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Performance analysis of near-field thermophotovoltaic system with 2D grating tungsten radiator

Naphatsorn Vongsoasup [a,*], Mathieu Francoeur [b], Katsunori Hanamura [a]

[a] Department of Mechanical and Control Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8550, Japan
[b] Radiative Energy Transfer Lab, Department of Mechanical Engineering, University of Utah, Salt Lake City, UT 84112, USA

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ABSTRACT

The effect of hyperbolic modes on near-field thermophotovoltaic (TPV) system performance is investigated by implementing a hyperbolic metamaterial (HMM) radiator. Specifically, the near-field TPV system consists of a 2D grating tungsten radiator and a gallium antimonide (GaSb) cell separated by a gap thickness varying between 100 nm and 500 nm. The temperatures of the radiator and the TPV cell are fixed at 2000 K and 300 K, respectively. The effective medium theory (EMT) is proposed to solve the near-field radiative heat transfer problem with a uniaxial anisotropic radiator. Near-field TPV performance is evaluated via maximum power output and conversion efficiency. Enhanced radiative heat transfer is observed within the spectral band where hyperbolic modes are supported by the radiator. As a result, the radiative heat flux absorbed by the cell is enhanced from broadband tunneling of evanescent waves. Furthermore, near-field TPV maximum power output and conversion efficiency are improved. The highest maximum power output and conversion efficiency are 4.28×10^5 W m^{-2} and 35%, respectively. When the gap thickness is smaller than 300 nm, the effect of hyperbolic modes is strong, and radiative losses affect the conversion efficiency as radiative flux is enhanced both below and above the cell bandgap. For gap thicknesses larger than 300 nm, the effect of hyperbolic modes is weak and the conversion efficiency is mostly affected by the spatial distribution of radiative flux absorbed in the cell. In this study, radiative heat flux enhancement and the improvement of near-field TPV performance are attributed to hyperbolic modes supported by the radiator. These findings will further contribute to the design of near-field TPV experimental systems outperforming their far-field counterparts.

1. Introduction

A thermophotovotaic (TPV) system converts thermal energy into electricity. TPV systems mainly consist of a radiator and a low bandgap photovoltaic (PV) cell. The radiator is heated by an external thermal energy source and emits radiation towards the cell. The PV cell absorbs radiation and generates electricity from electron-hole pair (EHP) generation. There are many alternatives for thermal energy sources making TPV systems versatile and attractive, especially in waste heat recovery applications. The typical power output of a TPV system is 10^4 W m^{-2} with 20–30% in internal conversion efficiency [1]. The major disadvantages of TPV systems are low conversion efficiency and power output. To potentially improve TPV performance, systems capitalizing on the near-field effects of radiation where heat transfer can exceed Planck's blackbody limit have been proposed. Near-field TPV systems have been investigated by many researchers both numerically [2–8] and experimentally [9,10]. To capitalize on the near-field effects of radiation, the vacuum gap separating the radiator and the cell must be smaller than the thermal wavelength. Significant enhancement of radiative transfer in the near field occurs when the size of the vacuum gap is on the order of a few tens to a few hundreds of nanometers. In particular, surface modes and hyperbolic modes in near-field radiation can potentially improve the performance of TPV systems. Surface modes can provide quasi-monochromatic radiation while hyperbolic modes support broadband frustrated modes. Both surface modes [4,11–16] and hyperbolic modes [17,18] have been reported to improve near-field TPV performance. Yet, surface mode mediated near-field TPV power generation suffers from a few shortcomings. Indeed, strong enhancement of heat exchange requires materials with close resonant frequencies. Furthermore, recombination of EHPs at the cell surface is a limiting factor of surface modes. It was shown that in a near-field TPV system made of a gallium antimonide (GaSb) cell, surface modes only outperform frustrated

* Corresponding author.
E-mail address: vongsoasup.n.aa@m.titech.ac.jp (N. Vongsoasup).

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modes (tungsten radiator) when the gap thickness is very small, i.e., 10 nm, due to the low penetration depth associated with these surface modes [8]. Hence, it is suggested that frustrated modes are preferable for near-field TPV systems [8,19].

In this work, the impact of hyperbolic modes on near-field TPV performance is investigated by using a two-dimensional (2D) grating radiator supporting hyperbolic modes. Hyperbolic metamaterials (HMMs) are anisotropic structures that exhibit hyperbolic dispersion relations because their dielectric functions have different signs [20–22]. Unlike isotropic materials that have elliptic dispersion relations, there is no boundary for frustrated modes within HMM spectral bands. The impact of hyperbolic modes on near-field radiative heat transfer has been investigated in several structures, for example, nanowires [17,19–21,23–25], carbon nanotubes [26], multilayers [18,19,21,24,27–30] and gratings [24,31].

Due to the advances in nanofabrication technology, manufacturing near-field TPV systems is becoming feasible. Yet, a necessary step before manufacturing near-field TPV systems outperforming their far-field counterpart is to implement an appropriate model to evaluate performance in realistic conditions. The objective of this work is to provide the aforementioned evaluation when hyperbolic modes are supported by a HMM radiator, i.e., a 2D grating radiator. In addition, the hyperbolic mode mechanisms leading to near-field TPV performance enhancement are elucidated and quantified. For that purpose, a model that includes radiative and electrical losses in a near-field TPV system is implemented and a 2D grating of tungsten supporting hyperbolic modes is considered as the radiator. The rest of the paper is organized as follows. In the next section, the problem under consideration is presented along with the model for predicting near-field TPV performance. Afterwards, near-field TPV performance calculations are presented in terms of radiative heat flux, power output and conversion efficiency. The energy density above the 2D grating emitter and the spatial distribution of radiative heat flux absorbed by the cell are discussed to interpret the results. Finally, concluding remarks are provided.

2. Methods

2.1. Description of the near-field TPV device

A schematic representation of the near-field TPV system analyzed in this study is shown in Fig. 1. It consists of a 2D grating radiator and a GaSb cell separated by a vacuum gap of thickness *d*. The radiator is modeled as a semi-infinite medium while the cell has a thickness t_{cell} of 10.4 μm. The temperature of the radiator is kept constant at 2000 K while the temperature of the TPV cell is maintained at 300 K via a thermal management system. The GaSb cell is modeled as a single p-n junction and has an absorption bandgap of 0.723 eV at 300 K. The doping levels of the p-doped and n-doped regions are 10^{19} and 10^{17} cm^{-3}, respectively.

Since the 2D grating radiator is inhomogeneous, the effective medium theory (EMT) is proposed to approximate the 2D grating radiator as an effectively homogeneous medium. The 2D grating radiator is made of tungsten and is assumed to be symmetric along the ρ-direction of a cylindrical coordinate system. Grann et al. [32] showed that 2D gratings exhibit uniaxial properties when the grating is symmetric and has an optical axis perpendicular to the grating vector. Hence, the 2D grating radiator in this study is treated as a uniaxial medium with its optical axis along the *z*-direction (see Fig. 1). The grating period is *P* and the square cross-section of the grating has a side length of *W*. Thus, the filling fraction of the 2D grating radiator is calculated as $f = (W/P)^2$. Note that a 2D grating of tungsten is chosen here due to its simplicity of fabrication. To manufacture a 2D grating, a pattern is created on a substrate using electron beam lithography (EBL) and the substrate is afterwards etched using reactive ion etching. Direct writing EBL does not require expensive projection optics and mask production. Hence, direct writing EBL is widely used and many commercial systems have been developed. When high throughput work is needed, projection printing EBL is a suitable choice since it can create relatively large-sized pattern through the mask [33]. A pillar array structure that is very close to the 2D grating analyzed here with a pitch as fine as 40 nm can be manufactured [34].As the EMT is an approximation, there are several conditions that should be satisfied in order to obtain accurate results. In far-field radiation, the EMT generally provides good results when the thermal wavelength λ_{th} is significantly larger than a unit cell size of nanostructures [30,35]. In near-field radiation, nonlocal effects due to surface modes [36–38] or large wavevector featured modes such as hyperbolic modes [39] can cause inaccuracy in the EMT. In this study, there exists hyperbolic modes. Hence, the conditions for using the EMT in the near field when hyperbolic modes occur are considered. According to Liu et al. [30], if $d/P \geqslant \max(1.85|\sqrt{-\varepsilon_{\parallel}/\varepsilon_{\perp}}|, 2.59)$ is satisfied, the EMT should provide fairly accurate results with a

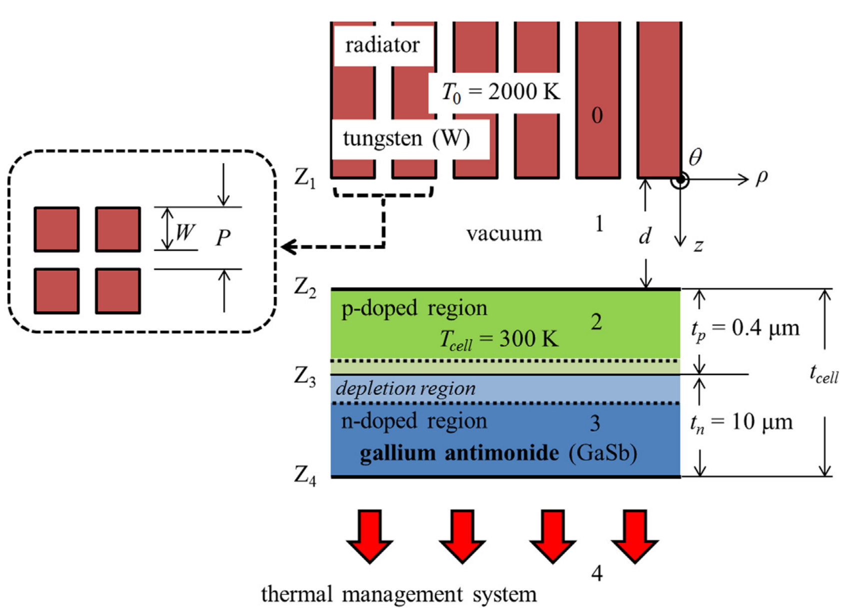

Fig. 1. Schematic representation of the near-field TPV power generator under study.