Control of thermal emission for thermophotovoltaic systems

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Abstract. Thermal emitters play a key role in controlling the thermal radiation emitted in thermophotovoltaic systems and in increasing their energy conversion efficiency. Here, we present different designs of emitters with spectrally selective properties, based on easy-to-fabricate multilayer structures and characterized by a sharp transition from high to low emissivity in the region of interest. Those structures make use of refractory materials to allow working at high operating temperatures and they can be easily customized to maximize the thermal emission in the region of the desired wavelengths.

In recent years, the interest in thermal emissions in the infrared (IR) range is growing fast as the control of thermal emissions in that region is crucial for reaching high efficiency in various energy systems. However, it involves different other fields and applications like thermography [1], thermophotovoltaic (TPV) systems [2], radiative cooling [3, 4], infrared spectroscopy [5, 6], etc.
A TPV system employs a photovoltaic (PV) module and a thermal collector and allows the direct conversion of the thermal radiation emitted from an object heated at temperatures typically higher than 1000 K to electricity.
Hence, in those devices, the control of thermal emission is fundamental to improve their thermal efficiency, defined as

$$\eta = \frac{P_{generated}}{P_{absorbed}}, \tag{1}$$

where $P_{generated}$ and $P_{absorbed}$ are the electrical power generated by the PV cell and the total thermal radiative power absorbed, respectively.
As a result of the well-known PV cell operation, the radiation incident on the PV cell must match its bandgap. Hence, the key role of the thermal emitter, a device that emits thermal radiation and for which selectivity is required: to reduce the amount of wasted heat, it must emit only the photons with energy included in the range of interest to make the PV cell work properly.

Recalling the Kirchhoff's law of thermal radiation, any object in thermal equilibrium radiates a quantity of power that is equal to the power absorbed. Hence, in the case of negligible transmission through the designed structure, the emissivity of an object equals its absorptivity, and we can consider the calculated absorptivity and emissivity as equal:

$$\alpha(\lambda) = \varepsilon(\lambda) \tag{2}$$

The ideal spectrally selective thermal emitter must have the maximum emissivity for photons with energy in the region of interest (ε=1), while zero emissivity for photons with energy lower than the bandgap energy of the PV cell. In addition, due to the high working temperatures, stability and durability above 1000 K are required.

The structures investigated so far are mainly based on the use of metamaterials [7] and metasurfaces [8,9], photonic crystals [10], gratings [11,12], and plasmonic structures [13-15]. A recent review article [16] highlights the advantages and disadvantages of the various types of emitters, the latter are mostly linked to the thermal and chemical stability at high temperatures. In addition, all of them lack the possibility of being easily reproduced on a large scale. Therefore, in this work, we want to describe and demonstrate the feasibility of easy-to-fabricate selective emitters based on a multilayer structure with a controlled thermal emission.

The materials involved in the metamaterial structure are selected from metals, oxides, carbides, and nitrides, all characterized by good thermal stability and high melting point. In addition, the appropriate choice of a sub-layer allows for ensuring negligible transmissivity in the whole range of investigated wavelengths.
A preliminary result on the simulated absorption spectrum obtained from a multilayer made of Si, W, SiO_2 and Cr_2O_3 is depicted in Figure 1. It has a narrow emission peak with absorptivity close to 1 centered around 1100 nm, reaching a negligible value of emissivity already before reaching 1500 nm.

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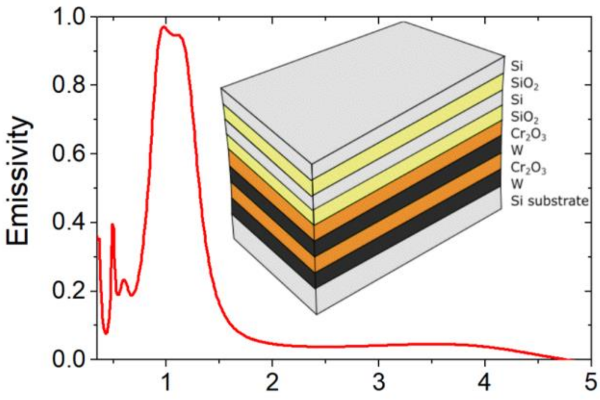

Fig. 1: Absorption spectrum of a multilayer based on Si, W, SiO_2, and Cr_2O_3.

The thermal radiation can be described by the spectral emissivity, $\varepsilon(\lambda)$, and the thermal radiation from a black body, $I_{BB}(\lambda, T)$, according to the Eq. (3):

$$I(\lambda, T) = \varepsilon(\lambda) \cdot I_{BB}(\lambda, T) \qquad (3)$$

Figure 2 shows that the emission spectrum of the selective emitters occurs over a narrower region and is always lower than that of the blackbody at the same temperature, highlighting its selective behavior.

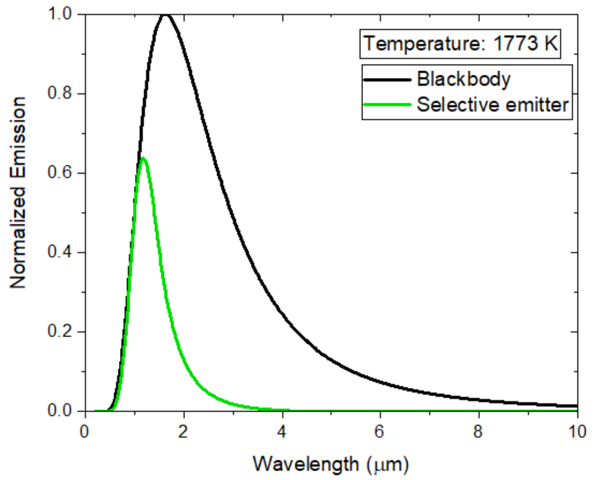

Fig. 2: Normalized spectral radiation emitted by the BB (black line) and the designed selective emitter (green line) calculated at 1773 K.

Further studies are in progress to tune the emission peak at longer wavelengths and to obtain an even more selective behavior in the emissivity curve. In this way, selective emitters could further increase the efficiency of a thermophotovoltaic system compared to what has been demonstrated in [15], and substantially help in thermal energy storage [17].

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