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Coherent thermal emission from one-dimensional photonic crystals

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Coherent thermal emission from surface relief gratings holds promise for spectral and directional control of thermal radiation but is limited to transverse magnetic waves, which can excite surface plasmon or phonon polaritons in the grating structure. We show in this letter that a coherent thermal source can be constructed with a thin polar material coated on a one-dimensional photonic crystal. The excitation of surface waves at the interface of the coated layer and the photonic crystal results in highly spectral and directional emission in the infrared for both the transverse electric wave and the transverse magnetic wave. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2010613]

Thermal radiation emitted from solids is generally manifested by a broad spectrum and quasi-isotropic angular behavior. Coherent thermal emission has drawn much attention lately for applications in thermophotovoltaic devices, optoelectronics, and space thermal management. Coherent thermal sources have been constructed using surface relief gratings[1–3] by excitation of surface polaritons, which are localized electromagnetic waves that propagate along the interface and decay into each medium. However, the grating structure can support surface polaritons only for transverse magnetic (TM) waves, where the emission direction is perpendicular to the grooves. Spectral and directional oscillations have been observed from a planar semitransparent layer due to interference effects.[4] In this case, the emission distribution contains multiple peaks that are generally much broader than those due to surface waves. Coherent emission sources based on metamaterials with a refractive index much less than unity[5] or singe negative materials[6] have also been proposed; however, these materials have not been fabricated in the near-infrared and mid-infrared spectral regions, which are the most important wavelengths for thermal radiation.

A large number of recent studies utilize the unique features of modulated microstructures (i.e., photonic crystals) to control and improve the optical and radiative properties for specific applications.[7–11] A photonic crystal (PC) is a periodic array of unit cells, or photonic lattices by analogy with those in real crystals, that replicate infinitely into one, two, or three dimensions. A salient feature of PCs is the existence of photonic band structures. In a pass band, electromagnetic waves can propagate freely, whereas in a stop band or forbidden band, no energy-carrier waves can exist inside a PC.[12] The unit cell of a one-dimensional (1D) PC is a binary layer of dielectric materials. Yeh, Yariv, and Hong[13] showed that a PC can support surface modes or surface waves for both the TM wave and the transverse electric (TE) wave in the stop band. If a metallic layer is coated on a 1D PC, surface waves can be excited by a propagating wave in air; this will result in a strong reduction in the reflectance at the resonance frequency.[14]

Here, we describe a potential coherent thermal emission source based on a multilayer structure made of a polar material and a 1D PC in the half plane. When the thicknesses and dielectric properties are adjusted, surface waves can be excited in the stop band of the PC by radiative waves propagating in air, for either polarization. Subsequently, the emission from the proposed structure contains sharp peaks within a narrow spectral band and towards well-defined directions. Therefore, the gratingless multilayer structure may be used for the construction of coherent thermal sources for both the TE wave and the TM wave.

SiC is a polar material with strong lattice absorption for wavelengths (λ) between 10 and 13 μm. The wavelength-dependent dielectric function of SiC (ε_s) can be calculated from the functional expression given in Ref. 15. The unit cell of a 1D PC is defined by the thicknesses: a_1, d_b, and a_2, where $a_1+a_2=d_a$ as shown in Fig. 1. Here, subscripts a and b denote the two types of dielectric materials, respectively. For demonstration of the concept, we choose $a_1=a_2=d_b/2$. Consequently, the photonic lattice constant $\Lambda=d_a+d_b$ is the only geometric parameter that affects the PC's band structure. For convenience, the refractive indices for the two types of dielectrics are taken to be constant, $n_a=2.4$ and $n_b=1.5$, in the wavelength region of interest. These values approximate those of ZnSe ($n\approx 2.4$) and KBr ($n\approx 1.52$) near $\lambda=11$ μm.[15]

According to Kirchhoff's law, the spectral-directional emissivity $\varepsilon_{\lambda,\theta}$ is the same as the spectral-directional absorptivity, which is determined by $1-R_{\lambda,\theta}$. To evaluate the reflec-

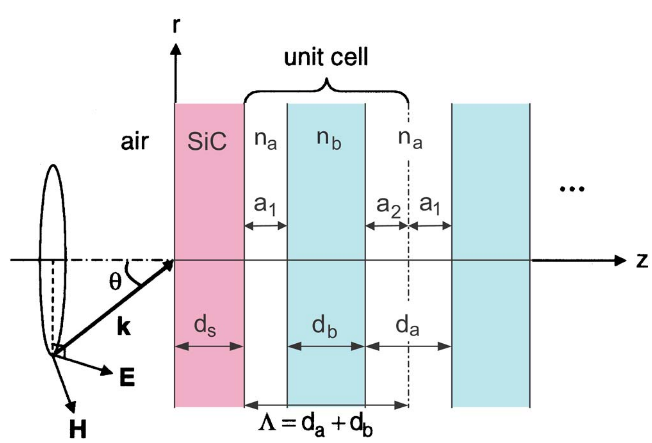

FIG. 1. (Color online) Schematic of the planar structure made of a SiC layer coated on a 1D PC. The unit cell consists of a dielectric (type a) on both sides of a dielectric (type b) with a lattice constant $\Lambda=d_a+d_b$, where $d_a=a_1+a_2$.

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tance $R_{\lambda,\theta}$, we consider a plane monochromatic wave incident from air at an angle of θ (see Fig. 1). Because the planar structure is axially symmetric, the cylindrical coordinates are shown in the figure, in which r is parallel to the surface and z is perpendicular to the surface. For a TE wave, the electric field is always perpendicular to the radial direction. A transfer matrix method can be used to evaluate the reflectance of the multilayer structure.[13] To apply the 1D transfer matrix formulation for plane waves, the Cartesian coordinates are used in which the x-z plane defines the plane of incidence and the y axis defines the polarization. Alternatively, an equivalent layer method designed for 1D periodic structures may be used to calculate $R_{\lambda,\theta}$.[14]

A surface electromagnetic wave propagates along the interface and decays exponentially into both media. In order to excite a surface wave, evanescent waves are required in both the SiC layer and the PC structure. Evanescent waves exist in SiC, regardless of the angle of incidence, when its dielectric function ε_s is negative, since the normal component of the wave vector $k_{s\perp}=(\omega^2\varepsilon_s/c^2-k_{\parallel}^2)^{1/2}$ is imaginary. Here, ω is the angular frequency, c is the speed of light in vacuum, and $k_{\parallel}=\omega \sin\theta/c$ is the parallel component of the wave vector. In reality, the dielectric function of SiC is a complex quantity, and an evanescent wave can exist when the real part of ε_s is negative and the imaginary part of ε_s is much smaller than unity. This is the case in the phonon absorption band of SiC between $\lambda=10.5$ and 12.5 μm. On the other hand, an effective evanescent wave exists inside the PC at the stop band.[12] The wavelength range corresponding to the stop band of a PC can be scaled by changing the photonic lattice constant Λ. To match the phonon absorption band of SiC, we choose $\Lambda=3$ μm in the present study.

In the calculation, 30 periods of unit cells are sufficient for the PC to be approximated as semi-infinite. Figure 2(a) shows the emissivity spectra at $\theta=0°$, 30°, and 60° for each polarization. Since the emission peak depends on the thickness of SiC, d_s can be tuned to maximize the emissivity for a given emission angle and polarization. Here, the thickness of SiC is set to be $d_s=1.45$ μm, which results in a close-to-unity emissivity at $\theta=60°$ for the TE wave and slightly lower emission peaks at other conditions. For TE waves shown in the upper panel of Fig. 2(a), very large $\varepsilon_{\lambda,\theta}$ occurs in a narrow wavelength band centered at $\lambda_c=11.479$, 11.293, and 10.929 μm for 0°, 30°, and 60° emission angles, respectively. The emissivity is very small outside the band. The spectral emission peaks clearly indicate temporal coherence of thermal emission. The corresponding quality factors ($Q=\lambda_c/\Delta\lambda$, where $\Delta\lambda$ is the full width at half maximum) of the emissivity peaks are 230, 185, and 133, respectively, which are comparable to those for gratings[3] and single negative materials.[6] It can be seen from the lower panel of Fig. 2(a) that the TM wave result is identical to the TE wave result when $\theta=0°$. At the emission angles $\theta=30°$ and 60°, the peak locations and emissivity maxima for TM waves are slightly different from those for TE waves, while the bandwidths are nearly the same at each emission angle.

The spatial coherence of the proposed structure is illustrated by the angular distributions of the emissivity, overlaid in Fig. 2(b) at the three peak wavelengths for TE waves. Due to axial symmetry of the planar structure, the coherent emission exhibits circular patterns, in contrast to the antenna shape for grating surfaces. Recall from Fig. 1 that for TE waves the electric field is tangential to the ring. The patterns

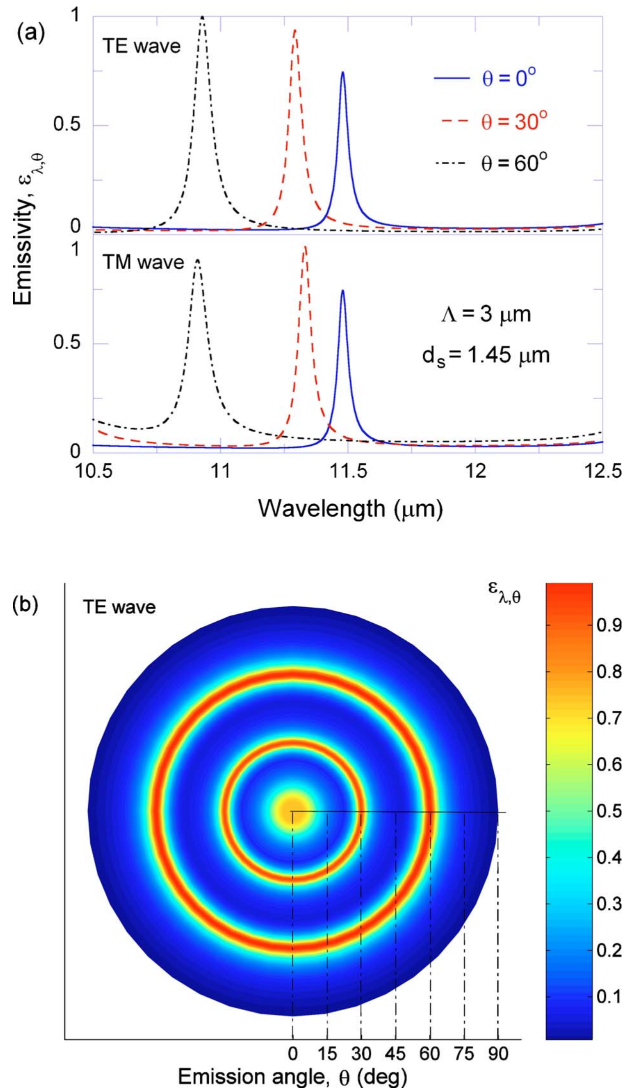

FIG. 2. (Color online) The spectral-directional emissivity $\varepsilon_{\lambda,\theta}$ of the SiC-PC structure: (a) spectral dependence at $\theta=0°$, 30°, and 60° for TE waves (upper panel) and TM waves (lower panel); (b) angular distributions at $\lambda_c=11.479$, 11.293, and 10.929 μm for TE waves.

are very similar for TM waves at the corresponding peak wavelength. The emissivity at each λ_c is confined in a very narrow angular region, although the angular spread corresponding to the peak at $\theta=0°$ is larger than the other peaks.

The large enhancement of the emissivity is due to excitation of the surface wave. The dispersion relation of surface wave can be obtained using the method described in Ref. 14 to determine the resonance wavelength or frequency at a given incidence angle, although the actual location will vary slightly with the SiC thickness. It should be noted that surface waves between SiC and 1D PC are somewhat different from the surface waves due to polaritons. As an example, consider the surface plasmon between air and a metal. Evanescent waves are required in both the metal and air. Therefore, attenuated total reflection configuration is routinely employed to excite a surface polariton. For the surface wave in PCs, there is no actual evanescent field inside the dielectric layers as discussed in the following.

Figure 3 shows the square of the electric field, normalized to the incident, inside the SiC-PC structure at normal incidence. The real part of the complex electric field is used to show the actual field inside the structure. The solid line

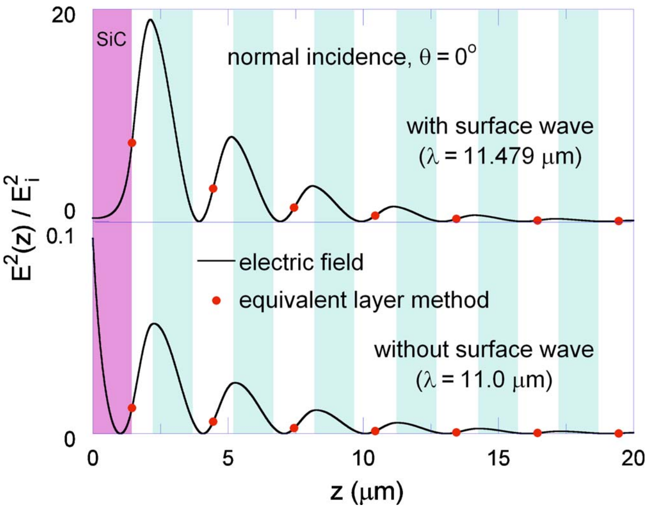

FIG. 3. (Color online) The square of the electric field (solid lines), normalized by the incident, inside the SiC-PC structure at normal incidence. The dots indicate the field at the boundaries of the unit cell. The upper panel represents the case where a surface wave is excited, whereas the lower panel illustrates a case without a surface wave.

represents the field calculated from the transfer matrix formulation. An oscillating field exists inside the PC, and the amplitude of the oscillating field decays gradually towards larger z. The dots represent the electric field obtained using the equivalent layer method, which matches the matrix solutions at the boundaries of each unit cell.[14] The upper panel corresponds to the wavelength ($\lambda=\lambda_c=11.479\ \mu$m) when a surface wave is excited, and the lower panel corresponds to $\lambda=11.0\ \mu$m without a surface wave. The field strength at the boundary between the SiC and the PC is enhanced by more than an order of magnitude due to excitation of the surface wave. When a surface wave is excited, the incident energy is resonantly transferred to the surface wave, which causes a large absorption in the SiC. Because SiC is the only material in the structure that can absorb the incident energy, it is also responsible for the emission of radiation from the SiC-PC structure. It is interesting to note that the maximum electric field is slightly off from the interface between the SiC and the PC, which has been observed previously.[14] If a smooth curve is used to connect all the dots shown in Fig. 3, it will be the maximum at the SiC-PC interface and decay gradually deep into the PC. Furthermore, the Poynting vector or energy flux in the z direction is zero inside the PC at the stop band. Therefore, the effective field inside the PC at the stop band resembles an evanescent wave in a semi-infinite medium. The fact that the field near the SiC-PC interface is greatly enhanced confirms the existence of a surface wave. Further, surface waves at the interface between the SiC and the PC can be excited at any angle of incidence and for both polarizations.

Using a 1D PC coated with a thin SiC layer, we have shown that surface waves can be excited for both polarizations in the stop band to enable coherent thermal emission from the SiC-PC structure. The calculated emissivity exhibits very sharp peaks in a narrow wavelength band and well-defined directions. The proposed planar structure involves only dielectric films, which can be fabricated with available vacuum deposition techniques. Future research is needed to measure the spectral-directional emissivity from the proposed SiC-PC structure.

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[1] P. J. Hesketh, J. N. Zemel, and B. Gebhart, Nature (London) **324**, 549 (1986).
[2] M. Kreiter, J. Oster, R. Sambles, S. Herminghaus, S. Mittler-Neher, and W. Knoll, Opt. Commun. **168**, 117 (1999).
[3] J.-J. Greffet, R. Carminati, K. Joulain, J.-P. Mulet, S. Mainguy, and Y. Chen, Nature (London) **416**, 61 (2002).
[4] O. G. Kollyukh, A. I. Liptuga, V. Morozhenko, and V. I. Pipa, Opt. Commun. **225**, 349 (2003).
[5] S. Enoch, G. Tayeb, P. Sabouroux, N. Guérin, and P. Vincent, Phys. Rev. Lett. **89**, 213902 (2002).
[6] C. J. Fu, Z. M. Zhang, and D. B. Tanner, Opt. Lett. **30**, 1873 (2005).
[7] S. Maruyama, T. Kashiwa, H. Yugami, and M. Esashi, Appl. Phys. Lett. **79**, 1393 (2001).
[8] E. F. Schubert, N. E. J. Hunt, A. M. Vredenberg, T. D. Harris, J. M. Poate, D. C. Jacobson, Y. H. Wong, and G. J. Zydzik, Appl. Phys. Lett. **63**, 2603 (1993).
[9] M. U. Pralle, N. Moelders, M. P. McNeal, I. Puscasu, A. C. Greenwald, J. T. Daly, E. A. Johnson, T. George, D. S. Choi, I. El-Kady, and R. Biswas, Appl. Phys. Lett. **81**, 4685 (2002).
[10] S. Y. Lin, J. Moreno, and J. G. Fleming, Appl. Phys. Lett. **83**, 380 (2003).
[11] B. Temelkuran, M. Bayindir, E. Ozbay, R. Biswas, M. M. Sigalas, G. Tuttle, and K. M. Ho, J. Appl. Phys. **87**, 603 (2000).
[12] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals* (Princeton University Press, Princeton, NJ., 1995).
[13] P. Yeh, A. Yariv, and C. S. Hong, J. Opt. Soc. Am. **67**, 423 (1977).
[14] J. A. Gaspar-Armenta and F. Villa, J. Opt. Soc. Am. B **20**, 2349 (2003).
[15] E. D. Palik, *Handbook of Optical Constants of Solids I & II* (Academic, Boston, 1991).