Near-field radiative heat transfer between a nanoparticle and a rough surface

Svend-Age Biehs

Design de matériaux à propriété radiatives fonctionalisées:
de l'angstrom au millimètre

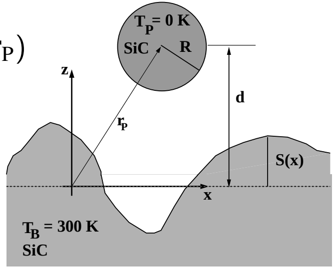
Dipole model - LDOS

- for $\lambda_{\text{th}} \gg R$ and $d \gg R$:

$$P^{\mathrm{B}\rightarrow\mathrm{P}} = \int_0^\infty \mathrm{d}\omega\, 2\omega\alpha''(\omega)\Theta(\omega, T_{\mathrm{B}})D(\omega, \mathbf{r}_{\mathrm{P}})$$

- polarizability

$$\alpha = 4\pi R^3 \frac{\epsilon_{\mathrm{P}} - 1}{\epsilon_{\mathrm{P}} + 2}$$



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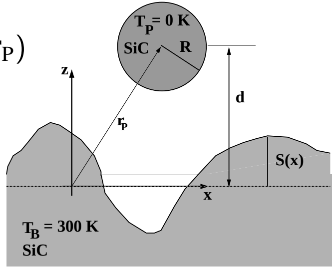

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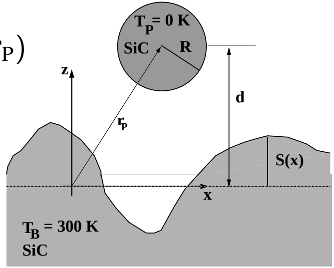

- mean energy of oscillator T_{B}

$$\Theta(\omega, T_{\mathrm{B}}) = \frac{\hbar\omega}{e^{\hbar\omega/(k_{\mathrm{B}}T)} + 1}$$

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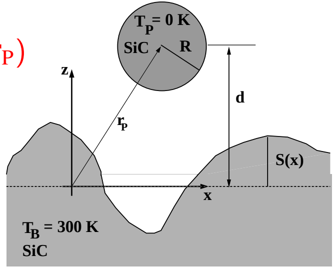
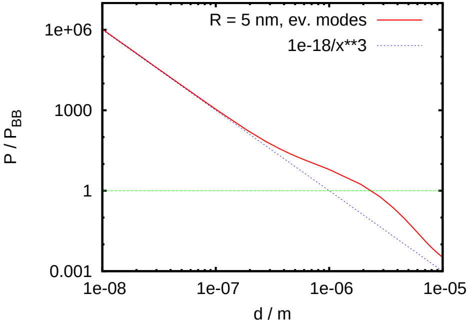
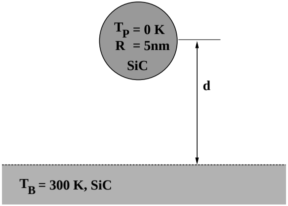
- Local density of states (LDOS)

$$D(\omega, \mathbf{r}_{\mathrm{P}}) = \frac{\omega}{\pi c^2} \mathrm{Im}\, \mathrm{Tr}\, \mathbb{G}(\mathbf{r}_{\mathrm{P}}, \mathbf{r}_{\mathrm{P}})$$



Flat surface





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- $P \propto d^{-3}$
- dominated by SPhP
- $\Rightarrow$ p-modes

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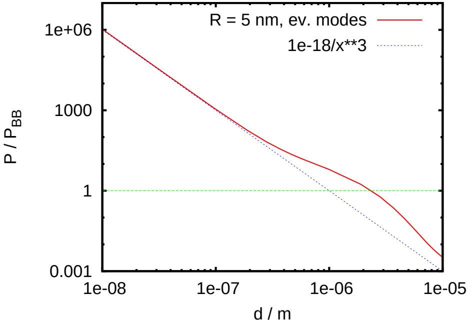

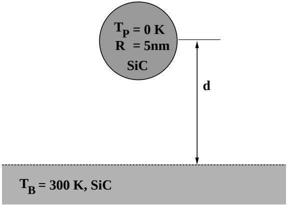

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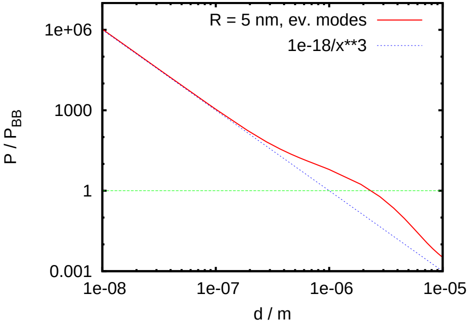

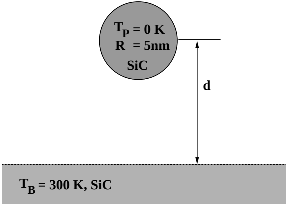

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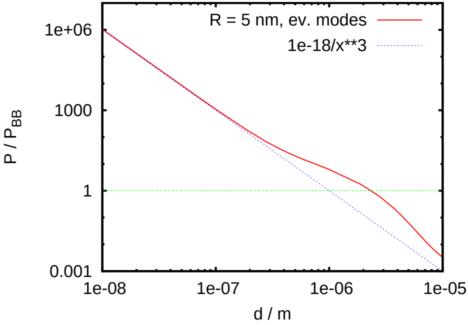

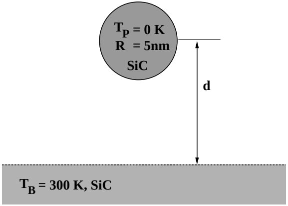

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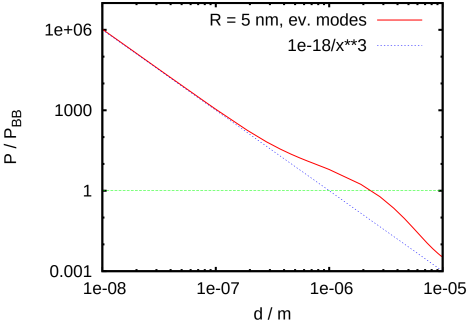

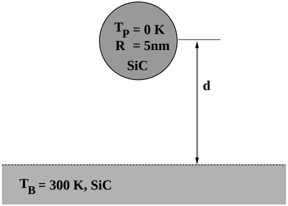

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Stochastic surface profile

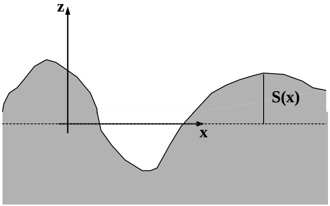
- gaussian profile $S(\mathbf{x})$

$$\langle \tilde{S}(\boldsymbol{\kappa}) \rangle = 0,$$
$$\langle \tilde{S}(\boldsymbol{\kappa}) \tilde{S}(\boldsymbol{\kappa}') \rangle = (2\pi)^2 \delta(\boldsymbol{\kappa} + \boldsymbol{\kappa}') \delta^2 g(\kappa)$$

- power spectrum

$$g(\kappa) = \pi a^2 \mathrm{e}^{-\frac{\kappa^2 a^2}{4}}$$

- root mean square (rms) δ, correlation length a



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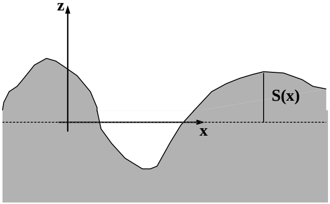

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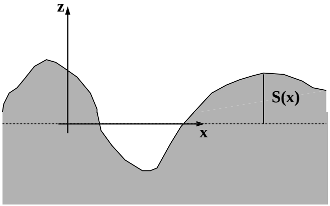

Mean LDOS above a rough surface

- ensemble average

$$\langle D^{(0)-(2)}(\omega, d)\rangle = D^{(0)} + \langle D^{(1)}\rangle + \langle D^{(2)}\rangle$$

- reflection coefficient

$$\langle r_{\mathrm{p}}^{(0)-(2)}\rangle = r_{\mathrm{p}}^{(0)}(\kappa) + r_{\mathrm{p}}^{(2)}(\kappa a)$$

- main contribution for $\kappa \approx d^{-1}$
- 3 regimes for $r_{\mathrm{p}}^{(2)}$:
  - $\kappa a \ll 1$, $(a \ll d)$
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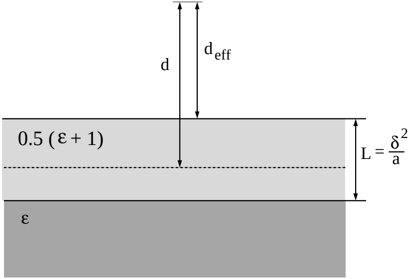
Large distance approximation (LDA), $d \gg a$

- approximating $r_{\rm p}^{(2)}$ for $1 \gg \kappa a$
  - $r_{\rm p}^{(2)} \propto \frac{\delta^2}{a}$, $(a \ll d_{\rm s})$
- effective layer (Maradudin and Rahman)
- $\langle D^{(2)} \rangle, \langle P^{(2)} \rangle \propto \frac{\delta^2}{a}$



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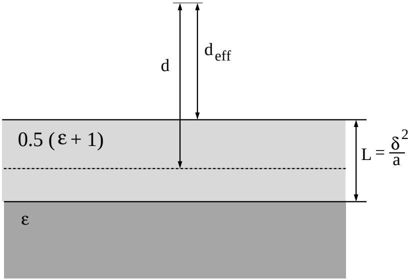

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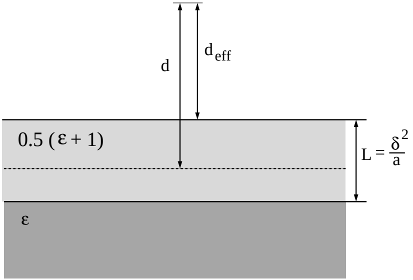

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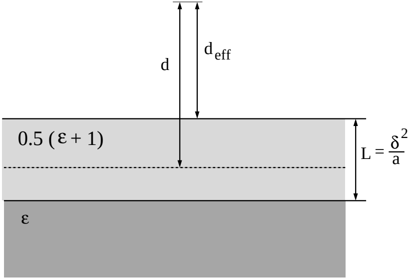

Proximity approximation (PA), $d \ll a$

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  - $\frac{\langle D^{(2)} \rangle}{D^{(0)}}, \frac{\langle P^{(2)} \rangle}{P^{(0)}} > 0$, do not depend on a, ϵ, T
- PA for $\delta \ll d \ll a$

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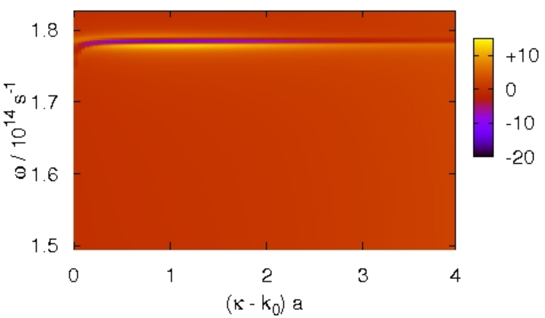
$$\approx D^{(0)}(d) + 6\frac{\delta^2}{d^2}D^{(0)}(d) + \dots$$

Intermediate distances $d \approx a$ ($\kappa a \approx 1$)

- $\mathrm{Im}(r_\mathrm{p}^{(2)})/\mathrm{Im}(r_\mathrm{p}^{(0)})$ for SiC and $\omega_\mathrm{t} \leq \omega \leq \omega_\mathrm{l}$
- $a = 200\,\mathrm{nm}$, $\delta = 5\mathrm{nm} \rightarrow \frac{\delta}{a} = 0.025$



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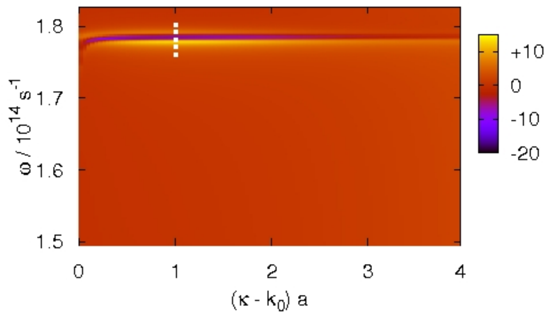

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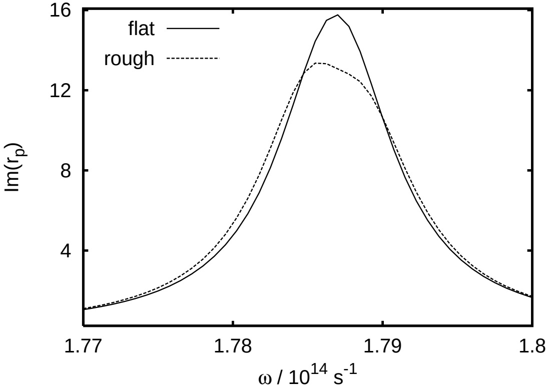

Distance dependence of LDOS

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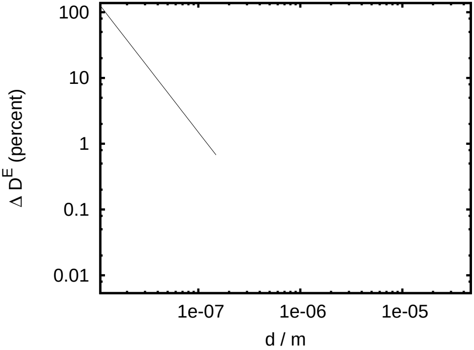

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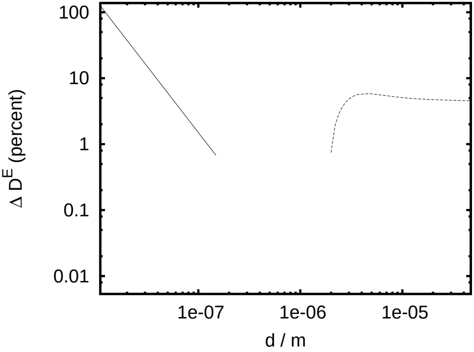

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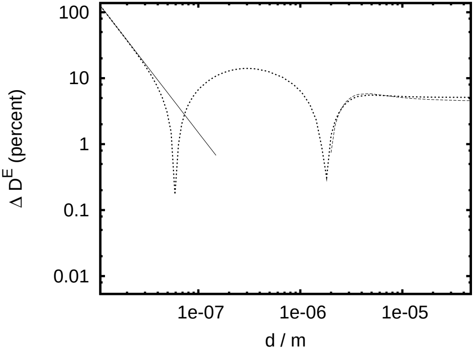

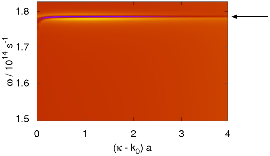

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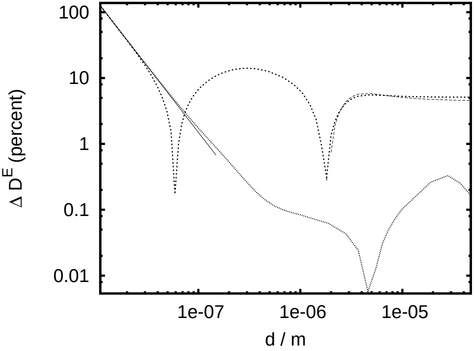

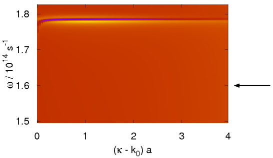

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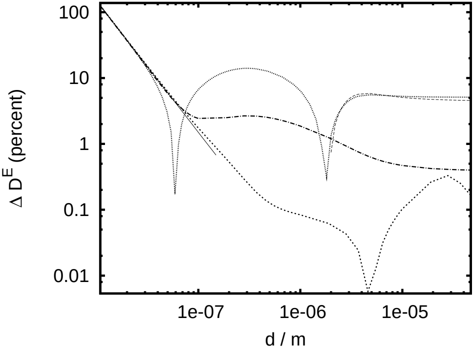

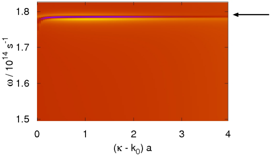

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Distance dependence of heat transfer rate

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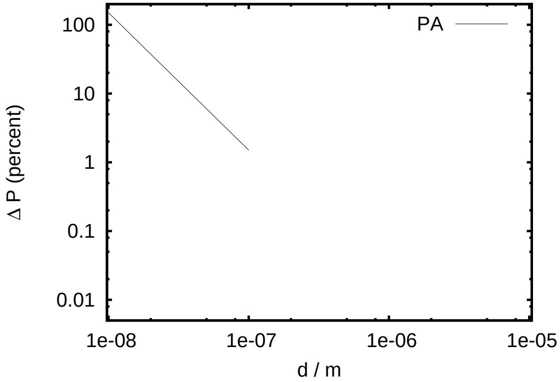

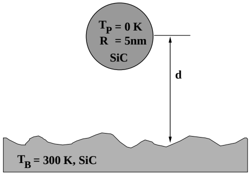

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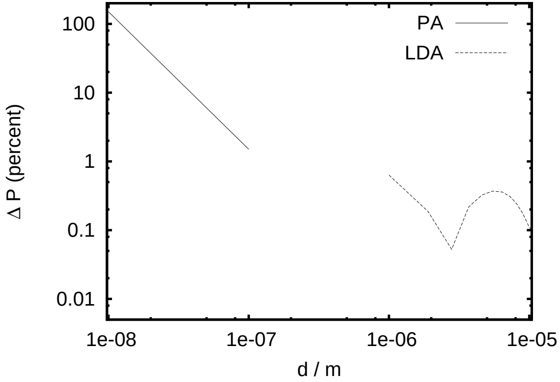

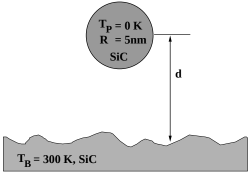

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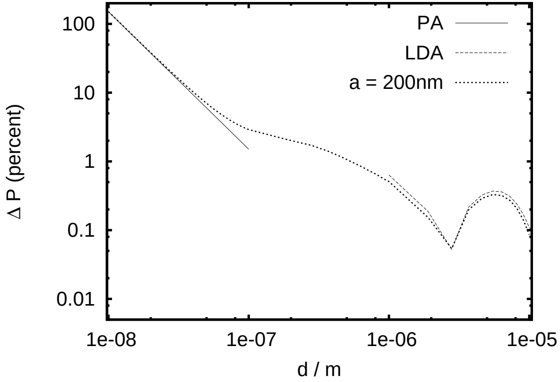

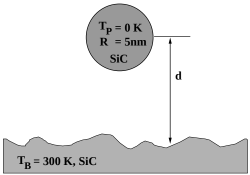

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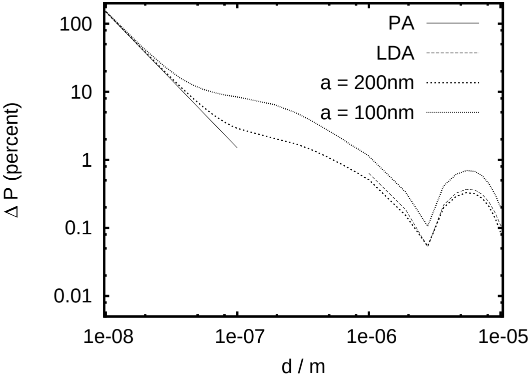

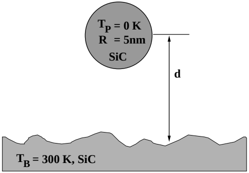

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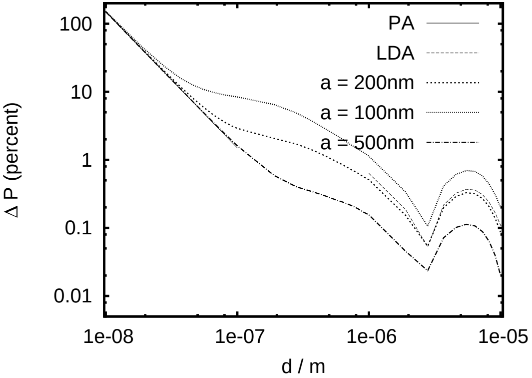

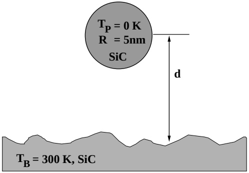

Summary

- ΔP and ΔD non-monotonous (ev. modes)
  - $d \ll a$:
    $$\Delta D, \Delta P \approx 6\frac{\delta^2}{d^2}$$
    - coincides with PA
    - independent of a, ϵ, T
  - $d \gg a$ (LDA):
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Merci pour votre attention !!!

Direct perturbation theory

- plane-wave representation of $\mathbf{E}_\mathrm{i}$, $\mathbf{E}_\mathrm{r}$ and $\mathbf{E}_\mathrm{t}$
- bc via extinction theorem (Rayleigh hypothesis)
- expand with respect to $S(\mathbf{x})$
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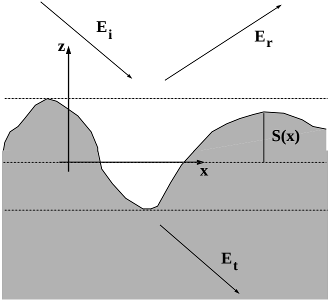

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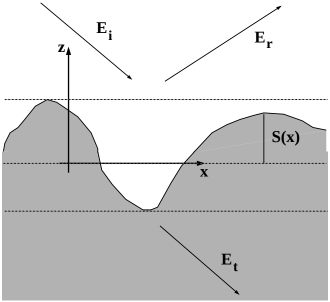

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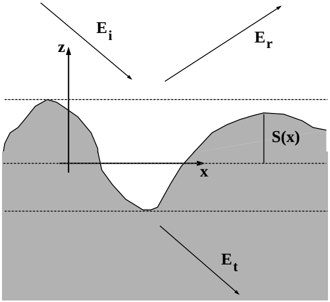

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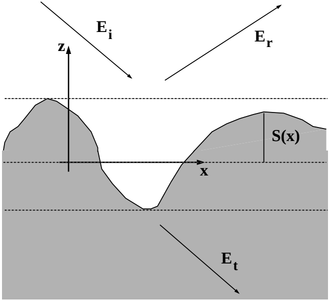

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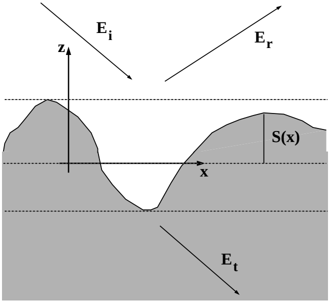

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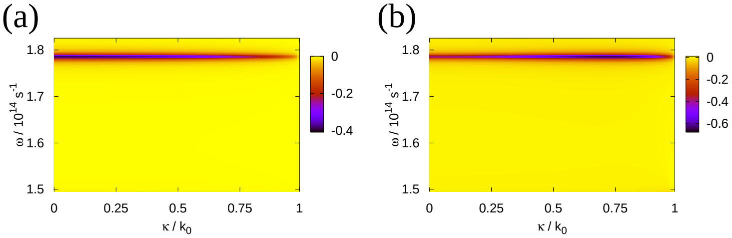
Propagating modes

- $\mathrm{Im}(r_s^{(2)})/\mathrm{Im}(r_s^{(0)})$ and $\mathrm{Im}(r_p^{(2)})/\mathrm{Im}(r_p^{(0)})$



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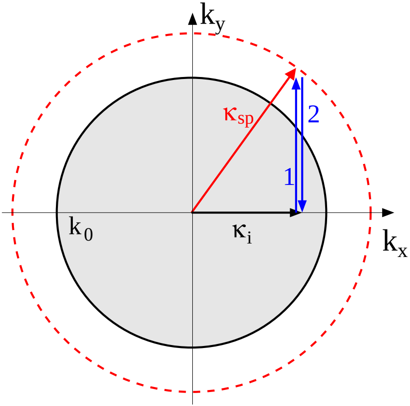
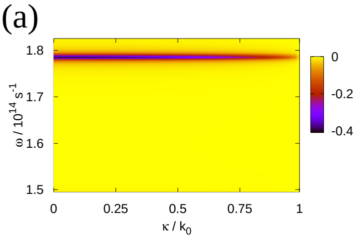
Coupling of prop. modes to SPhP

- s-polarized wave with **E** in y-direction and κ_i





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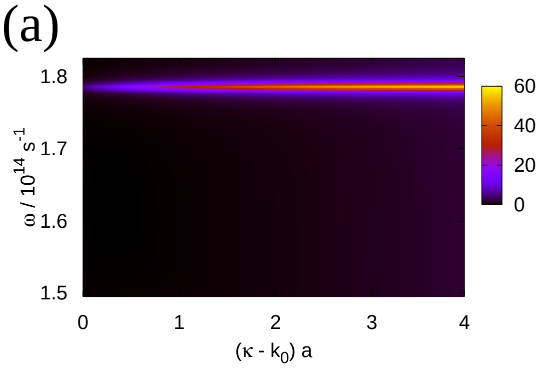
Evanescent modes

- $\mathrm{Im}(r_s^{(2)})/\mathrm{Im}(r_s^{(0)})$



Near-field Scanning Thermal Microscope