Modulation of near-field heat transfer between two gratings

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We present a theoretical study of near-field heat transfer between two uniaxial anisotropic planar structures. We investigate how the distance and relative orientation (with respect to their optical axes) between the objects affect the heat flux. In particular, we show that by changing the angle between the optical axes it is possible in certain cases to modulate the net heat flux up to 90% at room temperature, and discuss possible applications of such a strong effect. © *2011 American Institute of Physics*. [doi:10.1063/1.3596707]

Since the prediction by Polder and Van Hove[1] that the heat exchange between two media at short separations can be much higher than the black body limit, numerous works have been carried out to investigate both theoretically and experimentally the physics involved in this transfer. Experimentally, it was shown[2,3] that the radiative heat flux increases for distances shorter than the thermal wavelength and can vastly exceed the black body limit.[4,5] Moreover, very recent experiments[6,7] were in good quantitative agreement with theoretical predictions. On the theoretical side, we can highlight the studies of the heat flux for layered media,[8,9] for photonic crystals,[10] metamaterials,[11] and porous media.[12] In addition, the dependence of the heat transfer on the geometry has attracted much interest and has been investigated in a sphere-plane geometry,[13,14] for spheroidal particles above a plane surface[15] and between two spheres or nanoparticles.[16–20] Somewhat more applied studies have attempted to take advantage of the potential of the tremendous increase in the radiative heat flux on the nanoscale for thermal imaging of nanostructured surfaces.[21–24] Finally, the formulation of the heat flux in terms of the scattering matrix[25,26] paves the way for the study of further geometries and the Landauer concept[27,28] opens up a deeper understanding of the trade-off between heat transmission and the number of modes contributing to the heat flux.

While considerable progress has been made over the last decades to actively manage heat flow carried by phonons in nanostructures,[29–31] very few attention has been paid so far on the control of noncontact heat exchanges at nanoscale. In 2010, a pioneer work carried out in this way by Otey *et al.*[32] proposed a thermal rectifier based on photon tunneling between two thermally dependent polar materials separated by a vacuum gap. The efficiency of the thermal rectification was found to be about 40%. More recently, a device made with phase-change materials has been introduced by van Zwol *et al.*[33] to modulate heat flux between two materials using an electric ac current as external power source. However, due to the properties of these materials, such modulator works reversibly only during a limited number of cycles which typically oscillate between 10^7 and 10^{12}. Moreover, such devices work at two discrete levels of flux, one for each state of the phase-changing material.

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In this letter, we investigate the near-field heat transfer between two polar/metallic misaligned gratings in the long wavelength limit, where they may be described by effective homogeneous anisotropic permittivities. We show that it is possible to get a strong heat flux modulation without cycle limitation just by rotating the relative position of the grating's optical axes.[34] Our approach combines the standard stochastic electrodynamics[35] and the effective medium theory[36–38] for the gratings.

A sketch of the geometry considered is depicted in Fig. 1. It shows two semi-infinite host materials of complex permittivity $\epsilon_i(\omega)$ $(i=1,2)$ with a one-dimensional grating engraved on each. The relative orientation of the two gratings is arbitrary in the (x,y) plane, and we assume that their trenches are sufficiently deep so as to (i) render the substrate below those gratings irrelevant and (ii) allow us to consider the x- and z-directions as equivalent. Moreover, these structures are separated by a vacuum gap of thickness d and kept at two different temperatures T_1 and T_2 in local thermal equilibrium. By choosing a coordinate system with the z-axis perpendicular to the interfaces, we can write the permittivity in the form[39,40]

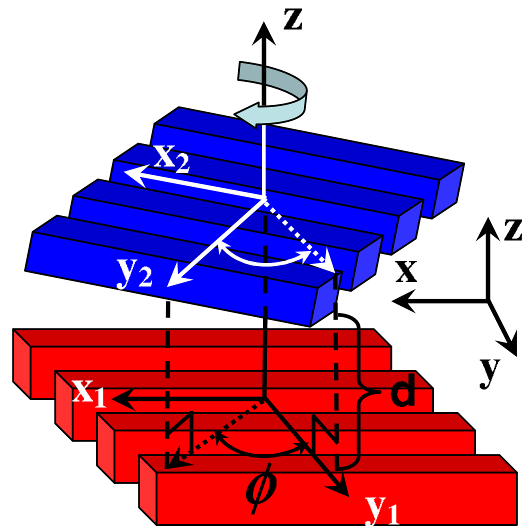

FIG. 1. (Color online) Two gratings separated by a distance d, and relatively twisted by an angle ϕ.

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$$\bar{\bar{\epsilon}} = \begin{bmatrix} \epsilon_{\perp_i} \sin^2 \phi_i + \epsilon_{\|_i} \cos^2 \phi_i & (\epsilon_{\perp_i} - \epsilon_{\|_i}) \sin \phi_i \cos \phi_i & 0 \\ (\epsilon_{\perp_i} - \epsilon_{\|_i}) \sin \phi_i \cos \phi_i & \epsilon_{\perp_i} \cos^2 \phi_i + \epsilon_{\|_i} \sin^2 \phi_i & 0 \\ 0 & 0 & \varepsilon_{\|} \end{bmatrix}, \quad (1)$$

where ϕ_i is the angle between the optical axis of the ith structure and the axis defined $k_{\|}$, and $\epsilon_{\|}$ and $\epsilon_{\perp}$ are given by the effective medium expressions[36–38]

$$\epsilon_{\|} = \epsilon_{h_i}(1 - f_i) + f_i, \quad \epsilon_{\perp_i} = \frac{\epsilon_{h_i}}{(1 - f_i) + f_i \epsilon_{h_i}}, \quad (2)$$

where f_i and ϵ_{h_i} are, respectively, the vacuum filling factor and permittivity of the host material in the ith grating. These expressions are valid for arbitrary filling factors as long as the grating periods Λ_i are much smaller than the thermal wavelength $\lambda_{th} = c\hbar / k_B T$, that in our case (300 K) is about 7.68 μm. Within the near-field regime this condition for the validity of the homogenization is different. As discussed in more detail in Ref. 12 the expressions for the effective permittivity in the near-field regime are valid if Λ_i is smaller than the spacing d between the gratings.

According to standard stochastic electrodynamics,[1,35] the heat flux exchanged between the two bodies per unit surface is given by the statistical average of the Poynting vector normal component S_z

$$\langle S_z \rangle = \int_0^\infty \frac{d\omega}{2\pi} [\Theta(\omega, T_1) - \Theta(\omega, T_2)] \int \frac{d\mathbf{k}_{\|}}{(2\pi)^2} T(\omega, k_{\|}), \quad (3)$$

where $\Theta(\omega, T) = \hbar\omega / [e^{\hbar\omega/k_B T} - 1]$ is the mean energy of a harmonic oscillator and the transmission factor $T(\omega, k_{\|})$ (Ref. 27) can be written as[12]

$$T(\omega, \kappa; d) = \begin{cases} \mathrm{Tr}[(\mathbb{1} - \mathbb{R}_2^\dagger \mathbb{R}_2) \mathbb{D}^{12} (\mathbb{1} - \mathbb{R}_1 \mathbb{R}_1^\dagger) \mathbb{D}^{12\dagger}], & \kappa < \omega/c \\ \mathrm{Tr}[(\mathbb{R}_2^\dagger - \mathbb{R}_2) \mathbb{D}^{12} (\mathbb{R}_1 - \mathbb{R}_1^\dagger) \mathbb{D}^{12\dagger}] e^{-2|\gamma_r| d}, & \kappa > \omega/c \end{cases} \quad (4)$$

for propagating $(\kappa < \omega/c)$ and evanescent $(\kappa > \omega/c)$ modes where $\gamma_r = \sqrt{\omega^2/c^2 - \kappa^2}$ and $\mathbb{D}^{12} = (\mathbb{1} - \mathbb{R}_1 \mathbb{R}_2 e^{2i\gamma_r d})^{-1}$. The reflection matrix $\mathbb{R}_i$ of the ith structure is a 2×2 matrix in the polarization representation. Its four elements R_{kl} with $k, l \in \{s, p\}$ for the scattering of s- or p-polarized plane waves into s- or p-polarized plane waves for the considered structures are determined with the method presented in Ref. 40.

Now, we discuss the numerical results obtained with the above expressions for two Au gratings. In Fig. 2(a) we show $\Delta\langle S_z \rangle \equiv [\langle S_z(\phi = 0°) \rangle - \langle S_z(\phi = 90°) \rangle] / \langle S_z(\phi = 0°) \rangle$ over the filling factor for three different distances $d = 100$, 500, and 1000 nm. Here, $\phi = \phi_1 - \phi_2$ is the twisting angle between the optical axes of the gratings. One can observe that the difference in the heat flux between both configurations, i.e., two parallel or perpendicular gratings, is larger than 70% for all three distances and for a wide range of filling factors ranging from $f = 0.1$ to 0.9 and can even reach about 90% for $d = 100$ nm. In Fig. 2(b) the dependence of $\langle S_z(\phi) \rangle$ on the twisting angle ϕ for a fixed filling factor of $f = 0.3$ shows that for all considered distances the heat flux is very sensitive to a twisting of the gratings. The flux drops at least by 50% for relatively small twisting angles of $\phi = 30°$. We note that

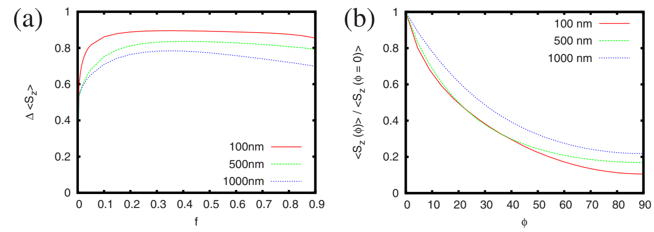

FIG. 2. (Color online) The heat flux between two Au gratings. (a) $\Delta\langle S_z \rangle \times (f)$ is defined as the difference in the heat flux between two parallel and two perpendicular gratings, normalized by the former (see also text). (b) normalized by the flux $\langle S_z \rangle(0°)$ when the gratings are aligned. The angle ϕ measures the relative twisting between the gratings, and the filling factor is fixed at $f = 0.3$.

$\langle S_z(\phi = 0) \rangle$ is about 12, 3.8, and 2.5 times the black body value ($\langle S_{bb} \rangle \approx 459.3$ W/m^2) for $d = 100$, 500, and 1000 nm and $f = 0.3$.

The observed sensitivity of the heat flux with respect to the twisting angle ϕ can be understood by the following consideration. When we have two parallel Au gratings, both still have a metallic response for a plane wave with polarization parallel to the grating structure. On the other hand, for a plane wave perpendicularly polarized to the gratings we have, according to Eq. (2), a dielectriclike response dictated by $\epsilon_{\perp}$.[41] For plane waves with polarizations between these two cases we have a mixture of metallic and dielectric response, but the crucial point is that we have always a symmetric situation which favors a larger heat flux.[42] By twisting the two Au gratings we break this symmetry. In particular, it is impossible to have a simultaneous metallic response of both gratings for any fixed polarization.

Finally, we will focus on the numerical results for two dielectric gratings made of SiC. In Fig. 3(a) we show the same plots of $\Delta\langle S_z \rangle$ as in Fig. 2(a) but for two SiC gratings. Obviously, in this case the difference in the heat flux in the parallel and perpendicular configurations is smaller than for the two gold gratings and it varies much more with respect to the filling factor. The heat flux is in this case also less sensitive with respect to the twisting angle as shown in Fig. 3(b). We note that $\langle S_z(\phi = 0°) \rangle$ is about 22.9, 4.2, and 2.8 times the black body value for, respectively, $d = 100$ nm, 500 nm, and 1000 nm with $f = 0.3$. While the drop in the heat flux when twisting the gratings can still be ascribed to the breaking of the symmetry, the underlying physical mechanisms are more involved, since in contrast to Au gratings for SiC gratings coupled surface modes and frustrated modes determine the heat flux at $T = 300$ K. By changing the filling factor the mode structure of these surface and frustrated modes is changed and we find that new surface modes and bands of frustrated modes appear as was also found for porous media.[12] By twisting the gratings the coupling between these

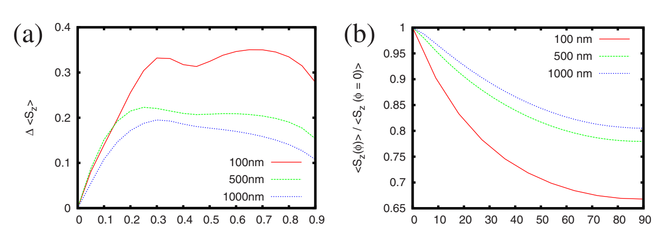

FIG. 3. (Color online) The same plots as in Fig. 2, but for SiC instead of Au.

modes becomes less efficient resulting in a smaller heat flux.

In conclusion, we have theoretically shown that the near-field heat flux exchanged between two parallel grating structures can be modulated up to 90% by acting on the relative position of the optical axes of the gratings. We have also demonstrated that the flux magnitude is very sensitive to the twisting angle, even for low filling factors. This allows for manipulating the heat flux at nanoscale which can be useful for thermal management in microelectromechanical/nanoelectromechanical devices. On the other hand, an efficient active control of transmission properties by mechanically driven grating structures might be impractical. However, one can expect a similar effect for materials such as liquid crystals or metal ferromagnetic structures for which the optical axis can be easily controlled by applying external fields.

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[41]In the infrared ϵ_h is negative for metals and $|\epsilon_h| \gg 1$. Therefore, in this case even for small filling factors $\epsilon_\perp > 0$ so that the response is not metallic anymore. From a physical point of view this is clear, since by ruling the grating the conductivity in direction of the grating vector is inhibited.
[42]We have carried out calculations between two isotropic semi-infinite Au bodies using $\epsilon_{1,2} = \epsilon_\parallel$ as permittivity. We have compared these results with one semi-infinite medium with $\epsilon_1 = \epsilon_\parallel$ and the other with $\epsilon_2 = \epsilon_\perp$. In the latter asymmetric case the heat flux was much smaller than the one found in the symmetric situation.