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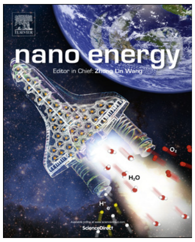

RAPID COMMUNICATION

High performance multi-scaled nanostructured spectrally selective coating for concentrating solar power

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Abstract
Spectrally selective coatings (SSCs) are a critical component that enables high-temperature and high-efficiency operation of concentrating solar power (CSP) systems. In this Letter, we describe a novel design for a high-performance SSC based on multi-scaled nanostructures. Optimal design of the new structure for high optical performance of the SSC is predicted by the effective medium theory. To demonstrate the feasibility of the design, we fabricate the SSCs using fractal nanostructures with characteristic sizes ranging from ~10 nm to ~10 μm. Optical measurements on these structures show unprecedentedly high performance with ~90–95% solar absorptivity and <30% infrared emissivity near the peak of 500 °C black body radiation. The newly developed concept of SSC could be utilized to design solar absorbers with high thermal efficiency for future high temperature CSP systems.
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Introduction

Solar energy can potentially play a significant role in the global energy supply [1]. There are two main methods for generating electricity from sunlight: direct solar-electricity conversion using photovoltaic (PV) solar cells and concentrating solar power (CSP) which generates electricity from solar thermal

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energy [2,3]. Despite PV technology's rapid development, CSP still offers several unique advantages: higher energy-conversion efficiency, higher thermal energy storage capability (specifically, a higher capacity factor [4]), and the potential to retrofit current coal power plants. Therefore, large-scale deployment of CSP could enable a higher overall penetration of solar energy [5]. As of 2011, the cumulatively installed CSP capacity reached ~1.17 GW, and ~17 GW of CSP is under development worldwide [6].

Among the various components in a CSP system, the solar absorber plays a critical role in overall system performance. To increase the Carnot efficiency of the power generation system, it is desirable that the temperature of the heat transfer fluid (HTF) is 600 °C or higher [7]. In order to increase the temperature of the receiver, a solar absorber has to maximally absorb solar energy while minimizing losses due to black body emission. At a receiver temperature of 500–800 °C, black body emission peaks at wavelengths longer than 2 μm. Most energy within the solar spectrum is located at wavelengths below 2 μm, allowing for the possibility of optimizing receiver performance through tuning the spectral absorptivity (equivalent, at equilibrium, to spectral emissivity). As most materials do not naturally have the desired behavior, engineered composites are needed. Figure 1a illustrates the schematic diagram of a solar absorber with a SSC. An ideal SSC has to exhibit high spectral absorptivity, α_s, in the solar spectrum (0.3–2.0 μm wavelengths), and low spectral emissivity, ε_{IR}, in the IR spectrum (2.0–15 μm wavelengths) (Figure 1b).

The optical performance of the SSC is usually characterized by the ratio of solar absorptivity and IR emissivity at a given operation temperature, which directly dictates the photo-thermal conversion efficiency of solar receivers [8],

$$\eta_{th} = 1 - \frac{Q_{loss}}{Q_{in}} = \alpha_{s,eff} - \frac{\varepsilon_{IR,eff}\,\sigma(T_R^4 - T_0^4)}{CI} \tag{1}$$

where the effective IR emissivity, $\varepsilon_{IR,eff}$, is defined as,

$$\varepsilon_{IR,eff} = \frac{\int_0^\infty \varepsilon(\lambda)[I_\lambda(T_R,\lambda) - I_\lambda(T_0,\lambda)]d\lambda}{\int_0^\infty [I_\lambda(T_R,\lambda) - I_\lambda(T_0,\lambda)]d\lambda}. \tag{2}$$

and the effective solar absorptivity, $\alpha_{s,eff}$, is determined by,

$$\alpha_{s,eff} = \frac{\int_0^\infty \alpha(\lambda) I_s(\lambda)d\lambda}{\int_0^\infty I_s(\lambda)d\lambda} \tag{3}$$

In the equations, Q_{in} is heat input from the concentrated solar flux, and Q_{loss} is heat loss due to radiation, conduction, and convection heat transfer (negligible when the receiver is placed in an evacuated enclosure). The Stefan-Boltzmann constant is σ ($=5.67\times10^{-8}\,\mathrm{Wm^{-2}K^{-4}}$), C stands for the solar concentration ratio and I is the solar insolation. $I_S(\lambda)$ and I_λ (T, λ) are the spectral intensities of solar insolation and blackbody radiation at T, respectively. T_R and T_0 correspond to the temperature of the receiver and ambient, respectively. The spectral absorptivity and emissivity of the SSC are denoted by $\alpha(\lambda)$ and $\varepsilon(\lambda)$, respectively. When the temperature of the HTF is 600 °C or higher for high Carnot efficiency [7], the surface temperature of the SSC would be 700 °C or higher. It is therefore important for SSCs to possess high $\alpha_{s,eff}$ and low $\varepsilon_{IR,eff}$ to satisfy both high operation temperature and power conversion efficiency.

There has been an extensive search for mid- to high-temperature SSC materials [9]. Typical SSC structures fall into one or several of the following schemes: 1. Intrinsic selective materials, the simplest structure usually in the form of thin films with proper intrinsic material selectivity [10]. 2. Semiconductor-metal tandems, which are made from semiconductors with proper bandgaps (E_g~0.5 eV–1.26 eV) that absorb solar radiation in tandem with an underlying metal that provides high IR reflectance. The main drawbacks of this structure include the need for an anti-reflection coating, oxidation of the semiconductors at elevated temperatures, and non-scalable processes for producing semiconductor thin films such as CVD [11] or vacuum sputtering. 3. Multilayer absorbers, which use multilayer stacks of metals and dielectrics to achieve high selectivity due to the interference effect. This scheme is limited by the high cost of the multi-stack fabrication process, such as sputtering and CVD [12,13], as well as high-temperature instability [14]. 4.Textured surfaces, which consist of porous and nano-scale structures for the required spectral selectivity through optical trapping of sunlight [15]. The spectral emittance can be adjusted by modifying the microstructure of the coating. However, these highly textured metal surfaces tend to degrade quickly at elevated temperature [16,17]. 5. Metal-dielectric composites, which utilize a highly solar-absorbent and IR-transparent material deposited onto a highly IR-reflective

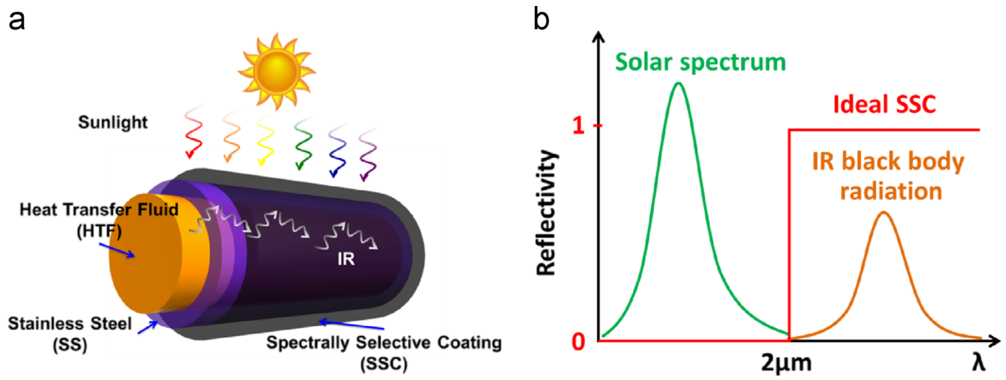

Figure 1 Spectrally selective coating (SSC) for concentrated solar power. (a) Schematic of a solar absorber with stainless steel (SS) tube coated with the SSC. (b) Optical reflectance of an ideal SSC. In the solar spectrum (short wavelength), the reflectance is zero (or the absorptance is 100%); in the IR spectrum, the reflectance is 100% (or the emittance is zero). Such an ideal SSC will have the maximum absorptance for solar energy but with minimal heat loss due to the blackbody IR thermal radiation of the absorber itself.