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Meshed doped silicon photonic crystals for manipulating near-field thermal radiation

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ABSTRACT

The ability to control and manipulate heat flow is of great interest to thermal management and thermal logic and memory devices. Particularly, near-field thermal radiation presents a unique opportunity to enhance heat transfer while being able to tailor its characteristics (e.g., spectral selectivity). However, achieving nanometric gaps, necessary for near-field, has been and remains a formidable challenge. Here, we demonstrate significant enhancement of the near-field heat transfer through meshed photonic crystals with separation gaps above 0.5 µm. Using a first-principle method, we investigate the meshed photonic structures numerically via finite-difference time-domain technique (FDTD) along with the Langevin approach. Results for doped-silicon meshed structures show significant enhancement in heat transfer; 26 times over the non-meshed corrugated structures. This is especially important for thermal management and thermal rectification applications. The results also support the premise that thermal radiation at micro scale is a bulk (rather than a surface) phenomenon; the increase in heat transfer between two meshed-corrugated surfaces compared to the flat surface (8.2) wasn't proportional to the increase in the surface area due to the corrugations (9). Results were further validated through good agreements between the resonant modes predicted from the dispersion relation (calculated using a finite-element method), and transmission factors (calculated from FDTD).

1. Introduction

Manipulating heat transfer is of engineering interest for its potential applications in thermal storage, thermal management and thermal logic [1] and memory [2–4] devices. However, controlling heat transfer is a challenge due to the lack of perfect thermal insulators, unlike in the case of electricity. Vacuum is an efficient thermal insulator, however not perfect since radiative heat transfer can still flow through vacuum. Nevertheless, using near-field effects, thermal radiation enhancement and/or suppression through vacuum can result in desired tailoring of heat transfer.

It has been demonstrated that near-field thermal radiation can enhance the radiative heat transfer dramatically, even beyond the classical theoretical limit of the blackbody radiation [5,6]. The transfer of thermal energy by near-field radiation occurs when a thermal emitter and receiver are brought very close to each other, at distances near or below the characteristic wavelength of thermal radiation. At this close proximity, in addition to propagating harmonic electromagnetic waves (as in the case of blackbody radiation), evanescent (i.e., non-propagating) waves which are confined to the thermal emitter's surface (i.e., can only propagate along the surface) participate in the thermal energy transfer. The extra channels for heat flow created by these evanescent waves increase the rate of heat transfer exchange exponentially with decreasing separation gap (i.e., the smaller the gap, the stronger the evanescent fields are and the higher the thermal radiation exchange rate) [7,8]. These particularities of near-field thermal radiation make it ideal for thermal modulation applications, such as with thermal memory, thermal diode [9–13] and thermal switches [14,15].

Near-field thermal radiation has been of interest to scientists since the 1960s [16,17], and it has become increasingly an engineering research topic for the past two decades with advances in nano/microfabrication techniques. Research efforts to enhance near-field thermal radiation range from the use of nano/microstructures [18–23], thin layers of polar dielectrics [24,25], patterned layers of graphene [26,27], extremely-thin photonic crystals [28] and metal-dielectric structures that have hyperbolic dispersion [29–31]. Despite the numerous approaches, very few are practical from the engineering standpoint; thin films of polar dielectrics [32] would be an example. Most significant engineering barriers include the fabrication of nanometric separation gaps and the implementation of exotic materials such as graphene.

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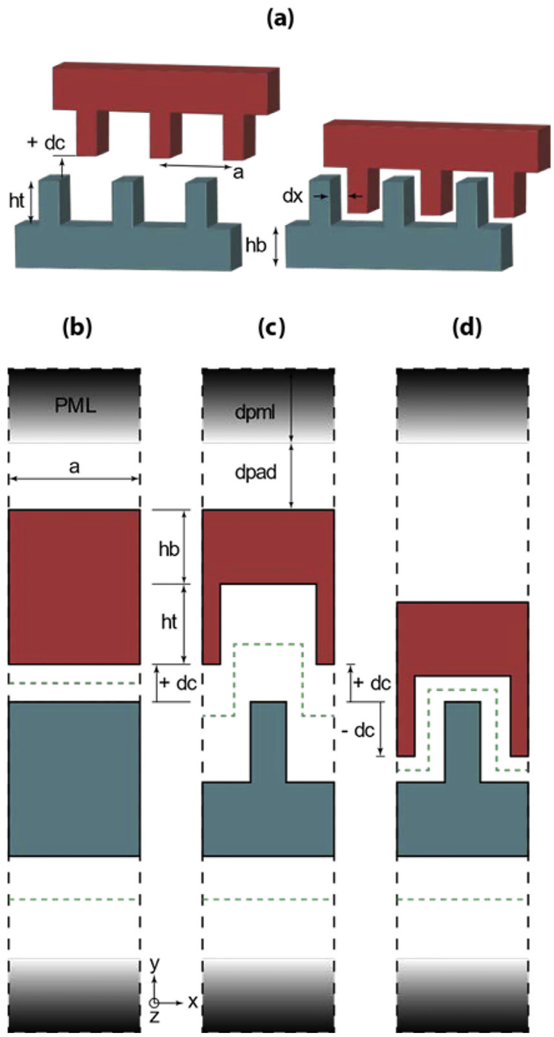

Fig. 1. Meshed photonic crystal layout (a) and computational domain (b-c).

In this paper, we are introducing a practical method for enhancing near-field thermal radiation, without necessarily using extremely small nanometer gaps. We propose using meshed photonic crystals with variable separation gaps as shown in Fig. 1. The meshing increases the area available for heat transfer by thermal radiation and introduce new resonant electromagnetic modes. Both effects are expected to enhance the rate of radiative heat transfer. The meshed photonic crystals have a minimum separation gap of 0.5 µm, achievable with standard microfabrication techniques (i.e., projection lithography and deep reactive ion etching). We used gratings since they are one of the simplest structures and have commonly been used in optics applications. The photonic crystals are made out of doped-silicon which is fully compatible with most standard microfabrication techniques, well characterized, and most importantly, its optical properties can be controlled by varying its doping level [33]; it can be engineered to act as an opaque metal or transparent dielectric. We investigated the meshed photonic crystal numerically using a first principle finite-difference time-domain technique (FDTD). The technique solves Maxwell's equations with added fluctuating current source (to simulate thermal radiation source). We investigate the effect of tooth depth and meshing on the heat transfer and discuss the resonant modes leading to the observed enhancement in heat transfer. In parallel, we calculated the dispersion relation using finite-element method to verify the resonance frequencies in heat transfer from the FDTD results.

2. Methods

The geometry of the meshed photonic crystal investigated in this study is shown in Fig. 1. It is defined by its period *a*, tooth height *ht*, spacing between meshed teeth *dx*, separation distance *dc*, and base thickness *hb*. We model the near-field thermal radiation using a first-principle technique that simulate the source, scattering and absorption of thermal electromagnetic waves. We use finite-difference time-domain (FDTD) method to solve Maxwell's equations with random fluctuating current density source to represent the origin of thermal radiation. We adopted the same method introduced by Luo et al. [34] to simulate the fluctuating current based on the Langevin approach. With this method, a simple variation is made to the FDTD algorithm [35] by introducing a randomly fluctuating component (in both magnitude and direction) to the polarization equation. The polarization equation defines the material's polarization response due to local electric field, and it is used to update the value of the electric field in time stepping through the FDTD algorithm [34]

$$\frac{d^2\mathbf{P}}{dt^2} + \gamma\frac{d\mathbf{P}}{dt} + \omega_0^2\mathbf{P} = \frac{\omega_p^2}{\varepsilon_v}\mathbf{E} + \mathbf{K}(t) \quad (1)$$

where ε_v is the vacuum permittivity. γ, ω_p and ω_0 are the parameters of the Lorentz damped-harmonic oscillator model that describes the polarization response to electric field. γ is the frictional coefficient or scattering rate, ω_p is the plasma frequency, and ω_0 is the polarization resonant frequency. $\mathbf{K}(t)$ is a random variable added to the polarization equation to introduce thermal fluctuations. In this work, we use doped-silicon which optical properties in the infrared regime ($\lambda > 2\,\mu$m) can be modeled using the Drude model [33]. The photonic crystal structures are modeled using heavily doped-silicon (p-type 5×10^{20} [cm^{-3}]) with the following Drude model parameters: $\varepsilon_\infty = 11.7$, $\omega_p = 2.0738 \times 10^{15}$ [rad/s], and $\gamma = 1.3557 \times 10^{14}$ [rad/s].

To simulate the source of thermal radiation, the random fluctuations in the current density need to follow the fluctuation-dissipation theorem:

$$\left\langle \mathbf{J}_\alpha^{\mathbf{r}}\left(\mathbf{r}', \omega\right)\mathbf{J}_\beta^{\mathbf{r}*}\left(\mathbf{r}'', \omega'\right)\right\rangle = \frac{1}{\pi}\left(\omega\varepsilon_v\varepsilon_r''(\omega)\right)\Theta(\omega, T)\delta\left(r' - r''\right)\delta\left(\omega - \omega'\right)\delta_{\alpha\beta}, \quad (2)$$

Where $\mathbf{J}_\alpha^r$ is the current density in direction α (x, y, or z), $\Theta(\omega, T)$ is the mean energy of Planck's oscillator;

$$\Theta = \frac{\hbar\omega}{e^{\frac{\hbar\omega}{k_BT}} - 1} \quad (3)$$

$\delta(r' - r'')$ and $\delta(\omega - \omega')$ are Dirac delta functions, indicating that currents are uncorrelated in both spatial space and frequency domain. $\delta_{\alpha\beta}$ is the Kronecker delta which equal 1 for $\alpha = \beta$, and zero otherwise, for an isotropic medium. ε_r'' is the imaginary part of the relative permittivity of the material incorporating the fluctuating current, and ε_v is the permittivity of free space.

To achieve fluctuations in current density that satisfies Eq. (2), $\mathbf{K}(t)$ needs to have a frequency profile of the form [34]:

$$\left\langle \mathbf{K}_\alpha^{\mathbf{r}}\left(\mathbf{r}', \omega\right)\right\rangle \mathbf{K}_\beta^{\mathbf{r}*}\left(\mathbf{r}', \omega'\right) = C\ \delta_{\alpha\beta}\delta_{\omega\omega'}\ \Theta(\omega, T) \quad (4)$$

where C is a constant comprising material's parameters and volume of discretization elements used in FDTD. The correlation in Eq. (4) is colored noise and it is possible to incorporate it in the FDTD algorithm. However, there are two inconveniences: the simulation will be only valid for a fixed temperature (used to calculate $\Theta(\omega, T)$), and the generating colored noise needs more computation power and memory than the simple Gaussian white-noise