UNIVERSITY OF TECHNOLOGY SYDNEY

PAM Review

Subject 68412
www.uts.edu.au

Efficiency of 2D Photonic Crystal Emitters in Thermophotovoltaic Systems

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DOI: http://dx.doi.org/10.5130/pamr.v3i0.1422

Abstract:
Thermophotovoltaic (TPV) systems have the potential to convert energy in a very efficient way by using 2D photonic crystal (PhC) emitters. Recent advancements in TPV technology have developed many methods for effectively generating power. These recent advancements propose that emitters can suppress low energy photon emissions while increasing higher energy photon emissions. This can be achieved by utilising new 2D photonic crystal (PhC) structures on the surface of the emitter with varying diameter and shape.

In this meta study we consider the multiple design fabrications of photonic crystal emitters and compare the efficiencies, power densities, and their potential use for converting different wavelengths into heat and power. This is done by analysing the thermodynamic factors present in the system that could potentially reduce the efficiency, and therefore power generation, of the thermophotovoltaic cell. This study found that certain shapes and materials can impact on the PhC structure and its ability to emit energy.

Keywords: Thermophotovoltaic (TPV), thermodynamics, efficiency, power density, 2D photonic crystals,

1. Introduction

Thermophotovoltaic (TPV) cells are capable of converting thermal radiation from man-made high temperature sources into electricity through the use of photonic crystals (PhC). This ability poses a viable alternative to fossil fuels, which is very beneficial, especially in space stations and extraterrestrial habitats where fuel takes up large amounts of cargo space.

The technology was first conceptualised in the early 1960s, and it still remains an active area of research today. A basic TPV cell consists of a thermal radiator which emits photons when heated, and uses a photovoltaic (PV) cell to convert these photons into usable energy. In practice, not all of the photons that reach the PV cell will have suitable energies for the band gap of the semiconductor in the PV cell, so it is important to increase the efficiency of the system by recycling these photons using a selective filter that lets suitable photons through but reflects unsuitable photons back into the radiator.

TPV cells can theoretically boast a high power density, taking up a relatively small amount of space for the energy they produce. They are reliable, as they don’t contain a large amount of mechanical or moving parts, and they require little to no maintenance to operate for extended periods of time. TPV cells work on a similar principal as a PV cell, however, instead of converting solar radiation into electricity it converts thermal radiation emitted from high-temperature sources. The temperatures at which TPV cells work is in the range of 1100-1500 K, which, although far less than the temperature of the Sun at over 5000 K, is still extremely hard to produce and use, as most materials at this temperature are near their melting point, or are too hot for humans to exist within the vicinity of. The only way we can get any form of efficiency is by producing materials with a very small band gap e.g. GaSb (Gallium Antimonide) and InAs (Indium Arsenide).

A potential way forward in this field is by looking into 2D (PhC) photonic crystals. This idea has the possibility to lead to new technology and greater results in terms of the power output of a thermophotovoltaic cell. 2D photonic crystals are important in the process as they provide the ability to control the motion of photons of light or energy. This can be important in TPV cells as it allows control of how much and what type of waves are allowed in. These 2D crystals, along with other constantly improving technology, can lead to a better, more efficient way to decrease our energy needs and enable us to potentially produce a large amount of energy for longer periods of time.

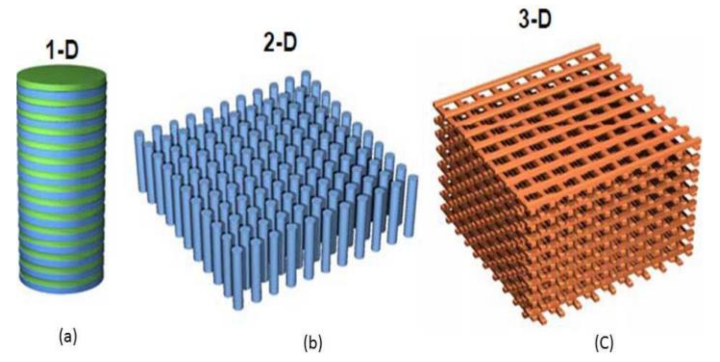

Figure 1 : Illustration of a (a) 1D, (b) 2D, and (c) 3D photonic crystal structure (http://www.intechopen.com/books/advances-in-photonic-crystals/photonic-crystal-ring-resonator-based-optical-filters) 2/5/2016

The TPV system is a photonic heat engine that has thermodynamic limitations caused by entropy generation. The maximum efficiency of the system can be calculated by taking into account the temperatures of both the heat source and the heat sink. The efficiency can be given by:

$$n(carnot) = (T_h - T_c)/T_h$$

Controlling the absorption spectra on the TPV cell is done using the 2D PhC emitters. Large peaks in emission are often observed, however these peaks can be selected by suppressing low energy photon emissions while further enhancing the high energy photon emissions.

2. Methods

This meta study was found on peer review papers publish in this field. The papers studied were research papers with first hand data and results. The papers selected for inclusion in this meta study were ones that had been referenced to in multiple other papers to ensure reliability in the data collected. They have also been chosen as they provide the required information to enable the group to get any form of a result.

Searches within the databases (SCOPUS, Sciencedirect, Google Scholar and Access Science) were relating to 2D photonic crystals and thermodynamic processes. The study was restricted to 2D PhCs with a specific focus on how different materials and different hole shapes are able to influence the efficiency and power density of a TPV. This reduced the amount of papers needed and enabled more specific information to be acquired. Papers measuring efficiencies of TPV cells were collated and organised with respect to the specific design fabrication used and then referenced using refworks.

An analysis of the research papers allowed for comparisons of efficiency in the specific system. Compensations were made for differing variables such as wavelength of radiation and temperature of the system to allow for the accurate comparison of the data. By unifying these variables, assumptions of the performance can be made for different environments. In the cases where the efficiency is not given, the performance is compared to a blackbody where radiation is absorbed entirely giving a maximum theoretical efficiency of 100%.

3. Results

There are numerous fabrication methods that are being used to improve the TPV system. 1D (Band gap lines), and 2D, such as Circular holes, Square holes and Hexagonal holes, have all been researched, manufactured in some way and have led to very useful knowledge. There are differences in terms of cost to produce, different temperature output and the efficiency of the cell.

3.1. 1D (band gap lines) fabrication

1D PhCs are made of inorganic materials that are in alternating stacks of SiO2 and TiO2 for the best result, in terms of the reflection they are able to replicate, the reflective index of SiO2 thin films is 1.24 and for TiO2 it is 1.74. This large range of movement of reflection means it is the ideal material for reflecting lower and higher wavebands into the system, as shown in Figure 2.

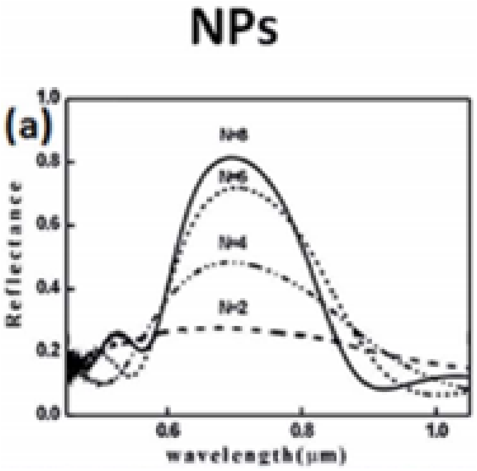

Figure 2 - showing the reflectance of different wavelengths in a material - (Huaizhong Shen et al), 2011

This allows 1D photonic crystals to dramatically improve the efficiency of the TPV system however is not the most efficient in terms of spectral control and efficiency. Fabricating 1D PhCs is often done by using low-pressure chemical vapor deposition process. Then a ten layered structure is created with a gap correlating to the subjected wavelength to ensure correct emission spectra is matched. This will give a reasonable result, however

3.2 2D fabrication techniques

The methods of fabricating 2D photonic crystals encountered in this study were the etching of holes into the material, or by sputtering the material on top of a bulk substrate. Etching is achieved by drilling some holes into a semiconductor, creating the 2D PhC, this traditionally occurs along the Z direction, or the direction normal to the incident plane, this requires technology that can build these crystals to enable the desired waveguides into a small structure. While sputtering involves ejecting particles into a material, causing bombardments and energising the particles and releasing heat.

3.2.1 Planar vs 2D

There is a large difference between using a planar sheet of material which is a 1D structure and 2D PhC structures. This is shown by an experiment measuring the emittance of both the planar and 2D emitter, in this case using Tungsten as shown in figure 3.

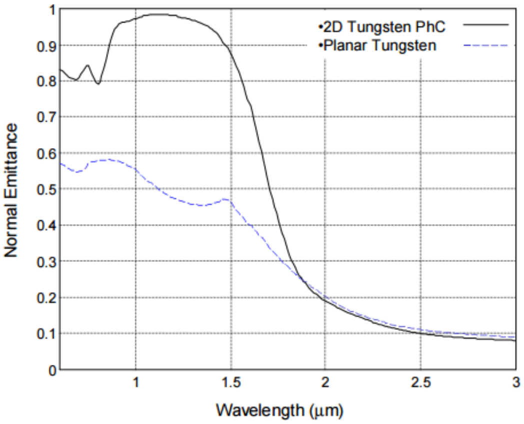

Figure 3 - Normal Emittance vs Wavelength, comparing 2D Tungsten PhC and Planar Tungsten (Celanovic et al), 2011

3.2.2 Selective photon emissions from the PhC fabrications

Selective photon emissions comes directly from the design structure of the PhC emitters. Factors affecting the emission wavelength and power density include the shape of the structure as well as the diameter. In the first case we will look at the circular hole structure that follows a layered pattern in both the x and y planes of the surface. The material analysed is Tungsten with a diameter given as *a*. Comparing the two different structures of the circle we can see the wavelength vary as both diameter and temperature vary. The diameter used in figure (a) is 2.00 micrometers.

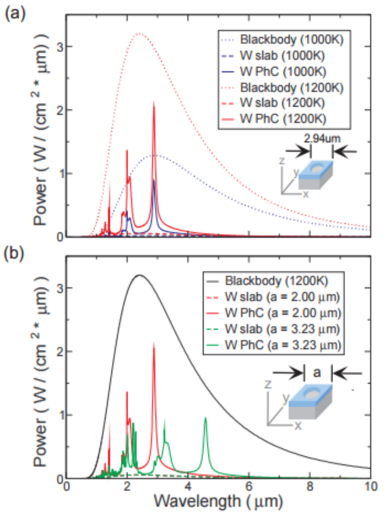

Figure 4 - The variation of wavelength as temperature and diameter of the circle increase. 2011

As we can see the emission spectrum of the 2D PhC is once again much larger than the PhC slab at all wavelengths and all temperatures.

3.3. Differing temperatures and efficiency

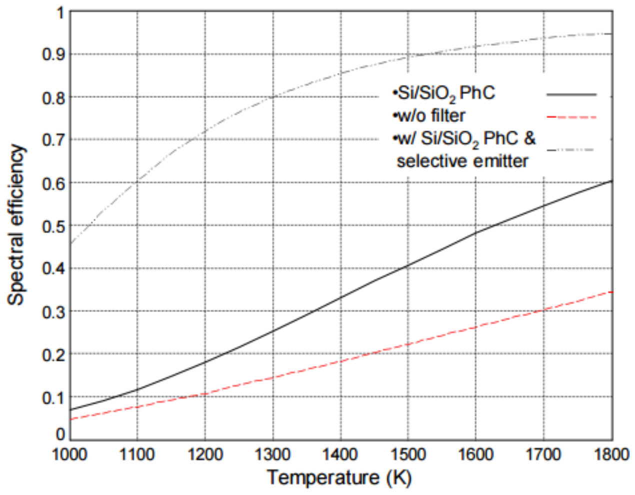

Figure 5 - Simulated spectral efficiency of a black body source without spectral control compared with a silicon dioxide PhC with a blackbody emitter and PhC with a 2D tungsten emitter. (Celanovic et al.), 2011

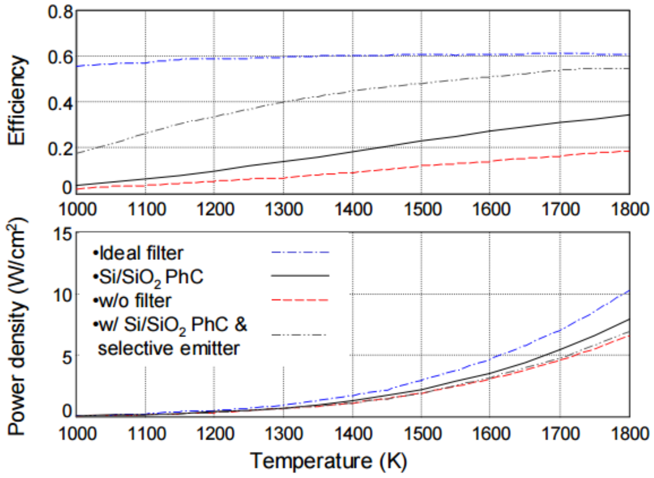

Figure 6 - Simulated system efficiency and power density of an ideal filter and various silicon oxide PhC emitters. (Celanovic et al), 2011

The 2D PhC emitter used a hexagonal shaped hole pattern with hole diameter 0.8 micrometers. Tungsten is a good example of selective spectra control as the high reflectivity of tungsten suppresses thermal emission in the longer wavelengths. The tungsten also has a high absorption below the 1.8 micro meter range enhancing this wavelength range.

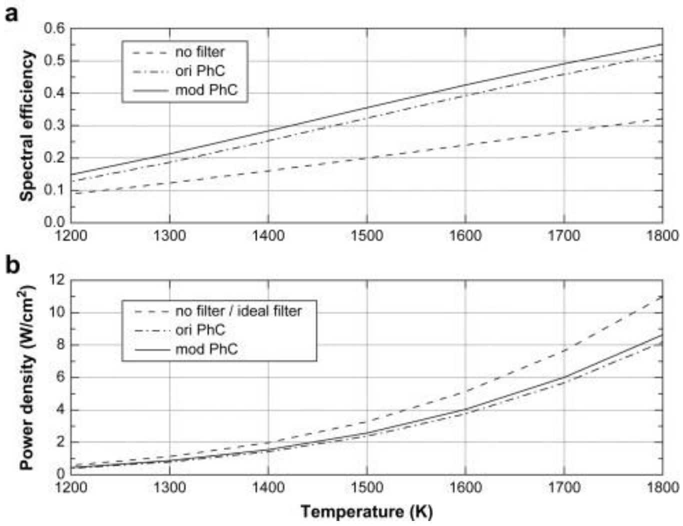

Figure 7 - Simulated spectral efficiency and power density of TPV systems as functions of the radiator temperature with an ideal filter, modified 1D PhC, original PhC, and no filter. (Lei Mao, Hong Ye), 2001

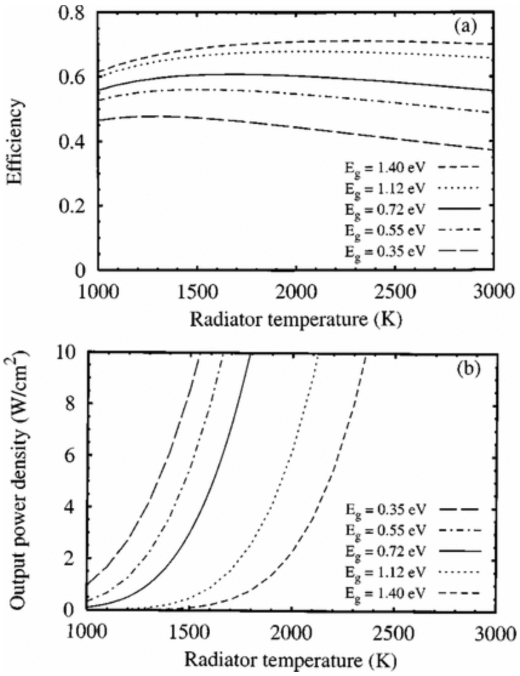

Figure 8 - Efficiency and power density of a PV cell as a function of radiator temperature, for different band gaps, corresponding to the PV cell materials InAs(0.35eV), InGaAs(0.55eV), GaSb(0.72eV), Si(1.12eV), and GaAs(1.4eV). (Zenker et al), 2001

As shown in figure 8, in terms of output power density over the smallest change in temperature, the ideal material for use in thermophotovoltaic cells being InAs (Indium arsenide). However, with the increase in temperature it also has the lowest efficiency, which means it may not be the ideal choice as it heats up during use. Another issue with indium arsenide is that the temperature required to get any decent power density is close to the melting point of this material, as InAs has a melting point of 1215 K. Most papers focus on GaSb for the reason that it is easy to manufacture and develop. It also shows similar power density to indium arsenide, but with a greater efficiency.

5. Discussion

In this meta study, the papers researched and used had appropriate and similar information. However, there were usually only direct correlations with a few of the parameters that wanted to be researched. This suggests that more research needs to go into comparing the different shapes of the holes. While it was clear that the material being used made a difference to the efficiency and power density, it wasn’t clear if it is best to use a circular, square, hexagonal, or even if other shapes like triangles can be used to increase the performance of these cells.

6. Conclusions

To conclude this meta study, several things must be made clear. First of all, the information contained within this paper is from a field that has been only slightly studied to the degree that other, older fields have. This means that new knowledge is always being found, thus leading to new discoveries that may run contrary to this article. Secondly, this paper has focused entirely on the thermodynamic side of this study. Everything has been looked at in relation to entropy, enthalpy, and other such variables. Cost has been mostly overlooked, though power density has been included to a fair degree, as it is an important variable in this study.

Although it is clear that the shape of holes in 2D photonic crystals leads to a difference in the overall performance of the TPV cell, there was not enough evidence in the papers researched to conclude the exact differences in performance. It should be noted that the most common hole shape encountered was circular.

GaSb and Si based TPV cells were by far the most commonly used across the sources studied. This is likely due to the ease of manufacturing TPV cells made from these materials, as well as their high power density and efficiency. Although InAs and InGaAs cells displayed superior power density to the alternatives, efficiency problems arise as these cells heat up significantly during use, and this operating temperature is close to the melting point of the material.

Acknowledgments

The authors of this article wish to thank the University of Technology: Sydney for assisting with the research process and providing access to extensive research databases.

Wish to thank Jurgen Schulte for his insight and advice concerning the production of this article.

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