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Near-field thermal emission from metamaterials☆

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Abstract

A closed form expression for the local density of electromagnetic states (LDOS) due to a thermally emitting metamaterial bulk is derived from Maxwell's equations combined with fluctuational electrodynamics. The final form is the same as that for nonmagnetic materials, where the influence of the magnetic permeability is embedded in the Fresnel reflection coefficients. Spectral distributions of LDOS near metallic- and dielectric-based metamaterials are investigated. Results reveal that LDOS profiles are dominated by surface polaritons (SPs) in both TE and TM polarization states. A detailed discussion is provided on the necessary conditions for exciting TM- and TE-polarized SPs via a dispersion relation analysis that accounts for losses. Beyond the conventional conditions for excitation of SPs, the lossy dispersion relation analysis demonstrates mathematically that SPs exist when the imaginary parts of the permittivity or permeability, as well as $n'n''$, are close to zero, where n' and n'' are the real and imaginary parts of the refractive index, respectively. An asymptotic expression for the extreme near field LDOS is derived, showing a Δ^{-3} power law relationship, as for nonmagnetic media, between LDOS and distance from the emitting bulk Δ. Results obtained from this study will assist in assessing material properties of arbitrarily electromagnetic materials in applications related to energy harvesting.

Keywords: Near-field radiation; Thermal emission; Mie resonance; Local density of electromagnetic states; Dispersion relation

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1. Introduction

Near-field radiative heat transfer is distinguished from the classical far-field regime when the exchanging bodies are separated by distances on the order of, or smaller than, the dominant emitting wavelength [1,2]. In the near-field regime, tunneling of evanescent modes can result in energy exchange exceeding Planck's blackbody distribution by orders of magnitude. These evanescent modes include evanescent waves generated by total internal reflection (TIR) and surface polaritons (SPs). Enhanced energy transfer at subwavelength distances may benefit numerous technological fields such as thermal rectification [3–5], thermal switches [6], imaging [7], and thermophotovoltaic (TPV) power generation [8–12], among others.

Tuning the electromagnetic response of materials is now a possibility due to the emerging field of metamaterials. Electromagnetic metamaterials consist of subwavelength unit structures referred to as meta-atoms. Exotic properties such as negative electric permittivity, magnetic permeability, and/or refractive index are achievable by manipulating these meta-atoms [13–17]. It is also possible with metamaterials to design magnetic media from nonmagnetic constituents and to tune near-field thermal radiative properties. However, the majority of the effort in this area has been toward the design of selective thermal emission and absorption in the far field [18–22].

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To date, only five papers have been published regarding near-field thermal emission from metamaterials consisting of three-dimensional meta-atoms. Joulain et al. [23] were the first to study the near-field heat flux spectra between two identical metamaterials made up of an array of split-ring resonators (SRRs) and wires. Zheng and Xuan [24] calculated heat transfer between two bulks of a similar SRR-wire metamaterial, establishing a general procedure for analyzing near-field energy transfer in one-dimensional layered media of arbitrary permittivity and permeability. They expanded their effort by analyzing energy transfer between yet another SRR-wire metamaterial and other media, i.e., doped silica and aluminum [25]. Basu and Francoeur [26] calculated the penetration depth of SP mediated near-field thermal radiation when exchanged between two bulks of SRR-wire metamaterial. They observed that it was possible to achieve different penetration depths for magnetic and electric resonances depending on the material properties. Francoeur et al. [27] performed heat flux calculations between two identical metamaterials made up of silicon carbide (SiC) spheres in a potassium bromide (KBr) host medium. They concluded that near-field thermal spectra can be controlled by varying the metamaterial adjustable parameters such as the SiC sphere diameter. All four groups identified an additional channel through which significant energy exchange can occur with electromagnetic metamaterials: TE-polarized SPs. This phenomenon occurs only when the materials involved are effectively magnetic. Note that in all these aforementioned studies, the effective medium theory (EMT) was employed for predicting the effective electric permittivity and magnetic permeability of metamaterials.

Smith and Schurig [28] introduced the idea of indefinite media with hyperbolic dispersion, or hyperbolic metamaterials, and identified one-dimensional layered media (i.e., one-dimensional meta-atoms) as an avenue for generating such a metamaterial. Recently, the application of hyperbolic metamaterials to near-field thermal emission has attracted considerable interest [29–35]. Biehs et al. [30] showed that hyperbolic metamaterials can be considered the near-field analog of a blackbody, since the near-field enhancement from such structures is broadband. Tschikin et al. [35] questioned the validity of the EMT for hyperbolic metamaterials made of thin films and observed that the EMT did not provide accurate results in the near field when SPs are present. Similar results were shown by Guo et al. [32] in their study on hyperbolic metamaterials. This conclusion was drawn by comparing EMT results against direct near-field thermal emission predictions based on an S-matrix approach [36–45].

This paper focuses on near-field thermal emission by metamaterials comprised of three-dimensional subwavelength inclusions. While hyperbolic metamaterials made of thin films are easier to fabricate than the structures considered here, the broadband enhancement of the near-field thermal spectrum is not suitable for applications such as nanoscale-gap TPV (nano-TPV) power generators [12]. Three-dimensional meta-atomic structures, such as those discussed in Refs. [23–27], are preferable in order to achieve quasi-monochromatic near-field thermal emission, which is needed for viable and highly efficient nano-TPV power generation [10,12]. Direct calculation of near-field thermal emission by metamaterials consisting of three-dimensional meta-atoms, i.e., particulate media, is currently intractable. As such, near-field thermal emission is predicted in this paper using the local density of electromagnetic states (LDOS) with electric permittivity and magnetic permeability calculated from the EMT. The results thus obtained will provide general trends and significant insights into the near-field thermal spectra emitted by metamaterials. Additionally, these predictions will be crucial in assessing the validity of the EMT when direct calculation of near-field thermal emission by particulate media will be possible.

The LDOS has been used to quantify the near-field radiative characteristics of thermal systems in various configurations. It has been calculated due to free emission near a bulk [46], near a film [36], between two identical bulks [47], between two identical films [41,48], and near layered media [38,49], all of which involve nonmagnetic materials. In this work, a general thermal emission LDOS expression is derived near a bulk material of arbitrary electric permittivity and magnetic permeability. The purpose of this paper is to outline the derivation of the LDOS equation and to explore the physics of TM- and TE-polarized near-field thermal emission by metamaterials via a dispersion relation analysis that accounts for losses. Such a study will provide general trends for the evaluation of candidate materials for use in near-field energy exchange applications, such as nano-TPV power generators.

In Section 2, the equation for LDOS due to thermal emission is rigorously derived from first principles. Section 3 discusses near-field emission for two different metamaterial configurations and includes an exploration of the LDOS results with an accompanying lossy SP dispersion relation analysis. Finally, conclusions are provided in Section 4. Further details regarding the derivation of the LDOS expression are provided in Appendix.