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Consideration of enhancement of thermal rectification using metamaterial models

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A B S T R A C T

We present a systematic study to highlight some of the fundamental physics that governs metamaterial based electromagnetic thermal rectifiers. In such thermal rectifiers, the rectification arises from the alignment or misalignment of surface resonances in the forward or reverse scenarios, whereas the bulk states of metamaterials do not contribute to rectification. Therefore, we show that one can understand the behavior of such rectifiers by examining the relative excitation strength of the surface and bulk resonances. We verify such an understanding by accounting for the dependence of the contrast ratio on various parameters that define the dielectric response of the metamaterials.

1. Introduction

Manipulating heat flow at nanoscale has generated substantial interests for thermal management of electronic and optical devices and energy systems [1]. A key technique for manipulating nanoscale heat transfer is through the use of near-field electromagnetic heat transfer. Electromagnetic heat transfer in the near-field regime exceeds the far-field blackbody limit due to coupling between thermally excited surface resonances [2,3]. Significant theoretical [4–13] and experimental [14–19] progresses have been made in the past decade in this research area, and potential applications are now emerging [20–26].

These recent progresses have pointed to the importance of the capability for designing and controlling the properties of near-field thermal transfer. Thus, while earlier studies of near-field thermal transfer typically assumed the use of naturally existing materials, there are now interests in exploring the use of metamaterials for additional flexibility in designing the properties of near-field thermal transfer [27–32]. Similarly, while earlier studies focused on near-field thermal transfer primarily as a passive process, there are now significant efforts in developing active control of near-field thermal transfer. In particular, thermal rectification schemes in electromagnetic heat transfer have been extensively studied [33–40] since its initial proposal five years ago [33].

In Ref. [33], the rectification arises from the alignment or misalignment of surface resonances in the forward or backward temperature biased scenarios, respectively. The concept in Ref. [33] has been implemented numerically assuming a variety of naturally occuring materials, including various polytypes of SiC [33,34], SiO_2 [35], heavily doped silicon [36], and phase-changed materials [37–39]. The performances of the rectifiers in each of these cases are dictated by the resonant properties of these materials. On the other hand, with the development of metamaterials, one should be able to, at least in principle, control the resonant properties. Therefore, it is important to understand how various resonant properties, in general, influence the performance of a thermal rectifier.

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In this paper, we present a systematic study to highlight some of the fundamental physics that governs metamaterial-based electromagnetic thermal rectifiers, where two metamaterial planar bodies are brought in close proximity. Thermal transfer is determined by the permittivity and the permeability of the materials. The use of metamaterials enables one to achieve permittivity and/or permeability in a range of positive, zero, or negative values. In this paper, we consider a material described by the Drude model; such a model can be achieved either with metamaterials [41,42] or with heavily doped semiconductors [4,5]. We show that one can understand the behavior of such rectifiers by examining the relative excitation strength of the surface and bulk resonances.

This paper is organized as follows. In Section 2, a model system of electromagnetic thermal rectifier is presented. In Section 3, we introduce an analytic theory for maximizing thermal rectification. In Section 4, we present numerical results and illustrate how the thermal rectification phenomenon is controlled by various parameters that define the dielectric response of the metamaterials, by accounting for the dependence of the contrast ratio of the surface state to the bulk state excitations on these parameters. The paper is then concluded in Section 5.

2. Model system

We consider a metamaterial with its permittivity described by a Drude model:

$$\varepsilon_d(\omega) = \varepsilon_\infty - \frac{{\omega_p}^2}{\omega(\omega + ig_m)}, \tag{1}$$

ε_∞, ω_p, g_m, and ω are the permittivity at infinite frequency, the plasma frequency, the damping constant, and the frequency, respectively. We assume an $\exp(-i\omega t)$ convention throughout the paper. With metamaterial design, one should be able to control both ε_∞ and ω_p in Eq. (1) [42]. Therefore, the goal of our study is to elucidate how the material parameters in Eq. (1) influence the behavior of a thermal rectifier.

We will see that such an influence can be understood in terms of the dependency of various resonant properties on the material parameters. Thus we first briefly review the relevant resonances. In the lossless case, with $g_m = 0$, the material supports a bulk plasmon resonance occuring at $\varepsilon_d(\omega_{bp}) = 0$ with $\omega_{bp} = \omega_p/\sqrt{\varepsilon_\infty}$. In addition, an interface between such metamaterial and vacuum supports a surface plasmon resonance occuring at $\varepsilon_d(\omega_{sp}) = -1$ with $\omega_{sp} = \omega_p/\sqrt{\varepsilon_\infty + 1}$.

Using such a metamaterial model we consider an electromagnetic thermal rectification system, as shown in Fig. 1(a). It consists of two semi-infinite metamaterial plates separated by a vacuum gap. The vacuum gap, the bottom and the top plates are labeled as 0, 1, and 2, respectively. The two metamaterial plates are maintained at different temperatures T_H and T_L ($T_H > T_L$). Since $T_H \neq T_L$, the system is in a nonequilibrium condition. We assume that both plates are described by the Drude model of Eq. (1). To achieve thermal rectification, the dielectric properties of the metamaterial must be temperature dependent [33–40]. In the forward biased scenario (left panel, Fig. 1a), with plate 1 at temperature T_H and plate 2 at T_L, we assume that both metamaterial plates have the same permittivity $\varepsilon_d(\omega)$, hence the surface resonances at the two material-vacuum interfaces have the same frequencies, whereas in the reverse biased scenario where we reverse the temperature bias (right panel, Fig. 1a), we assume that the two metamaterials have their dielectric functions described by

$$\varepsilon_{d,\pm\Delta\omega_p}(\omega) = \varepsilon_\infty - \frac{(\omega_p \pm \Delta\omega_p)^2}{\omega(\omega + ig_m)}. \tag{2}$$

In the reverse biased case the surface resonances at the two interfaces differ by a frequency $2\Delta\omega_{sp} = 2\Delta\omega_p/\sqrt{\varepsilon_\infty + 1}$.

The heat transfer between the plates is calculated using the framework of the fluctuational electrodynamics. The electric and magnetic fields are calculated by integrating contributions from the thermal current sources whose strengths are provided by the fluctuation dissipation theorem, and by using the dyadic Green's functions of the system. Then the ensemble average of Poynting vector, represented as a cross correlation function of the electric and magnetic fields, is determined [2]. The cylindrical coordinate system (R, ϕ, z) is used in the computation. Using the formalism described above, the net heat flux ϕ_F for the forward scenario is given by [4]

$$\phi_F = \int_0^{+\infty} d\omega[\Theta(\omega, T_H) - \Theta(\omega, T_L)] \times \int_0^{+\infty} Z(\omega, \beta, \varepsilon_1 = \varepsilon_d(\omega), \varepsilon_2 = \varepsilon_d(\omega))\beta d\beta, \tag{3a}$$

where the exchange function

$$\int_0^{+\infty} Z(\omega, \beta, \varepsilon_1, \varepsilon_2)\beta d\beta = \sum_{j=s,p}\left[\int_0^{k_0} \frac{(1-|r_{01,j}|^2)(1-|r_{02,j}|^2)}{4\pi^2|1 - r_{01,j}r_{02,j}e^{2i\gamma_0 d}|^2}\beta d\beta + \int_{k_0}^{+\infty} \frac{Im(r_{01,j})Im(r_{02,j})e^{-2Im(\gamma_0)d}}{\pi^2|1 - r_{01,j}r_{02,j}e^{-2Im(\gamma_0)d}|^2}\beta d\beta\right], \tag{3b}$$

$\Theta(\omega, T) = \hbar\omega/(e^{\hbar\omega/(k_B T)} - 1)$ is the mean thermal energy of a single optical mode at a frequency ω. $\hbar$ and k_B are the reduced Planck constant and the Boltzmann constant, respectively. $r_{uv,j}$ is the Fresnel reflection coefficient from media u to v and the subscripts $j = s, p$ represent the two polarizations. γ_0 is the z-component of the free space wavevector $\boldsymbol{k_0}$ ($k_0 = |\boldsymbol{k_0}|$) and has the form $\gamma_0 = \sqrt{{k_0}^2 - \beta^2}$, ($\beta < k_0$) for propagating waves and $\gamma_0 = i\sqrt{\beta^2 - {k_0}^2}$ ($k_0 < \beta$) for evanescent waves. β is the radial-component of $\boldsymbol{k_0}$. Eq. (3b) includes the contributions of both propagating and evanescent waves. Similar to the forward scenario, the net heat flux ϕ_R for the reverse scenario is calculated with the exchange function $Z(\omega, \beta, \varepsilon_1 = \varepsilon_{d,+\Delta\omega_p}(\omega),\ \varepsilon_2 = \varepsilon_{d,-\Delta\omega_p}(\omega))$.

3. Theoretical consideration for maximizing the contrast ratio in thermal rectifier

As a typical example of a thermal rectifier, we consider the system shown in Fig. 1, with a parameter set described