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Enhanced near-field radiative heat transfer between a nanosphere and a hyperbolic metamaterial mediated by coupled surface phonon polaritons

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ABSTRACT

We study the near-field radiative heat transfer between a silicon carbide (SiC) nanosphere and a SiC–SiO_2 multi-layered hyperbolic metamaterial (HMM) by means of fluctuational electrodynamics. Results show that the absorbed mean power at the volume resonant frequency of the SiC nanosphere is one order of magnitude stronger than that of bulk SiC medium. This enhancement of near-field radiative heat transfer is mediated by the coupled surface phonon polaritons at the forbidden region of the Bloch mode. Moreover, the forbidden region of the Bloch mode is tuned by the geometry structure of the multi-layered HMM and overlapped with the volume resonant frequency of the SiC nanosphere, thus generating stronger absorption.

1. Introduction

Radiative heat transfer between two hot bodies in the near field has attracted considerable attention over the past years [1–3], since it can exceed the blackbody limit by orders of magnitude when the separation distance is of the order, or less than Wien's wavelength, especially for materials supporting either surface or hyperbolic modes [4–8]. This near-field thermal effect promises to affect a variety of applications such as thermal rectification [9–11], coherent thermal sources [12] and thermophotovoltaic (TPV) power generation [13–18]. Several recent experimental measurements of the near-field heat transfer are important in verifying the enhanced near-field effect and vital for the near field scanning and probing techniques. Chen's group [19,20] has measured the near-field radiative transfer between a microsphere and a substrate using a bimaterial atomic force microscope cantilever. Chevrier's group [21–23] has shown that bilayer levers of atomic force microscope can be used as sensitive probes to measure near- and far-field radiative heat flux between vanadium dioxide media. Also, this bimaterial cantilever has been used in near-field imaging techniques [24–26], which form the thermocouple of the near-field scanning thermal microscope. By scattering scanning near-field optical microscopy in combination with Fourier-transform spectroscopy, Jones et al. [27] have characterized the thermal radiation in the near field, in which a heated atomic force microscope tip is used as both a local thermal source and scattering probe. Babuty et al. [28] have investigated the local spectra of the near-field thermal emission recorded by a Fourier-transform infrared spectrometer in thermal equilibrium, using an unheated tungsten tip as a local scatterer for coupling the near-field thermal emission to the far field. Among all the experiments described above, tip-plane geometry is employed to

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detect and model the near-field heat transfer. However, the near-field thermal signal is still of the order of nanowatt limited by the detecting distance and tip–sample coupling efficiency, which is faint to give a direct experimental characterization. On the other hand, Dorofeyev [29–31] has theoretically shown that the thermal field dissipated in the tip of a probe microscope is inversely proportional to the cube of the distance between tip and the heated plane sample. Pendry [32] has investigated the photon tunneling effect in scanning tunneling microscope on the enhanced heat flow. Volokitin [33] has studied the dissipative van der Waals interaction between a small particle and a metal surface. Mulet et al. [34] have modeled the radiative heat transfer between a silicon carbide (SiC) nanosphere and a bulk SiC substrate and shown a nonmonochromatic absorption power peak. This is due to the fact that absorption resonance frequency of the SiC nanosphere differs from the surface phonon polaritons resonance frequency supported by the bulk SiC material. If the nanosphere tip and bulk emitter were constituted by different media, it would also reduce the intensity of the near-field signal. Therefore, how to control the near-field heat transfer and achieve stronger tip–sample coupling efficiency are important to detect the near-field thermal signal and improve the performance of near-field thermal management.

Hyperbolic metamaterials (HMMs) are artificial media that support radiative modes with extremely large lateral wavevectors [35]. These non-magnetic anisotropic media have a hyperbolic dispersion by effective medium theory, which is different from the usual elliptical dispersion in conventional uniaxial media. The unique electromagnetic properties of the HMM have attracted considerable interests in subwavelength imaging [36], nanoscale waveguides [37,38] and near-field filters [39], as well as acting as near-field thermal sources. Biehs et al. [40] have shown that HMM made of a periodical array of nanowires exhibits broadband near-field heat transfer, which is due to frustrated modes supported by these media. This kind of metamaterial can be invoked as perfect thermal emitters for near-field radiation or realizing analog of an usual blackbody in the near field. Guo et al. [5] have investigated the broadband super-Planckian thermal emission from multi-layered HMM, which is due to the thermal excitation of unique bulk metamaterial modes. Liu et al. [8] have investigated the near-field radiative heat transfer between HMMs made of graphite and vertically aligned carbon nanotubes which also support broadband hyperbolic modes. An exact scattering-matrix calculation of multilayer HMMs by Biehs et al. [6] has shown that the super-Planckian emission of such metamaterials is a mixed mode of surface phonon polaritons generated by the topmost layers and the Bloch mode generated by the multi-layered structures. In addition, the coupled surface phonon polaritons are restricted at the forbidden region of the Bloch mode, which can be tuned by the geometry of the HMM.

In this paper, we study the near-field radiative heat transfer between a SiC nanosphere and a SiC–SiO_2 multilayered HMM by means of the fluctuational electrodynamics. We focus on tuning the spectrum of the radiative heat transfer between the nanosphere and the HMM. The geometry of the multi-layered HMM is appropriately designed in order to exhibit strong absorption by the SiC nanosphere. This is due to the fact that the coupled surface phonon polaritons restricted at the forbidden region overlap with the volume resonant frequency of the SiC nanosphere, which generates significantly enhanced absorption. Our results show that the multi-layered HMM may be a better thermal source in detecting thermal signal in the near field.

2. Calculation model

The geometry of the system is schematically illustrated in Fig. 1. The HMM acting as the near-field thermal emitter is composed of SiC–SiO_2 multi-layered structure which locates at the lower space ($Z<0$). A SiC nanosphere is located on the upper space ($Z>0$) with radius R and separation distance D to the HMM. We set SiC as the topmost layer of the HMM, which supports phonon polaritons in the operating wavelength of the HMM. Lorentz model is used for the dielectric function of SiC [41], $\varepsilon_{SiC} = \varepsilon_\infty[1+(\omega_L^2-\omega_T^2)/(\omega_T^2- \ \omega^2-i\Gamma\omega)]$, where the high frequency dielectric constant $\varepsilon_\infty = 6.7$ and damping constant $\Gamma = 0.9\times10^{12}$ rad/s. The coupling between the optical phonons and light make the real part of the permittivity ε_{SiC} become negative in the Reststrahlen band, ranging from the transverse optical phonon resonance frequency $\omega_T = 1.49.5\times10^{12}$ rad/s to the longitudinal optical phonon resonance frequency $\omega_L = 182.7\times10^{12}$ rad/s. The dielectric function of SiO_2 layer is described using the oscillator model

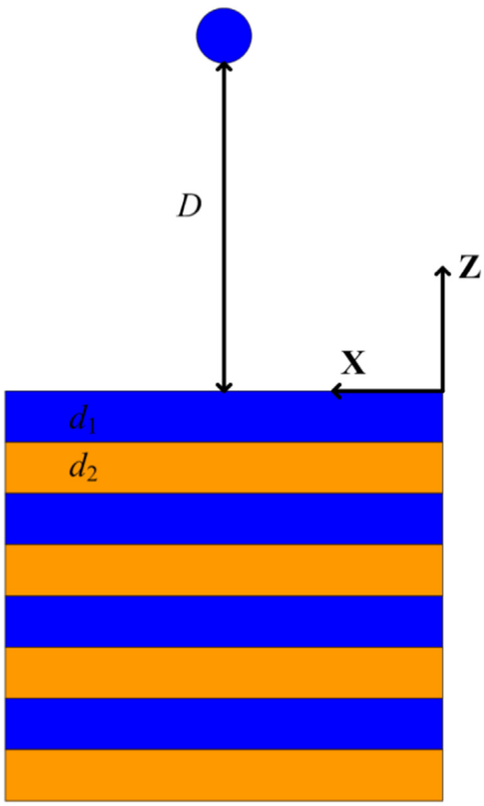

Fig. 1. Schematic diagram of the heat transfer between a SiC nanosphere and a SiC – SiO_2 multi-layered HMM.