Near-Field Heat Transfer for Anisotropic Media

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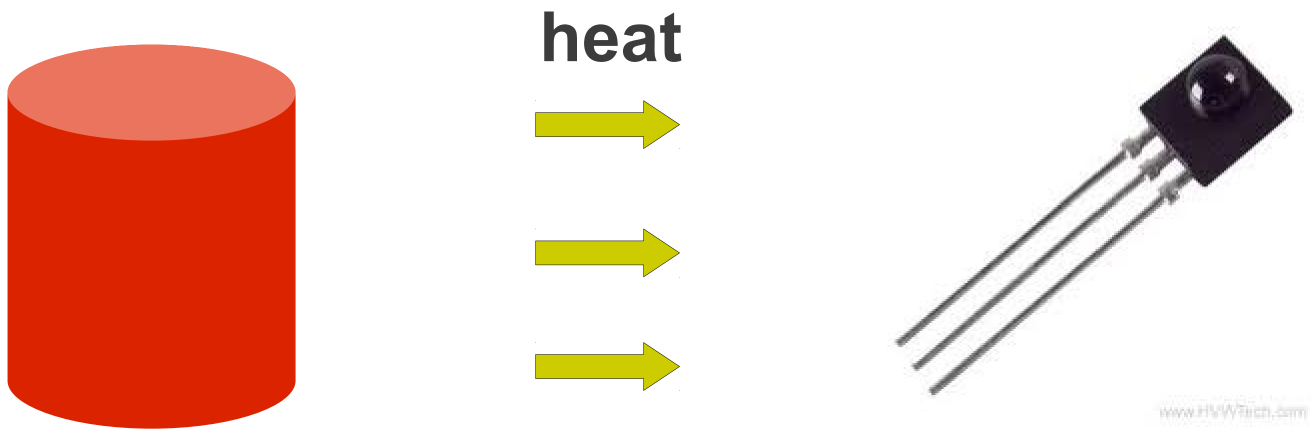
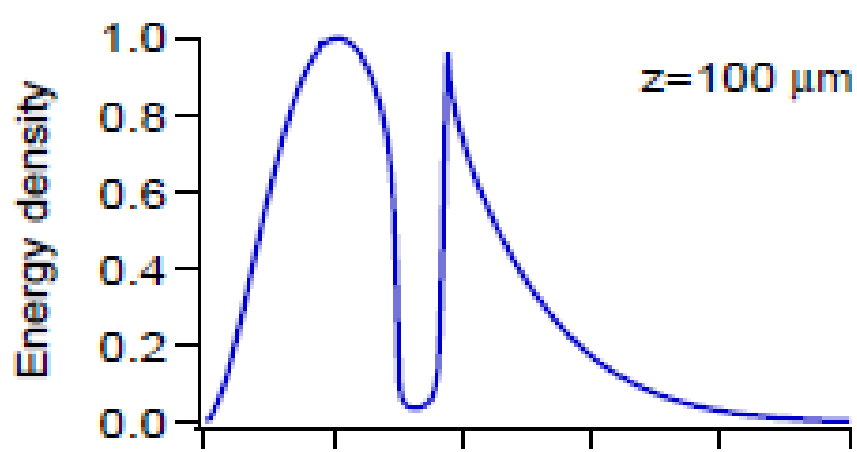
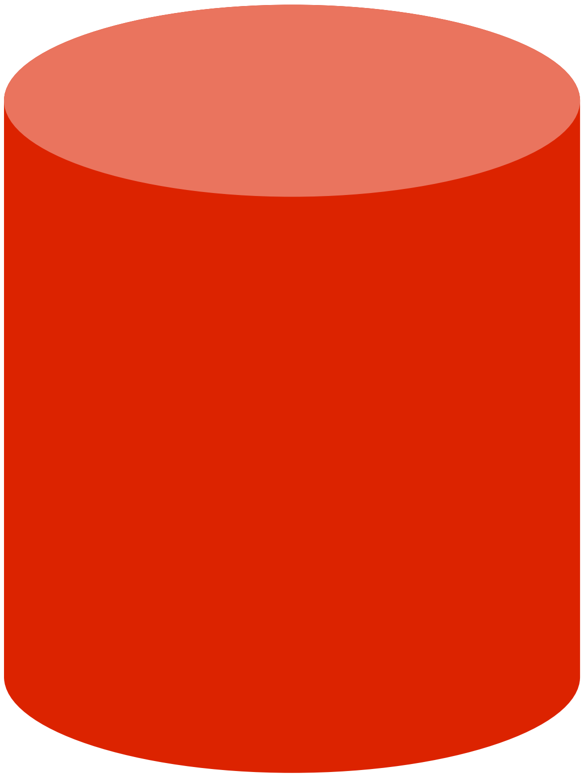
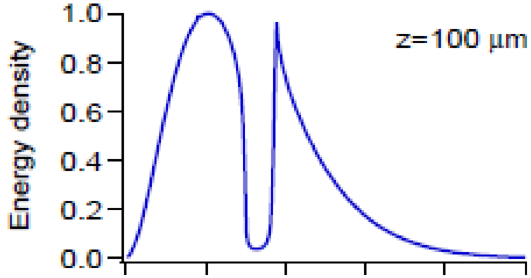
Near-Field Heat Transfer

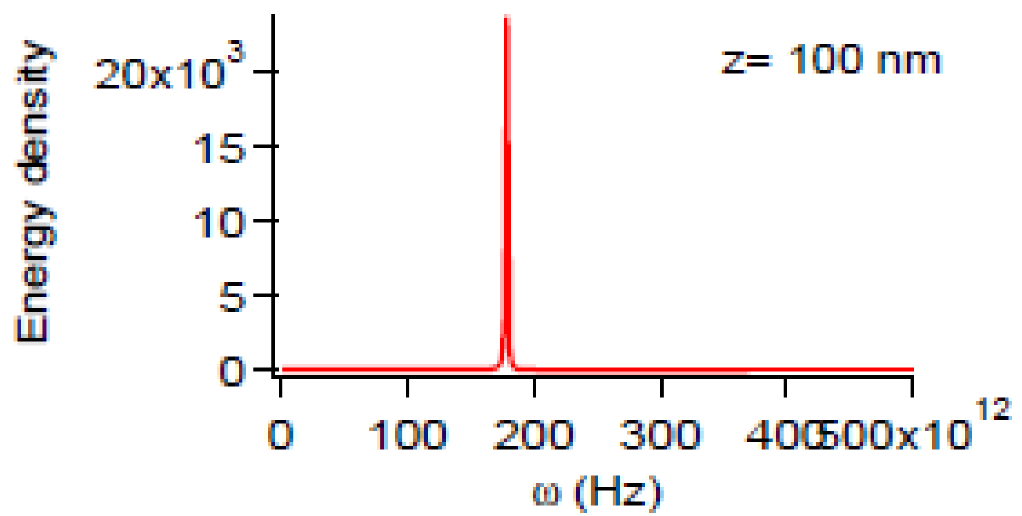




But when we put the detector very close...



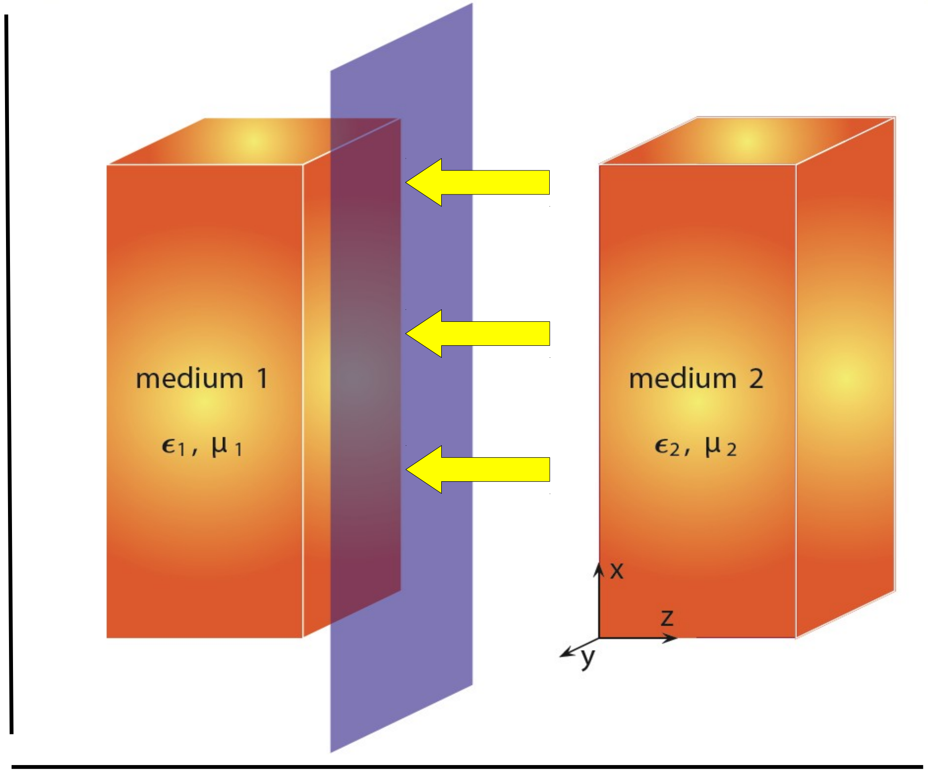




The heat flux is given in by the Poynting vector

$$\Phi = \int_A \mathrm{d}\mathbf{A} \cdot \langle \mathbf{S} \rangle = A \langle S_z \rangle$$

$$\mathbf{S} = \mathbf{E} \times \mathbf{H}$$



Expressing the fields in terms of the stochastic sources

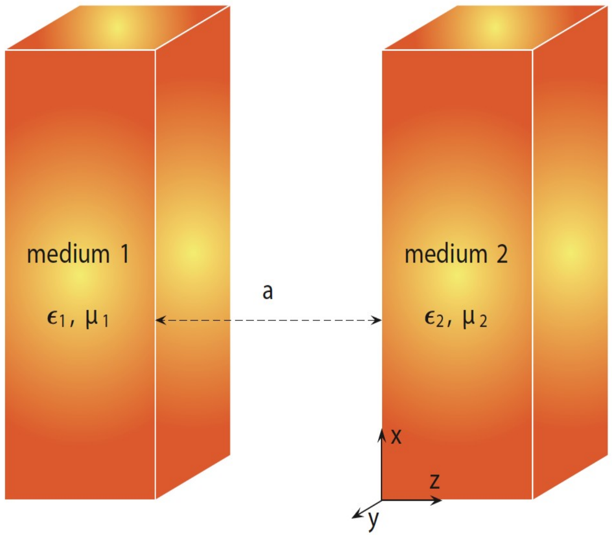
$$\tilde{\mathrm{E}}^{\mathrm{f}}(\mathrm{r},\omega) = \mathrm{i}\omega\mu_0 \int_V \mathrm{d}\mathrm{r}'' \mathrm{G}^{\mathrm{E}}(\mathrm{r},\mathrm{r}'',\omega) \cdot \tilde{\mathrm{j}}^{\mathrm{f}}(\mathrm{r}'',\omega)$$

$$\tilde{\mathrm{H}}^{\mathrm{f}}(\mathrm{r},\omega) = \mathrm{i}\omega\mu_0 \int_V \mathrm{d}\mathrm{r}'' \mathrm{G}^{\mathrm{H}}(\mathrm{r},\mathrm{r}'',\omega) \cdot \tilde{\mathrm{j}}^{\mathrm{f}}(\mathrm{r}'',\omega),$$

and assuming local equilibrium for each body

$$\langle j_i^{\mathrm{f}}(\mathbf{r},\omega) j_j^{\mathrm{f}}(\mathbf{r}',\omega')\rangle = 2\pi\omega\Theta(\omega,T)\left[\bar{\epsilon}_{i,j}(\omega) - \bar{\epsilon}_{j,i}^{*}(\omega)\right]\delta(\omega-\omega')\delta(\mathbf{r}-\mathbf{r}').$$

$$\Theta(\omega,T) = \frac{\hbar\omega}{2} + \frac{\hbar\omega}{e^{i\hbar\omega/(k_B T)} - 1}$$



we get an expression for the HT in terms of Green's functions

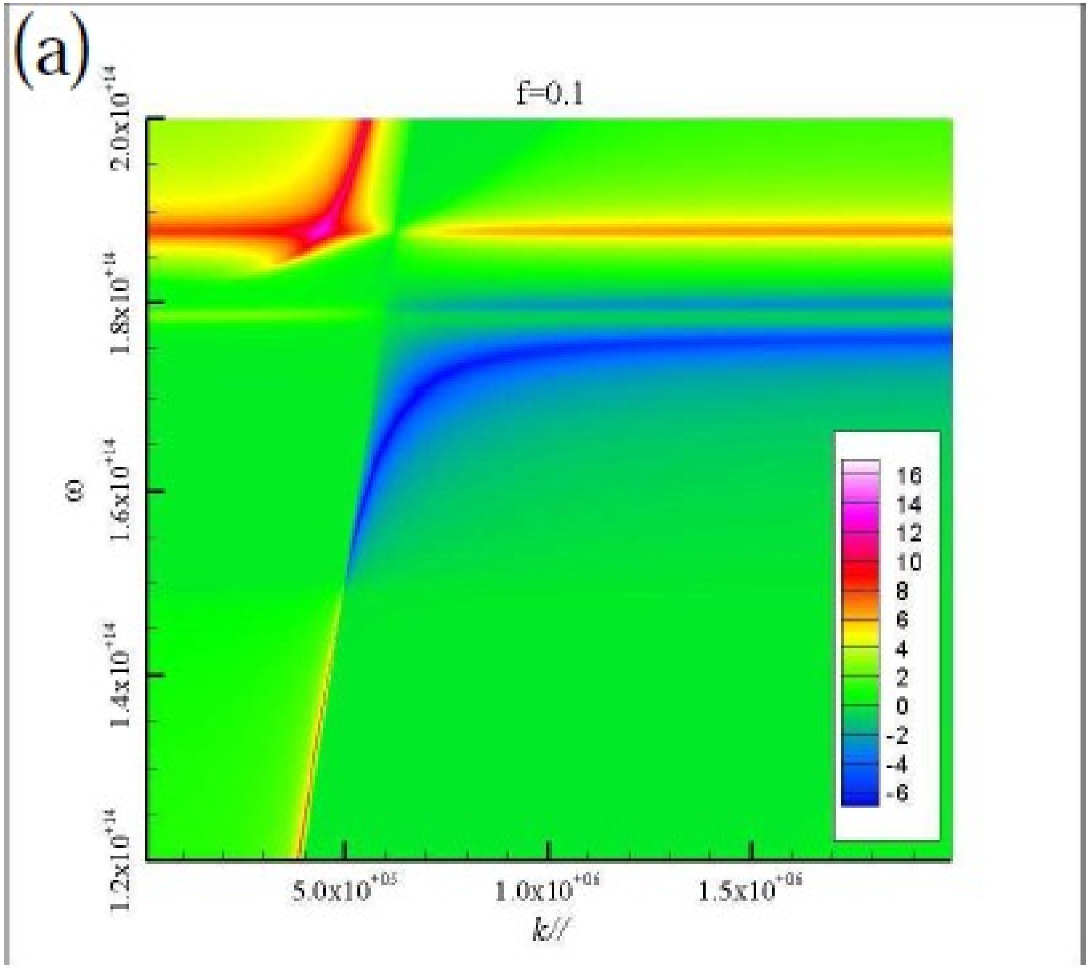
$$\Phi \sim A \int d\mathbf{r}' d\mathbf{r}'' G_E(\mathbf{r},\mathbf{r}') G_H(\mathbf{r},\mathbf{r}'') \ldots$$

In the isotropic case we have the famous Polder & van Hove result

$$\Phi(d,T_1,T_2) = \int_0^\infty \frac{d\omega}{2\pi}[\Theta(\omega,T_1)-\Theta(\omega,T_2)]$$
$$\sum_{j=s,p}\left[\int_0^{k_0}\frac{\mathrm{d}^2\kappa}{4\pi^2}\frac{(1-|r_j^1|^2)(1-|r_j^2|^2)}{|1-r_j^1 r_j^2 e^{-2i\gamma d}|^2} + \int_{k_0}^\infty \frac{\mathrm{d}^2\kappa}{4\pi^2}\frac{4\mathrm{Im}(r_j^1)\mathrm{Im}(r_j^2)e^{-2\mathrm{Im}(\gamma)d}}{|1-r_j^1 r_j^2 e^{-2\mathrm{Im}(\gamma)d}|^2}\right]$$

$$r_j^{s,s}(\omega,\kappa) = \frac{\gamma-\gamma_s}{\gamma+\gamma_s} \qquad r_j^{p,p}(\omega,\kappa) = \frac{\epsilon_j\gamma-\gamma_s}{\epsilon_j\gamma+\gamma_s}$$

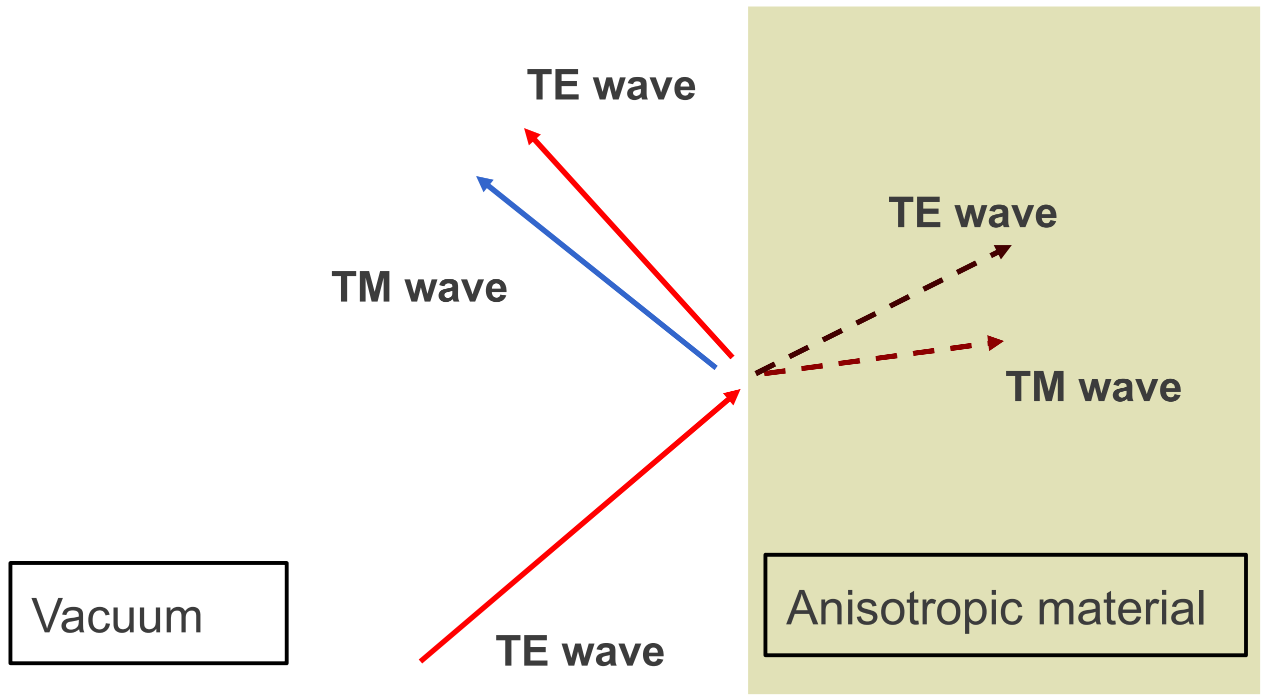
$$\gamma = \sqrt{k_0^2-\kappa^2} \qquad \gamma_s = \sqrt{\epsilon_j k_0^2-\kappa^2}$$



(a)
f=0.1
ω
k//
2.0x10+14
1.8x10+14
1.6x10+14
1.4x10+14
1.2x10+14
5.0x10+05
1.0x10+06
1.5x10+06
16
14
12
10
8
6
4
2
0
-2
-4
-6

Anisotropy

Anisotropy mixes TE and TM components



the reflection matrices are now given by

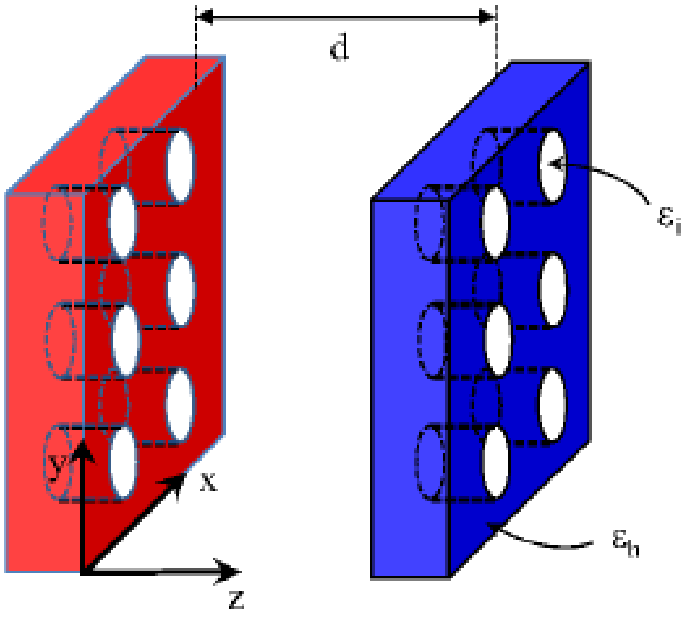
$$\mathbb{R}_i = \begin{bmatrix} r_i^{s,s}(\omega,\kappa) & r_i^{s,p}(\omega,\kappa) \\ r_i^{p,s}(\omega,\kappa) & r_i^{p,p}(\omega,\kappa) \end{bmatrix}$$

The generalization of heat transfer to the anisotropic case turns out to be the intuitive guess

$$\Phi = \int_0^\infty \frac{d\omega}{2\pi} \left[\Theta(\omega,T_1) - \Theta(\omega,T_2)\right] \sum_{j=\{s,p\}} \int \frac{d^2\kappa}{(2\pi)^2} \mathcal{T}_j(\omega,\kappa;d)$$

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

Out-of-plane Anisotropy



The media still supports TE and TM waves, meaning that

$$r_i^{s,p}(\omega,\kappa) = r_i^{p,s}(\omega,\kappa) = 0,$$

and also

$$r^{s,s}(\omega,\kappa) = \frac{\gamma - \gamma_s}{\gamma + \gamma_s}$$

$$r^{p,p}(\omega,\kappa) = \frac{\epsilon_{\|}\gamma - \gamma_p}{\epsilon_{\|}\gamma + \gamma_p}$$

$$\gamma_{\rm s} = \sqrt{\epsilon_{\|}\omega^2/c^2 - \kappa^2},$$

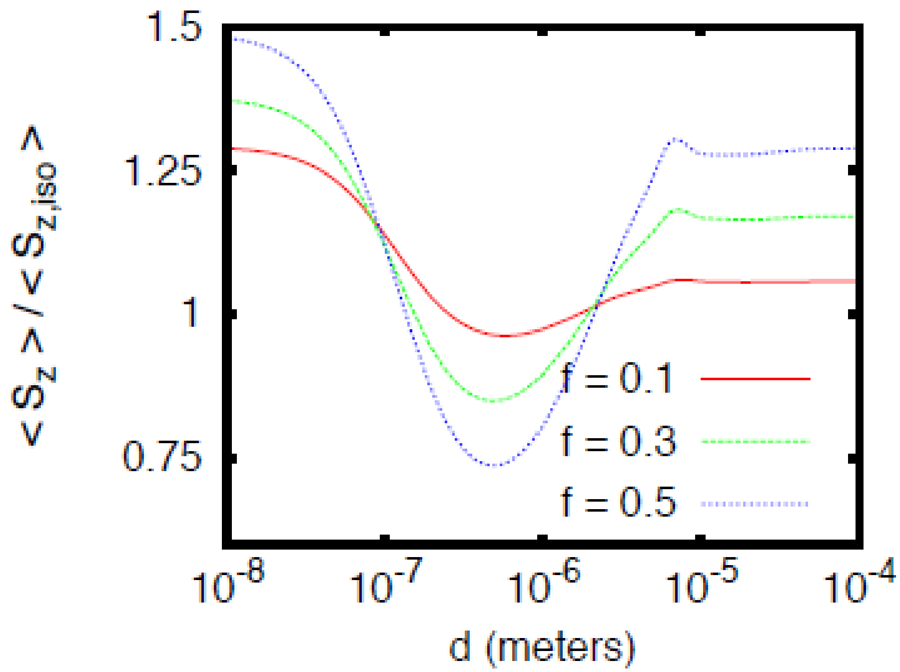
$$\gamma_{\rm p} = \sqrt{\epsilon_{\|}\omega^2/c^2 - \frac{\epsilon_{\|}}{\epsilon_{\perp}}\kappa^2},$$

and so the problem is similar to the isotropic one. Using a Maxwell-Garnett approximation for the materials

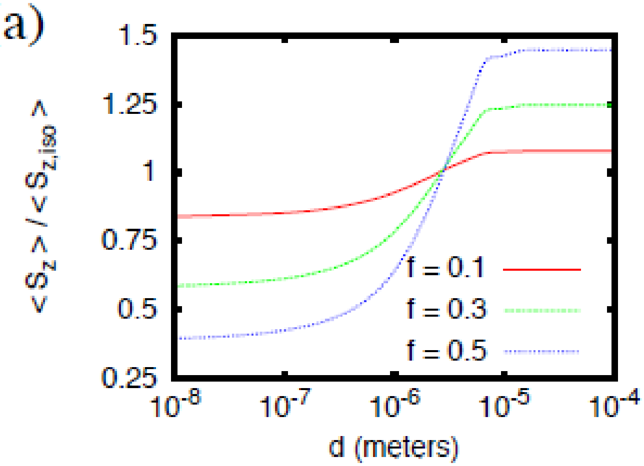
$$\varepsilon_{\|} = \varepsilon_{\rm h}\frac{\varepsilon_{\rm i}(1+f)+\varepsilon_{\rm h}(1-f)}{\varepsilon_{\rm i}(1-f)+\varepsilon_{\rm h}(1+f)},$$

$$\varepsilon_{\perp} = \varepsilon_{\rm h}(1-f)+\varepsilon_{\rm i}f,$$

we get


1.5
1.25
1
0.75
< Sz > / < Sz,iso >
f = 0.1
f = 0.3
f = 0.5
10-8
10-7
10-6
10-5
10-4
d (meters)

(a)


1.5
1.25
1
0.75
0.5
0.25
< Sz > / < Sz,iso >
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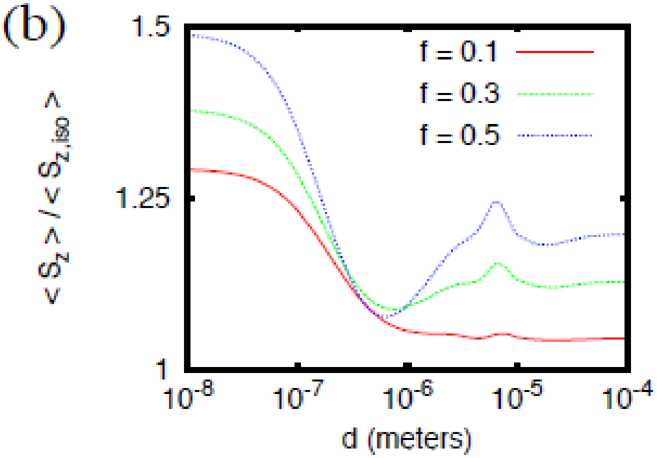
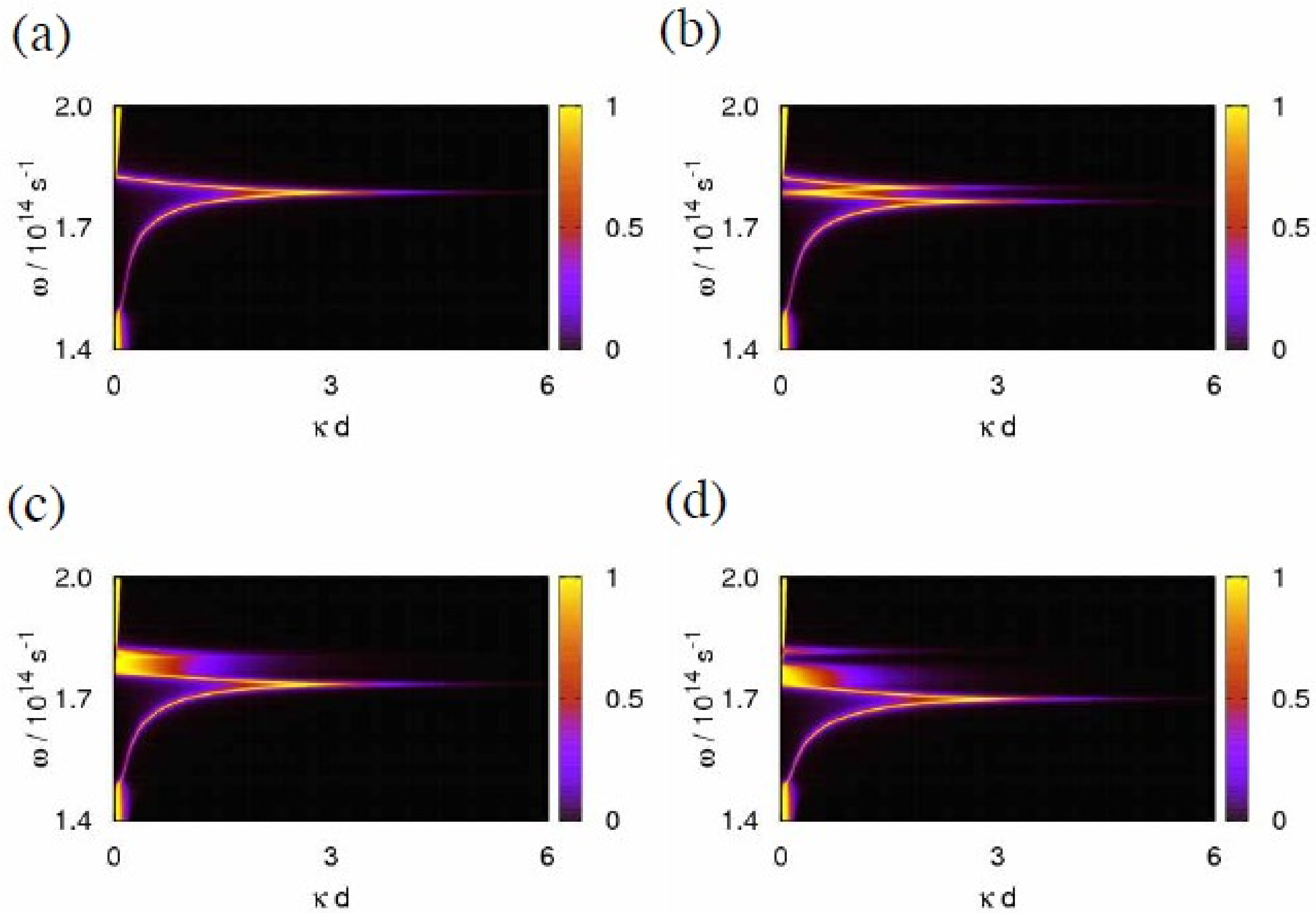
f = 0.3
f = 0.5
10-8
10-7
10-6
10-5
10-4
d (meters)

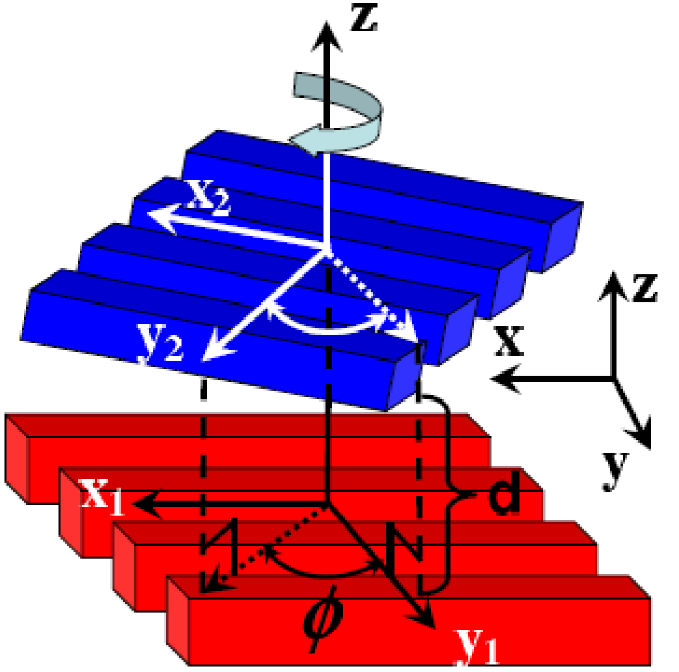
(b)

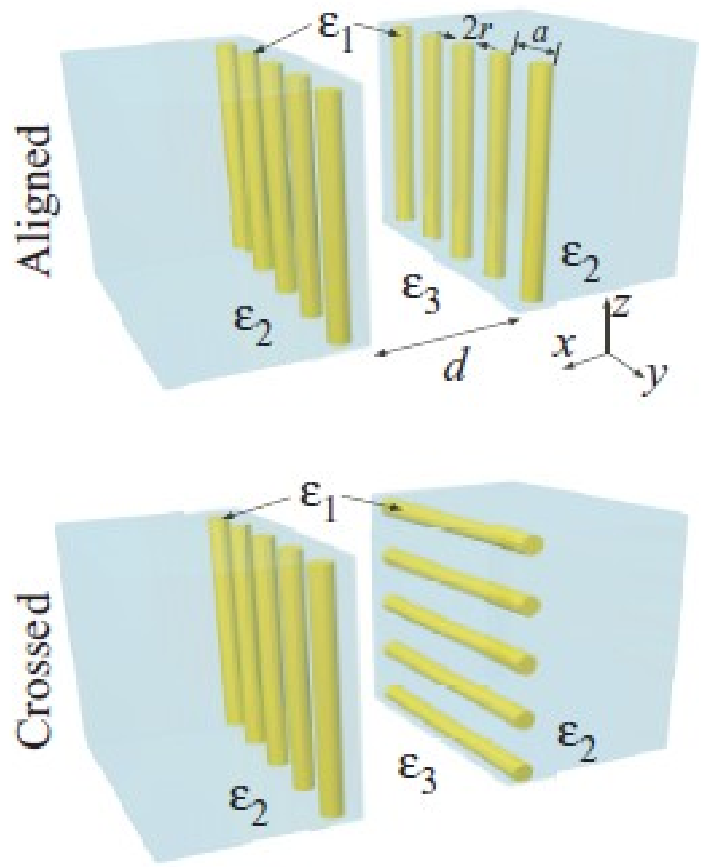

1.5
1.25
1
< Sz > / < Sz,iso >
f = 0.1
f = 0.3
f = 0.5
10-8
10-7
10-6
10-5
10-4
d (meters)



S.-A. Biehs et al., Opt. Exp. 19, A1088 (2011).

In-plane Anisotropy





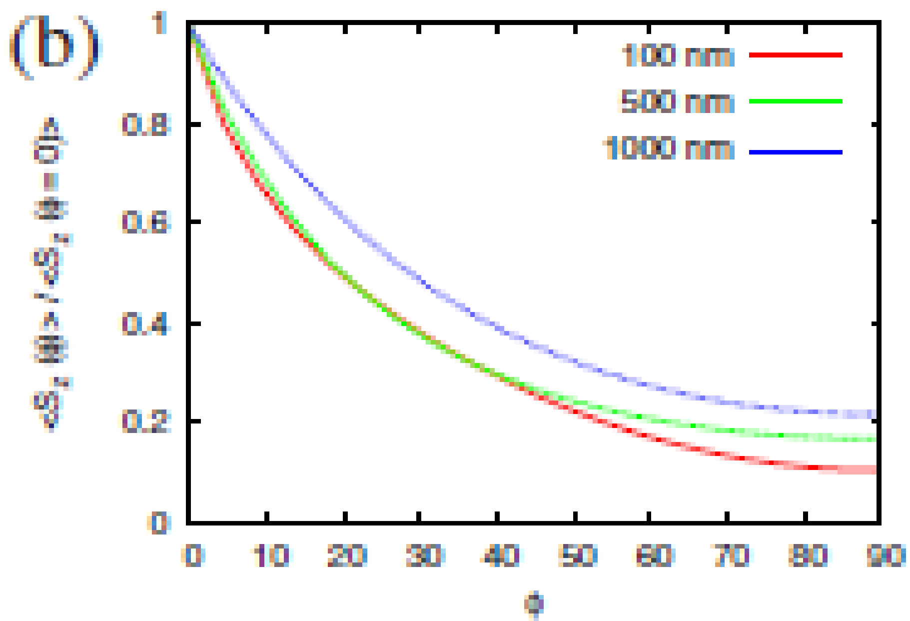
In this case we have full-fledged anisotropy

$$\Phi = \int_0^\infty \frac{d\omega}{2\pi} \left[\Theta(\omega, T_1) - \Theta(\omega, T_2)\right] \sum_{j=\{s,p\}} \int \frac{d^2\kappa}{(2\pi)^2} \mathcal{T}_j(\omega, \kappa; d)$$

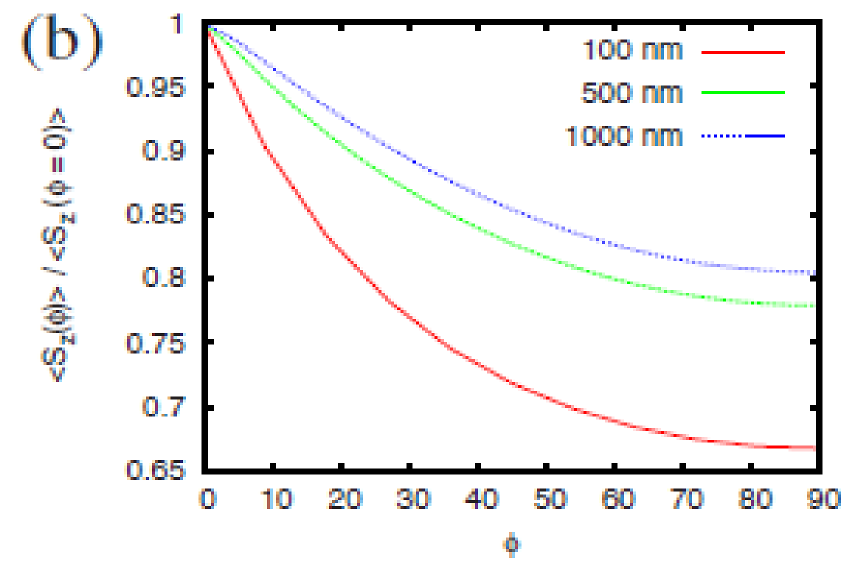
$$T(\omega,\kappa;d) = \begin{cases} \mathrm{Tr}\left[(\mathbb{1} - \mathbb{R}_2^\dagger \mathbb{R}_2)\mathbb{D}^{12}(\mathbb{1} - \mathbb{R}_1 \mathbb{R}_1^\dagger)\mathbb{D}^{12\dagger}\right], & \kappa < \omega/c \\ \mathrm{Tr}\left[(\mathbb{R}_2^\dagger - \mathbb{R}_2)\mathbb{D}^{12}(\mathbb{R}_1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

- FSSR et al., PRA 78 032117 (2008)
- S. Teitler and B.W. Henvis, J. Opt. Soc. Am. {\bf 60}, 830 (1970)
- V.A. Parsegian and G.H. Weiss, J. Adhes. {\bf 3}, 259 (1972).
- Y. Barash, Izv. Vyssh. Uchebn. Zaved. Radiofiz. {\bf 12}, 1637 (1978)
- T.G. Philbin and U. Leonhardt, arXiv:0806.4752, (2008).
- ...

Metals



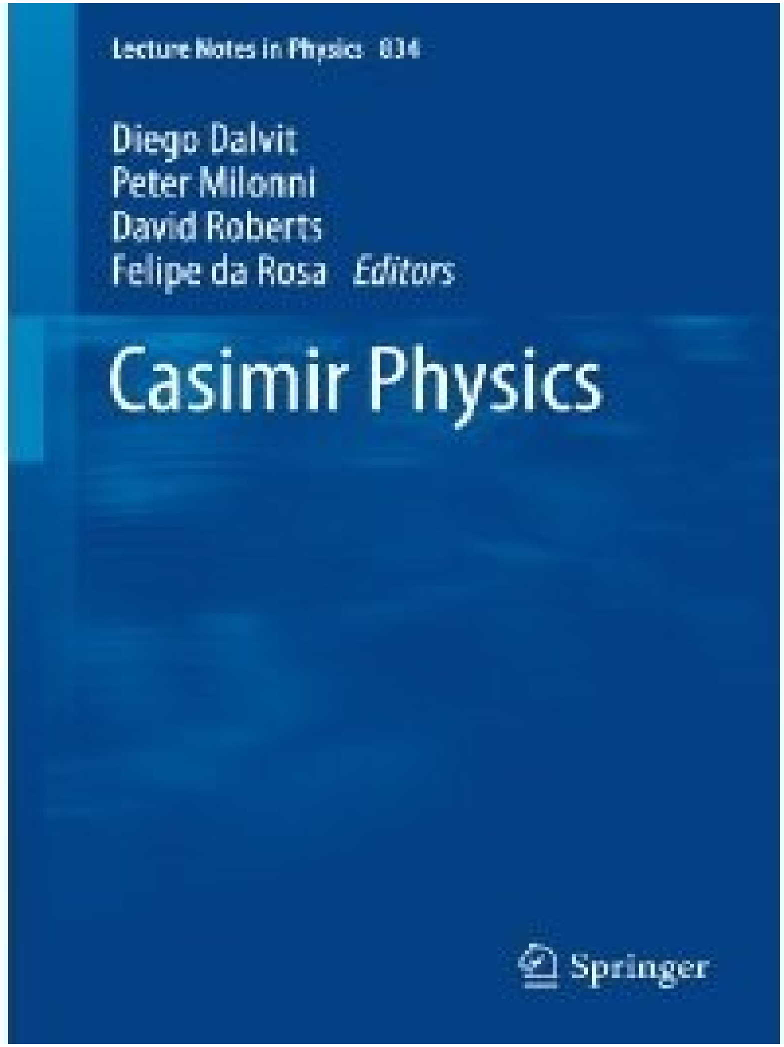
Dielectrics



S.-A. Biehs, FSSR, P. Ben-Abdallah, APL 98, 243102 (2011).

Prospects

- To go beyond effective medium theory
- To consider simple thermalization problems
- Temperature in the surface ?



...and thank you!