Metamaterial-enhanced Near-field Thermophotovoltaic Conversion by Excitation of Magnetic Polariton

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Abstract: We study a near-field thermophotovoltaic system made of an InGaSb cell and a tungsten grating metamaterial emitter, in which magnetic polariton is excited to spectrally enhance near-field radiative transfer. Fluctuational electrodynamics incorporated with scattering matrix method and rigorous coupled-wave analysis is used to exactly calculate the spectral heat flux. The preliminary results show improved conversion efficiency and almost doubled total electrical power output over that with plain tungsten emitters at a vacuum gap distance of 100 nm.

Near-field thermophotovoltaic (TPV) systems have attracted lots of interests due to the possible higher power generation from near-field heat transfer enhancement over the far-field thermal radiation. Park et al. [1] theoretically studied the performance of a near-field TPV system with plain tungsten emitters from coupled radiative and charge transports. Recently, graphene was proposed to cover TPV cells and enhance near-field radiative transfer from a boron nitride emitter due to coupled surface waves across the vacuum gaps [2]. Moreover, tungsten nanowire emitter supporting hyperbolic modes has also been studied to enhance the performance of near-field TPV [3]. On the other hand, magnetic polaritons (MP) have shown great promise in designing selective metamaterials as efficient far-field TPV emitters [4, 5]. However, the effect of MP or magnetic resonance on the performance of near-field TPV systems has not been investigated or understood.

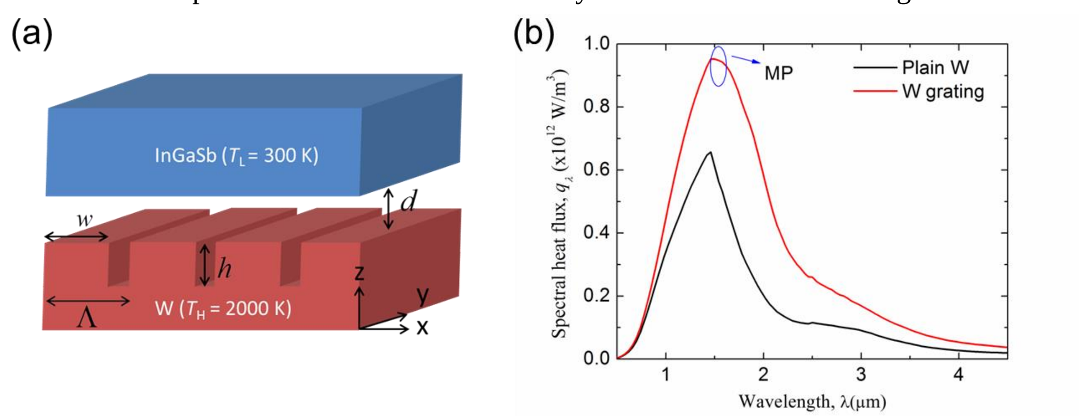

Figure 1. (a) Schematic of the near-field TPV system with an InGaSb cell and a tungsten grating emitter. (b) The spectral heat flux between the TPV cell and plain tungsten (W) or tungsten grating emitter at a gap of 100 nm.

Very recently, with the fluctuational electrodynamics incorporated with scattering matrix method and rigorous coupled-wave analysis [6], we theoretically demonstrated the effect of MP on spectrally enhancing near-field radiative transfer between two SiC gratings separated by subwavelength vacuum gaps [7]. In this work, we will employ the same exact method to analyze the conversion performance from a near-field TPV system made of an InGaSb cell and a tungsten grating metamaterial emitter as depicted in Fig. 1(a). The tungsten grating metamaterial is considered with period Λ = 400 nm, width w = 320 nm, and height h = 200 nm, for which MP can be excited at selected wavelengths above cell bandgap (i.e., 2.22 μm) as shown from the far-field radiative property study [5]. The emitter and TPV cell temperatures are set as T_H = 2000 K and T_L = 300 K, respectively.

Figure 1(b) presents the spectral heat fluxes between the TPV cell and the tungsten grating or plain tungsten emitter at a vacuum gap distance of 100 nm from the exact calculation. By comparison, the spectral heat flux is much enhanced with the grating emitter around the wavelength λ = 1.55 μm, at which the MP can be excited [5]. With the assumption of 100% quantum efficiency (i.e., the ideal case) for the TPV cell, the total electrical power output is estimated to be doubled from 0.2 MW/m^2 to 0.4 MW/m^2, and the conversion efficiency is improved from 28.87% to 31.11%, when tungsten grating emitter is used instead of plain tungsten. For a more practical consideration, if cell quantum efficiency is taken from the data in response to far-field thermal radiation, the total electrical power output can be improved from 0.14 MW/m^2 to 0.27 MW/m^2, while conversion efficiency is enhanced from 20.31% to 21.15%. Note that the current theoretical model does not allow to consider the coupled radiative and charge transports with nanostructured grating metamaterials. Therefore, the exact quantum efficiency in response to the metamaterial enhanced near-field radiation cannot be exactly obtained.

To further understand and elucidate the effect of MP on the near-field TPV performance, the contour plot of transmission coefficient between tungsten grating emitter and TPV cell will be studied. Electromagnetic field simulated with finite-different time-domain method will be presented to confirm the excitation of MP in the near-field regime. In addition, an inductor-capacitor circuit model will be used to analytically predict the MP resonance frequency. Effects of geometric parameters and vacuum gap distances on the near-field TPV system performance will also be investigated. This work will pave a new way to improve the energy conversion system in near field with MP-based metamaterials.

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