MNHMT2016-6695

A THERMOPHOTOVOLTAIC SYSTEM USING
A PHOTONIC CRYSTAL EMITTER

Walker R. Chan,[*] **Veronika Stelmakh, Marin Soljacic,**
John D. Joannopoulos, Ivan Celanovic
Massachusetts Institute of Technology
Cambridge, Massachusetts, 02139
Email: wrchan@mit.edu

Christopher M. Waits
Sensors and Electron Devices Directorate
US Army Research Laboratory
Adelphi, Maryland, 20783

ABSTRACT

The increasing power demands of portable electronics and micro robotics has driven recent interest in millimeter-scale microgenerators. Many technologies (fuel cells, Stirling, thermoelectric, etc.) that potentially enable a portable hydrocarbon microgenerator are under active investigation. Hydrocarbon fuels have specific energies fifty times those of batteries, thus even a relatively inefficient generator can exceed the specific energy of batteries. We proposed, designed, and demonstrated a first-of-a-kind millimeter-scale thermophotovoltaic (TPV) system with a photonic crystal emitter. In a TPV system, combustion heats an emitter to incandescence and the resulting thermal radiation is converted to electricity by photovoltaic cells. Our approach uses a moderate temperature (1000–1200°C) metallic microburner coupled to a high emissivity, high selectivity photonic crystal selective emitter and low bandgap PV cells. This approach is predicted to be capable of up to 30% efficient fuel-to-electricity conversion within a millimeter-scale form factor. We have performed a robust experimental demonstration that validates the theoretical framework and the key system components, and present our results in the context of a TPV microgenerator. Although considerable technological barriers need to be overcome to realize a TPV microgenerator, we predict that 700–900 Wh/kg is possible with the current technology.

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[*]Address all correspondence to this author

INTRODUCTION

For durations greater than one day, the energy demands of portable electronics and micro robotics are too large to be comfortably supplied by batteries and yet too small to warrant a conventional gasoline or diesel generator. Microgenerators promise to fill the 1–100 W range in a compact form factor by harnessing the high specific energy of hydrocarbon fuels at 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, many different technologies are under active investigation for both military and commercial applications: fuel cells, mechanical engines, thermoelectrics, and thermophotovoltaics [1, 2].

Thermophotovoltaics (TPV) is a method of converting heat to electricity using infrared light as an intermediary. As shown in Fig. 1, combustion heats an emitter to incandescence and the resulting thermal radiation is converted to electricity by a photovoltaic (PV) cell. The difference between a solar PV system and a TPV system is that a TPV system produces its own light— the spectrum does not need to be the solar spectrum or even a blackbody, and the cells do not need to be silicon. Despite the indirect energy conversion pathway, TPV offers some advantages over batteries and other microgenerator technologies: a static conversion process allows favorable scaling down to the millimeter scale, the high power density of combustion and thermal radiation results in a compact microgenerator, the hot and

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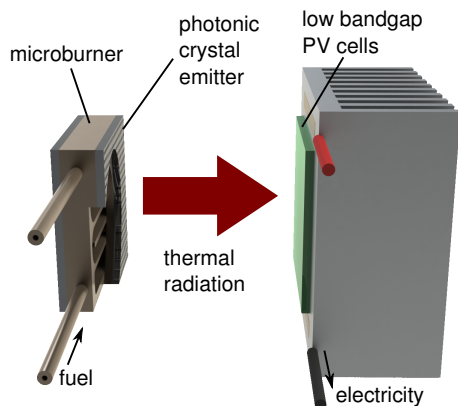
FIGURE 1. IN THE TPV CONVERSION PROCESS, COMBUSTION IN A MICROBURNER HEATS AN EMITTER TO INCANDESCENCE AND THE RESULTING THERMAL RADIATION DRIVES A LOW-BANDGAP PV CELL.

FIGURE 2. THERMAL RADIATION SPECTRUM OF THE 2D PHOTONIC CRYSTAL EMITTER AT 1300 K WITH THE IN-BAND REGION HIGHLIGHTED. INSET: AN SEM MICROGRAPH OF THE PHOTONIC CRYSTAL.

cold sides are physically separated, and continuous combustion allows for complete combustion of conventional fuels at the millimeter scale.

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 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 radiation (photon energies below its bandgap) is 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 experimentally achieved efficiency is not a fundamental limitation of TPV: fuel-to-electricity efficiency of 30% is predicted [7].

PHOTONIC CRYSTAL EMITTER

A selective emitter has a high in-band emissivity and low out-of-band emissivity in order to spectrally confine the thermal radiation to the wavelength band convertible by the PV cell. Recent advances in photonic crystals allow near step function emissivity and have spurred renewed interest in TPV [8, 9]. Photonic crystals are classified as 1D, 2D, or 3D according to the number of periodic dimensions and their emission spectrum is primarily determined by the geometry rather than by specific material properties, allowing the cutoff wavelength to be tuned. More-
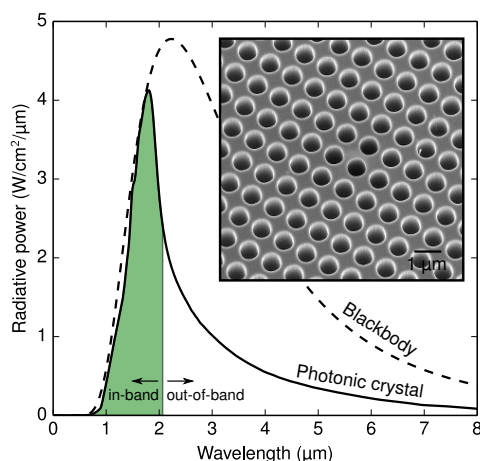
over, they typically offer near blackbody emission resulting from resonant phenomenon at the desired wavelengths and near-zero emission elsewhere resulting form the low-loss materials from which they are fabricated.

Photonic crystal emitters offer advantages over other spectral control approaches such as a cold side filter or naturally spectrally selective materials. A cold side filter, implemented as a tandem plasma and interference filter between the emitter and cell, transmits some wavelengths to the cell and reflects others back to the emitter [10]. Cold side filters require a low-loss emitter-filter-cell optical cavity which is difficult to achieve in a practical microgenerator. Natural emitters, such as erbium [11], tend to have low overall emissivity, allowing parasitic heat loss mechanisms to dominate the heat balance.

The 2D photonic crystal used in this work was comprised of a square array of cylindrical cavities etched in a metallic substrate as shown in Fig. 2, and offered a combination of high emissivity, high spectral selectivity, and relative ease of fabrication. The thermal emission spectrum was 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. Fig. 2 shows the normal high-temperature emission of our 2D photonic crystal compared to a blackbody at the same temperature. The convertible region of an InGaAs cell is shown for reference. The current 2D photonic crystal is capable of hemispherically averaged in-band emissivity of $\varepsilon_{in} = 0.59$ and out-of-band emissivity of $\varepsilon_{out} = 0.17$ [12].

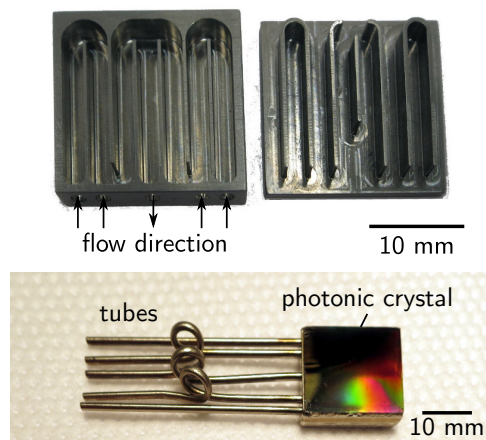The photonic crystal was fabricated by interference lithog-

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FIGURE 3. UNASSEMBLED (TOP) AND ASSEMBLED (BOTTOM) MICROBURNER WITH THE PHOTONIC CRYSTAL EMITTER.

FIGURE 4. EXPERIMENTAL RESULTS INCLUDING THE SILICON SYSTEM FROM REF. 6 FOR COMPARISON.

raphy and deep reactive ion etching using a silicon dioxide hard mask in a polished tantalum substrate then coated with hafnia by atomic layer deposition [13]. A refractory metal was used due to its high melting temperature, low vapor pressure, and low optical loss in the infrared. Tantalum was chosen over other refractory metals (tungsten, molybdenum, niobium, and rhenium) [14] based on the commercial availability of relatively low-cost foil of high metallurgical quality as well as its fast etch rate.

MICROBURNER

The microburner, shown in Fig. 3, was fabricated from Inconel because of its high temperature oxidation resistance, machinability, off the shelf availability, and because it can be integrated with the tantalum photonic crystal by welding or brazing. The microburner was a $20 \times 20 \times 3$ mm chip with an internal serpentine channel, designed after our previous work in silicon MEMS microburners [6]. Propane and oxygen were flowed through the channel and reacted on the catalyst-coated walls to generate heat. The heat was then conducted through the metal to the emitters attached on the front and back surfaces, which radiated the heat to the PV cells.

The channel was dimensioned for complete combustion under the assumption that diffusive transverse transport of unreacted gases to catalyst sites on the channel wall was the dominant time constant. Thus, the channel was made sufficiently long and narrow to ensure residence time was much greater than the diffusion time. The channels were fabricated in a block of Inconel by conventional machining. Small diameter tubes, doubling as fluidic connections and mechanical supports, were welded into holes drilled into the edge of the microburner. A loop was bent
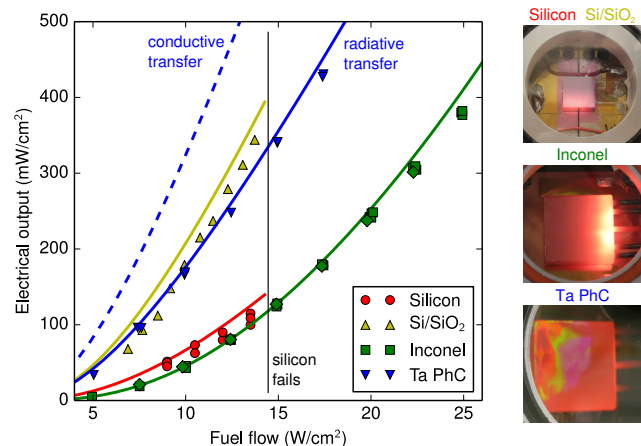
in all but two tubes for strain relief. Finally, the exposed channels were sealed by welding on a cover. The finished assembly was mounted in our experimental apparatus by welding. The microburner was operated in vacuum to eliminate convective losses.

We characterized the microburner as described fully in Ref. 15. The microburner was ignited by optical preheating with a halogen lamp until the propane kinetics over the catalyst were sufficient for autothermal operation at which point the lamp was shut off. The fuel flow was increased in small increments and infrared temperature measurements were made. These measurements agreed well with our simple analytical heat balance model as well as a computational fluid dynamics model.

SYSTEM DEMONSTRATION

The microburner and photonic crystal were integrated by electron beam welding. The hot side assembly was partially surrounded with either InGaAsSb [16] or InGaAs [17] (reported electrical output was scaled for a full set of 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) to prevent oxidation of the photonic crystal and convective losses.

The microburner was ignited and operated as described previously and the electrical power output (at the maximum power point) was recorded at steady state for series of fuel flows. We characterized both an oxidized Inconel emitter with uniform $\varepsilon = 0.8$ emissivity and the photonic crystal emitter, as reported in Fig. 4. 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
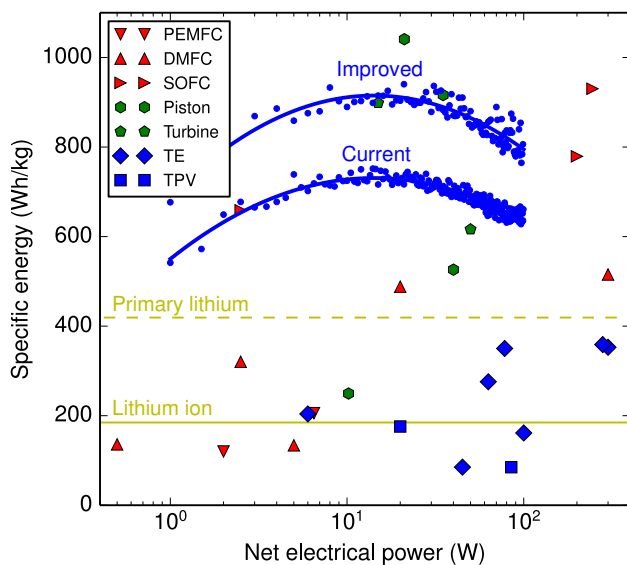
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FIGURE 5. ESTIMATED SPECIFIC ENERGY FOR A TPV MICROGENERATOR ON A THREE DAY MISSION.

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 simulated electrical output for conductive heat transfer between the microburner and photonic crystal is shown in Fig. 4.

TOWARDS A MICROGENERATOR

The microburner-emitter-cell TPV system is only one component of a complete TPV microgenerator: a microgenerator additionally requires hermetic vacuum packaging, cell cooling, fuel storage and delivery, an ignition mechanism, and control and power electronics. One immediate requirement in moving from the present bench-top demonstration to a portable microgenerator is an air-breathing microburner capable of processing conventional liquid fuels (gasoline, diesel, and JP-8 military logistics fuel). The current microburner relies on propane and oxygen for simplicity. Transitioning from a gaseous single component, light hydrocarbon fuel to a liquid multi-component, heavy hydrocarbon fuel 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. Furthermore, 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.

Although considerable engineering challenges must be overcome to realize a TPV microgenerator, we extrapolated its specific energy from the experimental system. We cannot rely solely on the fuel mass estimated from the experimental fuel-to-electricity efficiency because the mass of the microgenerator itself contributes significantly to the total mass for a real mission of finite duration. Thus, we attempted to estimate the mass of a completed TPV microgenerator by assuming that the mass was dominated by the heat sink required to cool the cells. We coupled a temperature-dependent cell model with a fan-cooled heat sink model and numerically optimized the heat sink area, TPV system area, and fan power for lowest total mass for each net electrical output power [18, 19]. The analysis was repeated for a photonic crystal emitter with improved hemispherical emissivity and a cold side filter [12]. Results are plotted in Fig. 5 with other microgenerators from literature for comparison [20]. We predict ~700 Wh/kg using the current photonic crystal (with conductive heat transfer) and ~900 Wh/kg with improvements for a net output power of 10 W. These numbers significantly exceed the specific energy of lithium ion batteries, indicating that a TPV micrognerator would be a viable replacement for certain applications.

CONCLUSION

We have performed a robust experimental demonstration of a photonic crystal enabled TPV system that validates the theoretical framework and the key system components. Our demonstration is initial work on a high specific energy, hydrocarbon fueled TPV microgenerator that would fill the 1–100 W gap between batteries and conventional generators. We predict that our approach to a TPV microgenerator is capable of 700–900 Wh/kg at a 10 W output, thus extending the high specific energy of hydrocarbon fuel to the millimeter scale.

ACKNOWLEDGMENT

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