DESIGN AND OPTIMIZATION OF ONE-DIMENSIONAL TiO_2/SiO_2 PHOTONIC CRYSTAL FOR THERMOPHOTOVOLTAIC FILTER

A. MERABTI[a,b,*], A. BENSLIMAN[a], H. ISSANI[a], S.NOUR[a]
[a]*Higher Normal School of Béchar, Algeria*
[b]*Laboratory of Renewable Energy Development and their Applications in the Saharan areas, University Tahri Mohammed Béchar, Algeria*

Thermophotovoltaic (TPV) energy conversion systems convert solar energy into electricity via thermally radiated photons at tailored wavelengths to increase energy conversion efficiency. In this study, we report the design and analysis of a TPV system with one-dimensional photonic crystals (1DPCs) filter using thermal electrical model that includes the thermal coupling between the emitter/filter (PhCs)/PV cell. The performance of the proposed structure, one-dimensional photonic crystals $(TiO_2/SiO_2)^6$ with P periods of Titanium Dioxide (TiO_2)and Silicon Dioxide (SiO_2) of thermophotovoltaic system, has been studied by Mbakop et al [1] and Banerjee et al[2]. The temperature distribution and electrical power output of TPV cell are calculated at a heat varying from 1000 K to 1600 K using parametric solver at a regular interval of 25 K. Furthermore, voltaic efficiency distribution in a concentrating thermal photovoltaic system is presented.

(Received June 24, 2020; Accepted September 10, 2020)

Keywords: Thermophotovoltaic, Filter, Photonic crystals, TPV cell

1. Introduction

The thermophotovoltaic (TPV) technology is a promising approach that directly converts radiated thermal energy into electricity by using photovoltaic effect [3]. The TPV systems consist of heat source and thermal radiator (emitter) assumed to be an ideal blackbody (BB), filter and photovoltaic PV cell. Compared to solar PV conversion, the heat source is significantly closer to the PV cell, resulting in photon flux and power density that is orders of magnitude higher. Virtually, it can be observed that the heat source of a TPV system can be provided by various fuel typologies such as waste heat [4], fossil fuels [5], nuclear fuels, etc. Concentrated solar radiation can also be used as a TPV heat source [6]. The main advantages of this energy system can be found in the promises to be a recycling of the waste heat, low produced noise levels as well as increasing the conversion efficiency [7]. A highly efficient TPV demands the optimization of the output power and throughput. The output power can be achieved through the use of either front-side (filter structures filter deposited on the front side of the TPV cell) and/or backside reflectors (deposited on the back-side of the PV cell). In recent years 1D photonic crystals designed as one-directional mirrors (made from a range of different material systems) have been studied extensively for a range of applications in Photonics and optoelectronics. [8-9].

In this paper, the use of 1D TiO_2/SiO_2 (1DPhCs) as a filter for the TPV system having GaSb TPV cell is proposed and numerically studied [10], and concentrated solar radiation used as a TPV heat source. The multi-layer TiO_2/SiO_2 filter structure was required to realize simultaneously the optimal matching with the spectral distribution of a high temperature emitter and the quantum efficiency of the photovoltaic cell.

2. Optimal device structure

In this article we propose a system made up of three devices, including a thermal emitter, a filter (one-dimensional photonic crystals $(TiO_2/SiO_2)^6$ with P periods of Titanium Dioxide (TiO_2)

[*] Corresponding author: merabti73@yahoo.com

and Silicon Dioxide (SiO_2) deposited on a substrate), and a GaSb photovoltaic cell, as shown in Fig.1. The emitter is a blackbody source with refractive index n_{BB}, that is separated from the filter by a thin air gap and the GaSb photovoltaic cell corresponds to the band gap energy 0.7 eV and band gap wavelength 1.78 μm, respectively. The spectral power of the radiation (Planck's law) of the source at high temperature is:

$$E_{(\lambda,T)} = \frac{2\pi hc^2}{\lambda^5 (e^{\frac{hc}{\lambda KT}} - 1)} \tag{1}$$

where K is the Boltzmann constant, c the speed of the light in the vacuum and h the Planck's constant.

Stefan's law gives the total power radiated by a body:

$$P = \sigma T^4 \tag{2}$$

The absorbed solar radiation is applied to the heat transfer equation of the PV cell layers as an internal heat generation (Q) is defined by:

$$Q = \frac{(1 - \eta_{TPV}).S.A_{pan}}{V_{pc.cll}} \tag{3}$$

where η_{TPV} is the electrical efficiency of the PV panel, A_{pan} the front area of the PV panel and $V_{pc.cell}$ the volume of the PV cells in the panel.

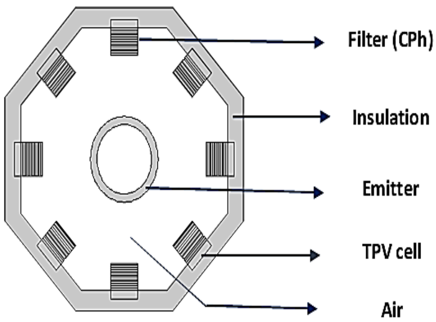

Fig. 1. Geometry of the modeled TPV system.

The role of the 1D photonic crystal deposited on the front side of the PV diode is to transmit all the photons with energies above E_{gap} to the GaSb photovoltaic cell, while reflecting all the photons with energies below E_{gap} back to the emitter.

The parameters that play an important role in achieving the best performance of the filter are the number of periods P, the thickness of each TiO_2 and SiO_2 layer. The TiO_2 and SiO_2 used for the filter are respectively high (H) and low (L) refractive index materials. The refractive indexes are n_H =2.4 for TiO_2 and n_L =1.46 for SiO_2. The substrate material for the filter has a refractive index taken as n_b= 1.5 in the entire range of wavelengths.

Heat source (q) is defined by:

$$q = -G\eta_{TPV} \tag{4}$$

where G is the irradiation flux (W/m^2) and η_{TPV} the efficiency of PV cell. The latter depends on the local temperature, with a maximum of 0.2 at 800 K

$$\eta_{TPV} = \begin{cases} 0.2\left[1-\left(\dfrac{T}{800K}-1\right)^2\right], & T \leq 1600\ K \\ 0 \qquad\qquad , & T > 1600\ K \end{cases} \tag{5}$$

2. Results and discussion

In the study, the emitter temperature is swept from 1000 K to 2000 K at a regular interval of 25 K and the results such as temperature distribution, voltaic efficiency distribution and electric power output of the TPV cell are observed and are discussed as follows.

3.1. Behavior of the temperature in a TPV cell

With eight filters (1D CPhs) and TPV cells, the temperature of PV cell for different operating conditions of emitter temperature is shown in Fig. 2. The results showed that the TPV system experienced a remarkable temperature evolution that varied almost linearly with the operating conditions. The PV cell temperature can reach up to 1814.5 K, which is significantly higher than the maximum operating temperature of 1600 K above which the photovoltaic efficiency is zero.

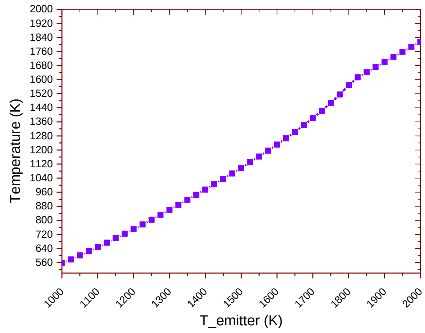

Fig. 2. TPV cell temperature versus emitter temperature.

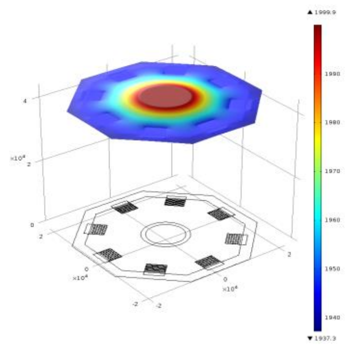

Fig. 3. Temperature distribution in the TPV system when the emitter temperature is 1400 K.

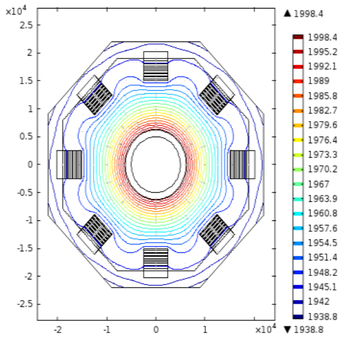

Fig. 4. Isothermal Contour plot of TPV cell with emitter at 2000 K.

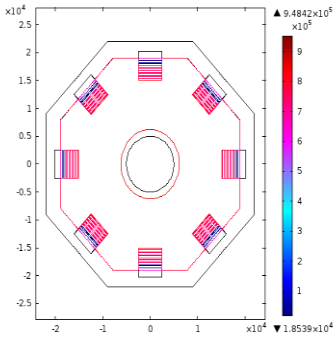

Fig. 5. Radiosity plot of TPV cell with emitter at 2000 K.

The result in Fig. 3 depicts the visual temperature distribution for the TPV systems, different operating conditions of emitter temperature. The TPV cell is experienced by significant temperature distribution for varying operating condition of the emitter. To further understand the behavior of the temperature in a TPV cell, The isothermal contour plot and radiosity plot for an emitter temperature of 1814.5 K are shown in Figs. 4 and 5.

3.2. Electric power Output

To investigate the optimal temperature at which the system TPV can result in maximum electric power output, a plot is generated for electric power output versus operating temperature as shown in Fig. 6. When the emitter is at 1600 K, the TPV cells reach an output power of 30876 W/m^2, that resulted a temperature of approximately 1250 K, which they can withstand without any problems. Above of T_{heater} value, the output power began to drop sharply and eventually came to zero at 1900 K. It can be inferred that any system operation outside these temperature is a waste of resources because the output power becomes zero.

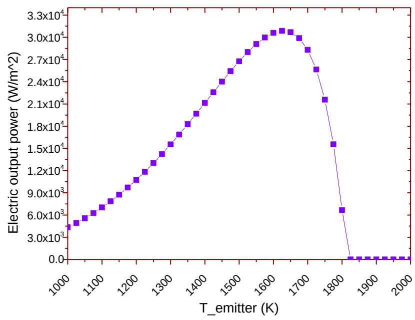

Fig. 6. Electric power output versus Emitter temperature.

3.2. TPV cell voltaic efficiency

Using Expression described in Equ. 5, estimates of η_{TPV} using GaSb PV cells for temperatures above 1000 K were obtained. The results are illustrated in Fig. 7. As T increases, η_{TPV} decreases primarily, and As the upper plot in Fig. 2 shows, the PV cells reach a temperature of approximately 1814.5 K. This is significantly higher than their maximum operating temperature of 1600 K, above which their photovoltaic efficiency is zero. The latter depends on the local temperature, with a maximum of 0.2 at 800 K.

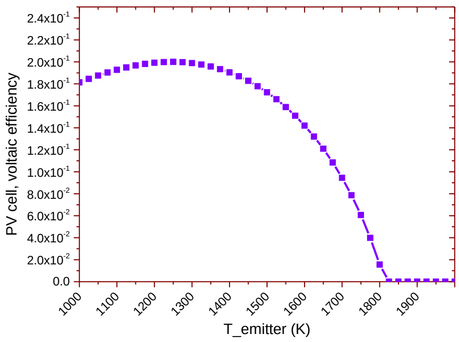

Fig. 7. TPV cell voltaic efficiency versus temperature.

4. Conclusions

It has been widely acknowledged that the goal of developing TPV systems that meet performance bench-marks in terms of efficiency and power density relies heavily on the effectiveness of the system's spectral components.

In the present work, we have studied a one-dimensional photonic crystal (1D TiO_2/SiO_2 PhC), for development of filters that are to be used in TPV applications. The one-dimensional PhC filter shows its advantages of simple structure and fabrication process and can be conveniently applied to spectral control of the TPV system. It is observed that the proposed TPV cell produces a maximum of 30876 W/m^2 electrical power output at an emitter temperature of 1625 K and solar temperature of 1266 K.

The results presented in this article substantiate the assumption made at the beginning of this article that photonic crystal filter can be used as practical, high-performance spectral components within a TPV context.

References

[1] Fabrice Kwefeu Mbakop, Noël Djongyang and Danwé Raïdandi, Journal of the European Optical, Society-Rapid Publications **12**, 23 (2016) .
[2] P. P. Banerjee, L. Han, R. Aylo, G. Nehmetallah, Proc. SPIE 8093, Metamaterials: Fundamentals and Applications **IV**, 80930P1-7 (2011).
[3] T. J. Coutts, Solar Energy Materials & Solar Cells **66**, 443 (2001).
[4] T. J. Coutts, Renew. Sust. Energ. Rev. **3**, 77 (1999).
[5] M. Zenker, A. Heinzel, G. Stollwerck, J. Ferber, J. Luther. IEEE Trans. Electron. Dev. **48**, 367 (2001).
[6] V. M. Andreev, V. A. Grilikhes, V. P. Khvostikov, O. A. Khvostikova, V. D. Rumyantsev, N. A. Sadchikov, M. Z. Solar Energy Materials & Solar Cells **84**, 3 (2004).
[7] S. I. Mostafa, N. H. Rafat, S. A. J. Ren .Energy **45**, 245 (2012).
[8] A. Merabti, A. Hasni, M. Elmir, Journal of Nano- And Electronic Physics **8**(8), 03046 (2016).
[9] A. Merabti, A. Bensliman, M. Habab, American International Journal of Multidisciplinary Scientific Research **5**(2), 2019.
[10] A. Alyamani, N. Mustapha, T.S.Alkhuraiji, H. Idriss, J Ovonic Res 15(5), 301 (2019).