# Holographie numérique hétérodyne et thermoreflectance appliquées à des mesures thermiques haute résolution

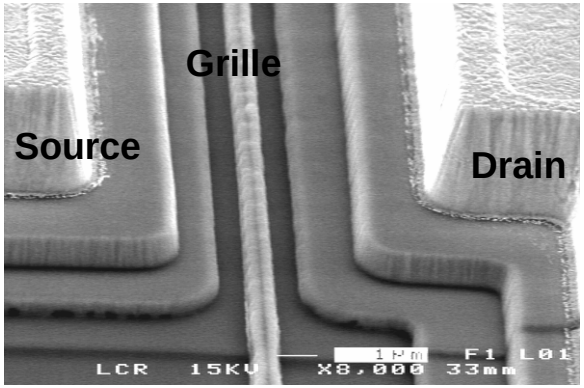
Gilles Tessier – Institut Langevin, UMR 7587, ESPCI
Holographie numérique : Sarah Suck (doctorante), N. Warnasooriya (post doc)
Thermographie résolue en temps : Virginie Moreau (post doctorante)

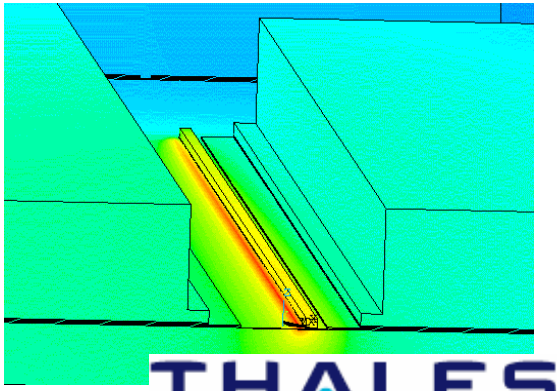
D. Fournier – LPEM, UPRA005, ESPCI
F. Joud, M. Gross, LKB, ENS
P. Bun,M. Coppey-Moisan, Inst. J. Monod

1- Thermoréflectance
résolue en temps
résolue en fréquence
2- Holographie numérique
imagerie de nanoparticules

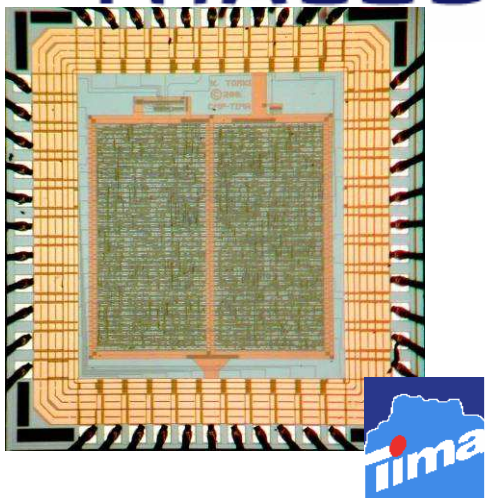
# Quelques problème thermiques en électronique intégrée / optronique

• **<u>Transistors de puissance</u>** :
échauffement dans la zone grille - drain



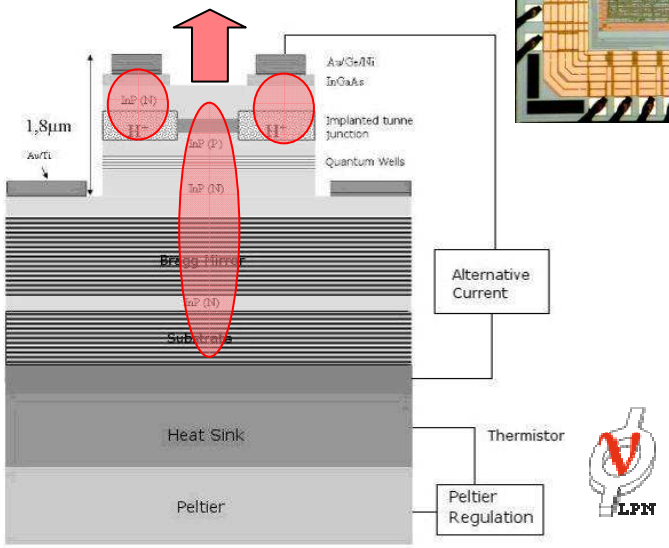
THALES



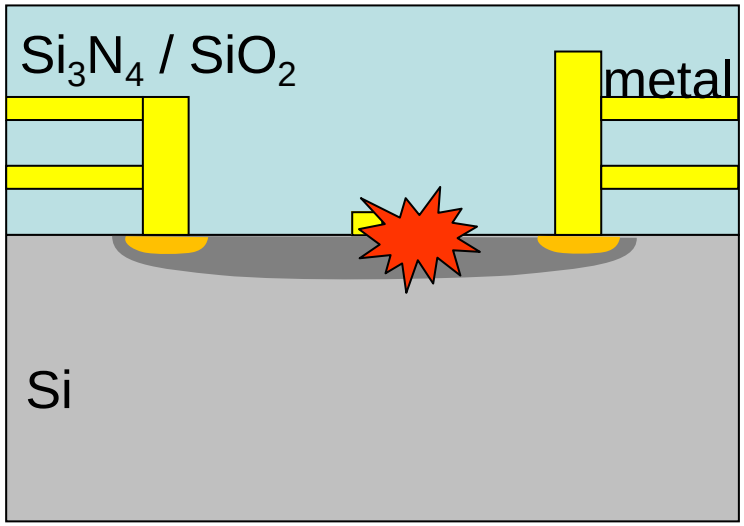
• **<u>MOS</u>** : Courant transitoire lors du basculement

⟹ augmente avec la fréquence

• **<u>Diodes laser</u>** :
- Effet Joule à l'injection
- Absorption du faisceau dans les couches



# Détection de points chauds / imagerie de température
# Dans les circuits intégrés



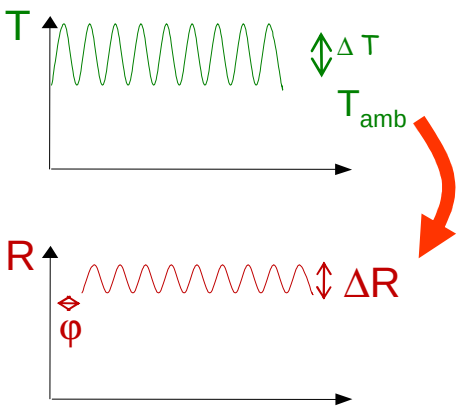

- temperatures élevées
- petites échelles
- Dispositifs 3D

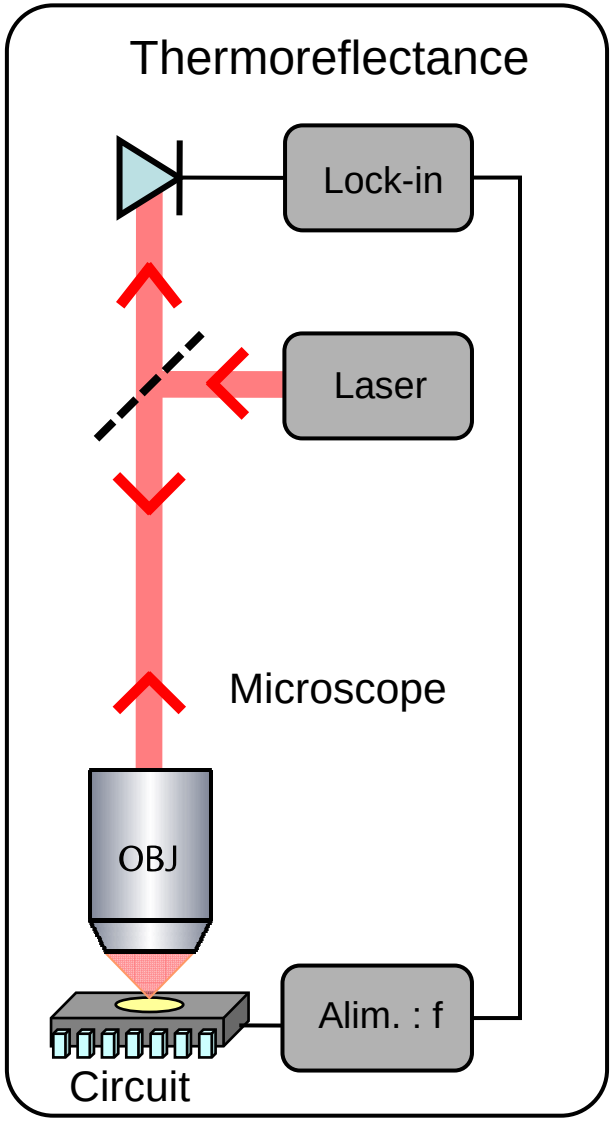
# Photoreflectance ou Thermoreflectance avec une sonde laser

Le coefficient de réflexion d'une surface dépend de sa température :

$$\Delta R = \frac{\partial R}{\partial T} \Delta T$$

$10^{-3}$ à $10^{-5}$

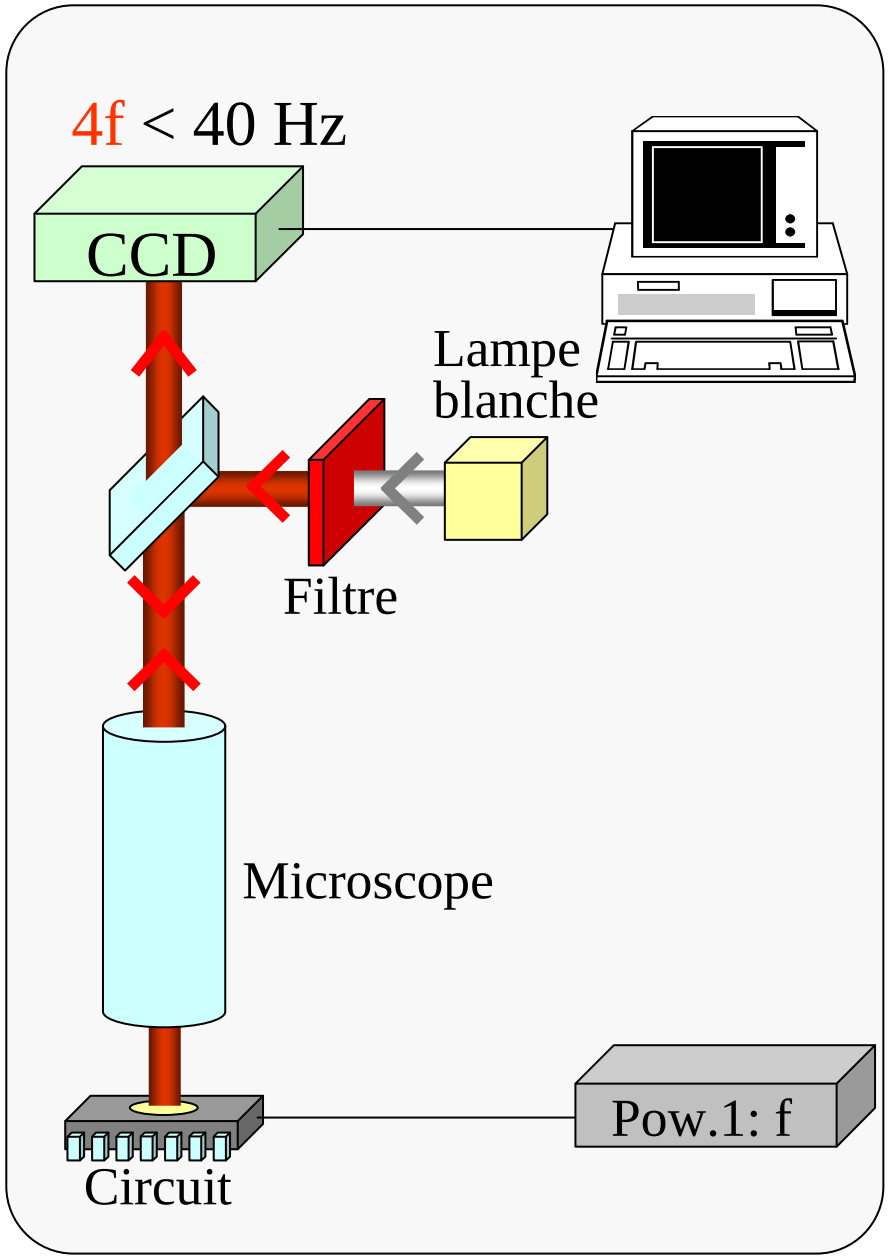


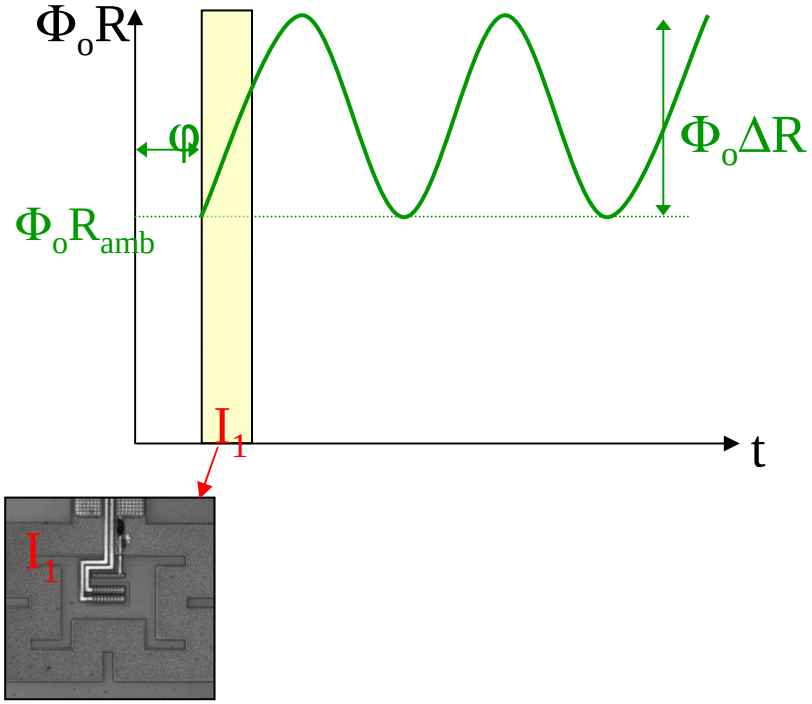




Mesure de ΔR <u>à n'importe quelle longueur d'onde</u>

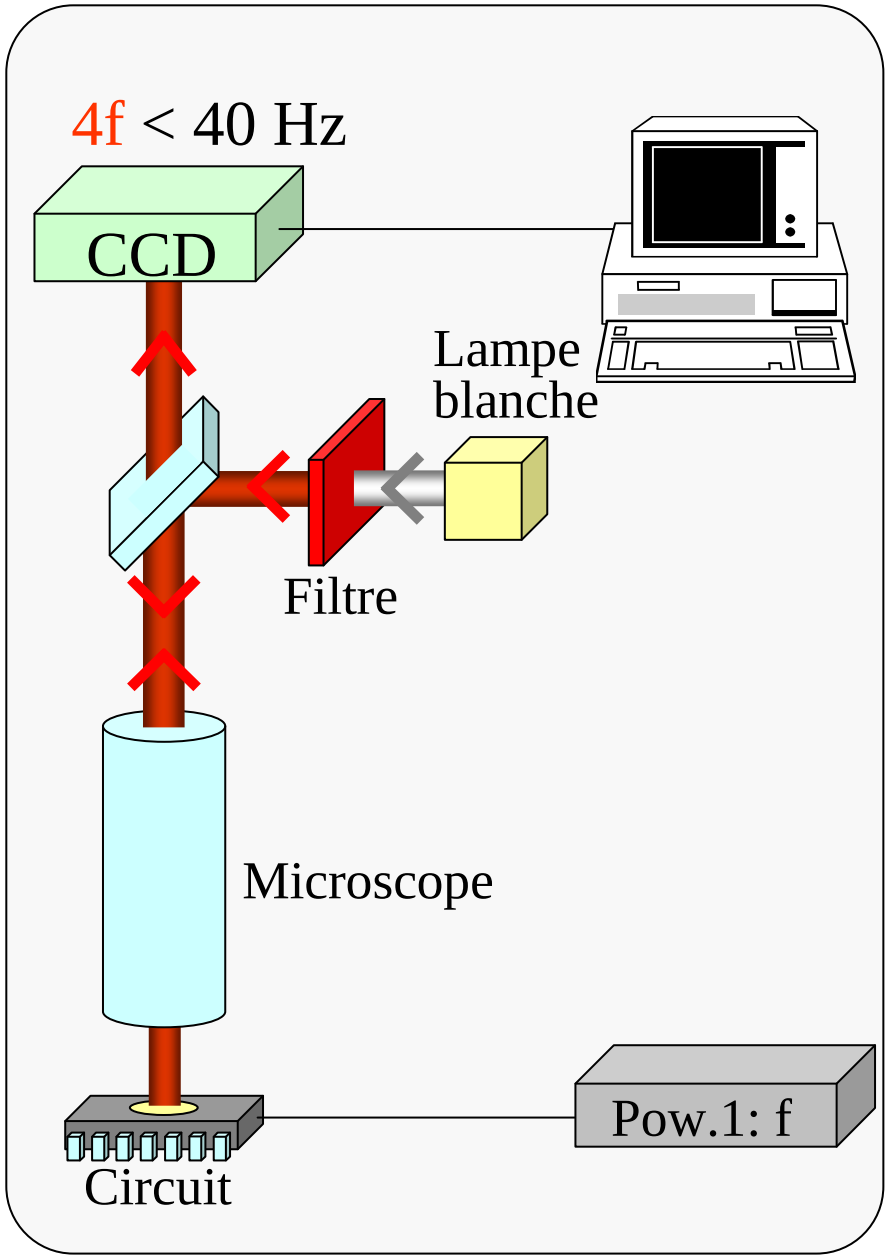
⇒ Variation de temperature ΔT

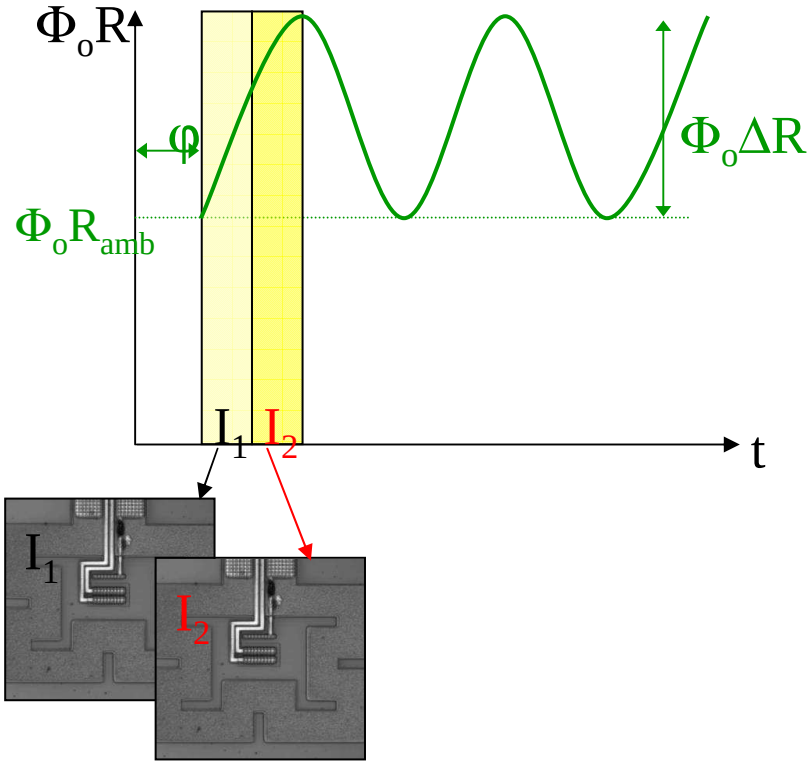
# Imagerie de thermoreflectance CCD



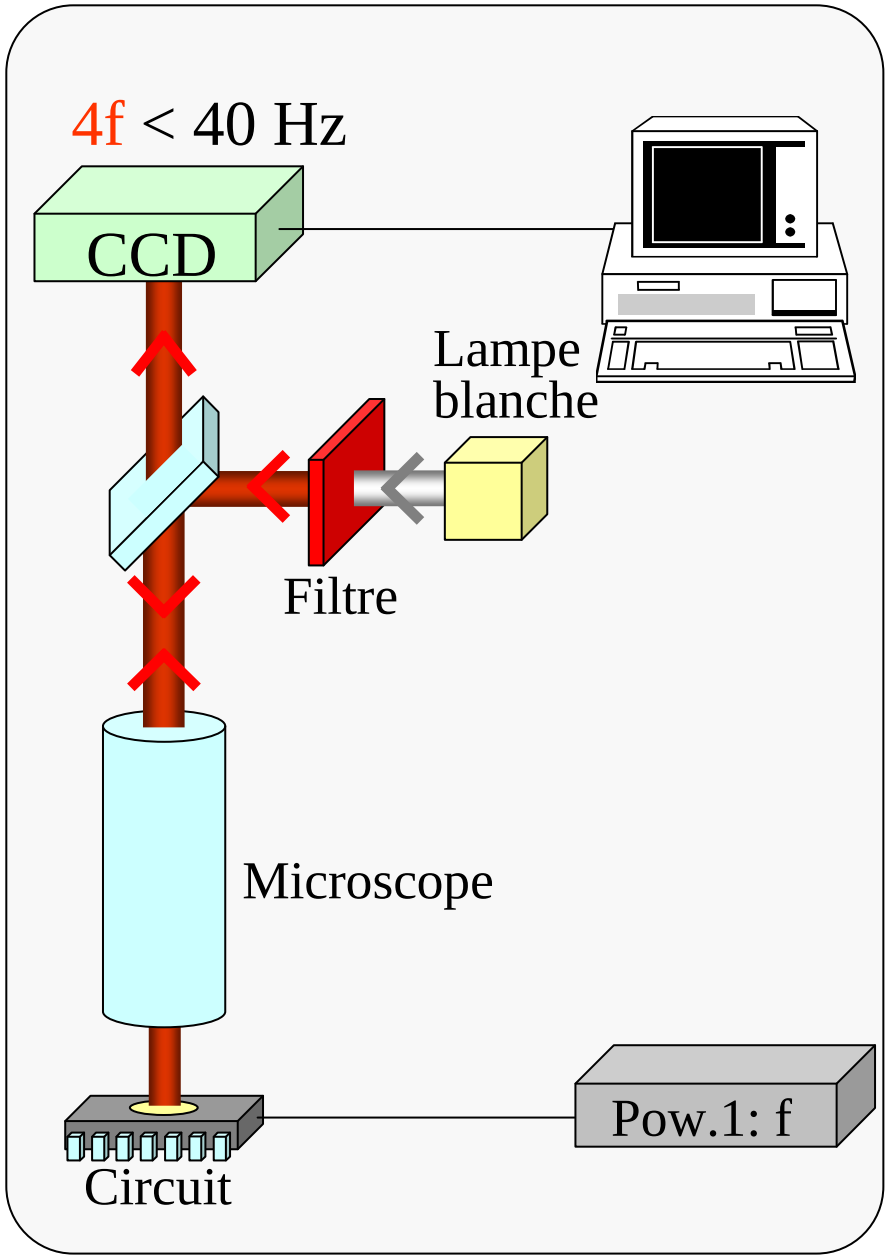



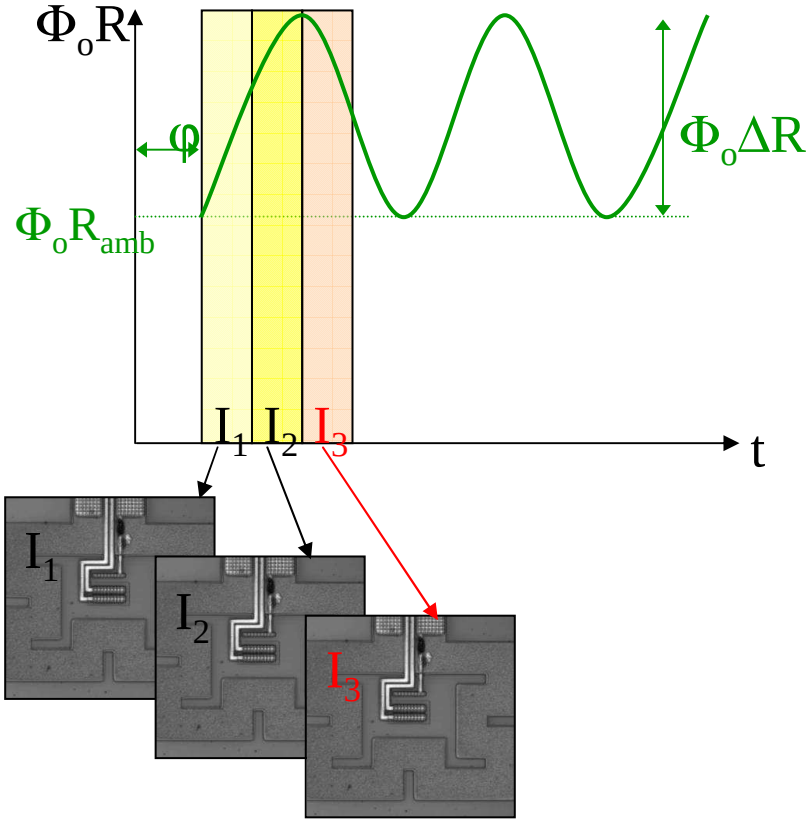
# Imagerie de thermoreflectance CCD



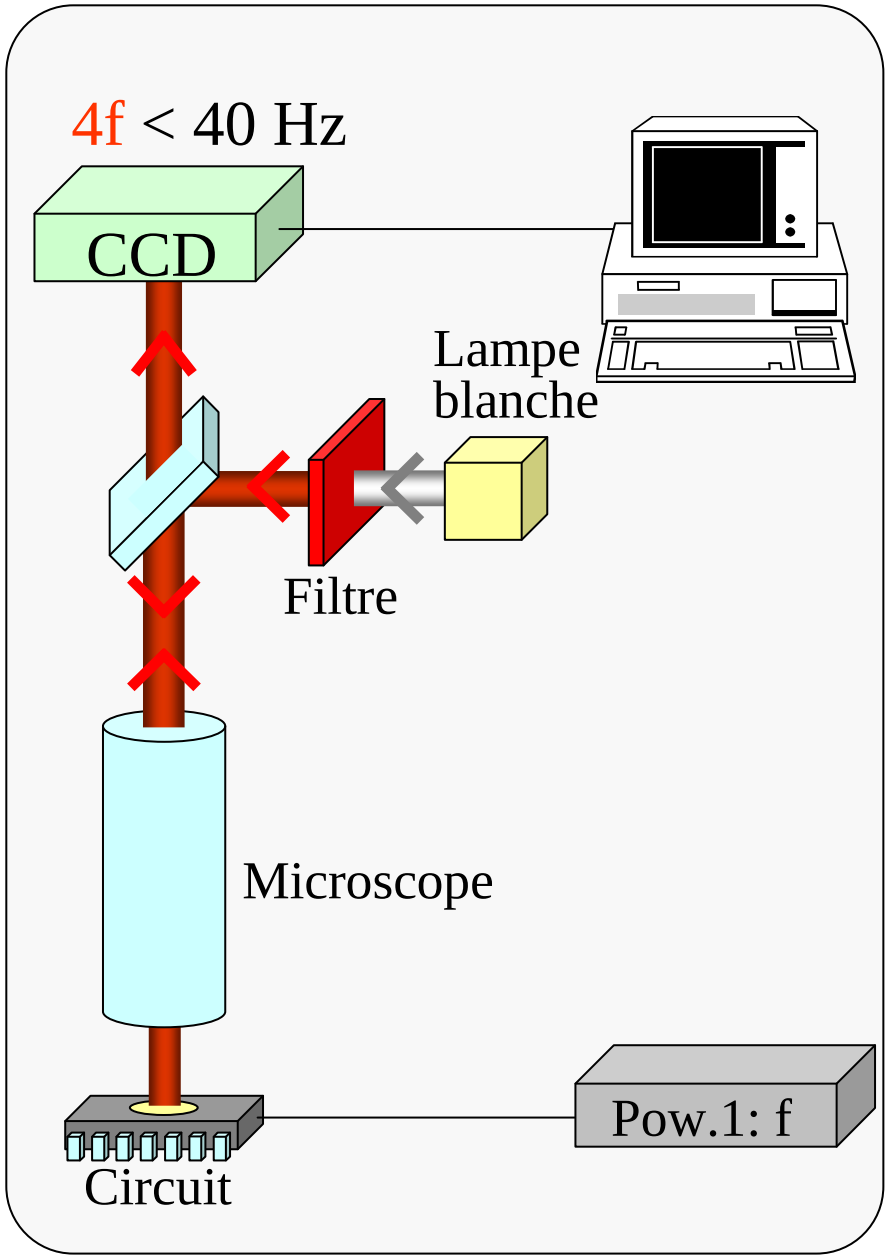



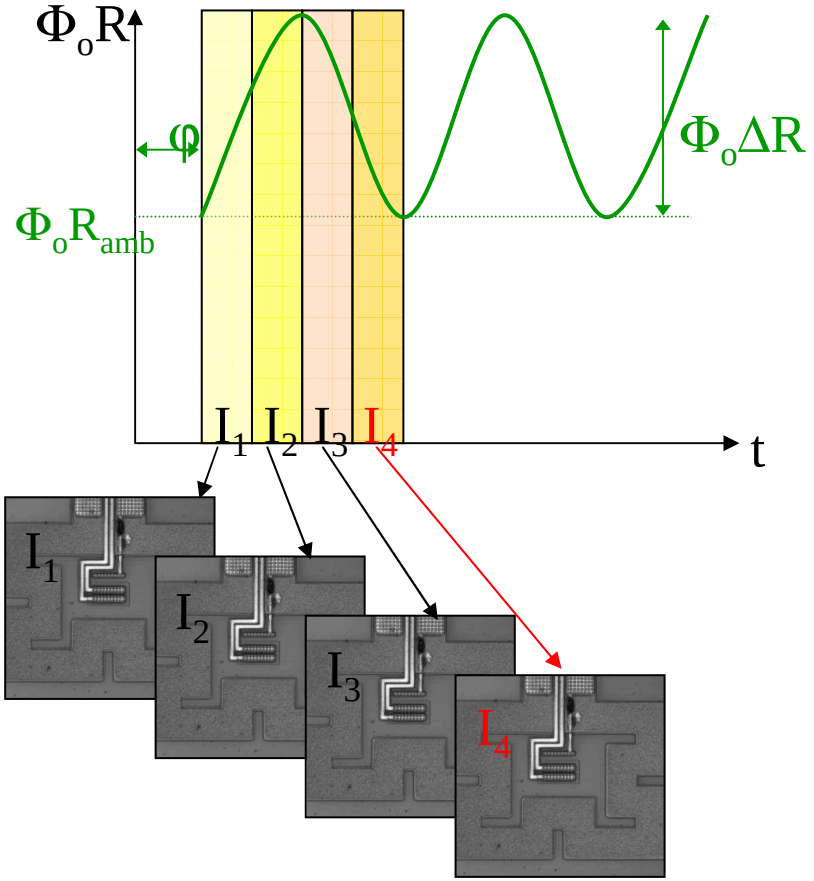
# Imagerie de thermoreflectance CCD



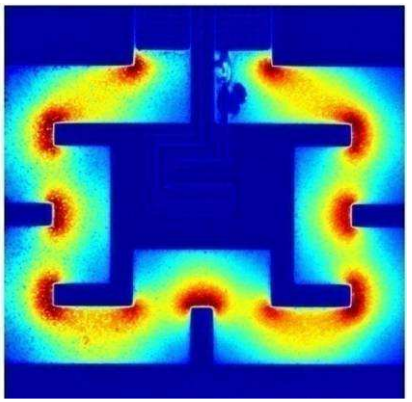
# Imagerie de thermoreflectance CCD



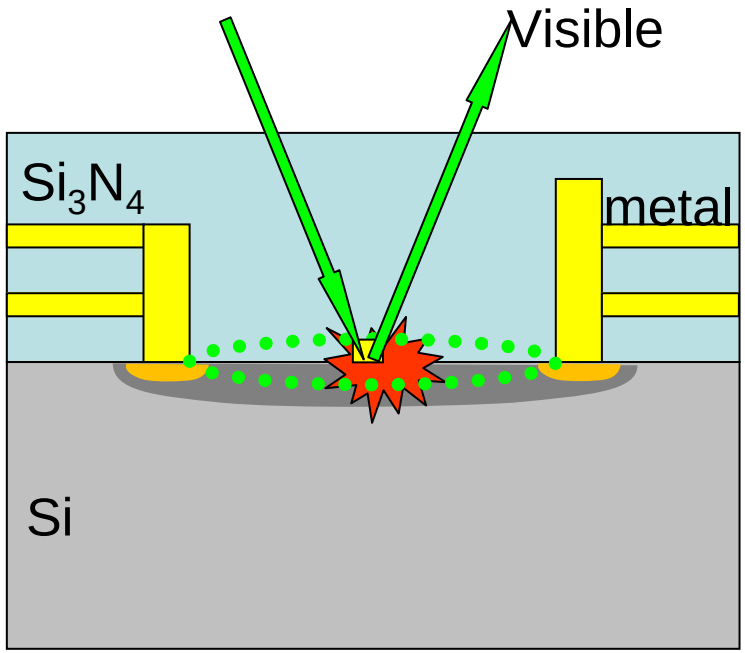

Amplitude (ou phase)

$$|\Phi_0 \Delta R| = \sqrt{\frac{(I_1 - I_3)^2 + (I_2 - I_4)^2}{4}}$$



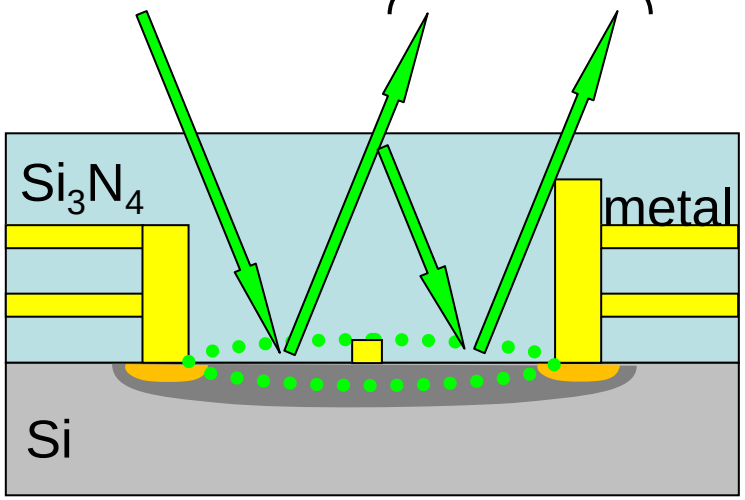
1

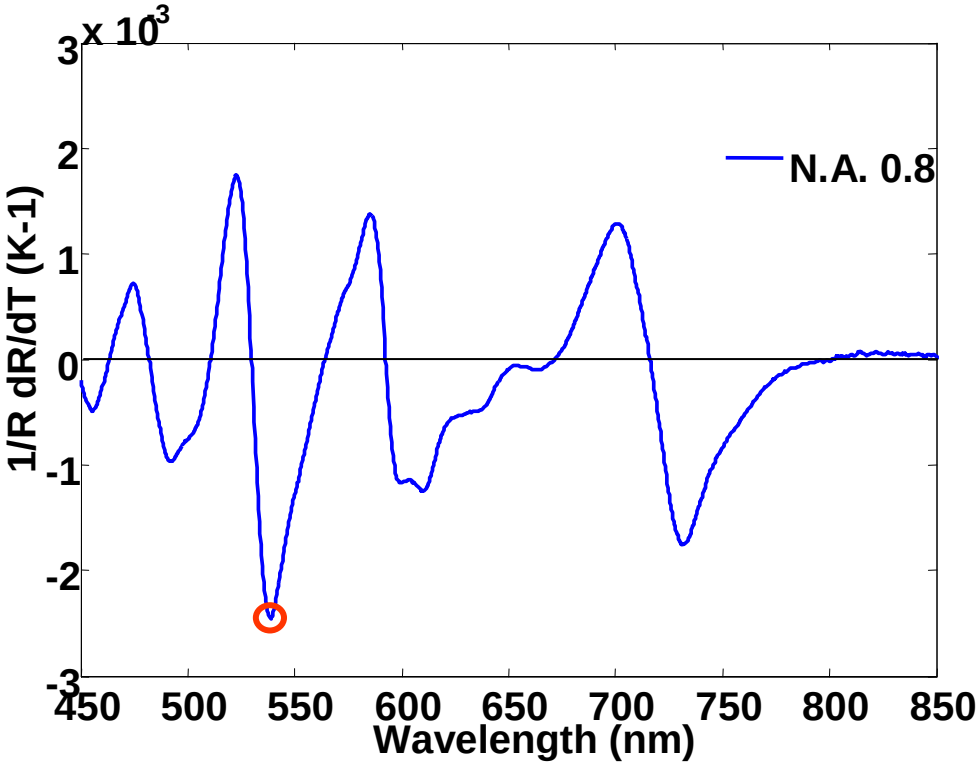
# Thermoreflectance sous illumination visible

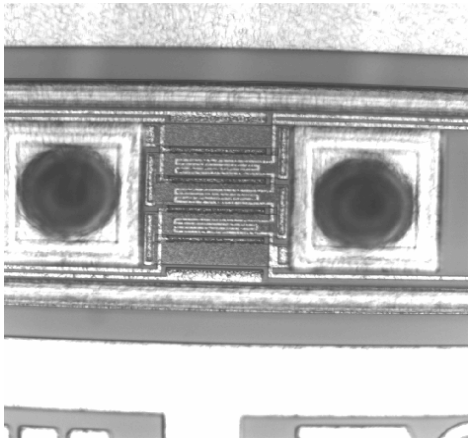


# Interférences et thermoreflectance

interferences ⟹ Variations abrupte de R et $\frac{\partial R}{\partial T}$

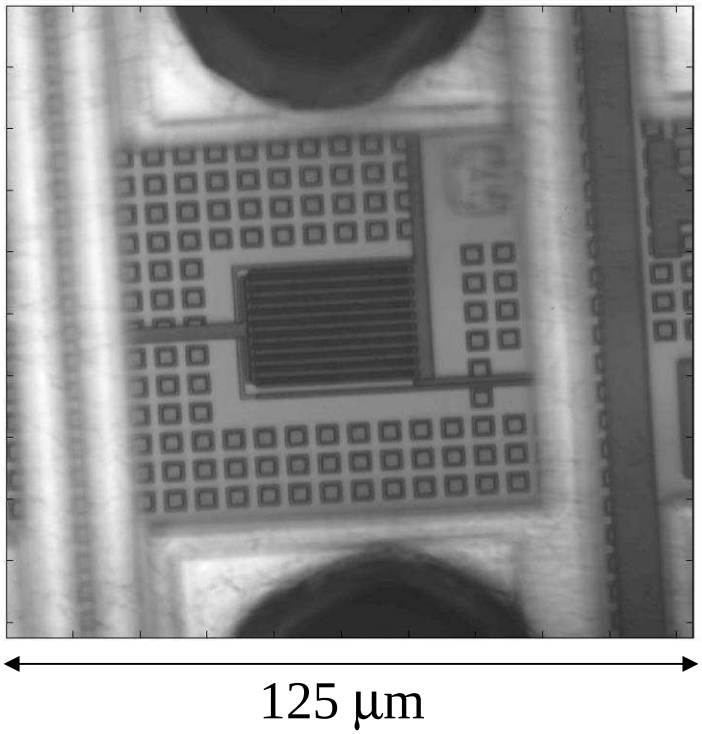


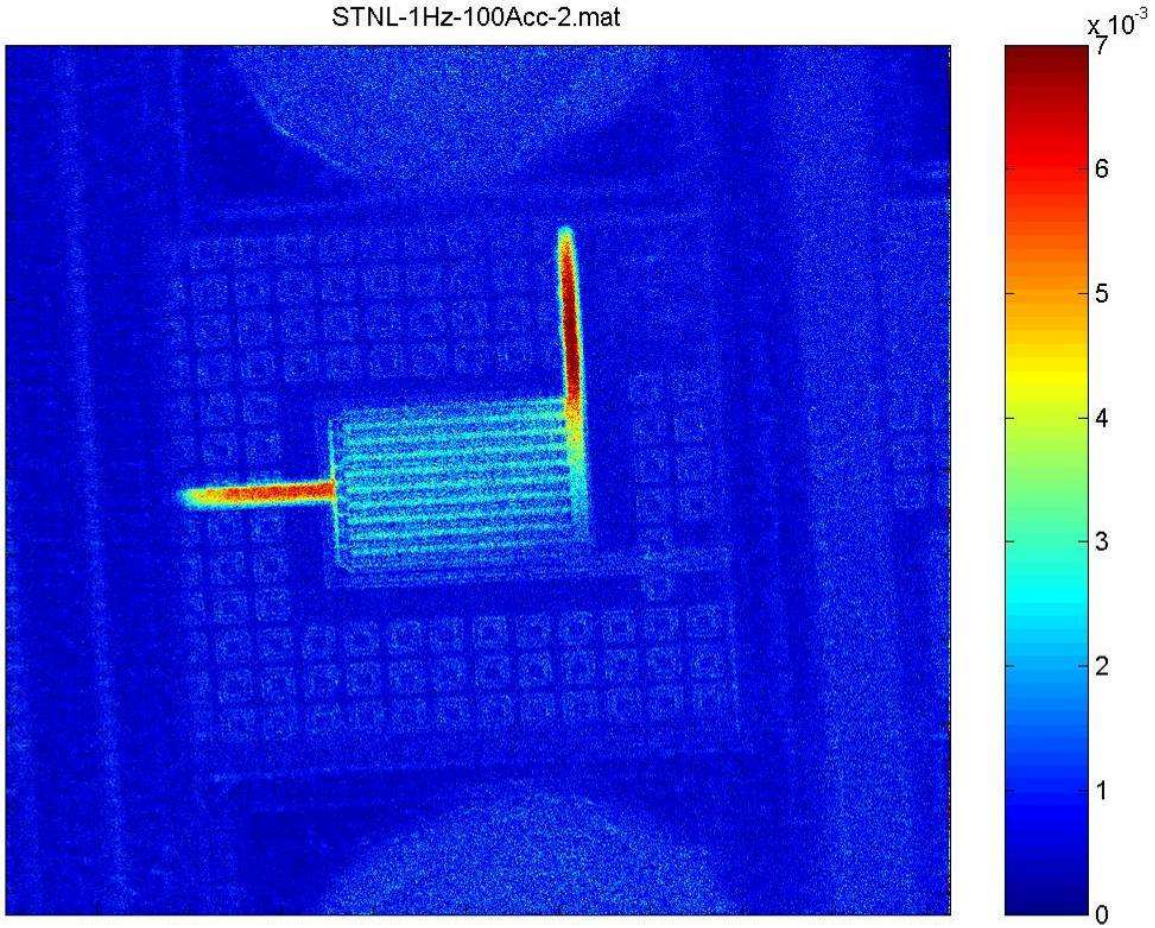



Poly Si resistors / Si3N4 / polyamide
0.12 mW.µm² ΔTsurf.=100℃
1 min integration

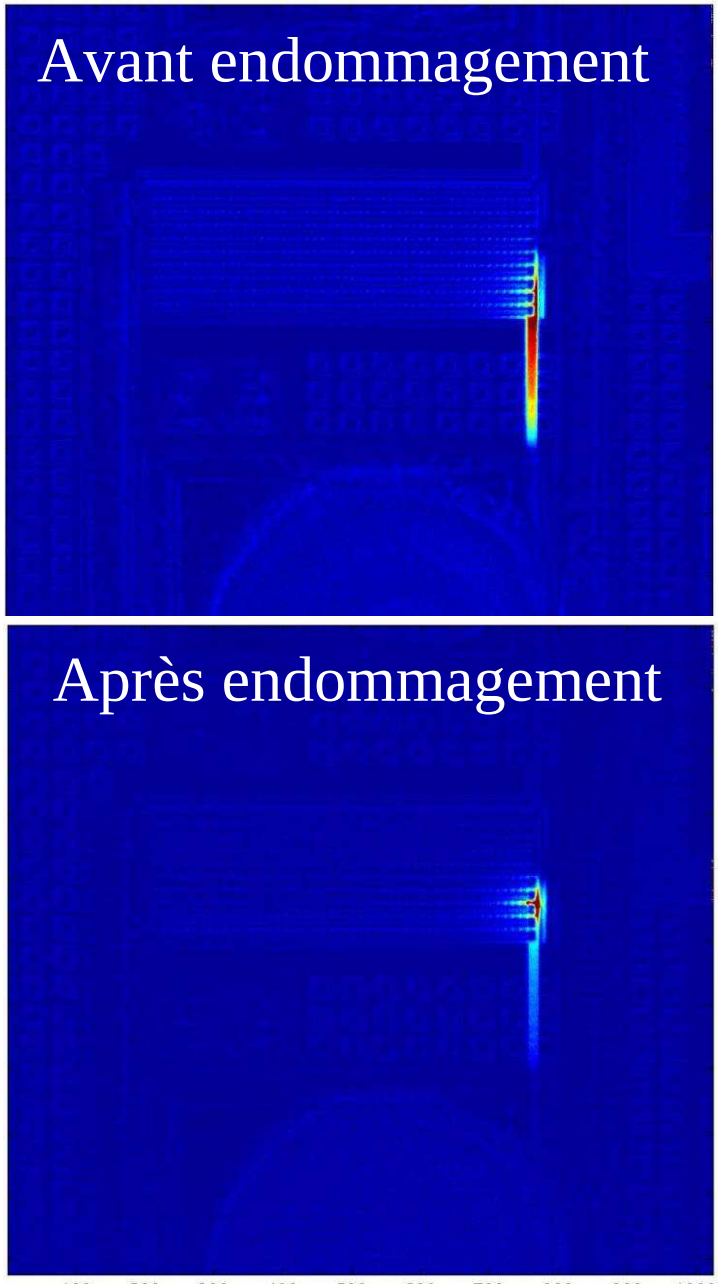
# Réseau de transistors (ST Microelectronics)




Structure sans fuites:
Pas de points chauds

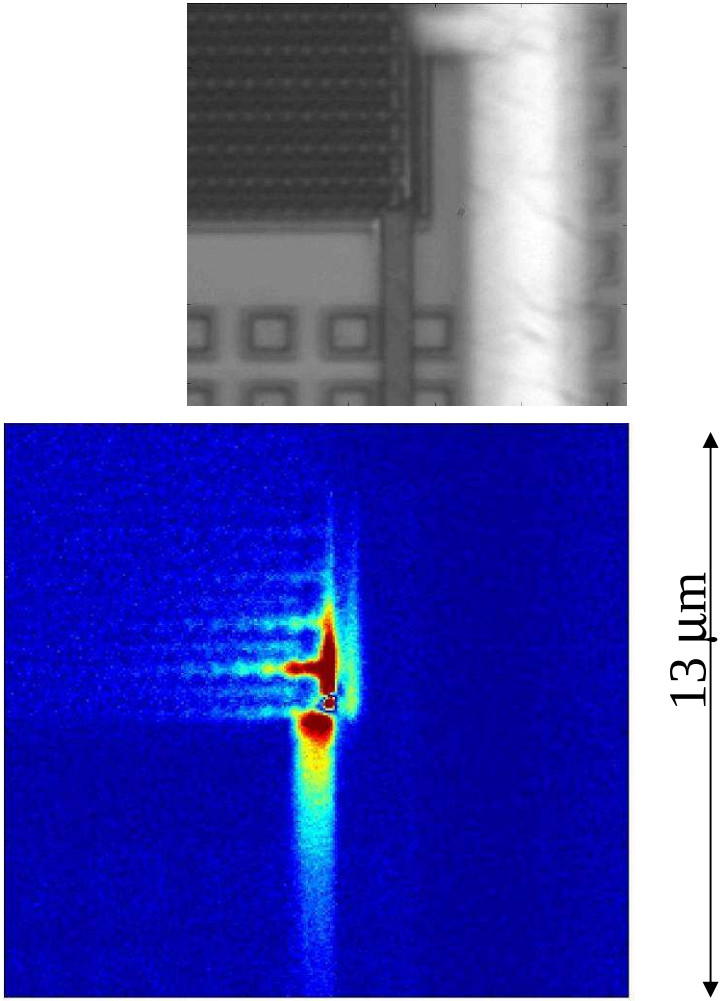


# Réseau de transistors (ST Microelectronics)



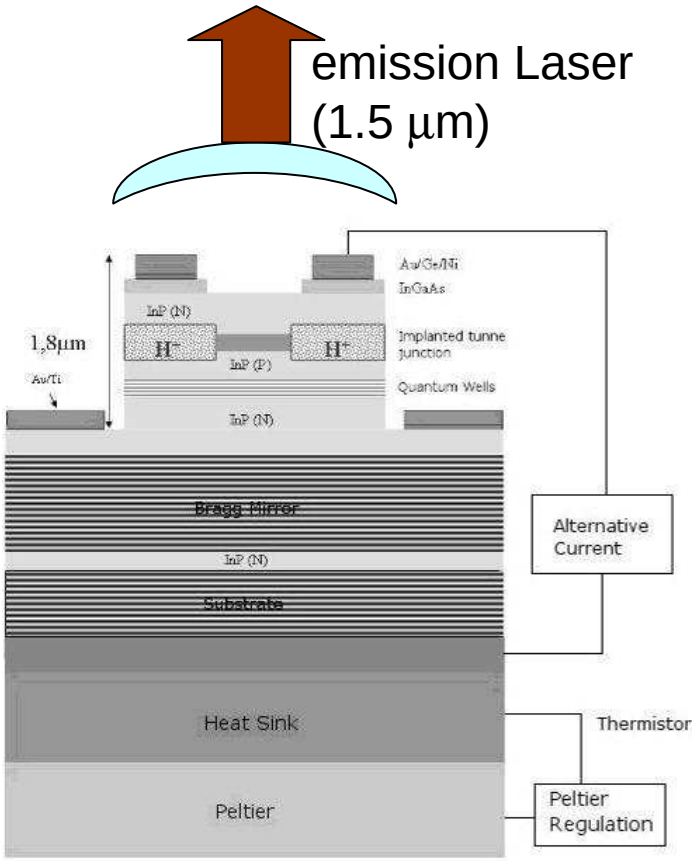

Resolution spatiale< 340 nm

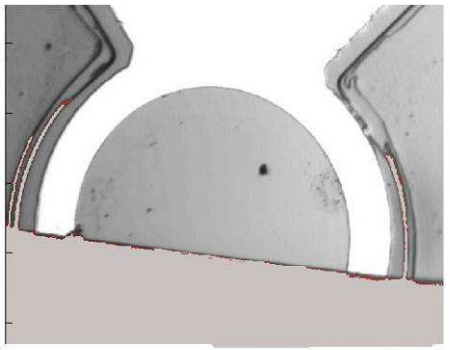
Imagerie à travers 6 µm de diélectrique

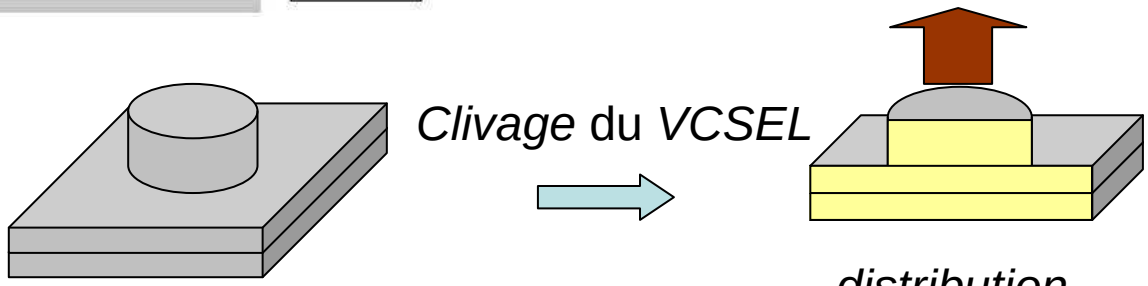


# Vertical Cavity Surface Emission Lasers (VCSELs)

M Bardoux, ESPCI, S. Bouchoule, A. Bousseksou, LPN

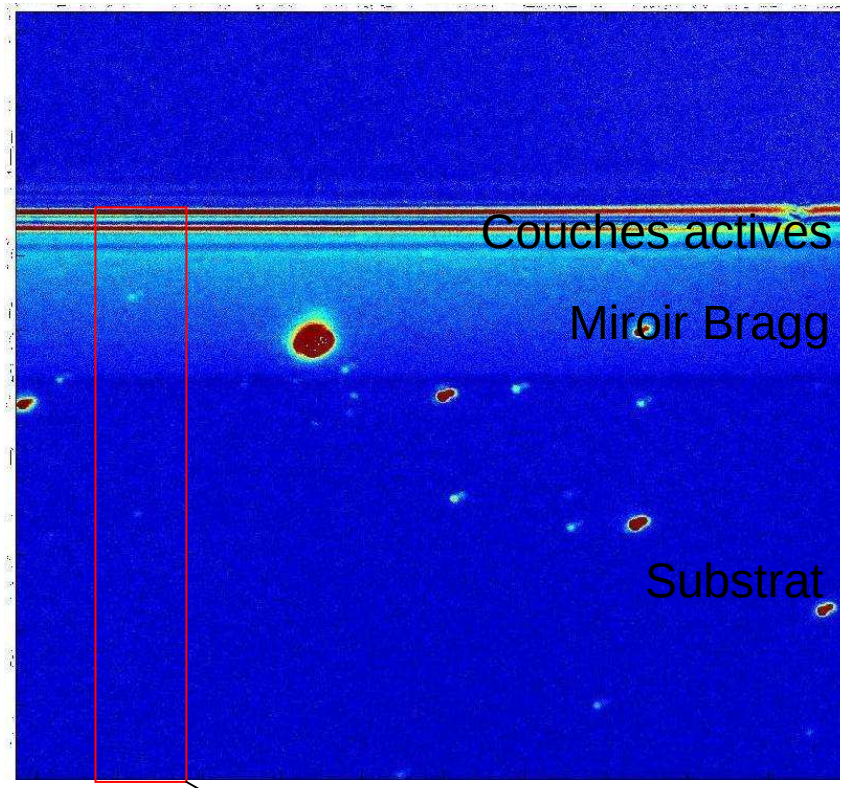


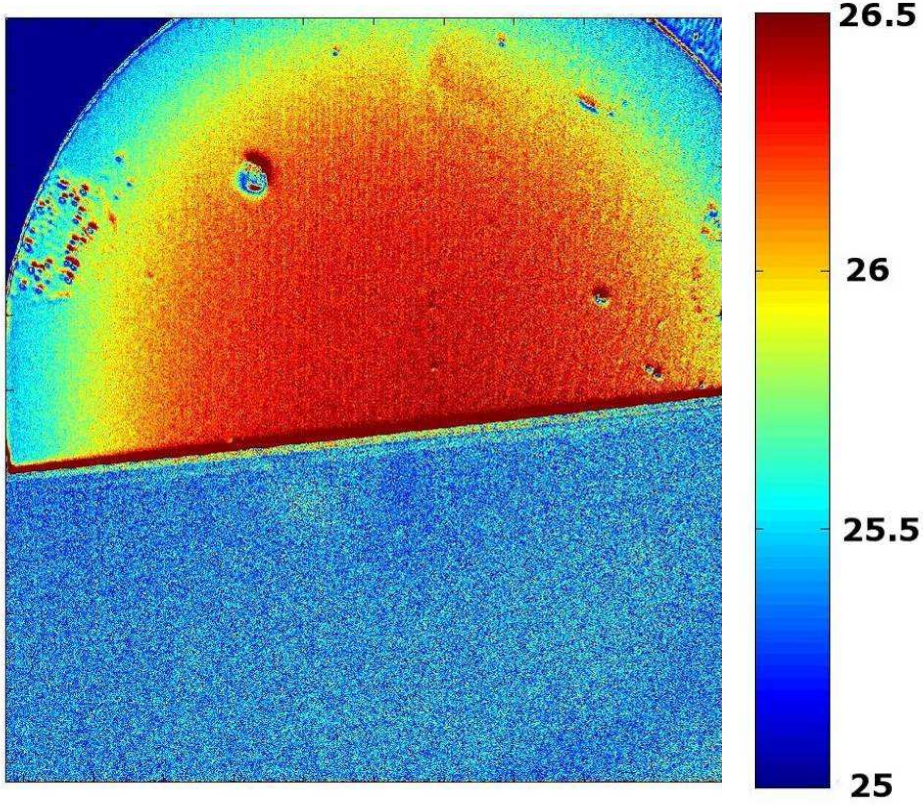


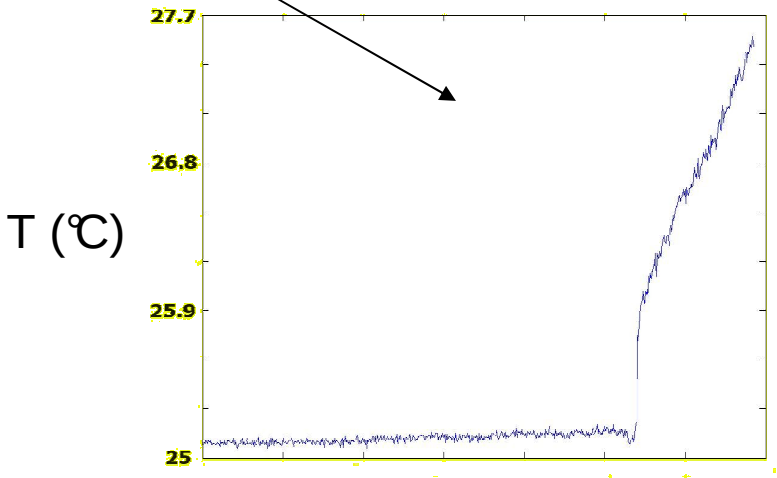

*distribution*
*Verticale de la temperature*

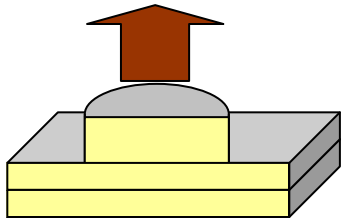
Vue de côté (substrat, mirror, active layers)



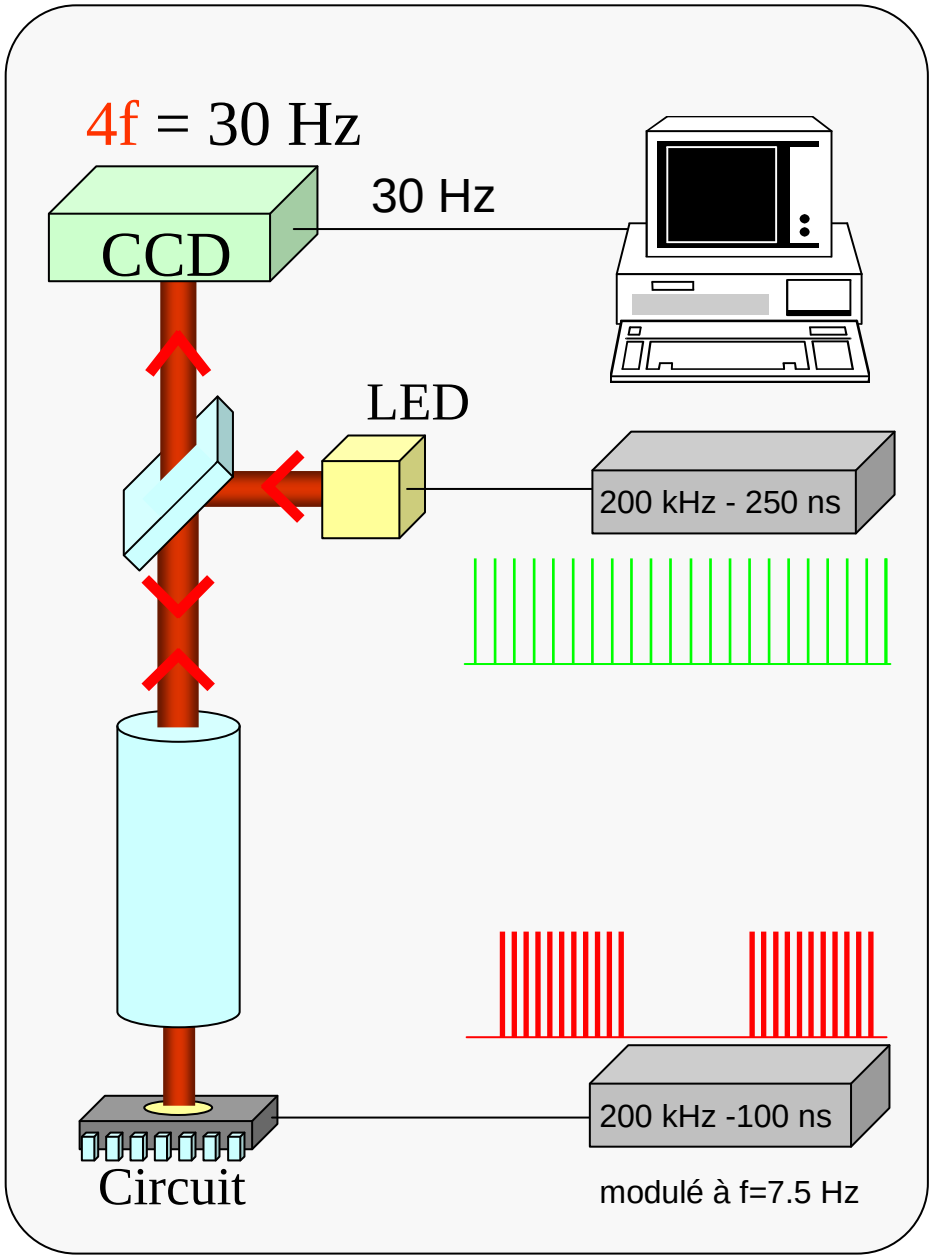

Vue de dessus (facette d'émission)



# Thermoreflectance résolue en temps



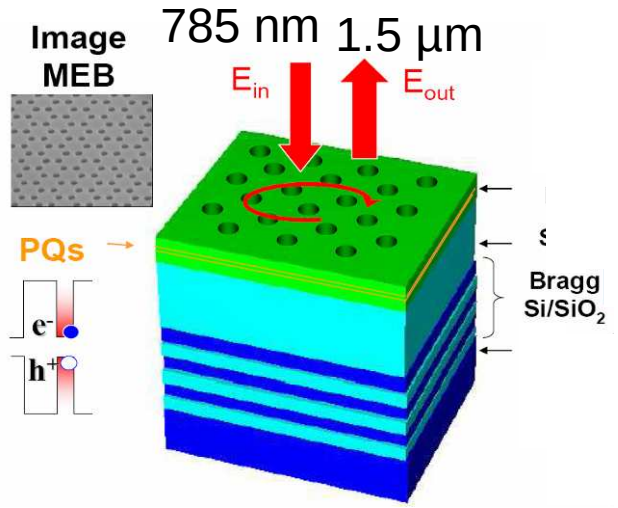

Impulsions lumineuses : 250 ns

= Résolution temporelle

# Thermoréflectance résolue en temps

V. Moreau
Collaboration M. Brunstein, A. Yacomotti, R. Raj, A. Levenson, LPN Marcoussis

## Photonic crystal active structures emitting at 1.55 µm




**Active structures**

Quantum wells InGaAs/InP

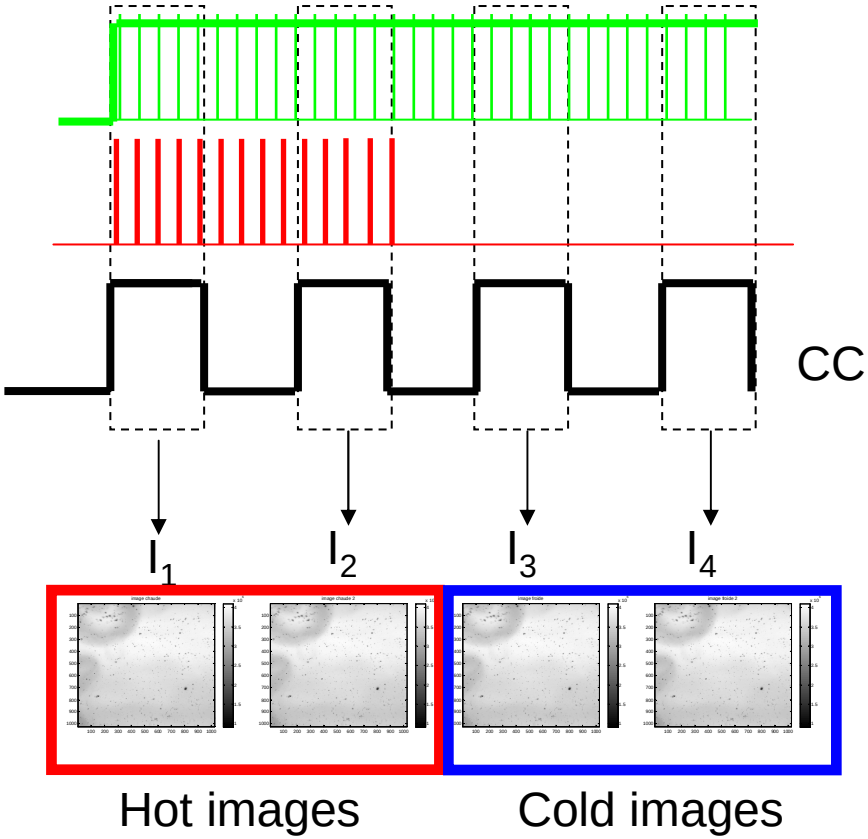
Quantum dots InAsP/InP

} Optical pumping

- For many applications, such as laser effect or non-linear studies, the pump can be intense and the heating should be managed.
- In other cases, these effects can be useful : thermo-optical switches

**Need for a non invasive spatio- temporal high resolved system for temperature measurement**

# Transient thermoreflectance principle : stroboscopic principle




Lighting signal

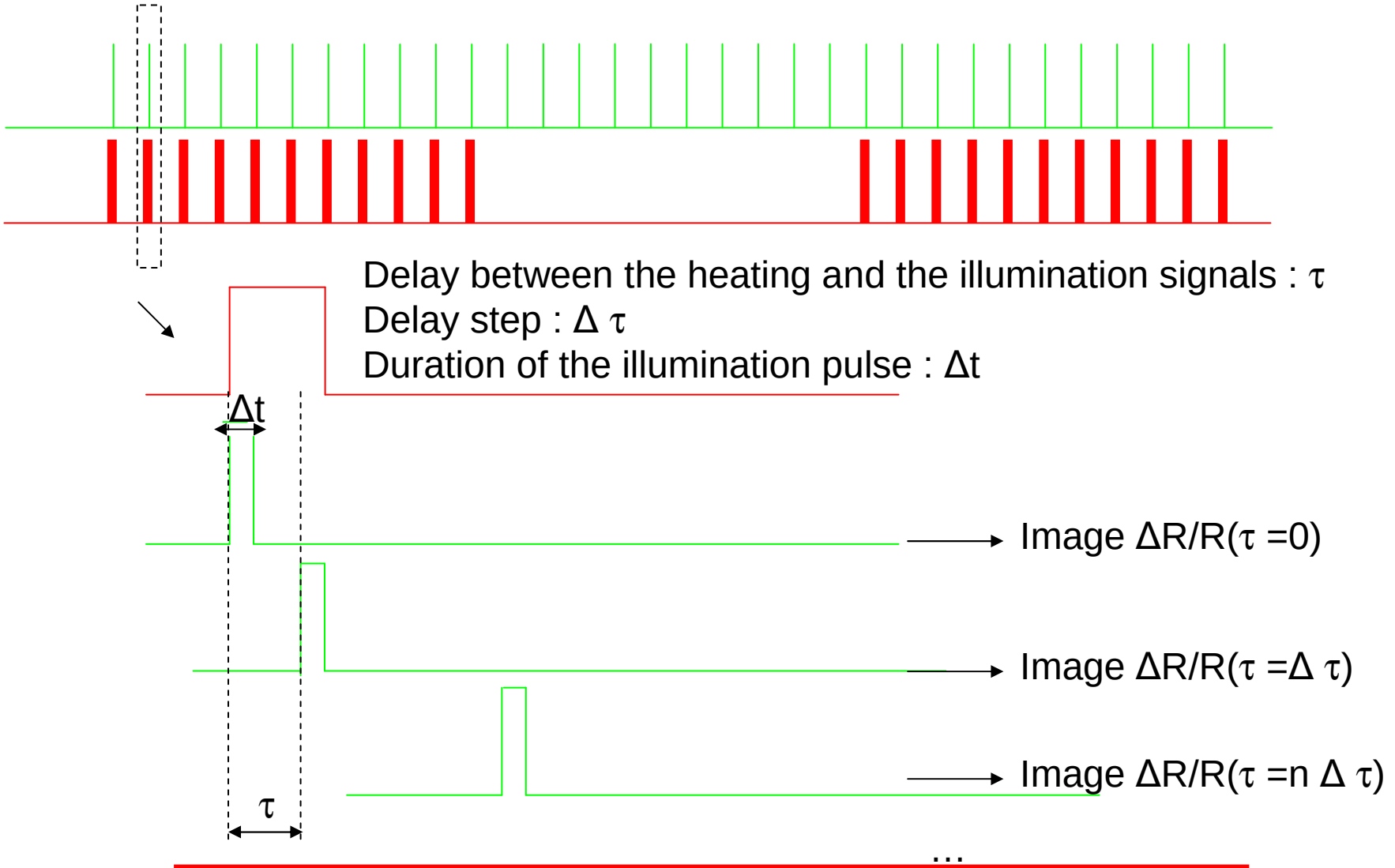
Heating signal
7.5 Hz

CCD camera acquisition signal
30 Hz

**Each picture is averaged temperature on the duration of the illumination pulse**

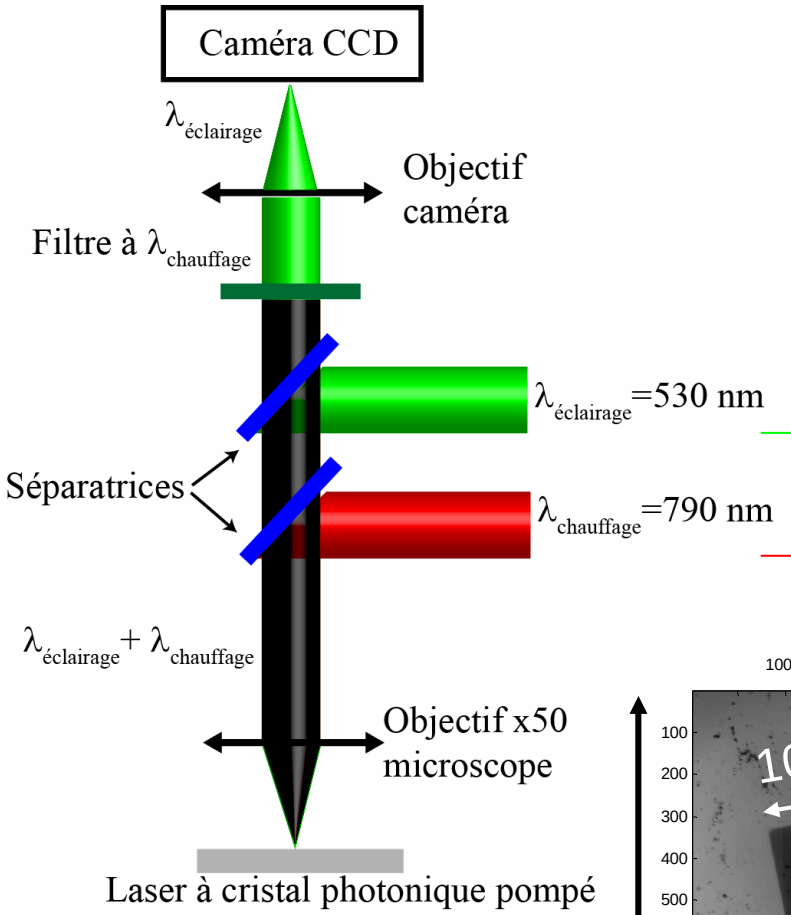
$$\frac{(I1-I3)+i(I2-I4)}{(I1+I2+I3+I4)/4} \rightarrow \Delta R/\langle R \rangle$$

# Transient thermoreflectance principle

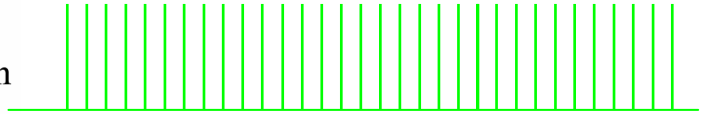



ΔR/R(τ) gives the average temperature on a duration Δt

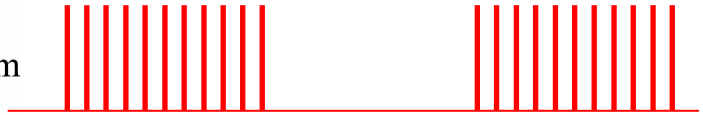
# Transient thermoreflectance on a photonic crystal laser



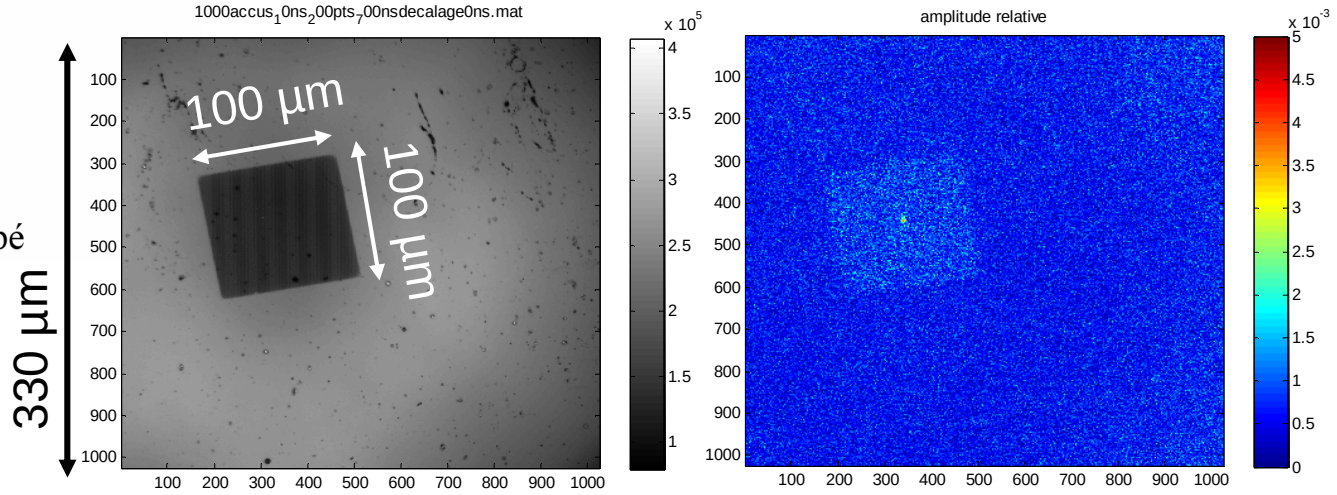

30 Hz



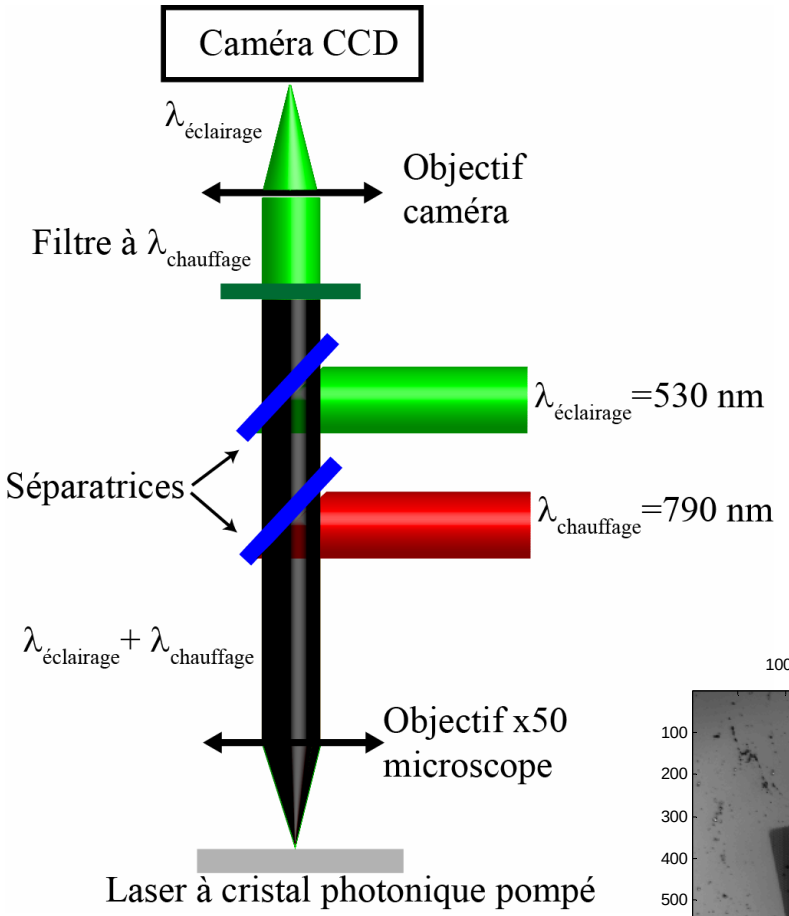
200 kHz_250 ns

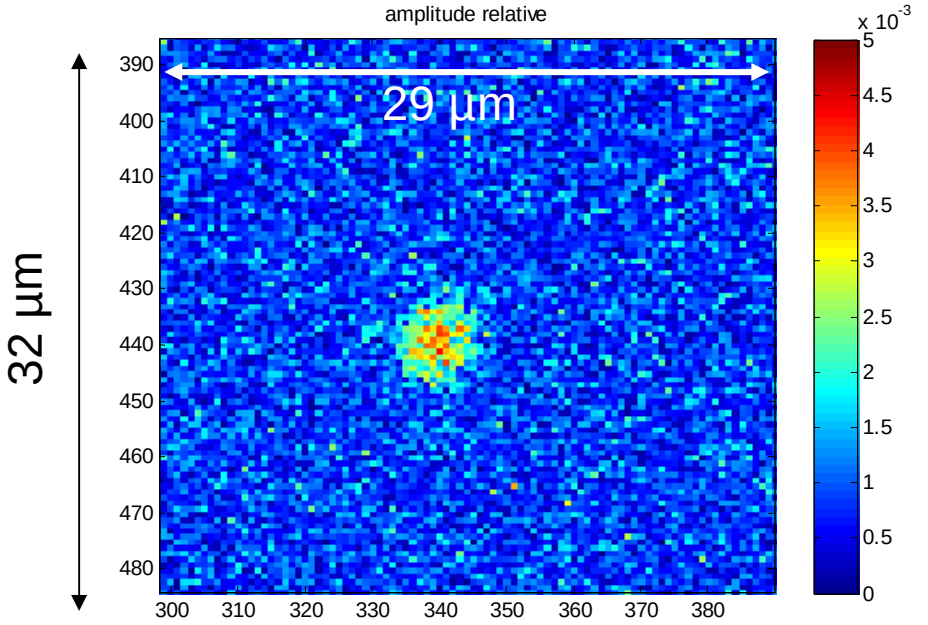


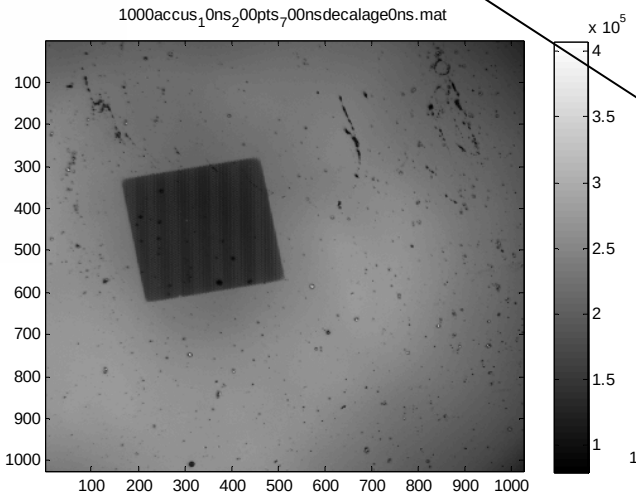
200 kHz_100 ns
modulated at 7.5 Hz

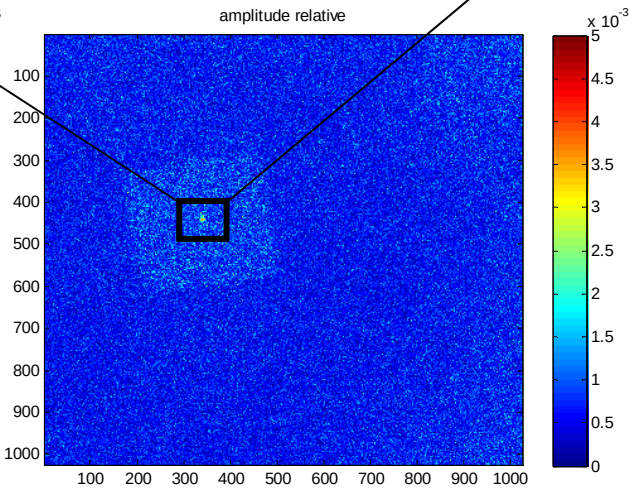


# Transient thermoreflectance on a photonic crystal laser

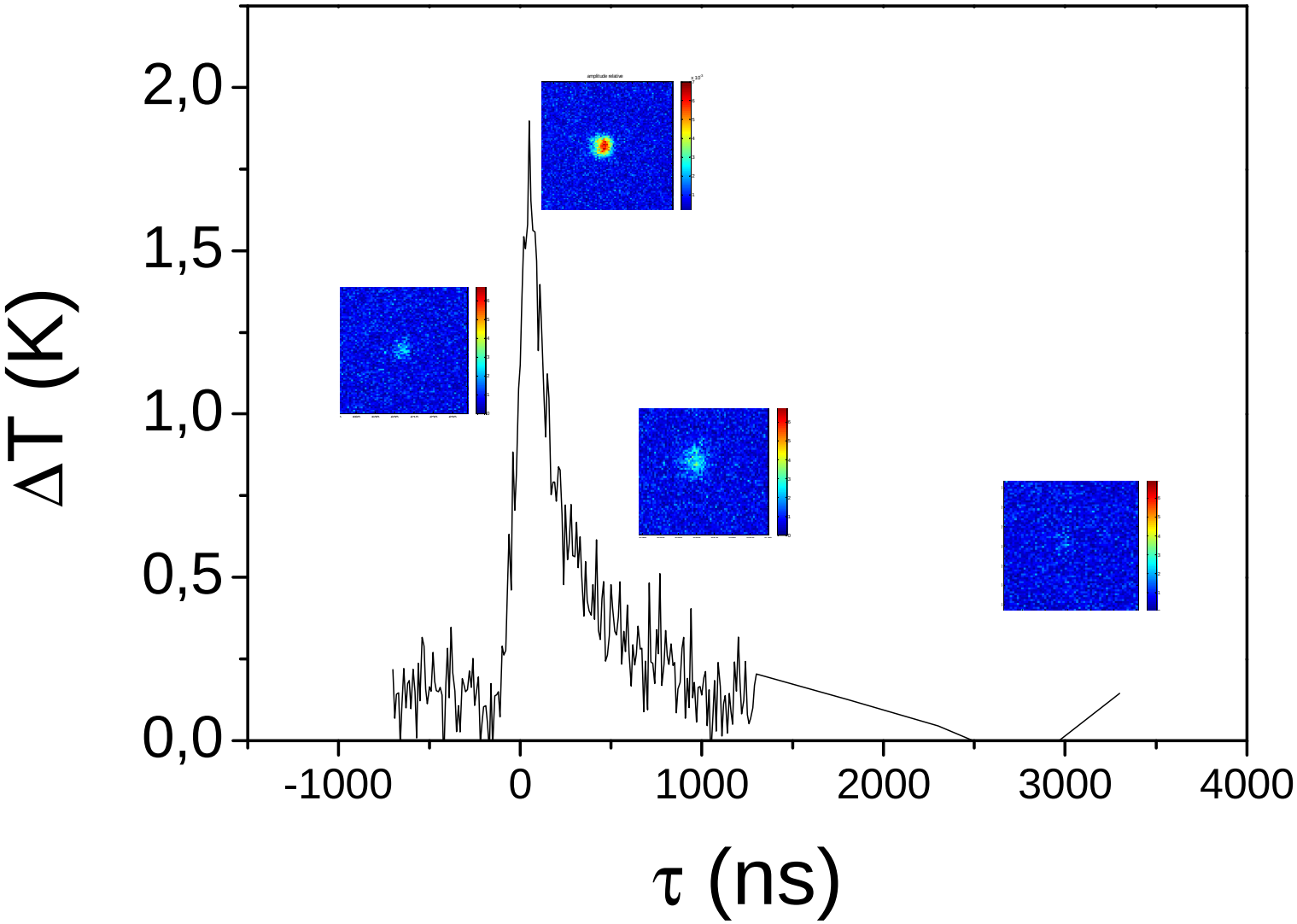


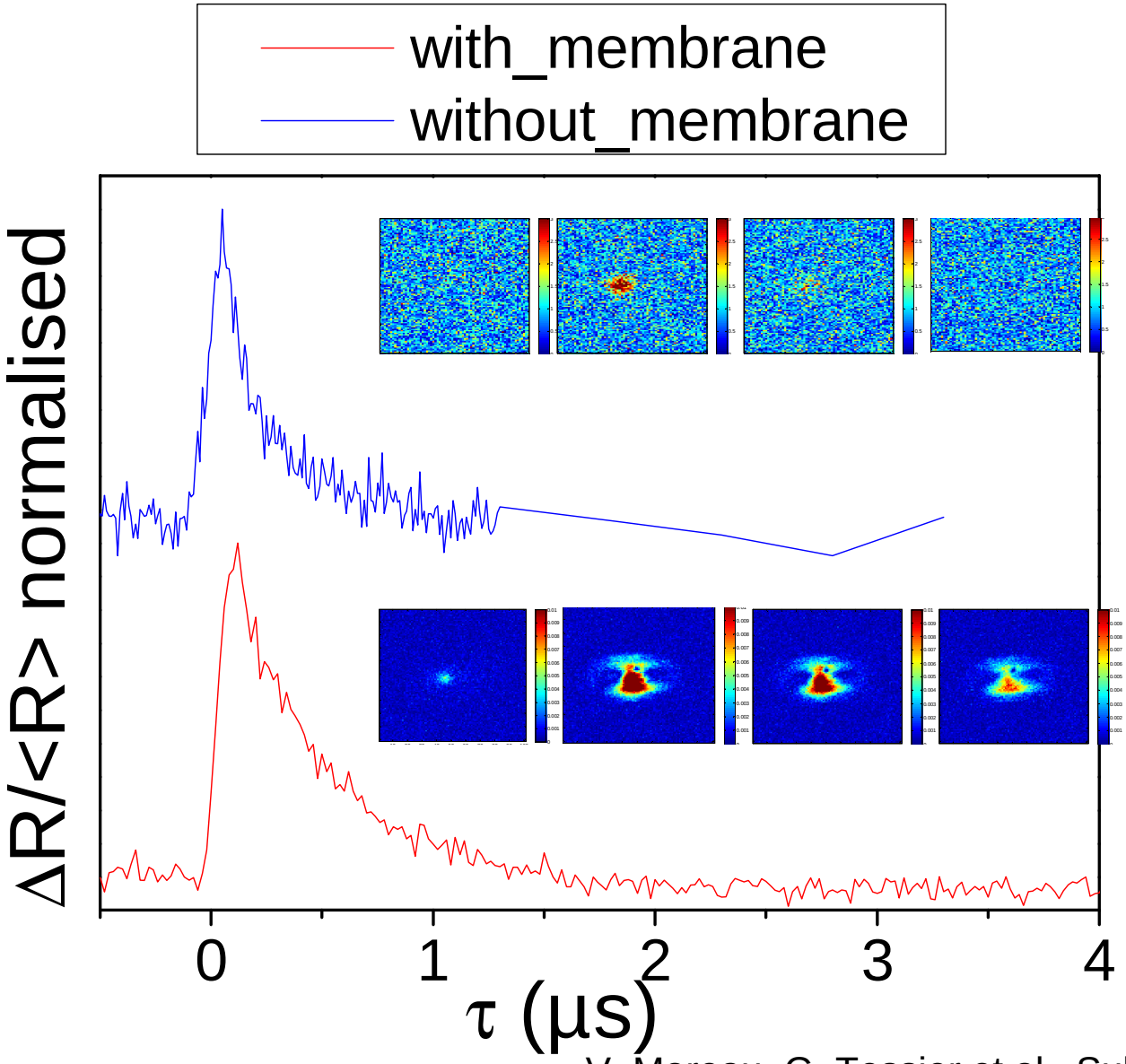



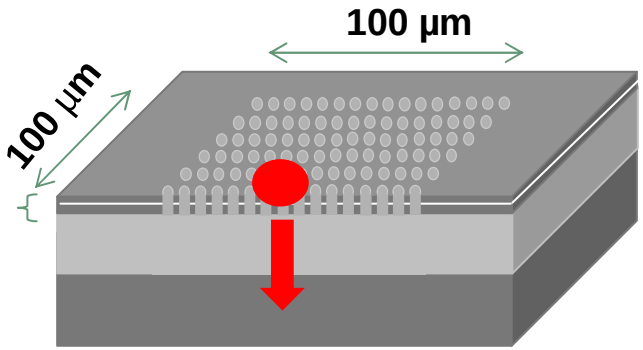
## Spatio-temporal distribution of temperature on 2D photonic crystal lasers



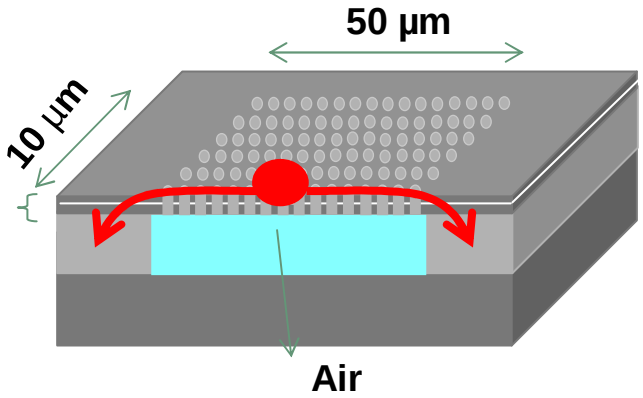

**Dissipation time < 1 µs and increase of temperature around 2 K**

## Different mechanisms of thermal evacuation



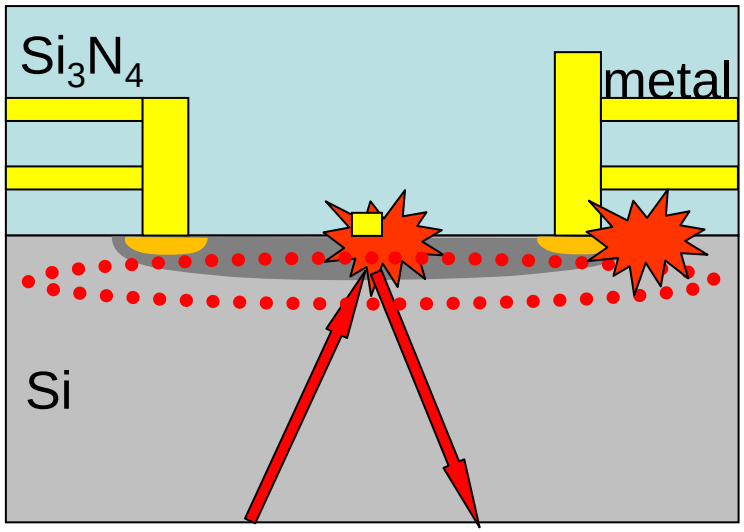

Spherical evacuation




Lateral evacuation

V. Moreau, G. Tessier et al., Submitted to Applied Physics Letters

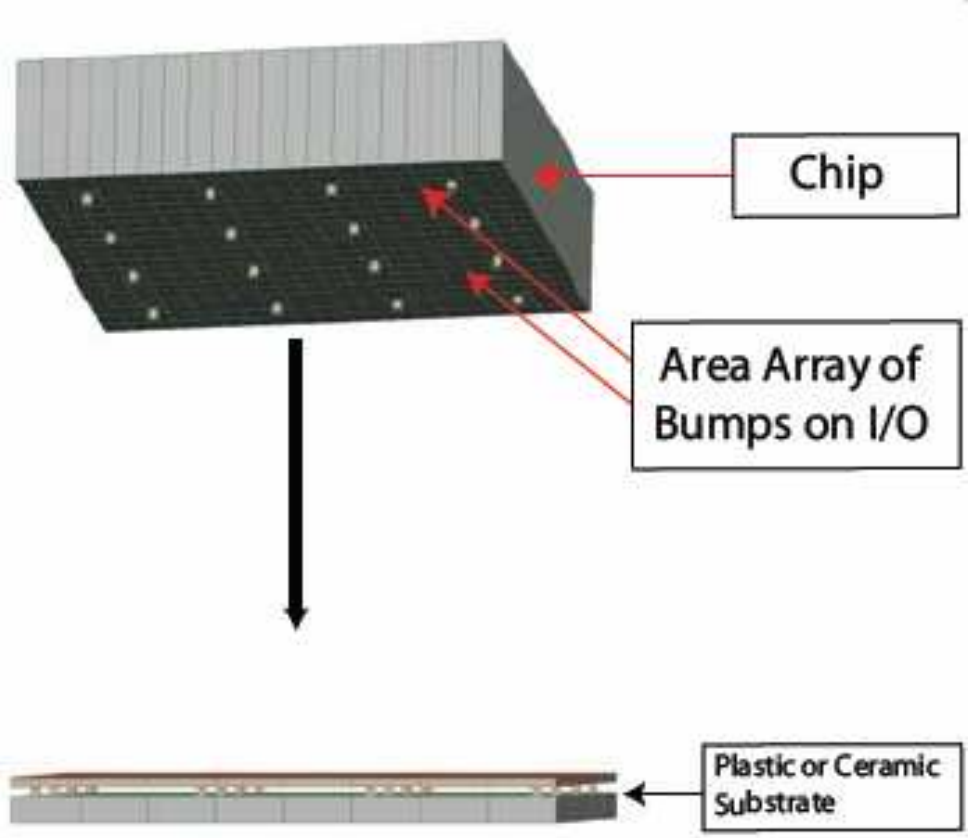
# 2
# Thermoreflectance dans l’Infra Rouge

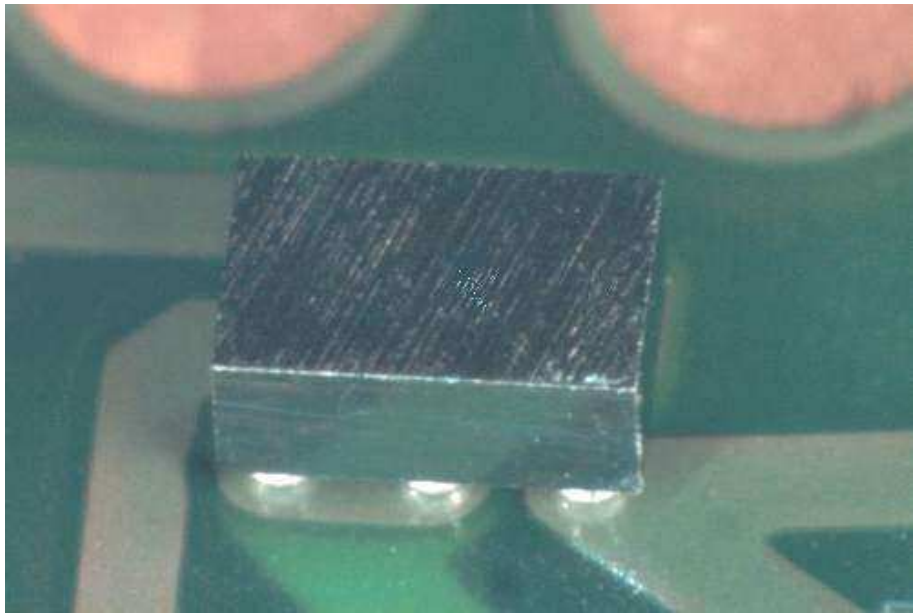



Infrarouge proche

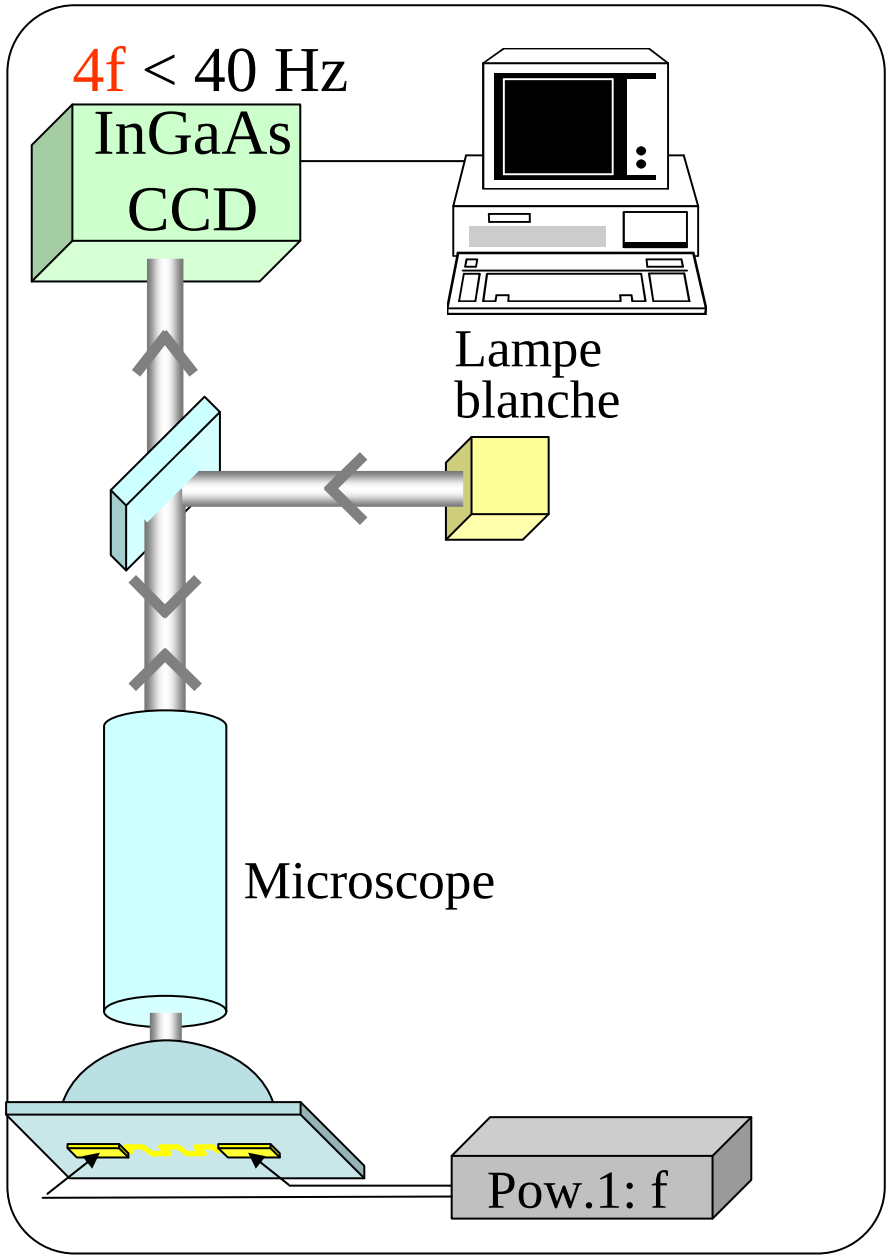
# Configurations « flip chip »

Substrat retourné ⟹ face active en contact thermique avec le support

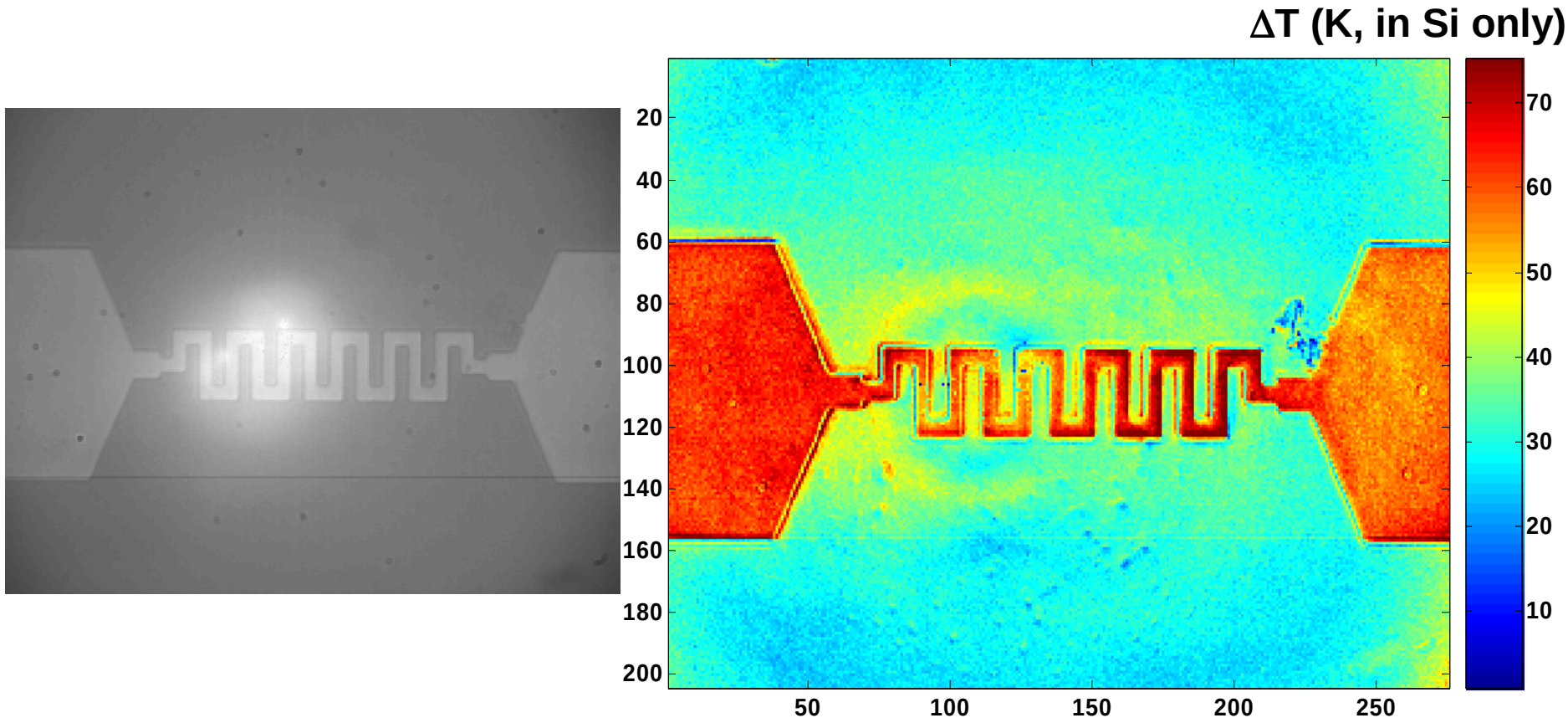


# Thermoreflectance avec une caméra InGaAs



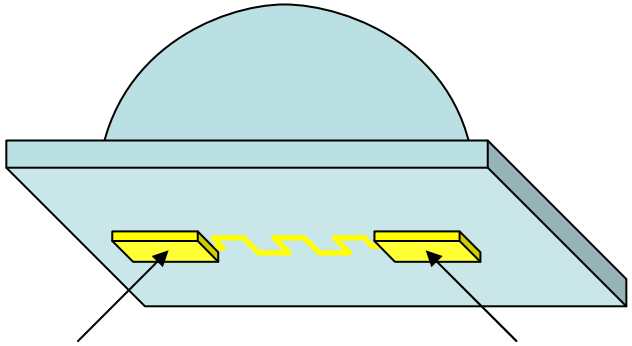
# Imagerie proche infrarouge en face arrière

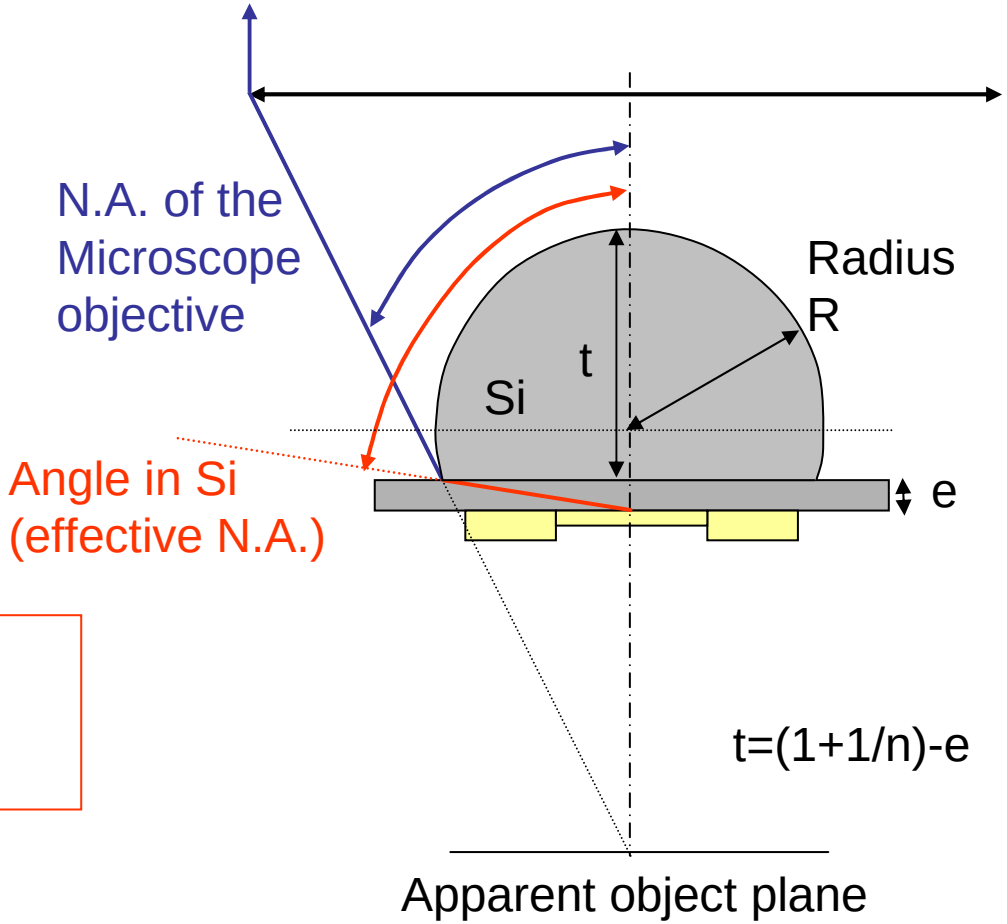



Puissance dissipée : 500 mW
objectif X50, 0.6N.A.
Résolution limitée par la diffraction : 1.7 µm

# Lentille à immersion solide: Si

$n_{Si} = 3.5$

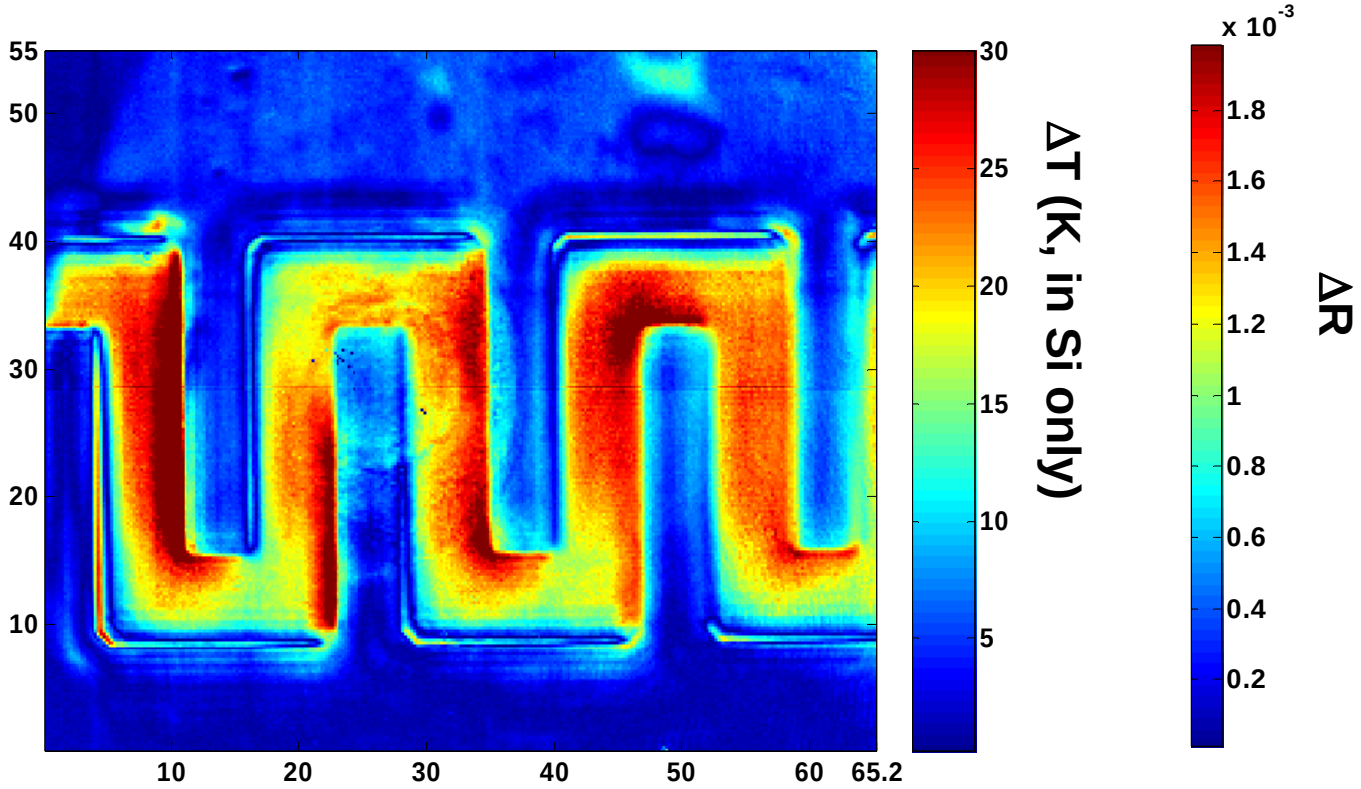





Resolution limit : 1.22 λ / 2 NA

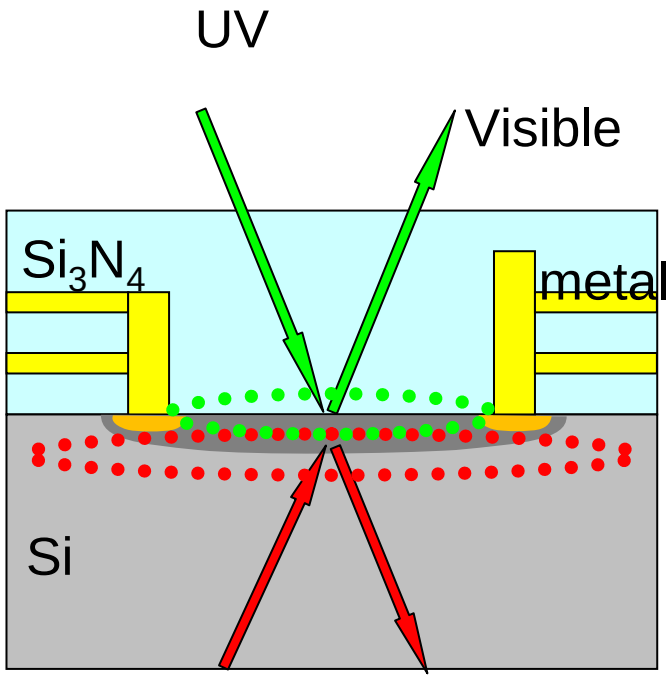
in silicon : 245 nm at λ = 1.3 μm

# Thermoreflectance proche infrarouge avec Lentille à Immersion




Résolution moyenne 440 nm
Ouverture numérique 2.36

G. Tessier, M. Bardoux, C. Boué, C. Filloy, D. Fournier, Appl. Phys. Lett. 90, 171112 (2007

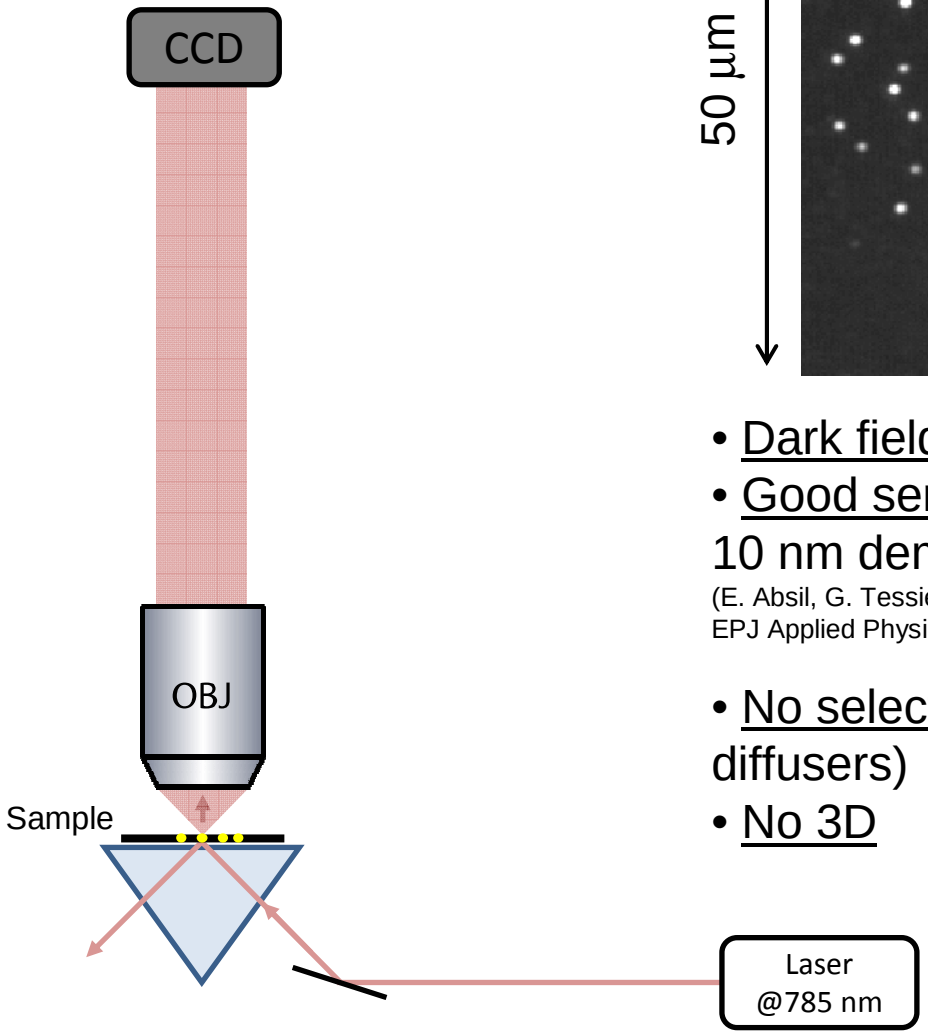



→ Resolution 300 nm – 350 nm

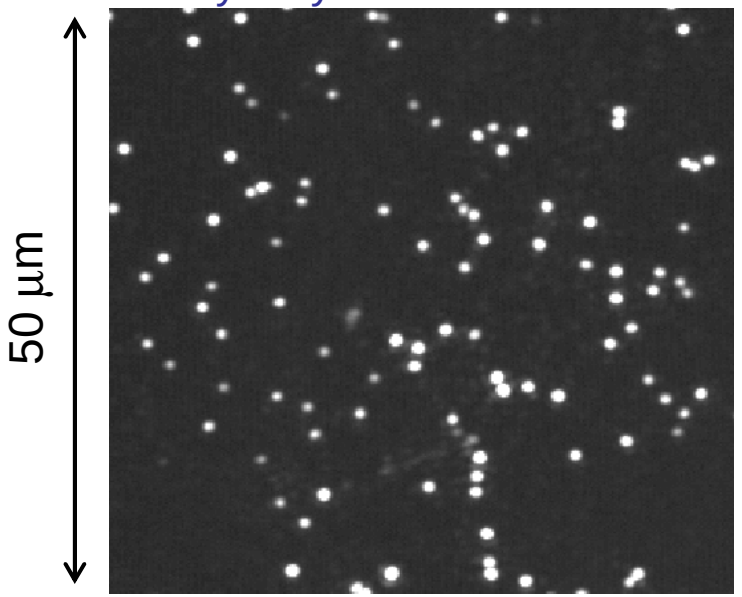
Infrarouge proche

→ Resolution 1. 7 μm sans lentille Si
440 nm avec lentille Si

# Direct detection of nanoparticles




50 nm Au beads
in Poly Vinyl Alcohol




- Dark field
- Good sensitivity :

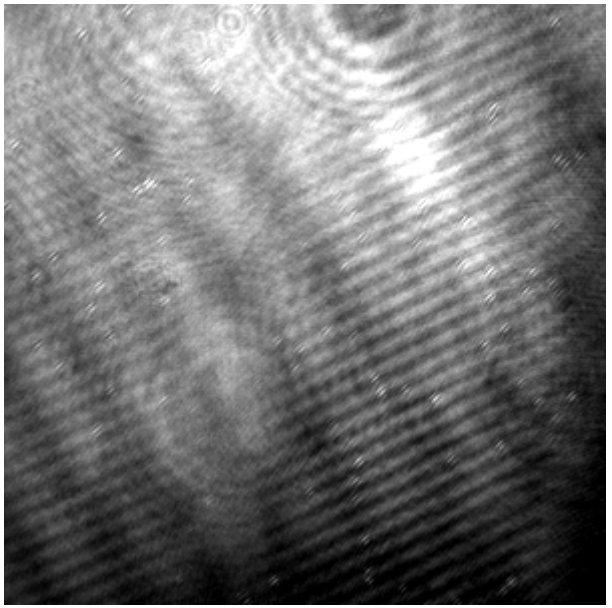
10 nm demonstrated

(E. Absil, G. Tessier, D. Fournier, M. Atlan, M. Gross, EPJ Applied Physics)

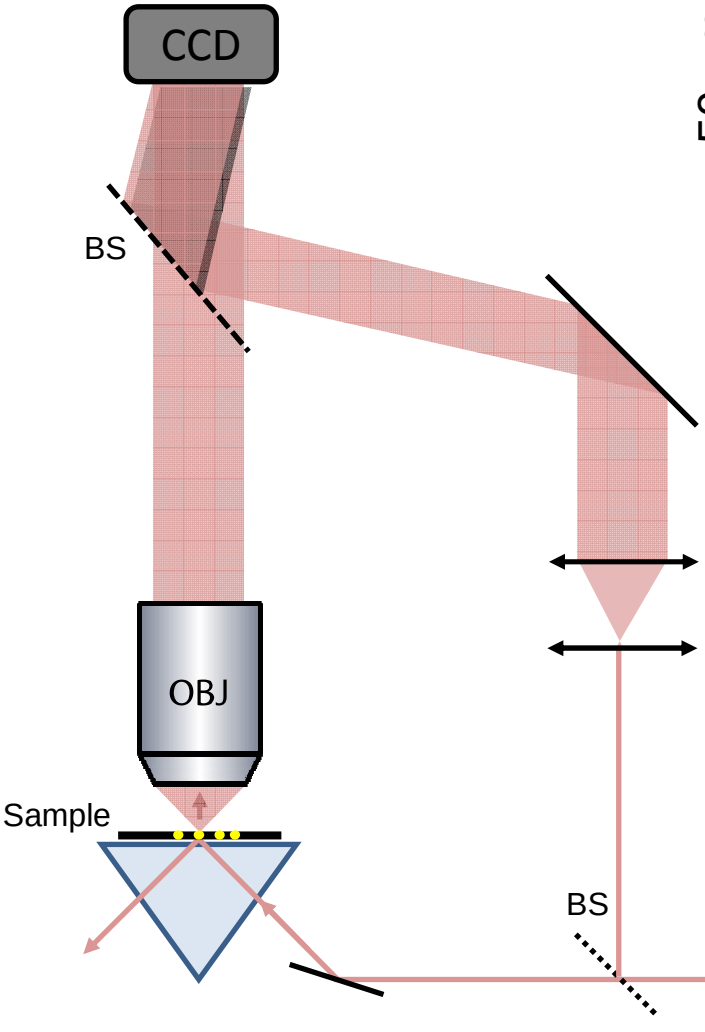
- No selectivity (dust or other diffusers)
- No 3D

# Numerical holography

Hologram (50 nm Au beads)



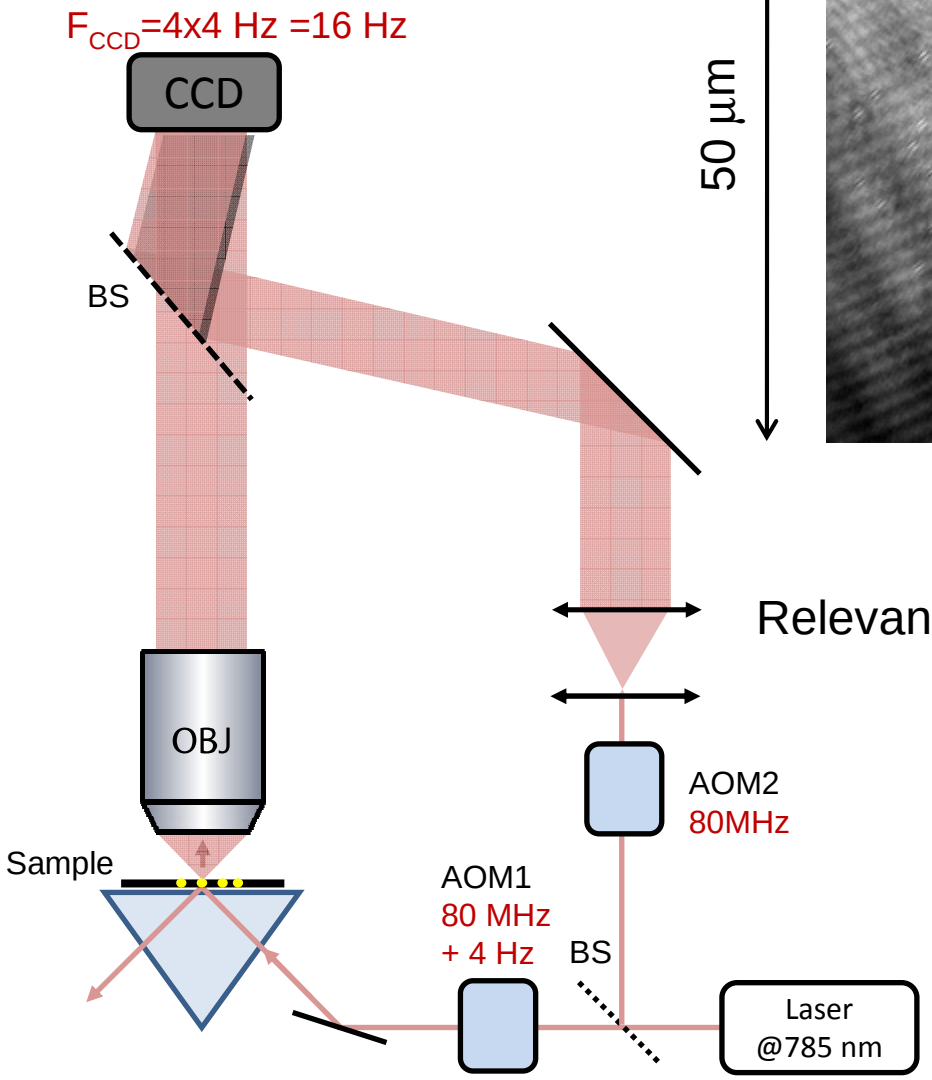
50 µm



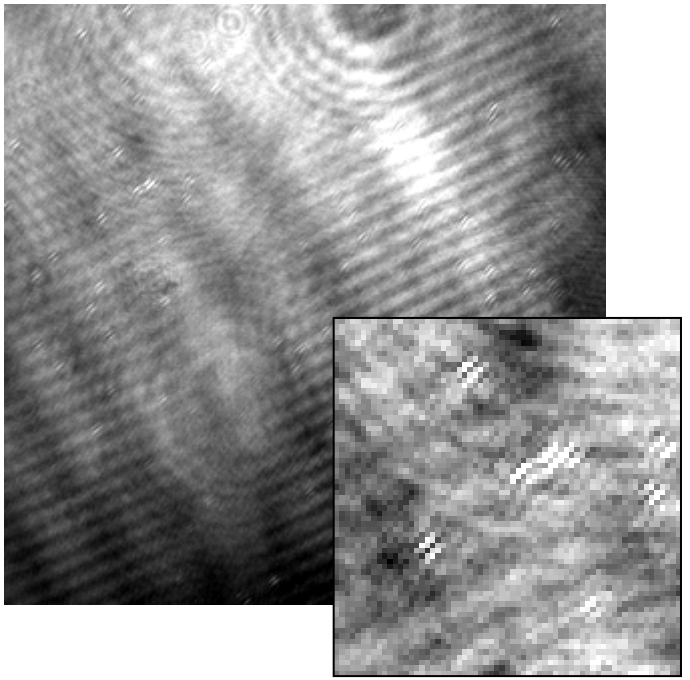

Au particles (50 nm) in PVA
TIRF illumination

Diffusion * Reference :
Holographic Gain

# Heterodyne Numerical holography

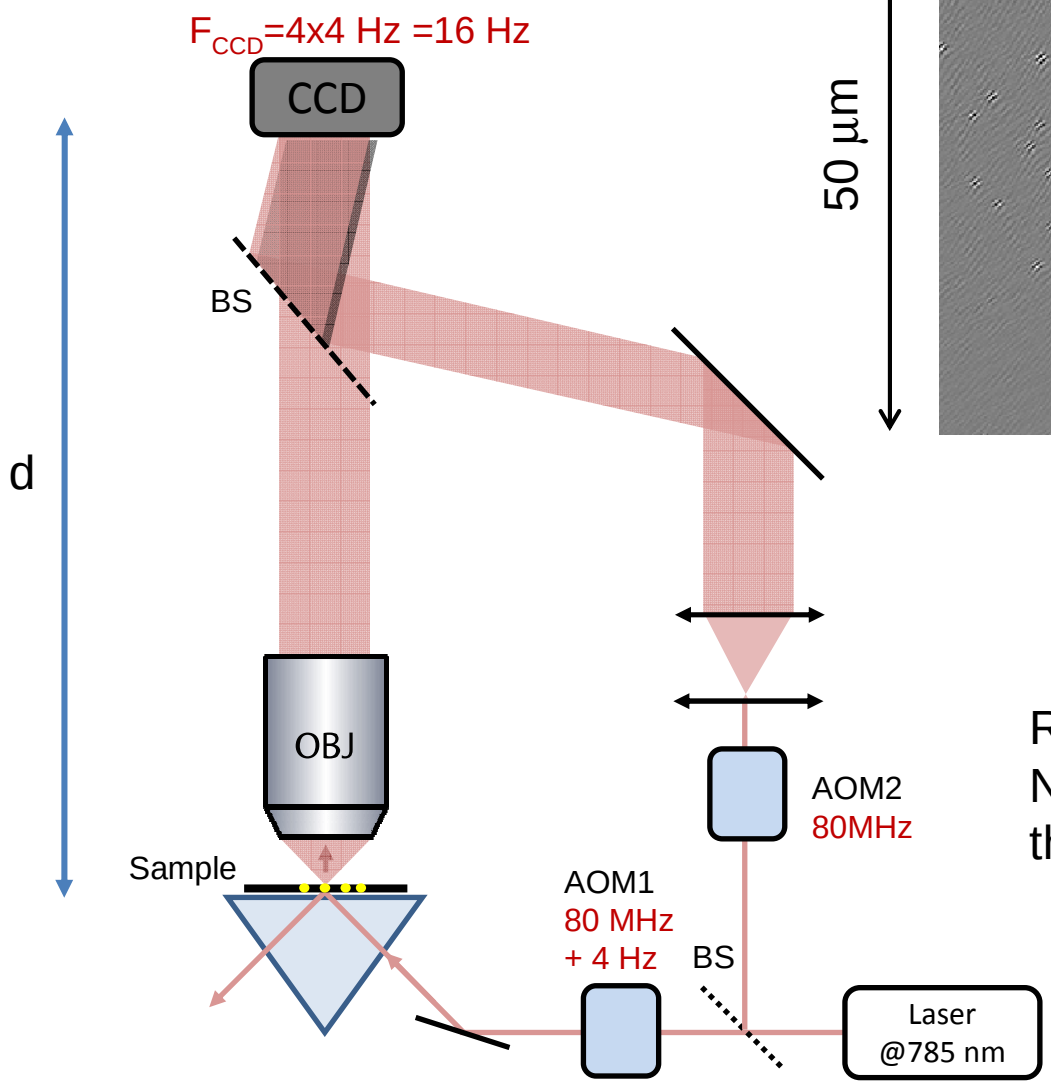



Heterodyne Hologram (50 nm Au beads)

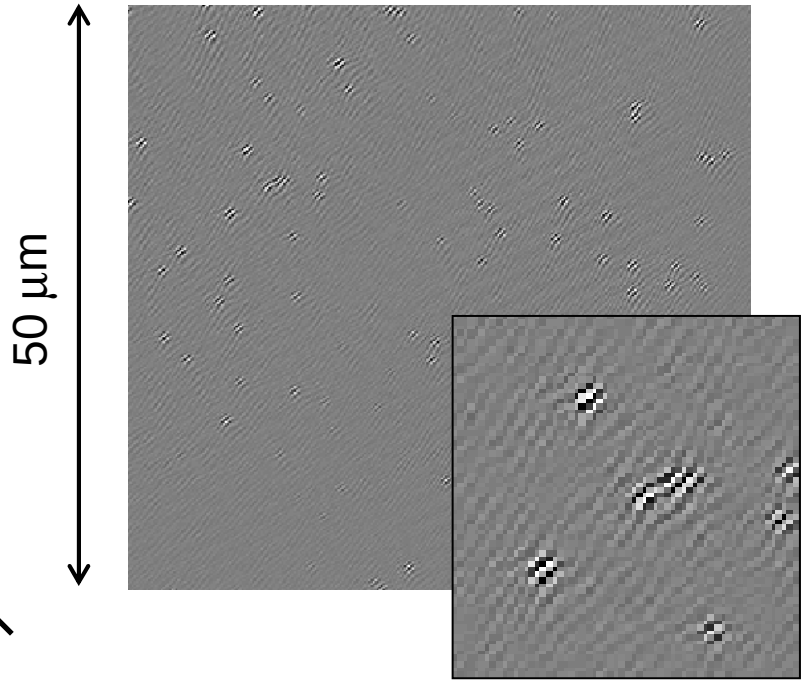



Relevant fringes modulated at 4Hz

# Heterodyne Numerical holography




Demodulated hologram (50 nm Au beads)




Reconstruction of the image:
Numerical « propagation » of the wave over d

⟹ 2 Fourier transforms

# Numerical propagation from the detector to a chosen plane

Recorded Hologram : $H(x, y, 0)$

Hologram in the $k$-space of wave vectors : $\tilde{H}(k_x,k_y,0) = \mathrm{FFT}[H(x,y,0)]$

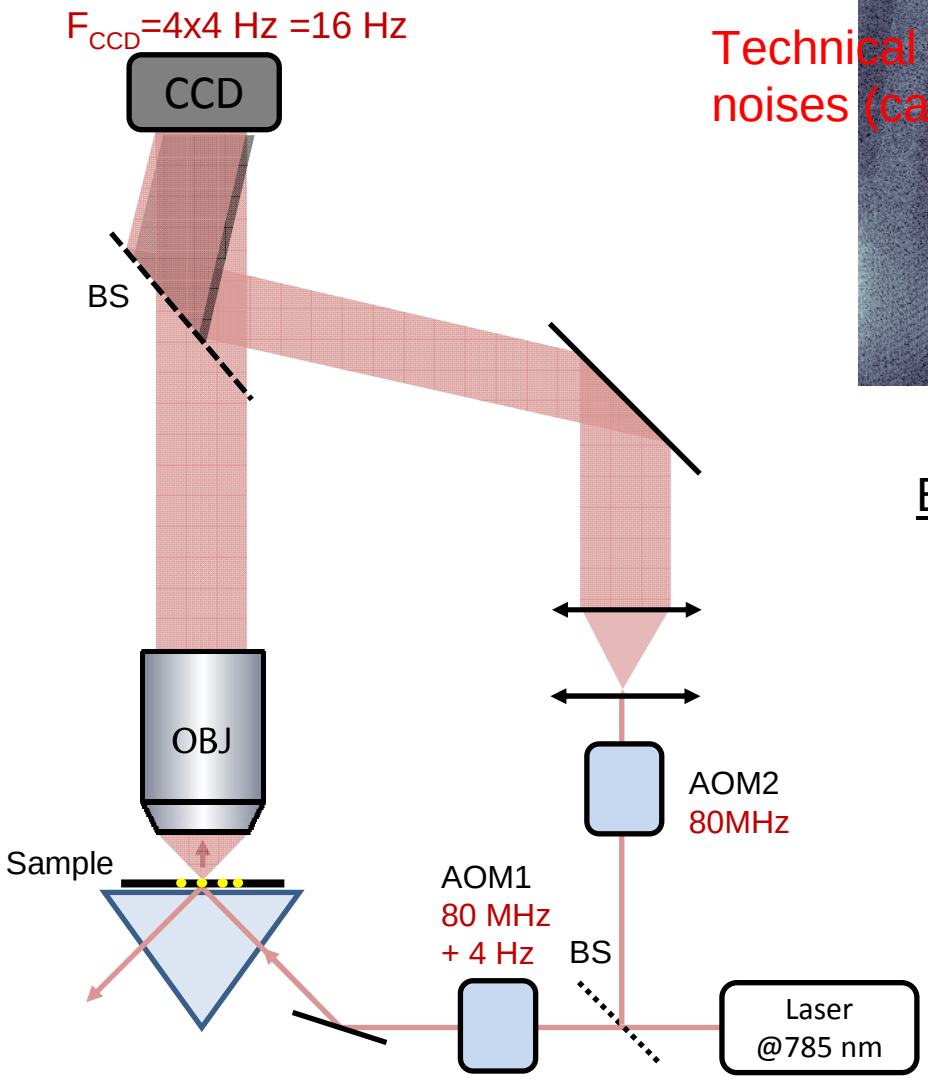
Propagation over distance $z$ : $\tilde{K}(k_x,k_y,z) = e^{jz(k_x^2+k_y^2)/k}$

$$\tilde{H}(k_x,k_y,z) = \tilde{K}(k_x,k_y,z)\tilde{H}(k_x,k_y,z)$$

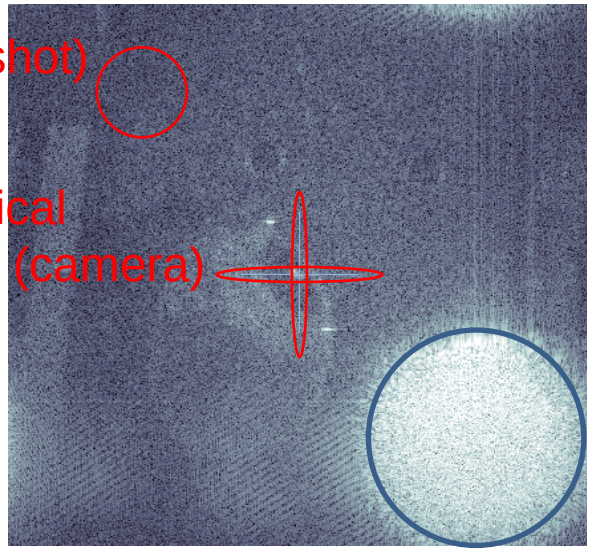
Reconstructed hologram in the chosen plane ($z=d$): $H(x,y,z) = \mathrm{FFT}^{-1}[\tilde{H}(k_x,k_y,z)]$

⟹ 2 Fourier transforms

# Heterodyne Numerical holography




2D Fourier transform of the hologram

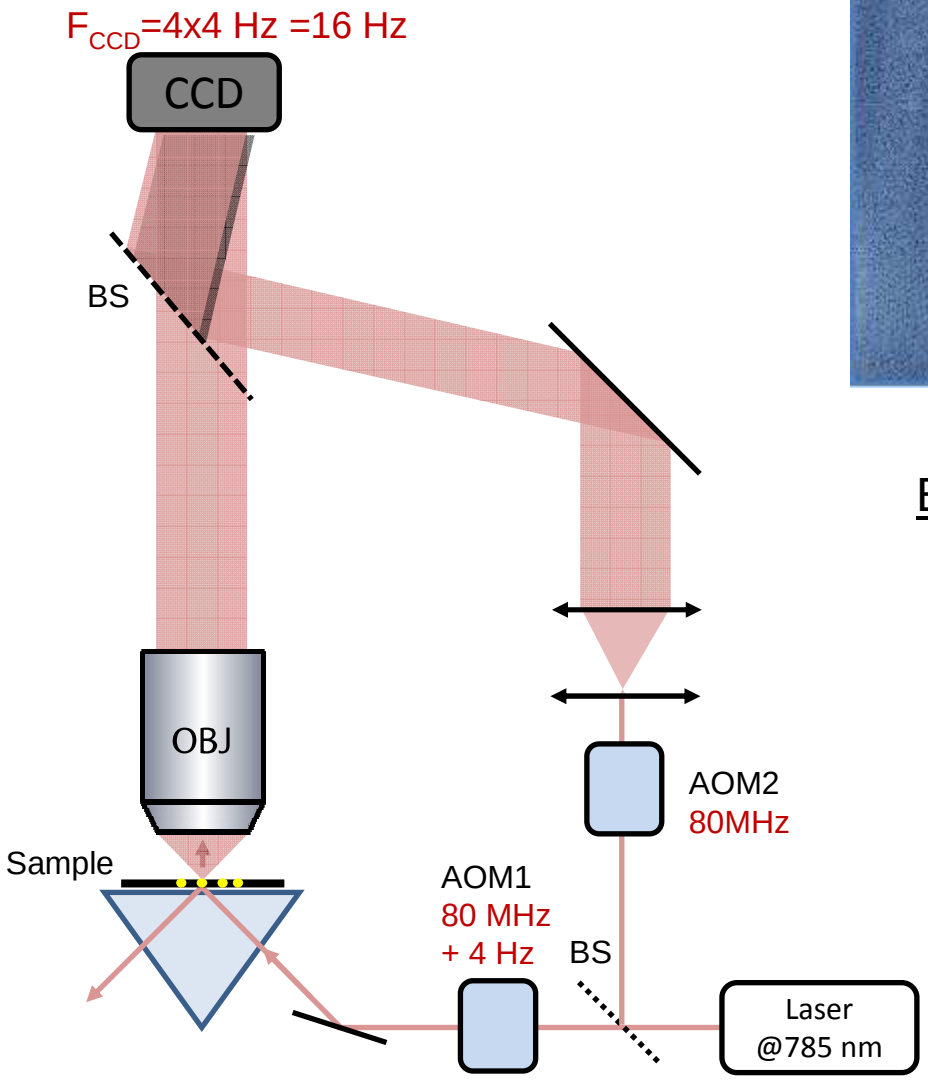



Relevant signal:
Exit pupil of the objective

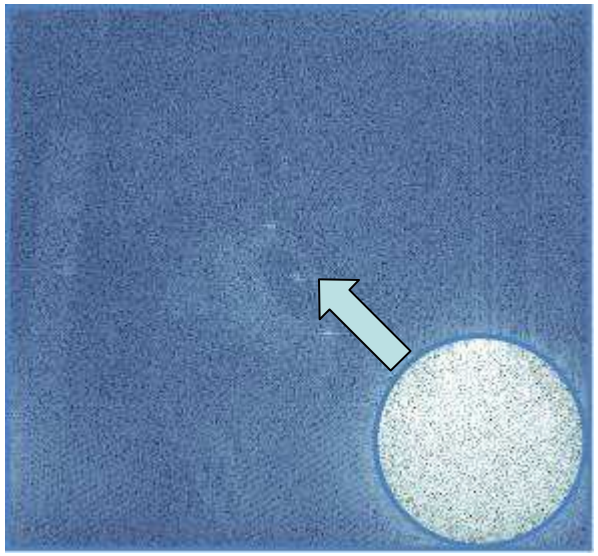
1st Fourier transform :

Wave vectors, k

# Heterodyne Numerical holography



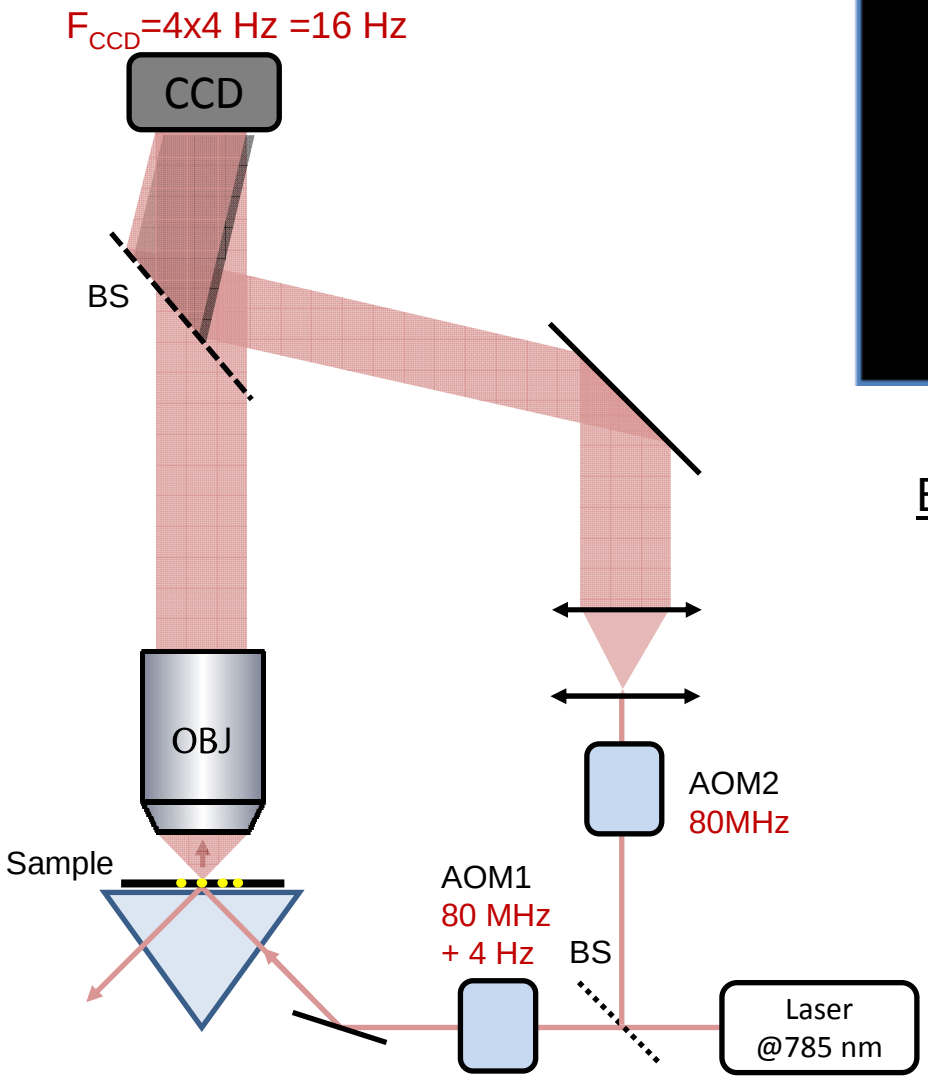

2D Fourier transform of the hologram



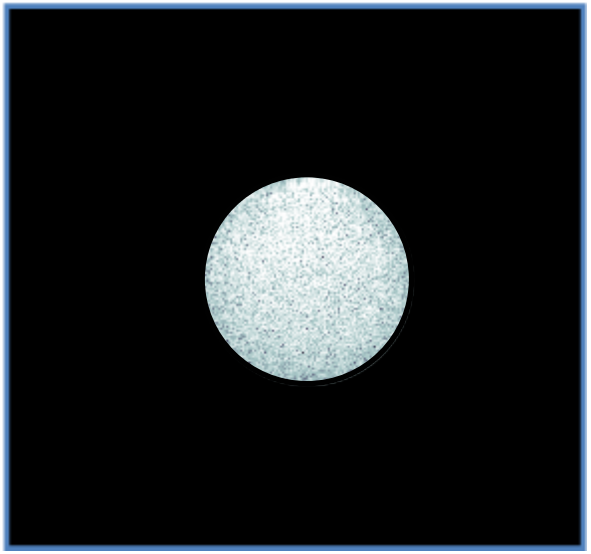
Relevant signal:
Exit pupil of the objective

Filtering in the wave vectors space

# Heterodyne Numerical holography




2D Fourier transform of the hologram

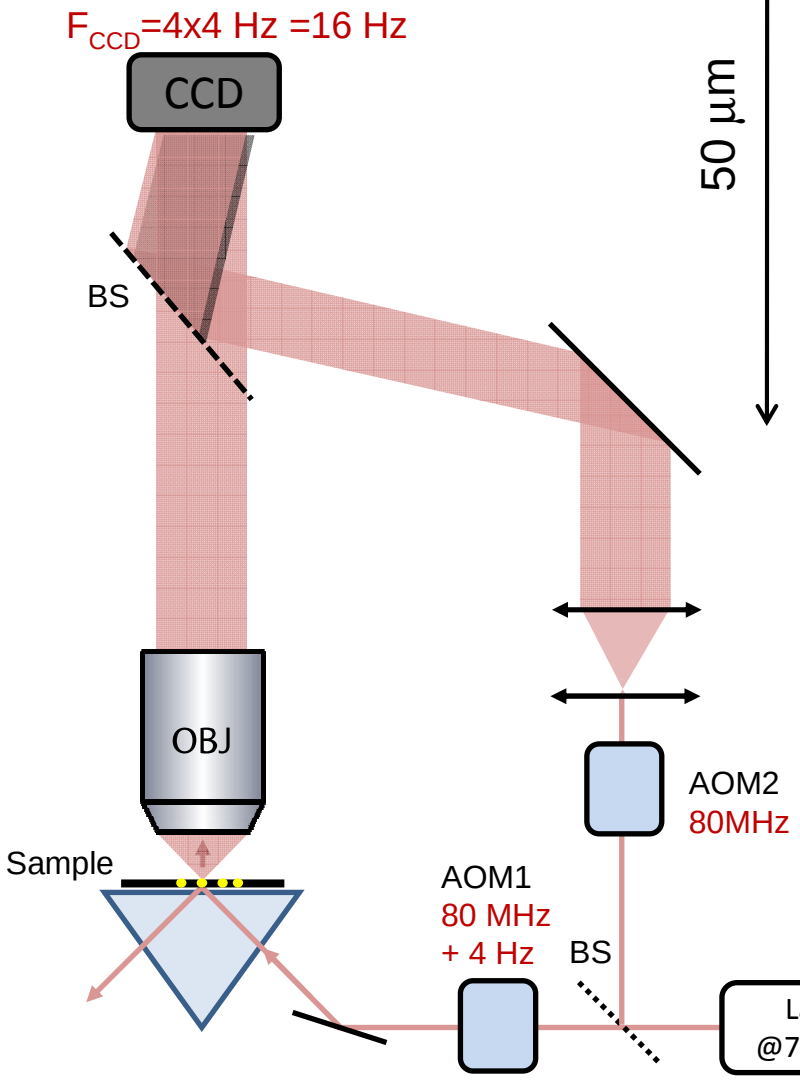


Relevant signal:
Exit pupil of the objective

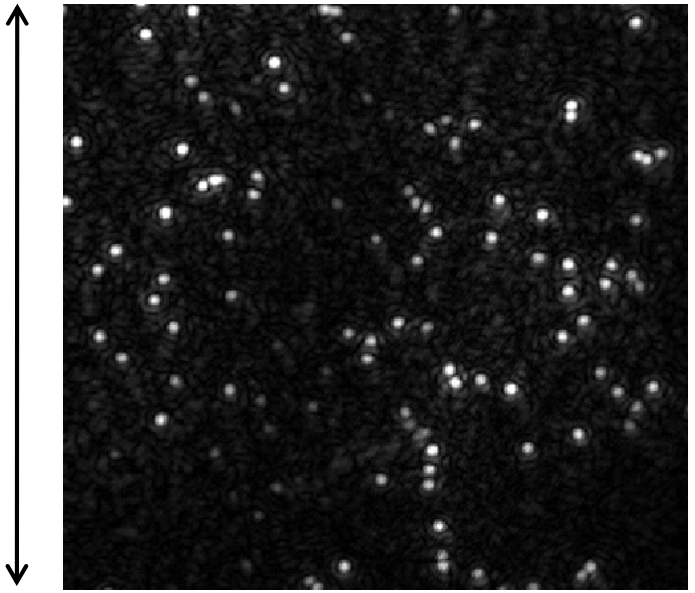
Filtering in the wave vectors space

2nd Fourier transform

# Heterodyne Numerical holography




Reconstructed image (50 nm Au beads)

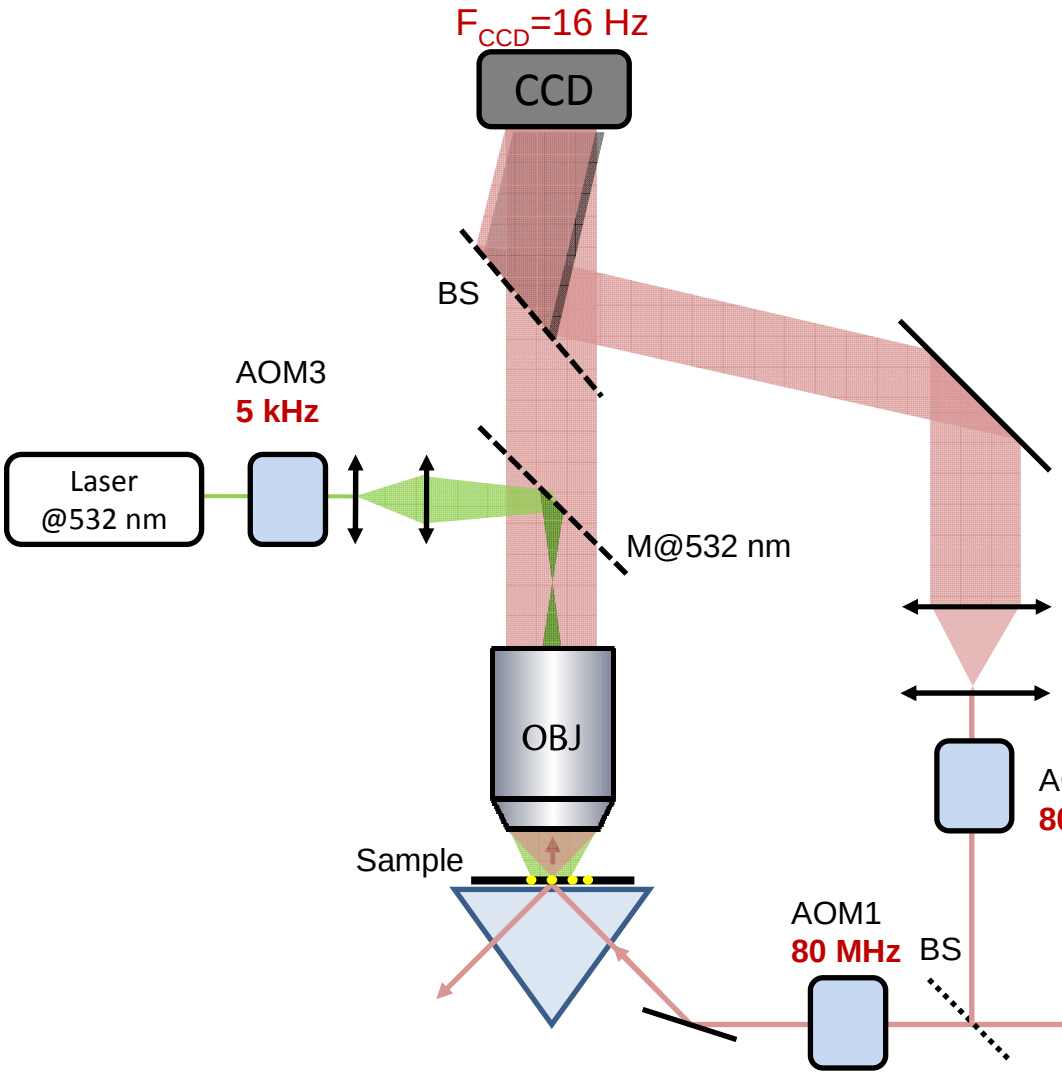


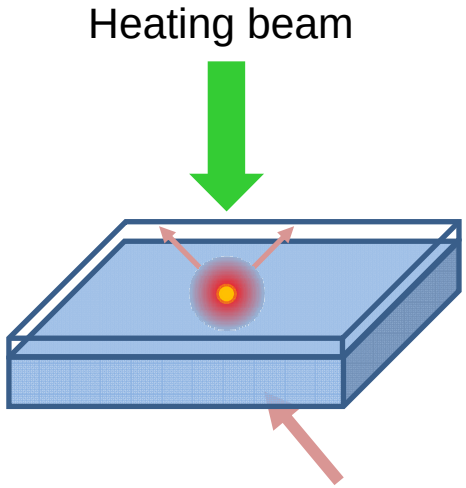

- Photon-noise limited detection[1]
- Sensitivity[1] : 1 photon per second per pixel

- <10 nm

[1] M. Atlan , M. Gross, E. Absil, Opt. Lett. 32, 1456 (2007)
M. Gross, M. Atlan, Opt. Lett. 32, 909 (2007)

# Photothermal
# Numerical holography



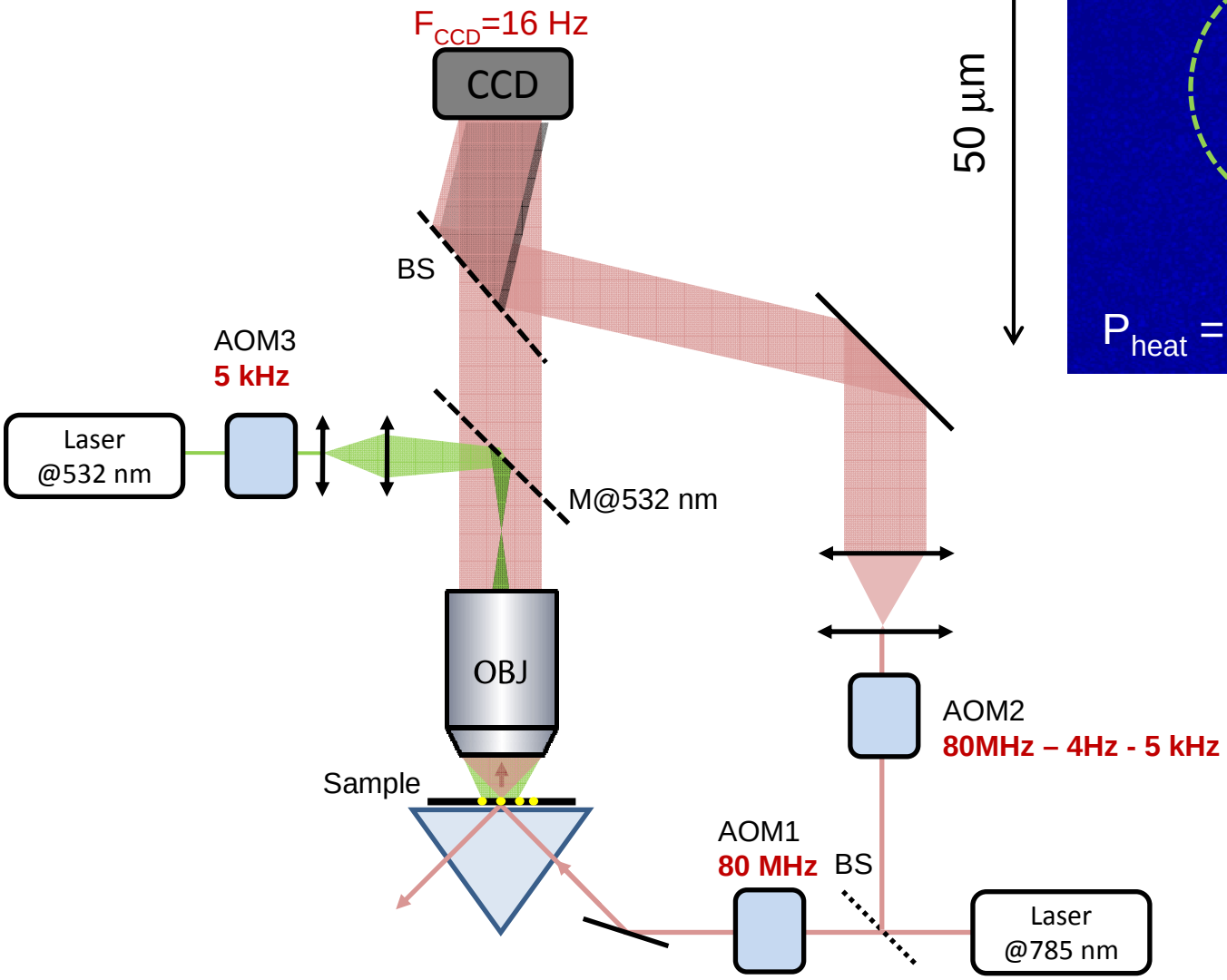

- Heat diffusion around the sphere :

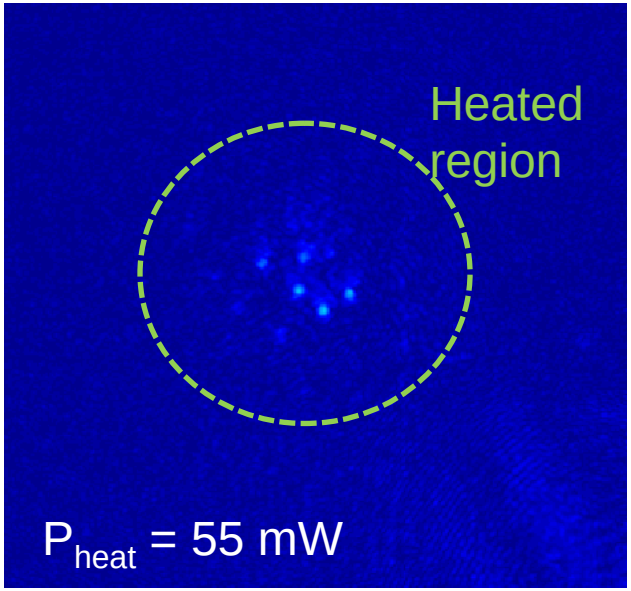
$$\mu = \sqrt{\frac{D}{\pi F}} \approx 7 \ \mu m \text{ at } 5 \text{ kHz} >> 50 \text{ nm !}$$

- Absorption decreases as $d^3$
  (Scattering decreases as $d^6$ )

⟹ Smaller particles ?

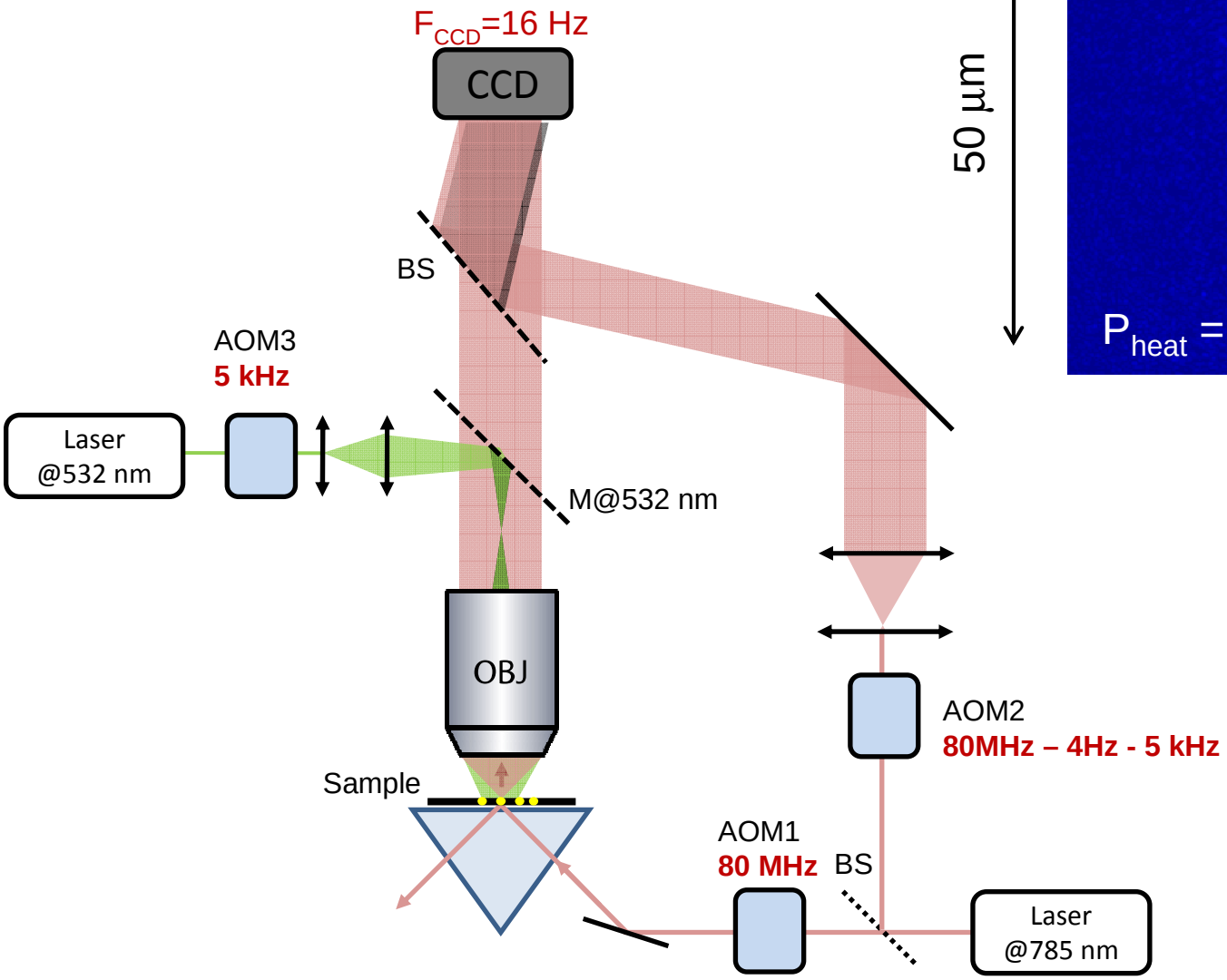
# Photothermal
# Numerical holography

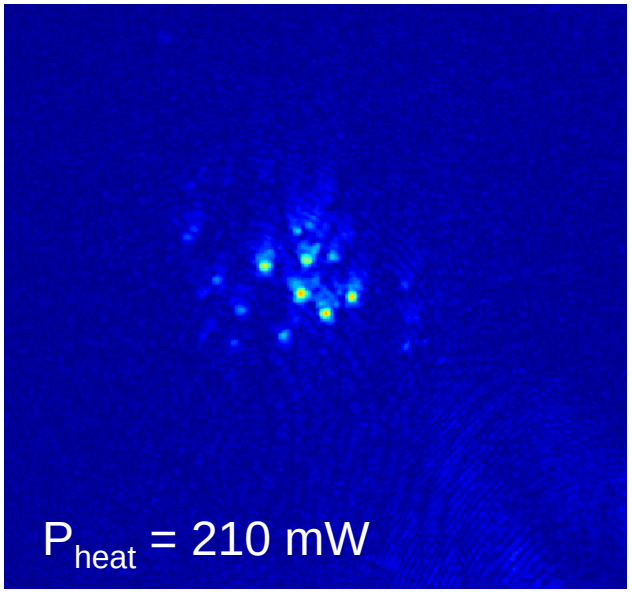


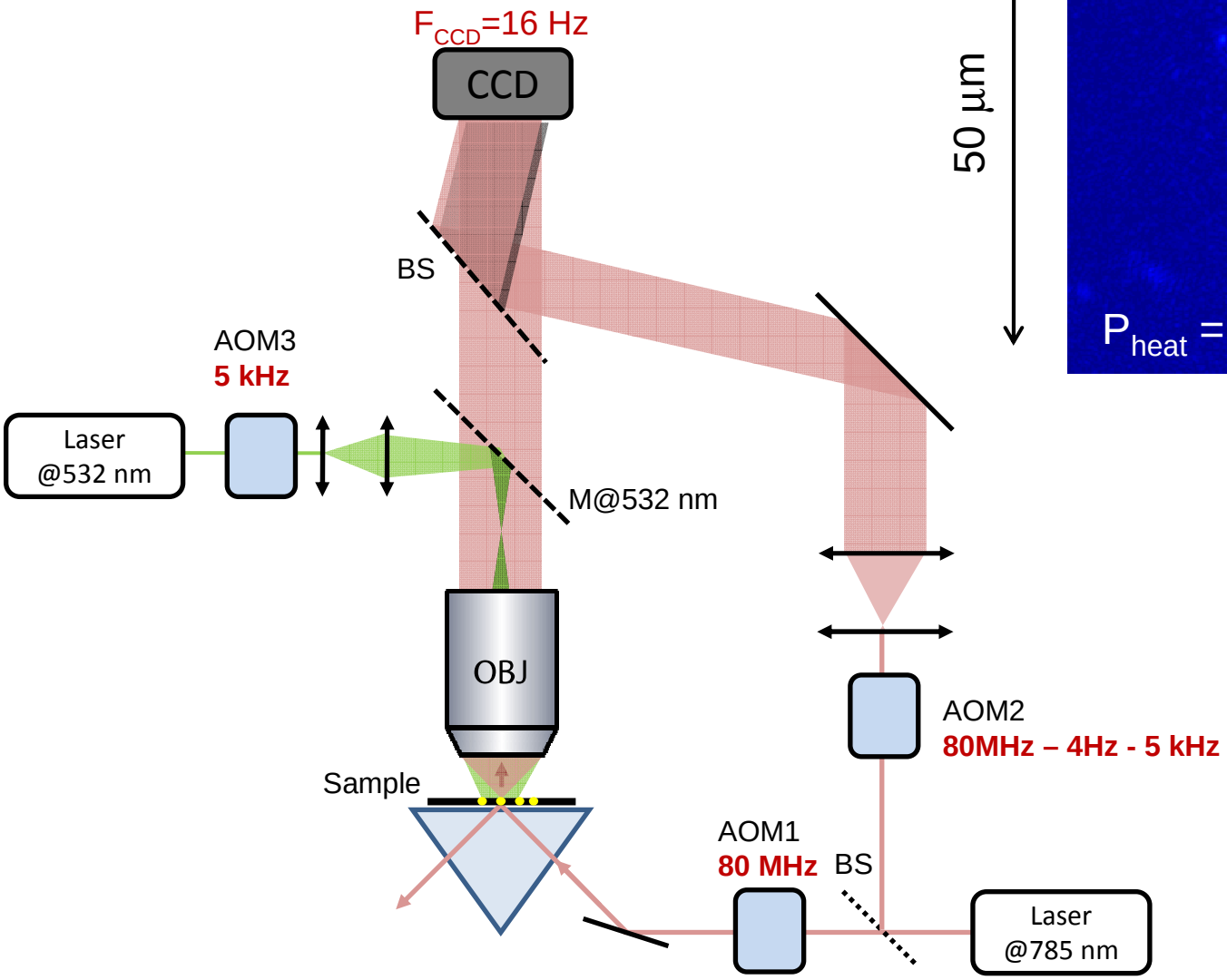

High selectivity

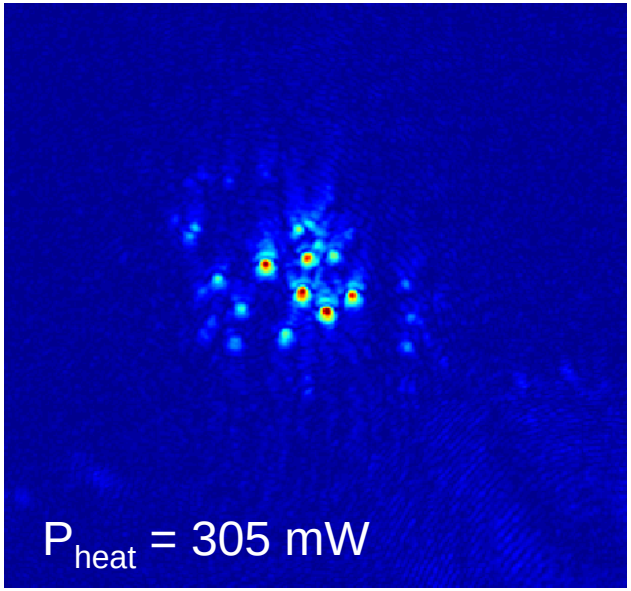
# Photothermal
# Numerical holography



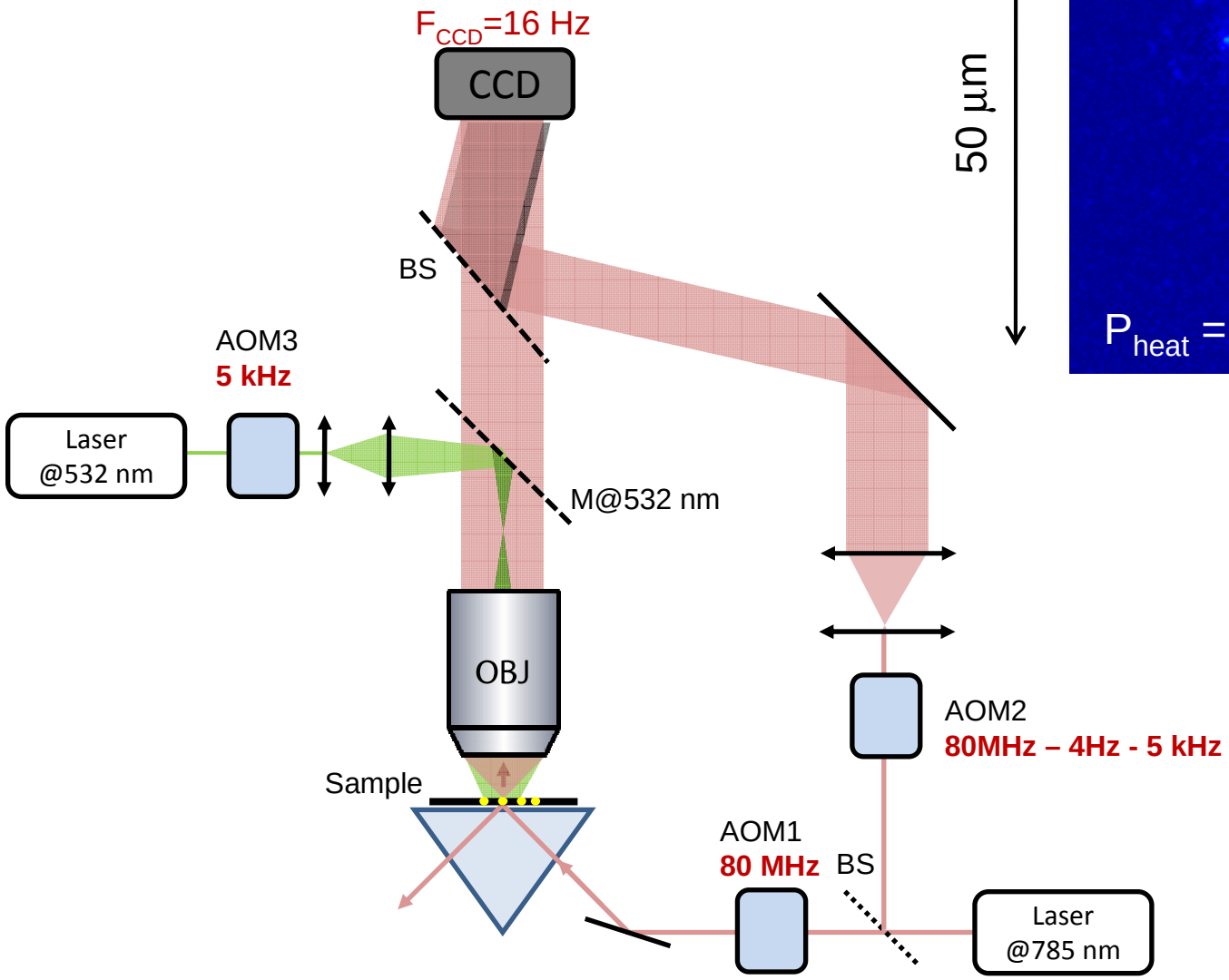



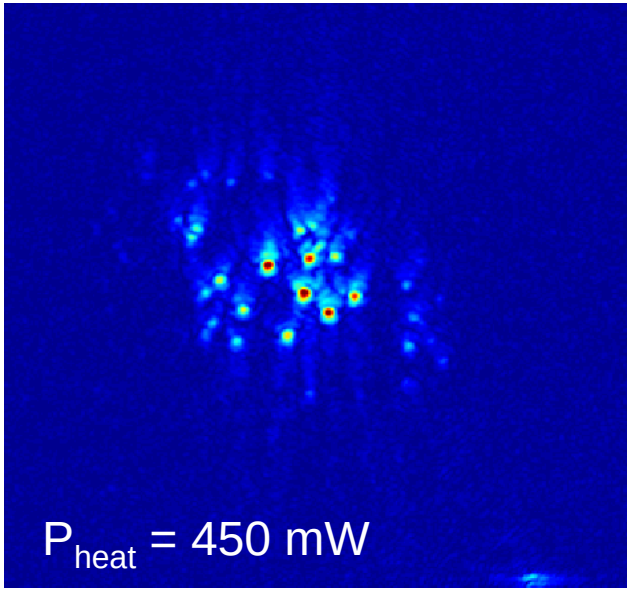
# Photothermal
# Numerical holography



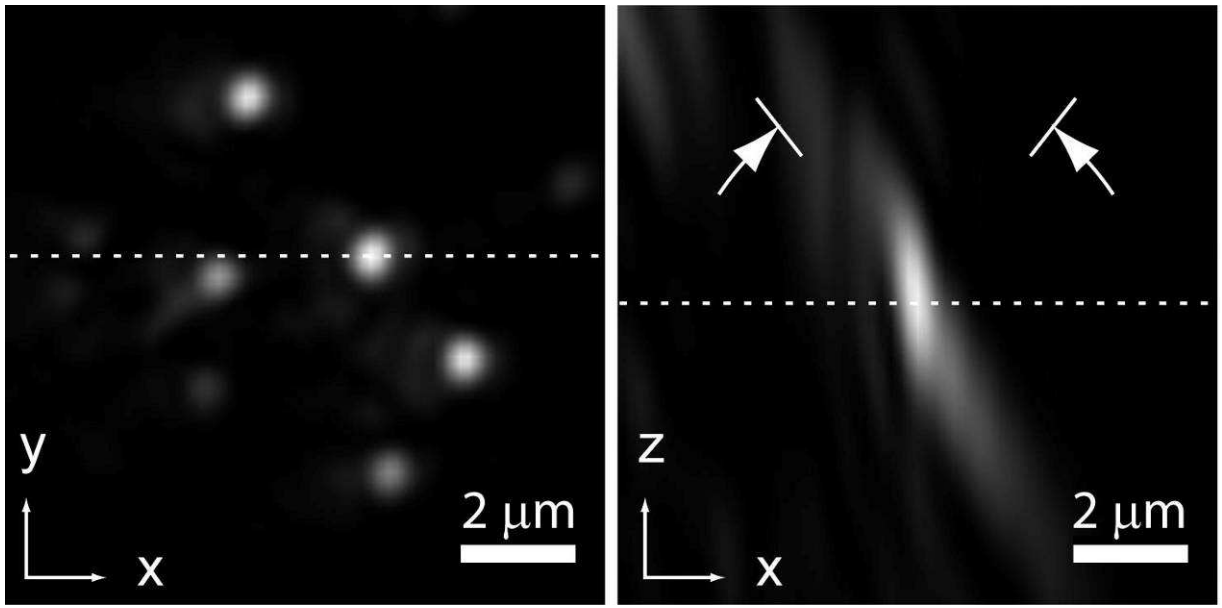
# Photothermal
# Numerical holography

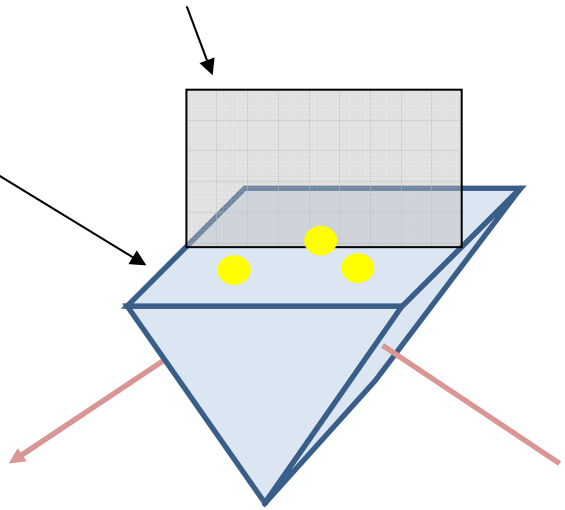



E.Absil, Optics Express (2009)

# 50 nm particles

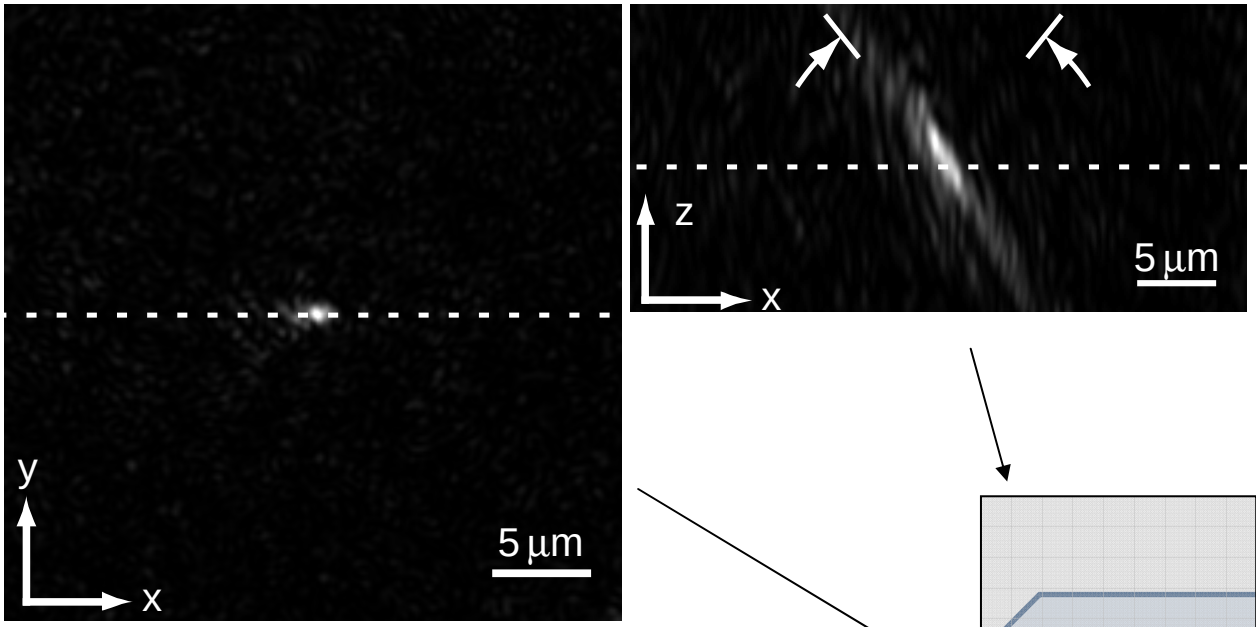


Heating :
5 kHz, 450 mW.

E.Absil, Optics Express (2009)

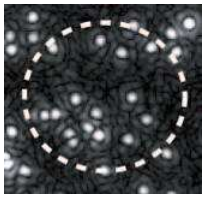
# 10 nm particles



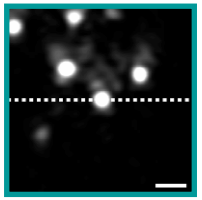

Heating :
5 kHz, 450 mW.

E.Absil, Optics Express (2009)

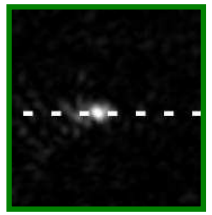
# Comparison of the signals



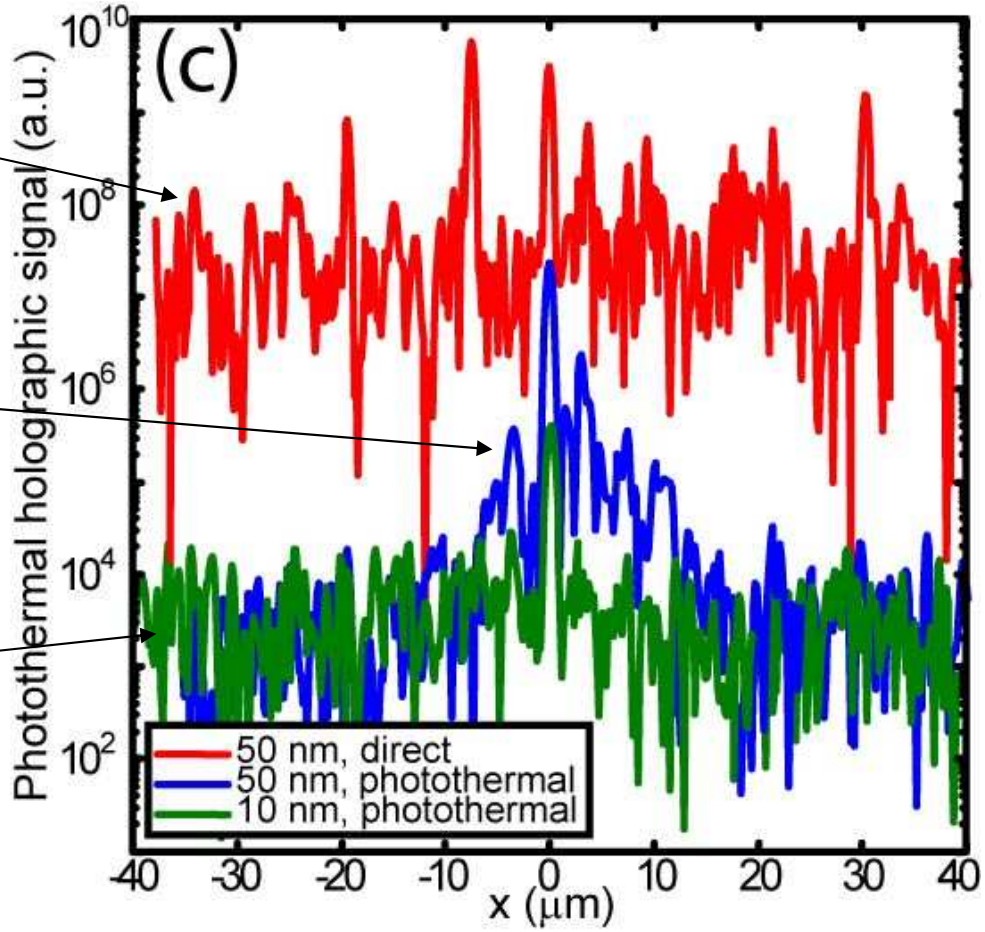
50 nm,
Non photothermal



50 nm,
Photothermal

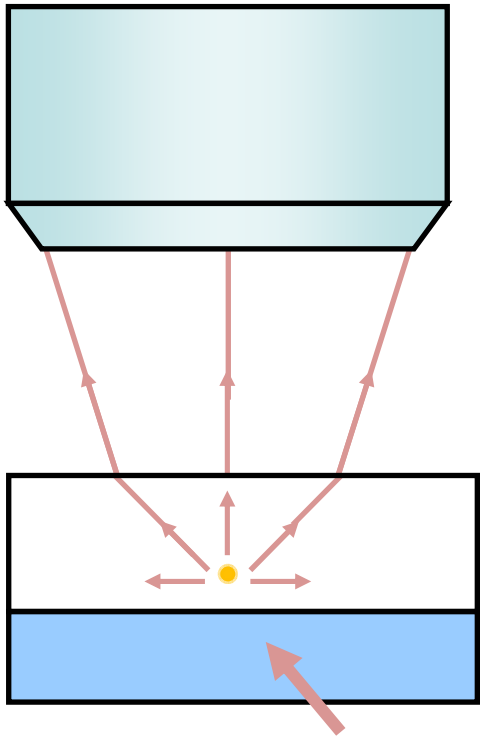


10 nm,
Photothermal

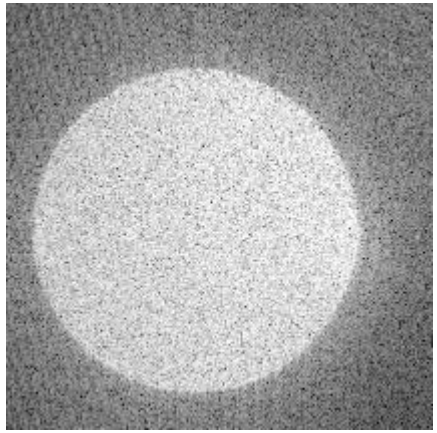



- The signal (scattering) is lower in photothermal mode
- BUT the signal to noise ratio is 1000 times higher for 50 nm beads

Reconstruction at the
exit pupil of the objective :
*k* wave vectors



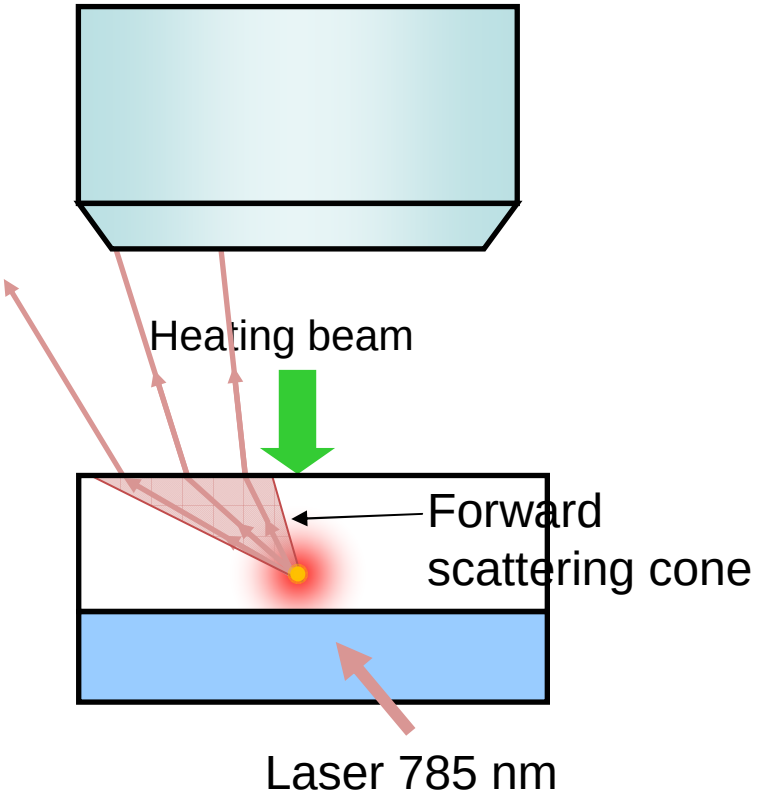
Laser 785 nm

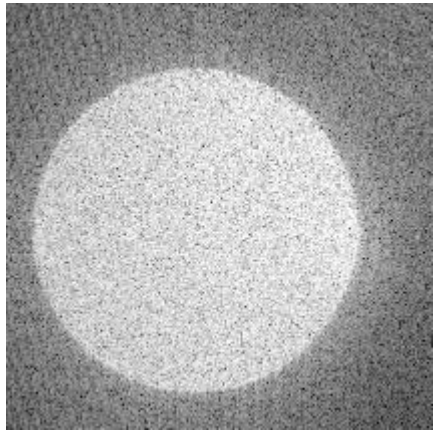


50 nm beads,
non photothermal

Quasi isotropic
scattering

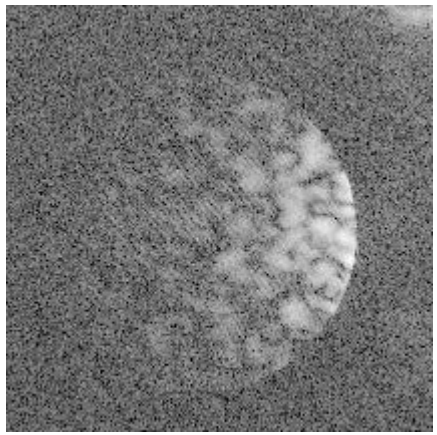
Reconstruction at the
exit pupil of the objective :
*k* wave vectors



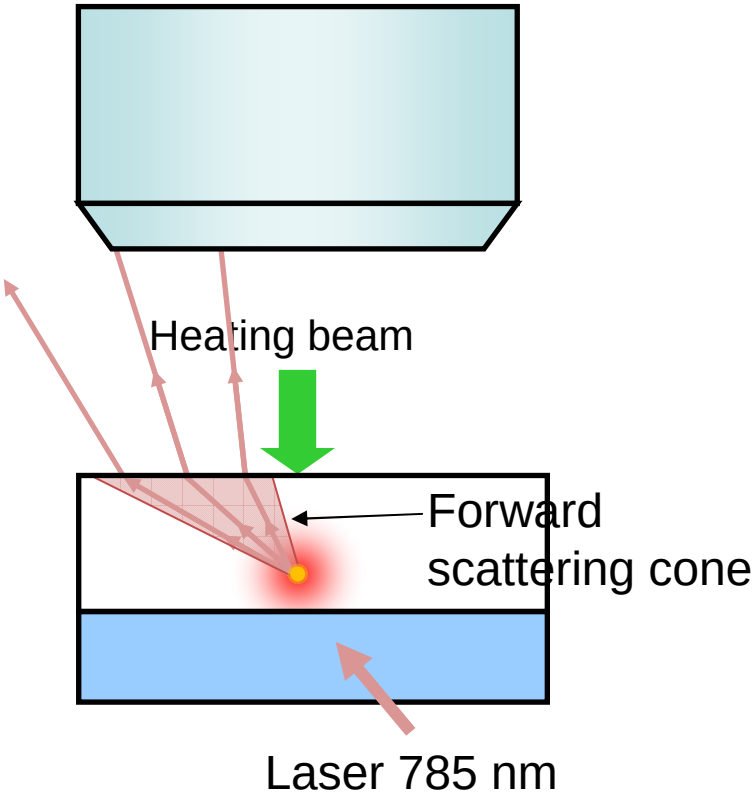
50 nm beads,
non photothermal

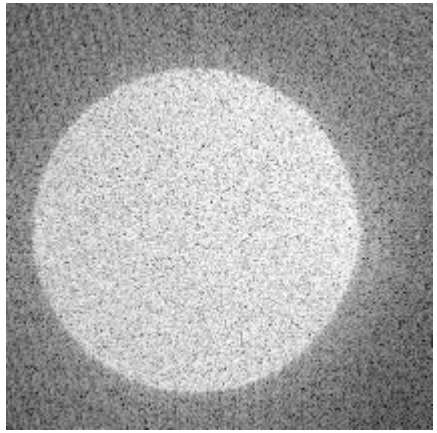
Quasi isotropic
scattering



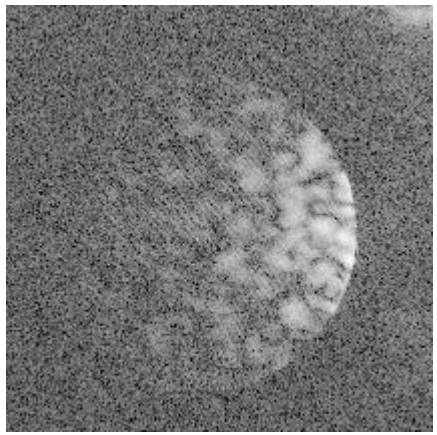
50 nm beads,
photothermal

Reconstruction at the
exit pupil of the objective :
*k* wave vectors



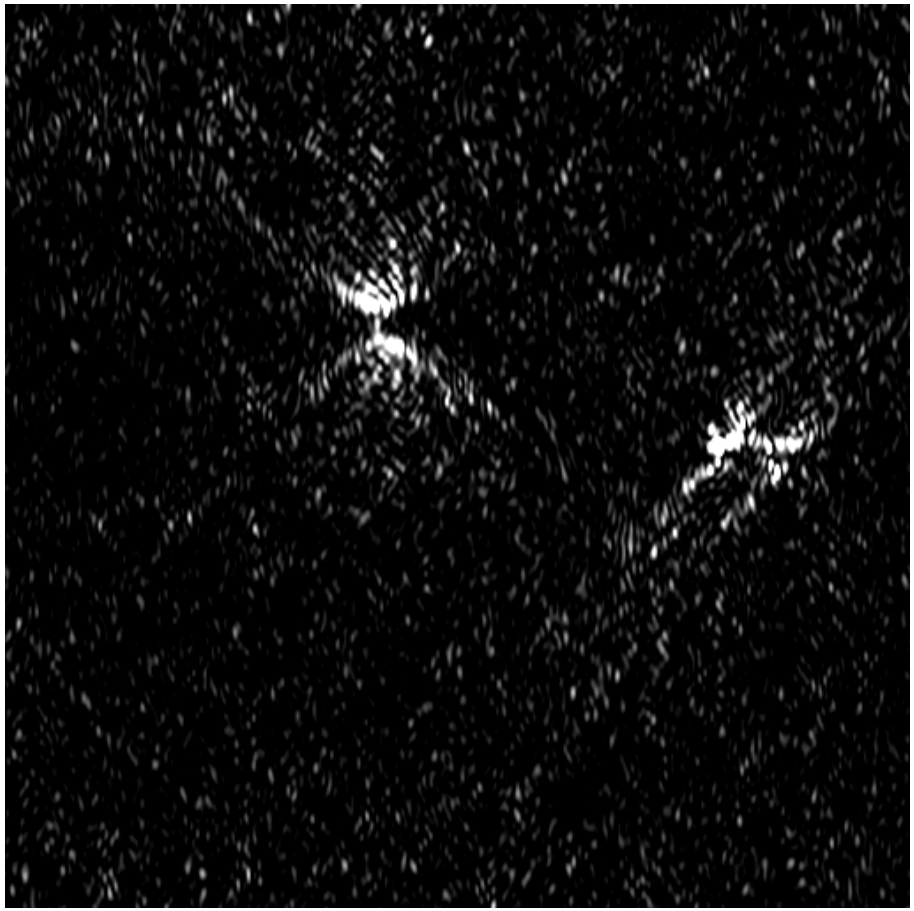



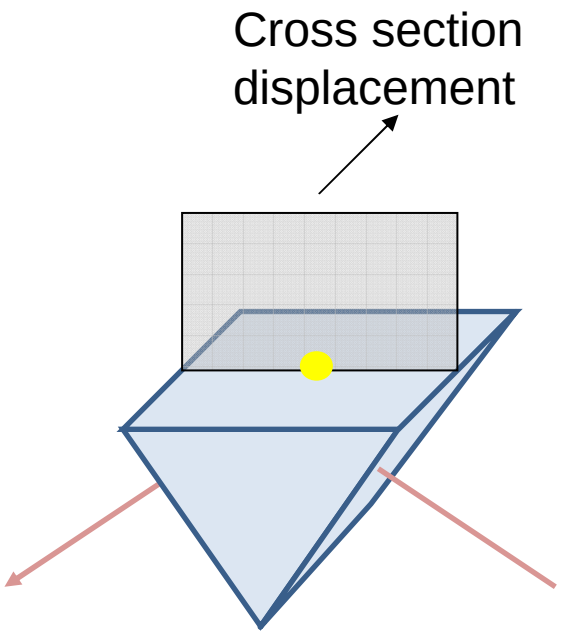
50 nm beads,
non photothermal



50 nm beads,
photothermal

10 nm beads,
photothermal



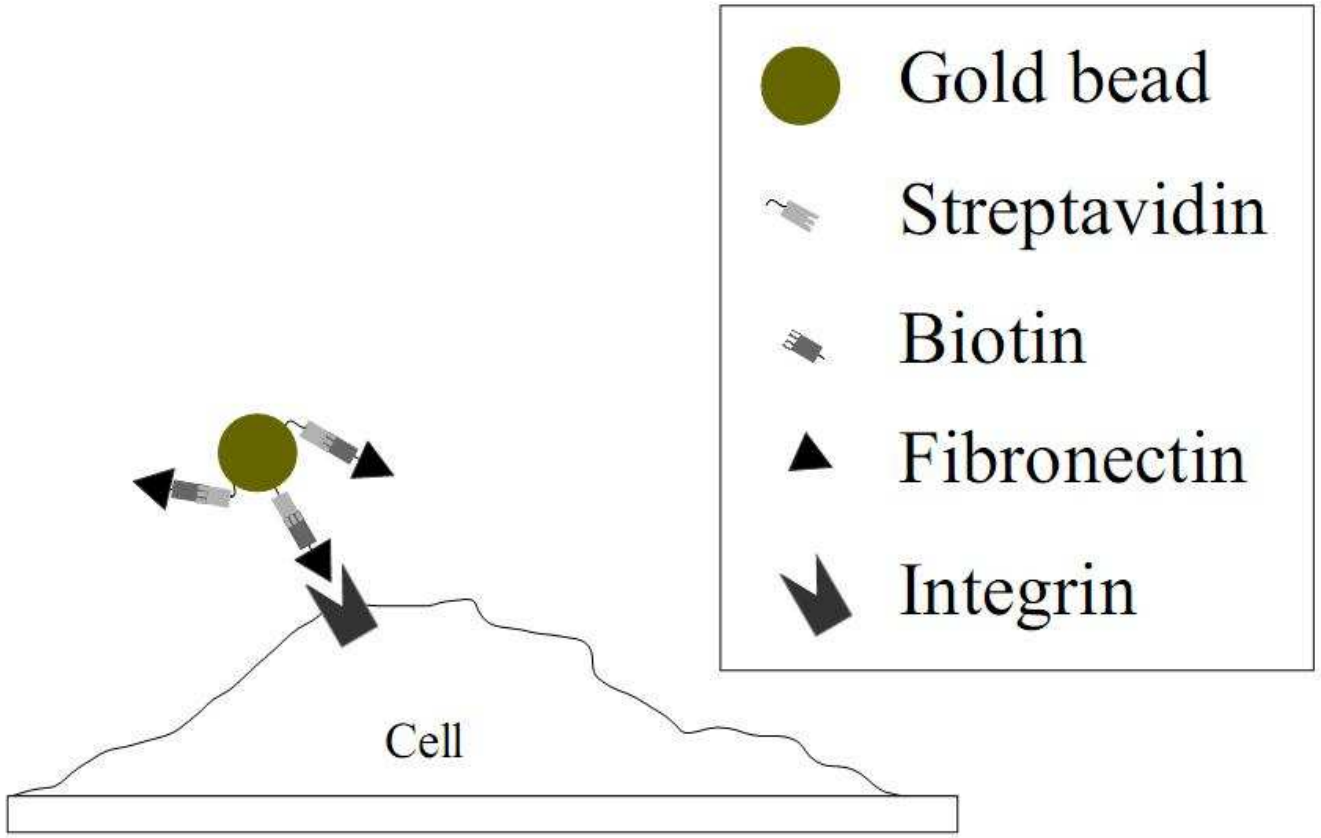



10 nm beads

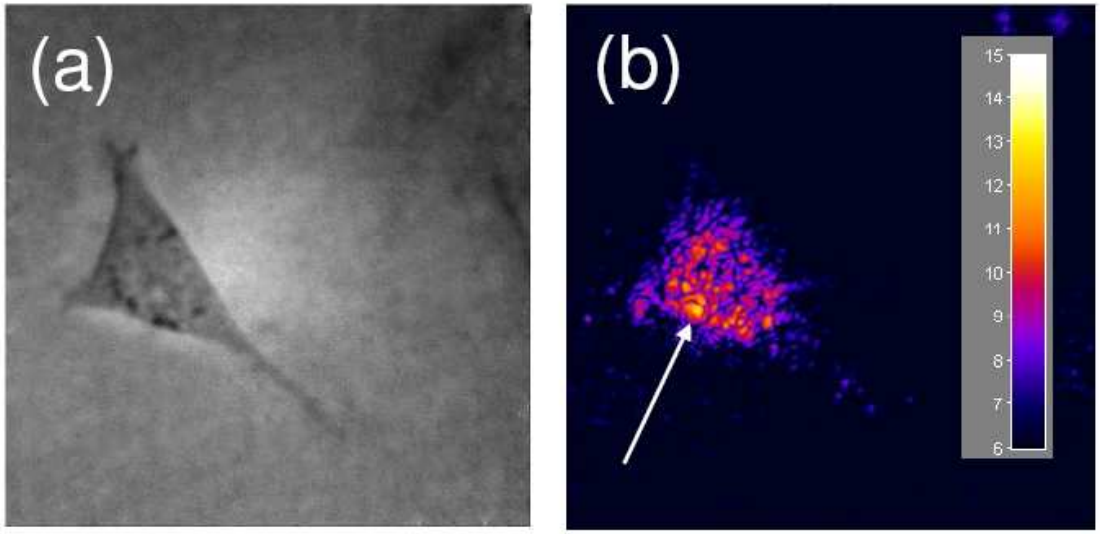
Different scattering from gold beads and dust
Film reconstructed from a single hologram (acquisition < 5s)

# Sample preparation

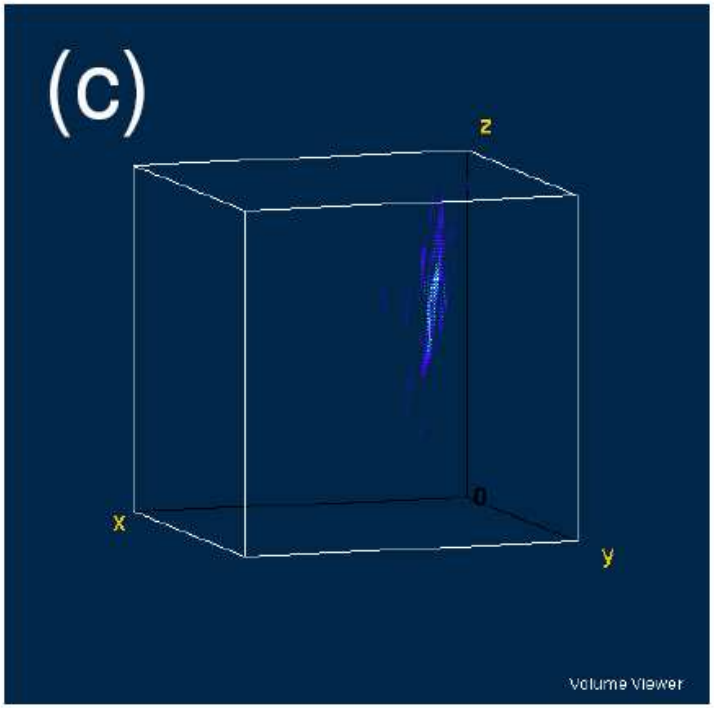
**Sample: 3T3 mouse fibroblast + 40 nm gold particles**



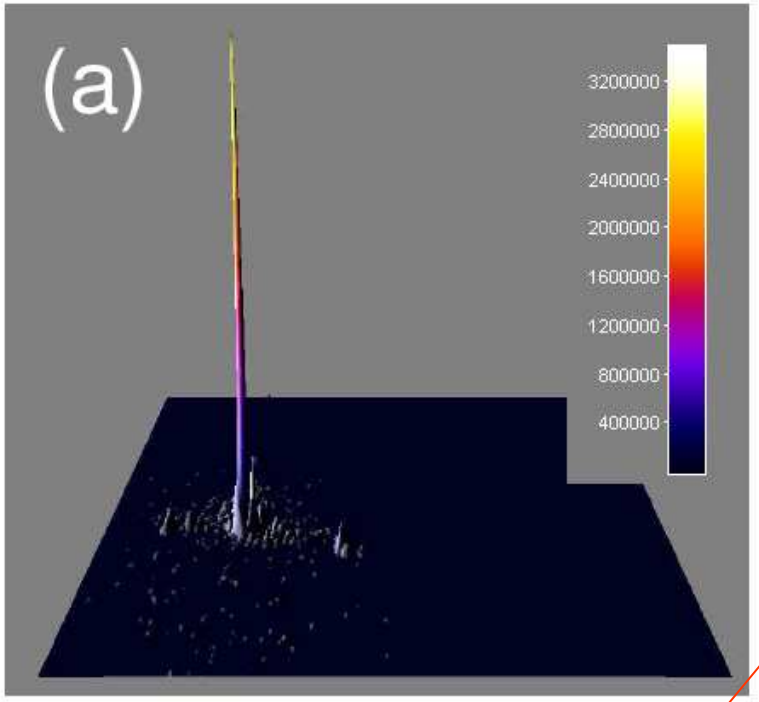

(Philippe Bun, Maïté Coppey-Moisan: Département de Biologie Cellulaire, Institut Jacques Monod, Paris.)

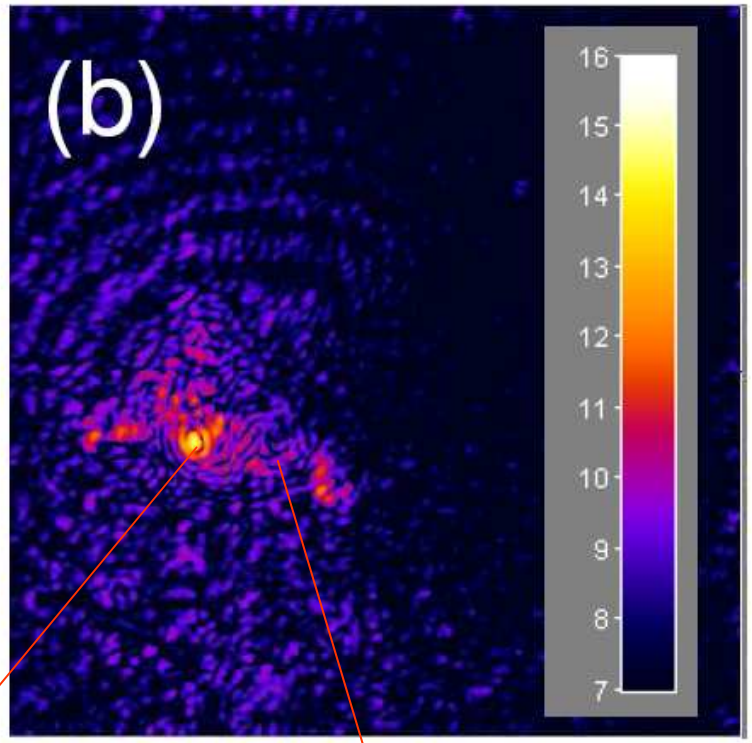



Bille d’or 40 nm
Accumulation 32 images
(env. 2s)

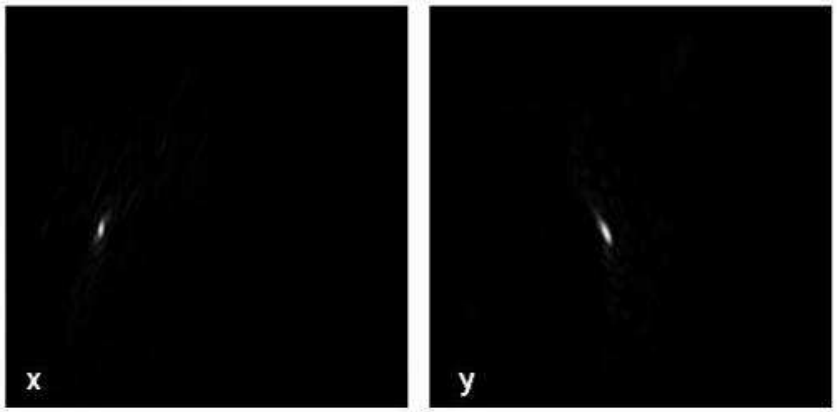



N.Warnasooriya, F. Joud et al., submitted to Optics Express

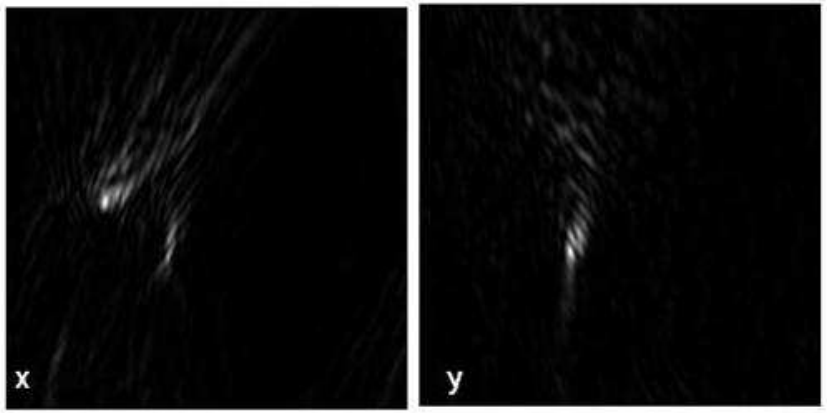



Coupes dans la reconstruction 3D :

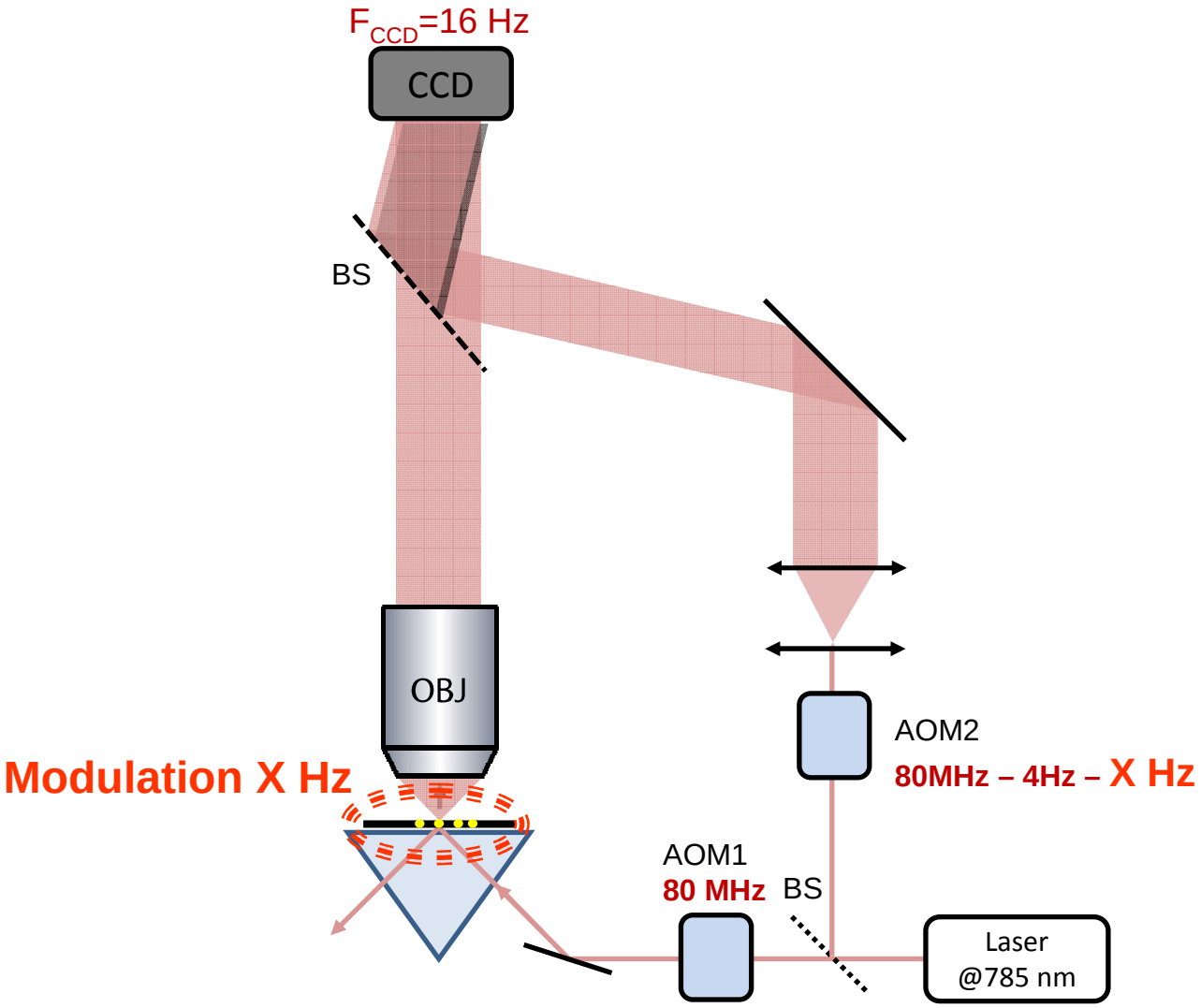



Bille



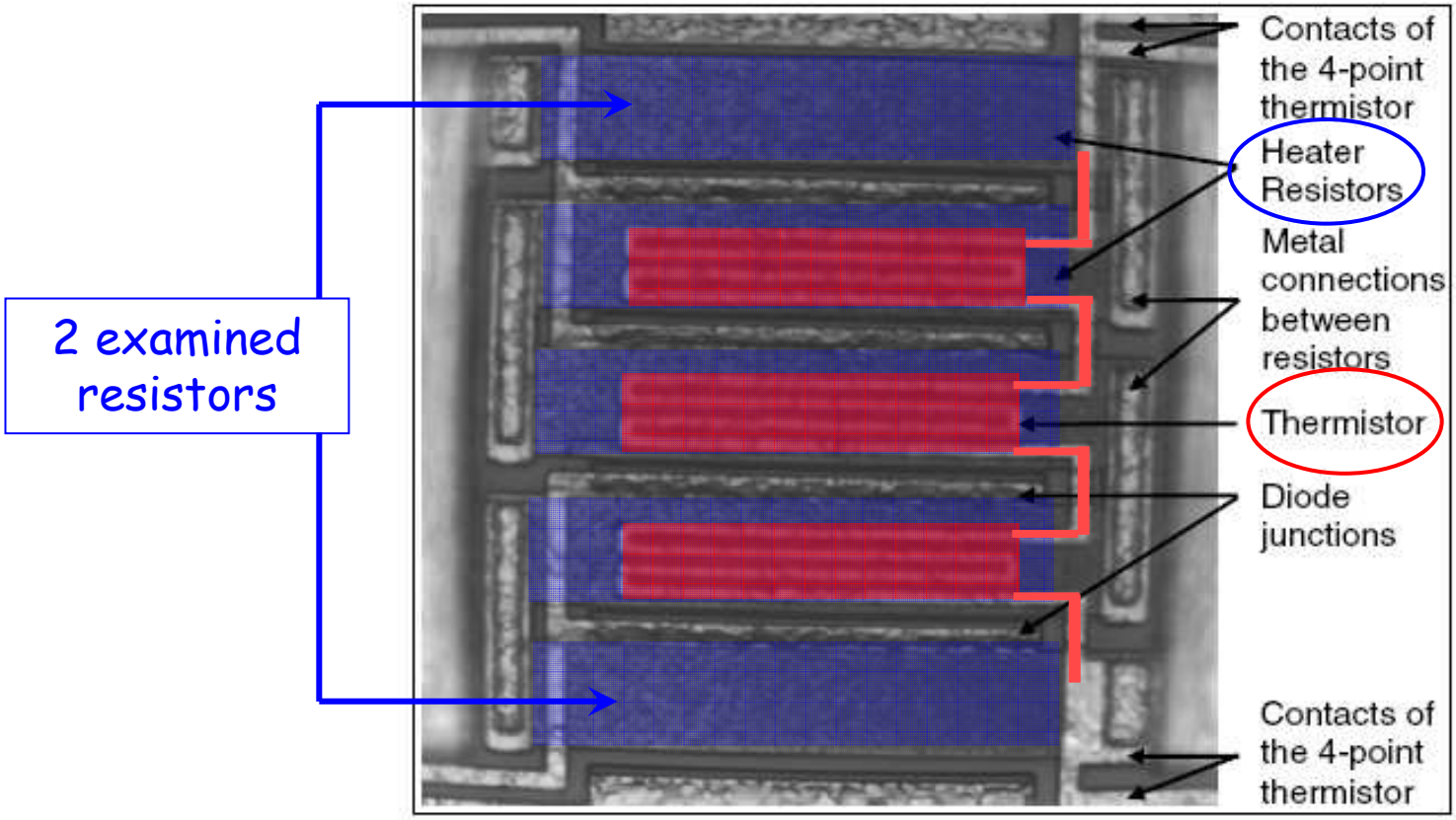

cellule

# D’autres types de modulations ?



# Test-Sample

Integrated circuit consisting of 5 resistors: $R_{Heat} \approx 500\ \Omega$

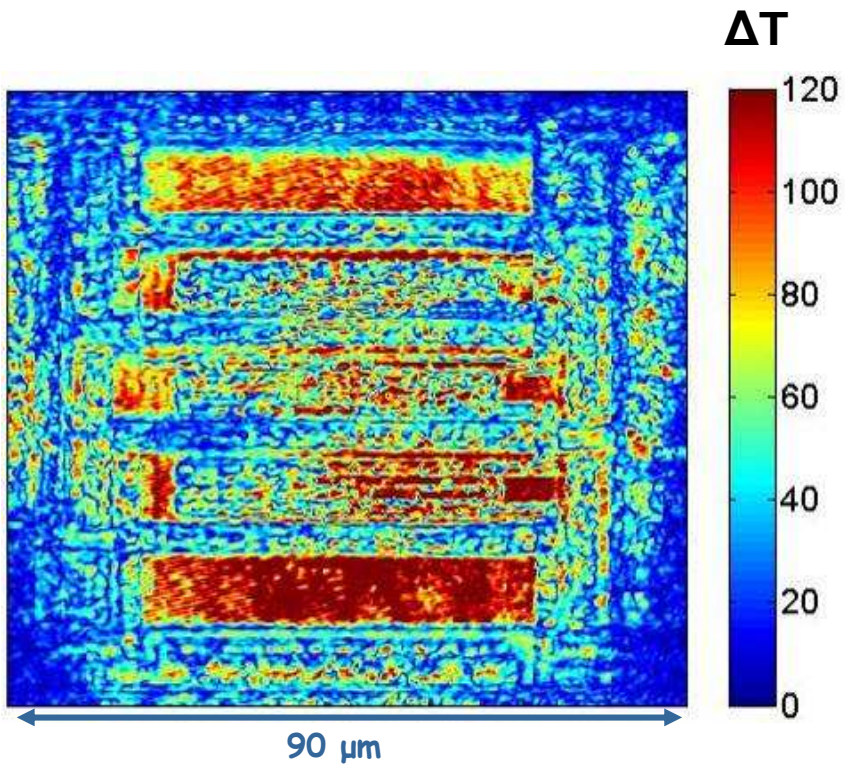



G. Tessier et al., JPD-AP **39**, 4159, (2006)

# Imaging and Calibration

$\Delta f = \frac{1}{4} \cdot f_{CCD} + F_H$

Heater ON : $F_{VAR} = F_H$ – const.




- Accumulation time : 15 sec
- Definition: 410 x 410 pixel

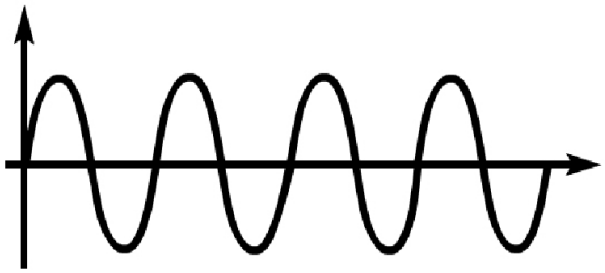
- Temperature resolution:
  ΔT=0.35 K for acquisition time of ~15 sec
  ΔT=0.70 K for acquisition time of < 5 sec

- Resolution = diffraction limit ( λ/(2*NA) )

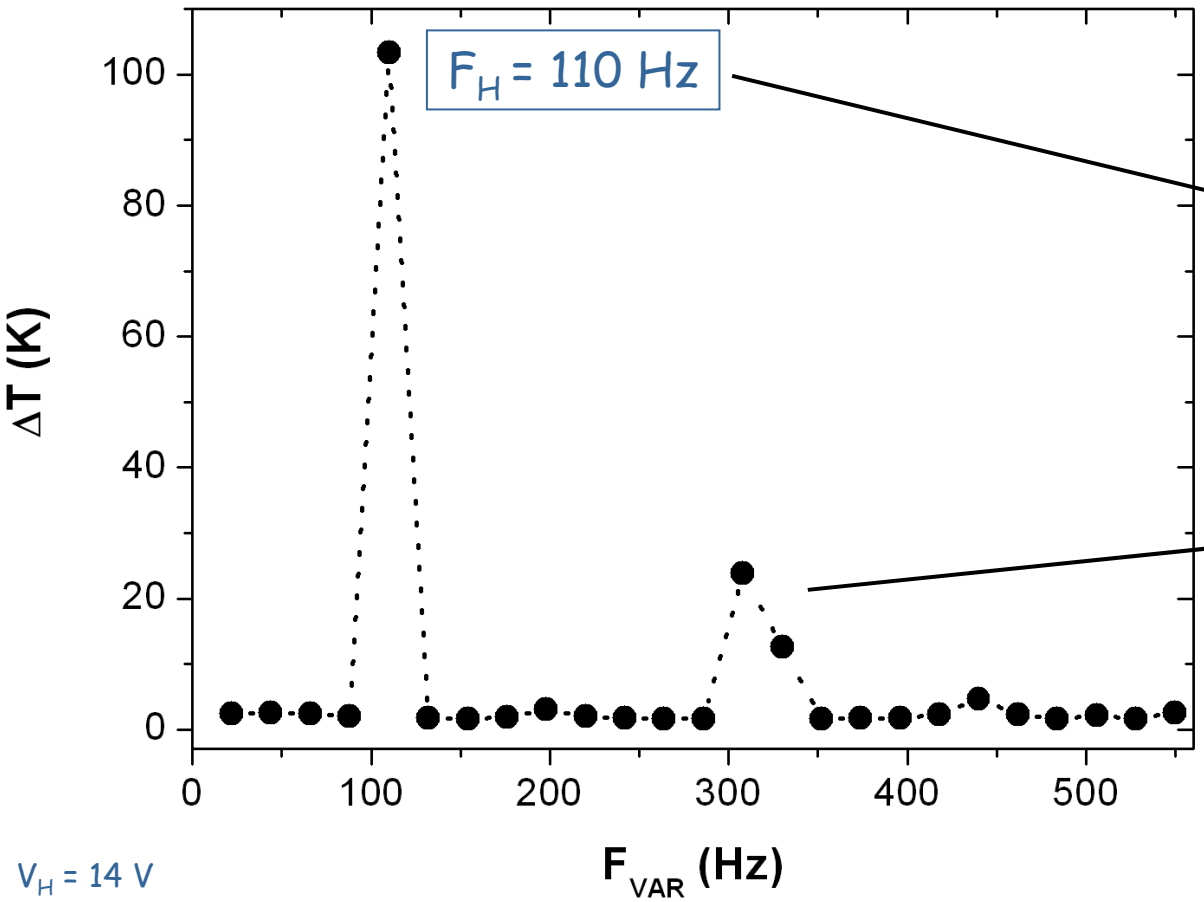
# Thermal response of a sine wave excitation

**3. $\Delta f = \frac{1}{4} \cdot f_{CCD} + F_{VAR}$**

V (t) Heater ON : $F_H$ =110 Hz, sinus



frequency-domain :




Peak at $F_{VAR}$ = 110 Hz (= $F_H$)

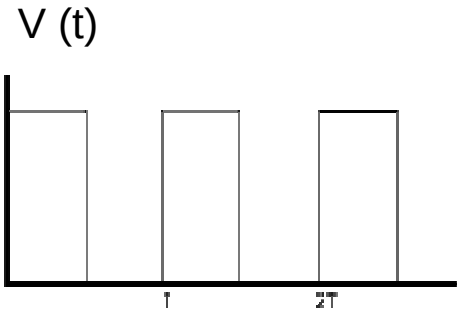
Peaks at $F_{VAR}$ > 110 Hz
➔ parasitic signals

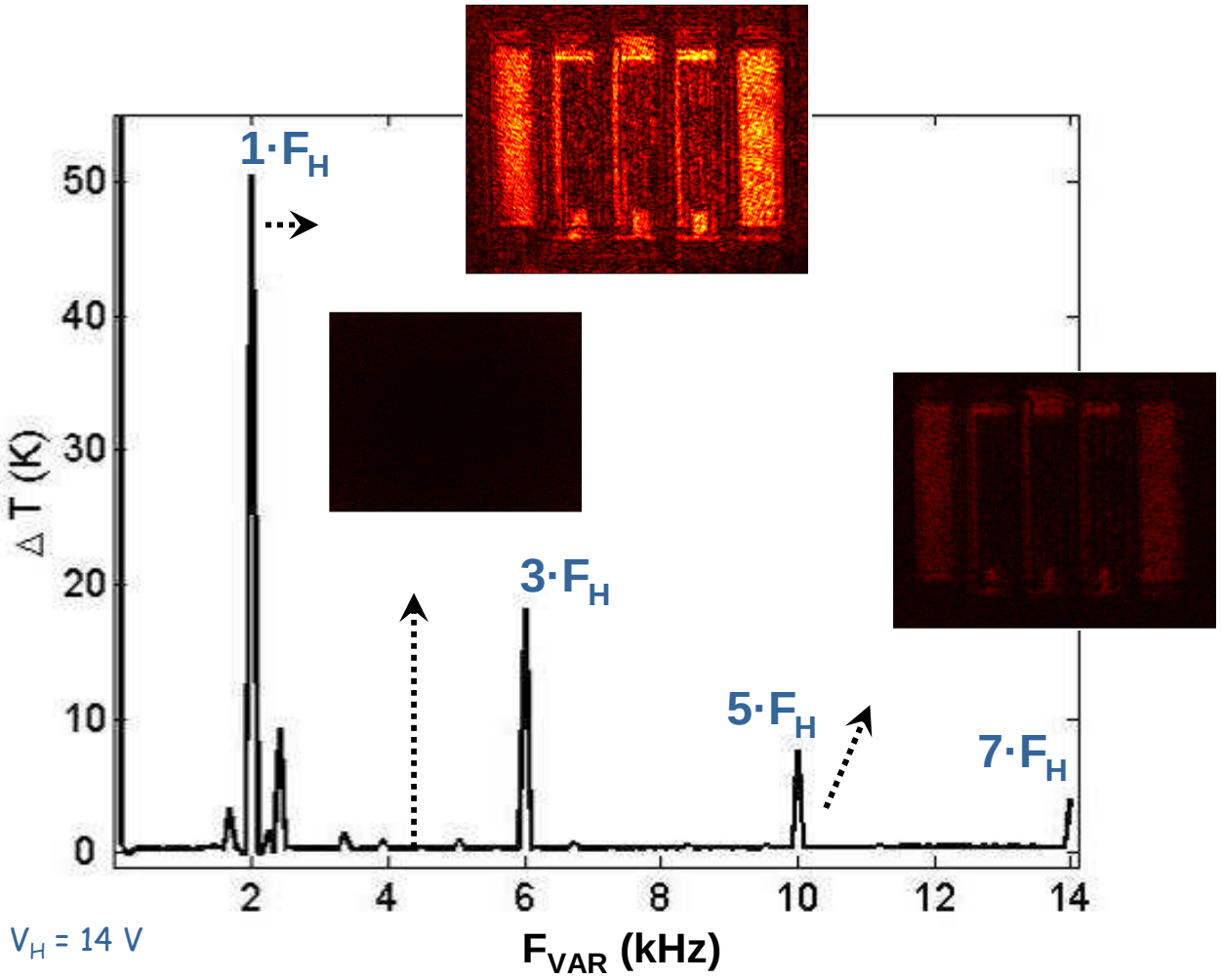
$V_H$ = 14 V

# Thermal square wave excitation

**3. $\Delta f = \frac{1}{4} \cdot f_{CCD} + F_{VAR}$**

Heater ON : $F_H$ = 2 kHz, square wave




➔ Harmonics at

$F_{VAR} = (2n-1) \cdot F_H$

S. Suck et al. Submitted to Appl. Phys. Lett.