# Transfert radiatif entre milieux complexes

## Films et métamatériaux

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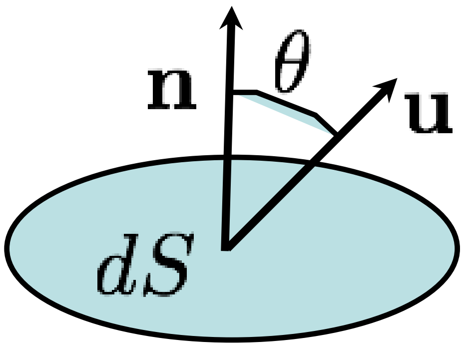
# Rayonnement thermique classique

Luminance $I_\omega(\mathbf{r},\mathbf{u})$




Flux de chaleur à travers une surface $d\Phi = I_\omega(\mathbf{r},\mathbf{u})\cos\theta dS d\Omega$

Propriétés optiques
- emissivité
- absorptivité

$$I_\omega(\mathbf{r},\mathbf{u}) = \epsilon_\omega(\mathbf{r},\mathbf{u}) I^0_\omega(\mathbf{r},\mathbf{u})$$

$$\epsilon_\omega(\mathbf{r},\mathbf{u}) = \alpha_\omega(\mathbf{r},-\mathbf{u})$$

# Rayonnement classique: hypothèses et limites

**Hypothèses**

- Rayon lumineux
- Addition des intensités
- Propriétés locales
- Propriétés surfaciques (corps opaques)

**Limite aux petites échelles**

- Diffraction $L \ll \lambda$
- Interferences $L \ll l_{coh}$
- Non localité $L \ll \begin{cases} \lambda \\ l_{coh} \end{cases}$
- Rayonnement volumique $L \ll \delta$

# Radiométrie et electromagnétisme

## Radiométrie

- **Flux d'énergie**

$$q = \int I(\mathbf{r},\mathbf{u})\mathbf{u}d\Omega$$

- **Densité d'énergie**

$$u = \int \frac{I(\mathbf{r},\mathbf{u})}{c}d\Omega$$

- **Luminance** $I(\mathbf{r},\mathbf{u})$

## Electromagnétisme

- **Vecteur de Poynting**

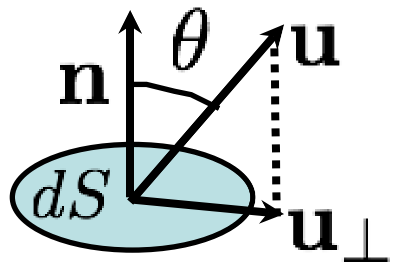
$$\langle \Pi \rangle = \langle \mathbf{E} \times \mathbf{H} \rangle$$

- **Densité d'énergie**

$$u = \epsilon_0 \frac{E^2}{2} + \mu_0 \frac{H^2}{2}$$

- **Luminance** ?

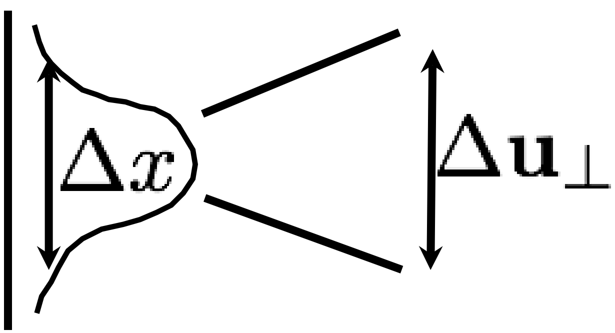
# Luminance

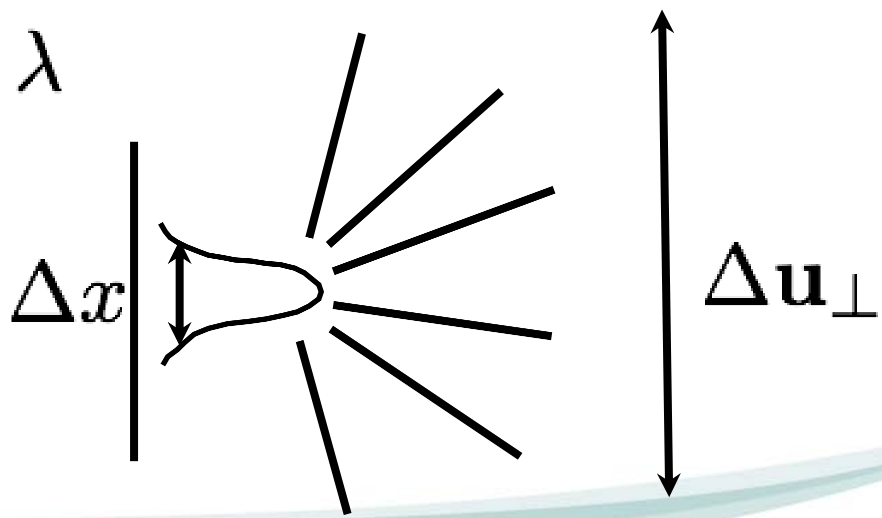



**Définition statistique de la luminance**

$$I(\mathbf{r},\mathbf{u}) = \left(\frac{k}{2\pi}\right)\cos\theta \int \langle E(\mathbf{r}+\mathbf{r}'/2)E^*(\mathbf{r}-\mathbf{r}'/2)\rangle \exp(-ik\mathbf{u}_\perp\cdot\mathbf{r}')d^3\mathbf{r}'$$

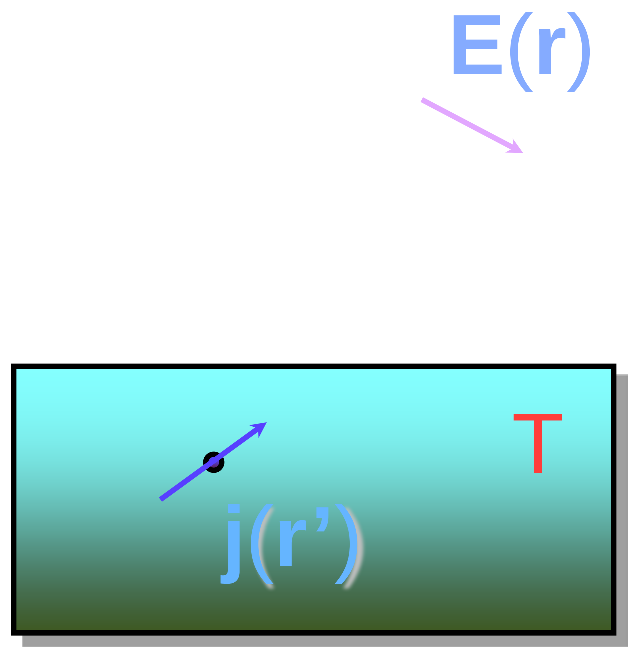
$$\Delta x \Delta \mathbf{u}_\perp \sim \lambda$$



# Rayonnement thermique de champ proche

- Electrodynamique fluctuationelle
- Fonctions de Green
- Théorème de fluctuation-dissipation




$$\mathbf{E}(\mathbf{r}) = \int \mathbf{G}(\mathbf{r},\mathbf{r}') \cdot \mathbf{j}(\mathbf{r}') d^3\mathbf{r}'$$

$$\langle j_n(\mathbf{r}) j_m(\mathbf{r}')\rangle = \frac{\omega \epsilon_0 Im(\epsilon)}{\pi} \Theta(\omega, T) \delta_{nm} \delta(\mathbf{r} - \mathbf{r}')$$

$$\Theta(\omega, T) = \frac{\hbar\omega}{e^{\hbar\omega/k_b T} - 1}$$

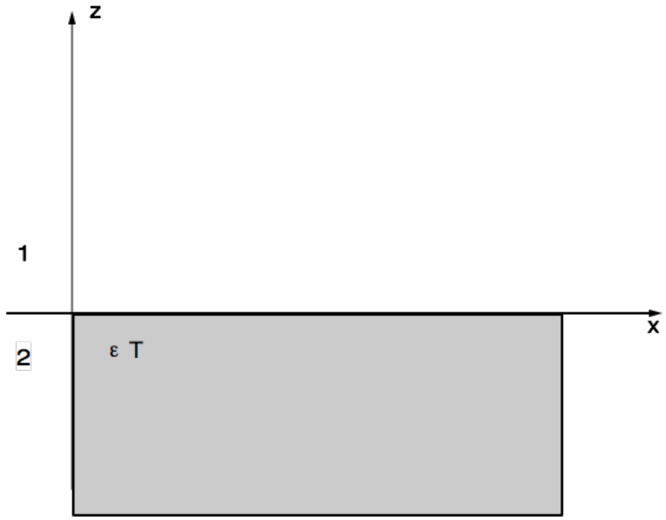
# Rayonnement thermique au-dessus d'une surface

Densité d'énergie

$$U(\mathbf{r},\omega) = \frac{\hbar\omega}{exp(\hbar\omega/k_bT)-1}\frac{\omega}{\pi c^2} ImTr\left[G(\mathbf{r},\mathbf{r},\omega) + \frac{c^2\nabla_{\mathbf{r}}}{\omega^2}\times\left[\nabla_{\mathbf{r}'}\times^T G(\mathbf{r},\mathbf{r}',\omega)\right]^T|_{\mathbf{r}=\mathbf{r}'}\right]$$

Densité d'état

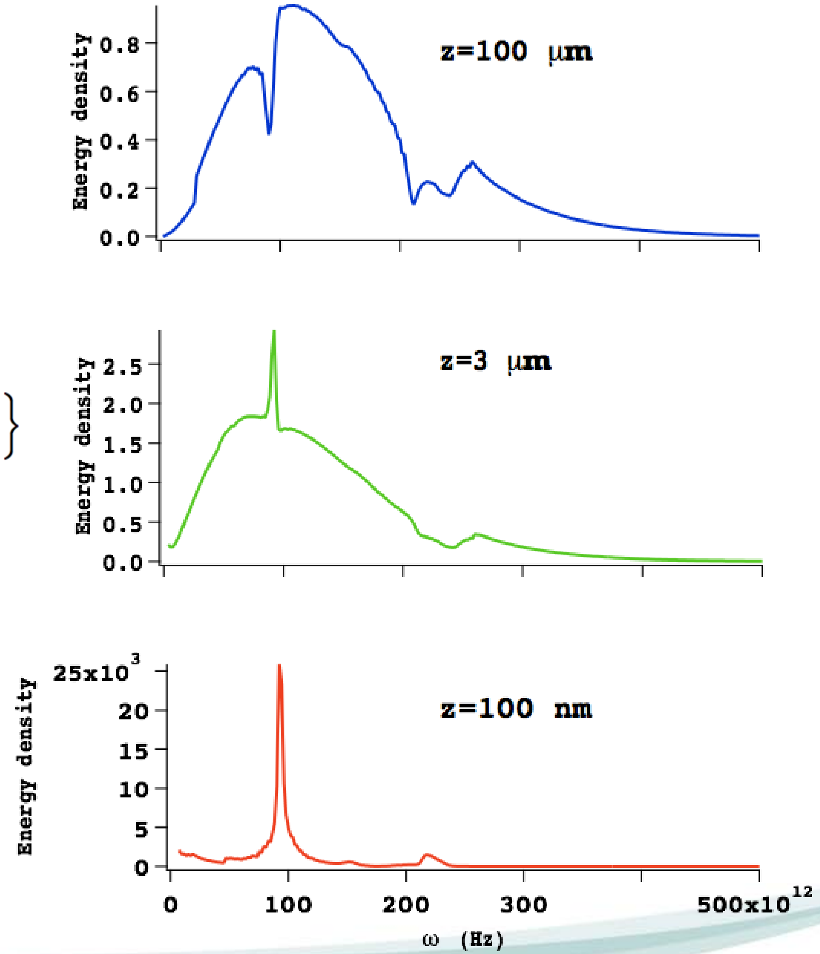
$$U(\mathbf{r},\omega) = \frac{\hbar\omega}{\exp(\hbar\omega/k_bT)-1}\rho(\mathbf{r},\omega)$$



# Rayonnement thermique au-dessus d’une surface

- Densité d’énergie

$$U(\mathbf{r},\omega) = \frac{\hbar\omega^3}{2\pi^2 c^3(\exp\hbar\omega/k_bT - 1)} \times$$
$$\left[\int_0^1 \frac{udu}{\sqrt{1-u^2}}\left\{2 + u^2[Re(r^s e^{2i\sqrt{1-u^2}\omega z/c}) + Re(r^s e^{2i\sqrt{1-u^2}\omega z/c})]\right\}\right.$$
$$\left. + \int_1^\infty \frac{u^3du}{\sqrt{u^2-1}} e^{-2\sqrt{1-u^2}\omega z/c}[Im(r^s) + Im(r^p)]\right]$$



# Emission thermique au-dessus d'une surface

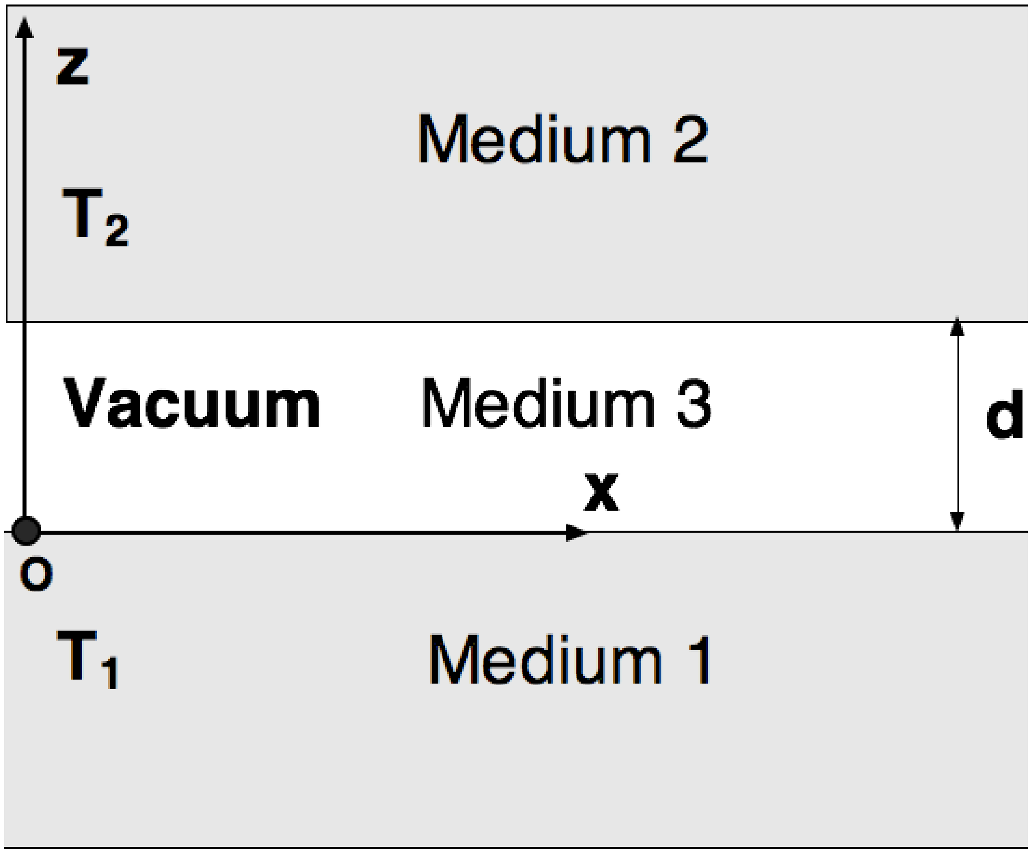
- Densité de flux

$$\langle S_z(\mathbf{r},\omega)\rangle = \frac{\hbar\omega^3}{2\pi^2c^2\exp(\hbar\omega/k_bT)-1} \times \int_0^1 udu\frac{1-|r_{12}^s|^2+1-|r_{12}^p|^2}{2}$$

- Emissivité

$$\epsilon = \frac{1-|r_{12}^s|^2+1-|r_{12}^p|^2}{2}$$

# Transfert en champ proche entre deux surfaces planes arbitraires



# Transfert en champ proche entre deux surfaces planes arbitraires

- Flux de chaleur monochromatique

$$\langle S_z^{\text{prop}} \rangle = \pi [I_\omega^0(T_1) - I_\omega^0(T_2)] \sum_{\lambda=s,p} \int_0^1 u du \frac{(1-|r_{31}^\lambda|^2)(1-|r_{32}^\lambda|^2)}{|1-r_{31}^\lambda r_{32}^\lambda e^{2i\sqrt{1-u^2}\omega d/c}|^2}$$

$$\langle S_z^{\text{evan}} \rangle = 4\pi [I_\omega^0(T_1) - I_\omega^0(T_2)] \sum_{\lambda=s,p} \int_1^\infty u du \frac{Im(r_{31}^\lambda) Im(r_{32}^\lambda) e^{-2\sqrt{u^2-1}\omega d/c}}{|1-r_{31}^\lambda r_{32}^\lambda e^{-2\sqrt{u^2-1}\omega d/c}|^2}$$

G. Bimonte , Phys. Rev. A, **80**, 042102 (2009)

# Interprétation en termes de nombre de modes couplés

- Formalisme de Landauer

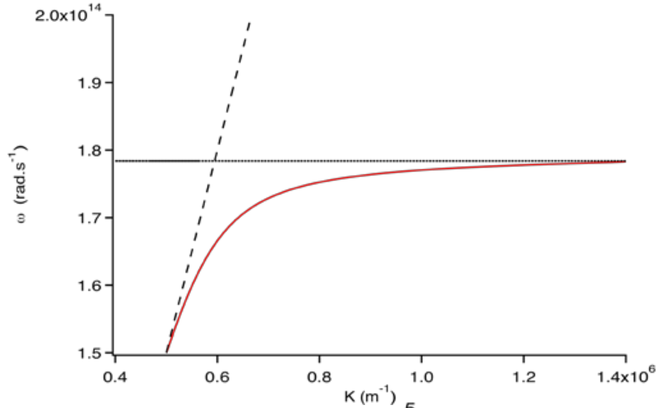
$$\varphi = \int_0^\infty \frac{\hbar\omega}{\exp(\hbar\omega/k_bT)-1} N(\omega) \frac{d\omega}{2\pi}$$

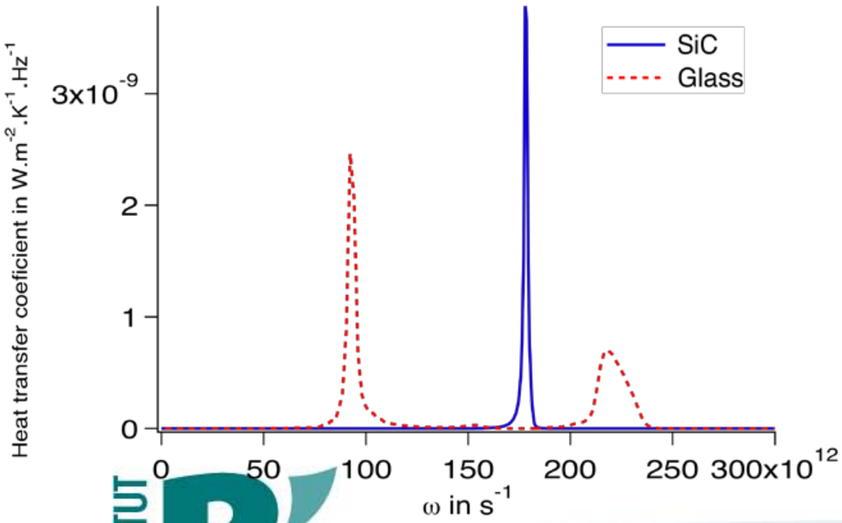
- Nombre de modes couplés

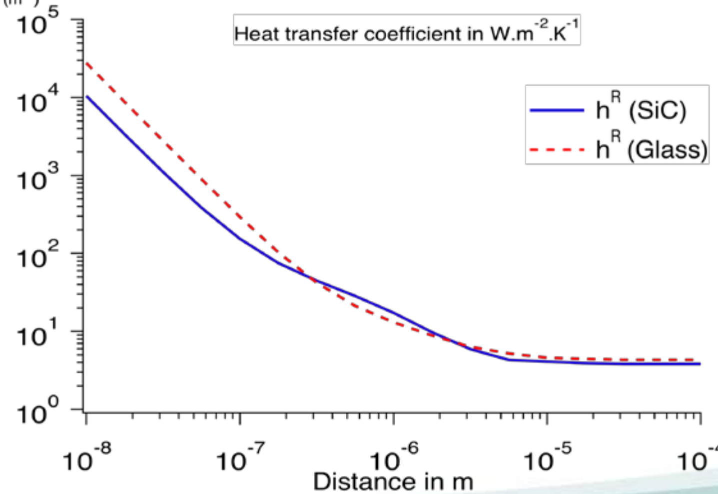
$$N(\omega) = \langle S_z(\omega) \rangle \times \frac{2\pi(\exp(\hbar\omega/k_bT)-1)}{\hbar\omega}$$

# Augmenter le transfert thermique

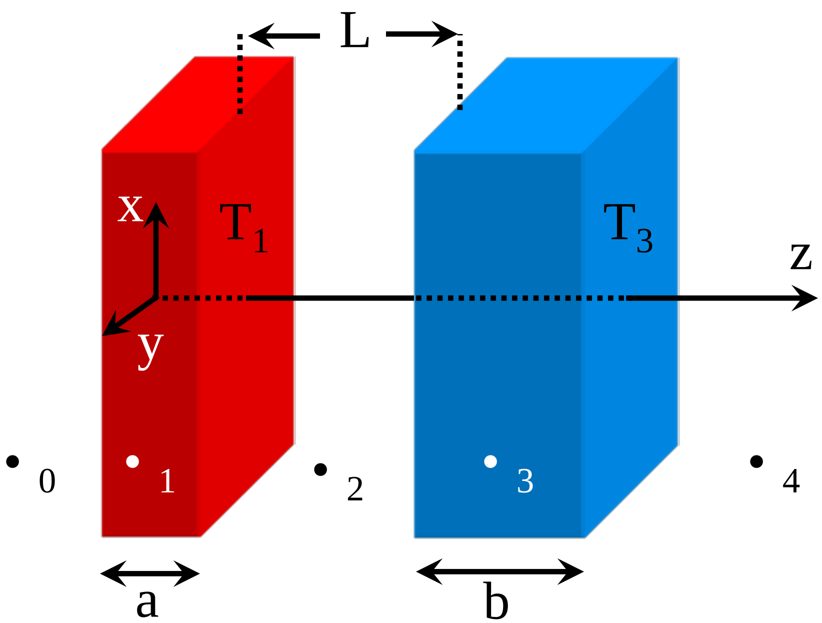
## Surface polariton

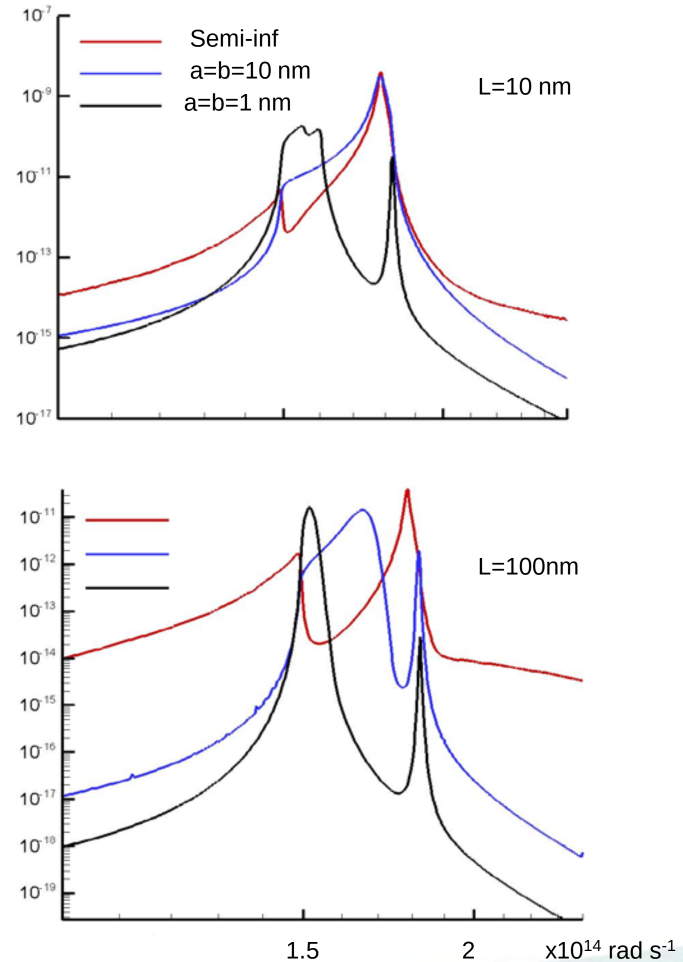


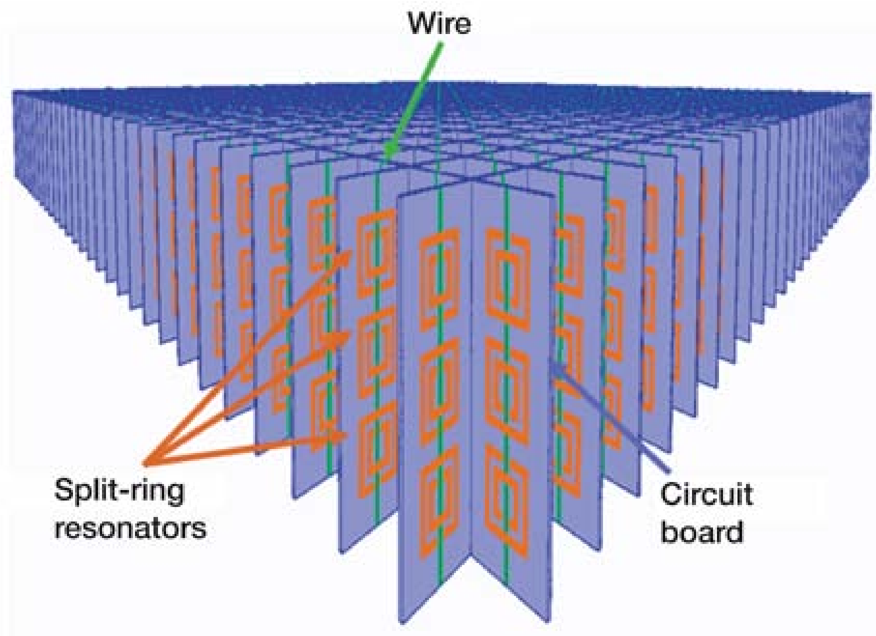
# Transfert entre films

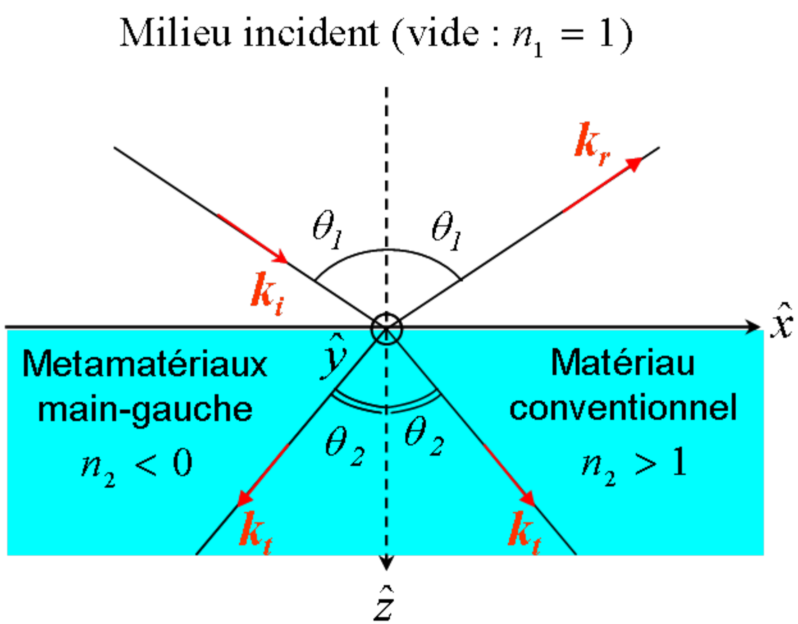


# Transfert entre métamatériaux

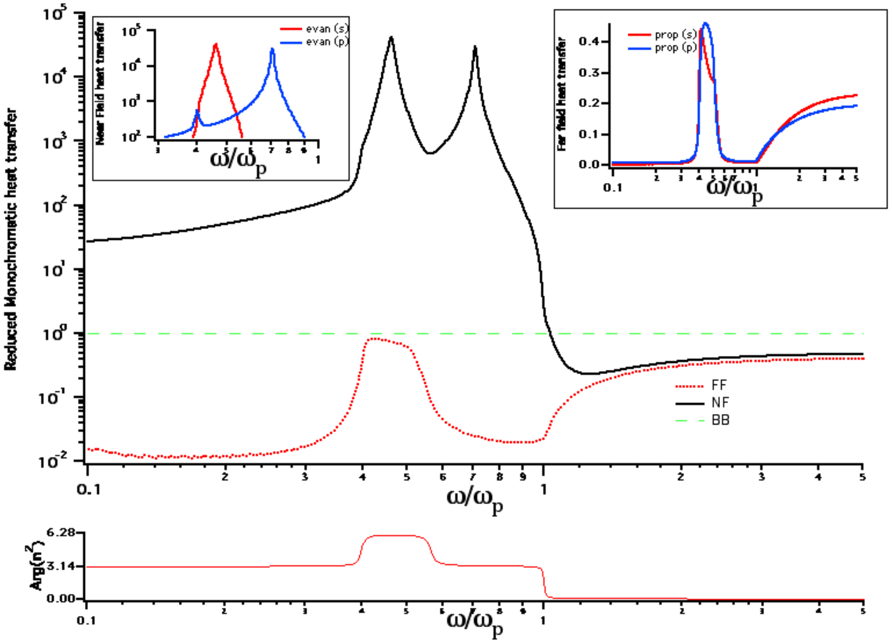
- Métamatériaux

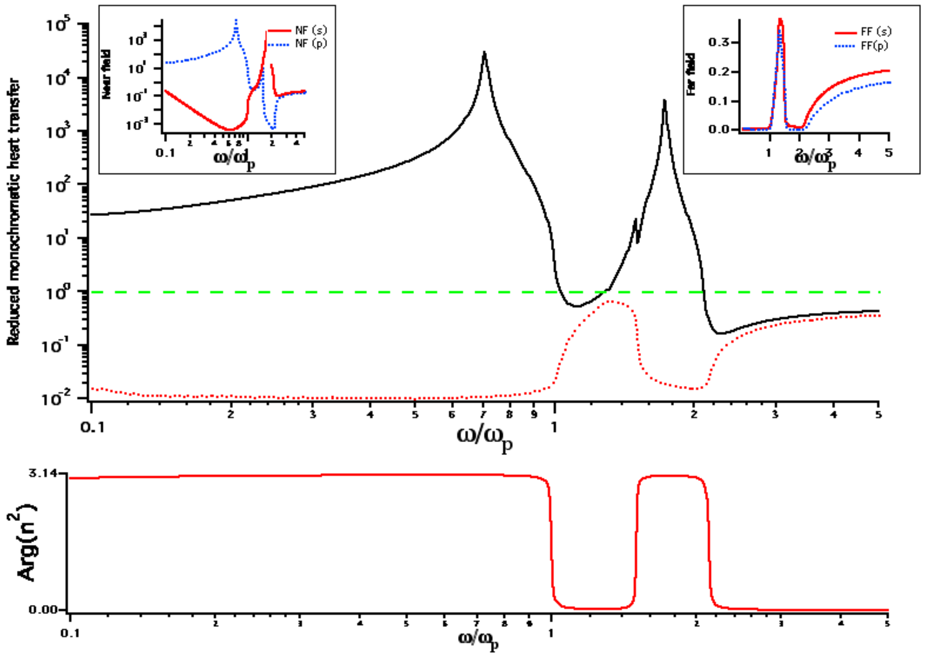


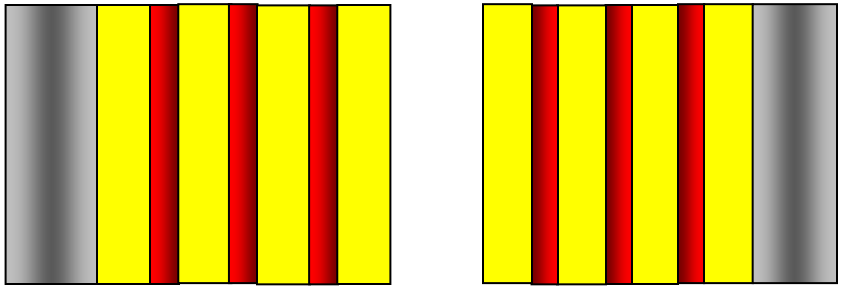
# Transfert entre métamatériaux

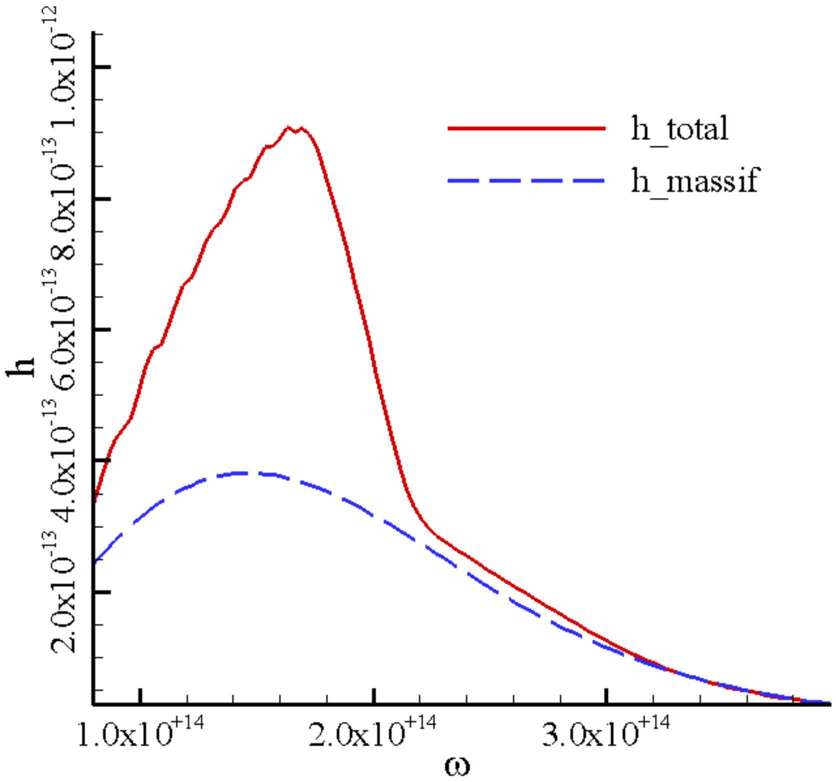
- Métamatériaux



# Transfert entre cristaux photoniques





# Perspectives

- Trouver les limites du transfert à petite échelles
- Augmenter le nombre de modes couplés entre corps chauffés
- Applications : augmenter le niveau de signal TPV.