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# High Spectral Irradiance Metamaterial Emitter for Enhanced Efficiency in Low-Bandgap Thermophotovoltaic Cells

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## Abstract

This study investigates the design and optimal high spectral irradiance metamaterials that will optimize low-bandgap thermophotovoltaic (TPV) systems in terms of efficiency. Through electromagnetic engineering of these metamaterials, structures are realized that radiate thermal radiation with high spectral selectivity corresponding precisely to the wavelengths the specific TPV cells absorb. The metamaterials use carefully designed geometries of nanoscale patterned multilayer thin films, which manipulate light-matter interactions by resonant mechanisms. These mechanisms allow the metamaterials to concentrate thermal emission into tightly bound spectral bands at operating temperatures of 1400K-1700K, optimized for energy harvesting. Simulation results indicate that such structures exhibit enhanced emissivity and spectral power density at the desired wavelengths, leading to higher efficiency energy transfer. The multilayer architectures also offer enhanced spectral performance of 94.6% below the cutoff wavelength 2.2μm, durability, and thermal stability in high-temperature use, which is suitable for an InGaAs cell. Overall, such designed metamaterial emitters have significant potential for overcoming spectral mismatch limitations of conventional TPV systems and thereby enabling more efficient recovery of waste heat and promoting sustainable energy conversion technologies.

**Keywords:** Metamaterial, Thermophotovoltaic, Near-Infrared Emitter, Light Matter Interaction, High Temperature, Low Band Gap Cell

### Introduction

The search for efficient energy conversion devices has intensified with the onset of global climate change and the rise in the need for clean energy. Of numerous approaches being explored, thermophotovoltaic (TPV) systems have been considered as promising candidates for converting waste heat into electricity [1-3]. However, the efficiency of traditional TPV systems is likely to be limited by the spectral characteristics of the emitted thermal radiation, particularly in low-bandgap materials that are responsive to specific wavelengths [4-6]. This has prompted researchers to pursue new solutions, including the use of metamaterials to enhance the efficiency of TPV cells.

Metamaterials, artificial materials with characteristics not found in nature, offer remarkable capabilities in manipulating electromagnetic waves [7]. It is possible to realize high spectral irradiance emitters with potentially significant improvement of thermal emission spectra by designing such artificial materials carefully [8,9]. The metamaterial emitters can be engineered to radiate at specific wavelengths to match the absorption properties of low-bandgap TPV cells and thereby have the highest energy conversion efficiency [10,11]. It is able to surpass the natural shortcomings of conventional thermal emitters.

Recent advances in nanofabrication techniques have enabled the practical application of metamaterial geometries [12]. Various architectures were experimentally realized by researchers, which exhibit increased thermal emission through photonic crystal effects and resonant cavities [13,14]. These geometries can be engineered to emit high emissivity at target frequencies, particularly for low-bandgap materials. By boosting the spectral irradiance of the emitted light, these metamaterials can significantly increase the available energy harvested by TPV cells [15,16].

The use of high spectral irradiance metamaterials in TPV systems not only promises higher efficiency but also offers scope for better thermal management [17]. Through the tunability of the emission properties, there is less complexity in achieving enhanced thermal coupling between the emitter and TPV cell, therefore less thermal loss and system performance improvement [18,19]. This is particularly useful in applications where the recovery of waste heat is most important, such as industrial processes and concentrated solar power systems.

In short, the development of high spectral irradiance metamaterial emitters is a landmark achievement in thermophotovoltaics. By taking advantage of the very unique characteristics of metamaterials, researchers are creating new opportunities for more efficient energy conversion technologies that are capable of dealing with low-bandgap materials at ease. With environmental considerations increasingly driving the need for greener energy solutions, such advances will be extremely significant in the transition to an ever more sustainable and energy-efficient future.

## Background

The global movement towards renewable energy sources has directed attention to discovering new technologies that will efficiently translate thermal energy into electricity [20,21]. Among such technologies, thermophotovoltaic (TPV) systems are particularly promising as they transfer thermal radiation to electrical power [22,23]. TPV cells can transfer industrial waste heat, concentrated solar power systems, and other high-temperature sources to usable energy [17,24,25]. However, the operation of traditional TPV systems has been foiled by the spectral nature of thermal radiation, particularly when utilizing low-bandgap semiconductor materials.

Low-bandgap materials, while effective in harvesting lower energy photons, suffer from poor spectral response [26]. The thermal radiation emitted by conventional sources is not optimally coincident with the absorption spectrum of such materials and leads to inefficient energy conversion [27,28]. The consequential spectral mismatch leads to large losses, limiting the overall efficiency of TPV systems [29,30]. To address this issue, scientists are currently exploring new materials and geometries that will maximize thermal emission and provide spectral matching between radiated radiation and low-bandgap TPV cells' absorption characteristics.

Metamaterials, i.e., artificially engineered materials with specially designed electromagnetic properties, have been a game-changing technology in this sense. By being capable of controlling the nanoscale interaction between light and light, metamaterials can be engineered to exhibit engineered thermal emission properties [31]. Such high spectral irradiance emitters are able to emit radiation at specific wavelengths that perfectly overlap with the optimal absorption window of low-bandgap materials. Modern developments in nanofabrication have enabled the fabrication of these metamaterial structures with precision, and they are now practical to implement in real TPV systems.

The potential benefits of including high spectral irradiance metamaterials in TPV technology extend beyond enhanced efficiency. Improved thermal management can be achieved by optimizing the emitter-TPV cell coupling to maximize and minimize thermal losses [32]. This is a significant factor in applications where recovery of as much energy as possible from waste heat is vital. As technology in thermophotovoltaics continues to advance, the use of metamaterials is a significant step towards realizing the full potential of the technology and for a clean energy future.

There are already previously designed broadband emitters with a wide range in the infrared region. But the most frequently utilized metals in the metamaterials are ordinarily aluminum and gold [33,34]. These low-melting-point metals present difficulties in the design of the emitters for the latest TPV cells because the aluminum has a low melting point of 1000K and the gold has a low melting point of 1300K. In order for a broadband emitter to achieve optimal power emitted, it has to be raised to a temperature at which the peak of the blackbody radiation emission curve is shifted to the desired wavelength, see Figure 1 [35]. By using Wien's displacement law (Eq. (1)), we may calculate the appropriate temperature for a specified peak target wavelength.

$$\lambda_{max} T = b \quad (1)$$

Where λmax is the peak wavelength, T is the temperature of the blackbody in Kelvin, and b is Wien's displacement constant, which is equal to 2.898 x 10-3 m.K. For instance, an emitter for an InGaAs TPV cell with a band gap of 0.75 eV, which corresponds to a wavelength of 1.65 μm, would require an operating temperature of 1500°C. Metamaterials constructed from gold or aluminum would, nevertheless, deteriorate well below this theoretical temperature.

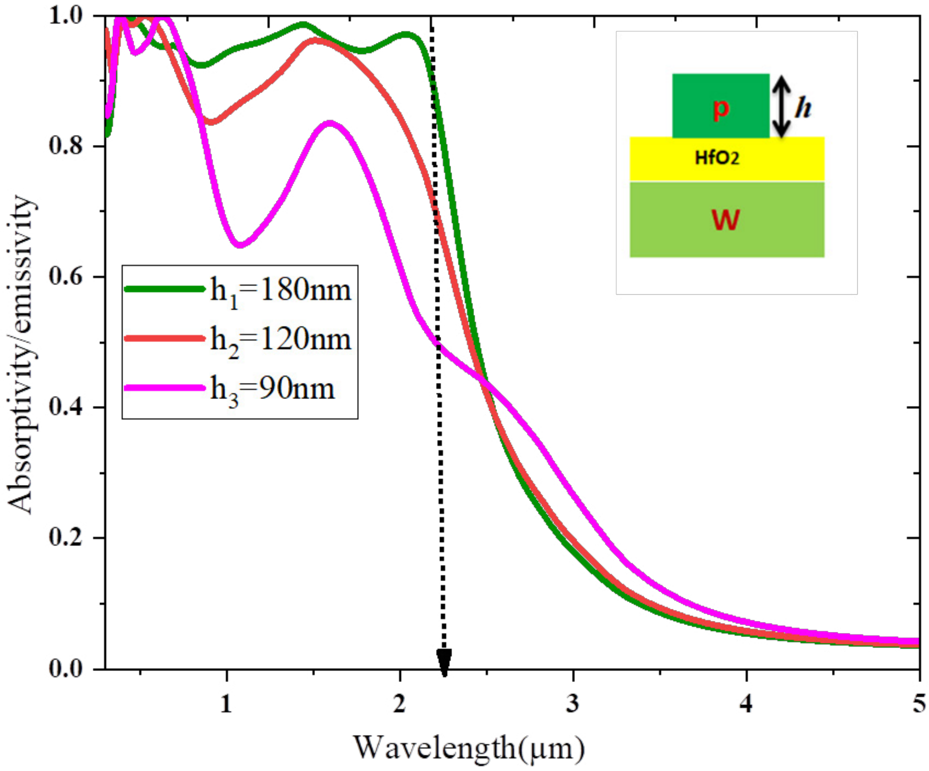


**Figure 1: Comparison of Generated Power and Bandwidth for a Blackbody (Dashed Lines) at Temperatures of 1200K (Red) and 1600K (Blue), Alongside the Power Output of their Corresponding Emitters (Solid Lines) Aimed at a Wavelength of 2.1 μm**

To develop broadband thermal emitters to couple with available TPV cells, we used platinum and tungsten as the starting materials for metamaterials to be tailored for various wavelengths. The metals were chosen considering their high melting points of approximately 2600°C and 3422°C, respectively.

## Numerical Simulation

## Method

Wien's displacement law was employed to determine the peak wavelength of a blackbody at the given temperatures. At 1000°C, the peak wavelength was 2.12μm, and at 1500°C, it was 1.72 μm. Platinum was chosen as the metal for an optimized emitter for 1000°C. However, previous research demonstrated that platinum nanostructure degrades at temperatures much below its melting point, and hence tungsten was used in the 1600°C optimized broad band emitter.

Simulations were conducted using COMSOL Multiphysics software using three layers: tungsten as ground metal and hafnium dioxide as spacer, and either platinum or tungsten was used as top metal to tailor spectral irradiance that could appropriately match the narrow band gap energy of InGaAs semiconductor.

Shockley and Queisser [8] demonstrated that the efficiency of a photovoltaic (PV) cell is highly dependent on the ratio of the bandgap energy of the cell, Eg, to the temperature of the radiation source, TE, for a blackbody radiation source.

In order to achieve maximum efficiency for a blackbody source, the ratio Eg/kTE should be around 2.0. For silicon (Si), the most efficient photovoltaic cell at the time, this would require the emitter temperature to be approximately 6000 K.

No material can survive these high temperatures. Therefore, for effective thermophotovoltaic (TPV) energy conversion at more realistic temperatures, a blackbody source is not feasible. This has focused TPV research on designing the radiation of an emitter to fit the bandgap energy of the photovoltaic cell. Specifically, by generating radiation in a narrow energy range above the bandgap energy of the cell—where the cell has its highest efficiency—a good system can be achieved. Additionally, just as with blackbody emitters, there is an optimum ratio of Eg/kTE. For practical emitter temperatures (close to 2000 K), this optimum case is achieved for a bandgap energy close to 1.0 eV. Therefore, photovoltaic cells with low bandgap energy are necessary to attain high efficiency, as well as radiation with an equivalent energy of the cell's bandgap. The optimization process started with a preliminary adjustment of the absorption peak by altering the dimensions of the metamaterial pattern and the size of the unit cell.

## Simulation Results

Figure 2 below shows how the absorptivity/emissivity spectra of the suggested metamaterial are related to height profiles of the top metallic tungsten layer, i.e., h1, h2, and h3. The figure shows how to optimize spectral efficiency by observing these height profiles. Apparently, the analysis suggests that one of the heights, most likely h2 or h3reaches higher and more sharply defined spectral absorptivity at the target wavelength suitable for the low-bandgap TPV cell. Higher spectral overlap improves overall spectral efficiency so that the material radiates more efficiently in the desirable wavelength window for energy conversion. Indeed, for top metal height of h3 = 50nm, the absorptivity is near one, which signifies the average spectral irradiance of 98.9% that could match the low band gap TPV cells like InGaAs.

The most important observation from Figure 2 is that accurate adjustment of the tungsten layer height significantly influences spectral properties. The set-up with the best spectral efficiency is the set-up in which spectral peaks are closest to the target emission wavelength, providing maximum energy transfer efficiency and loss reduction. Thus, among the tested heights, the optimal square unit cell of 1μm, h3, provides greater average spectral efficiency compared to other structures (e.g., h1 and h2) and must be the most appropriate arrangement for practical TPV application.

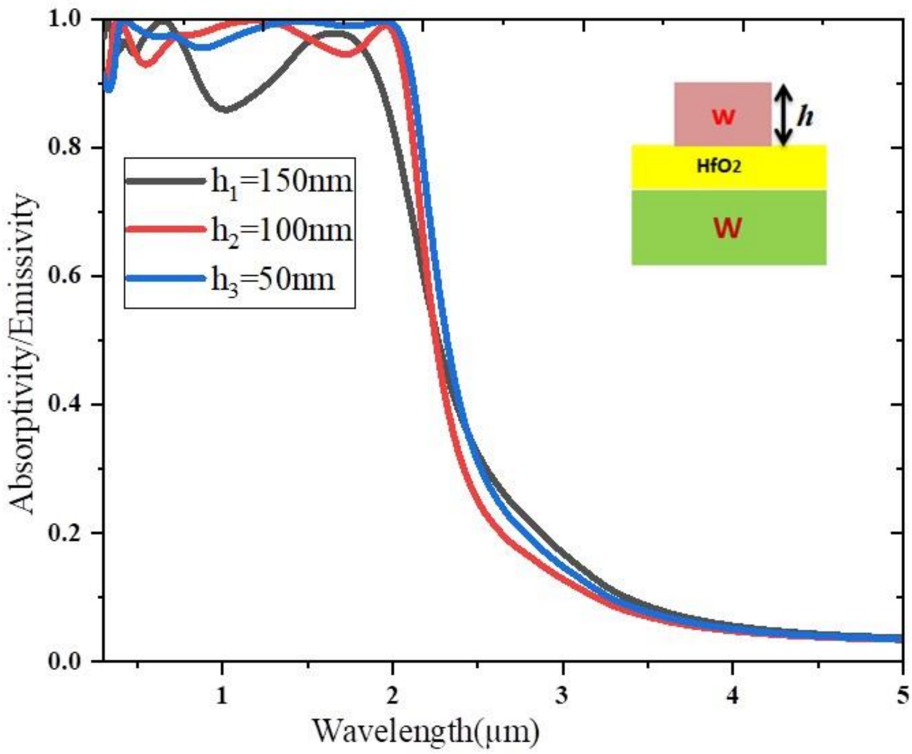


**Figure 2: Absorptivity/Emissivity of the Designed Metamaterial for Varying the Height of the Top Metal Tungsten**

Figure 3 compares the absorptivity/emissivity spectra of the optimized metamaterial for different heights of the top platinum metal layer, i.e., $h_1$, $h_2$, and $h_3$. This is important for determining what configuration gives rise to the highest average spectral efficiency, especially since platinum is used as the top metal in this design. The diagram shows that of all the various heights, the $h_1$ arrangement is linked with a peakier spectral response that is also closer to the desired range of wavelength for low-bandgap TPV cells. This maximizes spectral efficiency through optimum emission in the optimal energy band, and off-band emissions are reduced, which lessens thermal losses.

Analysis yields proof that $h_2$ height configuration achieves the medium average spectral efficiency compared to $h_1$ and h3. This is due to the fact that the spectral characteristics of $h_1$ have a greater emissivity of 89.8% at the necessary wavelength with the least broadening, leading to enhanced coupling with TPV photovoltaic cells. Therefore, the selection of a proper height for the top layer of platinum is critical in order to maximize the performance of the metamaterial emitter, and the data show that $h_1$ does the best job.

Tungsten exhibits greater absorptivity compared to platinum in the evolved metamaterials, as is evident from the spectra in Figures 2 and 3. Its greater high-temperature stability and greater absorption properties offer greater efficiency of tungsten for thermal emission. Thus, tungsten-based metamaterials suit high-temperature emitters with greater absorptivity and efficiency than platinum in the analyzed spectral range.

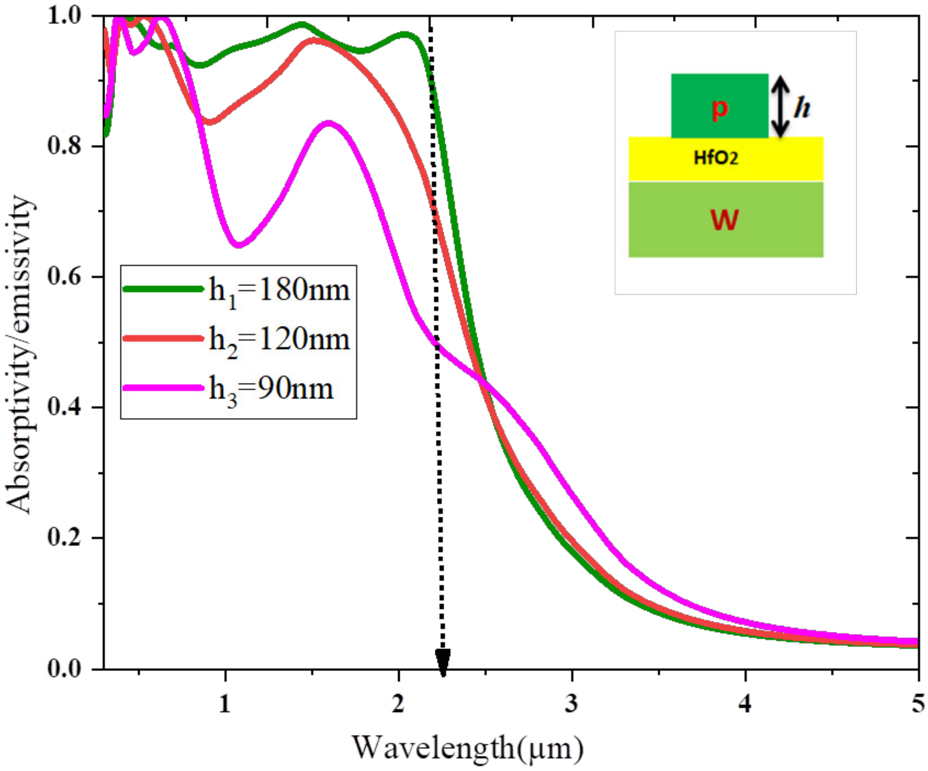


**Figure 3: Absorptivity/Emissivity of the Designed Metamaterial for Varying the Height of the Top Metal**

## Fabrication Method

The metamaterial may be synthesized through highly sophisticated nanofabrication methods such as electron beam lithography (EBL) or focused ion beam (FIB) milling to accurately pattern the nanoscale geometry. Techniques such as sputtering or evaporation can be employed for depositing 50nm of the top metal layer (tungsten or platinum) and the alumina capping layer. Using layer-by-layer assembly along with etch processes, the geometries can be achieved such that the required dimensions and periodicity for maximum absorptivity/emissivity can be accurately controlled.

## Conclusion

This paper shows the successful design and simulation of metamaterials for the particular application of thermal emission enhancement in thermophotovoltaic (TPV) systems. By optimizing the metal structure geometric parameters, particularly with tungsten and platinum, the top metal authors achieved spectral absorptivity and emissivity of 94.6% using tungsten–hafnium dioxide–tungsten that are appropriate for low-bandgap TPV cells. The use of high-melting-point metals and multilayered structures also enhanced the high-temperature stability and performance of the emitters. These results demonstrate the potential of metamaterials engineering for the drastic improvement of energy conversion efficiency, minimization of thermal losses, and facilitating the development of sustainable high-performance TPV systems for waste heat recovery and clean energy applications.

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