



Thermophotovoltaic power conversion systems : current performance and future potential

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Thermophotovoltaic (TPV) systems offer a unique, solid-state approach to converting heat into electricity based on thermal radiation. TPV is particularly suitable for certain classes of problems that are difficult for standard engines, such as long, remote missions where repairs are difficult, and portable generation where space and weight are at a premium. While standard thermophotovoltaics are limited in their conversion efficiency, photonic crystals can improve performance by an order of magnitude for a number of systems. Finally, two exemplary systems are discussed: TPV μ reactors for portable power generation in a mm-scale form factor, and solar TPV for long-term off-grid power generation from sunlight. In both cases, photonic crystals can enable an order of magnitude enhancement in performance, implying potential performance exceeding that of many other well-known technologies, such as single-junction photovoltaics.

Keywords : thermophotovoltaics, photonic crystals, low-bandgap photovoltaics, spectral shaping, photonic bandgap, thermal emittance

1. Introduction

The vast majority of energy generation approaches used in today's world, including coal and natural gas-fired power plants, internal combustion engines, and nuclear power plants, aim to convert heat into useful work. The ultimate performance is limited in all cases by the Carnot efficiency η_c , given by :

$$\eta_c = 1 - T_c / T_h \quad (1)$$

where T_h is the temperature of the initial heat input, while T_c is the temperature of the cold heat sink. In principle, properly designed mechanical engines can closely approach this limit, in the absence of parasitic losses or mechanical failure. In practice, the high-efficiency regime of high input temperatures introduces a host of parasitic loss mechanisms—conductive, convective, and radiative—that depend on the surface area to volume ratio. Thus, mechanical engines are most efficient for larger devices.

There are a number of situations where a solid-state alternative to mechanical engines could be preferable. In particular, they are preferred for long missions in stressful environments where repairs are prohibitively expensive, such as deep sea or space. For example, NASA has deployed a radioisotope thermoelectric generator for its unmanned probes such as Voyager 1 and 2.¹⁾ Another

situation where solid-state devices may be preferred is for small systems operating at high temperatures. Radiative losses grow quartically with temperature and tend to dominate overall thermal losses at high temperatures. However, if these radiative losses could instead be used to generate power, that would make small-scale, portable devices much more attractive. Because of the way they work, thermophotovoltaics may be an attractive choice for such applications.

Thermophotovoltaic power systems convert heat into electricity via a mechanism illustrated in the inset of **Figure 1**. Briefly, input heat is used to warm a thermal emitter, which is arranged to radiate onto a photovoltaically active diode. The latter produces a combination of usable electricity and low-grade waste heat. First proposed independently by Henry Kolm and Pierre Aigrain in the early nineteen-fifties,^{2,3)} the approach is closely related to the photovoltaic cell for harvesting electricity directly from sunlight—except that the source of thermal radiation is man-made instead of celestial. In principle, the conversion efficiency of a thermophotovoltaic system can be much higher than a single-junction photovoltaic cell, and approaches that of a Carnot engine.⁴⁾ In practice, since a manmade thermal emitter is generally much cooler than the surface of the sun, the best performance will result from using a smaller bandgap material than in a photovoltaic device. The

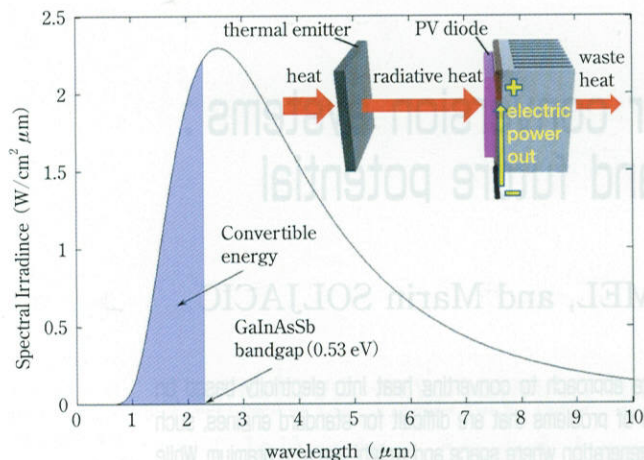


Figure 1. Illustration of the emission of a blackbody source at 1200 K, with the shaded region corresponding to high-energy photons that can be converted into electricity. (Inset) The flow of energy in a standard thermophotovoltaic device, from input heat to radiative emission onto a thermophotovoltaic diode, which generates both electric power and waste heat.

main part of Figure 1 illustrates that thermally emitted photons can be used as long as their energy is at least equal to that of the photovoltaic material, in this case, GaInAsSb with a bandgap of 0.53 eV. This particular system generally works well around 1200 K, since an appreciable fraction of blackbody radiation has at least that energy. At higher temperatures, a larger bandgap is preferred. Using the same methodology as Shockley and Queisser,^{5,6)} the maximum efficiency as a function of bandgap, temperature and emission bandwidth has been calculated in multiple papers.⁷⁻¹⁰⁾ For blackbody/graybody emitters, efficiencies are limited to fairly modest values, well short of the Carnot efficiency of equation (1). The reason for this is that at room temperature, photovoltaic receivers typically have an open circuit voltage corresponding to the electronic bandgap, less a penalty of about 0.3–0.4 eV.⁶⁾ Thus, it is necessary to use fairly high electronic bandgaps, albeit low enough to absorb a non-negligible fraction of blackbody radiation. Even for an extremely hot blackbody emitter, such as the sun at a temperature of approximately 5780 K, the maximum efficiency is only 31% — a value known as the Shockley–Queisser limit. However, unlike the sun, the spectrum of the emitter can be shaped in different ways to suppress or recycle unwanted photons. A flexible class of materials suitable for this purpose is referred to as photonic crystals, and is the subject of the next section.

2. Using Photonics to Enhance TPV Performance

Photonic crystals (PhCs) are structures consisting of two or more materials arranged in a periodic pattern in

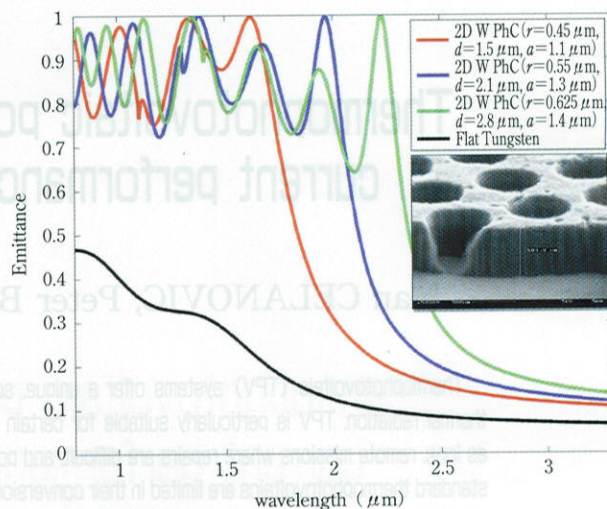


Figure 2. Emittance versus wavelength for both flat tungsten and several 2D tungsten photonic crystal designs. Compared the planar case, 2D PhCs exhibit higher emittance throughout the spectrum, with a large jump to values close to one at the chosen cutoff wavelength (adapted from Ref. 14).

one or more dimensions. Their most characteristic feature is a photonic bandgap—a range of frequencies in which all propagating modes are forbidden.¹¹⁾ The photonic bandgap can be chosen by modifying the structure of the PhC. This flexibility gives rise to an unprecedented ability to control and mold the flow of light.¹¹⁾ In the context of thermal systems such as TPV, photonic crystals can be used to modify blackbody emission, and selectively reflect (or filter) what is emitted. In particular, a photonic bandgap can be introduced into a selective thermal emitter at low frequencies, to ensure that the majority of light is emitted above the TPV diode's electronic bandgap. Furthermore, another photonic bandgap can be used to reflect the low frequencies that are emitted back to the source, in a process known as photon recycling^{12,13)}.

In Figure 2, an exemplary system for tailoring thermal emission is illustrated. It is based on alternating regions of tungsten and air in a 2D pattern, in order to achieve high-temperature stability and a continuous bandgap induced by the metallic structure up to a cutoff frequency.¹⁴⁾ Low frequencies cannot enter into the photonic lattice: they see the surface as a slightly roughened piece of tungsten, and are reflected strongly. On the other hand, higher frequencies that do enter the photonic lattice can dwell there for some time. The cutoff frequency can be tuned by modifying the geometric parameters of the lattice, such as the period, hole radius, and hole depth. Furthermore, if one designs the lattice to allow high-frequency light to enter at a rate equal to the rate of

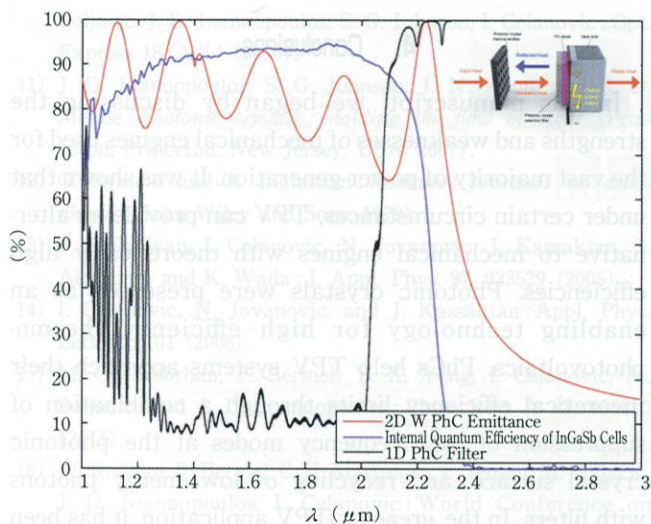


Figure 3. Emittance spectrum as a function of wavelength for a 2D tungsten photonic crystal, along with the reflectivity spectrum of a 1D photonic crystal filter at normal incidence, tuned for compatibility with the IQE curve of a GaInAsSb TPV diode. (Inset) Energy flow in an improved approach, which uses photonics to suppress and recycle low-frequency photons.

material absorption, this is known as Q-matching, and can lead to up to 100% absorption at the resonant frequency.¹⁵⁾

In **Figure 3**, the 2D tungsten PhC of **Figure 2** is tuned to have a cutoff wavelength equal to the external quantum efficiency (EQE) edge of the TPV diode—which corresponds to the effective electronic bandgap of the system. Furthermore, another PhC element, a 1D rugate filter, is introduced, in order to help recycle long wavelengths beyond the EQE edge back to their source. The overall effect of these two novel design elements is to raise the performance at 1200 K to a maximum conversion efficiency of 26.9%, assuming a realistic InGaAsSb diode.¹⁰⁾

3. Applications for Thermophotovoltaics

3.1 Portable Power Generators

As discussed previously, TPV offers unique advantages for small-scale power generation, since carefully arranged TPV cells can utilize thermal radiation that would typically be considered a parasitic loss. In **Figure 4**, a design for an experimentally fabricated and tested mm-scale TPV μ reactor is shown.^{10,16)} The typical efficiency of the device ranges from 0.5%¹⁰⁾ to 2.2%,¹⁶⁾ depending on whether all key design elements are included. In all cases, the system requires a silicon MEMS reactor for catalytic combustion of fuels such as propane and butane, and a GaInAsSb photovoltaic diode for efficient conversion of above-gap photons into electric-

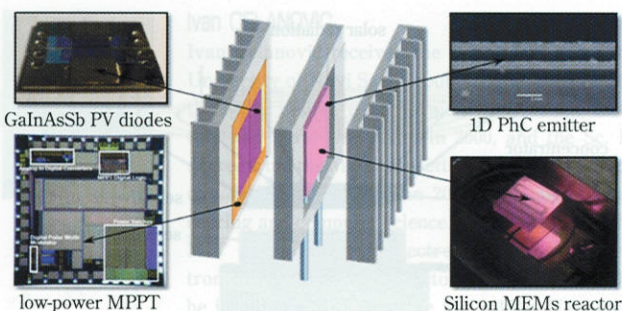


Figure 4. Design for a small-scale TPV reactor, with several key components called out: a silicon MEMS reactor for catalytic combustion of fuels such as propane and butane; a 1D photonic crystal emitter on its surface to suppress mid-IR radiation; GaInAsSb photovoltaic diodes for efficient conversion of the emitted high-energy photons into electricity; and a low-power maximum power-point tracker to ensure the maximum power is always generated under varying conditions.

ity. An additional design element for improved performance is a 1D photonic crystal emitter grown on the surface of the MEMS reactor to suppress mid-IR radiation. Finally, a low-power maximum power-point tracker can be added to ensure the maximum power is always generated under varying conditions.¹⁷⁾ With some relatively small tweaks to the existing 2.2% design, it has been predicted that an efficiency of 5.3% could be achieved.¹⁰⁾ Furthermore, if one raises the operating temperature to 1200 K, efficiencies as high as 21.7% would theoretically be achievable.¹⁰⁾

3.2 Solar Thermophotovoltaics

Solar thermophotovoltaics can be seen as an alternative to solar photovoltaics and solar thermal power generation. As shown in **Figure 5**, it consists of using concentrated sunlight as a heat source to drive a high-efficiency TPV system.^{7-10,18,19)} One of the unique challenges of solar TPV is designing the so-called selective solar absorber, and optimizing it to work in tandem with the TPV selective emitter and diode. Selectivity is needed because there is a tradeoff between absorbing sunlight and re-radiating infrared radiation, which fundamentally derives from Kirchoff's law.¹²⁾ If the efficiency of the solar TPV system as a whole were to be considered as a product of two subsystems, the selective solar absorber and TPV selective emitter and receiver, then the efficiency of the first subcomponent could be written as follows:

$$\eta_a = \frac{1}{C I_s} \int_0^\infty d\lambda \varepsilon(\lambda) \left\{ BC \frac{dI}{d\lambda} - \frac{2\pi hc^2}{\lambda^5 [\exp(hc/\lambda kT) - 1]} \right\} \quad (2)$$

Where C is the solar concentration, B is the transmissivity of the vacuum enclosure, I_s and $dI/d\lambda$ are the

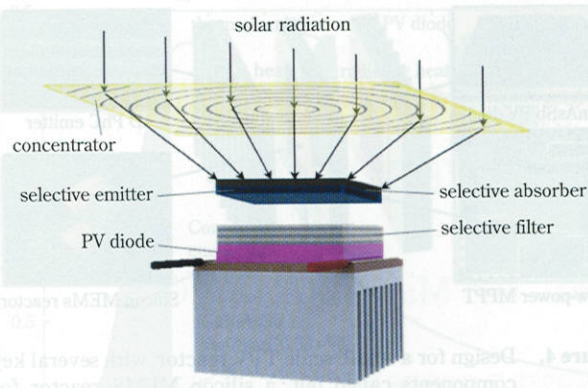


Figure 5. Schematic illustration of a concentrating solar thermophotovoltaic system. Sunlight is concentrated onto a selective absorber, which is thermally coupled to a selective emitter that functions in a similar fashion as other TPV energy conversion approaches.

integrated and wavelength-dependent intensities of the AM1.5 solar spectrum, and $\epsilon(\lambda)$ is the wavelength-dependent emissivity. It is evident that the highest values of η will be obtained for high concentrations and low operating temperatures. Optimal design for selective solar absorbers has been discussed extensively in previous literature.^{7-10,18-22)} However, the maximum efficiency of the TPV back end will increase with temperature. This implies that for a given solar concentration, there will be an optimal operating temperature and TPV bandgap where the product of these two components is at a maximum. Due to experimental constraints, previously built solar TPV systems, have diverged substantially from these values. In Datas et al., 2% efficient operation is observed at relatively modest concentrations and temperatures using germanium indirect bandgap photovoltaic cells.¹⁸⁾ Replacing those solar cells with a higher-performance III-V TPV cells would by itself roughly double the expected efficiency²³⁾. Other desirable changes would come from photonic crystal-based designs for more wavelength-sensitive selective solar absorbers, selective emitters, and filters for photon recycling. Combining all those elements and optimizing yields a theoretical prediction of 44% using a tandem junction for 100 sun concentration at 1000 K,¹⁰⁾ and up to 50.8% efficiency for a single junction under 46,200 suns at 2360 K.⁸⁾ Overall, the photonic design approach is predicted to yield up to an order of magnitude enhancement in the performance of these systems. Furthermore, these projected efficiencies exceed the Shockley-Queisser limit for single-junction photovoltaic cells under equal solar concentrations.

4. Conclusions

In this manuscript, we began by discussing the strengths and weaknesses of mechanical engines used for the vast majority of power generation. It was shown that under certain circumstances, TPV can provide an alternative to mechanical engines with theoretically high efficiencies. Photonic crystals were presented as an enabling technology for high-efficiency thermophotovoltaics. PhCs help TPV systems approach their theoretical efficiency limits through a combination of suppression of low-frequency modes at the photonic crystal surface, and recycling of low-energy photons with filters. In the μ reactor TPV application, it has been shown that 2D tungsten photonic crystals plus rugate filters can potentially enhance efficiencies by an order of magnitude to over 10% even on the mm-scale. For fuels such as propane, this implies a much higher energy density than commercial battery technologies. In the second application of solar TPV, it was shown that concentrated systems with single or tandem junction TPV diodes can be designed to offer efficiencies in excess of the single-junction Shockley-Queisser limit for solar photovoltaics. While an experimental demonstration of such high efficiencies has not yet been achieved, early experimental results matching with theory are encouraging, and the path to higher performance is fairly clear.

Acknowledgments

The authors thank John D. Joannopoulos, Yi Xiang Yeng, Michael Ghebrebrhan, and Walker Chan, for valuable discussions. IC was supported by the Army Research Office through the Institute for Soldier Nanotechnologies under Contract Nos. DAAD-10-02-D0002 and W911NF-07-D0004; PB and MS were supported by the MIT S3TEC Energy Frontier Research Center of the Department of Energy under Grant No. DE-SC0001299.

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(Received May 6 2011)



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