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Determination of thermal emission spectra maximizing thermophotovoltaic performance using a genetic algorithm

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ABSTRACT

Optimal radiator thermal emission spectra maximizing thermophotovoltaic (TPV) conversion efficiency and output power density are determined when thermal effects in the cell are considered. For this purpose, a framework is designed in which a TPV model that accounts for radiative, electrical and thermal losses is coupled with a genetic algorithm. The TPV device under study involves a spectrally selective radiator at a temperature of 2000 K, a gallium antimonide cell, and a cell thermal management system characterized by a fluid temperature and a heat transfer coefficient of 293 K and 600 Wm^{-2} K^{-1}. It is shown that a maximum conversion efficiency of 38.8% is achievable with an emission spectrum that has emissivity of unity between 0.719 eV and 0.763 eV and zero elsewhere. This optimal spectrum is less than half of the width of the spectra obtained when thermal losses in the cell are neglected. A maximum output power density of 41,708 Wm^{-2} is achievable with a radiator spectrum having emissivity values of unity between 0.684 eV and 1.082 eV and zero elsewhere when thermal losses are accounted for. These emission spectra are shown to greatly outperform blackbody and tungsten radiators, and could be obtained using artificial structures such as metamaterials or photonic crystals.

1. Introduction

Thermophotovoltaic (TPV) power generators are conceptually similar to solar photovoltaic (PV) cells in which thermal radiation is directly converted into electricity. Solar PV cells are irradiated by the sun while TPV power generators have a radiator component, in addition to the cell, that is heated by an external source [1,2]. The radiator and the cell are separated by a vacuum gap, and the external source of energy can potentially be anything that produces heat. Therefore, TPV power generation is a promising technology for the cogeneration of heat and electricity in residential appliances [3] and for recycling wasted heat in engines and industrial production processes [1] to name only a few. Overall TPV efficiencies (heat source to electricity) of 2.5% [4] and 4.7% [5] have been experimentally demonstrated when selectively emitting radiators are heated with a combustion process. TPV devices can also be used to harness solar energy in which the radiator is an intermediate layer between the sun and the cell. The intermediate layer absorbs solar radiation and reradiates this energy toward the cell. This allows for the radiation to be spectrally emitted in a way that better matches the absorption characteristics of the cell. It has been shown that the theoretical maximum overall efficiency (sun to electricity) for a solar TPV power generator that radiates monochromatically at a frequency corresponding to the absorption bandgap of the cell is 85.4% [6]. This efficiency assumes idealities that are likely not achievable in practice such as an infinite radiator to absorber area ratio and monochromatic emission from the radiator. Other work has been conducted on global optimization of TPV devices to improve overall efficiency for more realistic cases consisting of a finite radiator to absorber area ratio and broadband radiator emission [7–10]. The current experimental record for overall solar TPV efficiency is 3.2% [11]. Despite this important milestone, solar PV cells still largely outperform solar TPV power generators.

The low experimental overall efficiency is mostly due to low TPV conversion efficiency (radiator to electricity) [4,11,12]. In particular, Datas and Algora [12] pointed out that the low TPV conversion efficiency is largely caused by thermal losses leading to an overheating of the cell. Thermal losses are due to absorption of radiation by the free carriers and the lattice, non-radiative recombination of electron–hole pairs (EHPs) and thermalization of radiation with energy larger than the bandgap. Much effort has been dedicated to better understand the negative impacts of these thermal losses in PV (e.g., [13–16]) and TPV [17,18] devices. Thermal losses in PV and TPV cells cause the dark current to increase, due

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to an increase of the cell temperature, which opposes the generated photocurrent. By taking into account thermal losses in a TPV system capitalizing on the near-field effects of thermal radiation, it was shown in Ref. [18] that there is a high-energy cutoff in the radiator emission spectrum above which radiation has a net negative effect on TPV output power density. In addition to thermal losses, radiative and electrical losses in the cell also negatively affect TPV performance. Radiation absorbed by the cell with energy smaller than the bandgap that does not contribute to photocurrent generation is a radiative loss. Electrical losses are caused by EHPs recombining before reaching the depletion region, thus not contributing to photocurrent generation. Many papers have been devoted to the design of selectively emitting radiators in an effort to maximize TPV performance when accounting for only radiative losses (e.g., [19,20]), and radiative and electrical losses (e.g., [8,21–27]). An optimal radiator design, however, must also account for thermal losses in the cell due to their large impact on TPV performance. To the best of our knowledge, no attempt has been made to design radiator emission spectra maximizing TPV performance while taking into account all three loss mechanisms.

The objective of this work is to determine radiator emission spectra maximizing TPV conversion efficiency and output power density while accounting for radiative, electrical and thermal losses in the cell. This is achieved via a rigorous optimization framework in which a multi-physics model combining radiative, electrical and thermal transport [17] is coupled with the publicly available genetic algorithm (GA) PIKAIA [28]. The TPV power generator analyzed hereafter consists of a spectrally selective radiator, a cell made of gallium antimonide (GaSb) and a cell thermal management system. The TPV-GA framework is described in Section 2. In Section 3, radiator emission spectra maximizing TPV conversion efficiency and output power density are discussed, and TPV performances with the optimal spectra are compared against those obtained with blackbody and tungsten radiators. Concluding remarks are provided in Section 4.

2. Description of the thermophotovoltaic (TPV)-genetic algorithm (GA) model

When radiative, electrical and thermal losses are taken into account, determining the radiator emission spectrum maximizing TPV performance (conversion efficiency η or output power density P_m) is not a straightforward task, since these three loss mechanisms are strongly coupled with each other [18]. As such, it is very difficult, if not impossible, to derive a closed-form solution providing the optimal radiator emission spectrum. To find the emission spectrum maximizing TPV performance, a multi-physics model combining radiative, electrical and thermal transport in TPV devices [17] is coupled with a GA [28].

2.1. TPV model

The TPV power generator analyzed in this work, shown in Fig. 1, is modeled as a one-dimensional system for which only the variations along the z-direction are taken into account. The spectrally selective radiator, denoted as layer 0, is a semi-infinite medium maintained at a constant and uniform temperature T_{rad}. The cell consists of a GaSb p–n junction, where layers 2 and 3 are respectively the p-doped (thickness of 0.4 μm, doping concentration of 10^{19} cm^{-3}) and n-doped (thickness of 10 μm, doping concentration of 10^{17} cm^{-3}) regions. The absorption bandgap E_g of the GaSb cell at a temperature of 293 K is 0.723 eV (angular frequency ω_g of 1.10×10^{15} rad/s; wavelength λ_g of 1.71 μm) [17]. Note that GaSb is chosen as the cell material since its absorption bandgap in the near infrared matches the dominant wavelength emitted by typical TPV radiators ($T_{rad} \sim 1300$–2000 K) [29]. The radiator and the cell are separated by a vacuum gap of thickness d denoted as layer 1. Since all layers are assumed to be infinite along the ρ-direction, the view factor between the radiator and the cell is unity. In addition, the vacuum gap thickness d is assumed to be much larger than the dominant wavelength emitted, such that radiation heat transfer occurs exclusively via propagating modes [30]. Layer 4 is the cell thermal management system described by a fluid temperature T_∞ and a heat transfer coefficient h_∞.

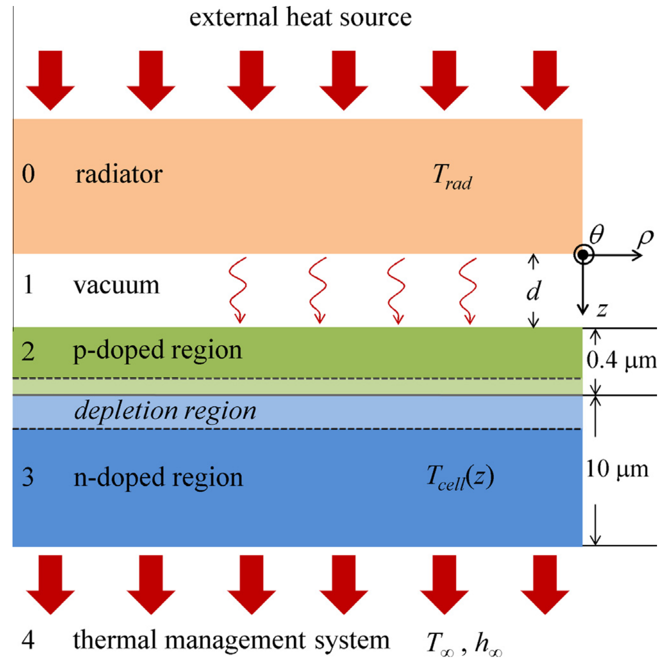

Fig. 1. Schematic representation of the TPV power generator under study: A spectrally selective radiator at temperature T_{rad} is separated from a GaSb cell by a vacuum gap of thickness d that is much larger than the dominant wavelength emitted.

TPV simulations are performed by discretizing the cell into N control volumes of thickness Δz_j. Radiation transport is modeled using fluctuational electrodynamics [31] in which stochastic currents are added to Maxwell's equations to account for thermal emission. This formalism has the advantage of being valid both in the far- and near-field regimes of thermal radiation [30]. The monochromatic radiative heat flux absorbed by a control volume Δz_j due to thermal emission by the radiator is given by [32]:

$$q_{\omega,abs}^{\Delta z_j} = \Theta(\omega, T_{rad}) \int_0^\infty \frac{k_\rho dk_\rho}{4\pi^2} \left[\overline{T}(k_\rho, z_j, \omega) - \overline{T}(k_\rho, z_{j+1}, \omega)\right] \tag{1}$$

where Θ is the mean energy of a Planck oscillator, k_ρ is the wavevector component along the ρ-direction, $\overline{T}$ is the energy transmission factor while z_j and z_{j+1} are the boundaries delimiting the control volume Δz_j. The energy transmission factors in Eq. (1) are calculated via dyadic Green's functions for layered media; the computational details can be found in Ref. [33]. Note that the radiative flux absorbed by the radiator due to thermal emission by the control volume Δz_j is calculated with Eq. (1) using $\Theta(\omega, T_{cell,j})$, instead of $\Theta(\omega, T_{rad})$, where $T_{cell,j}$ is the temperature of the cell within Δz_j.

Once Eq. (1) is solved, the local monochromatic generation rate of EHPs $g_\omega(z)$ is calculated using the radiation absorbed by the cell [17]. EHPs are generated only when the radiation energy is equal to or larger than the cell absorption bandgap. Radiation transport is then coupled with electrical transport by adding $g_\omega(z)$ to the minority carrier diffusion equations [17]: