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Optimization of a near-field thermophotovoltaic system operating at low temperature and large vacuum gap

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ABSTRACT

The present work successfully achieves a strong enhancement in performance of a near-field thermophotovoltaic (TPV) system operating at low temperature and large-vacuum-gap width by introducing a hyperbolic-metamaterial (HMM) emitter, multilayered graphene, and an Au-backside reflector. Design variables for the HMM emitter and the multilayered-graphene-covered TPV cell are optimized for maximizing the power output of the near-field TPV system with the genetic algorithm. The near-field TPV system with the optimized configuration results in 24.2 times of enhancement in power output compared with that of the system with a bulk emitter and a bare TPV cell. Through the analysis of the radiative heat transfer together with surface-plasmon-polariton (SPP) dispersion curves, it is found that coupling of SPPs generated from both the HMM emitter and the multilayered-graphene-covered TPV cell plays a key role in a substantial increase in the heat transfer even at a 200-nm vacuum gap. Further, the backside reflector at the bottom of the TPV cell significantly increases not only the conversion efficiency, but also the power output by generating additional polariton modes which can be readily coupled with the existing SPPs of the HMM emitter and the multilayered-graphene-covered TPV cell.

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1. Introduction

Near-field thermophotovoltaic (TPV) system is a promising technique for a power generation, in which an emitter is placed at a sub-micron distance from a TPV cell to significantly increase the radiative heat transfer in the near-field regime [1–23]. The TPV cell is an infrared-sensitive photovoltaic cell, which can directly convert absorbed infrared radiation into electricity and has potential to outperform other solid-state electricity-generation techniques, such as thermoelectric and thermionic converters [1,2]. In addition, the fact that a TPV system has no moving parts and is independent of pressure and gravitational force makes it attractive for space, industrial, residential and microelectronic applications [2,3].

In a TPV system, an emitter is first heated by an external thermal source and then re-emits the thermal energy in the form of infrared radiation. Because there is no restriction on material selection of the emitter, there has been a myriad of studies which show various kinds of near-field interaction between the emitter and the TPV cells [8–23], resulting in enhanced performance of the near-field TPV system. For example, a monolayer of graphene [8], metallo-dielectric multilayer structures [15,17], gratings [18,19], a nanowire array [13], a thin film [11] and a fictitious Drude emitter [14] have been employed as an emitter to increase the power output or the conversion efficiency of the TPV system by tuning the spectral emission. These nanostructures also can be applied on the top of the TPV cell: a monolayer of graphene [9,12], multilayered graphene [20], a nanowire array [21], and a thin film [23]. Further, on the backside of the TPV cell, a reflector, which can also be used as an electrode, is placed to reflect back the unabsorbed photons to the emitter, yielding an increment in the conversion efficiency [10,17]. Recently, several works introduced a thin TPV cell and a backside reflector such that thin-film waveguide mode as well as surface mode supported by the thin TPV cell can significantly enhance the performance of the TPV system [11,16,22,23].

Despite above plentiful theoretical works, experimental validation of the near-field TPV system is rather limited [24]. One of the main challenges in this demonstration is maintaining a nanogap between planar surfaces with a large area. Although two groups have reported drastically enhanced near-field radiation between two planar surfaces separated by 50 nm [25,26], heat transfer area in those works is considerably small. For the near-field TPV application, other groups demonstrated the near-field enhancement of the radiative heat transfer between two planar surfaces with a large area separated by 150–200 nm [27,28]. They increased the total radiative heat transfer rate by increasing the heat transfer area at the expense of a small vacuum gap between surfaces. Further, almost all of the experimental works maintained the temperature

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