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Radiative flux control via graphene-based spectrum tailoring

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ABSTRACT

This work numerically investigates a radiative flux management method via graphene-based metamaterial that exhibits tunable optical responses. The background spectrum tailoring, which can be considered as degeneration of Fabry-Perot resonance, has been investigated as the dominating factor to the radiation tuning. Two types of resonances, as surface plasmon polariton and phonon-mediated magnetic polariton, have been excited. The near field distributions have been studied to understand the physics for the resonances and background spectrum. Analytical modes, dispersion relationship for surface plasmon polariton and inductor-capacitor model for phonon-mediated magnetic polariton, have been utilized to verify the results. The fundamental understanding of graphene-associated background tuning gained herein will facilitate the design of thermally tunable metamaterial and broaden the basic understanding to broadband spectral tailoring.

1. Introduction

To control the heat flux is one of the most basic aspects in thermal management, and for radiation, metamaterial is usually employed to control thermal radiation. The advance of nanophotonics has provided various types of metamaterials in recent years. Moreau et al. proposed a novel metasurface with film-coupled colloidal nanoantennas [1]. Hossain et al. have fabricated a thermal emitter consisted of conical metamaterial pillars to generate near perfect absorption of unpolarized light [2]. Wang et al. have investigated the physics for frequency-tunable coherent thermal emission within periodic nanoscale structure [3]. Feng et al. have performed the analysis of multi-band emission metamaterial and discussed its application in radiative cooling [4]. Wang et al. have demonstrated the mechanism for phonon-mediated magnetic polaritons in the infrared region [5]. And most recently, it has been reported that metamaterial can maintain a temperature below that of the ambient air under direct sunlight [6].

Many metamaterials have a common shortcoming, whose spectral selectivity is a fixed value. The fixed radiative property can make their thermal controllability far from expect. Although electrochromic materials with tunable dielectric constant [7] have been researched in recent years, material incompatibility and the lack of spectral tunability are still inevitable drawbacks for this kind of material [8]. Thus a tunable selective metamaterial which can generally improve the designability of an active thermal control system is highly desired.

Graphene is a flat monolayer of carbon atoms tightly packed in a two-dimensional honeycomb lattice and exhibits remarkable electronic, thermal and mechanical properties that suggest its use in a variety of applications ranging from electronics to optics [9]. Especially, the optical properties of graphene can be tuned by varying its external voltage [10], and it has been employed in light communication and other utilizations like optical modulator [11], Fabry-Perot cavity [12], nanowire [13], and nanodisk [14]. Like most of the metamaterial, the resonant modes have been distinguished as the origin of optical tunability, but to control the thermal radiation, broadband background spectrum can be a more important one than narrow band resonances. In this paper, a graphene-based thermal radiation control method has been investigated, wherein the background spectrum tuning has been the dominating factor. Narrow band resonances, as surface plasmon polariton (SPP) and phonon-mediated magnetic polariton (MP), have been excited and verified but the investigations show that they are not the dominating factors for radiation control.

This paper is organized as follows: first, we numerically study the radiative properties and tuning heat exchange in the graphene-based metamaterial using rigorous coupled-wave analysis (RCWA). Tuning background, associated with resonant SPP and MP have been distinguished. Radiative properties contours have shown that background spectrum tuning has been the dominating factor to the radiative flux tuning. Analytical methods, SPP dispersion relationship and MP inductor-capacitor model have been utilized to verify the accuracy of numerical method. Second, physics

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for non-tuning origin of resonant modes have been investigated. Finally, the tuning background, which can be seen as the degeneration of the Fabry-Perot resonance, have been understood via the behavior of surface plasmons (SPs) within it.

2. Numerical method

The structure is illustrated in Fig. 1(a), a single sheet of graphene is laid atop the Ag gratings with a SiO_2 layer. In nanofabrication this layer can be several millimeters thick [15] and the penetration depth of light in infrared region, as current paper mainly discussed, can be only several micrometers [16], so it has been treated as semi-infinite as general. In visible region, penetration depth might not be that small, so a substrate has been included into ensure opaqueness. In the numerical calculation we assume that if light cannot been totally absorbed by the SiO_2 layer in visible region, it will general propagate into this substrate with little reflection, which is quite common for dielectric-dielectric interface [16]. The geometric parameters are defined as follows: the grating thickness is h, the grating period and groove width are P and b, respectively.

In the RCWA utilized for calculation, monochromatic reflected wave can be written as $E_R = \sum R_{\lambda i} \exp[-i(k_{x,i}x - k_{z,i}z)]$ for transverse electric (TE) wave and $H_R = \sum R_{\lambda i} \exp[-i(k_{x,i}x - k_{z,i}z)]$ for transverse magnetic (TM) wave, with the total diffraction efficiencies $R_\lambda = \sum R_{\lambda i} R_{\lambda i}^{*} \mathrm{Re}(k_{z,i}/k_{z0})$. Wherein $R_{\lambda i}$ is the reflection factor to certain order of diffracted wave, $k_{x,i} = 2\pi i/P$ and $k_{z,i}$ are the wavevectors for the diffracted wave in x and z axis, k_{z0} is the incident wavevector along z axis [16]. In this study, the incident wavevector is set as normal to the structure, and one can obtain hemispherical reflectivity for normal incident monochromatic wave from R_λ. Then using Kirchhoff's law, one can obtain the normal spectral emissivity ε_λ or the absorptivity α_λ by $\varepsilon_{\lambda,\mathrm{TE}}$ ($\varepsilon_{\lambda,\mathrm{TM}}$) = $\alpha_{\lambda,\mathrm{TE}}$ ($\alpha_{\lambda,\mathrm{TM}}$) = $1 - R_{\lambda,\mathrm{TE}}$ ($R_{\lambda,\mathrm{TM}}$) for transverse electric (TE) or transverse magnetic (TM) polarized waves. $E_{b,\lambda}$ (λ, T) is the spectral emissive power of blackbody defined as [16]:

$$E_{\mathrm{b},\lambda}(\lambda, \mathrm{T}) = \frac{2\pi hc^2}{\lambda^5 (e^{hc/k_B \lambda T} - 1)} \tag{1}$$

In the calculation, the sun is assumed as a blackbody with temperature T_{sun} = 5900 K to obtain the spectral distribution. The total incoming solar flux is set as 1000 W/m^2, which stands for the standard AM1.5 solar irradiation. The temperature of metamaterial T_{meta} is set as 297 K, and the temperature of surrounding atmosphere T_{atm} is set as 300 K. For atmospheric radiation, the equivalent blackbody temperature T_{atmrad} has been chosen as 235 K, which was predicted by J.B. Calvert [17]. The radiant heat flux can be defined as:

$$J = J_{\mathrm{meta}} - J_{\mathrm{sun}} - J_{\mathrm{atmrad}} + J_{\mathrm{nonrad}} \tag{2}$$

The net outgoing flux is considered as unidimensional and the positive value of J means the cooling of metamaterial. Wherein $J_{\mathrm{sun}} = \int \alpha_\lambda E_{\mathrm{sun},\lambda} \, d\lambda$ indicates the incident solar power absorbed by the metamaterial, $J_{\mathrm{meta}} = \int \alpha_\lambda E_{\mathrm{meta},\lambda} \, d\lambda$ is the power flow radiated by the structure, and $J_{\mathrm{atmrad}} = \int \alpha_\lambda E_{\mathrm{atmrad},\lambda} \, d\lambda$ is the absorbed power

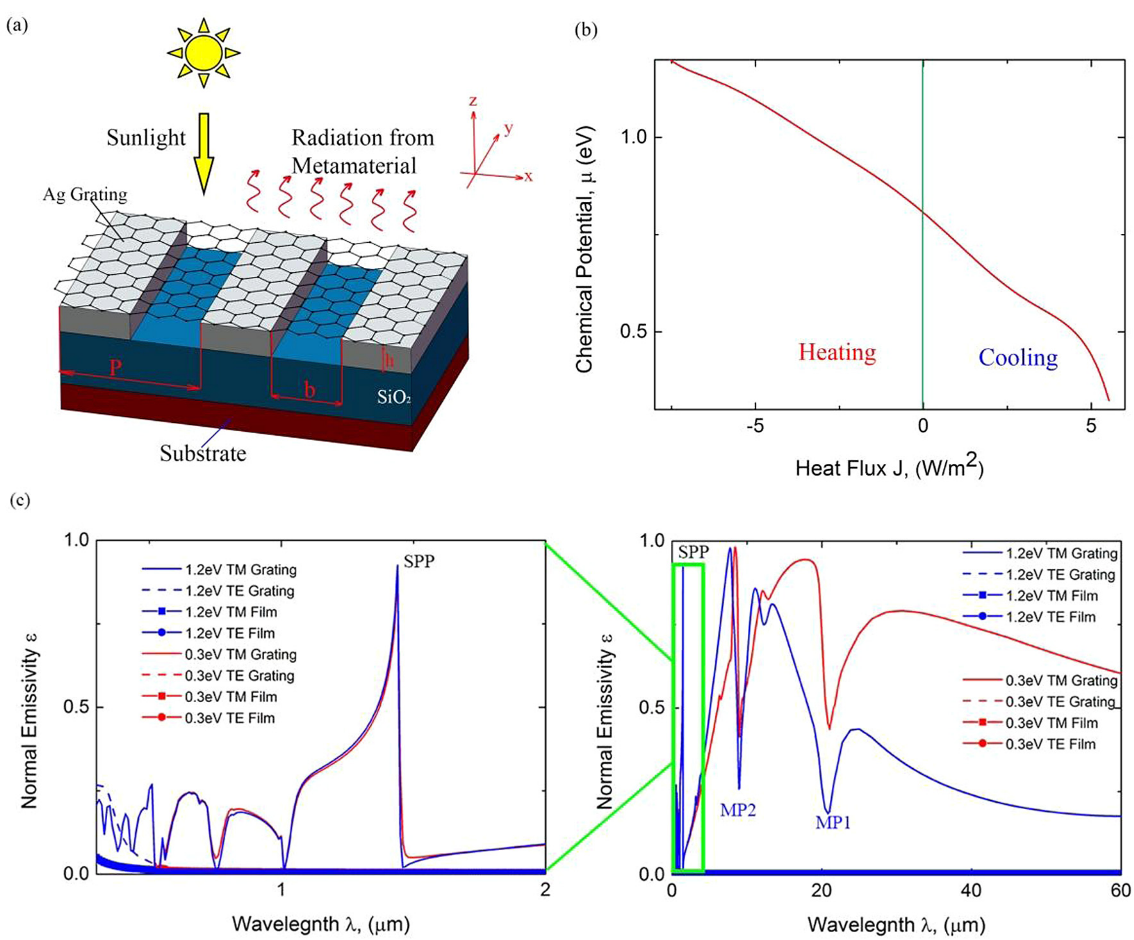

Fig. 1. (a) Schematic of the graphene-based tunable thermal metamaterial. (b) Heat flux of metamaterial as a function of chemical potential. (c) Spectral emissivity for TE and TM wave, the magnified plot of short wavelength region is also provided.