Thermal emission by photonic micro-textured surfaces

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Ordinary metallic photonic crystals (PCs) have photonic band gaps in which the density of states (DOS) is strongly modified. Thermal emission of photons can be suppressed and enhanced accordingly. We consider the thermal emission characteristics of a metallic photonic crystal slab with a tunable thickness which in the thick limit approaches that of a photonic crystal and in the thin limit approaches that of a textured surface. We find that a thick photonic crystal suppresses emission in a specific range while a thin slab suppresses low frequency emission.

Keywords: photonics, thermal emission, nanostructures

The study of thermal emission has been an active subject of research area for many years. At thermal equilibrium, the emissivity of a material at each frequency is equal to its absorptivity, if the transmittance is zero. This makes metals good thermal radiators at infrared and optical frequencies as common metals are usually good absorbers in these frequency ranges. Recent developments of photonic crystals has opened a new arena in controlling the absorption spectrum. If we want to suppress radiation at infrared frequencies, then by manipulating the geometry and materials parameters, one can design a metallic photonic crystal with large band gaps over the infrared frequencies. This makes the study of thermal emission by photonic crystals a fruitful research area, which has witnessed a rapid growth in recent years. However in reality, difficulties arise in fabricating three-dimensional (3D) photonic crystals, which prohibits its potential applications. Recently, Fleming et al. reported that only one layer of photonic crystal is sufficient to achieve strong attenuation of electromagnetic radiation. Regarding to their findings, here we propose a model system which only consists of a tungsten micro-particle layer, sitting on a thick tungsten slab. The present geometry exhibits excellent enhancement of absorption in the range of optical frequencies, while suppressing the absorption in other frequency ranges.

We begin by considering a tungsten face-centered cubic (FCC) photonic crystal with a lattice constant \( a = 0.5 \, \mu m \), for simplicity, the spherical tungsten micro-particles are embedded in a background medium with a dielectric \( \epsilon_0 = 1 \). The interparticle distance \( \alpha \) is given by \( \alpha = a/\sqrt{2} = 0.354 \, \mu m \) and the filling ratio \( f \) is given by \( f = 0.65 \, (r = 0.169 \, \mu m) \). The absorbance \( (A) \), reflectance \( (R) \) and transmittance \( (T) \) as well as the photonic band structure are calculated by using multiple-scattering formalism. It should be noted that, the present geometry is not the only method of choice, but it allows us to use the multiple-scattering formalism, which has been proven to have a high accuracy and is less computational costly than the finite-different time domain (FDTD) method.

In Fig. 1 we show the photonic band structure of the FCC tungsten photonic crystal. As seen, its band structure exhibits a large directional band gap at infrared frequencies, which suggests that the tungsten photonic crystal can effectively suppress the infrared radiation. However, it should be noted that the band structure calculation was based on an infinite lattice structure, while a realistic PC is constructed by a finite number of particle layers. Here one may ask how many layers are sufficient for the purpose of thermal emission? And more importantly, is it possible to use just one layer of (metallic) particles? In order to explore the answer to these questions, we consider a model system which consists of a single (111) layer of tungsten particles and a tungsten slab only. The tungsten slab is acting as a substrate and it also ensures the overall transmittance is zero at all frequencies. The tungsten slab is put at a distance \( l \) behind the center of the tungsten particles, with \( l = 0.5\alpha = 0.177 \, \mu m \), which is very close to the tungsten particles \( r = 0.169 \, \mu m \). In Fig. 2 we plot the absorbance spectrum of the proposed structure and compare it with the absorbance spectrum of a 128 layers tungsten photonic crystal. Again, the number of layers \( (128) \) is chosen such that no light can be transmitted. The spectra can be approximately separated into a high-frequency \( (\omega > 0.9 \, eV) \) region and a low-frequency region \( (\omega < 0.9 \, eV) \). At high-frequencies, the absorbance of the proposed ‘layer + slab’ (LS) surface \( (A_{LS}) \) is close to that...
of the photonic crystal ($A_{PC}$) for $\omega > 0.9$ eV. In particular, $A_{LS}$ is only 0.7% and 1.4% smaller than $A_{PC}$ at 3.11 eV ($\lambda = 0.4 \mu m$) and 1.78 eV ($\lambda = 0.7 \mu m$) respectively. Thus the present micro-textured surface should be a good thermal emitter at optical frequencies. At low-frequencies $A_{LS}$ is smaller than $A_{PC}$ in general. It is interesting to note there is a sharp increase of $A_{LS}$ between 0.3 eV and 0.5 eV. This is arising from the surface induced coupling between the particles and the slab surface, which is a Fabry-Perot effect. However in reality, it is difficult to observe such coupling as the surfaces of the particles and the slab are not perfect in general. We also observe a suppression in $A_{PC}$ between 0.7 eV and 0.9 eV, which is due to photonic bandgap effect. The reason of choosing 0.9 eV as a benchmark is not only phenomenological. In the region 0.6 eV $< \omega < 0.9$ eV, the magnitude of the real part of the dielectric constant ($\epsilon_r(\omega)$) drops more than 80%, and decreases gradually after 0.9 eV, while its imaginary part only has a small fluctuation. The decrease of the dielectric mismatch between 0.6 eV and 0.9 eV allows more photons to penetrate into the material, which results in the pronounced increase of $A_{LS}$. This can also be observed for a tungsten slab ($A_{slab}$). In Fig. 4 we replace tungsten by copper and plot the absorbance spectra. Again, there is a benchmark at $\omega \approx 2.2$ eV where $A_{LS}$ is very close to $A_{PC}$ for $\omega > 2.2$ eV and the drastic increase of the absorbance for a copper slab stops accordingly. The physical reason of this is the same as that of tungsten.

We are now at a position to compare the thermal emission spectra between the 'layer + slab' surface and the 128 layers photonic crystal. We will consider the case of tungsten only because its melting point ($\approx 3700$ K) is much higher than that of copper ($\approx 1360$ K), which makes tungsten a more feasible material as a thermal emitter, the results are shown in Fig. 4. The thermal emission spectrum is calculated by assuming Kirchhoff's law, the thermal emission spectrum $u_k(\lambda, T)$ of wavevector $k$ at temperature $T$ is given by:

$$u_k(\lambda, T) = u_{b,k}(\lambda, T) \times A_k(\lambda),$$

where $u_{b,k}(\lambda, T)$ is the Planck spectrum of blackbody radiation. The temperature effect on the tungsten di-
the infrared part of the spectrum is effectively suppressed and the optical spectrum is close to that of a blackbody radiation, thus the emission peaks of both spectra are blue-shifted. Additionally, the ‘layer + slab’ geometry emits less photons than that of the photonic crystal in the range \(1.2 < \lambda < 3.0 \, \mu m\), a direct consequence due to the small absorbance [Fig. 2]. Next we compare the spectra \(u_{LS}\) and \(u_{4LS}\). At short-wavelengths \((\lambda < 1.35 \, \mu m)\), the addition of extra layers only has an insignificant enhancement on the emission spectrum. In fact, \(u_{4LS}\) almost coincides with \(u_{PC}\) in this region. In other words, only a few layers of tungsten particles are sufficient for the purpose of optical emission, which is in accordance with the results of Fleming et al.\textsuperscript{14} We will have a detailed discussion about the layer dependency in the next paragraph.

The results of Figs. 2 and 4 suggest that, if compared with a 3D photonic crystal, a single tungsten particle layer should be a better choice as a thermal emitter at optical frequencies. On one hand it absorbs more optical photons than a thick slab does, and on the other hand the absorption of long-wavelength electromagnetic waves is also suppressed. It is thus instructive to examine the layer-dependence of the absorbance spectrum. In Fig. 3 we show the absorbance spectra of tungsten photonic crystals with different numbers of (111) layers \(N = 1, 2, 4, 32, 64\) and 128 (various lines with symbols). The absorbance spectrum of a tungsten slab is also shown (dashed line). The absorption is enhanced by the photonic crystals at all frequencies.

![Absorbance spectra of tungsten photonic crystals](image)

**FIG. 5**: Absorbance spectra of tungsten photonic crystals with different numbers of (111) layers, \(N = 1, 2, 4, 32, 64\) and 128 (various lines with symbols). The absorbance spectrum of a tungsten slab is also shown (dashed line). The absorption is enhanced by the photonic crystals at all frequencies.

Here a few comments are in order. The results of Fig. 2 and Fig. 4 suggest that, in order to emit the same amount of light, less energy will be required to heat the micro-textured surface, which is an advantage over the photonic crystal. The fabrication of the tungsten particle layer can be done by cutting-age techniques such as self-assembly\textsuperscript{15,16} Recently, Lu et al.\textsuperscript{17} demonstrated a novel technique in fabricating high-density silver nanoparticle layer. The interparticle distance is tunable and can be controlled precisely. Their technique can be adopted to fabricate a tungsten particle film. It should also be emphasized that our discussion here should be general for any 3D metallic photonic crystals. If one optimizes the geometric and materials, the suppression of absorption below a definite frequency can be accomplished by only a few (in our case, one) building blocks of photonic crystals. If the purpose is to suppress the absorption within a certain frequency range, one has to utilize the photonic bandgap effect and determine how many unit cells is necessary.

In this letter, we have proposed the use of a simple, micro-textured surface as a thermal emitter. We have studied its thermal emission behavior and compare it with that of a tungsten photonic crystal. The results suggest such geometry would be a promising thermal emitter. It is hoped that our study would inspire new ideas in the design of thermal emitting applications.

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