3% conversion efficiency in Thermally Enhanced Photoluminescence (TEPL) illuminated solely by sub-bandgap photons.

Assaf Manor, Nimrod Kruger, and Carmel Rotschild

We recently investigated TEPL[1], where the photon rate in photoluminescence (PL) is conserved with temperature increase, while the emission spectrum is blue-shifted up to a limit of abrupt transition to thermal emission. We demonstrated how TEPL is an ideal optical heat-pump that generates orders of magnitude more energetic photons than equivalent thermal emission. Here, we theoretically study TEPL at practical conditions that approaches 50% efficiency and experimentally demonstrate 3% efficiency of TEPL that is illuminated solely by sub bandgap photons at 600K.

TEPL is based on the chemical potential of PL[2]. An Ideal TEPL device is consists of a thermally-insulated low-bandgap photoluminescent absorber, able to completely absorb the solar spectrum above its bandgap (fig.1a-b). The otherwise lost thermalization heat raises the temperature of the absorber and induces blue-shifted PL with unity quantum efficiency (QE). A higher bandgap PV cell, maintained at room temperature, absorbs the emitted endothermic-PL thus converting the excessive thermal energy to increased voltage and efficiency. Efficiencies as high as 70%, at operating at temperatures below 1300K, were predicted for ideal configuration[1].

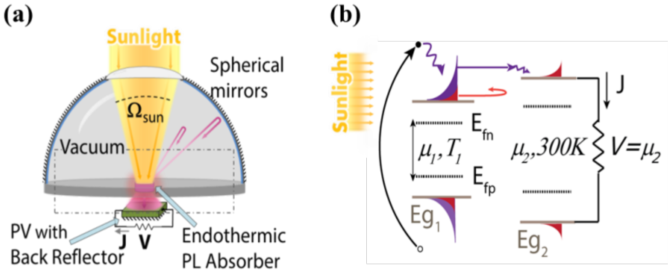

Figure 1: TEPL energy conversion device: (a) a scheme of a domed-planer TEPL converter consisting of a planar PL absorber, concentration lens and a reflective semi-ellipsoid dome, over a PV cell with a back reflector. (b) The absorber and PV energy diagram with the population of photo-excitations and current flows.

We now consider practical parameters governing the system's thermodynamics. These also include: **(i)** Solar concentration, **(ii)** photon recycling, **(iii)** conductive heat loss, **(iv)** absorber-QE. We analyse the effect of these parameters for ideal absorber and PV, with a step function emissivity of 1.1eV & 1.43eV respectively. Efficiency for various solar concentrations and operating temperature are presented in Figure 2a. Evidently, efficiencies higher than 49% can be reached, even for solar concentration as low as 50 suns. In Figure 2b we analyse the efficiency as function of photon recycling. Results are presented for solar concentration of 10 & 500 suns and absorber-QE of 0.98 & 1. As depicted, QE and photon recycling of values above 98% can support 43% conversion efficiency at solar concentration of 500 suns, or 39% for only 10 suns. We also compare the expected efficiency of TEPL with a thermal body, as in STPV, operating at similar conditions. As can be seen in Figure 2c, both concepts reach the same high efficiency at very high temperatures (above 2300K), while at practical temperatures below 2000K, the TEPL is far more efficient due to its low entropy generation.

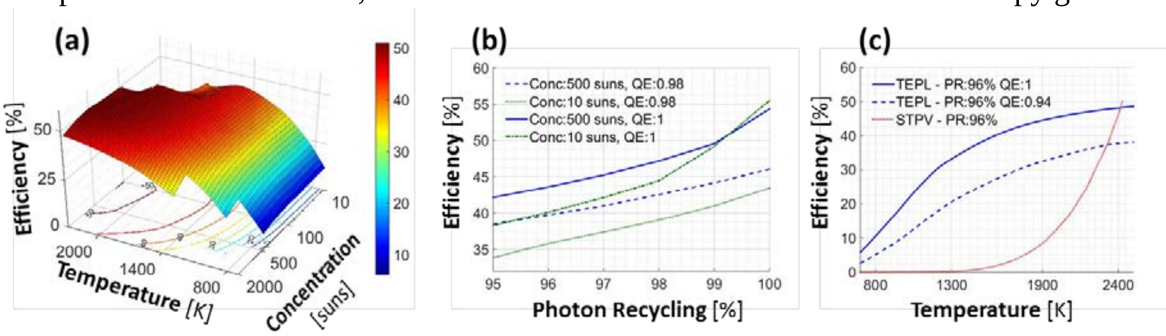

Figure 2: Efficiency at practical parameters. (a) Efficiency for various solar-concentration and operating-temperatures with 98% photon recycling. (b) Efficiency Vs. photon recycling for different solar concentrations and absorber-QE with Temperature<2000K. (c) Efficiency for both TEPL (absorber-QE 0.94 and 1) and TPV device (1.1eV absorber & PV bandgap) as a function of absorber temperature at 96% photon recycling and 500 suns.

For the TEPL device proof of concept we now elect a Nd^{3+}:Phosphate Glass PL system as was previously analysed. Rare-earth ions such as Neodymium and Ytterbium are an excellent material choice as their electrons are localized and insulated from interactions, resulting in their excellent QE conservation at high temperatures[3]. In this work, we ignore the poor overlap between the solar spectrum and the Nd^{3+} absorption, and leave its improvement of to future research. The experimental setup (fig. 3a) includes a vacuum-insulated sample coupled to a $1mm^2$ GaAs solar cell and a fiber coupled spectrum analyser. The sample is pumped by a high power 532nm laser in parallel to a 914nm laser, the latter being a source of sub-bandgap photons with respect to the GaAs cell.

First we turn on the 532nm high power laser until temperature reaches steady state. Then the laser is switched off and the 914nm pump is switched on. Under this scenario the high power 532nm laser acts only as a heat source, while the PV current is only due to the thermally induced blue shift of the 914nm pump, as shown in figure 3b for different temperatures. Figure 3c shows the conversion efficiency versus temperature. The red plot shows the up-conversion efficiency from the pumped 914nm line into energies above the GaAs bandgap of 1.44eV (λ<862nm). Although it peaks at almost 6%, the actual conversion efficiencies to expect from PV cells are lower, due to thermalization at the PV. The blue plot shows the conversion efficiency that a state-of-the-art (SOTA) cell [η=28.8% under 1 sun illumination] would yield when placed in the system, while the green plot shows our $1mm^2$ cell conversion efficiency (η=17% under 1 sun illumination). At room temperature, the blue shift is relatively small, resulting in ~0.3% - 0.5% efficiency for the tested and SOTA cells. The efficiency peaks at 600K to1.4% and 2.7% for the tested and SOTA cell, respectively. As can be seen, above 600K the efficiency is limited. This saturation effect was not evident with silica matrix[1].

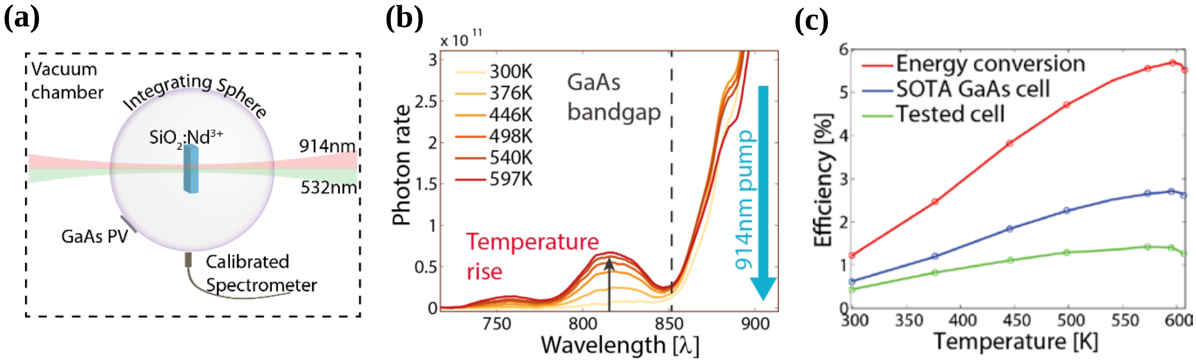

Figure 3. Experimental TEPL demonstration: (a) Experimental setup - Nd^{3+}: Glass sample, in an integration sphere in a vacuum chamber, co-pumped by 532nm and 914nm lasers. (b) Temperature dependence of the PL blue-shift. The 914nm pump is indicated to the right and the GaAs bandgap is indicated by the dotted line. (c) Total up-converted energy (red) State-of-the-art cell projected up-conversion efficiency (blue) and the tested PV efficiency (green) temperature dependence.

To conclude, in this paper we presented, thermodynamically analysed and demonstrated the concept of TEPL based solar energy converter. We shows that, in contrast to the long-standing STPV concept, which requires extremely high working temperatures, a TEPL converter is theoretically capable of reaching efficiencies of nearly 70% at moderate temperatures of ~1100K. To experimentally elucidate the potential the TEPL potential, we have measured 3% efficiency of a proof-of-concept TEPL system, at temperature of only 600K. Working with Silica matrix enables to reach 1300K with much higher efficiencies[1]. This together with broadening the absorption of solar spectrum will pave a new path in photovoltaic technology.

References

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