimensional layered structures are of high practical importance, since these predictions can guide the applications involving far-field emission from one-dimensional thermal photonic crystals, nanoscale-gap TPV devices, and thermal management problems of micro/nanoscale devices. It should be emphasized here that one-dimensional analysis does sufficiently describe the physics of many practical systems, as in most cases the separation distance between the bodies exchanging thermal radiation is much smaller than the other dimensions of the system. Indeed, Lee et al. [31,32] have recently developed a method to visualize the pathway of the Poynting vector due to evanescent waves. They have shown that two silicon carbide plates exchanging thermal radiation can be considered as semi-infinite (i.e., one-dimensional approximation) when the lateral dimension of the surfaces are about two hundred times larger than the gap separating them [32]. This means that surfaces with lateral dimensional of about 2 μm can be considered as semi-infinite when the separation gap is around 10 nm. This criterion demonstrates that the one-dimensional approximation in near-field thermal radiation is realistic and can arise for a variety of practical cases.