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Micron-gap thermophotovoltaic systems enhanced by nanowires

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Abstract

We introduce new micron-gap thermophotovoltaic systems enhanced by tungsten nanowires. We theoretically show that these systems allow the frequency-selective super-Planckian spectrum of radiative heat transfer that promises a very efficient generation of electricity. Our system analysis covers practical aspects such as output power per unit area and efficiency of the tap water cooling.

Keywords: Wire metamaterial; Hyperbolic metamaterial; Radiative heat transfer; Thermophotovoltaic system; Photovoltaic efficiency

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1. Introduction

As an estimate, up to 50% of the energy involved in the industrial processes finally delivers as waste heat. Mankind needs to exploit this energy to generate electric power. It can be done indirectly, e.g. via vapor (Stirling's) machinery, or directly. Several methods of the heat-electricity conversion are known: thermoelectric, pyroelectric, thermophotovoltaic, and thermophotogalvanic. Unlike Stirling's machines such direct generators do not have moving parts and no permanent technical service is needed. Thermophotovoltaic (TPV) conversion has attracted significant attention from the research community in the last decade [1] due to its potentially highest efficiency. TPV systems are based on the photovoltaic (PV) effect manifested by the photocurrent. The PV cell absorbs the thermal radiation produced by the rear side of emitter whose front side is connected to the heat source, e.g. flame, see in Fig. 1. For high temperatures of the emitter, corresponding to the near-infrared radiation (NIR), the TPV efficiency is higher compared to other known mechanisms of the direct heat-electricity conversion [2]. Not only wasted heat can be converted, using TPV devices. TPV generators with combustion cameras are also prospective for the domestic use [1,2].

In spite of striking advantages of TPV devices as electric generators, a key problem of these systems is a disappointing gap between the maximally achievable and practically achieved operation parameters. For given temperatures of the emitter and the PV panel the electric power output per unit area (p.u.a.) of any known TPV system is much below its theoretically possible maximum [3]. One of main reasons of this situation is non-advantageous, extremely broad spectrum of emitted radiation. It is commonly (and incorrectly [4]) adopted that the maximal thermal radiation in all possible situations is radiation of a black body to free space. Therefore, the emitters mimicking the black body are often considered as best ones. The spectrum of its radiation has relative bandwidth (BW) which, defined on the 10% level, exceeds 500% even for temperature as high as

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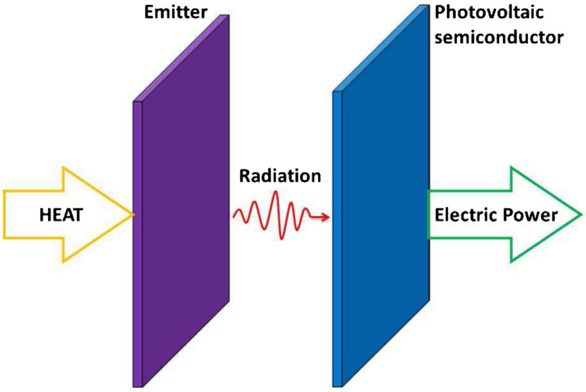

Fig. 1. Principle of a TPV system.

2000 °K. The operational band of a PV semiconductor is much narrower – its BW is nearly 100%. Therefore, a large amount of thermal radiation in a TPV system is unusable [5]. The radiation at frequencies below that of the semiconductor bandgap is completely harmful. At these frequencies, all thermal photons transmitted to the PV medium are dissipated and heat the PV panel destroying its operation. The PV operational band is narrower than the upper half of the thermal radiation spectrum (that above the bandgap frequency). Thus, the frequencies of thermal radiation which are twofold and greater than the bandgap frequency are also fully harmful. The harmful action of the unusable spectrum is prevented in TPV systems with optical filters. These filters, roughly speaking, transmit only a useful part of the spectrum removing the reflection in this band. The harmful radiation is reflected. As a rule, these filters represent a multi-layer structure of transparent dielectrics [1,2]. It is clear that filtering though allows a TPV system to operate does not solve the problem of losses.

Avoiding these losses is possible by squeezing the radiation spectrum compared to that of a black body. This regime may be offered by a frequency-selective emitter. Its radiation spectrum in the ideal case should mimic that of a black body within the PV operational band and vanish beyond it. Using frequency-selective emitters, one achieves high values of the TPV efficiency – up to 20% (see e.g. in [6]). Such advanced emitters may be based on photonic crystals or metamaterials. Particularly high TPV efficiency – up to 40% – is theoretically achieved for solar TPV systems, where advanced emitters also serve perfect absorbers of the sunlight [7–9]. However, the total radiation of any known advanced emitters over the PV operational band is noticeably lower than the Planckian limit. Practically, the spectrum of a metamaterial thermal emitter attains the black-body spectrum only at resonant frequency. Also, beyond the operational band the thermal radiation of these emitters is not negligible. Therefore, the electric power output p.u.a. in these systems is not very high. For emitters with temperatures $T^{(1)} = 2000\,^{\circ}\mathrm{K}$ this value in theoretical estimates [7–9] corresponds to 1.5–2 W/cm^2 that is only twice as higher as that achieved in best available TPV systems operating at the same temperature [10].

2. Micron-gap TPV systems enhanced by hyperbolic metamaterials

Recently, advanced TPV systems were introduced: so-called near-field systems comprising a nanogap between the PV medium and the emitter (see e.g. in [11]) and micron-gap ones fabricated by stacking the PV panel and the emitter separated by micron (or slightly submicron) spacers (see e.g. in [12,13]). They possess so-called super-Planckian (SP) radiative heat transfer (RHT). In a micron-gap TPV system the emitter transfers to the PV panel more power p.u.a. than the black body of the same temperature may do. The gain compared to a black-body emitter may be twofold and occurs due to the so-called photon tunneling effect [2,5,11,14]. In a near-field TPV system the photon tunneling is stronger and the gain compared to the black body may attain 3–4 orders of magnitude (see e.g. in [2,11]). Unfortunately, the concept of a TPV filter is very difficult to implement for these advanced TPV systems: the RHT decays across a filter and the SP effect is lost. Therefore, in spite of high radiation fluxes, higher electric output compared to conventional TPV systems has not been claimed for these advanced devices. Avoiding the harmful heating by unusable radiation, near-field TPV systems are only applied in the range of low, e.g. room, temperatures. Their practical purpose is temperature sensing [2,3,11].

An actual target for specialists in TPV systems is to develop a frequency-selective emitter compatible with the concept of a near-field or a micron-gap TPV system. More specifically (since the emitter characteristics cannot be determined separately in such devices), one has to create TPV systems which offer the frequency-selective SP RHT. In the PV operational band this RHT should be above the Planckian limit and beyond this range – sufficiently weak. Recently, some papers appeared on such a frequency-selective SP RHT in a near-field TPV system (e.g. [15]). However, we concentrate on micron-gap TPV systems. The latter ones are more suitable for the generation of electricity because (unlike near-field TPV systems) they can be implemented on macroscopic area – as large as few cm^2 – whereas the gap between the emitting and cold (PV) surfaces can be as tiny as 500 nm

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