Ultra-narrowband infrared thermal emitter based on Fabry–Perot-like vacuum resonance cavity

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Abstract

Coherent infrared thermal emitters are useful in various applications, especially in the spectral region where laser and LED light sources are lacking. The present study investigates a vertical resonant cavity narrowband infrared thermal emitter (VRCITE) with a Fabry–Perot-like vacuum resonance cavity separating the one-dimensional photonic crystal and the gold layer. This configuration overcomes the thermal stress problem, which is the biggest inherent obstacle in similar structures previously proposed by other workers, and could achieve an even narrower emission spectrum (about 4 nm). Theoretical analysis with a transfer matrix method (TMM) is given and the finite-difference time domain method (FDTD) has been adopted to simulate this structure. The results obtained by TMM and FDTD methods are consistent and thus its feasibility is confirmed.

Keywords: photonic crystals, thermal infrared emitter, surface waves

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Ordinary bulk thermal emission sources are commonly regarded as isotropic, broadband and incoherent electromagnetic radiation sources. However, researchers have found that surface microstructures can strongly affect the emission behaviour, which paves the way for tailoring the radiative properties of a thermal source \cite{1, 2}. Thermal emitters with a narrow spectrum and high emittance are useful in various applications such as biosensors, solar cells, thermophotovoltaic devices etc. Consequently, different theories and structures have recently been proposed to construct quasicoherent narrowband thermal emitters \cite{3–5}.

In the 1970s, Yeh \textit{et al} \cite{6} found that surface waves could exist in the forbidden bands of the truncated one-dimensional photonic crystals (1DPhC) for both p and s polarizations and this fact was later experimentally verified by reflectance spectroscopy in the near-infrared \cite{7}.

Furthermore, Gaspar-Armenta \textit{et al} \cite{8} showed that, when a thin metal film is deposited on 1DPhC, surface waves could be excited directly by the propagating waves in the air. Therefore, the attenuated total reflection (ATR) configuration that is normally applied to excite surface waves at the interface of the 1DPhC and air is eliminated. This makes it possible to construct a practical narrowband thermal emitter based on this theory.

Although some work has been done to construct narrowband thermal emitters based on this theory, no practical prototypes have been reported yet to the best of our knowledge. This is because of the biggest inherent difficulty in these
proposed structures, namely that of thermal stress [4, 9]. In this paper, we propose a vertical resonant cavity narrowband infrared thermal emitter (VRCITE). It has a Fabry–Perot-like vacuum resonant cavity between the truncated 1DPhC and the underlying gold layer. There are three major advantages of this novel configuration. Firstly, heat transfer by convection and conduction is minimized because the vacuum cavity separates the dielectric 1DPhC and the metal layer. Secondly, heat transfer by radiation can also be reduced if the materials adopted in the 1DPhC are transparent to the major spectral region of the light radiated from the gold layer. As a consequence of the previous advantages, the 1DPhC could stay at a low temperature when the metal layer is heated up to a high temperature and the thermal stress problem of the dielectric 1DPhC could be mitigated. Thirdly, the emission spectrum is narrower compared with that produced by a similar structure, but without a resonant cavity, as proposed by Lee et al [9].

To demonstrate the feasibility and advantages of the proposed structure, a specific VRCITE, whose emission spectral region ranges from 1.66 to 2.77 μm and the width of the emission spectrum is about 4.3 nm, is designed. The flexibility of shifting the central wavelength of the emission spectrum in the spectral region has been explained. Theoretical analysis by the transfer matrix method (TMM) is given and the finite-difference time domain method (FDTD) has been adopted to simulate this structure.

2. Design of the vertical resonant cavity narrowband infrared thermal emitter

Figure 1 shows the basic structure of the VRCITE. This could be expressed as MA(HL)4, following the nominating convention used in the optical thin film field in which: M: Au, A: air, H: Si, L: SiO2. The refractive indices of Si and SiO2 are 3.42 and 1.43, respectively, and are supposed to be constant and lossless in this spectral region of interest. The optical constant of gold used in theoretical analysis and numerical simulation is taken from the handbook [10] and the layer thickness is set to be 200 nm. The thickness of the Si and SiO2 layers are 145 nm and 368.7 nm, respectively, except for the bottom truncated silicon layer of the 1DPhC, whose thickness changes for designs requiring a different central emission wavelength.

Fluctuation–dissipation theorem is applied by some researchers to calculate directly the thermal emission from a multilayer structure [11]. However, we use the transfer matrix method [6] to analyse the band structure of the 1DPhC and calculate initially the spectrally directional reflectance of the VRCITE. We then use Kirchhoff’s law [12] to deduce the spectrally directional emittance. According to Kirchhoff’s law, the emittance equals the absorptance: \( \varepsilon_{\lambda,\theta} = A_{\lambda,\theta} = 1 - R_{\lambda,\theta} - T_{\lambda,\theta} \). The thickness of the gold layer is 200 nm, which is more than ten times the skin thickness of the light in the emission spectral region defined by the 1DPhC, so the transmittance is negligible. The emittance can then be deduced from the reflectance directly: \( \varepsilon_{\lambda,\theta} = A_{\lambda,\theta} = 1 - R_{\lambda,\theta} \).

2.1. Band structure of the 1DPhC

Figure 2 shows the calculated band structure of the 1DPhC for both polarizations, in which the vertical axis and horizontal axis are denoted by the reduced angular frequency and the reduced wavevector, respectively. The shaded regions represent the stop band and the unshaded regions represent the
pass band. In the normal direction, the s and p polarizations are degenerate, as this structure is rotationally symmetry about the normal axis. The diagonal is the propagating light in vacuum with an incident angle of 90°. This line is also the boundary of two distinct regions. The upper left region of the line denotes where propagating waves could exist in air, while the lower right region denotes where only evanescent waves could exist.

As the surface waves, which exist in the forbidden band of the truncated 1DPhC, are the origin of the narrowband thermal emission of the VRCITE, so the first forbidden band defines the emission spectral region of the VRCITE. From the vertical axis in figure 2, one can see that the upper and the lower boundaries of the first forbidden band are at about 0.31 and 0.185, respectively. The vertical axis is represented by the reduced angular frequency $\bar{\omega} = \omega / (2 \pi c)$. After simplifying and rearranging this equation, it could be expressed by the wavelength: $\lambda = \Lambda / \bar{\omega}$. Thus, the emitting spectral region in the normal direction is $0.31 \leq \lambda \leq 0.185$, namely from 1.66 to 2.77 μm.

2.2. Optical characteristics of the VRCITE

Although the first forbidden band of the 1DPhC defines the emission spectral region, it does not indicate the value of the central wavelength of the light emitted by the VRCITE. The central wavelength and the emittance value could be fine-tuned by changing the thicknesses of the truncated silicon layer of the 1DPhC and the vacuum cavity. Details of the resonant cavity design and parametrization were achieved by lumped parameter models of transmission lines and perturbation theory [4]. In this paper, we use simulated annealing (SA) [13] to shift the central wavelength and optimize the emittance of the VRCITE. Several central wavelengths in the emission spectral region are achieved and the optimized thickness values are given in table 1. Figure 3 shows the emittance curves at normal direction of different emitting central wavelengths.

As shown in table 1 and figure 3, there are many possible VRCITE parameters with different central wavelengths. It is impossible to study all the possible structures in a single paper. Fortunately, this kind of narrowband thermal emitter is scalable and these different structures have similar characteristics. Therefore, without loss of generality, we focus on the specific VRCITE with a central wavelength of 2 μm to study the general properties from now on.

Figure 4 shows the spectrally directional emittance of both polarizations of the VRCITE with a central wavelength of 2 μm. At normal direction, the central wavelengths of the two different polarizations are both at 2 μm. It is consistent with the result shown in the band structure diagram. (In figure 2, in the normal direction, the p polarization and the s polarization are both degenerate too.)
Figure 4. Spectrally directional emittance of the VRCITE: (a) contour plot of the p polarization, (b) contour plot of the s polarization, (c) polar plot of three wavelengths for both polarizations.

From figures 4(a) and (b), we can see the central wavelength shifts slightly to the shorter wavelengths as the angle of incidence increases. The difference between figures 4(a) and (b) is not obvious, as the band structures of these two different polarizations are quite similar in the angular region from 0° to 30°. It can be seen from the insets that the s polarization bends a little more than the p polarization. From figure 4(c), ultra-narrow angular emission lobes in the
Table 1. Optimized thicknesses of truncated Si layer and vacuum cavity for each central wavelength and its corresponding optimized emittance.

<table>
<thead>
<tr>
<th>Central wavelength (μm)</th>
<th>Truncated Si layer thickness (nm)</th>
<th>Vacuum cavity thickness (nm)</th>
<th>Emittance at central wavelength (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7</td>
<td>180.4</td>
<td>716.9</td>
<td>88.3</td>
</tr>
<tr>
<td>1.8</td>
<td>212.7</td>
<td>716.5</td>
<td>100</td>
</tr>
<tr>
<td>1.9</td>
<td>236.1</td>
<td>735.0</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>254.0</td>
<td>771.5</td>
<td>100</td>
</tr>
<tr>
<td>2.1</td>
<td>271.0</td>
<td>820.4</td>
<td>100</td>
</tr>
<tr>
<td>2.2</td>
<td>284.2</td>
<td>881.7</td>
<td>100</td>
</tr>
<tr>
<td>2.3</td>
<td>294.0</td>
<td>952.6</td>
<td>100</td>
</tr>
<tr>
<td>2.4</td>
<td>299.4</td>
<td>1031.4</td>
<td>100</td>
</tr>
<tr>
<td>2.5</td>
<td>297.0</td>
<td>1111.8</td>
<td>100</td>
</tr>
<tr>
<td>2.6</td>
<td>274.1</td>
<td>1222.2</td>
<td>100</td>
</tr>
<tr>
<td>2.7</td>
<td>244.3</td>
<td>1321.6</td>
<td>97.5</td>
</tr>
</tbody>
</table>

well-defined direction near 70° are observed in this specific VRCITE. This phenomenon is called by researchers as thermal antenna [14].

The electric field distribution within each homogeneous layer can be expressed as a sum of a forward plane wave and a backward plane wave. The surface waves at the 1DPhC and the vacuum cavity are strongly affected by the backward wave [15]. The period number $N$ of the 1DPhC modulates the strength of the backward wave, and thus influences the characteristics of the emission spectrum. Figure 5 shows the emittance of different periods in the normal direction with central wavelength of 2 μm. From this figure, one can see easily that the width of the spectrum decreases as the period number increases. However, the emittance is not a monotonic function of the period number, but rather it increases initially, and then decreases. Period number 4 is the optimum period when taking both emittance and the width of the emission spectrum into consideration. That is why we chose period number four in our design of the VRCITE.

Figure 5. Normal emittance of the VRCITE when the number of periods of the 1DPhC varies.

Figure 6. Simulated normal emittance curve by FDTD. Static state electric field intensity distributions in the VRCITE of two different conditions are shown as insets: (a) at resonant condition ($\lambda = 2$ μm), (b) at nonresonant condition ($\lambda = 1.95$ μm). In the insets, the left vertical and the horizontal axis define the dimension of the simulated region in units of microns, while the right vertical colour bar shows electric field intensity scale.
3. Numerical simulations by FDTD

To verify the results obtained from TMM and get an intuitive understanding of the physical origin of the narrowband thermal emission, a powerful and widely used numerical method FDTD has been applied to simulate the designed VRCITE. Figure 6 shows the simulated normal emittance curve by FDTD using the optimized parameters for a central wavelength at $\lambda = 2 \mu m$. Compared to the magnified emittance curve obtained by TMM in figure 3, one can see the results obtained by these two different approaches are almost identical.

The static state electric field distributions in the VRCITE of two distinct states are also shown in figure 6 as insets. The materials employed in this VRCITE are silicon, silicon dioxide and gold. The first two materials are assumed nonabsorbent, so gold is the only candidate responsible for absorbing light.
At the resonant condition (a), the peak of the electric field intensity is proximate to the underlying gold layer and about 200 times that of the incident light, and thus the gold layer could effectively absorb the light. On the other hand, at the nonresonant state (b), the light is reflected back totally, because the electric field intensity decays exponentially along the depth of the 1DPhC. The maximum value of the electric field intensity is only about four and occurs near the top interface between the 1DPhC and air.

In conclusion, the reason why such a high emittance occurs is the strong resonance near the gold layer. The maximum value of the normalized electric field at the resonant condition is about 200 times that of the incident light, which is an indication of the high density of state (DOS) of this resonant cavity mode. This could provide an explanation of the high coherence of this proposed structure [16].

Figure 7(a) shows the simulated normal emittances with different numbers of periods of 1DPhC at the central wavelength of 2 μm and figure 7(b) shows their corresponding static electric field distributions at resonant condition. Figure 7(a) is similar to figure 5 with respect to the central wavelength and the width of the emission spectrum modulated by the number of periods. Figure 7(b) explains why the normal emittance reaches the maximum value when the number of periods equals four: as the number of periods increases, the maximum value increases first, reaches the maximum at a value of four, and then decreases. Therefore, we can conclude safely that the higher the electric field intensity in the air resonant cavity, the higher the value of emittance will be.

4. Conclusions

A vertical cavity resonant narrowband infrared thermal emitter has been proposed with a vacuum cavity separating the 1DPhC and the metal layer. The major advantage of this novel configuration is its potential to overcome the inherent obstacle of thermal stress of the previously proposed structures and the even narrower emission spectrum bandwidth that it could achieve. The band structure of the 1DPhC, the flexibility of shifting the central wavelength, the spectrally directional emittance and the influence of the numbers of period of the 1DPhC on the emitting characteristic are analysed by the transfer matrix method (TMM). The finite-difference time domain method (FDTD), which is a widely used and highly accurate numerical method, has been applied to simulate this structure. The results obtained by TMM and FDTD are consistent and both confirm the feasibility of this proposed narrowband thermal emitter. Furthermore, from the static electric field distribution within the VRCITE, a qualitative analysis of the reason why such high coherence and high absorptance occur is presented.

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References