Micro-cantilever heating induced by laser absorption: observation of a thermo-optical bistability

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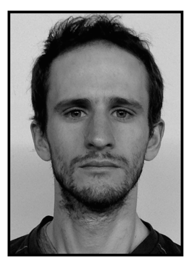
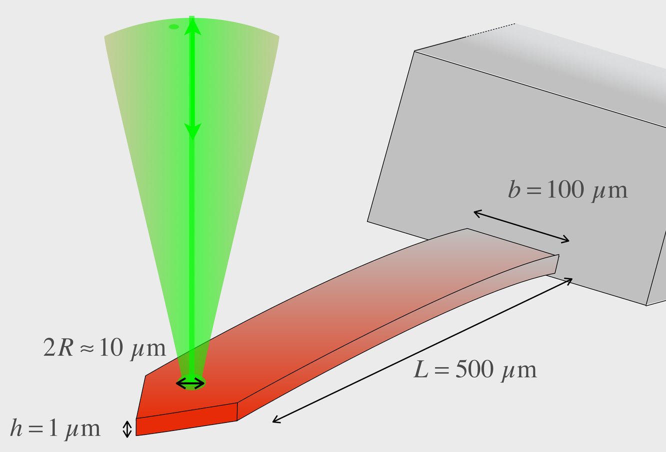



Temperature rise of a micro-cantilever in vacuum heated by a focused laser beam

We study the temperature rise in raw silicon micro-cantilever illuminated at his extremity by a focused laser beam. Since silicon is a poor mirror for visible light, with only 37 % of reflectivity, thus radiation absorption is large. In the case where the cantilever is in vacuum, the main dissipation process for the heat due to the absorption of light is thermal conduction along the cantilever. The non-linear stationary temperature profile can be estimated using Fourier law for heat transfer. Because of microscale cross-section, typically 100 µm², the temperature rise can be larger than a thousand °C with little more than 10 mW illumination.



Fourier's law

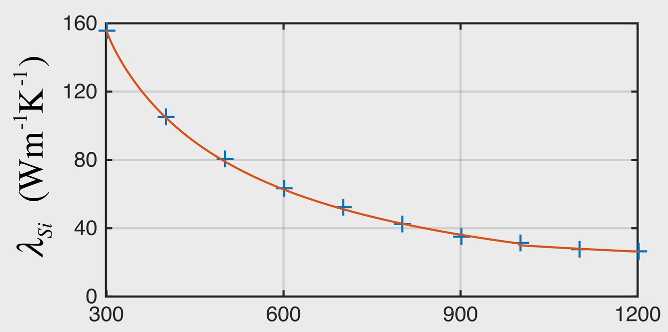
$$J_{th} = \frac{A I_0}{bh} = -\lambda_{Si}(\theta)\frac{d\theta}{dx}$$

- J_{th} Absolute value of the heat flux (W/m²)
- A Fraction of light absorbed by the cantilever (-)
- I_0 incident light power (W)
- λ_{Si} Thermal conductivity of silicon (W/m/K)

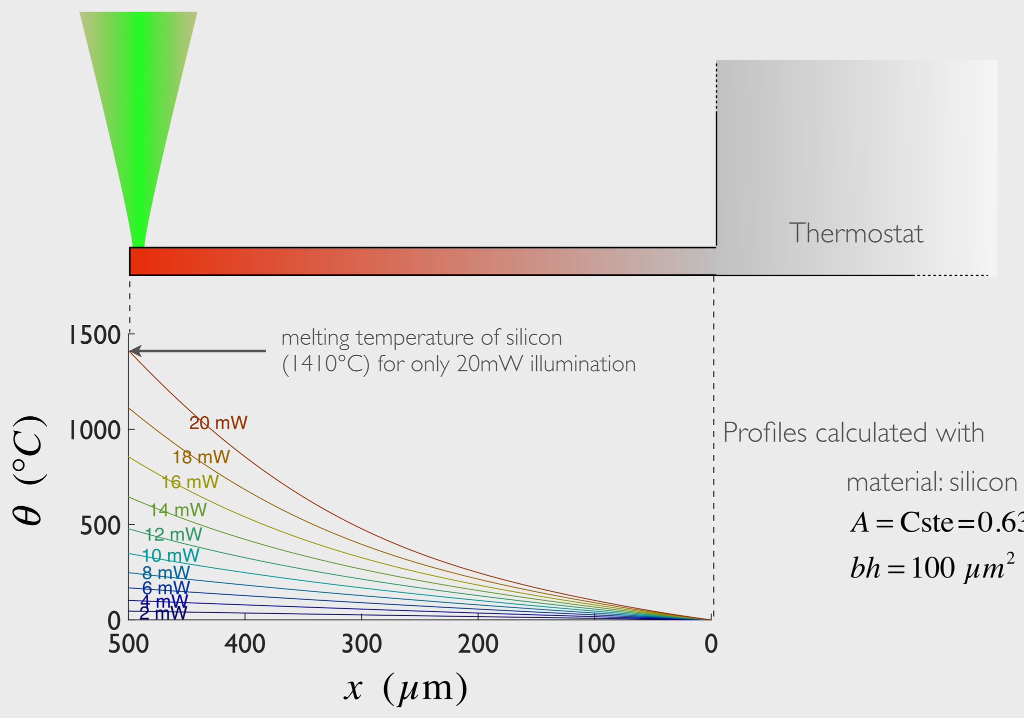
by integrating Fourier's law

$$\Lambda(\theta) = \int_{T_0}^{T} \lambda_{Si}(\theta')d\theta' = \frac{x}{bh} A I_0$$

$$\theta = \Lambda^{-1}\left(\frac{x}{bh} A I_0\right)$$



Non linear temperature profiles



Profiles calculated with

material: silicon

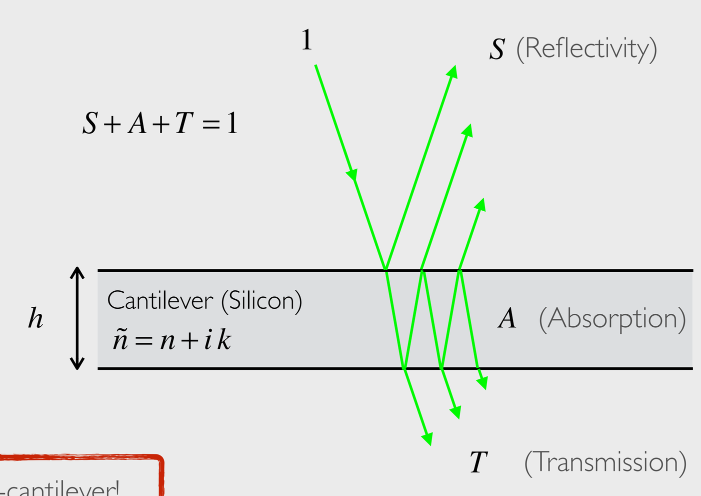
$A = \text{Cste} = 0.63$ (For a semi-infinite medium)

$bh = 100\ \mu m^2$

The micro-cantilever as a Fabry-Pérot cavity with absorption

When the thickness of the cantilever is comparable or less than the absorption length α_{Si}^{-1} (for visible light $\alpha_{Si}^{-1} \approx 1.5\mu m$), the cantilever is partially transparent. The intensity within the cantilever results from the interferences between multiple reflections at the two surfaces. In this limit, the cantilever must be treated as a Fabry-Pérot cavity with absorption. The part of the light absorbed by the cantilever is then a function of wavelength, local thickness and temperature.

Cantilever ≡ low Q Fabry-Pérot cavity



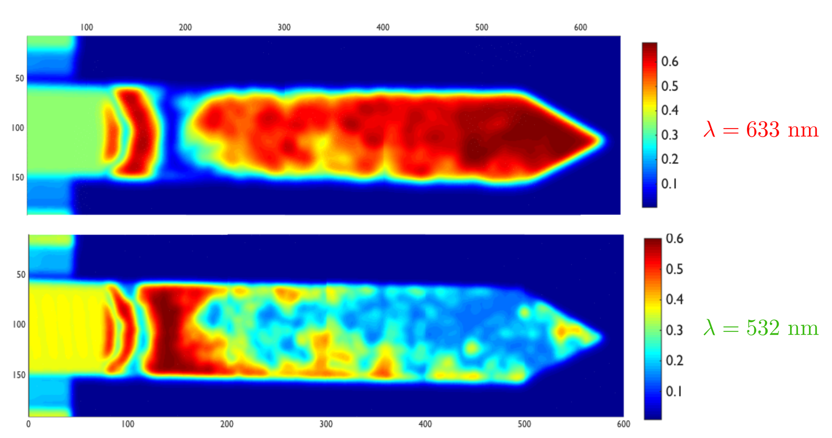
internal reflections in the micro-cantilever!

$A \neq \text{Cste}$

$A = A(h, \tilde{n}), \quad \tilde{n} = \tilde{n}(\lambda, \theta)$

Reflectivity map of a micro-cantilever ($1\mu m \times 100\mu m \times 500\mu m$)

Reflectivity S depends on
-the local thickness h
-laser wavelength λ



We can calculate absorption coefficient

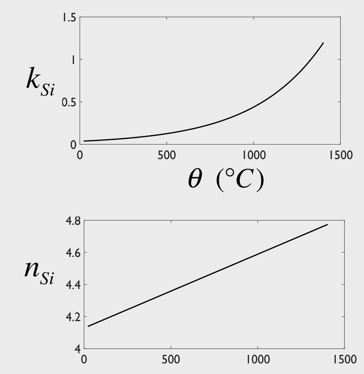
$$A(\lambda_0, \theta, h) = \frac{(1-R)\left(1 + Re^{-\alpha} - Re^{-2\alpha} - e^{-\alpha}\right)}{1 - 2Re^{-\alpha}\cos\phi + R^2 e^{-2\alpha}}$$

$$\phi = \frac{4\pi}{\lambda_0} nh$$

$$\alpha = \frac{4\pi}{\lambda_0} kh$$

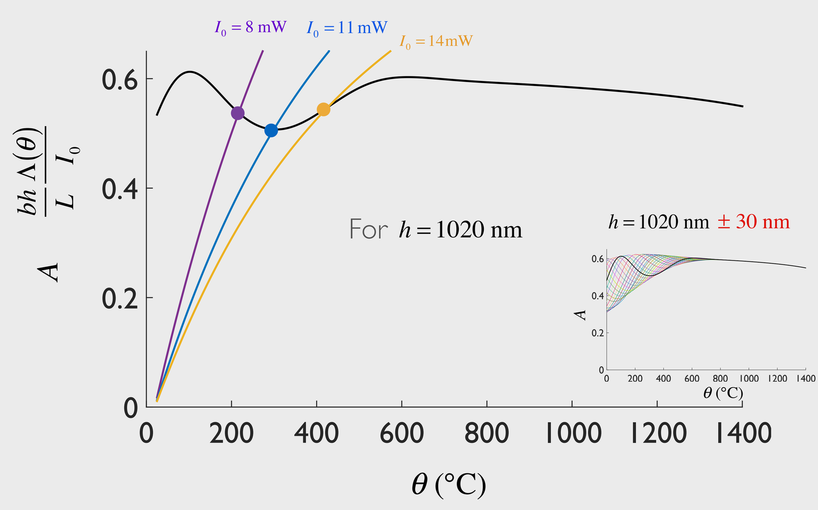
$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \quad \text{(reflectivity when } h \to \infty\text{)}$$

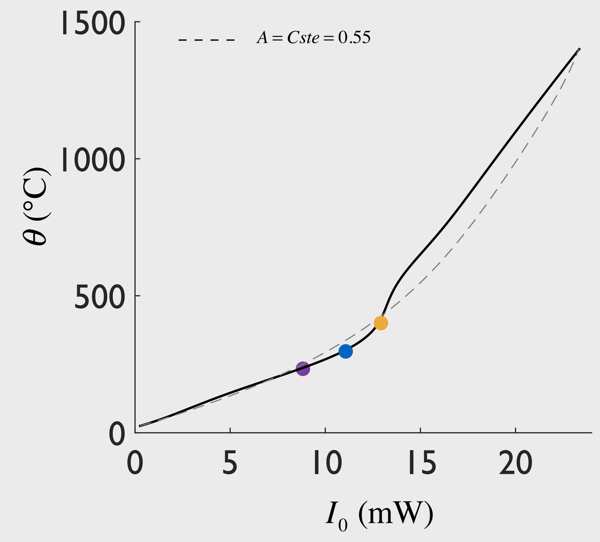
Optical properties of silicon ($\lambda = 532$ nm)



Thermo-optical coupling

We must solve $\frac{bh}{L}\Lambda(\theta) = A(\theta) I_0$

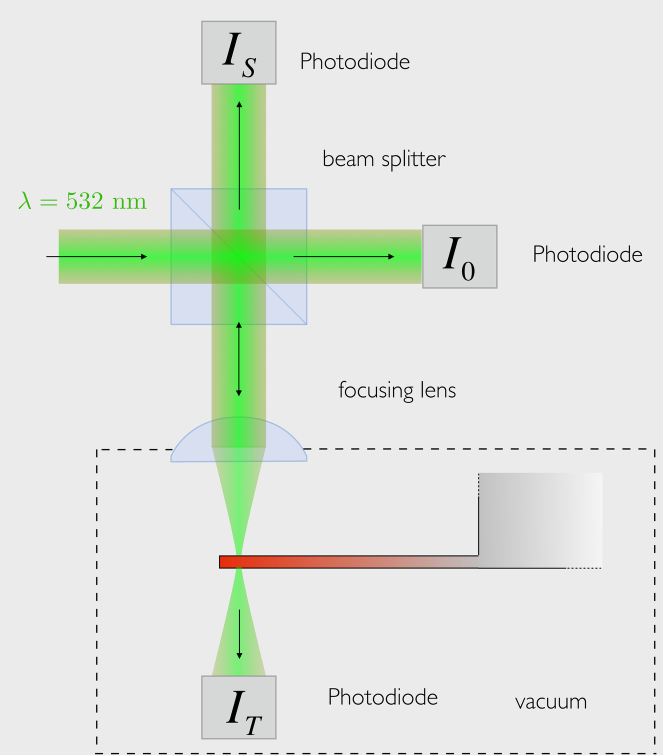




Graphical determination of the θ vs I_0 curve

Observation of a thermo-optical bistability

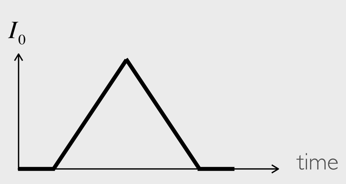
The setup

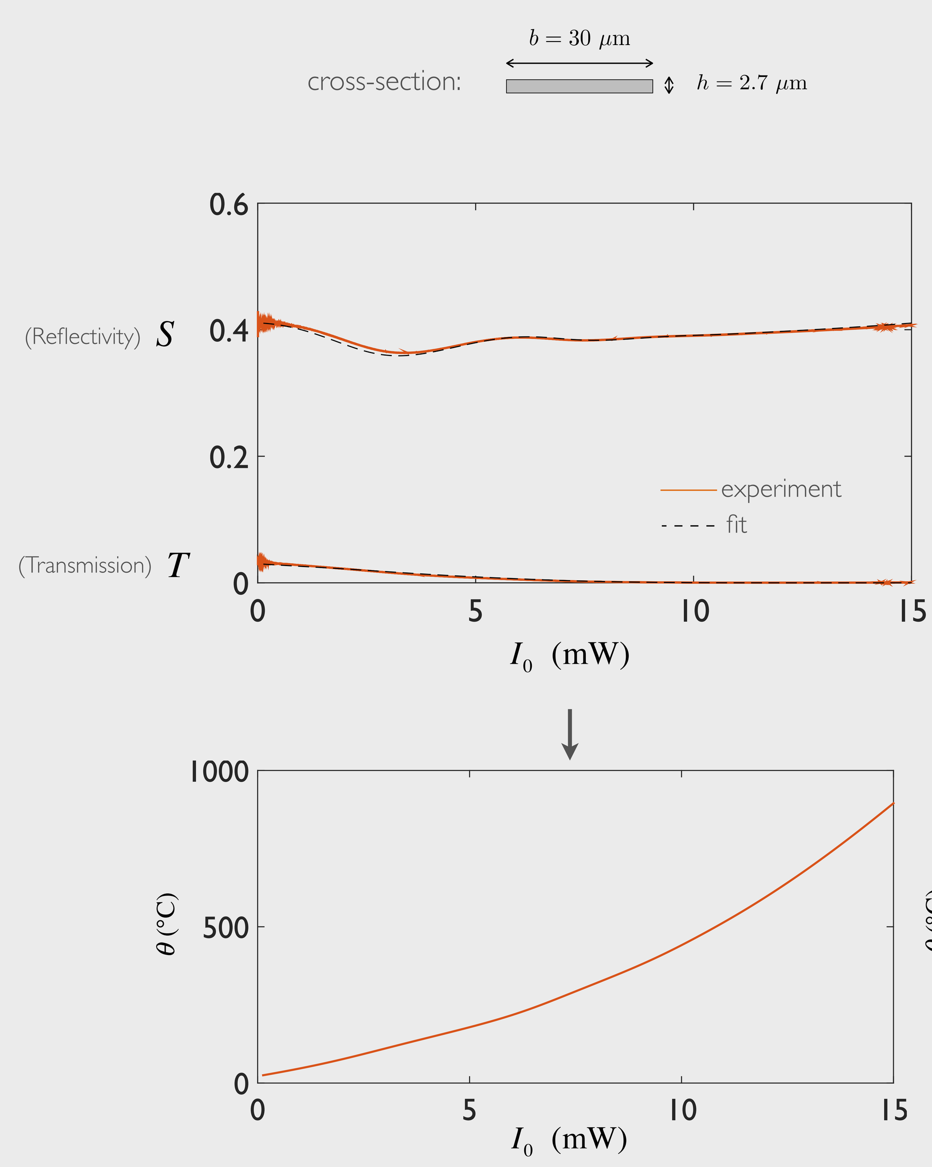


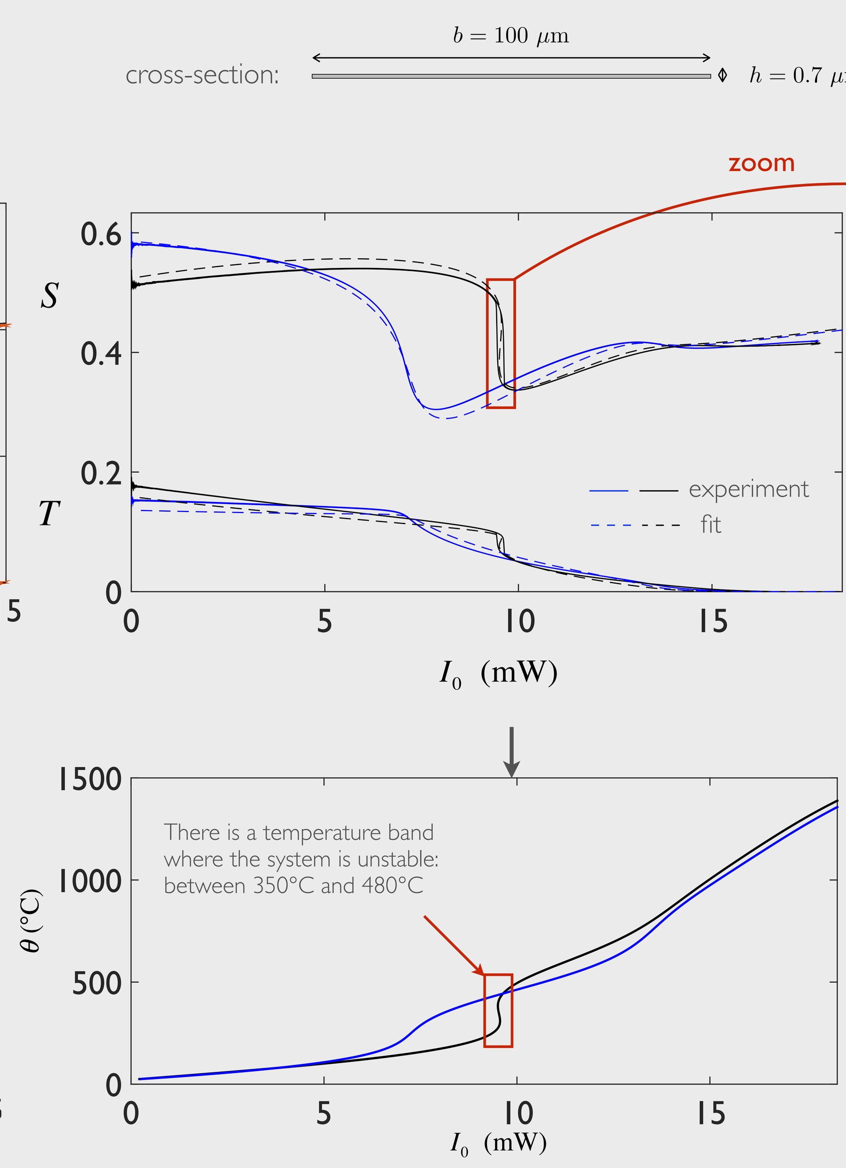
Experimentally, from the measured intensities, I_S, I_T, I_0 we determine

-reflectivity S

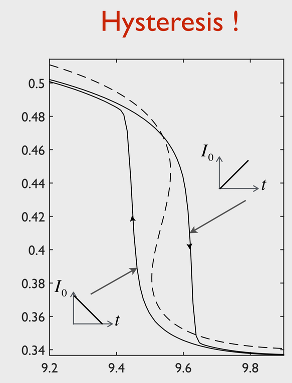
-transmission T







Hysteresis !



According to the fit

$h = 728$ nm

$h = 741$ nm

According to SEM image

$h = 733 \pm 5$ nm ✓

The evolution of the temperature strongly depends on the local thickness under the beam.