Journal of Quantitative Spectroscopy & Radiative Transfer 167 (2015) 156–163

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Metamaterial-based perfect absorbers for efficiently enhancing near field radiative heat transfer

Nan Zhou, Xianfan Xu*

School of Mechanical Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47907, USA

ARTICLE INFO

Article history:
Received 9 June 2015
Received in revised form
31 July 2015
Accepted 25 August 2015
Available online 3 September 2015

Keywords:
Radiative heat transfer
Metamaterials
Near field
Surface polaritons

ABSTRACT

The fascinating capability of manipulating light using metamaterials (MMs) has inspired a significant amount of studies of using MMs for energy related applications. In this work we investigate MM-based perfect absorbers for enhancing near field radiative heat transfer, which is described by the fluctuation dissipation theorem. MM structures designed at two wavelengths are analyzed, corresponding to two working temperatures. Both electric and magnetic surface polaritons are found to contribute to heat transfer, while natural materials support only electric polaritons. The near-perfect absorption is demonstrated to be related to the modification of effective optical properties, which is important for enhancing radiative heat transfer efficiently. By comparing different designs, the bandwidth of the heat flux spectrum is found to increase with the absorption bandwidth, which is originated from the spatial field distributions. This study will contribute to the understanding of surface polaritons in near field radiative heat transfer and facilitate the optimization of MMs for near field heat transfer applications.

1. Introduction

The demonstration of negative refractive index materials [1–3] has generated significant amount of interests in researches of metamaterials (MMs) [4–7]. The fascinating light manipulation capability of MMs has many potential applications related to energy utilization. For example, MMs can be designed for radiation selective surfaces tailoring the solar absorption and emission of light at a particular wavelength, i.e., selective absorbers or emitters [8–13]. This holds the potential in the field of thermal photovotaics, where the conversion efficiency could be significantly enhanced if the wavelength is matched to the bandgap of photovoltaic materials [14,15].

Nano-structured surfaces or meta-surfaces can also be designed to enhance near field radiative heat transfer (NRHT). Polder and Van Hove [16] found a heat flux increase between two parallel plates, separated by a distance smaller than λ_T due to the contribution from evanescent waves, where λ_T is the peak wavelength of the thermal radiation spectrum given by Wien's displacement law: $\lambda_T T \approx 2898\ \mu m\ K$. Recent work has shown that it is possible to enhance spectral heat flux by several orders of magnitude through resonantly excited surface phonon polaritons (SPhPs) in polar materials such as SiC and glass [17–19]. The intrinsic optical properties of polar materials limit the SPhPs to around 10 μm, corresponding to an operating temperature close to the room temperature. Other materials investigated in the infrared range include doped Si [20,21] and graphene [22,23], which enhance NRHT through exciting surface plasmon polaritons (SPP).

For noble metals that also support SPP, the resonance typically lies in the visible or UV wavelengths, which is

* Corresponding author. Tel.: +17654945639, fax: +17654940539.
E-mail address: xxu@ecn.purdue.edu (X. Xu).

http://dx.doi.org/10.1016/j.jqsrt.2015.08.015
0022-4073/

significantly above the thermal frequency range. This corresponds to an operating temperature higher than 2000 K which could melt the metal, thus limiting the direct application of metallic materials in NRHT. However, by applying nanostructures, the response can be strongly manipulated through the interaction between incident electromagnetic waves and the properly designed structures. The incident light can be coupled to not only electric surface polaritons, but also magnetic polaritons [11,13]. This method provides flexibility in tailoring the optical properties in a wide frequency range and thus provides a potential to effectively enhance NRHT.

Analysis of the NRHT usually employs fluctuational electrodynamics [24], which has been extended to MMs with arbitrary permittivity ε and permeability μ by Joulain et al. [25]. In classical electromagnetics, the Drude–Lorentz model is applied to ε $(=\varepsilon'+i\varepsilon'')$ and μ $(=\mu'+i\mu'')$, derived from the oscillation of charges or fictitious magnetic charges. For a dilute metal design with extremely low plasma frequency [26], an analytical expression was derived for the effective permittivity ε_{eff}, which still obeys the Drude–Lorentz model. Similarly, the average response of split ring resonator (SRR) MMs was also analytically characterized [27]. More generally, analytical solutions are not available for the collective optical response of inhomogeneous structures. Instead, the effective medium theory (EMT) is widely applied to homogenize the structure with the aid of the geometric filling ratio [28–30] or the *S*-parameters from numerical simulation [15,31,32]. It is accepted that EMT is generally applicable if the incident wavelength is much larger than size of the unit cell, and the distance to the structure surface is not smaller than the size of the unit cell [29–31]. Many researchers have developed alternative approaches for evaluating the MM-based NRHT with improved accuracy at small plate separations. A scattering approach [33] based on rigorous coupled-wave analysis (RCWA) has been applied to compute the NRHT between metallic [34] and dielectric [35] gratings. Wen [36] conducted direct simulations for NRHT between two parallel plates using Wiener chaos expansion, which has no explicit constraint on the geometry and relies on finding eigenmodes of the thermal fluctuating current. Liu and Shen [37] extended this method to hyperbolic MM consisting of metallic wire array. Other methods for solving NRHT problems in arbitrary configurations include direct finite-difference time-domain (FDTD) computations [38,39], boundary-element method (BEM) [40], and thermal discrete dipole approximation (T-DDA) [41].

In this study we focus on MMs that have a top metallic antenna array and a bottom metal ground layer, separated by a dielectric spacer. This type of MMs has been demonstrated both numerically and experimentally to provide near perfect absorption and functions as a blackbody at the desired wavelength [11,15]. We extend the study of these MMs to the field of near field radiative heat transfer between parallel plates, through enhancing the strength of surface polaritons and thus enhancing the NRHT. We also investigate the effect of temperature and compare different MM designs.

2. Methods and geometry

The parallel plates geometry under study is illustrated in Fig. 1, where the medium 3 between two plates is typically vacuum with $\varepsilon_3=1$. By applying the fluctuation dissipation theorem, the net radiative heat flux is given as [42]

$$P(T_1, T_2) = \downarrow\pi \int_0^\infty d\omega\left[I_\omega^0(T_1) - I_\omega^0(T_2)\right]$$
$$\downarrow\times \sum_{\alpha=s,p}\left[\int_0^{\omega/c} \frac{KdK}{(\omega/c)^2}\frac{\left(1-|r_{31}^\alpha|^2\right)\left(1-|r_{32}^\alpha|^2\right)}{\left|1\underbrace{-}_{Pr\ opagating} r_{31}^\alpha r_{32}^\alpha e^{2i\gamma_3 d}\right|^2}\right.$$
$$\left.+\int_{\omega/c}^\infty \frac{KdK}{(\omega/c)^2}\frac{4\,\mathrm{Im}(r_{31}^\alpha)\mathrm{Im}(r_{32}^\alpha)}{\left|1-r_{31}^\alpha \underbrace{r_{32}^\alpha}_{Evanescent} e^{-2\gamma''_3 d}\right|^2}e^{-2\gamma''_3 d}\right], \quad (1)$$

where K is the in-plane wave vector and $I_\omega^0(T) = \hbar\,\omega^3/4\,\pi^3c^2/(e^{\hbar\omega/k_BT}-1)$ is the intensity of blackbody radiation, which serves as a ω-domain filter that cuts off modes with $\omega >> k_BT/\hbar$ [42]. Both propagating $(K<\omega/c)$ and evanescent $(K>\omega/c)$ waves are accounted in Eq. (1). The denominator involving Fresnel reflection coefficients corresponds to multiple reflections. When the surface plasmon/phonon polaritons are excited, $\mathrm{Im}(r^s)$ is negligible while $\mathrm{Im}(r^p)\approx 2\mathrm{Im}(\varepsilon)/|\varepsilon+1|^2$ [17]. As a result, the p-polarized evanescent channel peaks at the same condition as the surface modes that originated from plasmon or phonon polaritons $(\varepsilon=-1)$, significantly enhancing the NRHT. Similar analysis can be applied to the s-polarized channel if the plate has a negative permeability μ', indicating the existence of surface magnetic polaritons. Thus, instead of applying naturally existed bulk materials, we design nanostructures or MMs to manipulate both ε and μ. The regions with both negative ε' or μ' will considerably enhance the NRHT.

According to the analysis in [31], the effective refractive index $(n=n'+in'')$ and impedance $(z=z'+iz'')$ are related to the complex reflection coefficient r and transmission coefficient t by

$$\cos(nk_0D) = \frac{1-r^2+t^2}{2\,t} \quad (2a)$$

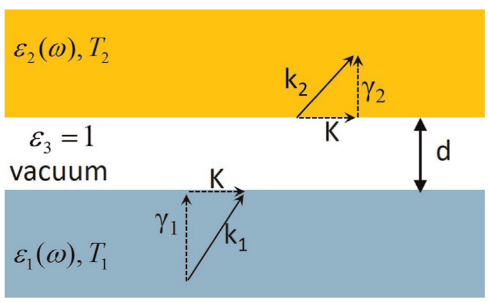

Fig. 1. Schematic of the nanoscale thermal radiation between two parallel plates.