Enhancing the Efficiency of Thermophotovoltaics with Photon Recycling

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Abstract: We show that photon recycling utilizing the spectral selectivity of the photovoltaic band edge enables 48% thermophotovoltaic heat-to-electricity conversion efficiency at 1200°C with $In_{0.47}Ga_{0.53}As$ cells, and present experimental methods to demonstrate this concept.
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1. Introduction

Thermophotovoltaics (TPV) converts heat energy to electrical energy through the photovoltaic conversion of thermal radiation. Rather than the Sun, the radiation source used in TPV is a local hot object, typically at a lower temperature of ~1200°C. In addition to the differences in illumination intensity and incident spectra relative to sunlight, the local nature of the source in TPV provides new means of spectral control that are not available in solar energy harvesting. One opportunity is to engineer the spectrum of the source emission to match the photovoltaic bandgap [1], but this makes it challenging to achieve high output power densities due to the narrow band of emission.

Alternatively, the spectral selectivity in the absorptivity of the photovoltaic band edge can be exploited for TPV. The unabsorbed below-bandgap photons can be returned to the source by a back reflector, so that their energy can be used for reheating the source. We show that large gains in TPV conversion efficiency are possible with this scheme.

2. Thermophotovoltaic Efficiency Enhancement by Photon Recycling

Fig. 1(a) shows a TPV cavity in which a radiative source is surrounded by photovoltaic cells with reflective back surfaces. In the presence of the reflectors, the internal radiation in the cavity (made up of below-bandgap photons) provides part of the power needed to keep the source at a high temperature, reducing the power that must be drawn externally. Furthermore, if the source has below-unity emissivity, a highly reflective cavity ensures that the below-bandgap photons will eventually be absorbed by the source after many reflections. Thus, the internal radiation will be close to that of a blackbody at the source temperature for energies below the bandgap, even for low emissivity.

For the simple, fully closed cavity shown in Fig. 1(a), the TPV conversion efficiency η_{TPV} is given by:

$$\eta_{TPV} = \frac{J_{OP} \cdot V_{OP}}{\int_0^\infty b_s(E,T_S)\,dE - R\int_0^{E_g} b_s(E,T_S)\,dE}, \tag{1}$$

where J_{OP} and V_{OP} are the cell's current and voltage at the maximum power point, E is the photon energy, $b_S(E, T_S)$ is the blackbody spectral irradiance (in power/area/photon energy) at a source temperature T_S, E_g is the cell bandgap, and R is the below-bandgap reflectivity of the cell. We assume complete absorption of above-bandgap photons for

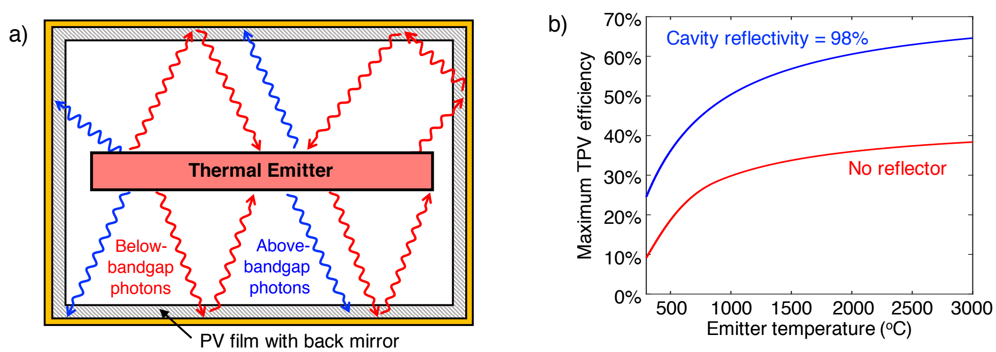

Fig. 1: (a) Reflective thermophotovoltaic cavity: above-bandgap photons (blue) are converted by the photovoltaic cells, while the unabsorbed below-bandgap photons (red) are returned to the emitter. (b) Maximum thermophotovoltaic conversion eficiency vs. temperature with and without photon recycling, calculated using detailed-balance methods [2].

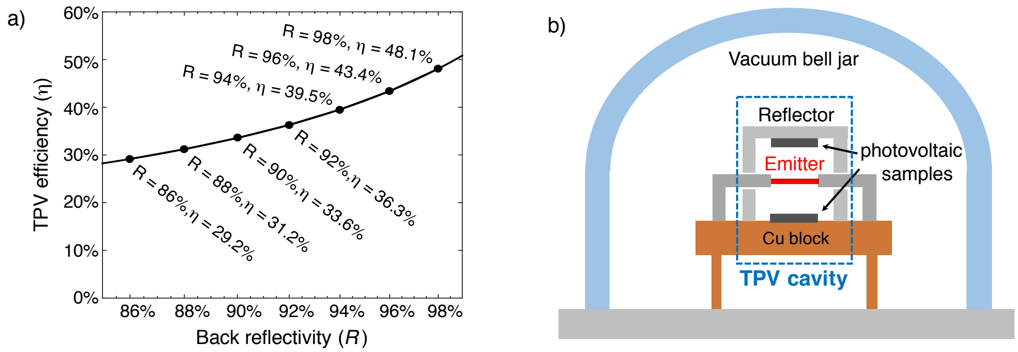

Fig. 2: (a) Predicted TPV efficiency using $In_{0.53}Ga_{0.47}As$ cells for various values of the back reflectivity, at a source temperature of 1200ºC. (b) Diagram of the test chamber to be used for experimental demonstration of TPV enhanced by photon recycling.

simplicity. The second term in the denominator represents the thermal radiation that is returned to the source. Fig. 1(b) compares the TPV efficiency without photon recycling to the cavity-enhanced efficiency with a cell reflectivity of $R = 98\%$. Optimal bandgaps and ideal materials were assumed in both cases. The presence of a good back mirror provides a substantial increase in TPV efficiency at any source temperature.

A suitable material for TPV at 1200ºC (practical for combustion heat sources) is $In_{0.53}Ga_{0.47}As$, which has a direct bandgap of 0.75 eV at room temperature. Fig. 2(a) shows the attainable TPV efficiency with this material for several values of the back reflectivity, calculated using the measured recombination lifetimes in $In_{0.53}Ga_{0.47}As$ [3]. With a reflectivity of 98%, an efficiency of 48.1% is possible. Prior experiments with InGaAs alloys and a 1039ºC source have achieved an efficiency of 23.6% [4], but without the benefit of high cell reflectivity. The need for very high cell reflectivity (>>90%) to reach high solar conversion efficiency has led to technological advances that enable the same for TPV [5]. Epitaxial liftoff can be used to separate a thin film of InGaAs from its substrate and transfer it to a metal surface [6], providing high cell reflectivity with minimal absorption of below-bandgap photons.

3. Experimental Demonstration of Thermophotovoltaic Cavity

We have observed the phenomenon of source reheating by recycled photons in a cavity consisting of a planar, ceramic electric heater with an emissive coating (232 cm^2, 0.85 average emissivity) and a copper plate (316 cm^2) placed 1 mm away. At a temperature of 1085ºC, the heater emits 16.4 W/cm^2 in thermal photons, but only requires 1.03 W/cm^2 of electrical input to sustain that temperature, with the remainder provided by reflected photons. This implies an effective cavity reflectivity of 94.6% including external losses and assuming a spatially uniform source temperature.

To experimentally confirm the efficiency gain provided by photon recycling, we have constructed the TPV cavity shown in Fig. 2(b). The reflective cavity surrounds a graphite strip, which acts as a thermal emitter via resistive heating to 1200ºC. Photovoltaic samples can be placed along the walls, maintained at room temperature by a water-cooled copper block at the cavity base. $In_{0.53}Ga_{0.47}As$ photovoltaic cells, with 4 mm^2 area and a measured open-circuit voltage of 400 mV under 1-sun solar illumination, will be used for this experiment. The cavity is enclosed in a vacuum bell jar at 10^{-5} Torr to minimize conductive and convective heat loss. We will evaluate the system's TPV efficiency by comparing the photovoltaic power output to the optical power incident upon the cell that is not reflected back.

4. Conclusion

We have shown that substantial improvements in TPV efficiency are possible by recycling unused photons back to the source, taking advantage of the photovoltaic band edge as the spectral filter. With the capability to produce highly reflective $In_{0.53}Ga_{0.47}As$ photovoltaic cells, 48% TPV efficiency can be reached at a 1200ºC source temperature. Future experiments using a reflective TPV chamber under vacuum will demonstrate the predicted efficiency enhancement.

5. References

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