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From light trapping to solar energy utilization: A novel photovoltaic–thermoelectric hybrid system to fully utilize solar spectrum

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ABSTRACT

In this paper, the comprehensive photon and thermal management approaches are proposed to increase the full-spectrum solar energy utilization in PV–TE (photovoltaic–thermoelectric) hybrid systems. The bio-inspired moth-eye nanostructured surface is adopted to suppress the reflection for full solar spectrum photons while the enhanced transmission film is used to improve the transmission for photons with energy below the band-gap of PV cells, making the reasonable utilization of solar spectrum energy. The PV–TE hybrid system is studied for both terrestrial and space applications, corresponding to different thermal management approaches. The effects of geometric parameters, incident angle, thermal concentration ratio, and optical concentration ratio on the system performance are discussed. The results show that the PV–TE hybrid system exhibits better performance under both AM1.5 and AM0 illumination without any optical concentration compared to pure PV cells under the same conditions. For an optical concentrated solar PV–TE system, although the efficiency of the system may decrease with the increment of optical concentration ratio, the total power output increases for both terrestrial and space applications. The results indicate that a lower concentration ratio is more suitable for PV–TE hybrid systems in both terrestrial and space applications unless more powerful temperature management tricks are taken.

1. Introduction

Energy plays a crucial role in human activities and has gradually become the foundation of modern economy all over the world. Due to prevalently utilizing fossil fuels, global warming and energy crisis are getting increasingly serious, resulting in an urgent research and development of renewable energy. Solar energy, which is known as a clean, reliable, and inexhaustible source of energy, is considered as a promising solution to mitigate the current crisis [1]. Converting solar energy into electricity has been given high priority to utilize solar energy because electric power is high-grade power source and has a wide prospect in both terrestrial and space applications.

Photovoltaic cells are a typical optoelectronic device that can directly convert solar energy into electricity by exciting electron–hole pairs in the semiconductor via the photovoltaic effect. However, the limited efficiency of solar cells has become a major obstacle in the realm of solar energy utilization. The key reason is that the photovoltaic cell could only utilize a part of energy in solar spectrum, which is determined by the band-gap of the semiconductor. Photons of energy larger than the band-gap value could dissipate as heat due to thermalization loss while that those photons with energy levels being lower than the band-gap energy could be transformed into heat by transmission loss as well [2]. In other words, the thermalization effect and the non-absorbed photons with energy lower than the band-gap energy of solar cells are the dominant loss processes limiting the conversion performance of solar cells. With regard to band-gap value at 1.31 eV, the thermalization loss occupies 29.8% while the below band-gap energy loss accounts for 25% in the full solar spectrum energy [3]. Hence, the energy of solar spectrum could not be fully utilized in photovoltaic cell operation. Solar TEGs (thermoelectric generators)

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can directly convert thermal energy into electricity via Seebeck effect, providing an efficient and alternative way to use solar radiation and waste heat [4–6]. Therefore, in order to make full use of solar spectrum energy, a so-called PV–TE (photovoltaic–thermoelectric) hybrid system has been proposed. This hybrid system combines the PV cells with TEGs as an integrated device, simultaneously using photovoltaic cell and excess waste heat to generate electricity. In this way, more electric power could be produced as expected.

Recently, two representative PV–TE hybrid system designs have been put forward and attract more and more attentions. In one design, a spectrum splitter is adopted in the hybrid system to partition the solar spectrum into PV and TE device. For example, Kramer et al. [7] developed a general optimization methodology to realize the full potential of such a hybrid system through a solar spectrum splitter. Ju et al. [8] presented the numerical modeling and optimization of a spectrum splitting PV–TE hybrid system, demonstrating the suitability of the hybrid system for working under high concentrations. In another design, the TE module is simply attached to the backside of the PV device to utilize the heat transferred from the solar cell. For instance, Van Sark [9] developed an idealized model to calculate the efficiency of such hybrid system by attaching the TEGs to the back of PV modules. Wang et al. [10] proposed a novel PV–TE hybrid device composed of a series-connected DSSC (dye-sensitized solar cell), a SSA (solar selective absorber) and a TEG, which achieved the efficiency increased from 9.39% to 13.8%. Su et al. [11] established an electric and thermal model of the hybrid device consisting of a DSSC and a TEG for exploiting the solar full spectrum. Similarly, Hsueh et al. [12] created series-connected $CuInGaSe_2$ (CIGS) PV cell with a TEG to form hybrid system. It should be noted that the efficiency was increased from 16.5% to 22.02%. Zhang et al. [13] developed a theoretical model for evaluating the efficiency of concentrating PV–TE hybrid system by adding the TE module to the back side of the different PV cells. They demonstrated that the polycrystalline silicon thin-film photovoltaic cell was suitable for concentrating PV–TE hybrid system while the polymer photovoltaic cell was suitable for non-concentrating PV–TE hybrid system. Wang et al. [14] proposed an updated thermionic-thermoelectric generator hybrid system, which exhibited a higher conversion efficiency and power output than either the thermionic generator or the thermoelectric generator. Lin et al. [15] analyzed the load matching in a PV–TE hybrid system. Their results demonstrated that the optimum performance of the hybrid system was related with the solar irradiance, load resistances, and structure parameters of the TEG. Beeri et al. [16] theoretically and experimentally investigated a concentrated PV–TE hybrid system composed of a multi-junction PV cell and a TEG to study the effect of the optical concentration on the performance of the PV–TE hybrid system.

Since the tandem type of PV–TE systems is relatively simple and easily realized, this paper is focused on this type hybrid system. To our knowledge, the above mentioned studies do not take into account the spectrum reflection loss at the front side of the PV cell. In fact, the reflection loss plays a prominent role in the process of energy harvesting since high reflection makes the incident photons hardly penetrate the internal system. Therefore, it is necessary to consider reflection loss in PV–TE hybrid system. To suppress the reflection loss, various nanostructures have been proposed including antireflective coating [17], gratings [18], pyramids [19], nanorods [20], nanoholes [21], and so on. Among these structures, bi-inspired moth-eye structures of parabola shape [22–25], demonstrating a nearly linear refractive index gradient, have shown ultra-low antireflection properties and exhibited wide prospect of application.

In this paper, we propose both photon and thermal management approaches to increase the solar energy utilization efficiency in PV–TE hybrid systems. We focus on the spectrum control to investigate the performance of PV–TE hybrid system. The key point is that the photons with energy larger than the band-gap of the solar cell will be absorbed by the PV cell while those with energy below the band-gap will transmit through the PV cell and be utilized by the thermoelectric modules. Not only can this method enhance the utilization of solar spectrum energy but also reduce the generated heat inside the solar cells. Based on this principle, we combine the bio-inspired moth-eye antireflective structured surface and enhanced transmission film together in order to realize an effective photon management. The moth-eye structured surface is introduced as a window layer while the enhanced transmission film is composed of silica (SiO_2) as a bottom layer in GaAs (gallium arsenide) PV cell that series connected to a TEG to form a PV–TE hybrid system. The hybrid system is illuminated under AM1.5 and AM0 conditions representing for both terrestrial and space applications. Water cooling and radiative cooling are selected as thermal management methods for terrestrial and space applications, respectively. The spectral properties are investigated by the FDTD (finite-difference time-domain) method. The effect of the geometric parameters is studied to obtain the minimum reflection and maximum transmission to make the reasonable use of the solar spectrum energy. Moreover, the effect of the incident angle as well as the polarization behavior is investigated to learn the multi-angular and polarization insensitive characteristics of the nanostructured surfaces. The performance of the PV cell is investigated by photoelectric coupling model while the efficiency of hybrid system is calculated by solving an energy balance equation. The impact of the thermal concentration ratio is studied to show the optimal operating condition of the PV–TE hybrid system. In addition, the influence of the optical concentration ratio is analyzed in detail as well. Finally, a comparison of performance between moth-eye structured surface and planar surface is investigated to demonstrate the superiority of nanostructured surfaces in designing a high-efficiency PV–TE hybrid system.

2. Description of PV–TE hybrid device and theoretical model

2.1. The geometric structure of the PV–TE hybrid device

The schematic diagram of the PV–TE hybrid device is shown in Fig. 1(a). The PV–TE hybrid system is composed of an optical concentrator, a PV cell, the TE modules, and a cooling subsystem. When the solar radiation impinges upon this hybrid device, the PV cell can utilize one part of the incident solar power to generate electricity by the photoelectric effect. Meanwhile, the part of the energy is lost as heat by natural convection and radiation to the environment from the front surface of the solar cell. Finally, the rest energy including the heat generated by the PV cell and the transmitted radiation power are transferred to the TE modules. Here it should be noted that solar radiation passes through the PV cell is assumed to be completely absorbed by the TE module. The TE modules can use a portion of energy for electricity output due to the Seebeck effect and the cooling system takes away the surplus energy. In this paper, the structure of the solar cells we study within one period is shown in Fig. 1(b). The GaAs nanostructured solar cell consists of a p-$Al_{0.8}Ga_{0.2}As$ moth-eye structured window layer, a heavily doped p-GaAs emitter, a lightly doped n-GaAs base, n-$Al_{0.3}Ga_{0.7}As$ back surface field, and SiO_2 enhanced transmission film. It should be noted that the moth-eye microstructure has a parabola shape and the mathematic expression can be defined as