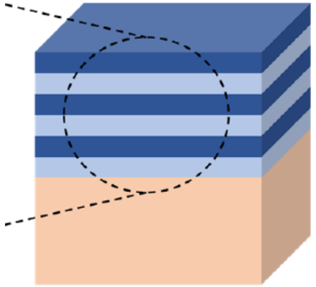
Paul Rouquette PhD 2019-2022

Design de structures présentant des diagrammes de rayonnement thermique contrôlés

Claude Amra, Paul Rouquette, François Thullier, Gabriel Soriano, Michel Lequime, Hélène Krol and Myriam Zerrad

1- Motivation initiale



Dans le domaine des **composants photoniques**,

*les phénomènes de **transfert thermique** sont devenus omniprésents:*

- des sources de plus en plus puissantes
- des volumes de plus en plus confinés

⇩

Hautes densités d'énergie électromagnétique ⟹ Températures élevées

⇩

Dérive/dégradation/endommagement

⇩

Modélisation de la température photo-induite

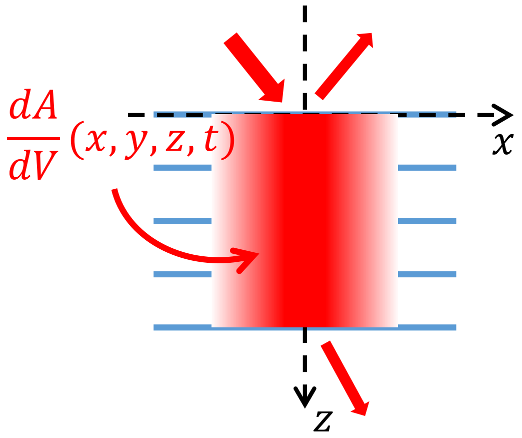
⇩

Rayonnement thermique photo-induit: difficulté ou opportunité?

2- Modélisation de la température photo-induite en régime spatio-temporel

A combien ça monte, à quelle vitesse, quand est-ce que ça casse, qu’est-ce qui chauffe?

- Z. M. Zhang, Nano/Microscale Heat Transfer, 2nd ed., Mechanical Engineering Series (Springer International Publishing, 2020
- M. Mansuripur, G. A. N. Connell, and J. W. Goodman, "Laser-induced local heating of multilayers," Appl. Opt. **21**, 1106–1114 (1982)
- B. Wang, X. Wang, Y. Qin, X. Ni, Z. Shen, and J. Lu, "Temperature field analysis of optical coatings induced by millisecond and nanosecond lasers," Optica Applicata **42**, 783–793 (2012).

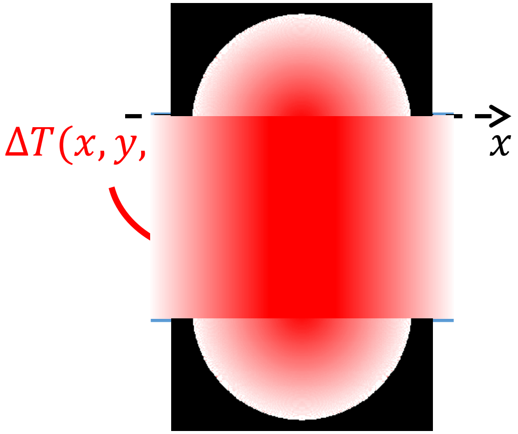


The incident field creates a **4D absorption density** within the stack

$$\frac{dA}{dz}(x,y,z,t)$$

Heat equation: $\Delta T_i(\vec{\rho},t) - \frac{1}{\boldsymbol{a_i}}\frac{\partial T_i}{\partial t}(\vec{\rho},t) = -\frac{1}{\boldsymbol{b_i}}\boldsymbol{S_i(\vec{\rho},t)}$

Heat source created by absorption



This absorption density is responsible

for a temperature distribution $T(x,y,z,t)$

The heat source in a spatio-temporal regime

Source term = volume density of losses

$$Maxwell\ equations \Longrightarrow \boldsymbol{S_i(\vec{r},z,t)} = \frac{\partial W_i}{\partial t} = \vec{E}_i.\frac{\partial}{\partial t}(\epsilon_i *_t \vec{E}_i) + \vec{H}_i.\frac{\partial}{\partial t}(\mu_i *_t \vec{H}_i)$$

Spatio-temporal envelope

$$\boldsymbol{S_i(\vec{r},z,t)} = \boldsymbol{\frac{\partial A_i}{\partial z}}(\vec{v}_0, z, f_0)\boldsymbol{g^2}(\vec{r},z,t)$$

Collimated and quasi-monochromatic source

$$E_0^+(\vec{r},z,t) = \boldsymbol{g(\vec{r},z,t)}\cos\big(2\pi(f_0 t - \vec{v}_0.\vec{r})\big) \quad \Longrightarrow$$

Monochromatic absorption

$$\frac{dA}{dz}(x,y,z,t) \sim \frac{\omega}{2}(\varepsilon''|E|^2 + \mu''|H|^2)$$

Solving the heat equation

Use an optics/thermal analogy !

Heat diffusion is similar to optical propagation in (specific) metallic media

Temporal frequency

Second Fourier plane: $T(\vec{r}, z, t) \longrightarrow \tilde{T}(\vec{r}, z, \Omega) \longrightarrow \hat{T}(\vec{\nu}, z, \Omega)$

Spatial frequency

$k = \omega\sqrt{\varepsilon(\omega)\mu(\omega)}$

Optics: $\frac{\partial^2 \hat{\vec{E}}_i}{\partial z^2}(\vec{\nu}, z, f) + \boldsymbol{\alpha_{i,op}^2}(\vec{\nu}, f)\hat{\vec{E}}_i(\vec{\nu}, z, f) = \hat{\vec{S}}_i^E(\vec{\nu}, z, f)$

Thermal: $\frac{\partial^2 \hat{T}_i}{\partial z^2}(\vec{\nu}, z, f) + \boldsymbol{\alpha_{i,th}^2}(\vec{\nu}, f)\hat{T}_i(\vec{\nu}, z, f) = -\frac{1}{b_i}\hat{S}_i(\vec{\nu}, z, f)$

$k = (1+j)\sqrt{\frac{\Omega}{2a}}$

Température $\Leftrightarrow$ $champ\ électrique\ (TE)$

Flux de chaleur $\Leftrightarrow$ $champ\ magnétique$

Claude Amra, David Petiteau, Myriam Zerrad, Sébastien Guenneau, Gabriel Soriano, et al.. « *Analogies between optical propagation and heat diffusion: applications to microcavities, gratings and cloaks."* Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, Royal Society, The, 2015, 471 (2183), pp.20150143.

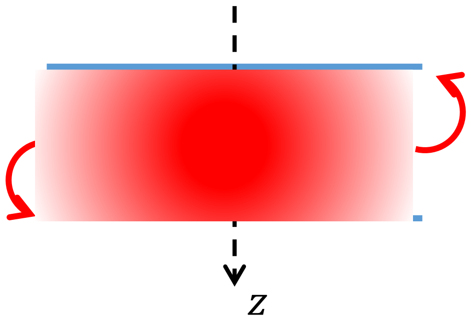
All optical formulae with admittances and effective indices can be used

$$\frac{\partial^2 \hat{T}_i}{\partial z^2}(\vec{v},z,f) + \alpha_{i,th}^2(\vec{v},f)\hat{T}_i(\vec{v},z,f) = -\frac{1}{b_i}\hat{S}_i(\vec{v},z,f)$$

The heat equation is reduced to an incoherent bulk scattering problem

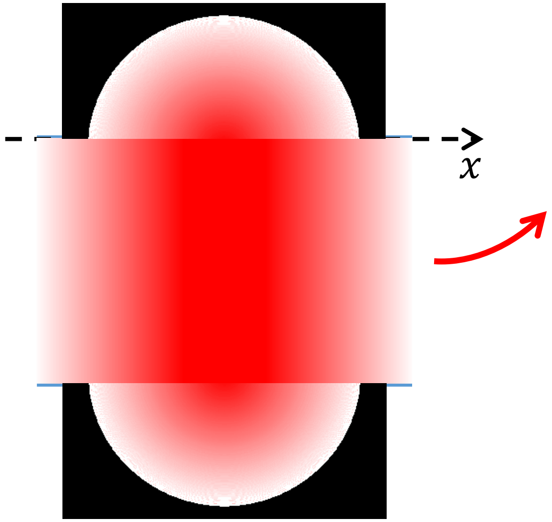
Each layer is a heat source

$$\hat{T}_{i,i} = \frac{c_i Q_i - d_i F_i}{c_i Y_i - d_i}$$



$$\hat{T}'_{i,i-1} = \frac{Q_i - Y_i F_i}{c_i Y_i - d_i}$$

The Tp at one surface is created by all heat sources



$$\hat{T}_j = \sum_i^p \hat{T}_{ij}$$

Heat sources do not interfere but the coating design impacts the temperature distribution

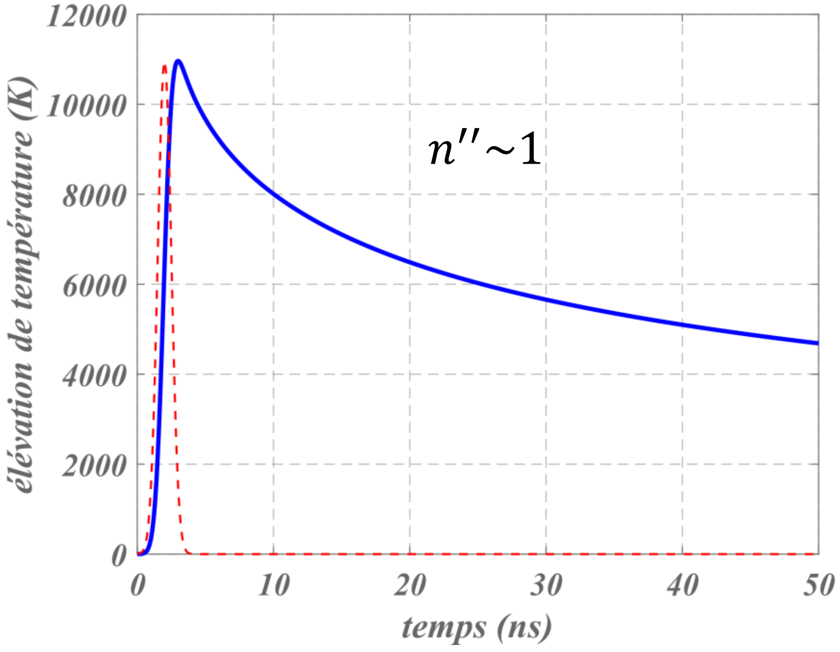
P. Rouquette, C. Amra, M. Zerrad, C. Grèzes-Besset, and H. Krol, "Photo-induced temperature in optical interference coatings," Opt. Express 30, 46575-46601 (2022)

Numerical calculation: order of magnitude versus absorption

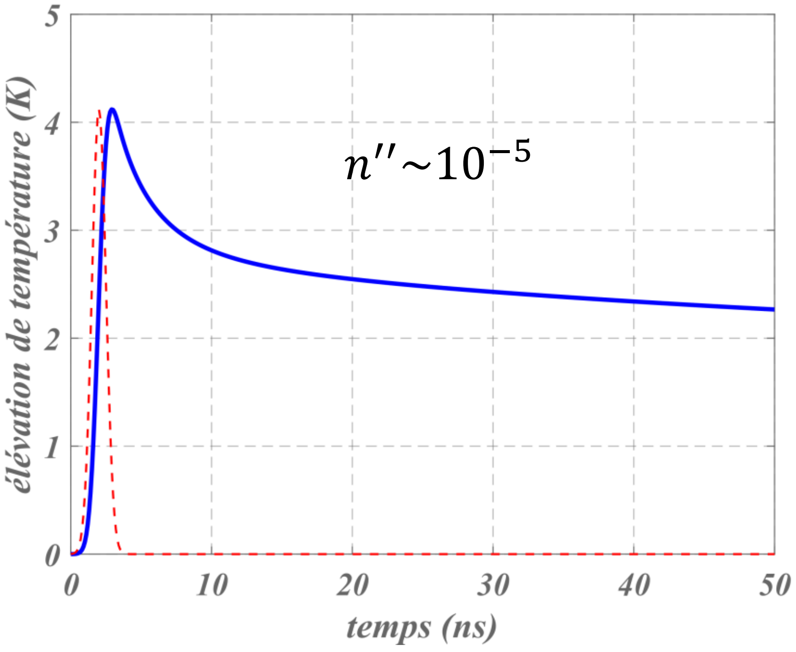
Metallic versus dielectric mirror @ 1064 nm

$$W = 1mJ, \Delta t = 1ns, r = 100\mu m$$

Metallic mirror (prohibitive Tp)



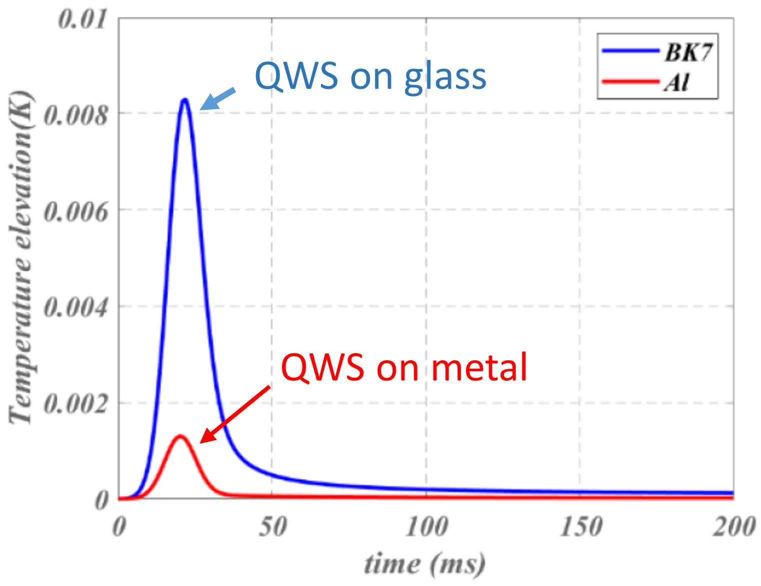
Multidielectric mirror (5K)



Tp difference ⟺ absorption values (dielectrics versus metals)

But absorption is not the only key: influence of thermal parameters

Comparison of 2 dielectric mirrors on different substrates (metal and glass)



Light does not see the mirror substrate (same absorption)…

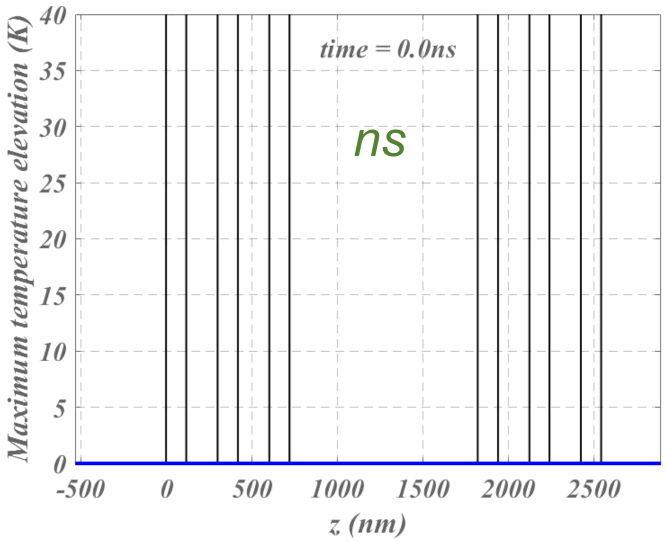
… but the Tp can see the thermal parameters of substrate (heat diffusion)

Tp resolution versus pulse duration

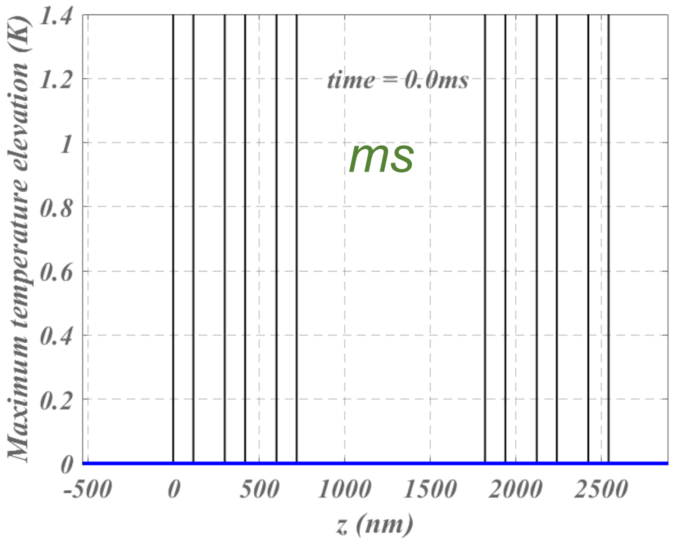
Fabry-Perot filter @ 1064 nm on glass, $n'' = 10^{-5}$

$$W = 1mJ, r = 100\mu m$$

$\Delta T_{max}(ns) = 40K$



$\Delta T_{max}(ms) = 1{,}4K$

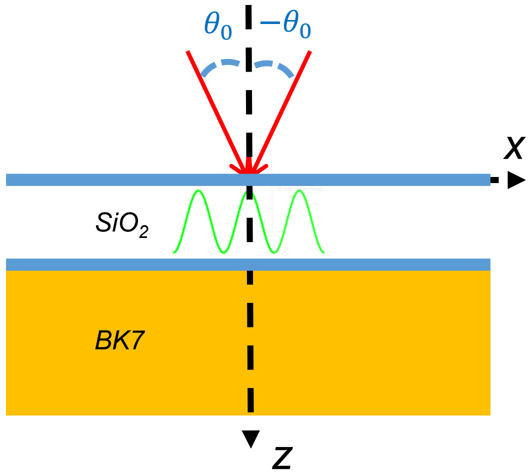


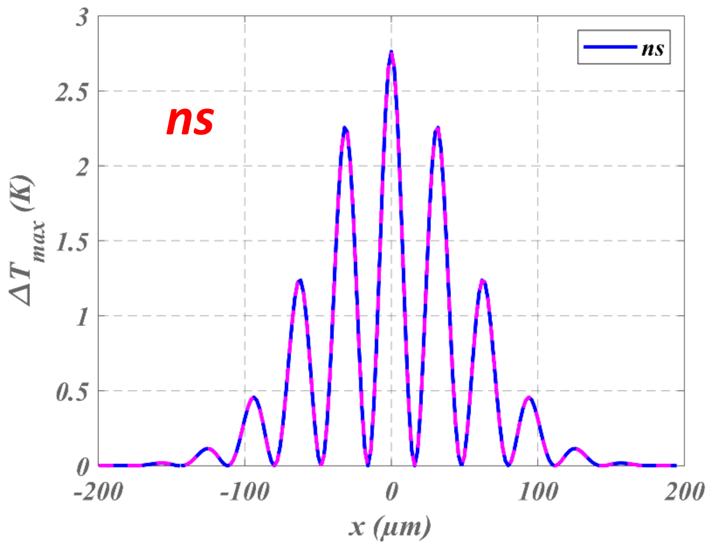
At short pulses (1ns), the temperature follows the stationary electromagnetic field

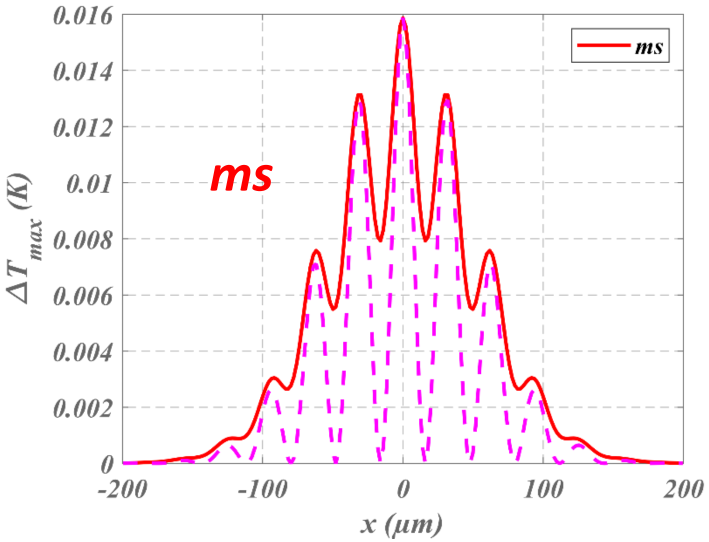
P. Rouquette, C. Amra, M. Zerrad, C. Grèzes-Besset, and H. Krol, "Photo-induced temperature in optical interference coatings," Opt. Express 30, 46575-46601 (2022)

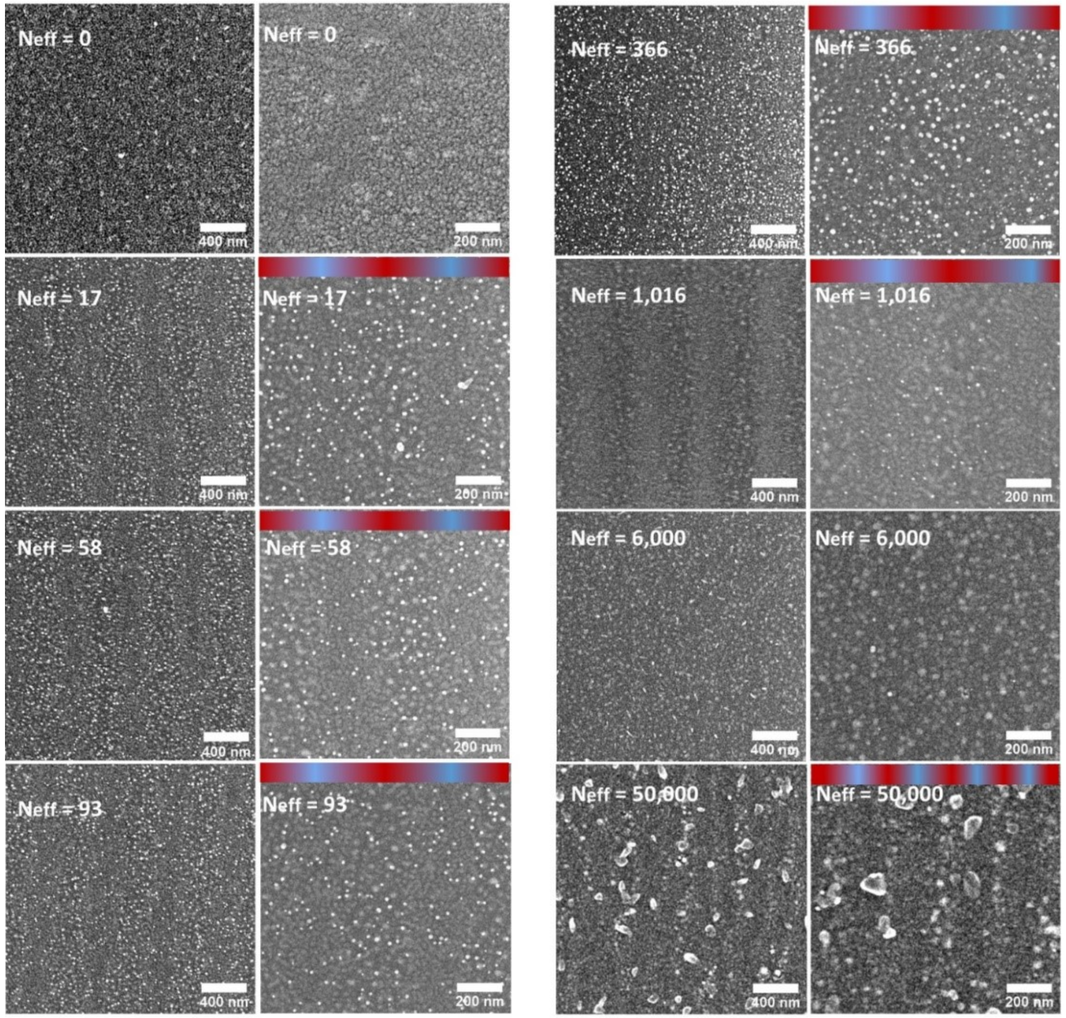
Optical fringes may create « thermal fringes »

2 beams interference









***Eles, Balint**, Rouquette, Paul, Siegel, Jan, Amra, Claude, Lumeau, Julien, Moreau, Antonin, Hubert, Christophe, Zerrad, Myriam and **Destouches, Nathalie**. "Mechanisms driving self-organization phenomena in random plasmonic metasurfaces under multipulse femtosecond laser exposure: a multitime scale study" Nanophotonics, vol. , no. , 2022*

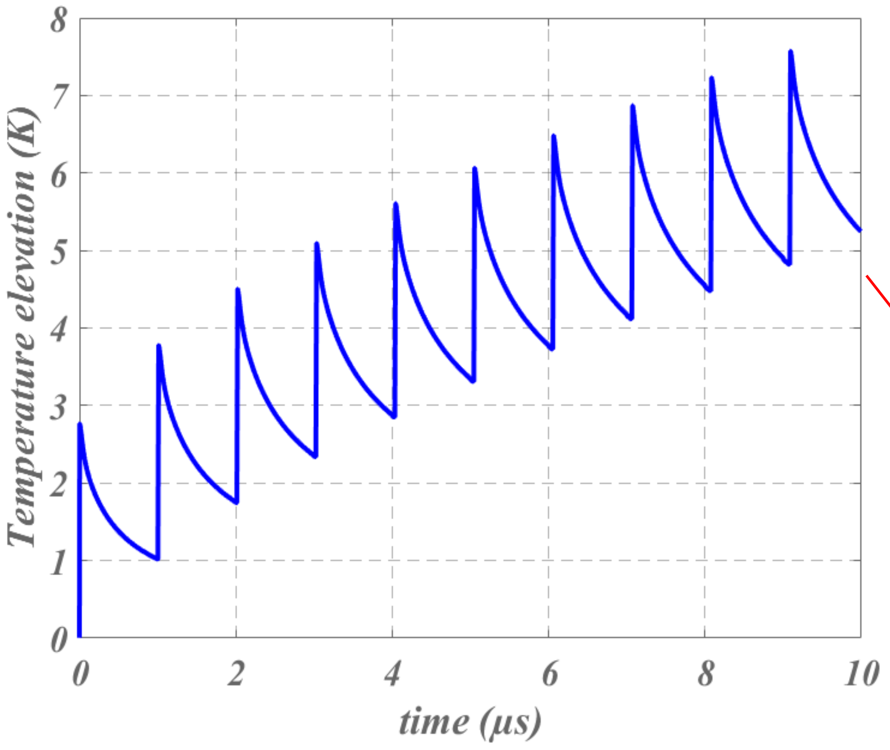
Influence of repetition rate

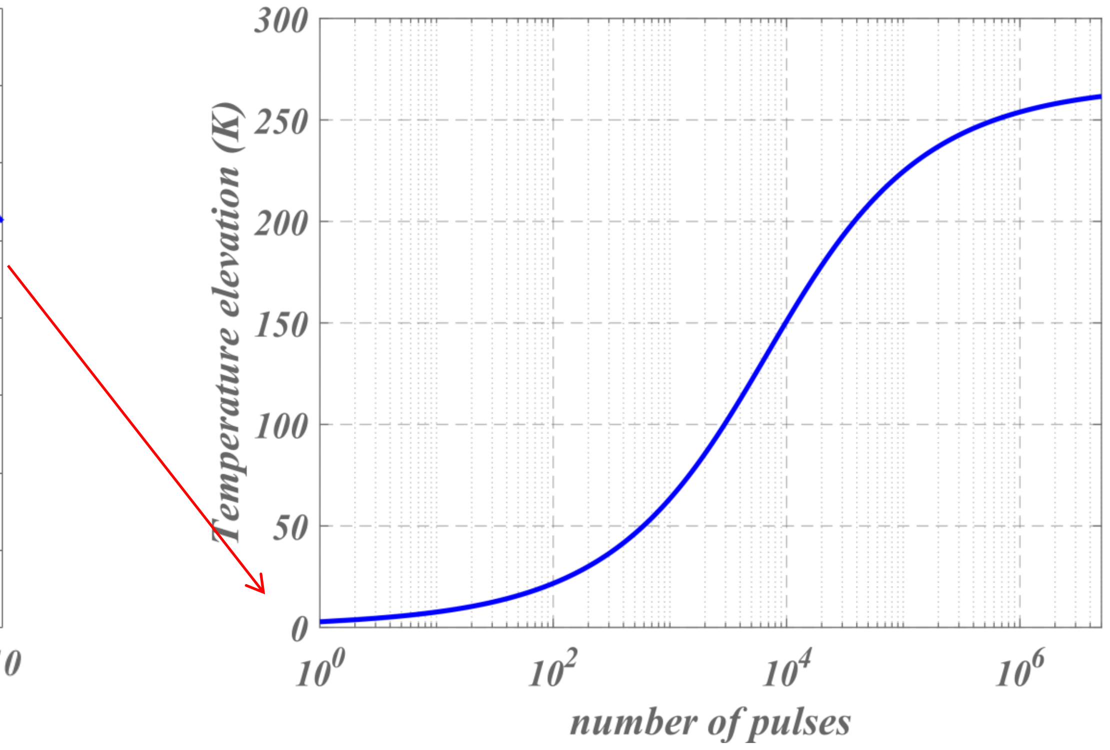
Ex : Pulse 1 ns @1MHz

$$n'' = 10^{-5}$$

$1\ pulse \Longrightarrow T_f = 3\text{K}$

$10^6 pulses\ (1s) \Longrightarrow T_f = 252K$

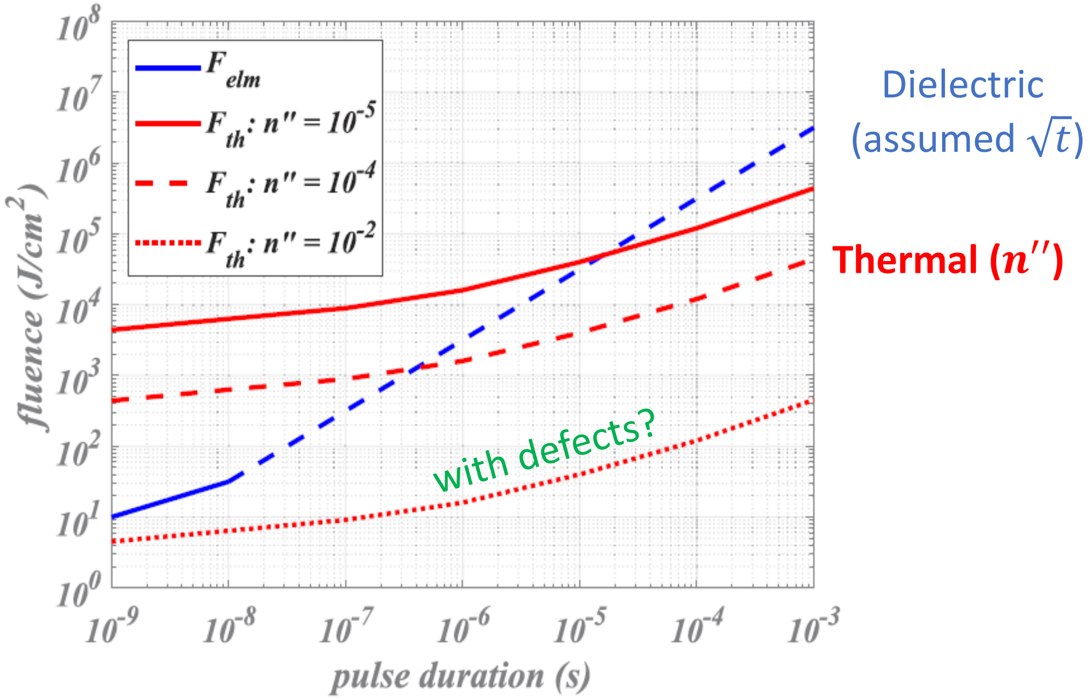




P. Rouquette, C. Amra, M. Zerrad, C. Grèzes-Besset, and H. Krol, "Photo-induced temperature in optical interference coatings," Opt. Express 30, 46575-46601 (2022)

Thermal damage threshold

$$T(pulse\ duration, energy, n'') = T_f \Longrightarrow \boldsymbol{Thermal\ damage \approx L(T_f, pulse\ duration, n'')}$$

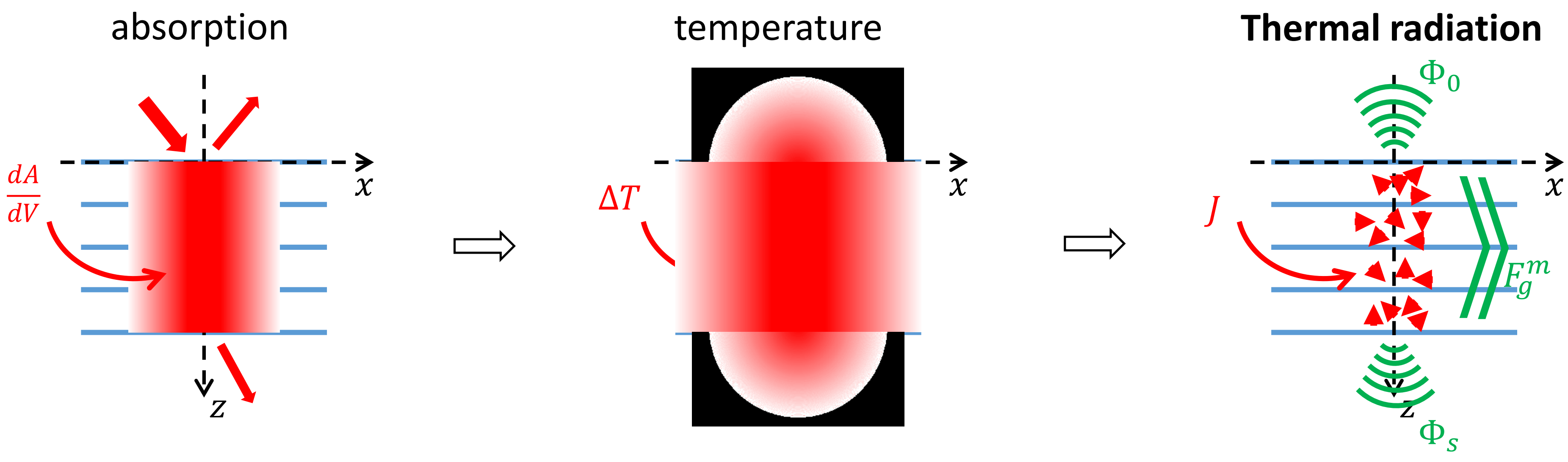


Thermal threshold is lower than the electromagnetic one, unless local defects intervene ($n'' > 10^{-2}$)

- *R. M. Wood, Laser-Induced Damage of Optical Materials, Series in Optics and Optoelectronics (Institute of Physics, 2003)*
- *D. Ristau, Laser-Induced Damage in Optical Materials (CRC Press, 2015)*
- *P. Rouquette, C. Amra, M. Zerrad, C. Grèzes-Besset, and H. Krol, "Photo-induced temperature in optical interference coatings," Opt. Express 30, 46575-46601 (2022)*

3- Rayonnement thermique photo-induit dans les filtres interférentiels

- S. M. Rytov, Yu. A. Kravtsov, and V. I. Tatarskii, *Principles of Statistical Radiophysics 3: Elements of Random Fields* (Springer-Verlag, 1989).
- Z. M. Zhang, *Nano/Microscale Heat Transfer*, 2nd ed., Mechanical Engineering Series (Springer International Publishing, 2020).
- L. P. Wang, S. Basu, and Z. M. Zhang, "Direct and indirect methods for calculating thermal emission from layered structures with nonuniform temperatures," J. Heat Transf. **133**, (2011).
- M. Francoeur, M. Pinar Mengüç, and R. Vaillon, "Solution of near-field thermal radiation in one-dimensional layered media using dyadic Green's functions and the scattering matrix method," J. Quant. Spectrosc. Radiat. Transf. **110**, 2002–2018 (2009)
- J.-J. Greffet, R. Carminati, K. Joulain, J.-P. Mulet, S. Mainguy, and Y. Chen, "Coherent emission of light by thermal sources," Nature **416**, 61–64 (2002)



Maxwell equations

$$rotE = j\omega\mu H + \boldsymbol{M[T(\vec{\rho},\omega)]} \qquad rotH = -j\omega\varepsilon E + \boldsymbol{J[T(\vec{\rho},\omega)]}$$

How to get the currents « thermal currents » (M , J) ?

S. M. Rytov, Yu. A. Kravtsov, and V. I. Tatarskii, *Principles of Statistical Radiophysics 3: Elements of Random Fields* (Springer-Verlag, 1989)

Fluctuation Dissipation Theorem (statistical physics)

$$\langle [x_0(t) - \bar{x}_0]^2 \rangle \ll 1 \Rightarrow x_0(t) \approx \bar{x}_0$$

$$\begin{cases} \mathcal{H}(x) = \mathcal{H}_0(x) - x f(t) \\ \langle x(t) \rangle = \bar{x}_0 + G *_t f \end{cases} \Rightarrow \begin{cases} \langle |\breve{x}(\omega)|^2 \rangle = \left(\frac{1}{\pi\omega}\right) \Theta(\omega, T)\, Im[\breve{G}(\omega)] \\ \Theta(\omega, T) = \frac{\hbar\omega}{e^{\frac{\hbar\omega}{k_B T}} - 1} \end{cases}$$

Application to the matter polarizations

$$E \longrightarrow \boxed{P_e = \varepsilon_0 \chi_e *_t E} \qquad H \longrightarrow \boxed{P_h = \chi_h *_t H}$$

$$\begin{cases} \langle P_e(t, \vec{\rho}) \rangle = \varepsilon_0\, \chi_e(t, \vec{\rho}) *_t E_0(t, \vec{\rho}) \\ \langle P_h(t, \vec{\rho}) \rangle = \chi_h(t, \vec{\rho}) *_t H_0(t, \vec{\rho}) \\ \delta W_e = -P_e . E_0 \delta V \;\; and \;\; \delta W_h = -\mu_0 P_h . H_0 \delta V \end{cases} \Rightarrow \begin{cases} \langle |\breve{P}_e(\omega, \vec{\rho})|^2 \rangle \delta V = \left(\frac{1}{\pi\omega}\right) \Theta(\omega, T(\vec{\rho}))\, Im[\breve{\varepsilon}(\omega, \vec{\rho})] \\ \langle |\breve{P}_h(\omega, \vec{\rho})|^2 \rangle \delta V = \frac{1}{\mu_0^2} \left(\frac{1}{\pi\omega}\right) \Theta(\omega, T(\vec{\rho}))\, Im[\breve{\mu}(\omega, \vec{\rho})] \end{cases}$$

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

*P. Rouquette, C. Amra, M. Zerrad, C. Grèzes-Besset, and H. Krol, "Photo-induced thermal radiation of optical interference coatings submitted to a spatio-temporal illumination," Opt. Express **31**, 35431-35452 (2023)*

The thermal currents are known

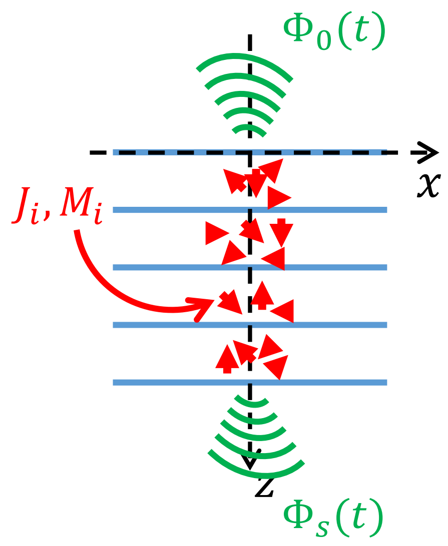
$$\theta(\omega,T) = \hbar\,\omega/(e^{\frac{\hbar\omega}{k_B T}}-1)$$

$$<|\tilde{J}(\omega)|^2> = \left(\frac{\omega}{\pi}\right)\theta(\omega,T)\,Im[\tilde{\varepsilon}(\omega)] \qquad <|\tilde{M}(\omega)|^2> = \left(\frac{\omega}{\pi}\right)\theta(\omega,T)\,Im[\tilde{\mu}(\omega)]$$

⇩

Similar to a luminescent microcavity (Optics)

$$rotE = j\omega\mu H + M[T(\vec{\rho},\omega)] \qquad rotH = -j\omega\varepsilon E + J[T(\vec{\rho},\omega)]$$



- *Each bulk is a source of thermal radiation*
- *All fields must be summed up:* $E_j = \sum_i^p E_{ij}$

⇩

$$\textbf{By reflection}: \quad \frac{\partial\Phi_0}{\partial f\,\partial\vec{v}\,dS} = 2\sum_{i=1}^{p} 4\pi f\,\tilde{\varepsilon}_i''\,\Re\{\tilde{n}_0\}\left|C'_{0,i-1}\right|^2 \frac{\beta_i^0(\nu,f)}{4|\tilde{n}_i|^2|\Delta Y_{i-1}|^2}\,\Theta\big(2\pi f, T_i(\vec{r},z_i)\big)$$

$$\textbf{By transmission}: \quad \frac{\partial\Phi_s}{\partial f\,\partial\vec{v}\,dS} = 2\sum_{i=1}^{p} 4\pi f\,\tilde{\varepsilon}_i''\,\Re\{\tilde{n}_s\}\left|C_{i,p}\right|^2 \frac{\beta_i^s(\nu,f)}{4|\tilde{n}_i|^2|\Delta Y_i|^2}\,\Theta\big(2\pi f, T_i(\vec{r},z_i)\big)$$

Claude Amra, Michel Lequime, Myriam Zerrad. Electromagnetic Optics of Thin-Film Coatings: Light Scattering, Giant Field Enhancement, and Planar Microcavities. Cambridge University Press, 2020, 9781108772372.

17

Physical quantities: static versus photo-induced

Double flux density: $$\frac{\partial \Phi}{\partial f \partial \vec{v}} = \sum_{i=1}^{q} L_i'(f,\nu)\left\{\int_{\vec{r}} \Theta\big(2\pi f, T_i(\vec{r}, z_i)\big) d\vec{r}\right\}$$ $$with \;\; \theta(\omega,T) = \bar{h}\,\omega/(e^{\frac{\bar{h}\omega}{k_B T}} - 1)$$

⇩

Per unit of wavelength and solid angle

$$\frac{\partial \Phi_u}{\partial \lambda \partial \Omega_u}$$

⇨

Radiative spectral intensity

(normalization by the « thermal » surface)

$$\frac{\partial \Phi}{\partial \lambda \partial \Omega_u \partial S}$$

Photo-induced Tp ←

Uniform Tp →

⇩

Angle-Resolved Thermal Radiation

(similar to angle-resolved scattering or $BRDF.\cos\theta$)

$$\frac{\partial \Phi_u}{\Phi_0^+ \partial \lambda \partial \Omega_u}$$

⇩

Emissivity

(normalization by black body radiation)

$$\epsilon_i(\lambda,\theta) = \frac{1}{I_b(\lambda,T_i)} \frac{\partial \Phi}{\partial \lambda \partial \Omega_u \partial S}$$

$$I_b(\lambda,T) = 2\frac{k_0^2}{4\pi^2}\frac{c}{\lambda^2}\Theta\left(\frac{2\pi c}{\lambda}, T\right)$$

unique Tp

Tp distribution

Blackbody radiation: $I_b(\lambda,T) = 2\frac{k_0^2}{4\pi^2}\frac{c}{\lambda^2}\Theta\left(\frac{2\pi c}{\lambda},\boldsymbol{T}\right)$

Coating radiation: $\frac{\partial\Phi}{\partial f\partial\vec{v}} = \sum_{i=1}^{q} L_i'(f,\nu)\left\{\int_{\vec{r}}\Theta(2\pi f,\boldsymbol{T_i(\vec{r},z_i)})d\vec{r}\right\}$

$\Longrightarrow$ *Emissivity depends on both optical and thermal parameters*

$\boldsymbol{\varepsilon_i(\lambda,\theta) \neq A_i(\lambda,\theta)}$ (short pulse regime)

Case of uniform temperature

$$\frac{\partial\Phi}{\partial f\partial\vec{v}} = \sum_{i=1}^{q} L_i'(f,\nu)\left\{\int_{\vec{r}}\Theta(2\pi f,T_i(\vec{r},z_i))d\vec{r}\right\} \approx \left\{\int_{\vec{r}}\Theta(2\pi f,T)d\vec{r}\right\}\sum_{i=1}^{q} L_i'(f,\nu)$$

Emissivity identifies to absorption:

$\boldsymbol{\varepsilon_i(\lambda,\theta) = A_i(\lambda,\theta)}$ (long pulse regime)

Not the case for the ns regime, not suitable for the trapped light

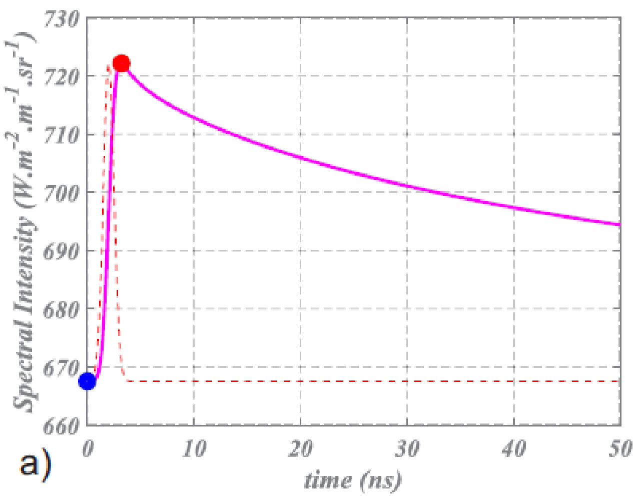
*P. Rouquette, C. Amra, M. Zerrad, C. Grèzes-Besset, and H. Krol, "Photo-induced thermal radiation of optical interference coatings submitted to a spatio-temporal illumination," Opt. Express **31**, 35431-35452 (2023)*

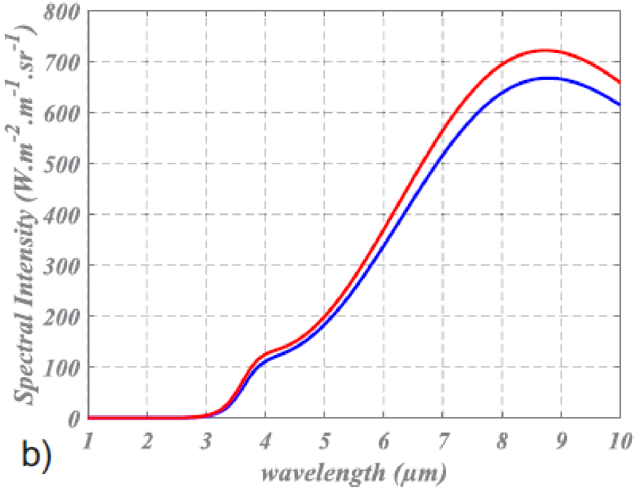
Variation versus time, wavelength and direction

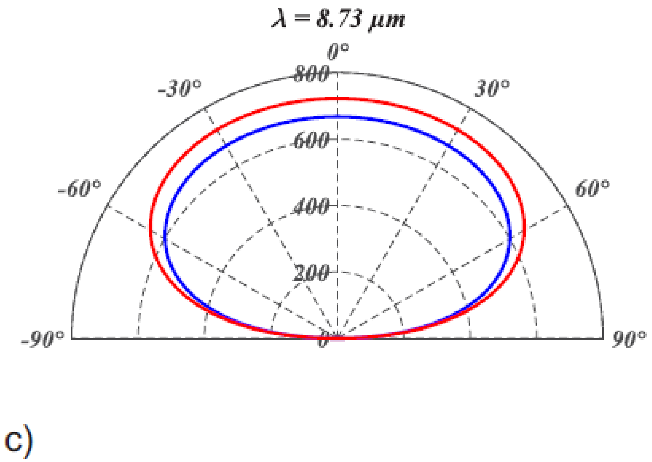
QW@2$\mu m, L = B_aF_2, H = G_e,$

$on\ G_e substrate, n'' = 10^{-4}$

$1mJ, 1ns, i = 0°$



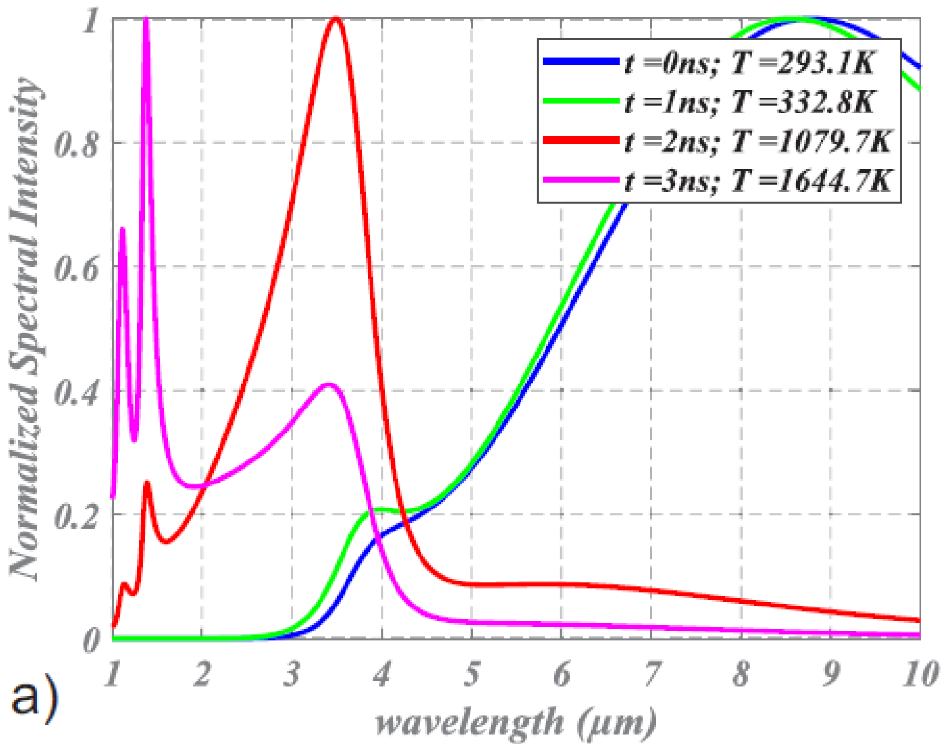




Slight temperature increase ⟺ slight modification of blackbody radiation

Variation with incident energy (or temperature)

(damage non considered)



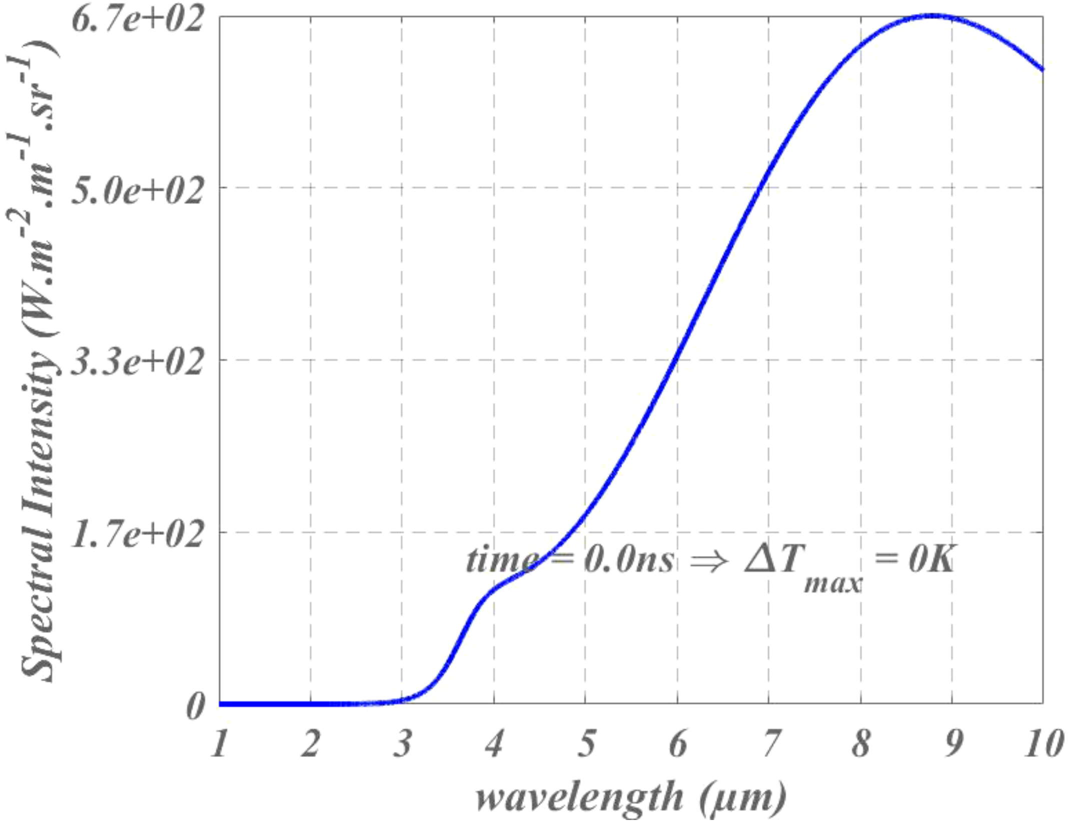
a)

At short wavelengths,

the coating filters its own radiation

Blackbody modification at short wavelengths = interaction with the multilayer

Real-time illustration



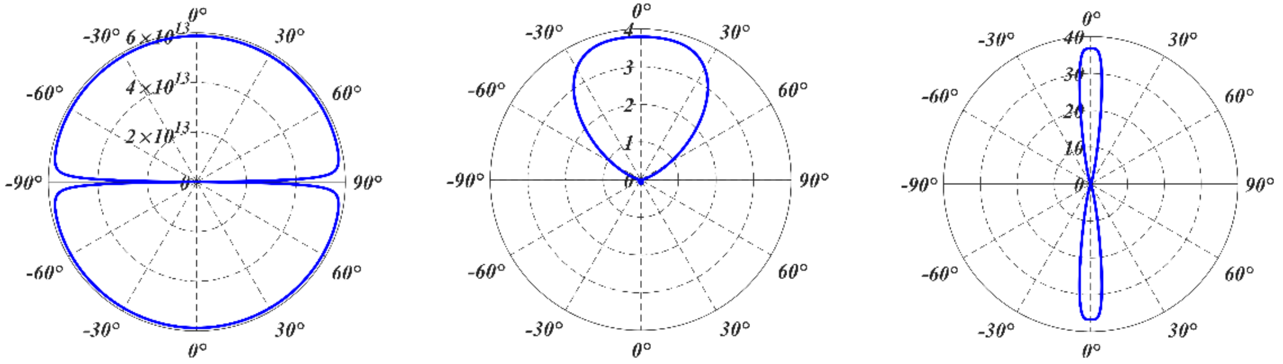
$QW@2\mu m, L = B_aF_2, H = G_e,$

$on\ G_e substrate, n'' = 10^{-4}$

$1mJ, 1ns, i = 0°$

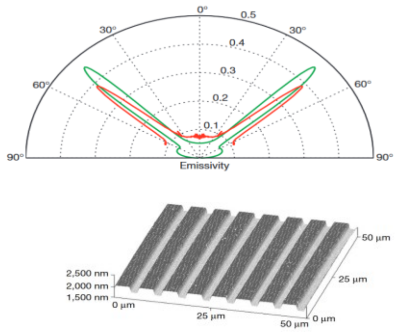
P. Rouquette, C. Amra, M. Zerrad, C. Grèzes-Besset, and H. Krol, "Photo-induced thermal radiation of optical interference coatings submitted to a spatio-temporal illumination," Opt. Express ***31****, 35431-35452 (2023)*

Shaping thermal radiation with multilayers?

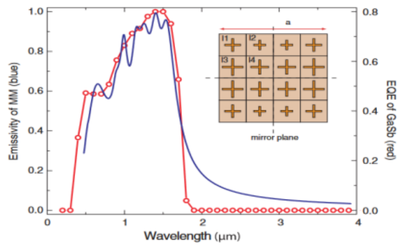


C. Amra, M. Lequime, M. Zerrad, «Electromagnetic Optics of Thin Film Coatings : Light Scattering, Giant Field Enhancement, and Planar Microcavities », Cambridge University Press, 2020, 9781108772372

Gratings and metasurfaces were already used to produce **narrow-band emissivity enhancement**

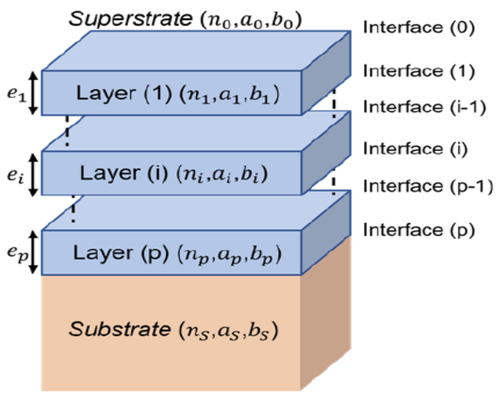


J.-J. Greffet, R. Carminati, K. Joulain, J.-P. Mulet, S. Mainguy, and Y. Chen, "Coherent emission of light by thermal sources," Nature **416**, 61–64 (2002).



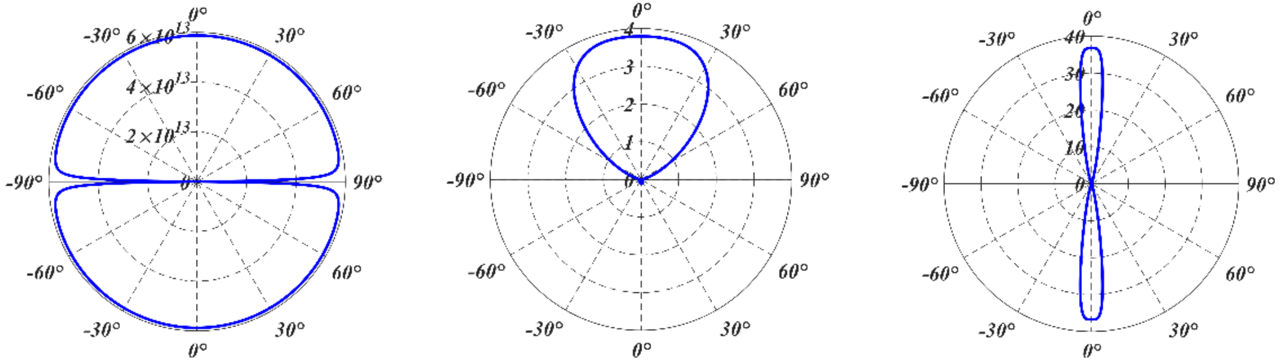
X. Liu, T. Tyler, T. Starr, A. F. Starr, N. M. Jokerst, and W. J. Padilla, "Taming the Blackbody with Infrared Metamaterials as Selective Thermal Emitters," Phys. Rev. Lett. **107**, 045901 (2011).

? ⟹



Multidielectrics are known to offer a large number of degrees of freedom

Retour aux techniques de microcavités luminescentes



$$\frac{\partial \Phi_0}{\partial f \partial \vec{v} dS} = 2\sum_{i=1}^{p} 4\pi f \tilde{\varepsilon}_i'' \Re\{\tilde{n}_0\} \left|C'_{0,i-1}\right|^2 \frac{\beta_i^0(\nu, f)}{4|\tilde{n}_i|^2 |\Delta Y_{i-1}|^2} \Theta\left(2\pi f, T_i(\vec{r}, z_i)\right)$$

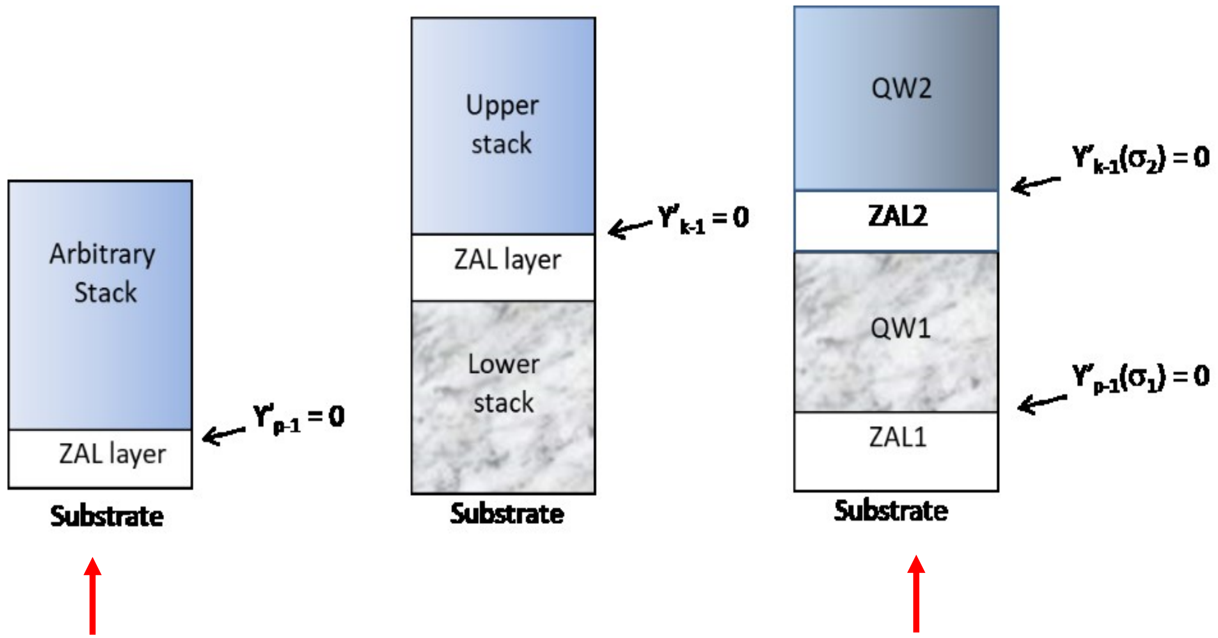
$$\frac{\partial \Phi_s}{\partial f \partial \vec{v} dS} = 2\sum_{i=1}^{p} 4\pi f \tilde{\varepsilon}_i'' \Re\{\tilde{n}_s\} \left|C_{i,p}\right|^2 \frac{\beta_i^s(\nu, f)}{4|\tilde{n}_i|^2 |\Delta Y_i|^2} \Theta\left(2\pi f, T_i(\vec{r}, z_i)\right)$$

La différence d'admittance ΔY_i est le paramètre clé qui régit les exaltations/inhibitions

Recherche d'une exaltation « géante » de l'émissivité

Exaltation à la fréquence $\nu_m \Leftrightarrow \Delta Y(\nu_m) = 0$

Pas de solution en espace libre $\Longrightarrow$ régime TIR dans un milieu $\Longrightarrow$ couche d'admittance nulle (ZAL)



Exaltation à une fréquence prédéfinie

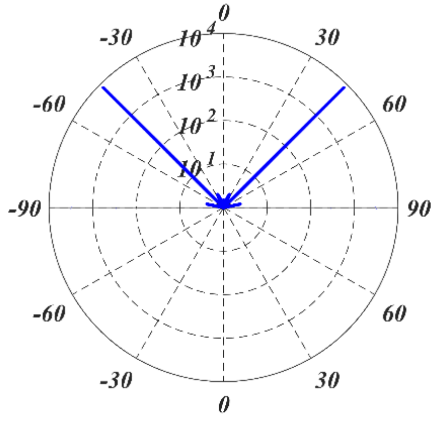
Exaltation à deux fréquences prédéfinies

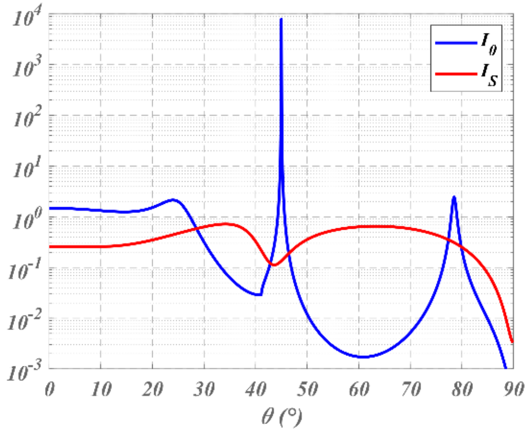
Claude Amra, Myriam Zerrad, Fabien Lemarchand, Aude Lereu, Ali Passian, et al.. Energy density engineering via zero-admittance domains in all-dielectric stratified materials. Physical Review A, American Physical Society, 2018, 97 (2)

Résultats numériques avec des structures ZAL

Exaltations de plusieurs décades à une fréquence et polarisation imposées

TE, 45°, 633nm



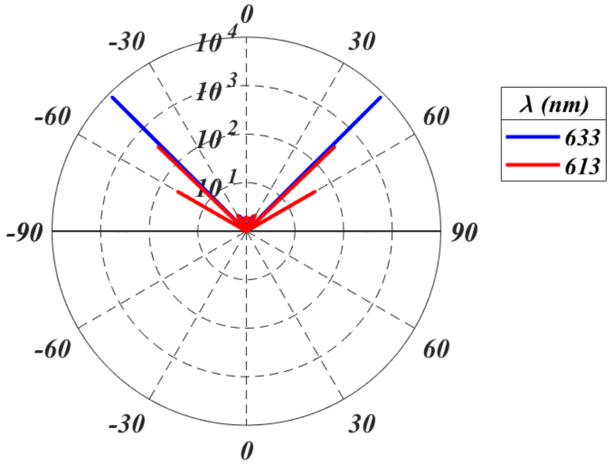


TE, 45°, 633nm

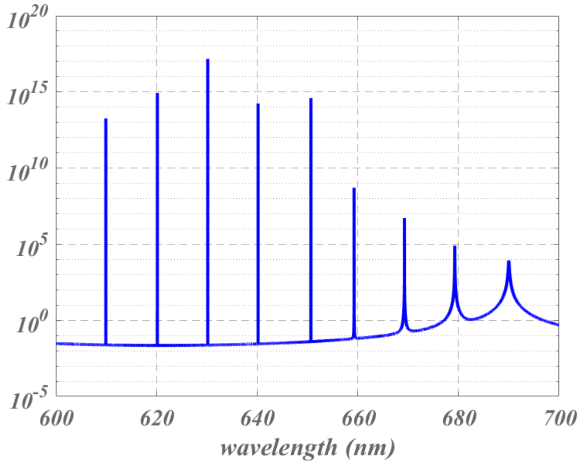
À des angles différents

633nm, 45°

613nm, 35°

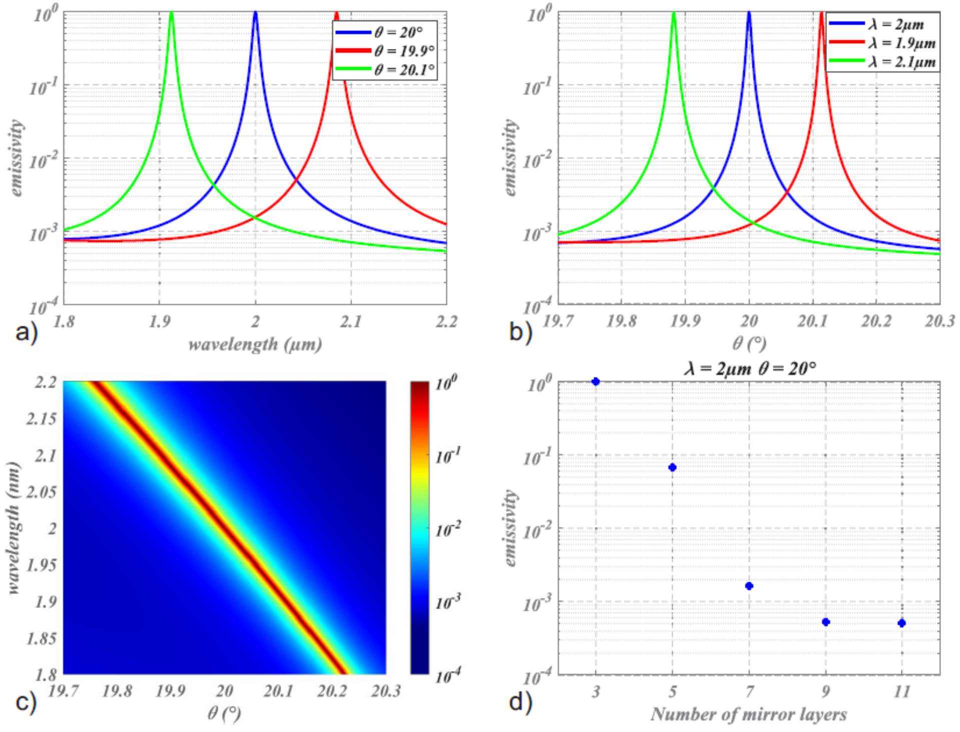


À plusieurs longueurs d'onde



*Paul Rouquette, Claude Amra, Myriam Zerrad, and Michel Lequime, "Micro-cavity optimization for ultra-sensitive all-dielectric optical sensors," Opt. Express **30**, 15344-15364 (2022)*

Application au rayonnement thermique



$Miroir\ multidiélectrique@2\mu m,$

$direction\ 20°, polarisation\ TE, n'' = 10^{-4}$

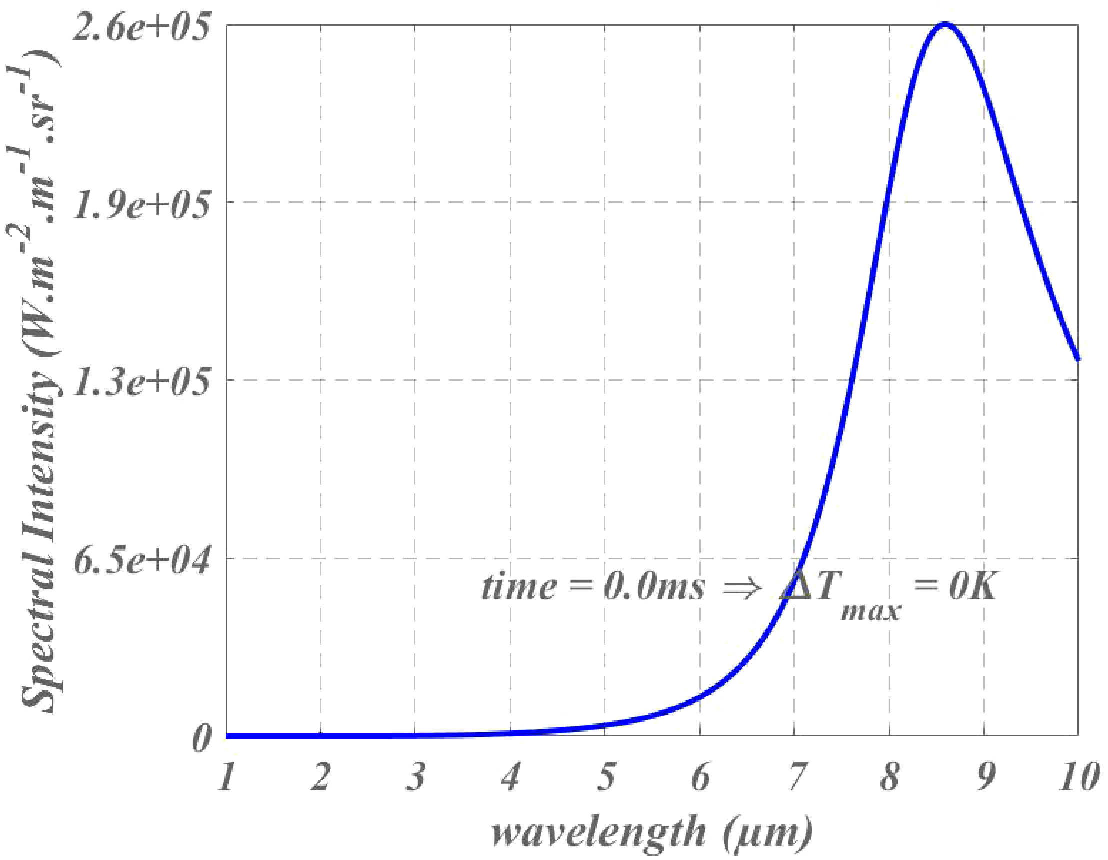
$\boldsymbol{\theta = f(\lambda)}$

Malgré un indice imaginaire de 10^{-4}, on peut imposer une **« émissivité bande étroite proche de 1 »**

dans des fenêtres spectrales ou angulaires **prédéfinies**

P. Rouquette, C. Amra, M. Zerrad, C. Grèzes-Besset, and H. Krol, "Photo-induced thermal radiation of optical interference coatings submitted to a spatio-temporal illumination," Opt. Express ***31****, 35431-35452 (2023)*

Real-time illustration



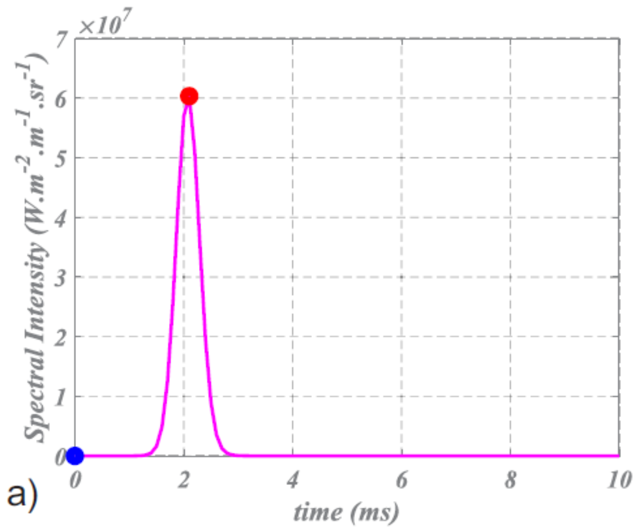
QW@$2\mu m, L = B_aF_2, H = G_e,$

$on\ G_e substrate, n'' = 10^{-4}$

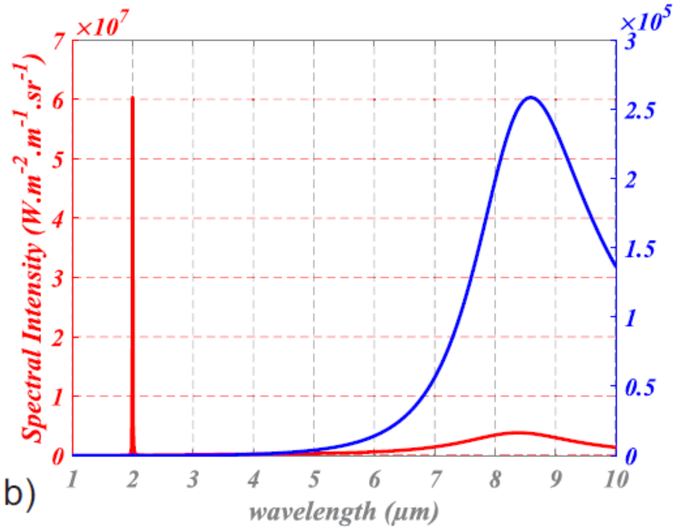
$1mJ, 1ms, 20°$, TE

*P. Rouquette, C. Amra, M. Zerrad, C. Grèzes-Besset, and H. Krol, "Photo-induced thermal radiation of optical interference coatings submitted to a spatio-temporal illumination," Opt. Express **31**, 35431-35452 (2023)*

ThR @$2\mu m, direction\ 20°$



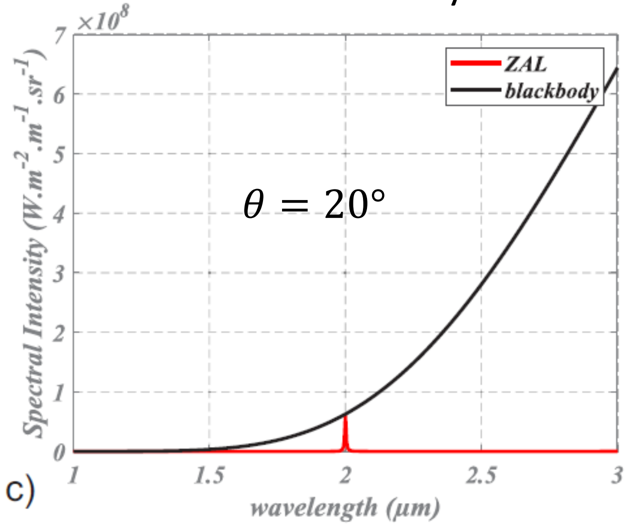
ThR at different times



Blue: 0K (0ms)

Red: 250K (2ms)

Comparison with black body

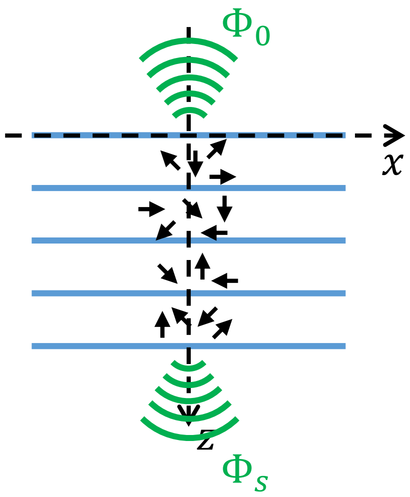


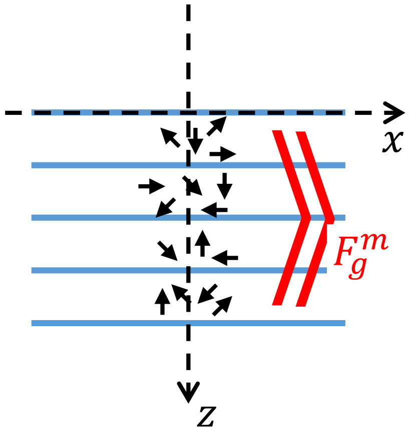
Conclusion partielle

- Pour l’instant: un effort limité pour la conception/réalisation d’étalons
- Ok en régime statique
- Puissance moindre avec des empilements métal/diélectrique
- Contrôle de Tp

4- Le rayonnement thermique piégé

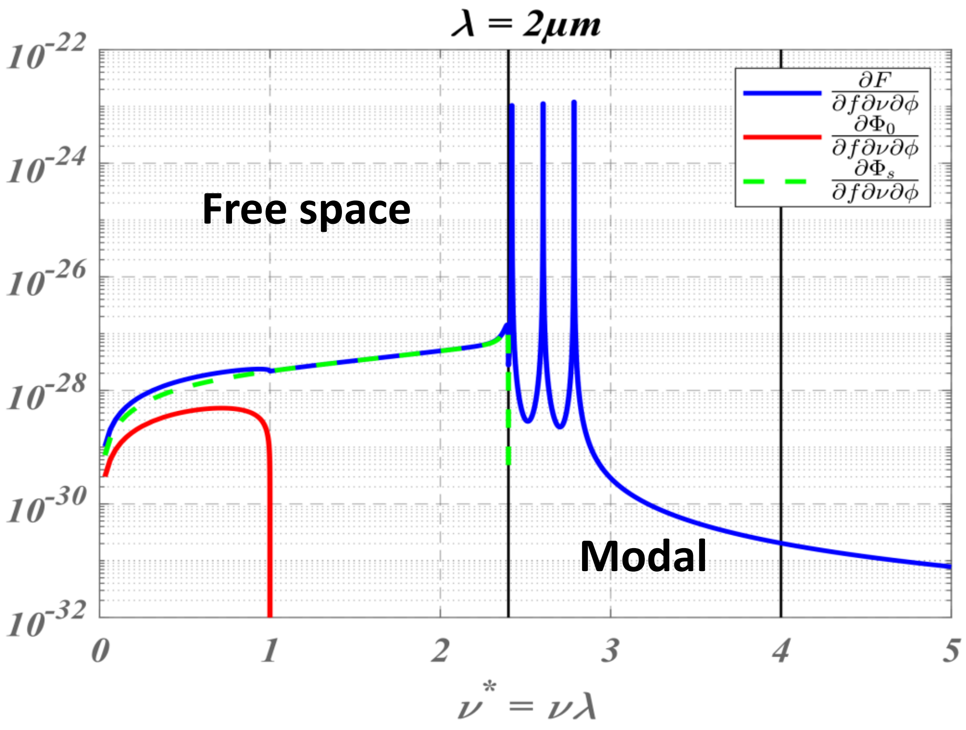
ThR trapped in the form of guided modes in multilayers





How much ThR in this range?

[redacted]



Trapped ThR is higher by a factor 10

P. Rouquette, C. Amra, M. Zerrad, and H. Krol, "Thermal radiation transferred to the guided modes of optical interference coatings," Opt. Express **32**, 12065-12080 (2024)

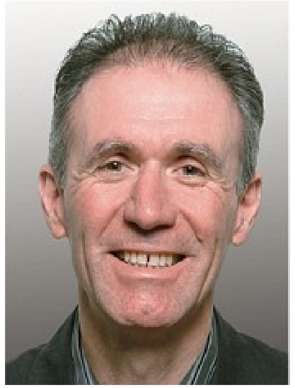
Merci!

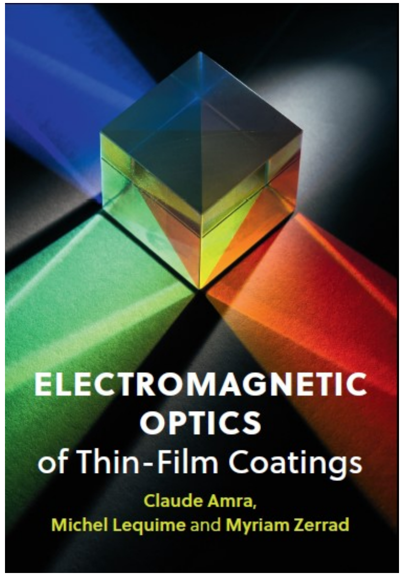
Co-authors

Paul Rouquette
PhD 2019-2022

Myriam Zerrad
Aix Marseille Univ

Michel Lequime,
Ecole Centrale Méditerranée





Gabriel Soriano
Aix Marseille Univ

Hélène Krol
CILAS

François Thullier
PhD 2023-2026

Acknowledgments to CNES & CNRS, Cilas Company and LabTop