Tuning Coherent Radiative Thermal Conductance in Multilayer Photonic Crystals

Wah Tung Lau,[1,2] Jung-Tsung Shen,[2] Georgios Veronis,[2] Shanhui Fan,[1,2*]
[1]*Department of Electrical Engineering, Stanford University, Stanford, California, 93405, USA*
[2]*Ginzton Laboratory, Stanford University, Stanford, California, 94305, USA*
[*] *shanhui@stanford.edu*

Photonic crystals can be used to drastically influence coherent radiative thermal conductance. In a multilayer crystal, radiative thermal conductance can transit from above to below vacuum value when temperature increases, due to photonic band effects.

OCIS codes: (350.4238) Nanophotonics and photonic crystals; (030.5620) Radiative transfer

Recently there has been a lot of interest in exploring coherent thermal transport at nanoscale [1-5]. Most of these studies have exploited phonons as heat carriers, and are restricted at low temperature to avoid strong phonon-phonon interaction in solids [1-3]. Meanwhile, interaction between photons is much weaker, thus coherent transport should occur at higher temperatures. For this reason, here we consider the thermal conductance of a multilayer photonic crystal, consisting of alternating layers of dielectric and vacuum (Fig. 1). Because of the vacuum layers, thermal transport should only be due to photons. With transparent material as the dielectric, the absorption length of photons can be much longer than the crystal periodicity, and hence heat conduction is essentially coherent. Here we show that the band structure significantly affects the thermal conductance of this system.

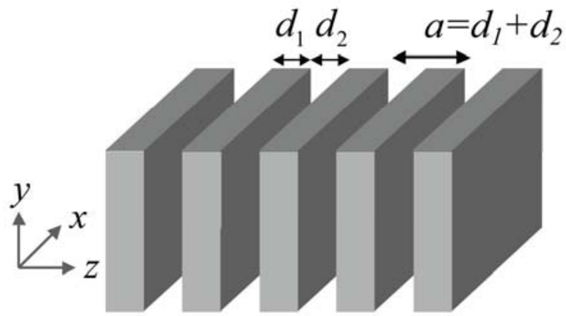

FIG. 1. Schematic of the geometry. Layers of lossless silicon slabs of refractive index $n=\sqrt{12}$, thickness d_1 and infinite cross sectional area, are periodically placed with spacing d_2 in vacuum to form a multilayer photonic crystal with periodicity a along the z-direction.

For heat conduction along the z-direction, the coherent radiative thermal conductance per unit area $G(T)$ in three-dimensional systems is [1]:

$$G(T) = k_B \int_0^\infty \frac{d\omega}{(2\pi)^3} \frac{[(\hbar\omega)/(k_B T)]^2 e^{(\hbar\omega)/(k_B T)}}{[e^{(\hbar\omega)/(k_B T)} - 1]^2} A(\omega), \tag{1}$$

where T is the operating temperature. ω is the photon frequency, and $\omega(\mathbf{k})$ is the dispersion relation of the crystal. At a constant frequency, $\omega_0 = \omega(\mathbf{k})$ describes a constant frequency surface in $\mathbf{k}$-space. $A(\omega = \omega_0)$ is the magnitude of the projected area of such constant frequency surface onto the k_x - k_y plane. For vacuum with both polarizations considered, $A_{\text{vac}}(\omega) = 2\pi(\omega/c)^2$. For our structure with cylindrical symmetry, $A(\omega) \equiv 2\pi \sum_{m,\zeta} \int_{k_{m,\zeta}^{(1)}(\omega)}^{k_{m,\zeta}^{(2)}(\omega)} k_\parallel dk_\parallel$, where $k_\parallel$ is the magnitude of $\mathbf{k}$ along the x-y plane, $k_{m,\zeta}^{(1)}(\omega)$ and $k_{m,\zeta}^{(2)}(\omega)$ are the minimum and maximum $k_\parallel$ values of the projected band with index m at ω . $\zeta = s, p$ denotes the s- or p-polarizations and $A(\omega) = A_s(\omega) + A_p(\omega)$. As an illustration, the projected band diagram for s-polarization of the structure with $d_2 = d_1$ is shown in Fig. 2(a) [6]. The photon states in $0 < k_\parallel < \omega/c$ are extended in vacuum, while states in $\omega/c < k_\parallel < n\omega/c$ are evanescent in vacuum. The regions in $0 < k_\parallel < n\omega/c$ with no photon state are the partial photonic bandgaps.

978-1-55752-859-9/08/$25.00 ©2008 IEEE

$A_s(\omega)/A_{\text{vac}}(\omega)$ can now be calculated and is plotted in Fig. 2(b). At small ω, there are substantial photon states evanescently coupled through vacuum and $A_s(\omega)/A_{\text{vac}}(\omega) > 1/2$. As ω increases, evanescent coupling strength becomes progressively smaller, while partial bandgaps persist below the vacuum light line in the entire frequency range. Hence $A_s(\omega)/A_{\text{vac}}(\omega) < 1/2$ at large ω. $A(\omega)/A_{\text{vac}}(\omega)$ behaves similarly.

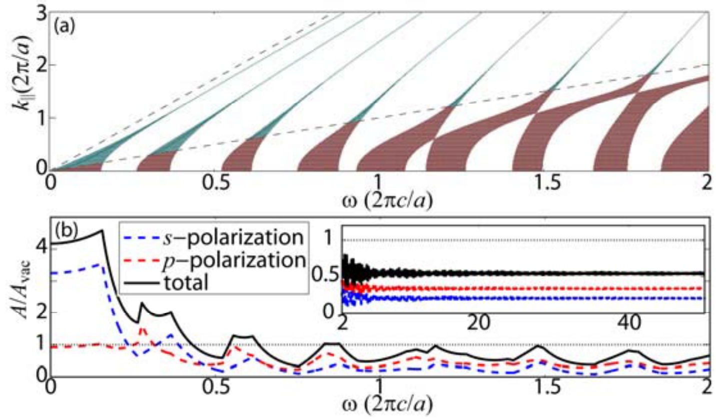

FIG. 2. (a) Projected band diagram $(\omega, k_{\parallel})$ of *s*-polarization of the structure in Fig. 1 with $d_2 = d_1$. The bands in $0 < k_{\parallel} < \omega/c$ (brown), and in $\omega/c < k_{\parallel} < n\omega/c$ (green) are separately colored. The vacuum ($\omega/c = k_{\parallel}$) and the material ($\omega/c = nk_{\parallel}$) light-lines are also shown. (b). The black line shows the total normalized projected area $A(\omega)/A_{\text{vac}}(\omega)$ for the same structure in (a), together with the contributions from *s*- (blue) and *p*- (red) polarized fields. The vacuum level $A(\omega)/A_{\text{vac}}(\omega) = 1$ is also indicated. The inset shows the result at high frequency.

We can now calculate $G(T)$ for $d_2 = d_1$ using Eq. (1). The result is normalized with respect to the vacuum value $G_{\text{vac}}(T) = (\pi^2 k_B^4 T^3)/(15\hbar^3 c^2)$, and is shown in Fig. 3 (black curve). At low temperature, photons populate a small bandwidth of ω where $A(\omega)/A_{\text{vac}}(\omega) > 1$, hence $G(T)/G_{\text{vac}}(T) > 1$. $G(T)/G_{\text{vac}}(T)$ then decreases to below 1 at higher temperature as photons distribute over a larger range of ω where $A(\omega)/A_{\text{vac}}(\omega) < 1$. Thus, photonic crystals can be used to generate a medium with thermal conductance below that of vacuum.

Using the same set of dielectric slabs, we can tune the thermal conductance by varying the slab separation at a constant temperature. In Fig. 3, we also plot the results for $d_2 = 9d_1$ and $0.111d_1$. For this range of d_2, thermal conductance generally decreases as d_2 increases. In particular, when the temperature is $T_a = 0.02(hc/k_B d_1)$, the thermal conductance can be tuned by more than an order of magnitude. With silicon as the dielectric, the choice of T_a here corresponds to $287.8K$ when d_1 is $1\mu m$. Thus, such effect is readily observed at room temperature.

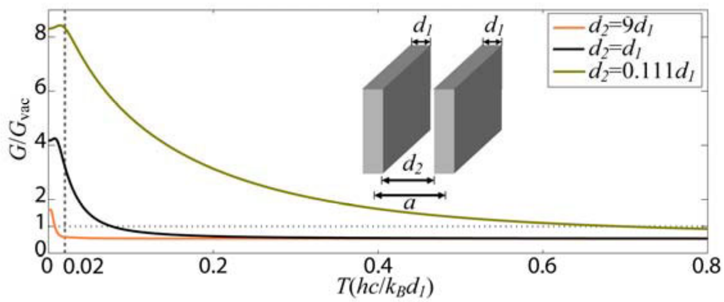

FIG. 3. Normalized radiative thermal conductance $G(T)/G_{\text{vac}}(T)$ for three structures with constant silicon slab thickness, but different slab separations. The temperature of $T_a = 0.02(hc/k_B d_1)$, where significant variation as a function of d_2 occurs, is indicated as a vertical dashed line. The vacuum conductance $G(T)/G_{\text{vac}}(T) = 1$ is shown as a horizontal line. The inset shows the schematic of the structure.

[1] K. Schwab, E. A. Henriksen, J. M. Worlock and M. L. Roukes, Nature (London) **404** 974 (2000).
[2] L. G. C. Rego, and G. Kirczenow, Phys. Rev. Lett. **81**, 232 (1998).
[3] G. Chen, J. Heat Transfer **121** 945 (1999).
[4] M. Meschke, W. Guichard and J. P. Pekola, Nature (London) **444**, 187 (2006).
[5] D. R. Schmidt, R. J. Schoelkopf and A. N. Cleland, Phys. Rev. Lett. **93**, 045901 (2004).
[6] A. Yariv and P. Yeh, *Photonics, Optical Electronics in Modern Communications* (Oxford University Press 6th edition, 2007).