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含负折射率介质的一维光子晶体构成的相干热辐射源的辐射特性及控制

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摘 要:采用传输矩阵法研究了带缺陷层含负折射率介质的一维光子晶体的热辐射性质和控制.研究发现,此相干热辐射源在很窄的波长范围以及特定的方向上表现出非常尖锐的辐射峰,其品质因子比普通材料辐射源高.辐射峰对入射角度、偏振以及此结构中光子晶体的尺度因子都不敏感.辐射峰的大小,品质因子,位置可以通过调节缺陷层的厚度和折射率来调节,实现了对热辐射的有效控制.

关键词:声子晶体;负折射率;辐射特性;控制
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Radiative Properties and Controlling of Coherent Thermal Radiation Source Consisting of One-dimensional Photonic Crystals Containing Negative-index Materials

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Abstract: The photonic crystals (PCs) with defect layer containing negative-index materials coated over a SiC substrate are investigated by a transfer matrix method. The results show that this coherent thermal radiation source has very sharp emissivity peaks within a narrow wavelength band at a well-defined direction; the quality factor of the emissivity peak is high. This emissivity peak is not sensitive to the emission angle, polarization, and scaling factor of the photonic crystals in the structure. The value, quality factor, and position of the emissivity peak can be effectively controlled by tuning the thickness and refraction index of the defect layer.

Key words: Photonic crystals; Negative-index; Radiative properties; Controlling

0 Introduction

Photonic crystals (PCs) are periodic arrays of unit cells (two or three lossless dielectrics layers) in one, two, or three dimensions[1]. Similar to the electrons moving in crystals, the electromagnetic wave propagation in PCs should satisfy the Bloch condition[2]. The most essential property of PCs is the existence of a photonic band gap (PBG); these PBGs are certain ranges of frequency (or

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wavelength) where the propagation of electromagnetic (EM) waves is strongly prohibited[3]. This property facilitates the active control and manipulation of the flow of EM waves or photons and is used in various applications for a wide range of optical devices[4]. Furthermore, PCs have been successfully used to control the absorption and radiation by the surface-wave, resonant-cavity, and Brewster modes[4].

Simultaneously, more metamaterials have been fabricated and used in controlling thermal emissions. For example, a metamaterial with a refractive index much less than unity has also been proposed as an emission source; the direction of its radiative wave is nearly perpendicular to surface of the metamaterial[5]. Furthermore, PCs such as negative-index materials (NIMs) have been recently intensively studied. The PCs made by alternating layers of positive-index materials (PIMs) and NIMs have a unique PBG, which is referred to as the zero-averaged-refractive-index (*zero*$-\bar{n}$) gap[6]. The properties of the *zero*$-\bar{n}$ gap are independent of the incident angles and polarizations, as well as insensitive to the unit-cell size scaling of the PCs[7]. These properties differ from those of the Bragg gap. Resonant tunneling modes of photonic quantum well (QW) based on the *zero*$-\bar{n}$ gap have been found to be almost constant for different incident angles, polarizations, and thickness defects. These features improve its performance as a multiple channeled filter. The photonic QW based on the *zero*$-\bar{n}$ gap has been proposed to control thermal radiation through its resonant tunneling modes[8]. Moreover, the defect mode of the *zero*$-\bar{n}$ gap for the NIM-containing PCs does not depend on the incident angle nor vary with the scaling of the PCs[7].

In this paper, we used the defect mode of one-dimensional PCs consisting of PIMs and NIMs to generate coherent thermal emission by coating the PCs onto the absorbing substrate SiC. Given the novel characteristics of the defect mode of the *zero*$-\bar{n}$ gap, this type of thermal emission is predicted to have promising radiative properties. The radiative properties of this type of coherent thermal emission are investigated using the transfer matrix method.

1 Model and theory

The structure of one dimensional photonic crystal consists of A and B periodic alternating layers of dielectric material[9]. The structure is inserted into a defect layer C and is coated over a SiC substrate. A is PIM, B and C are PIMs. The permittivity, permeability, and thickness in the PCs are assumed to be ε_1, μ_1, and d_1 for the PIM, ε_2, μ_2, and d_2, for NIM, and ε_c, μ_c, and d_c for the defect layer, respectively. The permittivity and permeability of the media surrounding the structure are assumed to be ε_0 and μ_0, respectively[10].

The dispersion relation can be obtained using the Bloch-Floquet theorem[9-11]

$$\cos[\kappa(d_1+d_2)]=\cos(k_{1z}d_1)\cos(k_{2z}d_2)+\frac{1}{2}\left(\frac{\sigma_2}{\sigma_1}+\frac{\sigma_1}{\sigma_2}\right)\sin(k_{1z}d_1)\sin(k_{2z}d_2) \tag{1}$$

with

$$\sigma_i=k_{iz}/\mu_i(i=1,2)\text{ for TE polarization} \tag{2}$$

and

$$\sigma_i=k_{iz}/\varepsilon_i(i=1,2)\text{ for TM polarization} \tag{3}$$

κ is the Bloch wave vector. k_{1z} and k_{2z} are the components of the wave vector along the z-axis in the PIM and NIM layers, respectively, which can be expressed as

$$k_{iz}=\pm(2\pi/\lambda)\sqrt{\varepsilon_i\mu_i-\varepsilon_0\mu_0\sin^2\theta}(i=1,2) \tag{4}$$

ω is the angular frequency; λ is the wavelength of light in air; θ is the incident angle.

The matrix of one-dimension PCs can be expressed as[12]

$$\boldsymbol{M}=\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{5}$$

The reflectance of the multilayered structure for either type of polarization can be calculated by

$$\boldsymbol{R}=\left|\frac{M_{21}}{M_{11}}\right|^2 \tag{6}$$

The effective permittivity and permeability of NIMs in our proposed structure are given by[13-14]

$$\varepsilon_2=a-\frac{\omega_{\mathrm{ep}}^2}{\omega^2} \tag{7}$$

and

$$\mu_2=b-\frac{\omega_{\mathrm{mp}}^2}{\omega^2} \tag{8}$$

where ω_{ep} and ω_{mp} are the electronic and magnetic plasma frequencies, respectively. Such dispersion can be realized in a composite made of periodically LC-loaded transmission lines[15].

The wavelength range corresponding to the *zero*$-\bar{n}$ gap of the PCs is tuned to approximately match the wavelength range for the phonon absorption band of SiC. Given that the wavelengths of other incident light that can pass through PCs are not located in the phonon absorption band of SiC, only the incident light with a wavelength equal to the defect mode of the *zero*$-\bar{n}$ gap can pass through the PCs and be absorbed by the SiC.

2 Results and discussion

If a defect layer is inserted into the PCs, the defect mode will appear in the *zero*$-\bar{n}$ gap. The chosen refraction index of the defect layer is $n_c=1.7$; the chosen thickness of the defect layer is $d_c=\alpha(\lambda_0/4n_c)$ (where α is a positive number). We choose $\alpha=1.3$ and the incident angle $\theta=0°$ in Fig. 1. The solid line is the reflectance of the PC without the defect, which is used for comparison; its reflectance is unity in the region from 10 μm to 13 μm that corresponds to the *zero*$-\bar{n}$ gap. The other line denotes the reflectance of the PCs with the defect. A dip appears in the *zero*$-\bar{n}$ gap, which is caused by the defect layer.

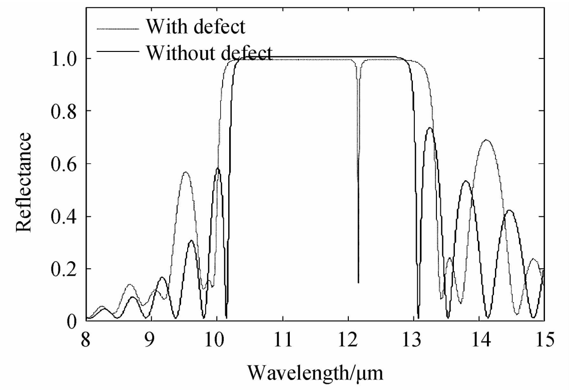

Fig. 1 Reflectance of the PC with a defect in the TE mode (the thickness of the defect layer is set)

SiC is an ideal polar material for coherent emission in the mid-infrared spectral region. The SiC can only absorb the incident light a wavelength within the phonon absorption band, regardless of its polarization and incident angle. Among all the incident light waves that could pass through the PCs, only the wavelength of the *zero*$-\bar{n}$ gap defect mode is located in the phonon absorption band of SiC. Thus, the radiative source can only absorb the incident light with the same wavelength as the *zero*$-\bar{n}$ gap defect mode. According to Kirchhoff's law, the proposed radiative source will only be able to emit light at a wavelength equal to the *zero*$-\bar{n}$ gap defect mode. When the thickness of the defect layer is $d_c=1.3(\lambda_0/4n_c)$ and the same n_c is used, the emissivity of the radiative source can be calculated at a different incident angle for TE polarization (Fig. 2). The emissivity peak position shifts slightly toward the short wavelength, and the emissivity peak value remains very high when the emissivity angle is increased from 0° to 30°. The temporal coherence of thermal emission is evident from the sharp spectral peak in the emissivity. The quality factors ($Q=\lambda_{\mathrm{peak}}/\Delta\lambda$) of the three emissivity peaks in Fig. 2 are 695.0, 689.7, and 719.5, respectively, where λ_{peak} is the wavelength of the emissivity peak and $\Delta\lambda$ is the full-width at half-maximum. The spatial coherence of thermal emission can be seen in the angular distributions of the emissivity. These angular distributions at the three peak wavelengths in Fig. 3 correspond with those in Fig. 2. Thus, the narrow angular lobe is in a well-defined direction.

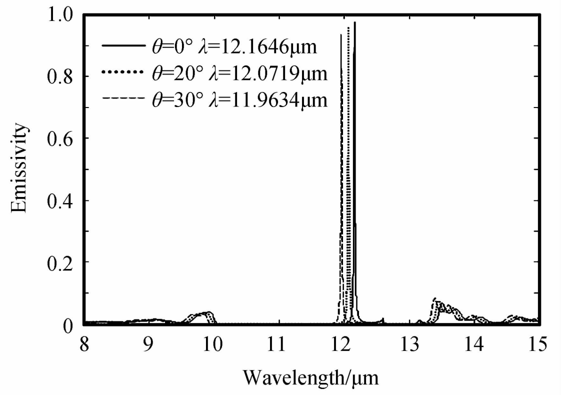

Fig. 2 Emissivity of the defect mode radiation structure under different angles for the TE mode when $n_c=1.7$, $d_c=1.3(\lambda_0/4n_c)$

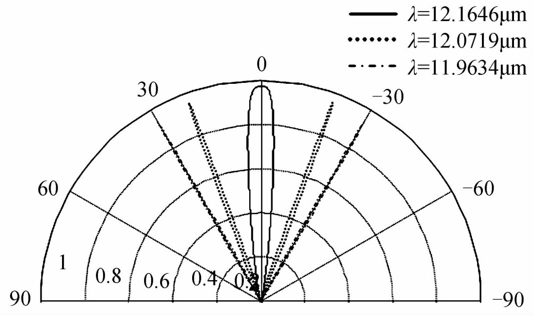

Fig. 3 Angular distribution of the emissivity for the defect mode radiation structure

The dependence of the emissivity peak position on the incident angle for different polarizations is shown in Fig. 4. The emissivity peaks of different polarizations are at the same position when the emission angle is $\theta=0°$. Both are slightly shifted toward the short wavelength, but they begin to separate when the emission angle increases. The emissivity peak positions change only at 0.8 μm (for the TE mode) and 0.7 μm (for the TM mode), respectively. The distance between them only increases to approximately 0.1 μm when the emission angle changes from 0° to 80°. Therefore, the defect mode of thermal radiation is very weakly dependent on the incident angle and polarization. Furthermore, the proposed radiative source ensures that the wavelength-selective thermal emission of both TE and TM polarization states follows a well-defined direction.

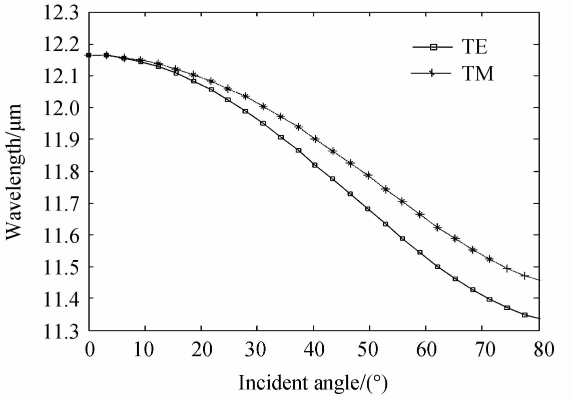

Fig. 4 Changes in the defect mode radiation peak position with the wavelength as a function of the emission angle

The emissivity peak values at different polarization levels are all extremely high, with a very wide emission angle range; these values can approach unity when the incident angle $\theta \leqslant 30^\circ$, as shown in Fig. 5. The quality factors Q of the emissivity peak at the different emission angles for TE and TM polarizations are shown in Fig. 6. Q for TE polarization is almost constant at approximately 700 when the emission angle is in the range of 0° to 60°. Q for the TM polarization increases from 700 to 3800 when the emission angle the increases from 0° to 80°. The quality factor of this kind emission is much higher than that for other materials like PCs, gratings, and single negative materials. The emissivity of the radiative source with different scaling factors ($s=90\%$, $s=100\%$, and $s=110\%$) of the PCs is at a normal emission angle for TE polarization (Fig. 7). The emissivity peak is almost constant even when the scaling factor changes.

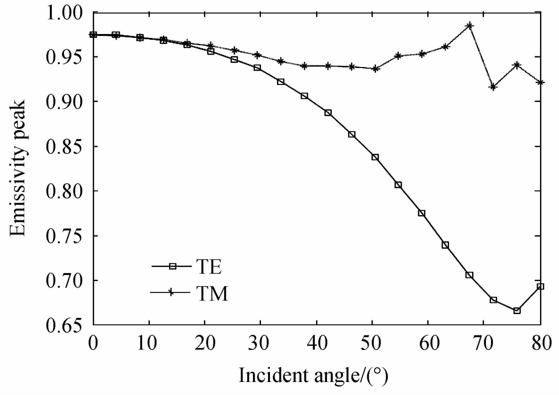

Fig. 5 Relationship of the defect mode radiation emissivity peak value and the incident angle

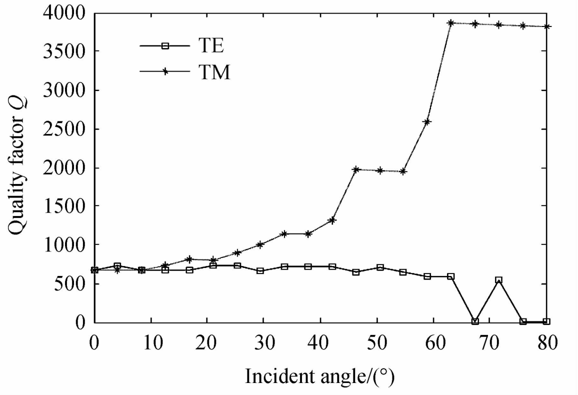

Fig. 6 Relationship of the defect mode quality factor of the radiation emissivity peak and the incident angle

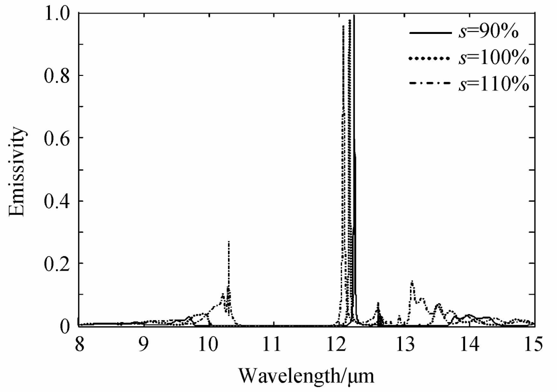

Fig. 7 Spectral emissivity of the defect mode radiation under different unit-cell sized scaling factors of the PC at an emission angle of $\theta=30^\circ$ for the TE mode

The characteristics of the emission peak under different optical thicknesses d_c of the defect layer are shown in Table 1, where in its refractive index is constant at $n_c=1.7$. E_{peak} and Q denote the value and quality factor, respectively, of the emission peak for different polarization values at the emission angle $\theta=0^\circ$. $\Delta\lambda_1$ denotes the deviation of the emission peak position in terms of the wavelength for the different polarizations at an emission angle of $\theta=30^\circ$; $\Delta\lambda_2$ denotes the variation of the emission peak position in terms of the wavelength for TE polarization when the emission angle changes from 0° to 30°. The emission peak value E_{peak} for $2.0(\lambda_0/4n_c)>d_c>1.1(\lambda_0/4n_c)$ is higher than that for $0<d_c<1.1(\lambda_0/4n_c)$. Q for d_c in the range of $0.7(\lambda_0/4n_c)$ to $1.1(\lambda_0/4n_c)$ is higher than that for other values of d_c. That is, Q for the emission peak in the center part of the $zero-\bar{n}$ gap is higher than that for the emission peak position bilateral to it. The smallest value for $\Delta\lambda_1$ was 0.004 9 μm when $d_c=0.8(\lambda_0/4n_c)$. This value may increase when d_c increases or decreases; whereas $\Delta\lambda_2$ will decrease when d_c decreases.

The characteristics of the emission peaks under different refractive indexes of the defect layer when its optical thickness is $d_c = 1.3(\lambda_0/4n_c)$ are shown in Table 2. The symbols in Tables 1 and 2 are the same. E_{peak} and Q both increase when the refractive index of the defect layer n_c decreases. $\Delta\lambda_1$ and $\Delta\lambda_2$ both decrease when the refractive index of the defect layer n_c increases. According to Tables 1 and 2, we can tune the properties of thermal radiation by choosing the parameters (d_c and n_c) of the defect layer that satisfy different requirements for its real-world application.

Table 1 Changes in the defect mode radiation structure with d_c of the defect layer when $n_c = 1.7$

d_c	E_{peak}	Q	$\Delta\lambda_1/\mu m$	$\Delta\lambda_2/\mu m$
$0.4(\lambda_0/4n_c)$	0.610 8	448.3	0.028 9	0.126 0
$0.5(\lambda_0/4n_c)$	0.606 7	585.1	0.022 5	0.138 3
$0.6(\lambda_0/4n_c)$	0.615 6	734.5	0.014 6	0.150 5
$0.7(\lambda_0/4n_c)$	0.638 8	976.6	0.005 3	0.162 7
$0.8(\lambda_0/4n_c)$	0.677 8	1 075.7	0.004 9	0.172 4
$0.9(\lambda_0/4n_c)$	0.723 1	1 009.4	0.015 0	0.182 0
$1.0(\lambda_0/4n_c)$	0.785 4	1 025.4	0.024 4	0.189 0
$1.1(\lambda_0/4n_c)$	0.852 1	966.6	0.033 8	0.195 1
$1.2(\lambda_0/4n_c)$	0.919 3	857.7	0.042 8	0.199 5
$1.3(\lambda_0/4n_c)$	0.974 7	695.0	0.050 6	0.201 3
$1.4(\lambda_0/4n_c)$	0.999 4	520.9	0.058 1	0.200 4
$1.5(\lambda_0/4n_c)$	0.958 4	364.5	0.064 1	0.198 7

Table 2 The proper values of the defect mode radiation structure change with n_c of the defect layer when $d_c = 1.3(\lambda_0/4n_c)$

n_c	E_{peak}	Q	$\Delta\lambda_1/\mu m$	$\Delta\lambda_2/\mu m$	$\Delta\lambda_3/\mu m$
1.0	0.993 8	1 133.6	0.126 0	0.425 3	0.239 8
1.5	0.9871	728.4	0.060 4	0.231 0	0.183 8
1.7	0.974 7	695.0	0.050 8	0.201 3	0.162 7
2.0	0.946 3	582.1	0.043 8	0.174 1	0.134 8
2.4	0.898 8	539.7	0.041 1	0.157 5	0.101 5

3 Conclusion

The radiative properties and controlling of coherent thermal radiation source consisting of one-dimensional photonic crystals containing negative-index materials are investigated. The calculated emissivity shows very sharp peaks in a narrow wavelength band and at a well-defined direction. The quality factor of this kind emission peak is higher than that for ordinary material. This kind emission peak is insensitive to the emission angles, polarizations, and scaling factor of the PCs in the. The characteristics of the emission peak can be tuned by properly changing the parameters (d_c and n_c) of the defect layer to satisfy the different requirements in the real-world applications.

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