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Photonic Crystal Enabled Thermophotovoltaics for a Portable Microgenerator

Walker R. Chan[1], Veronika Stelmakh[1,2], Christopher M. Waits[3], Marin Soljacic[4], John D. Joannopoulos[1,4] and Ivan Celanovic[1]

[1] Institute for Soldier Nanotechnologies, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
[2] Department of Electrical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, Massachusetts 02139, USA
[3] Sensors and Electron Devices Directorate, 2800 Powder Mill Rd., US Army Research Laboratory, Adelphi, Maryland 20783, USA
[4] Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, Massachusetts 02139, USA

E-mail: `wrchan@mit.edu`

Abstract. This work presents the design and characterization of a first-of-a-kind millimeter-scale thermophotovoltaic (TPV) system using a metallic microburner, photonic crystal emitter, and low-bandgap photovoltaic (PV) cells. In our TPV system, combustion heats the emitter to incandescence and the resulting thermal radiation is converted to electricity by the low bandgap PV cells. Our motivation is to harness the high specific energy of hydrocarbon fuels at the micro- and millimeter-scale in order to meet the increasing power demands of micro robotics and portable electronics. Our experimental demonstration lays the groundwork for developing a TPV microgenerator as a viable battery replacement.

1. Introduction

For durations greater than one day, the energy demands of micro robotics and portable electronics are too large to be comfortably supplied by batteries and yet too small to warrant a gasoline or diesel generator. Microgenerators promise to fill the 1–100 W range in a compact form factor by extending the high specific energy of hydrocarbon fuels into the millimeter scale. Hydrocarbon fuels have specific energies close to 12.8 kWh/kg whereas state of the art rechargeable batteries are closer to 180 Wh/kg. Thus, even a relatively inefficient generator can significantly exceed the specific energy of batteries. To this end, researchers have explored several possible energy conversion routes for providing next-generation portable power: micro mechanical heat engines, fuel cells, thermoelectrics, and thermophotovoltaics [1, 2].

In this work, we present a thermophotovoltaic (TPV) approach to a hydrocarbon-fueled microgenerator. TPV is the conversion of heat-to-electricity via the thermal emission of photons and their subsequent absorption and conversion to electricity by low bandgap photovoltaic (PV) cells. In our TPV system, shown in Fig. 1(a), propane is burned in a microburner to generate heat which brings a photonic crystal emitter to incandescence and the resulting thermal radiation drives a suitable low bandgap PV cell. This approach is extremely appealing for microgenerators

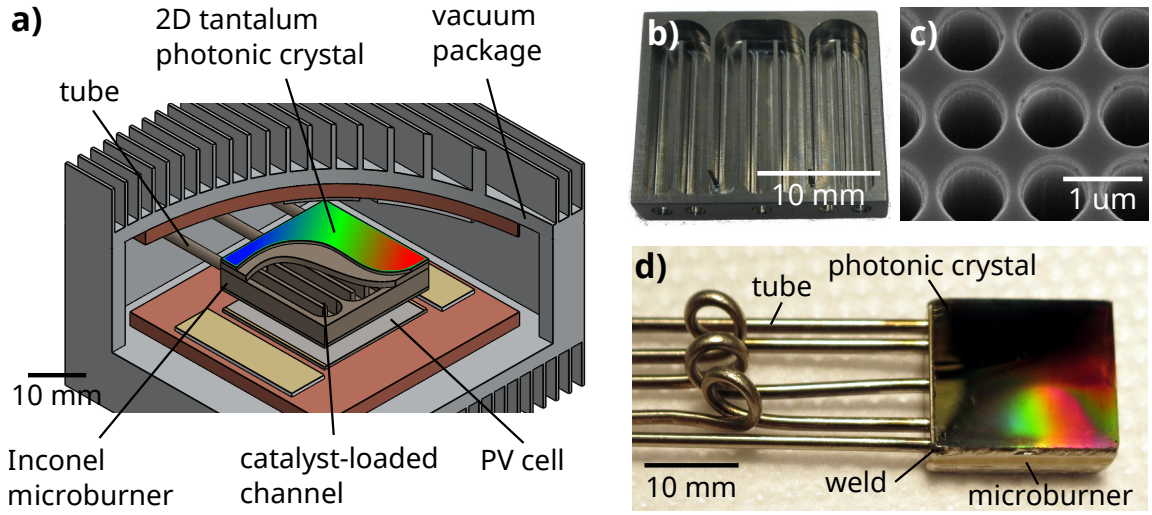

Figure 1. (a) A labeled CAD model of the conceptual TPV microgenerator based on our experimental setup comprised of an Inconel microburner to convert fuel into heat, a photonic crystal emitter to convert the heat into spectrally confined infrared radiation, and PV cells to convert the infrared spectrum into electricity. (b) A photograph of microburner interior with visible channels. (c) A SEM micrograph of the photonic crystal depicting etched cavities. (d) The microburner with attached tubes and photonic crystal.

because of its fully static conversion process, multifuel operation, and high specific power relative to other static conversion processes.

Unfortunately, the demonstrated fuel-to-electricity efficiency of millimeter-scale TPV systems has traditionally been limited to a few percent because of the need for high temperature material performance and synchronization between chemical, thermal, optical, and electrical domains [3–6]. One of the fundamental challenges to realizing a high efficiency is matching the radiated spectrum to the quantum efficiency of the PV cell. The PV cell can convert in-band radiation (photon energies above its bandgap) reasonably efficiently to electricity but out-of-band (photon energies below its bandgap) are wasted. Thus, a selective emitter with high in-band emissivity and low out-of-band emissivity is required. In this work we present a new approach to TPV enabled by a photonic crystal selective emitter, capable of near perfect spectral control, that promises to realize a high fuel-to-electricity efficiency. The low achieved efficiency is not a fundamental limitation of TPV: fuel-to-electricity efficiency of 30% should be achievable with this approach [7].

2. System demonstration

Although considerable technological barriers still need to be overcome to reach full performance, we have performed a robust experimental demonstration that validates the theoretical framework and the key system components. Our system was comprised of an Inconel microburner, 2D photonic crystal, and low bandgap PV cells.

The microburner, shown in Fig. 1, was a 20×20×3 mm chip with an internal catalyst-loaded serpentine channel suspended on tubes that doubled as fluidic connections [8]. Unmixed propane and oxygen were flowed coaxially through the inlet tubes which contained an inner capillary in a tube-in-tube configuration. Upon entering the channel, the gases mixed and reacted on the alumina supported platinum catalyst washcoated on the walls to generate heat. The exhaust gases exited through an outlet tube. The channel width and total length were designed for

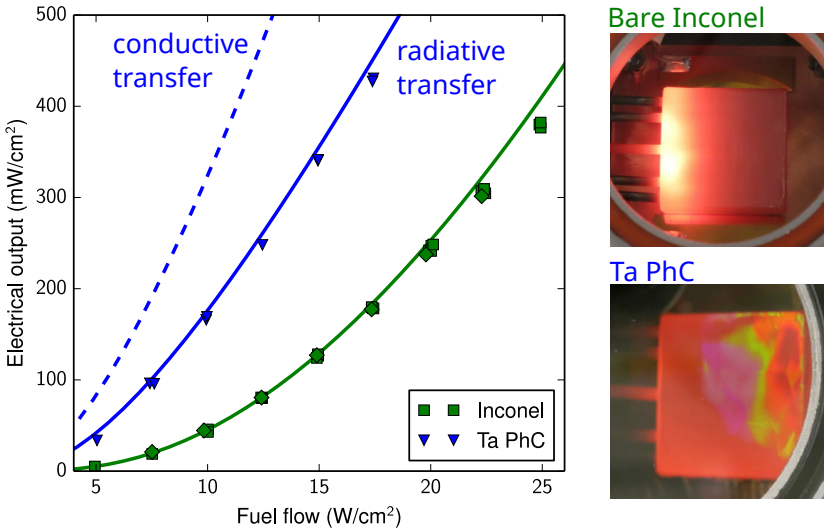

Figure 2. Fuel-to-electricity experimental results obtained from the TPV system. A microburner with and without a photonic crystal emitter, shown to the right, was characterized. Electrical power was scaled for a full set of cells.

complete combustion at the target fuel flow: the timescale for diffusive transverse transport of unreacted gases to catalyst sites on the walls was much shorter than the residence time in the channel. The microburner was fabricated from Inconel, which offers high temperature oxidation resistance, by machining and welding. The tubes were welded into holes drilled into the edge of the machined microburner, then the exposed channels were sealed by welding on a cover.

The 2D photonic crystal, shown in Fig. 1(c), was comprised of a square array of cylindrical cavities defined by interference lithography and deep reactive ion etching in a polished tantalum substrate [9]. The thermal emission spectrum was selectively enhanced through the introduction of cavity resonances in a wavelength range controlled by the geometry of the structure. Outside of the enhanced region, the thermal emission approached that of the metallic substrate. The present photonic crystal, which was only optimized for emission at normal incidence, achieved a hemispherically averaged in-band emissivity of $\varepsilon_{in} = 0.59$ and out-of-band emissivity of $\varepsilon_{out} = 0.16$. With dielectric-filled cavities, the in-band emissivity is predicted to increase to $\varepsilon_{in} = 0.92$ while maintaining the same out-of-band emissivity [10].

The microburner and photonic crystal were integrated by electron beam welding, as shown in Fig. 1(d). The hot side assembly was partially surrounded with either InGaAsSb [11, 12] or InGaAs [13] cells which were maintained at 20°C with a chilled water loop. The distance between the emitter and cells was approximately 1 mm. The microburner, emitter, and cells were contained in a vacuum chamber (5×10^{-5} Torr base pressure) to prevent oxidation of the photonic crystal and convective losses. A CaF window replaced cells on one side (the reported electrical output was scaled for a full set of cells on the front and back of the microburner) in order to allow for infrared temperature measurement and optical preheating.

To ignite the microburner, it was heated to approximately 400°C with a halogen lamp. Above that temperature, the propane kinetics over the catalyst were sufficient for autothermal operation, and the lamp was shut off. The fuel and oxygen flows were increased in small increments, maintaining an equivalence ratio of $\phi = 1.5$. Once steady state was reached, the electrical power output (at the maximum power point) was recorded and is reported in Fig. 2. Initial trials with a welded photonic crystal fell short of expectations because the weld was

only made around the perimeter resulting in poor heat transfer between the microburner and photonic crystal. Measured electrical output was consistent with pure radiative heat transfer between the microburner and emitter. We are currently brazing the photonic crystal to the microburner for improved heat transfer. The electrical output for conductive heat transfer between the microburner and photonic crystal is shown in Fig. 2.

3. Towards a TPV microgenerator

In order to move from this bench-top demonstration to a portable microgenerator, we need to redesign the microburner and develop vacuum packaging. The first challenge is developing a vacuum package to maintain a vacuum level sufficient to prevent convective losses and degradation of the photonic crystal. While difficult, vacuum packaging has been successfully demonstrated in MEMS devices and incandescent and fluorescent light bulbs.

The second challenge is to realize an air-breathing microburner capable of processing conventional liquid fuels (gasoline, diesel, and JP-8 military logistics fuel). Transitioning from a gaseous single component, light hydrocarbon fuel to a liquid multi-component, heavy hydrocarbon fuels will require the microburner to compensate for overall longer diffusion times in combustion dominated by surface reactions, fuel vaporization or atomization, and potentially increased carbon formation due to the sulfur and aromatic content of the fuels. The transition from pure oxygen to air-breathing will require the microburner to compensate for a higher flow velocity that both decreases residence time and increases the exhaust heat loss. Excess enthalpy through exhaust heat recirculation holds promise to counteract the variable thermodynamic properties, longer diffusion times, higher flow velocity, and provide heat for vaporization by pre-heating the fuel and air using heat exchanged from the exhaust. These challenges in microburner design are not insurmountable and can leverage the extensive knowledge in microchannel heat exchanger technology.

4. Conclusion

We performed an initial proof-of-concept demonstration of a TPV system as a step towards a TPV microgenerator that could fill the 1–100 W gap between batteries and conventional generators by extending the high specific energy hydrocarbon generators to the millimeter scale. Our TPV demonstration used an Inconel microburner, 2D photonic crystal emitter, and low bandgap TPV cells. Our initial results indicated that TPV can be used in a high specific energy microgenerator, and with modest improvements (improved microburner-emitter heat transfer, filled cavity photonic crystal) greatly improved fuel-to-electricity efficiency is possible. Furthermore, we presented a path towards a TPV microgenerator.

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