Super-Planckian Near-Field Thermal Emission with Phonon-Polaritonic Hyperbolic Metamaterials

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Abstract

The radiative heat flux between two bodies is for large separation distances limited by the Stefan-Boltzmann law in which only the propagating modes are taken into account. However, for distances smaller than the thermal wavelength $\lambda_{\rm th} = \hbar c/(k_{\rm B}T)$ evanescent modes start to contribute to the heat flux and can exceed the black body limit by orders of magnitude. The common paradigm is that a maximum near-field contribution can be obtained by using materials supporting surface polariton modes resulting in large quasi-monochromatic spectral heat fluxes restricted to a small frequency band around the surface mode resonance frequency. On the one hand, we show that using a metamaterial consisting of a periodic array of SiC nanowires with a dominant contribution in the near-field due to hyperbolic modes can surpass the surface mode contribution of bulk SiC. On the other hand, we investigate the heat flux between two periodic bilayer SiC/SiO$_2$ structures and show that the choice of the topmost layer material determines if the heat flux is dominated by surface or hyperbolic modes.

Radiative Heat Transfer at the Nanoscale

- Heat transfer coefficient (HTC)

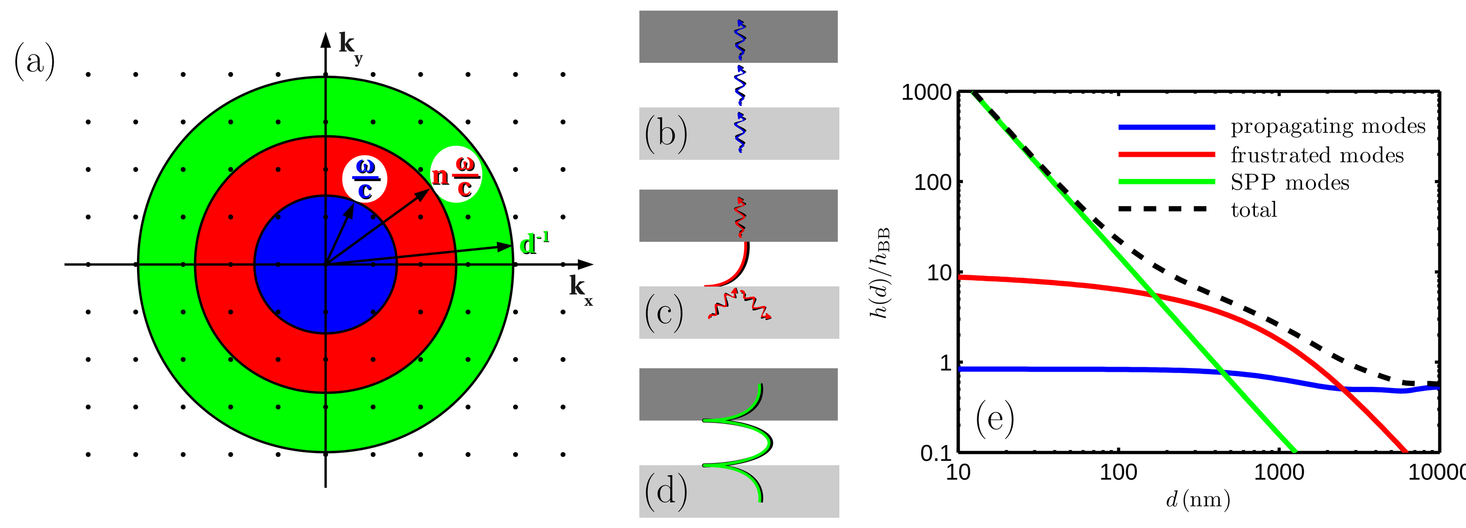
$$h(d) = \int_0^\infty \frac{{\rm d}\omega}{2\pi}\,\frac{\hbar^2\omega^2}{k_{\rm B}T^2}\,\frac{{\rm e}^{\frac{\hbar\omega}{k_{\rm B}T}}}{\left({\rm e}^{\frac{\hbar\omega}{k_{\rm B}T}}-1\right)^2} H(\omega,d).$$

- Spectral heat transfer coefficient

$$H(\omega,d) = \sum_{j={\rm s,p}} \int_0^\infty \frac{{\rm d}^2\kappa}{(2\pi)^2}\mathcal{T}_j(\omega,\kappa;d).$$

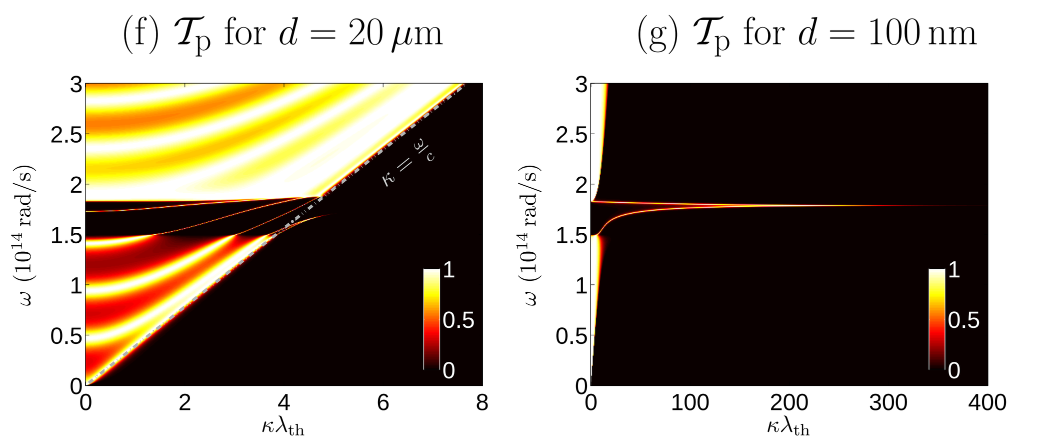
- Transmission coefficient

$$\mathcal{T}_j(\omega,\kappa,d) = \begin{cases} \frac{(1-|r_j^1|^2)(1-|r_j^2|^2)}{|1-r_j^1 r_j^2 {\rm e}^{2{\rm i}k_z d}|^2} &, \kappa \leq \frac{\omega}{c} \\ \frac{4\,{\rm Im}(r_j^1){\rm Im}(r_j^2){\rm e}^{-2{\rm Im}(k_z)d}}{|1-r_j^1 r_j^2 {\rm e}^{2{\rm i}k_z d}|^2} &, \kappa > \frac{\omega}{c} \end{cases}.$$



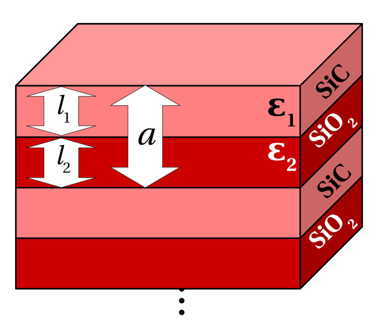
- (a) The dots mark the contributing modes in the quantized phase space.
- (b) Sketch of propagating modes; (c) frustrated modes; (d) surface modes.
- (e) HTC for SiC normalized to the black body value $h_{\rm BB} = 6.1\,{\rm Wm^{-2}K^{-1}}$.

Transmission coefficient for SiC with $\lambda_{\rm th} = 7.68\,\mu$m



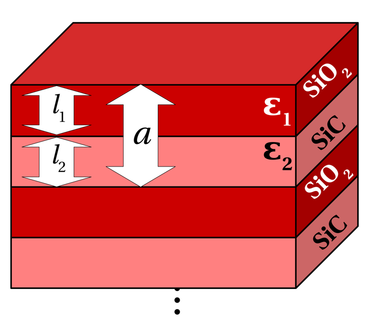
- (f) Propagating modes dominate the heat flux for $d > \lambda_{\rm th}$.
- (g) Contribution to Φ due to surface polariton modes $\propto 1/d^2$.

Layered Composite Structure [1]

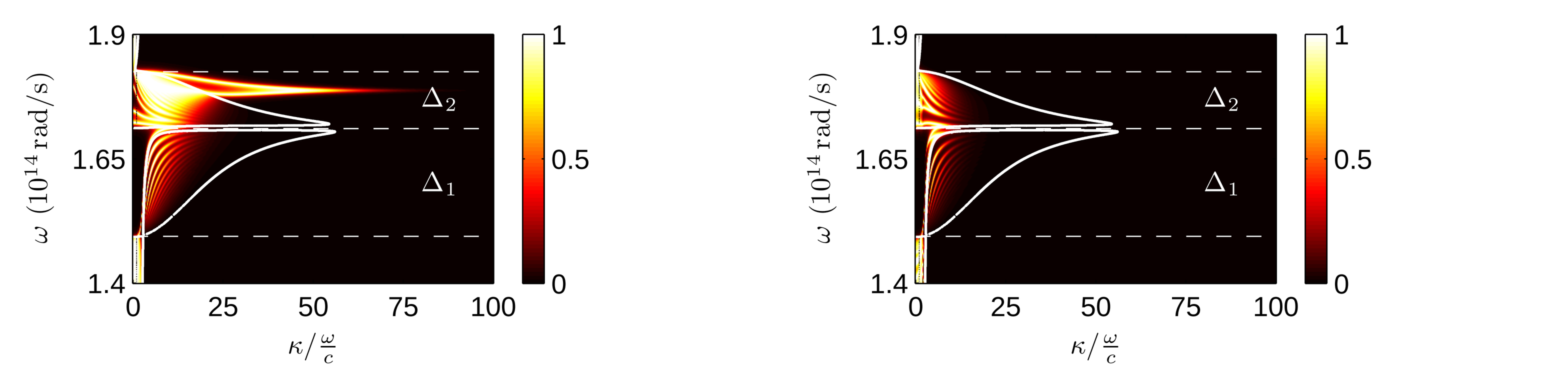


- The Bloch mode dispersion relation for p-modes:

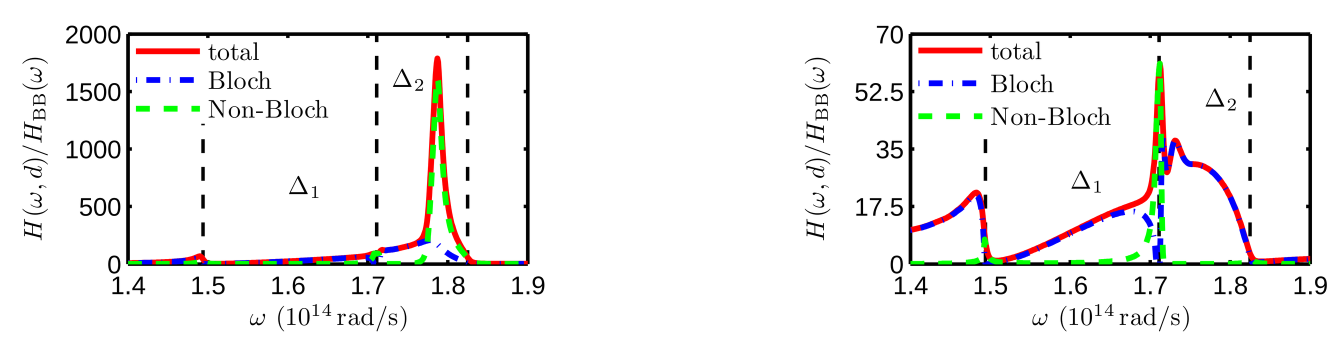
$$\cos(K_z a) = \cos(k_{z1}l_1)\cos(k_{z2}l_2)$$
$$-\frac{1}{2}\left(\frac{\epsilon_2 k_{z1}}{\epsilon_1 k_{z2}} + \frac{\epsilon_1 k_{z2}}{\epsilon_2 k_{z1}}\right)\sin(k_{z1}l_1)\sin(k_{z2}l_2).$$



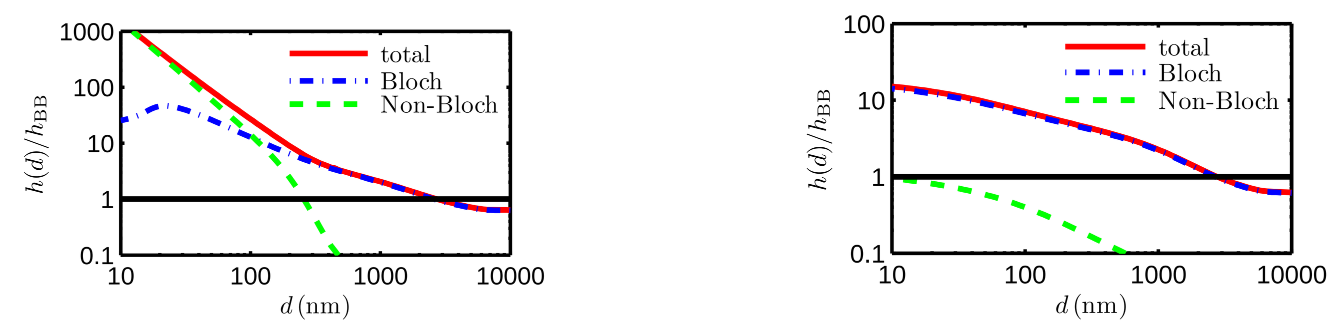
- Layered composite structure consisting of SiC and SiO$_2$ with (left) SiC and (right) SiO$_2$ as topmost material. Its permittivities are ϵ_1 and ϵ_2 and its layer thicknesses are l_1 and l_2. The period of the strukture is $a = l_1 + l_2$.



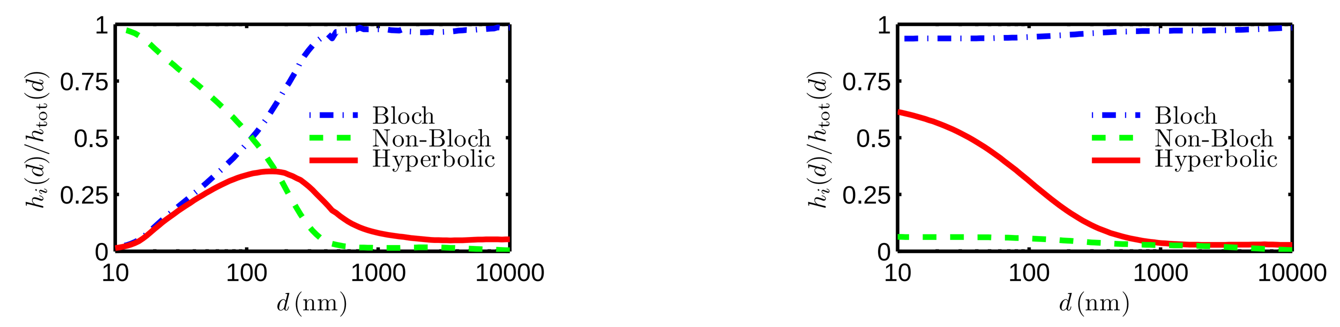
- Transmission coefficient $\mathcal{T}_{\rm p}$ for $l_1 = l_2 = 100\,$nm and $d = 100\,$nm with (left) SiC and (right) SiO$_2$ as topmost material. The white solid line mark the Bloch bands and the dashed lines mark the effective hyperbolic bands.



- Spectral heat transfer coefficient $H(\omega,d)$ normalized to the black-body result $H_{\rm BB}(\omega) = \omega^2/(2\pi c^2)$ with (left) SiC and (right) SiO$_2$ as topmost material for $T = 300\,$K.



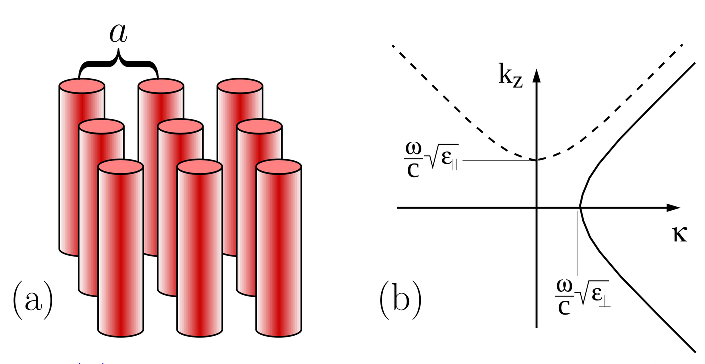
- Heat transfer coefficient $h(d)$ normalized to the black-body value $h_{\rm BB} = 6.1\,{\rm Wm^{-2}K^{-1}}$ with (left) SiC and (right) SiO$_2$ as topmost material.



- Heat transfer coefficients of the Bloch modes $h_{\rm B}$, the modes outside the Bloch bands $h_{\rm NB}$, and the hyperbolic modes $h_{\rm hm}$ normalized to the total heat transfer coefficient $h_{\rm tot}(d) = h_{\rm B} + h_{\rm NB}$ with (left) SiC and (right) SiO$_2$ as topmost material.

[1] S.-A. Biehs, M. Tschikin, R. Messina, and P. Ben-Abdallah, Appl. Phys. Lett. **102** 131106 (2013).

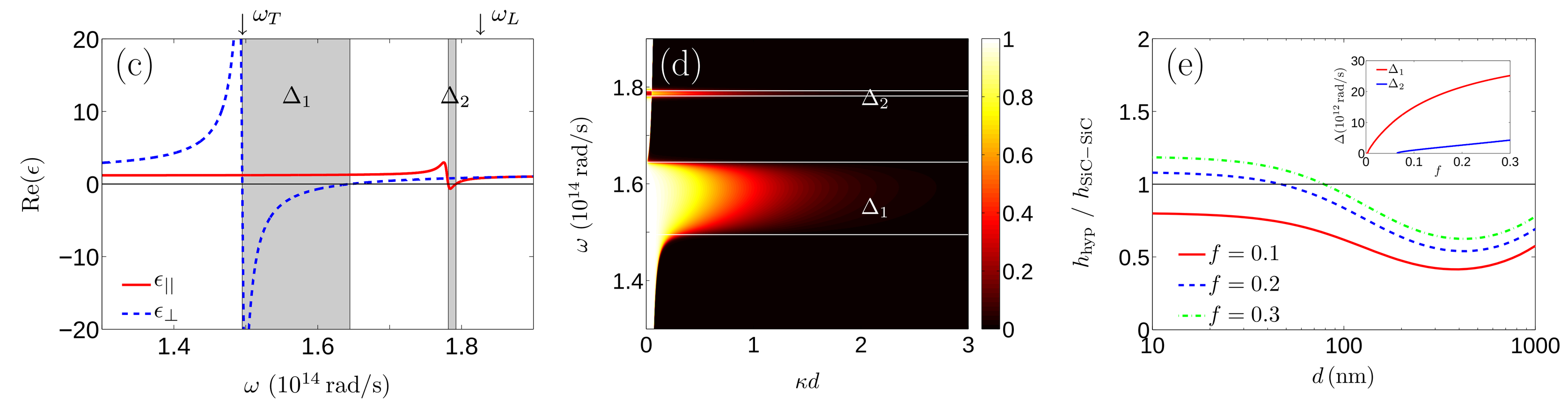
Hyperbolic Nanowire Material [2]



- For $\lambda_{\rm th} \gg a$: the effective material properties can be described by the Maxwell-Garnett expressions

$$\epsilon_{||} = \frac{\epsilon(\omega)(1+f)+(1-f)}{\epsilon(\omega)(1-f)+(1+f)},$$
$$\epsilon_{\perp} = (1-f)+\epsilon(\omega)f.$$

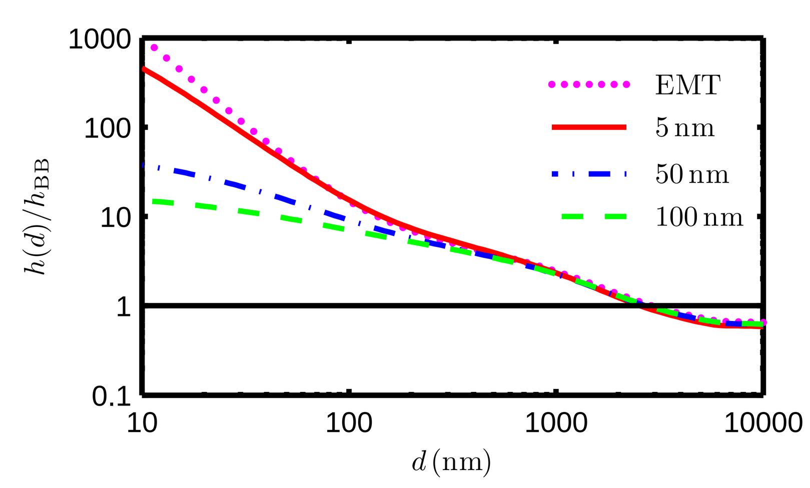
- Fig. (a) Hyperbolic material consisting of a periodical array of nanowires with f the volume filling fraction.
- Fig. (b) Hyperbolic dispersion relation $\frac{\kappa^2}{\epsilon_\perp} + \frac{k_z^2}{\epsilon_{||}} = \frac{\omega^2}{c^2}$ with different signs for $\epsilon_{||}$ and $\epsilon_\perp$ (i.e. $\epsilon_{||}\epsilon_\perp < 0$).



- Fig. (c) Real part of $\epsilon_{||}$ and $\epsilon_\perp$ for SiC nanorods embedded in vacuum with $f = 0.1$. Δ_1 and Δ_2 mark the hyperbolic regions.
- Fig. (d) Transmission coefficient $\mathcal{T}_{\rm p}$ for $f = 0.1$ and $d = 100\,$nm. High transmission in the hyperbolic regime. No surface modes!
- Fig. (e) Heat transfer coefficient for different filling fractions normalized to the value for two flat SiC half spaces ($T = 300\,$K). Inset: Δ_1 and Δ_2 over f.

[2] S.-A. Biehs, M. Tschikin, and P. Ben-Abdallah, Phys. Rev. Lett. **109** 104301 (2012).

Super-Planckian Hyperbolic Emitter [1]



- The heat transfer coefficient for the layer structure with the passive material SiO$_2$ as topmost layer for different layer thicknesses $l_1 = l_2$ ($f = 0.5$) of 100 nm, 50 nm, and 5 nm normalized to the black-body value $h_{\rm BB} = 6.1\,{\rm Wm^{-2}K^{-1}}$.
- For decreasing layer thicknesses the heat transfer coefficient increases drastically for small separation distances.
- The effective medium theory (EMT) tends to overestimate the radiative heat transfer.

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