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Solar thermophotovoltaic energy conversion systems with two-dimensional tantalum photonic crystal absorbers and emitters

Youngsuk Nam [a,b,*], Yi Xiang Yeng [a], Andrej Lenert [a], Peter Bermel [a], Ivan Celanovic [a], Marin Soljačić [a], Evelyn N. Wang [a,**]

[a] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[b] *Kyung Hee University, Yongin, South Korea*

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ABSTRACT

Solar thermophotovoltaic (STPV) systems convert solar energy into electricity via thermally radiated photons at tailored wavelengths to increase energy conversion efficiency. In this work, we report the design and analysis of a STPV system with 2D photonic crystals (PhCs) using a high-fidelity thermal-electrical hybrid model that includes the thermal coupling between the absorber/emitter/PV cell and accounts for non-idealities such as temperature gradients and parasitic thermal losses. The desired radiative spectra of the absorber and emitter were achieved by utilizing an optimized two-dimensional periodic square array of cylindrical cavities on a tantalum (Ta) substrate. Various energy loss mechanisms including re-emission at the absorber, low energy emission at the emitter, and a decrease in the emittance due to the angular dependence of PhCs were investigated with varying irradiation flux onto the absorber and resulting operating temperature. The modeling results suggest that the absorber-to-electrical efficiency of a realistic planar STPV consisting of a 2D Ta PhC absorber/emitter and current state of the art InGaAsSb PV cell (whose efficiency is only ~50% of the thermodynamic limit) with a tandem filter can be as high as ~10% at an irradiation flux of ~130 kW/m^2 and emitter temperature ~1400 K. The absorber-to-electrical STPV efficiency can be improved up to ~16% by eliminating optical and electrical non-idealities in the PV cell. The high spectral performance of the optimized 2D Ta PhCs allows a compact system design and operation of STPVs at a significantly lower optical concentration level compared with previous STPVs using macro-scale metallic cavity receivers. This work demonstrates the importance of photon engineering for the development of high efficiency STPVs and offers a framework to improve the performance of both PhC absorbers/emitters and overall STPV systems.

1. Introduction

Solar thermophotovoltaic (STPV) systems use an intermediate module that absorbs the solar radiation, and re-radiates photons at high temperatures with tailored wavelengths toward a photovoltaic (PV) cell (Fig. 1). By converting the incident solar radiation to a narrow-band thermal emission matched to the spectral response of the PV cell, STPVs have the potential to overcome the Shockley–Queisser limit for the efficiency of PVs (~33% for 1 sun) [1,2]. STPVs are also highly scalable for a wide range of power capacities, have no moving parts, and allow solar energy storage and the use of an alternative fuel to generate electricity.

Despite the significant potential of STPVs, very few experimental results have reported the system-level efficiency of these systems. Meanwhile, of those reported, the efficiencies were relatively low due to the poor performance of the emitter, absorber, and PV cell and insufficient understanding of the highly coupled energy transport processes among these components. A previous study using an eutectic emitter demonstrated an overall solar-to-electrical efficiency of ~0.025% [3] and a recent experiment with a cylindrical tungsten (W) thermal cavity and germanium (Ge) PV cells demonstrated an overall efficiency of ~0.7% with a high (~3000×) geometrical concentration factor [4]. With a similar cylindrical W cavity layout, ~1% overall efficiency was achieved using gallium antimonide (GaSb) PV cells [5].

One of the biggest challenges in developing high efficiency STPVs is tailoring the spectral response of the absorber and emitter, which operate at high temperatures (>1000 K). Previous studies have investigated various materials including metal-doped MgO, oxides of rare earth materials and tungsten for TPV applications but they have not yet approached the performance of an ideal emitter [6–10]. Recently, the use of photonic crystals (PhCs) with 1D periodic metal/dielectric layers, 2D arrays of cavities and 3D woodpile structures have been suggested to overcome this challenge [9–23]. The PhCs have photonic band structures of propagating and decaying states

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[*] Corresponding authors at: Department of Mechanical Engineering, Kyung Hee University, Yongin, 446-701, Korea. Tel: 82 (31) 201-3652.

[**] Correspondence to: Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, 3-461B, Cambridge, MA 02139, USA. Tel: 1 (617) 324-3311.

E-mail addresses: ysnam1@khu.ac.kr (Y. Nam), enwang@mit.edu (E.N. Wang).

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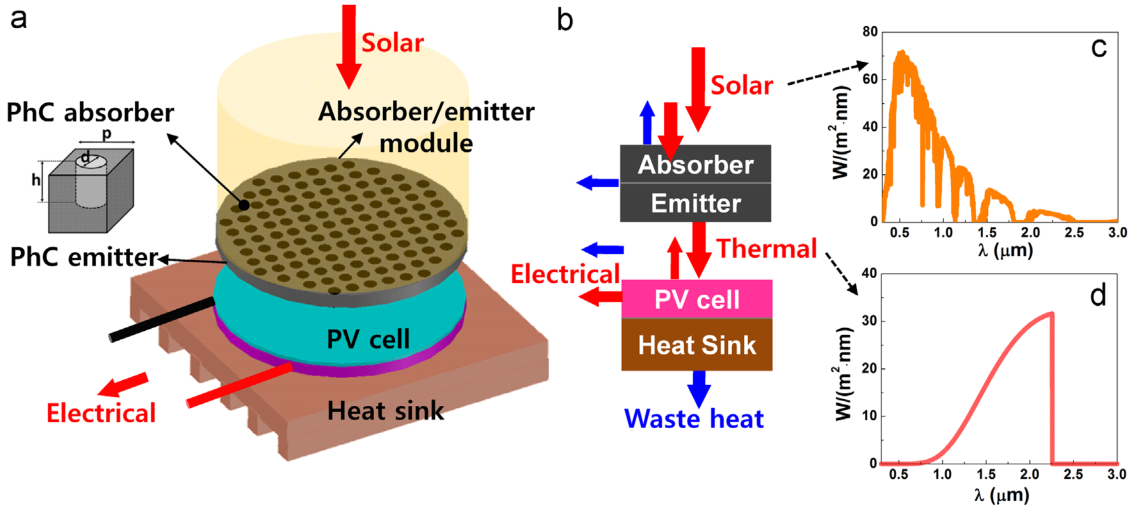

Fig. 1. (a) Schematic of a planar STPV consists of PhC absorber and emitter, (b) Energy flow diagram of the STPV that converts solar radiation with a wide spectrum (c) into a tailored spectrum matched to the spectral response of the PV cell (d).

in wavelengths comparable to the length scale of their periodic structures [11,12] and allow narrow-band [13–18] or wide-band thermal emission with sharp, tailored cutoff wavelengths [19–25]. In particular, metallic PhCs with a large band gap and high thermal stability have provided new opportunities in high temperature applications such as STPVs by amplifying absorption and emission within the designed wavelength range while suppressing emission outside [17,19,20,24,26–28]. Long wavelength reflection filters have also been introduced to reflect low energy photons back to the emitter [29–32].

These previous studies with PhCs, however, have focused on component-level rather than system-level performance. Therefore the realistic performance of STPVs and the energy loss mechanisms associated with the integration of these components have not been fully investigated. Furthermore, the spectral performance of the absorber/emitter and system-level thermal losses in STPVs are strongly affected by the operating temperature which is determined by the complex energy transport among the components. Therefore, accurate system-level analysis is critical for the development of high efficiency STPVs.

In this work, we developed a high-fidelity axisymmetric thermal-electrical hybrid system-level model for STPVs with a 2D Ta PhC absorber and emitter. Our model includes radiative and conductive thermal coupling between the absorber, emitter and PV cell, and precisely accounts for non-idealities such as thermal losses through the side wall and the gap between the emitter and PV cell. The emitter/absorber spectra are tailored by varying the dimension of a two-dimensional square array of cylindrical holes created on a Ta substrate. Unlike previous studies, we designed the PhCs through a global optimization process and included the angular dependence of PhCs in the system level analysis. Using our model, we show that ~10% absorber-to-electrical STPV efficiency can be achieved with the developed Ta PhCs and existing PV cells/filters at a relatively low irradiation flux of ~130 kW/m^2 and emitter temperature ~1400 K without introducing a complex macro-scale receiver cavity design.

2. Energy transport in a STPV

The simplified schematic and energy flow diagram of a planar STPV is shown in Fig. 1. The concentrated solar energy is converted into heat at the absorber and emitted at tailored wavelengths through the emitter that is thermally coupled to the absorber. The thermally radiated high energy photons create electron–hole pairs and generate electricity at the PV cell while low energy photons are wasted as heat. The photons reflected from the PV cell surface or emitted from the cell are re-absorbed on the emitter, or lost to the surrounding.

Due to the multiple energy conversion and transport steps in STPVs, the overall efficiency is determined from the balance between various component-level efficiencies:

$$\begin{aligned}\eta_{overall} &= \frac{H_{abs}\times A_{abs}}{H_c\times A_c}\frac{Q_{abs}}{H_{abs}\times A_{abs}}\times\frac{|Q_{emit}|}{Q_{abs}}\times\frac{|Q_{emit,(E\geq E_g)}|}{|Q_{emit}|}\\ &\quad\times\frac{Q_{cell,(E\geq E_g)}}{|Q_{emit,(E\geq E_g)}|}\times\frac{P_{elec,\ \max}}{Q_{cell,(E\geq E_g)}}\\ &=\eta_{collector}\times\eta_{absorber}\times\eta_{adiabatic}\times\eta_{spectral}\times\eta_{cavity}\times\eta_{cell}\\ &=\eta_{collector}\times\eta_{STPV(abs-elec)},\end{aligned}\tag{1}$$

where H_c and H_{abs} represent the amount of solar irradiation flux onto the collector and absorber surfaces, respectively. The A_c and A_{abs} are the areas of the collector and absorber. Q_{abs}, Q_{emit} and Q_{cell} represent the net amount of heat applied to the absorber, emitter and PV cell surfaces, respectively. $P_{elec,max}$ is the maximum power output produced by the PV cell whose band gap is E_g.

A certain amount of the solar irradiation onto the absorber is lost due to the reflection, transmission, and the re-emission losses at the absorber, and the ratio between the amount of absorption (Q_{abs}) and irradiation ($H_{abs}\times A_{abs}$) is defined as the absorber efficiency $\eta_{absorber}=Q_{abs}/(H_{abs}\times A_{abs})$, where H_{abs} is determined by multiplying the concentration ratio and the solar constant, $H_{abs}=C\times G_s$. The absorbed heat is transferred to the emitter via thermal conduction while losing a certain amount of heat through the side walls. The ratio of the net emission to absorption is defined as the adiabatic efficiency, $\eta_{adiabatic}=|Q_{emit}|/Q_{abs}$. Among the total net thermal emission from the emitter, only high energy ($E\geq E_g$) photons can generate electron–hole pairs in the PV cell, and the ratio of the high energy to the total net emission represents the spectral efficiency $\eta_{spectral}=|Q_{emit,(E\geq E_g)}|/|Q_{emit}|$. Part of the useful emission is lost between the emitter and PV cell, and the ratio of the useful emission arriving at the PV cell surface to the total useful emission defines the cavity efficiency $\eta_{cavity}=Q_{cell,(E\geq E_g)}/|Q_{emit,(E\geq E_g)}|$. Finally, electron–hole recombination, thermalization, and non-ideal optical/electrical performance of the PV cell limit the conversion efficiency and the ratio between the maximum power output to useful emission at the PV cell is defined as the cell efficiency $\eta_{cell}=P_{elec,\ \max}/Q_{cell,(E\geq E_g)}$. By multiplying these component level efficiencies, the system-level STPV