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Review

Optical nanostructures design, fabrication, and applications for solar/thermal energy conversion

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ABSTRACT

Optical nanostructures can control the optical absorption and emission properties of surfaces and are therefore being investigated for solar thermophotovoltaics, thermophotovoltaics, solar thermal, infrared sensing, infrared sources, incandescent light sources, and thermal imaging applications, among many others. This review article describes various modeling methods available for design of optical nanostructures to control light absorption and emission properties of surfaces, as well as various methods available for the fabrication of large area nanostructured surfaces. Throughout the review, we provide examples of state of the art energy generation devices using such optical nanostructures. A discussion of outstanding obstacles for the achievement of high efficiency solar thermophotovoltaics systems is provided along with examples of systems showing exceptional promise.

1. Introduction

Recently, there has been strong research activity in solar thermal (ST) (Thirugnanasambandam et al., 2010; Tian and Zhao, 2013), solar thermophotovoltaic (STPV) (Bauer, 2011; Bermel et al., 2010; Harder and Wurfel, 2003; Dupre et al., 2016), and thermophotovoltaic (TPV) (Ferrari et al., 2014; Bermel et al., 2012) systems for converting solar and heat energy to electricity. While hybrid PV and ST systems which convert some or all incident energy to heat for direct use (such as in a hot water heater) and in photovoltaic-thermal collectors have also seen significant advances, this review article focuses only on system which output electrical energy. Additionally, this article focuses on high temperature STPV and ST systems due to their potentially high efficiency. There is strong potential for growth in these areas, especially through the use of novel nanostructured surfaces to control light absorption and emission from surfaces and to achieve high efficiency. This spectral light control can be achieved by nanostructuring of surfaces, which can strongly modify their optical properties (Inoue et al., 2015; Lenert et al., 2014; Rephaeli and Fan, 2009). Recently, significant progress has been made in the modeling and fabrication of nanostructures to control optical absorption and emission properties of surfaces. Nanostructured surfaces, for example, can be designed to be significantly more absorbing than their flat counterparts. Similarly, surfaces can be designed to emit infrared radiation in a very narrow spectral range, providing spectrally selective surfaces (Granqvist, 1985; Collin, 2014). A schematic of an STPV device with a broad solar absorber in thermal contact with a selective emitter is shown in Fig. 1(A). Fig. 1(B) and (C) show the change in emission spectra from a blackbody emitter to a selective emitter using optical nanostructures. Some typical nanostructures are depicted schematically in Fig. 2.

STPV, ST, and TPV systems all share common surfaces but operate under different conditions. ST and STPV systems offer an alternative to PV power generation in alternative energy systems. Since both are heat engines, they are bounded by the Carnot limit and can theoretically exhibit extremely high efficiencies under high (but attainable) operating conditions. Additionally, since both ST and STPV systems rely on elements heated to high temperatures via concentrated solar energy, they are easy to modify for thermal storage of energy (Datas et al., 2013; Veeraragavan et al., 2014). This would allow them to operate into the night. An advantage of ST systems over STPV systems is that ST systems do not require the use of PV cells. The PV cells in STPV systems are expensive and can limit overall system size. Conversely, an advantage of STPV systems over ST systems is that STPV systems have no thermal fluid or moving parts. This leads to them being more stable and compact solutions. Overall, ST tends to lend itself to large, immobile power installations while STPV is better suited for small applications. TPV systems operate on the same principle as STPV systems, but rely on an external heat source instead of solar energy (Durisch et al., 2003). This allows them to be used in energy reclamation systems.

While both ST and STPV systems are capable of efficiencies

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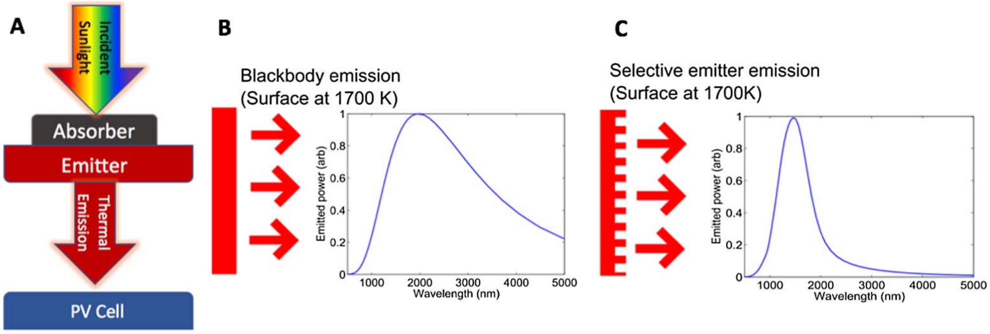

Fig. 1. (A) Schematic of STPV system capable of reshaping the solar spectrum. (B) Spectral emission of a blackbody vs. (C) A selective emitter. Note that the scales on each graph are in different arbitrary units; the graph is intended to show the relative narrowness of the spectrum using the selective emitter.

Fig. 2. Types of nanostructured absorbing and emitting surfaces: (a) random nanotexture (b) periodic nanotexture and (c) dielectric/metal stack.

approaching 85%, only ST systems have yet been realized with high real-world efficiency (Rephaeli and Fan, 2009; Reddy et al., 2013; Blerman et al., 2016). This is due primarily to the challenges related to the extremely high temperature operation of STPV systems; it is the view of the authors that this presents exciting opportunities for researchers in materials science, nanophotonics, and engineering to devise strategies for increasing the temperature stability of STPV components, and for increasing the performance of STPV components operating at lower temperature. STPV systems have many advantages, such as those listed in the previous paragraph, that make them attractive for further development.

Control of light absorption and emission properties allows the design of high efficiency solar and thermal energy conversion devices. It also has applications in the development of high efficiency infrared sources, sensors, and incandescent light sources. Various approaches have been demonstrated for controlling light absorption and emission from surfaces such as the use of photonic crystals (Rinnerbauer et al., 2014; Nam et al., 2014; Stelmakh et al., 2014; Celanovic et al., 2008), optical metamaterials (Wang et al., 2015; Liu et al., 2011; Khodasevvch et al., 2015), nanoparticles (Son et al., 2013; Filho et al., 2014; Katumba et al., 2008; Shah and Gupta, 2013), multilayer thin films (Schon et al., 1994; Rephaeli and Fan, 2009) and micro/nano textured structures (Narasimhan and Cui, 2013; Gupta et al., 2012; Gupta and Carlson, 2015; Iyengar et al., 2010). This review article describes various modeling methods available for design of optical nanostructures to control light absorption and emission properties of surfaces, the various methods available for the fabrication of large area nanostructured surfaces, and provides some examples of high-efficiency, state of the art, energy generation devices using such optical nanostructures. A path forward to more efficient solar and thermal energy generation devices using practical design methods and fabrication techniques is examined.

The limiting efficiency for ST and STPV systems with ideal absorbing and emitting surfaces comes from the Carnot efficiency (η) given by $\eta = 1 - \frac{T_c}{T_h}$, where T_c and T_h are the hot and cold temperatures, respectively. The absorbing surface efficiency is lowered due to radiative loss, given by $A \epsilon \sigma T^4$, where A is the area, ϵ is emissivity, σ is the Stefan-Boltzmann constant, and T is temperature. While the Carnot efficiency of the system will increase with temperature, the absorbing surface efficiency will decrease due to increased emission from the absorbing surface at high operating temperatures (Luque, 2007). The maximum operating efficiency of 85.4% is therefore reached at an operating temperature of 2600 K in the ideal case for both systems. Increasing the temperature beyond this will result in a decrease in system efficiency. This analysis assumes that incoming radiation is concentrated to the maximum achievable solar concentration of 46000×. At this concentration, the ideal surface is simply a blackbody absorber.

As the solar concentration is decreased, the ideal surface will be a blackbody absorber for wavelengths below some λ_{cutoff}, and an ideal reflector (generating lower emission) for wavelengths above the cutoff. The location of λ_{cutoff} depends on the temperature of the system, the power density of the emission from the emitter, and the solar concentration levels achieved in the system. Typical λ_{cutoff} values will be close to 2 µm due to the importance of absorbing a large portion of the solar spectrum (Rephaeli and Fan, 2009).

In the case of STPV systems, the emitting surface will also play a role in device efficiency. The ideal surface will be a monochromatic emitter that emits radiation with energy equal to the bandgap energy of the PV cell used in the system (Duomarco and Kaplow, 1984; Luque, 2007). Unfortunately, monochromatic emitters have a power density of 0, resulting in the requirement of an infinitely large emitting surface for practical power generation. Therefore, in practical STPV systems, an emitting surface with a small bandwidth will be desirable (Rephaeli and Fan, 2009). There also will be a certain system operating temperature that will lead to maximum operating efficiency due to competing effects between Carnot efficiency and heat loss due to thermal emission from the top surface (Luque, 2007; Gleckman et al., 1989). While it is true that the maximum thermal emission per unit area of the STPV emitter will be lower than that of the sun (because it is bounded by blackbody emission at a temperature that is lower than the suns temperature), the area of the emitter will be much higher than the absorber in a high-efficiency STPV system. Additionally, because the output spectrum of the STPV system is well-matched to the PV cell, and thermalization losses are greatly reduced, there will be much less thermal energy absorbed by the PV cell. This results in a lower PV cell operating temperature and a reduced requirement for cell cooling. Fig. 3 shows the evolution of maximum STPV system efficiency vs. temperature for an ideal system.

The temperature of 1000 °C was an upper limit chosen for practical ST systems based on existing technologies (Reddy et al., 2013; Tian and Zhao, 2013). This temperature was chosen for the purpose of comparing different nanostructured surfaces suitable for incorporation into ST systems. The performance of ST systems will generally increase up to a specific temperature (McGovern and Smith, 2012). The value of this temperature is dependent on the quality of surfaces used and the solar concentration value achieved. For tower-based (high-concentration) ST systems, this temperature is usually significantly above current operating temperatures, resulting in a desire for increased thermal stability. Most materials degrade at high temperatures for extended periods of operation, so a reasonable number of 1000 °C was assumed. This