Journal of Quantitative Spectroscopy & Radiative Transfer 158 (2015) 36–42

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

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

Multi-band near-field radiative heat transfer between two anisotropic fishnet metamaterials

Yang Bai [a], Yongyuan Jiang [a,b,*], Linhua Liu [c]

[a] Department of Physics, Harbin Institute of Technology, Harbin 150001, China
[b] Key Lab of Micro-Optics and Photonic Technology of Heilongjiang Province, Harbin 150001, China
[c] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Article history:
Received 30 September 2014
Received in revised form
15 January 2015
Accepted 17 January 2015
Available online 10 February 2015

Keywords:
Heat transfer
Multiple band
Near field
Fishnet metamaterial

ABSTRACT

We study the near-field radiative heat transfer between two metal–insulator–metal sandwiched-like fishnet metamaterials (FMMs) by fluctuation electrodynamics. Results show that multi-band heat flux between the fishnet metamaterials is achieved, which is attributed to the thermally excited surface modes within the FMM. Apart from the electric response mode of the near-field heat flux, magnetic modes are also existed, which are related with the excitations of the surface plasmon polaritons (SPPs) propagating on the outer surface of metal (external SPPs) and along the inner metal–dielectric interface (internal SPPs). Moreover, we show that the electromagnetic parameters of this anisotropic fishnet metamaterial depend on the angles θ of the incident light when heating the fishnet metamaterial, and thus the overall effect of the anisotropic FMM parameters is considered to predict the near-field radiative heat transfer. Different external-SPPs and internal-SPPs modes are excited at different frequencies which is attributed to the anisotropic electromagnetic response of FMM, which open new frequency channels of the near-field radiative heat transfer. This kind of anisotropic metamaterial should assist in thermal management in nanoscale.

1. Introduction

Near-field radiative heat transfer has attracted considerable attention over the past years [1–3], since it promises to affect a variety of applications such as the thermal rectification [4–6], coherent thermal sources [7–9], and thermophotovoltaic (TPV) power generation [10]. When the separation distance between two hot bodies is of the order or less than the Wien's wavelength, the upper limit of Planck's law is broken by orders of magnitude especially for materials supporting surface waves, such as SiC [11] and doped Si [12], which support surface plasmon polaritons (SPPs) and surface phonon polaritons (SPhPs), respectively. Many researchers have also studied the possibility of tailoring the near-field radiative heat transfer result from the coupled surface modes within thin films [13,14] or surface Bloch waves coupling between photonic crystals [15]. Phase-change materials [16] and graphene 2D system [17] are also investigated to control the enhanced near-field effect.

Metamaterials are artificially engineered structures with periodical electric and magnetic resonators, which have aroused much interest in designing the negative media [18–20], perfect lens [21] and optical cloaking [22,23], as well as acting as a thermal source. Joulain et al. have first investigated the heat transfer between two

* Corresponding author.
E-mail addresses: jiangyy@hit.edu.cn (Y. Jiang), lhliu@hit.edu.cn (L. Liu).

http://dx.doi.org/10.1016/j.jqsrt.2015.01.010
0022-4073/

hypothetical metamaterials with arrays of wires and split rings [24]. Results have shown that the near-field heat transfer is enhanced in both TE- and TM-polarizations and a new frequency channel of the magnetic surface mode is opened. Francoeur et al. [25–37] have investigated the near-field radiative heat transfer between the isotropic dielectric-based metamaterials made up of SiC spheres in a potassium bromide (KBr) host mediums, and the magnetic surface mode is attributed to the magnetic dipole resonances of the spheres. Cui et al. [28,29] have studied surface modes mediated heat transfer between the chiral metamaterials by taking magnetoelectric coupling effect into account. Also recently, a series work on hyperbolic metamaterials made of periodical nanowires [30] or multiple layered [31,32], has shown broadband heat transfer in the near field which is attributed to the hyperbolic modes within this anisotropic media. Among all the mentioned studies above, homogenization based on the effective medium theory (EMT) is employed in characterizing the effective electromagnetic parameters to predict the near-field radiative heat transfer due to its simplicity and low computational demand. On the other hand, many researchers have also explored the validity of EMT when dealing with the radiative heat transfer in the near field region. Biehs et al. [32] have studied the near-field heat flux for multi-layered hyperbolic metamaterials and compared the results calculated by EMT and scattering-matrix calculations. Liu and Shen [33] have investigated the near-field radiative heat flux between a SiC film and metal nanowire arrays and shown that EMT should overestimate the result calculated by the Wiener chaos expansion method at small gap distances. Joulain et al. [34] have studied the density of energy above a metamaterials made of nanowires in the microwave region and determined the valid distance for the homogeneous approximation. Zhang's group [35] has given a quantitative criterion for the validity of EMT in predicting the near-field radiative heat transfer between multilayered metamaterials. In general, the critical separation distance should not be smaller than the metamaterial period in order to ensure the validity of EMT in predicting the near-field radiative heat transfer.

The fishnet metamaterial (FMM) is composed of metal–dielectric–metal layers with arrays of holes, and it has been experimentally demonstrated in several frequency ranges by the advanced lithographic fabrication [36–38]. When acting as a function devices, this planar metamaterial is easier for illumination and detection compared with that of conventional metamaterial, such as wires and split rings [19]. In addition, multiple magnetic responses are supported by the FMM due to the excitation of the surface plasmon polaritons (SPPs) propagating on the outer surface of metal (external SPPs) and along the inner metal–dielectric interface (internal SPPs) [39–42], which should bring new characteristics to the near-field radiative heat transfer. In this paper, we investigate the role of multiple magnetic responses on the near-field radiative heat transfer between two FMMs by means of the fluctuational electrodynamics. The near-field heat flux with separation distance 500 nm is demonstrated to ensure the homogeneous approximation is valid. We show that multi-band radiative frequency channels are opened by the excitations of external-SPPs and internal-SPPs within the FMM.

2. Calculation model

The near-field radiative heat transfer between two FMMs is schematically illustrated in Fig. 1. D is the separation distance in vacuum between two FMMs at different temperatures T_1 and T_2. Each FMM is composed of metal–dielectric–metal sandwich-like structure with arrays of square apertures with lattice period Λ_x in X-direction and Λ_y in Y-direction. The size of the square hole is L_x in X-direction and L_y in Y-direction. MgF_2 is chosen as the dielectric layer with non-dispersive electric permittivity $\varepsilon_d = 1.9$. Silver is set as the metal layer with the dielectric function expressed by Drude model [43], $\varepsilon_m(\omega) = 1 - \omega_p^2/\omega(\omega + i\omega_c)$ where $\omega_p = 2175$ THz and $\omega_c = 4.35$ THz are the plasma frequency and the collision frequency, respectively. The thicknesses of Ag and MgF_2 are h_m and h_d, respectively. In the calculations, we set the lattice period as $\Lambda_x = \Lambda_y = 600$ nm, $h_m = 600$ nm, $h_d = 30$ nm, $L_x = 350$ nm and $L_y = 500$ nm to ensure that the working region of the FMM is in the near infrared, and each FMM is assumed at an equilibrium temperature, $T_1 = 1000$ K and $T_2 = 300$ K.

The near-field radiative heat transfer between FMMs is governed by the effective electric permittivity and magnetic permeability which are obtained by the S-parameter retrieval method [19,44,45] based on EMT. Here we use a commercial solver by CST Micro Wave Studio, based on the finite element method, to retrieve the S-parameters for the unit cell of FMM [46]. Plane waves in TM-polarization are assumed with incident angle θ with Z-direction for the excitation and detection. Periodic boundary conditions are used for both X- and Y-directions. The effective refractive index n and impedance z_c can be expressed as follows

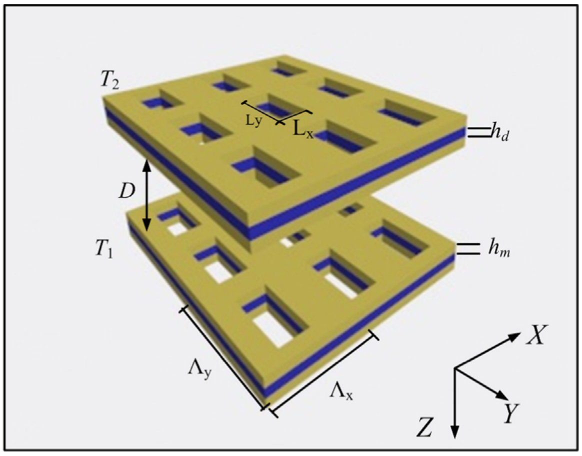

Fig. 1. Schematic diagram of the near-field radiative heat transfer between two FMMs (Λ_x is the lattice period in X-direction and Λ_y is the lattice period in Y-direction; the size of the hole is L_x in X-direction and L_y in Y-direction; h_m is the thickness of each metal layer and h_d is the thickness of dielectric layer and D is separation distance in vacuum between two FMMs).