COLLÈGE DE FRANCE 1530

Technologies quantiques émergentes

Pascale Senellart

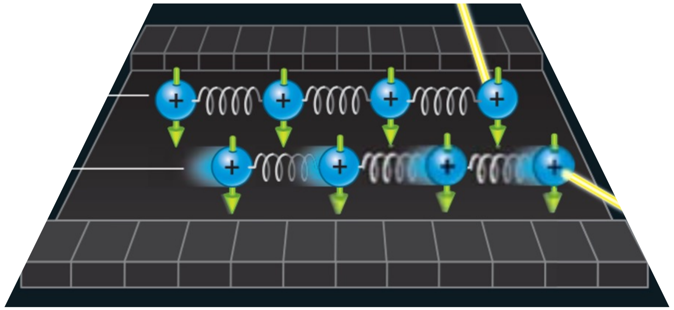
17 février 2026

Vibrations et technologies quantiques

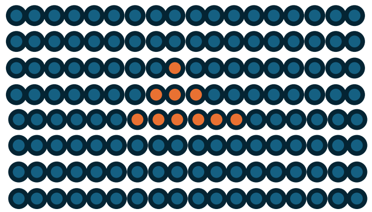
Vibrations et technologies quantiques

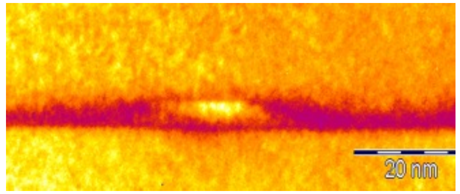
Source de décohérence ou système quantique contrôlé ?

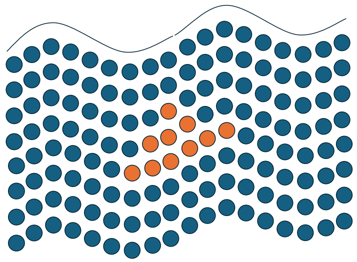
Porte quantique entre ions

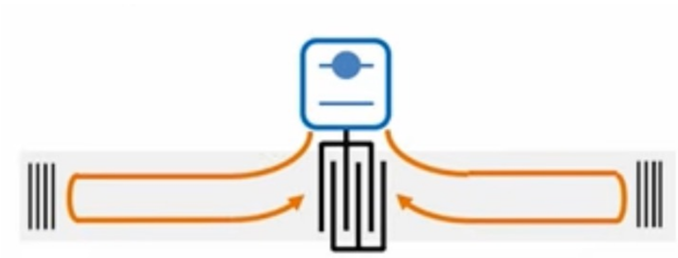


Sources de photons uniques



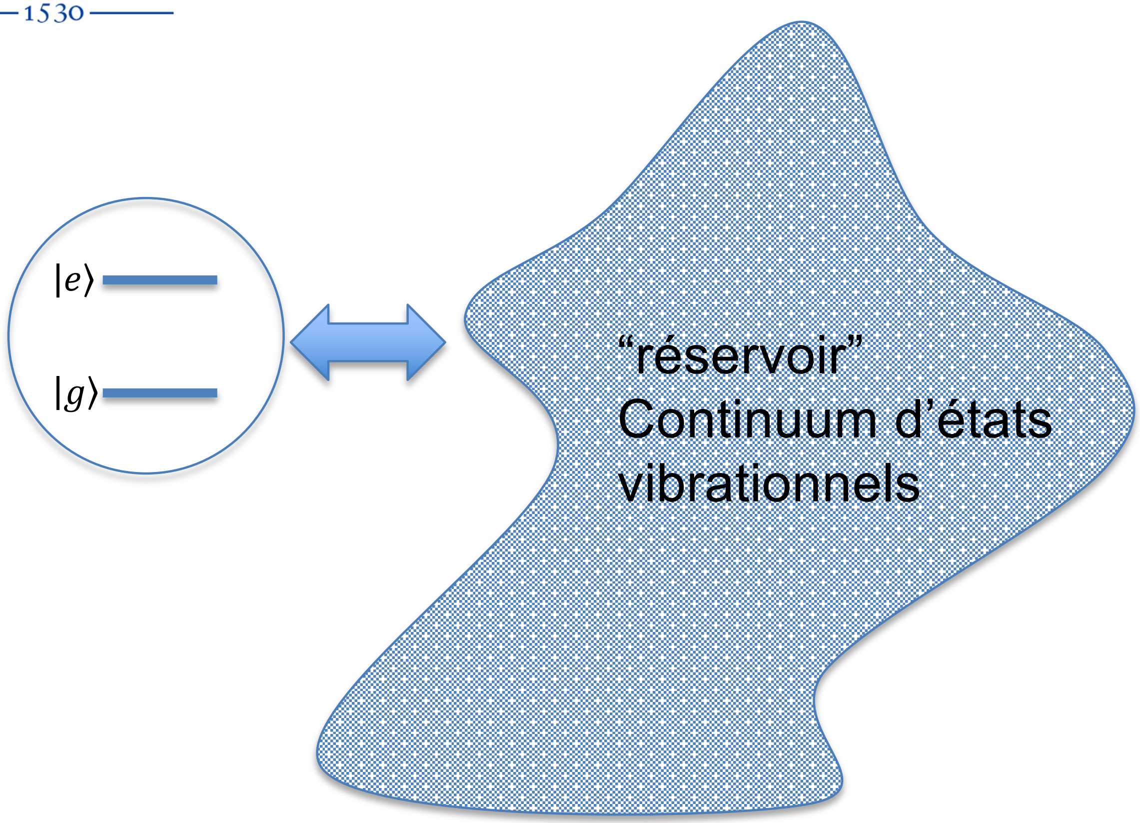


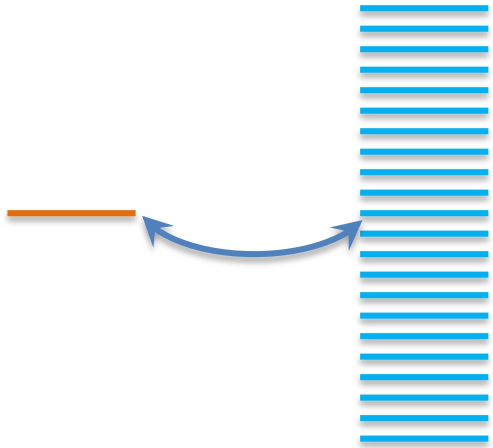




Phonon et qubit supra-conducteur
Cf. Séminaire Audrey Bienfait

Vibrations et technologies quantiques : décohérence

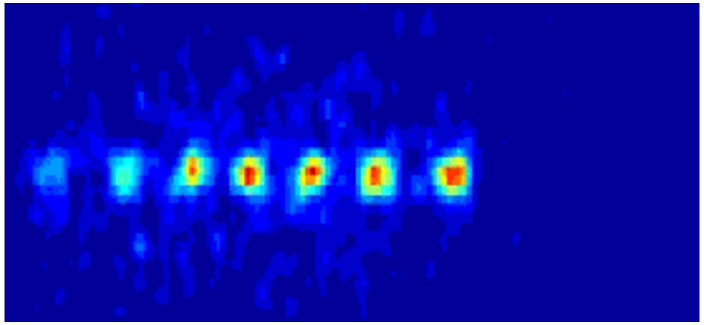




perte irréversible d'information

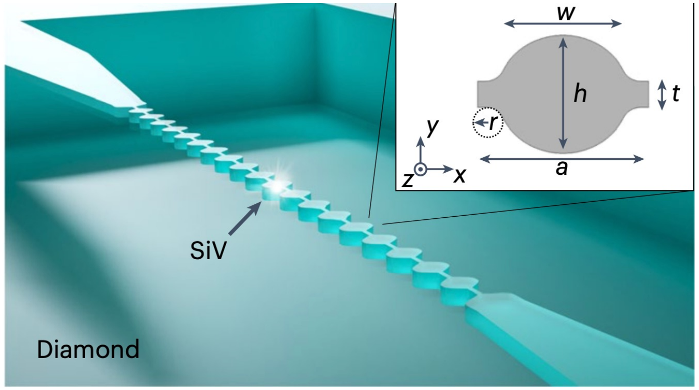
Vibrations et technologies quantiques : contrôle

Contrôle optique des mouvements



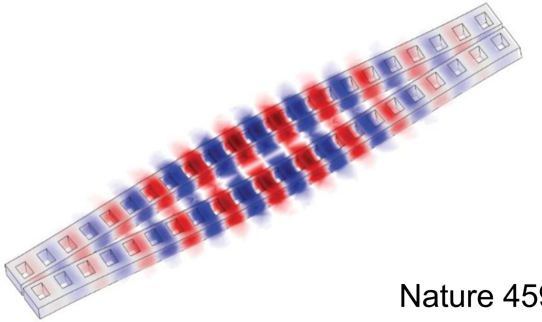
Optics Express 3, 89 (1998)

Résonateurs mécaniques



Nature Physics 21, 77–82 (2025)

Résonateurs opto-mécaniques



Nature 459, 550 (2009)

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Vibrations et technologies quantiques

Vibrations et décohérence

Phonons dans les solides

Contrôle des vibrations

Capteurs optomécaniques

Quelques éléments de nanofabrication

Régime quantique

Séminaire Pr. Markus Aspelmeyer

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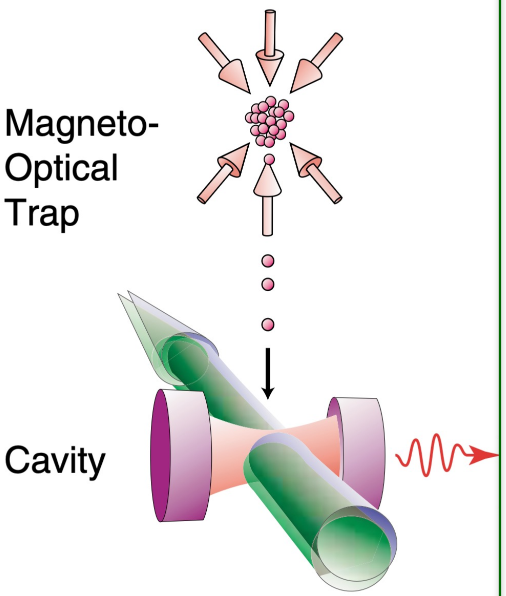
Vibrations et décohérences

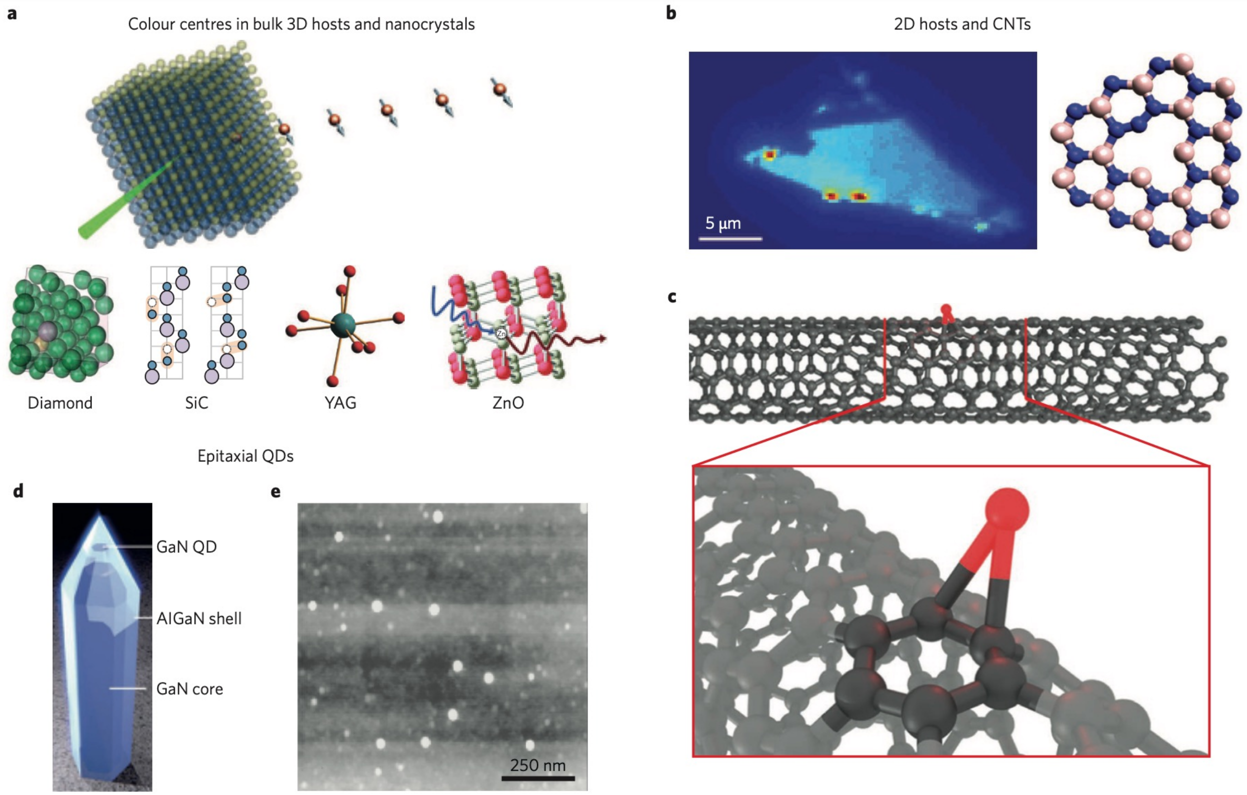
Sources de photons uniques : émetteurs

Atomes



Phys. Rev. Lett. 89, 067901 (2002)

Atomes artificiels



Nature Photonics 10, 631–641 (2016)

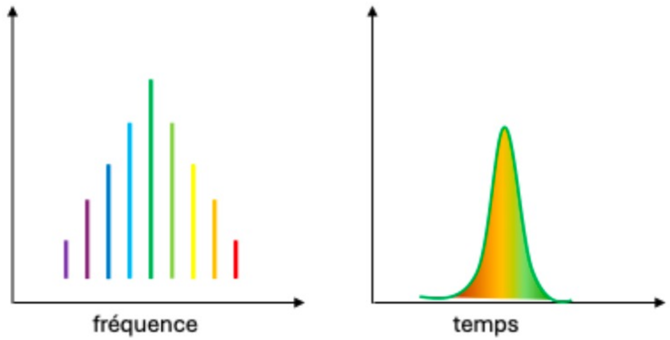
Générer des photons indiscernables

Impulsion à un photon

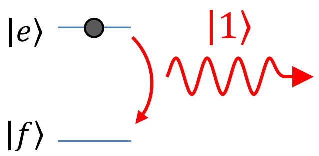
$$|1\rangle = \sum_{\ell} C_{\ell} \, |0, ..., 0, n_{\ell} = 1, 0, ...\rangle$$

avec

$$\sum_{\ell} |C_{\ell}|^2 = 1$$



Indiscernables : Photons dans un état pur en fréquence



Pas de décohérence pendant l'émission

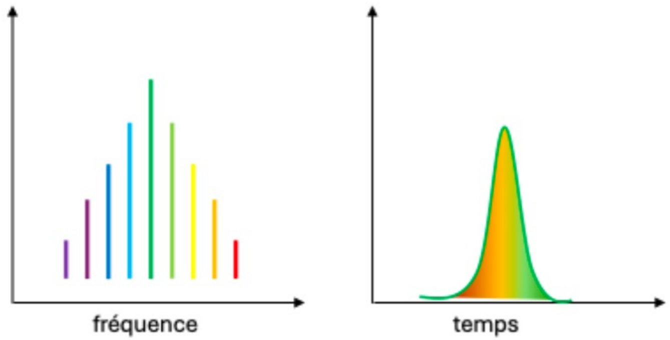
Générer des photons indiscernables

Impulsion à un photon

$$|1\rangle = \sum_{\ell} C_{\ell} \, |0, \ldots, 0, n_{\ell} = 1, 0, \ldots.\rangle$$

avec

$$\sum_{\ell} |C_{\ell}|^2 = 1$$



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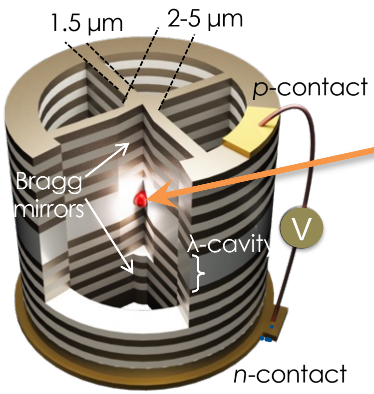

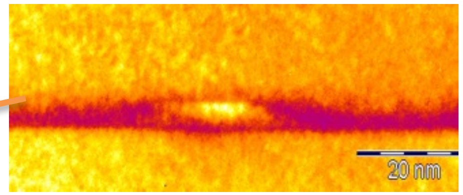

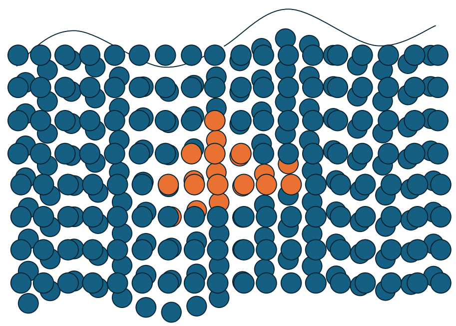

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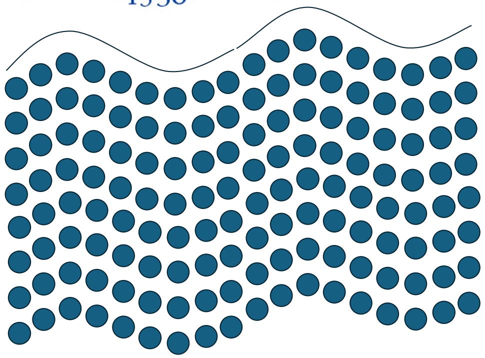
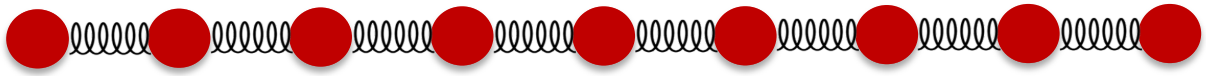
Phonons : description quantique





$$\hat{H} = \sum_{i=1}^{N} \frac{\hat{P}_i^2}{2m} + \frac{1}{2} m\omega^2 \sum_{i=1}^{N} \sum_{p\nu} (\hat{X}_i - \hat{X}_j)^2$$

Coordonnées normales

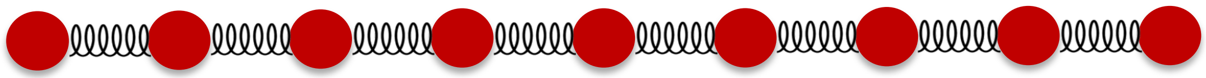
$$\hat{Q}_k = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \hat{X}_i \, e^{-jkia}, \qquad \hat{X}_i = \frac{1}{\sqrt{N}} \sum_{k} \hat{Q}_k \, e^{jkia},$$

Moments conjugués

$$\hat{\Pi}_k = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \hat{P}_i \, e^{jkia}. \qquad \hat{P}_i = \frac{1}{\sqrt{N}} \sum_{k} \hat{\Pi}_k \, e^{-jkia},$$

$$\hat{H} = \sum_{k} \left(\frac{\hat{\Pi}_k \hat{\Pi}_{-k}}{2m} + \frac{1}{2} m \, \omega_k^2 \, \hat{Q}_k \hat{Q}_{-k} \right)$$

Phonons : description quantique



$$\hat{a}_k = \sqrt{\frac{m\omega_k}{2\hbar}}\,\hat{Q}_k + \frac{i}{\sqrt{2\hbar m\omega_k}}\,\hat{\Pi}_{-k}$$

$$\hat{a}_k^\dagger = \sqrt{\frac{m\omega_k}{2\hbar}}\,\hat{Q}_{-k} - \frac{i}{\sqrt{2\hbar m\omega_k}}\,\hat{\Pi}_k$$

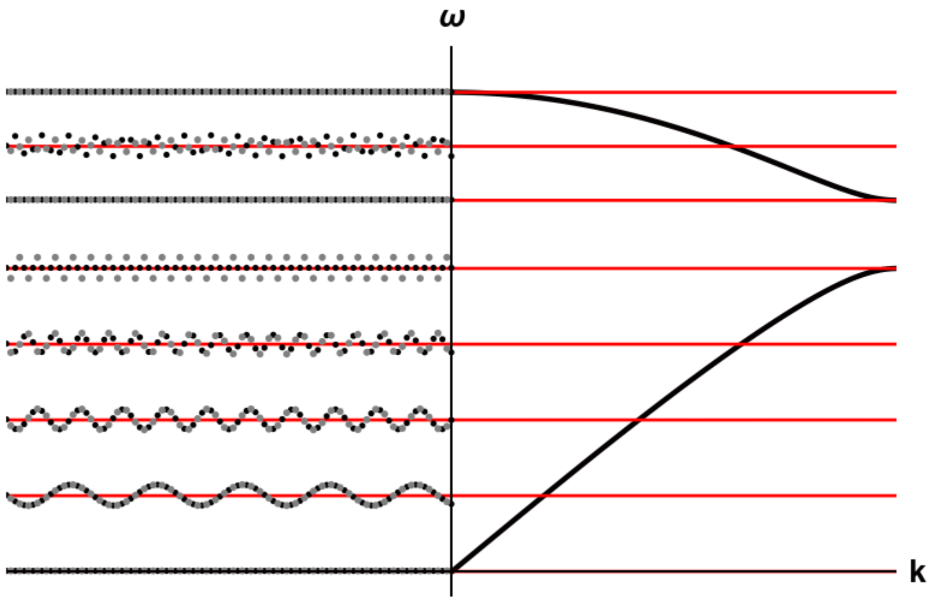
$$\hat{H} = \sum_k \hbar\omega_k \left(\hat{a}_k^\dagger \hat{a}_k + \frac{1}{2}\right)$$

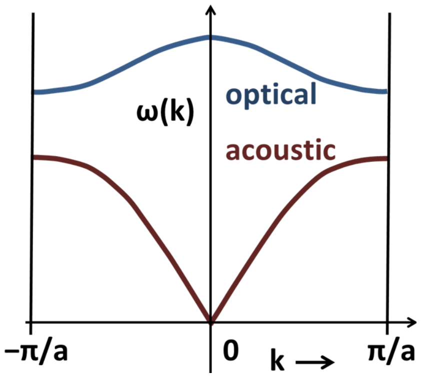
$$E_{n_k} = \hbar\omega_k \left(n_k + \frac{1}{2}\right)$$

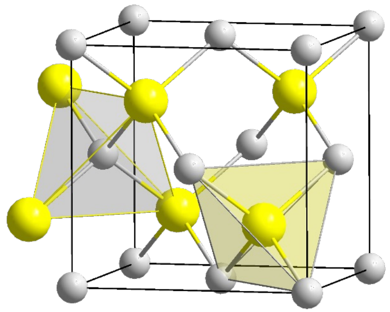
Pour une chaine 1D d'atomes identiques

$$\omega_k = \sqrt{2\omega^2(1-\cos(ka))} = 2\omega\left|\sin\left(\frac{ka}{2}\right)\right|$$

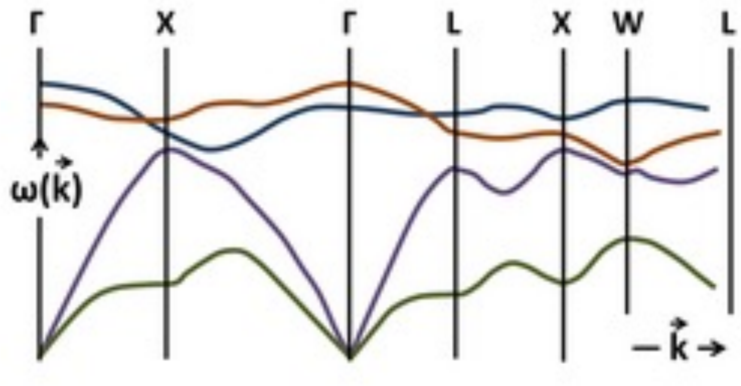
Phonons : exemples



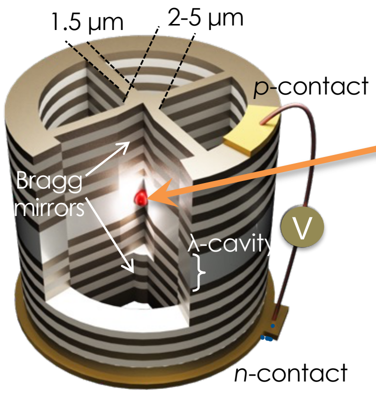


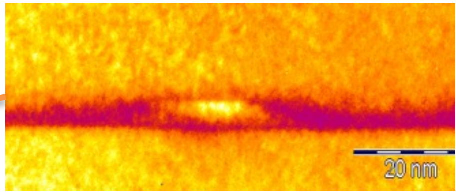


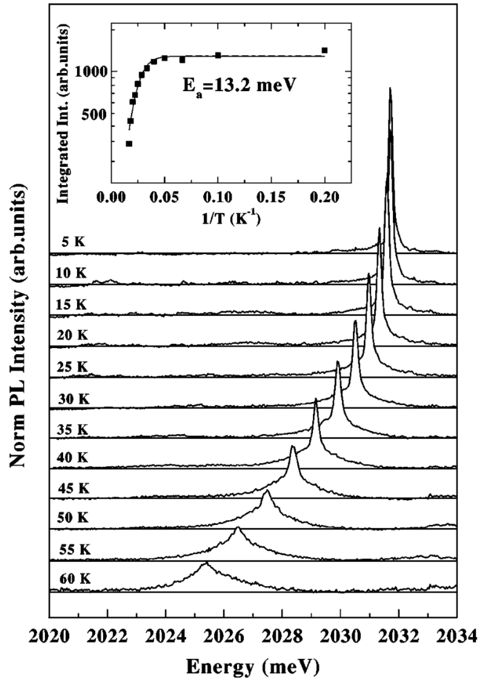
GaAs

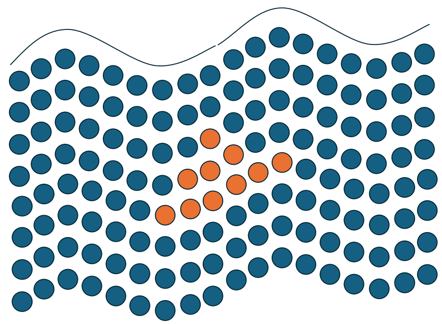


Phonons et atomes artificiels



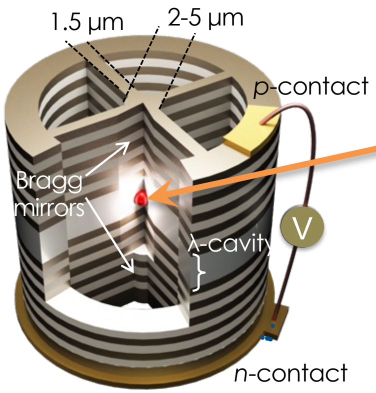


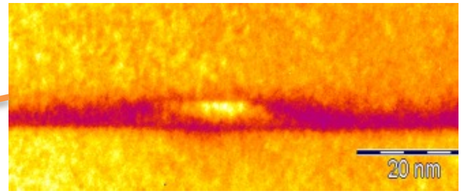


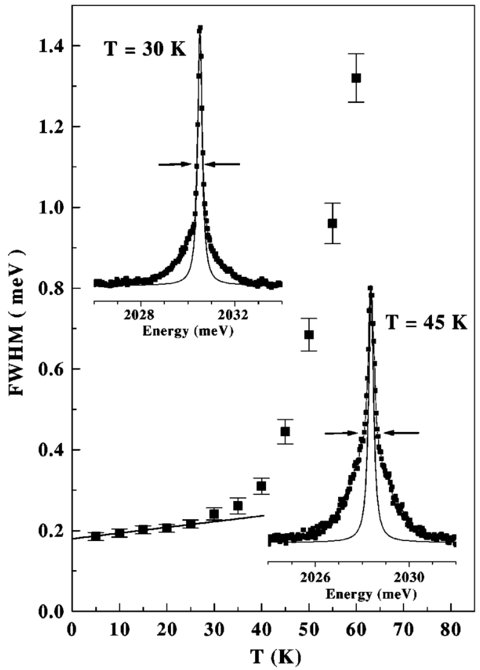


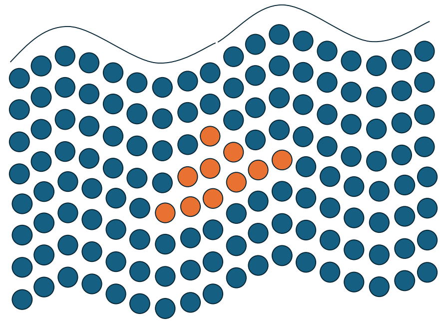
Phys. Rev. B 63, 155307 (2001)

Phonons et atomes artificiels



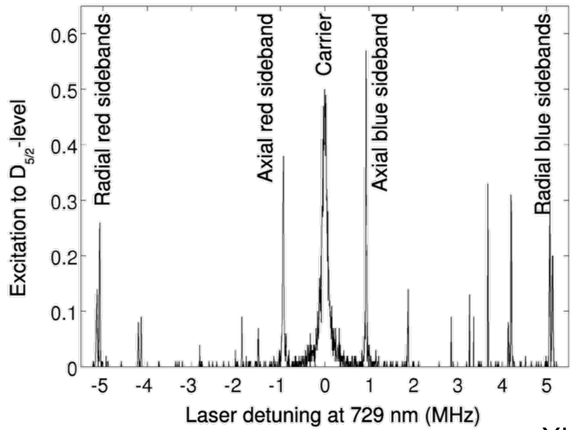






Phys. Rev. B 63, 155307 (2001)

Analogie : ion en mouvement



arXiv 0809.4368

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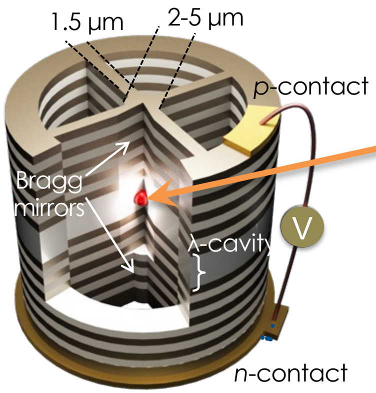
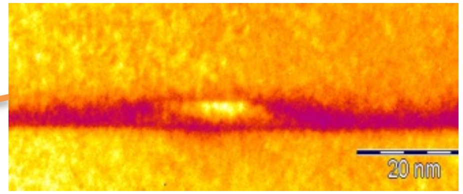
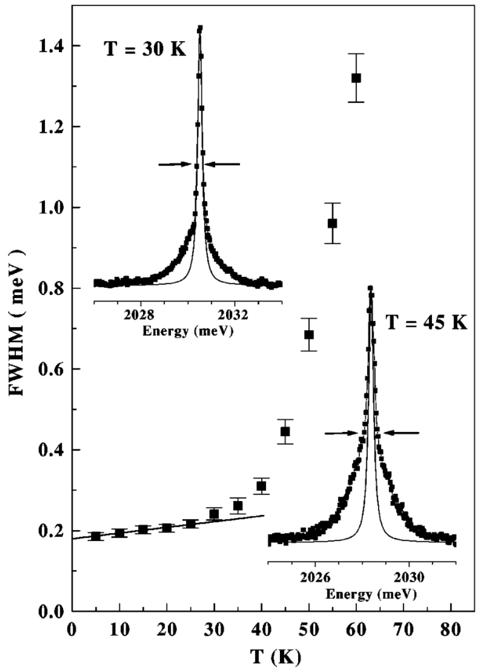
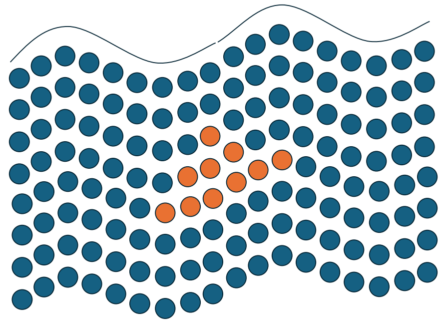
Phonons et atomes artificiels









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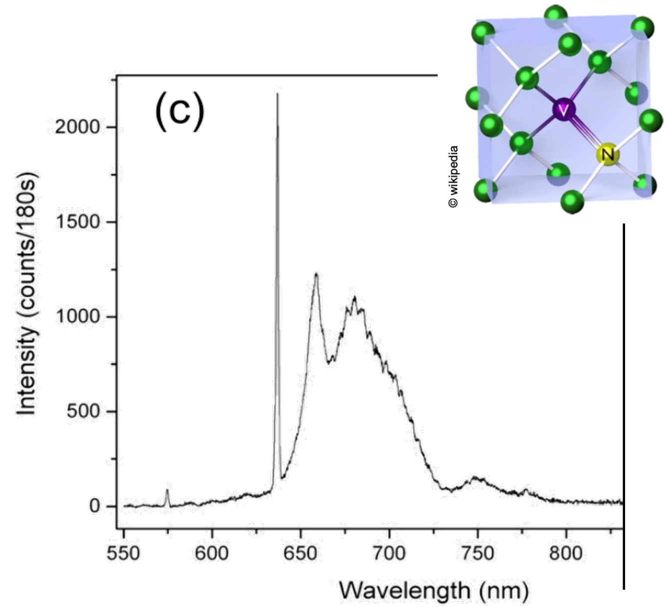
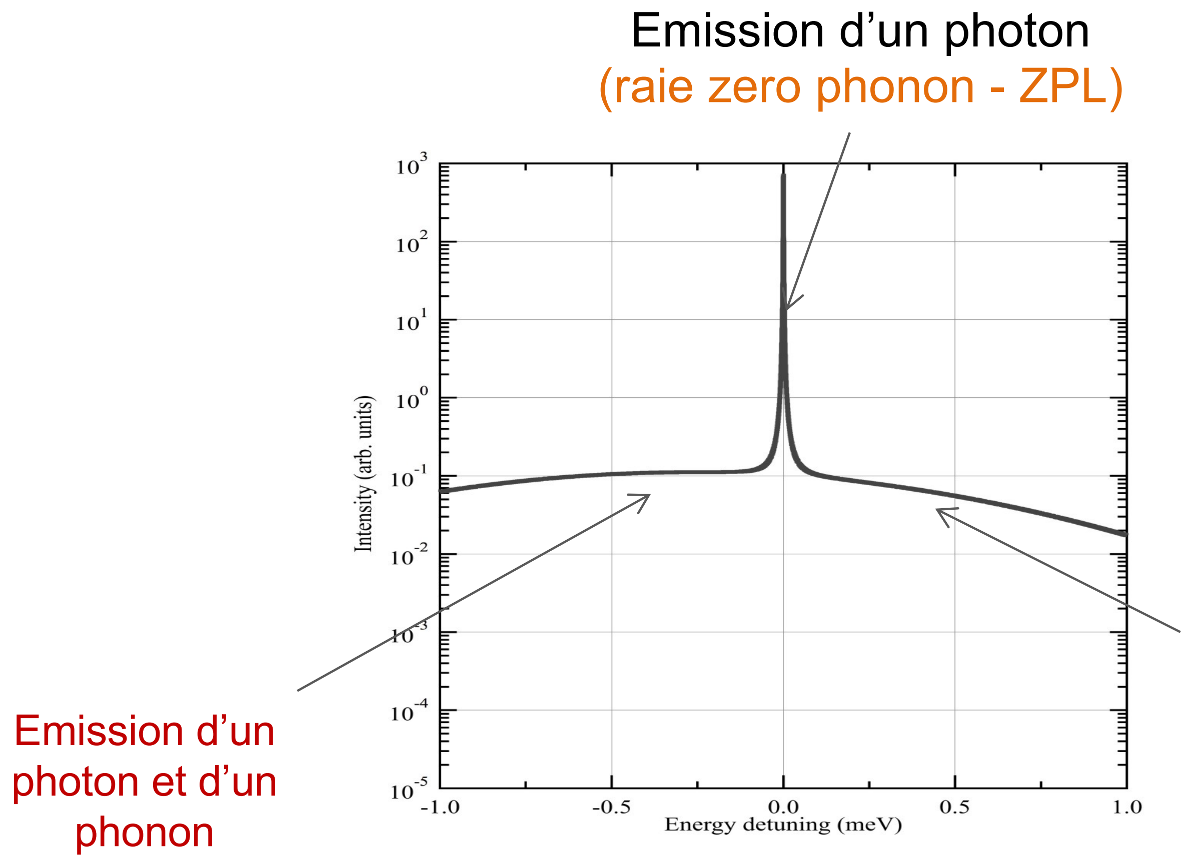


arXiv 0809.4368

Phonons, atomes artificiels : indiscernabilité des photons



Fraction d'émission dans la raie ZPL: η_{ZPL}

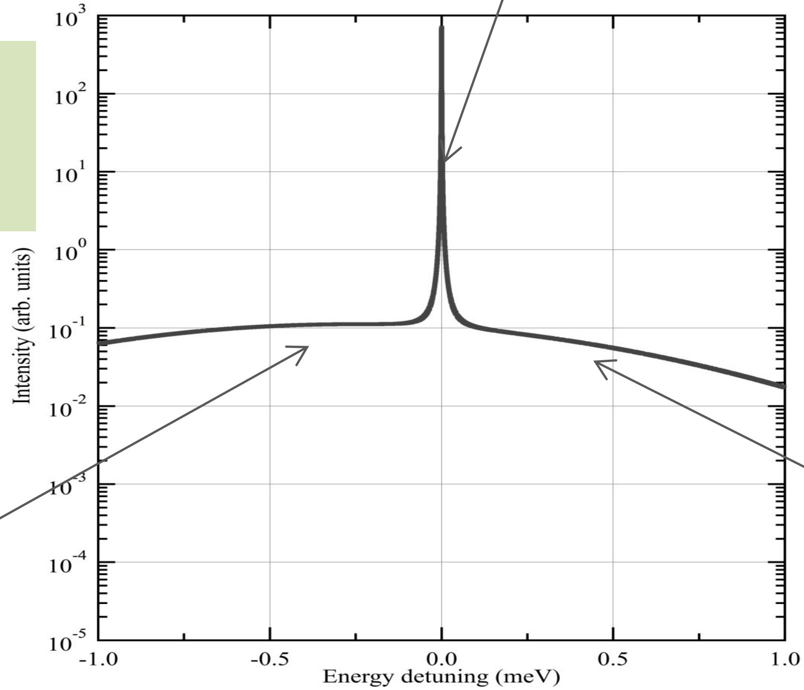
Indiscernabilité < η_{ZPL}^2

Phys. Rev. Lett. 118, 253602 (2017)

Phonons, atomes artificiels : indiscernabilité des photons

$$n_{phonon}(\omega) = \frac{1}{\exp\left(\frac{\hbar\omega}{k_B T}\right) - 1}$$

Emission d'un photon
(raie zero phonon - ZPL)



Emission d'un photon et d'un phonon $\propto (n_{phonon} + 1)$

Emission d'un photon et absorption d'un phonon $\propto n_{phonon}$

Fraction d'émission dans la raie ZPL: η_{ZPL}

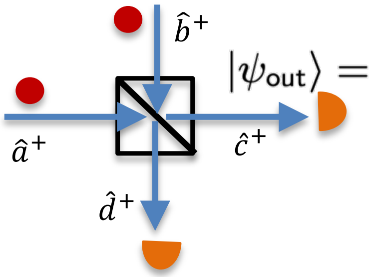
Indiscernabilité < η_{ZPL}^2

Phys. Rev. Lett. 118, 253602 (2017)

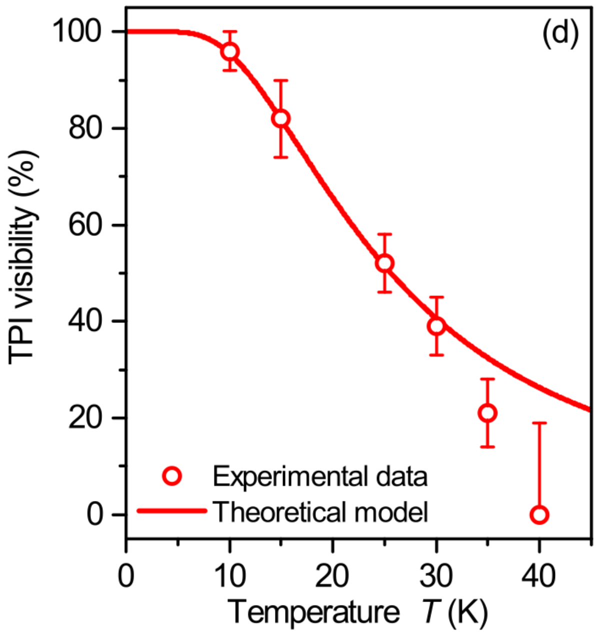
Phonons, atomes artificiels : indiscernabilité des photons

Cf. cours 5

Interférence de Hong Ou Mandel



$$|\psi_{\text{out}}\rangle = \frac{-i}{\sqrt{2}}\left(|2,0\rangle + |0,2\rangle\right)$$



Phys. Rev. Lett. 116, 033601 (2016)

Fraction d'émission dans la raie ZPL: η_{ZPL}

Indiscernabilité < η_{ZPL}^2

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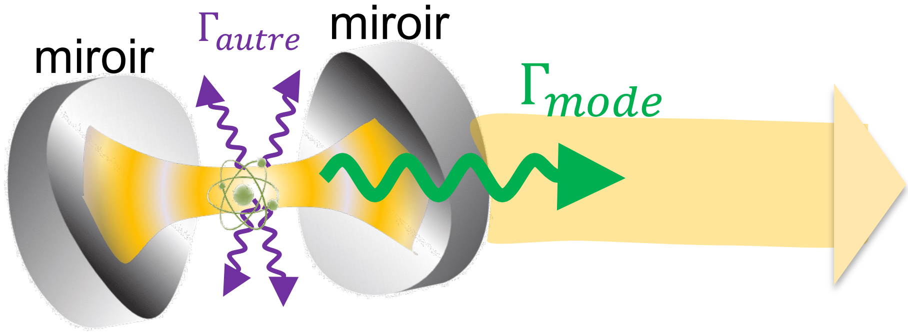
Cf. cours 4

Réduire le couplage aux phonons : effet Purcell



Fraction émise dans le mode de cavité

$$\beta = \frac{\Gamma_{mode}}{\Gamma_{mode} + \Gamma_{autre}}$$

Facteur de Purcell

Dépendence spatiale et spectrale

$$F = F_P \frac{\left|\langle e \,|\, \mathbf{d} \cdot \mathbf{u}(\mathbf{r}_{QD}) \,|\, g\rangle\right|^2}{\left|\langle e \,|\, \mathbf{d} \,|\, g\rangle\right|^2} \frac{1}{1 + \left(\frac{2Q}{\hbar\omega_c}\right)^2 (\hbar\omega_{eg} - \hbar\omega_c)^2}$$

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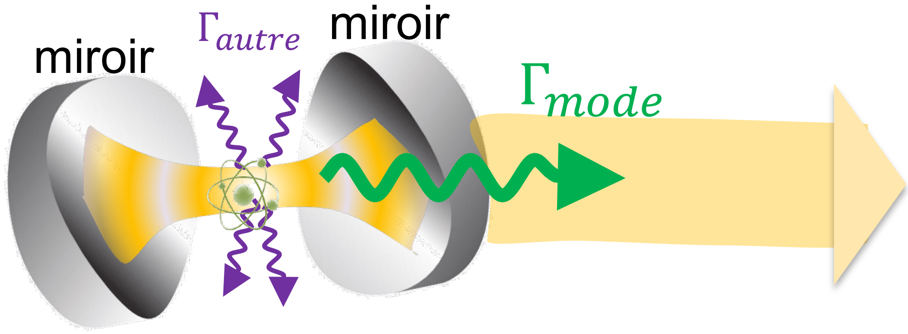
Rappel cours 4

Réduire le couplage aux phonons : effet Purcell



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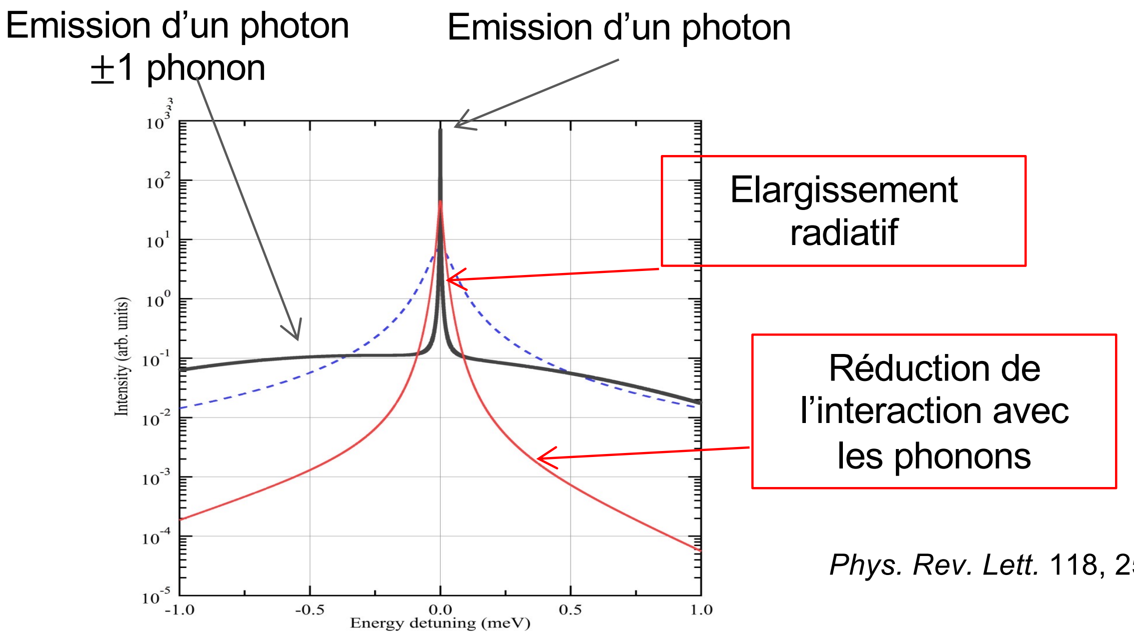

Phys. Rev. Lett. 118, 253602 (2017)

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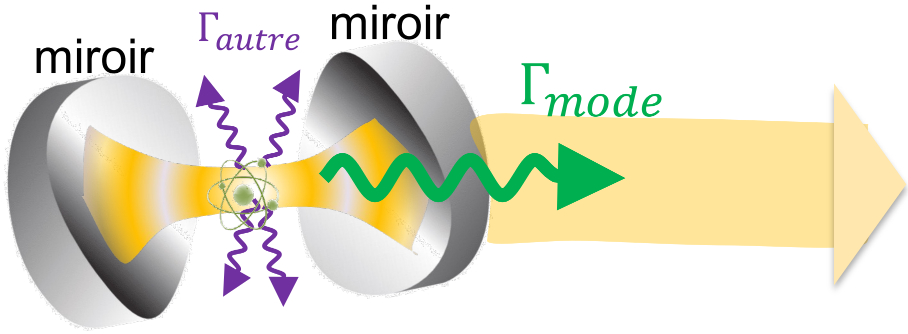
Rappel cours 4

Réduire le couplage aux phonons : effet Purcell



Fraction émise dans le mode de cavité

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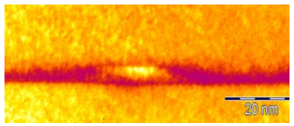
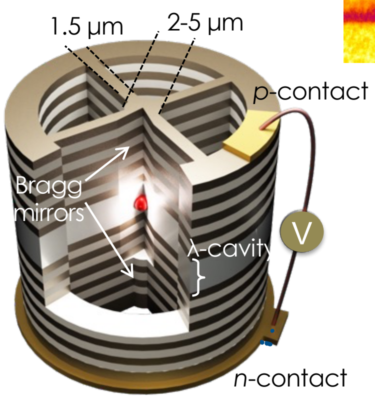
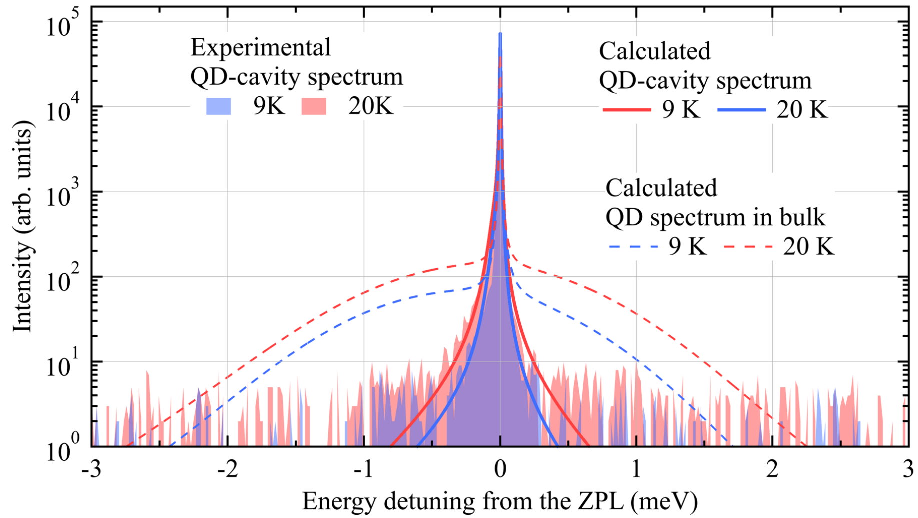


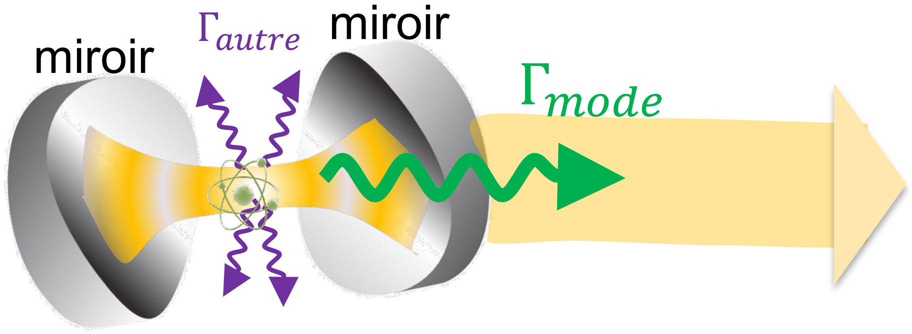




Phys. Rev. Lett. 118, 253602 (2017)

Rappel cours 4

Réduire le couplage aux phonons : effet Purcell



Fraction émise dans le mode de cavité

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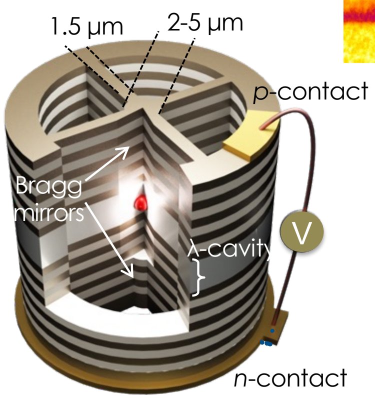
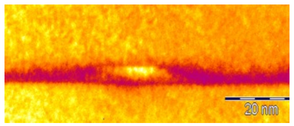
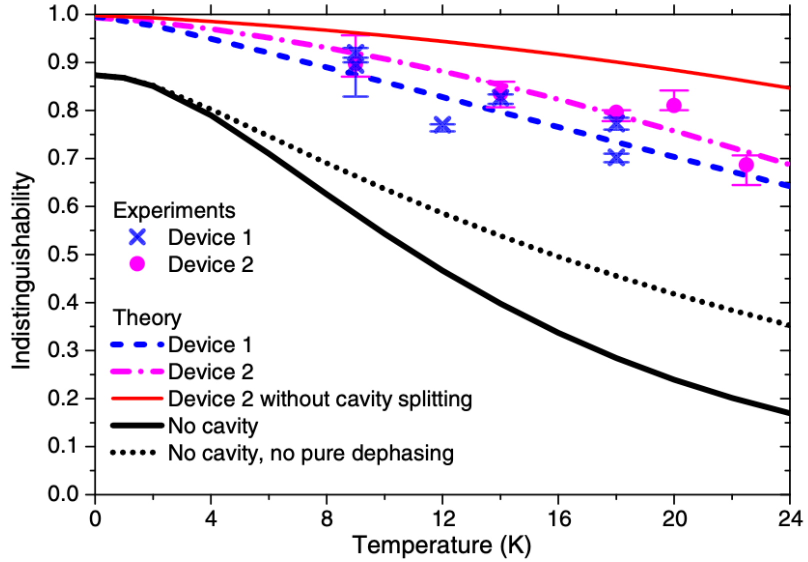
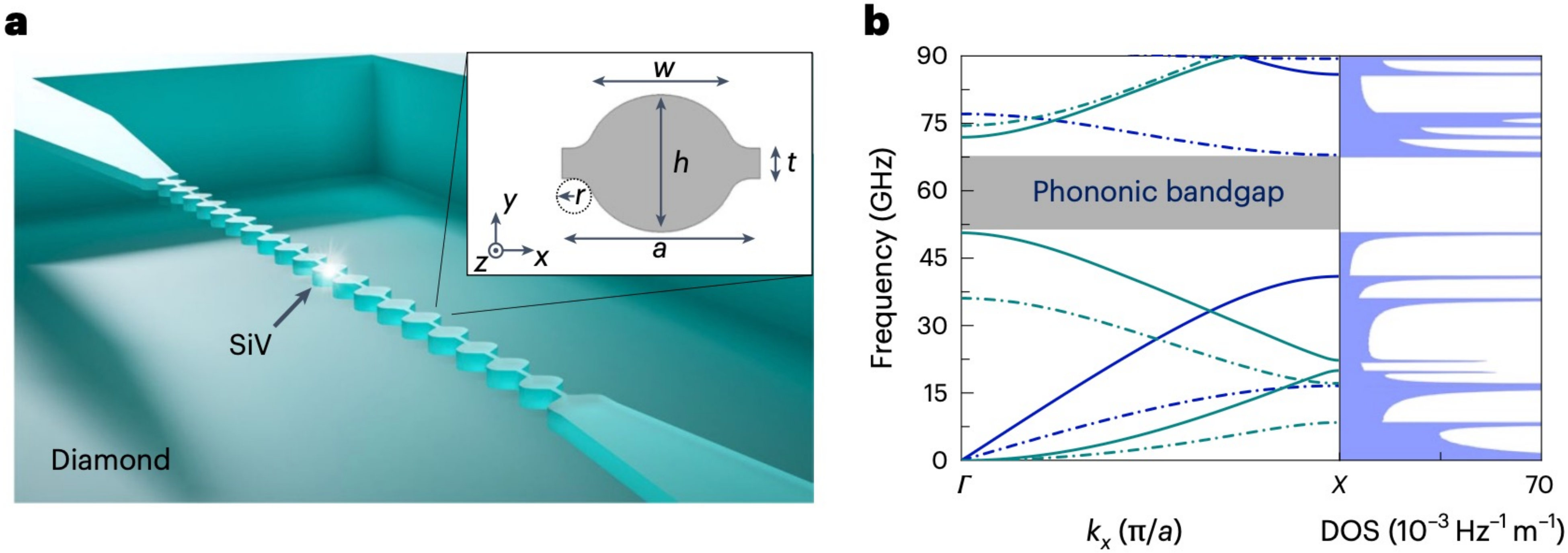






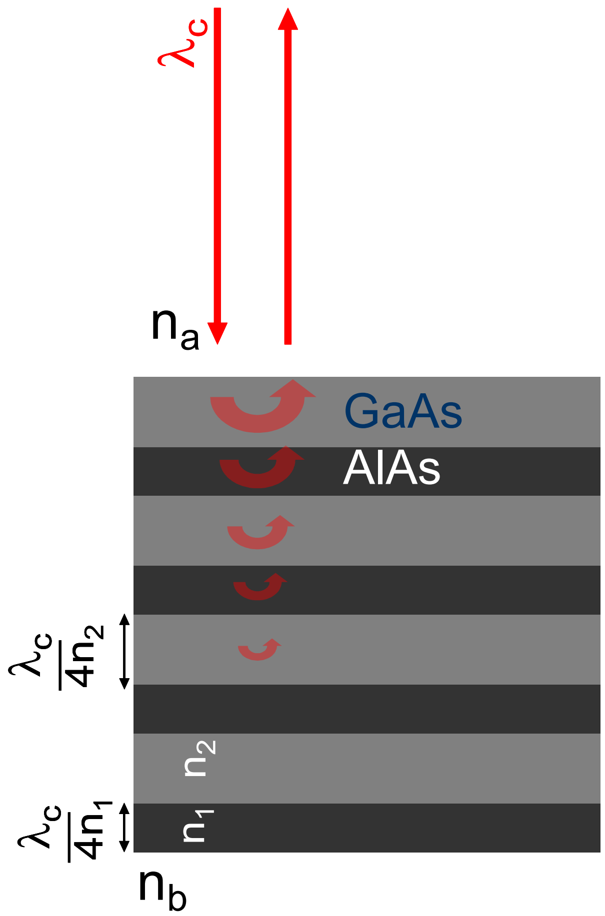
Phys. Rev. Lett. 118, 253602 (2017)

Contrôler la densité d'états phononiques

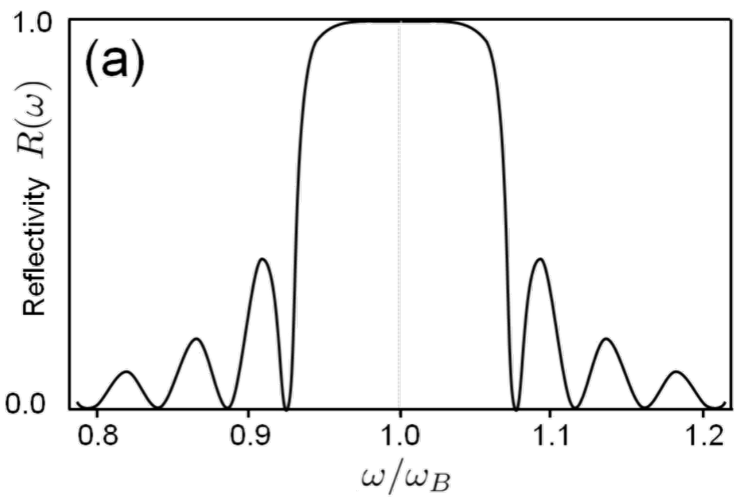


Nature Physics 21, 77–82 (2025)

Confiner la lumière : miroirs

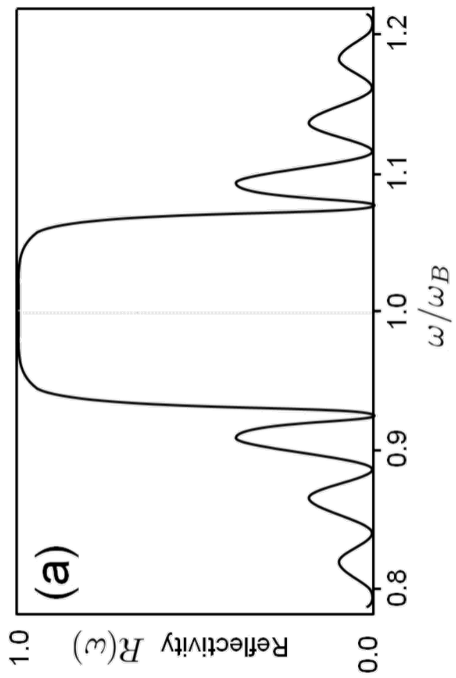


Miroirs interférentiels

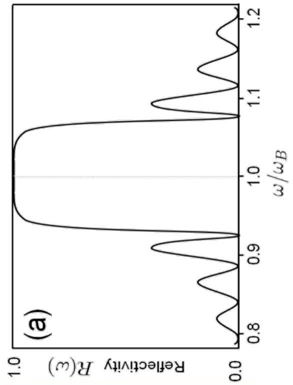


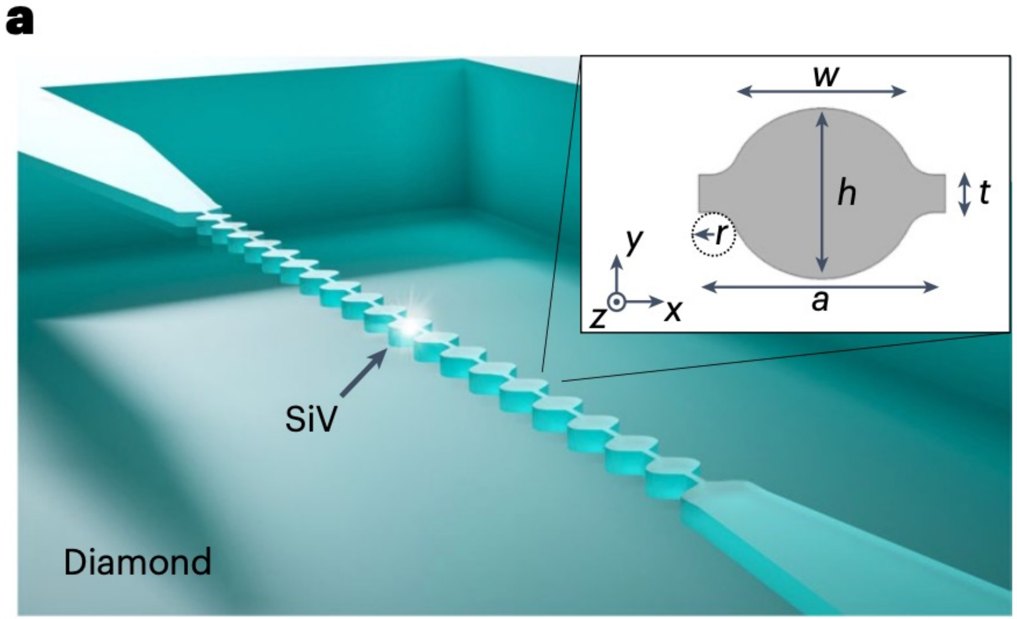
$$R(\omega_B) = \left[\frac{1 - \frac{n_a}{n_b}\left(\frac{n_1}{n_2}\right)^{2N}}{1 + \frac{n_a}{n_b}\left(\frac{n_1}{n_2}\right)^{2N}}\right]^2$$

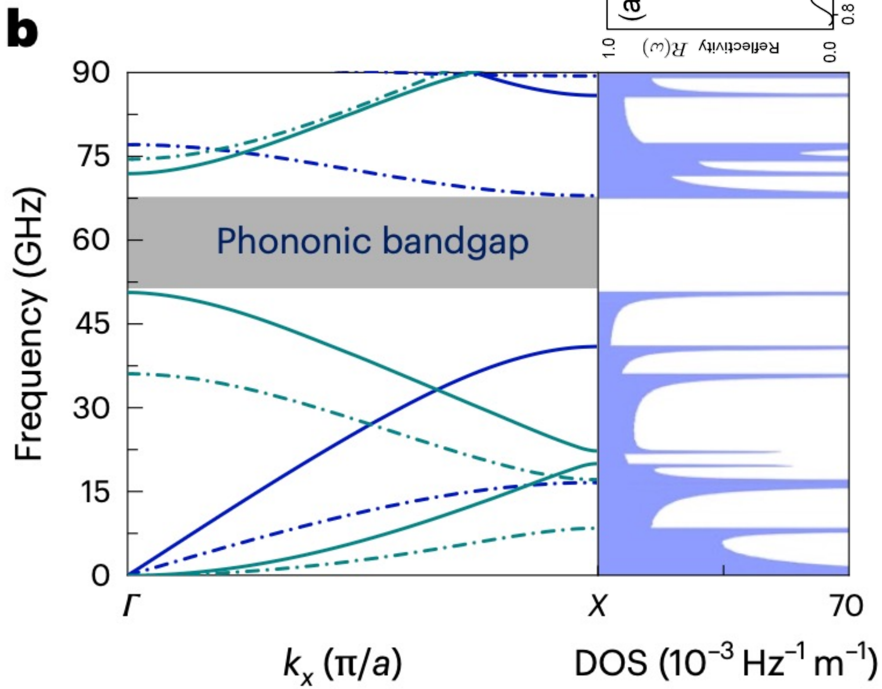
$$\Delta\omega = 4\frac{\omega_B}{\pi}\frac{n_1 - n_2}{n_1 + n_2}$$



Contrôler la densité d'états phononiques

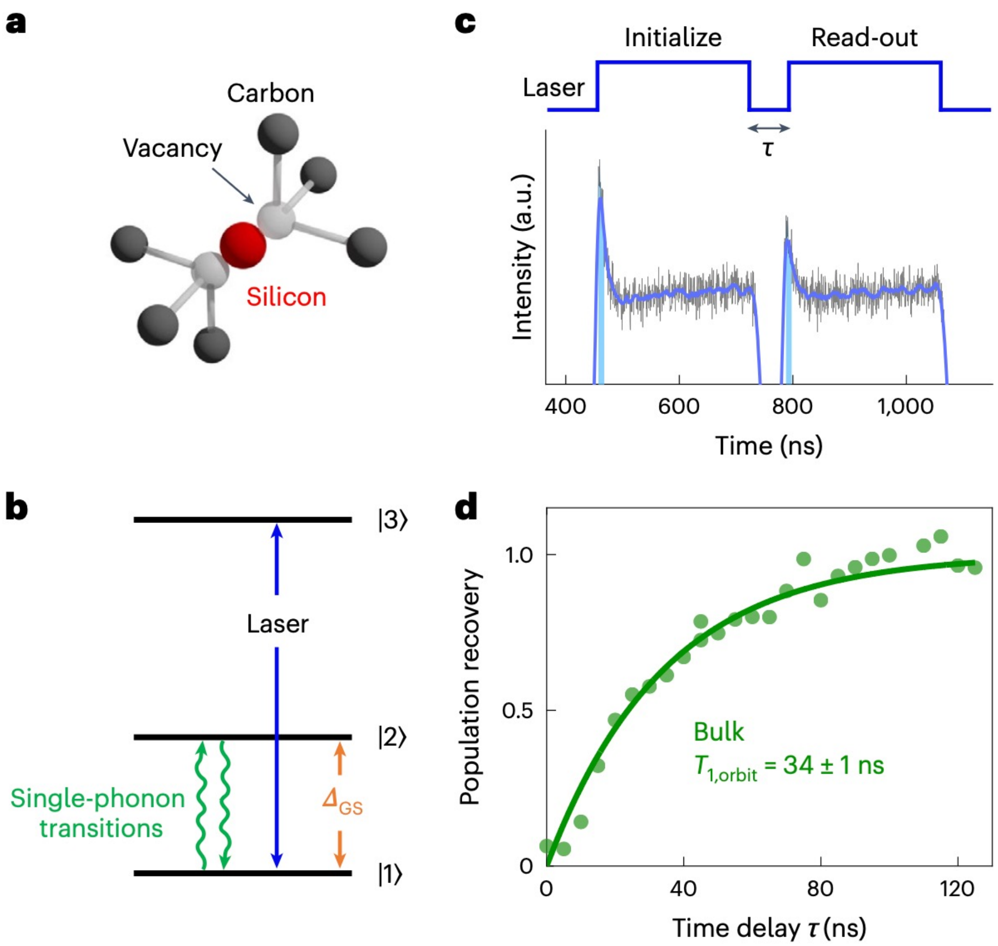






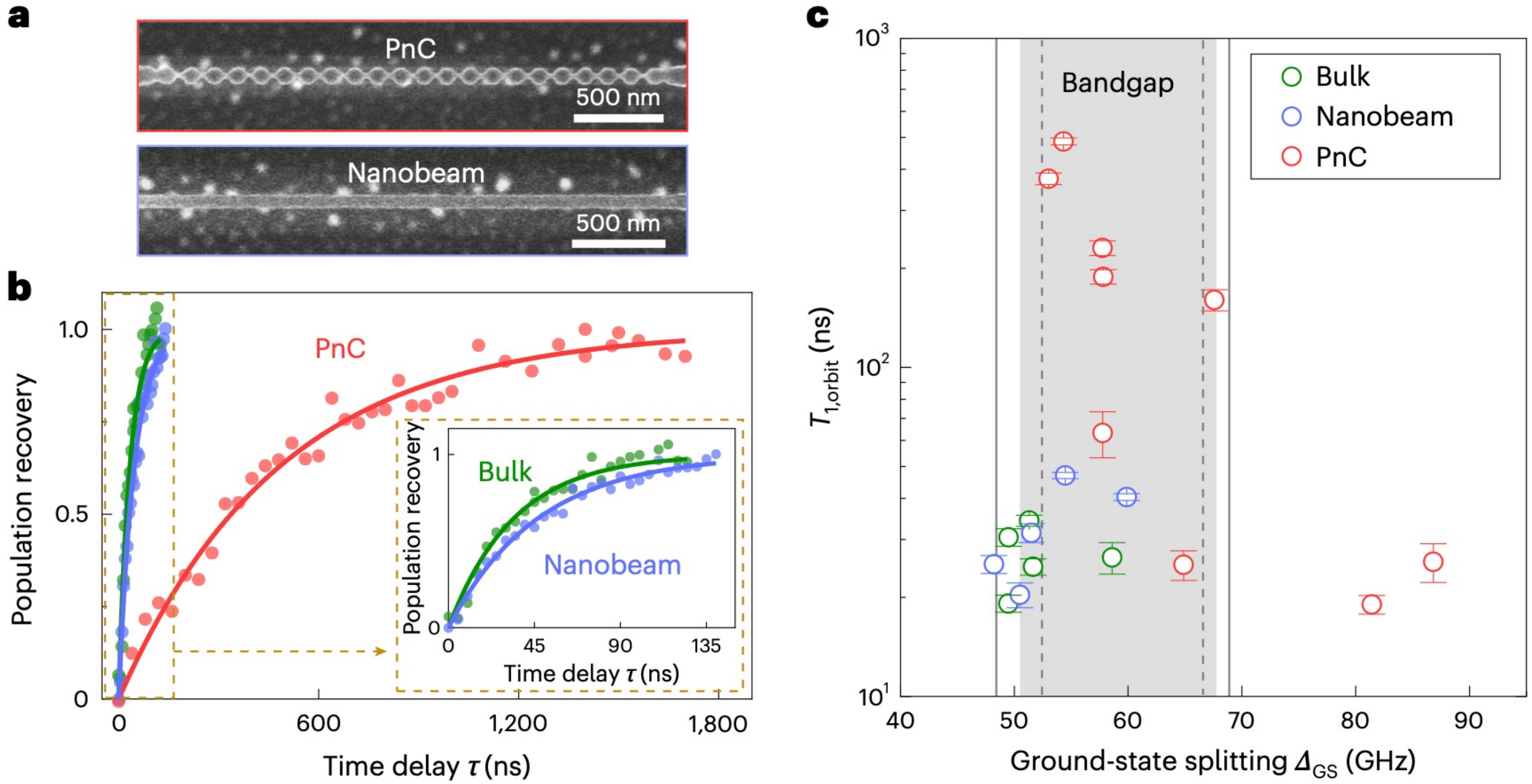
Nature Physics 21, 77–82 (2025)

Contrôler la densité d'états phononiques



Nature Physics 21, 77–82 (2025)

Contrôler la densité d'états phononiques



Nature Physics 21, 77–82 (2025)

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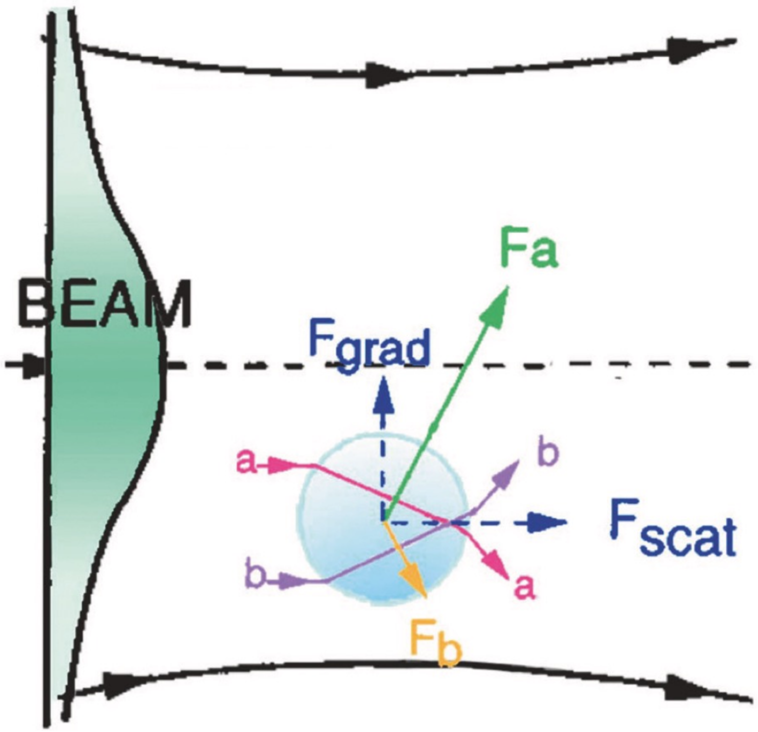
Résonateurs optomécaniques

Premiers systèmes optomécaniques : pression de radiation

A. Ashkin
Nobel Lecture 2018

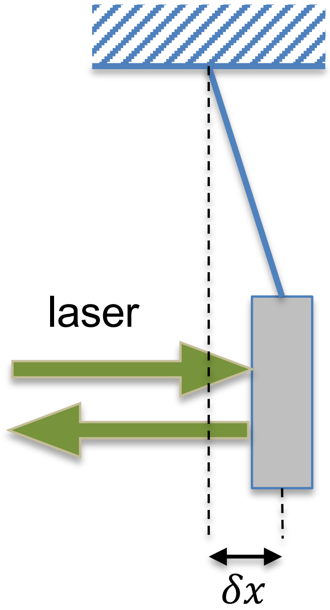


https://www.nobelprize.org/uploads/2018/10/ashkin-lecture.pdf

Pas de rétro – action

Phys. Rev. Lett.,. 24, No 4,. 156–159 (1970).
https://www.pnas.org/content/94/10/4853

Premiers systèmes optomécaniques : pression de radiation



$$\delta\phi = \frac{4\pi}{\lambda}\delta x$$

$\delta\phi = \frac{8\,\mathcal{F}}{\lambda}\delta x$, $\mathcal{F}$ finesse de la cavité

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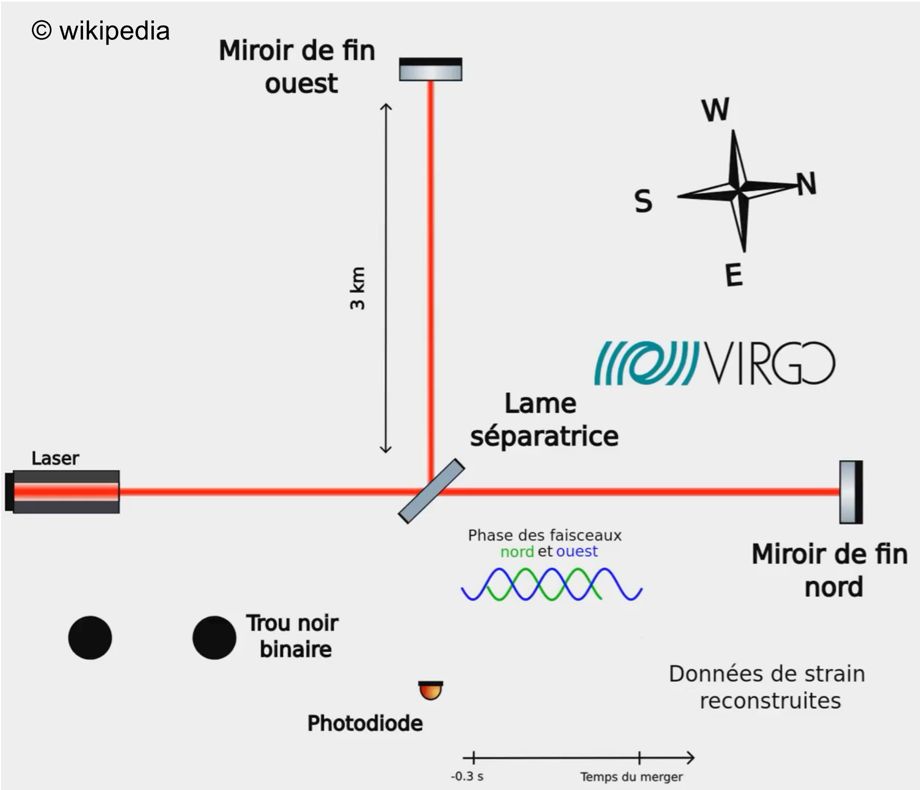
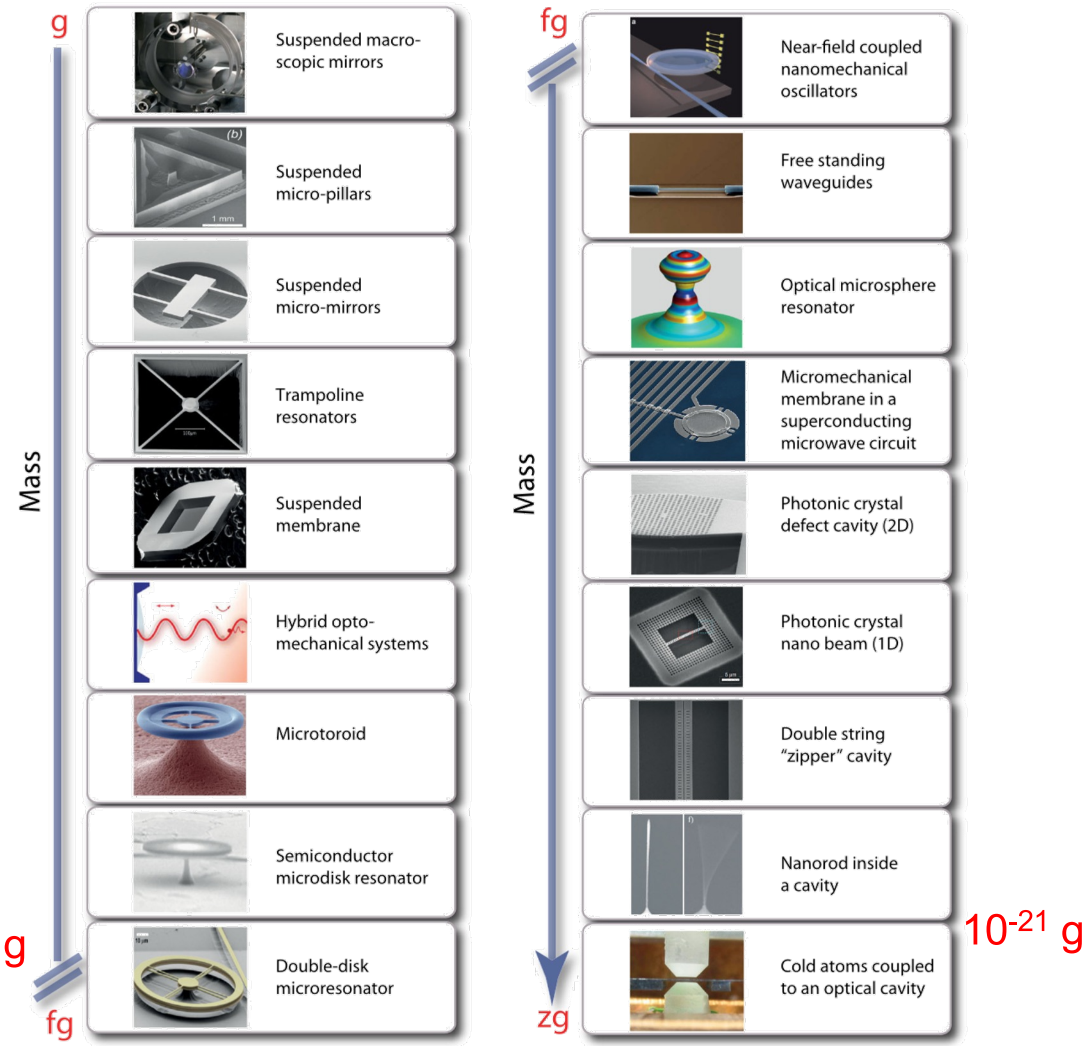
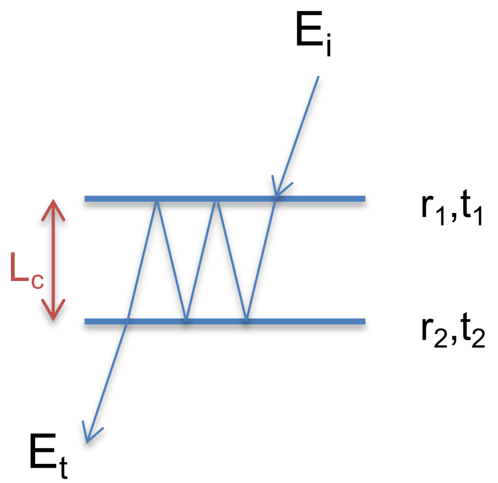
Résonateurs optomécaniques : grande diversité





Rev. Mod. Phys. 86, 1391 (2014).

Résonateur optique : description classique



Sans absorption

$$|r_i|^2 + |t_i|^2 = 1$$

Phase pour 1 aller retour, incidence normale

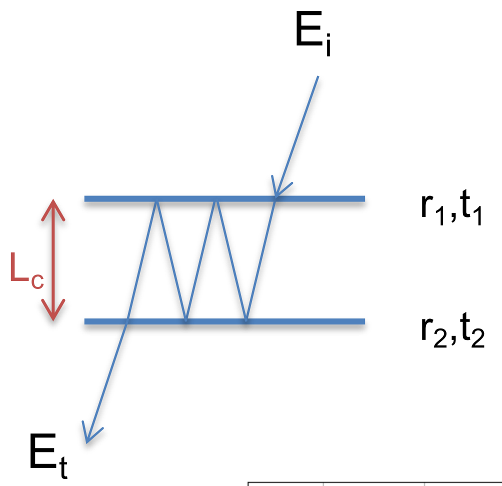
$$\phi = \frac{4\pi n L_c}{\lambda} = \frac{4\pi n L_c}{c} \nu$$

$$E_t = t_1 t_2 \, E_i \sum_{m=0}^{\infty} \left(r_1 r_2 e^{i\phi}\right)^m$$

Amplitude champ transmis

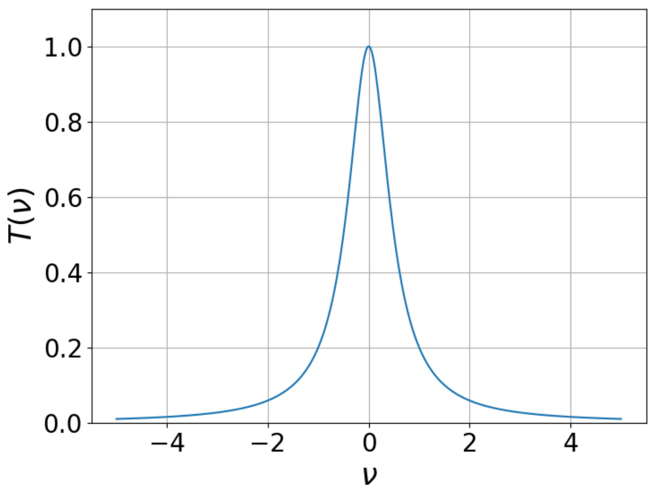
$$\boxed{E_t = \frac{t_1 t_2}{1 - r_1 r_2 e^{i\phi}} E_i}$$

Résonateur optique : description classique



$$T = \frac{|E_t|^2}{|E_i|^2} = \frac{|t_1|^2|t_2|^2}{|1 - r_1 r_2 e^{i\phi}|^2}$$

$$\boxed{\phi = 2m\pi \quad \Leftrightarrow \quad 2nL_c = m\lambda}$$



$$\boxed{T(\phi) = \frac{T_{\max}}{1 + F\sin^2\left(\frac{\phi}{2}\right)}}$$

$$F = \frac{4|r_1 r_2|}{(1 - |r_1 r_2|)^2}.$$

$\mathcal{F}_{finesse} = \pi\sqrt{F}$

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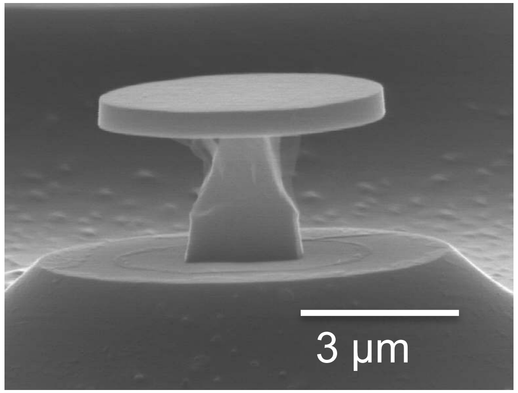
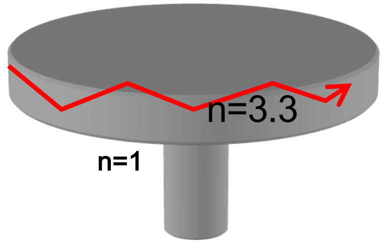
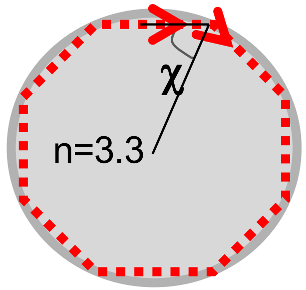
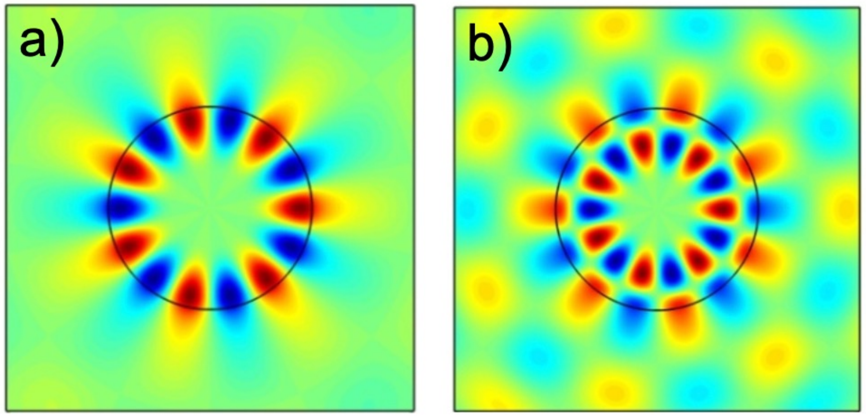
Résonateur optique : exemple du microdisque



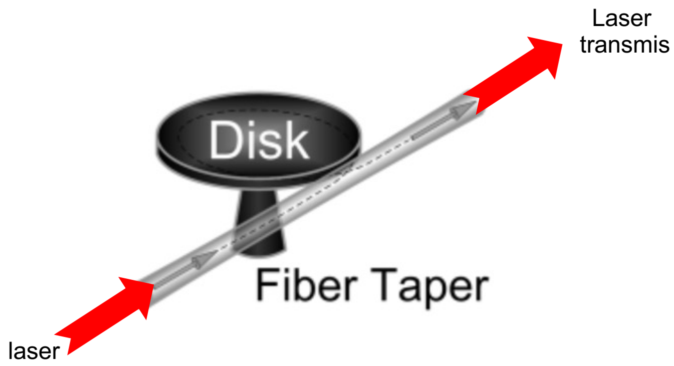




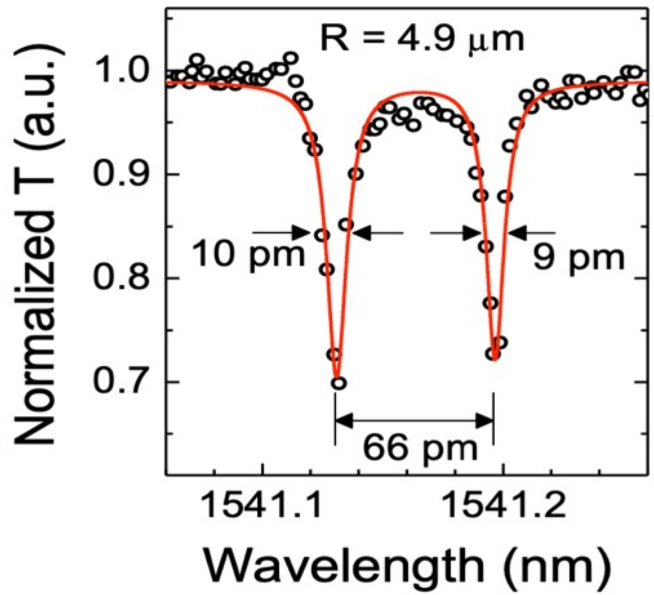


Thèse C. Baker 2013 – I. Favero

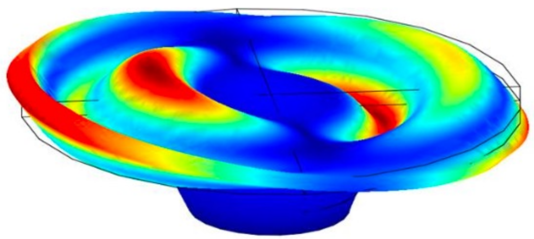
Résonateur microdisque : mesure des propriétés optiques



Phys. Rev. Lett. 105, 263903 (2010)

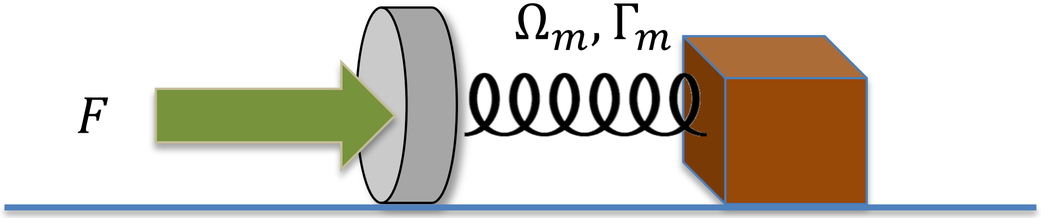


Exemple de mode mécanique



Thèse C. Baker 2013 – I. Favero

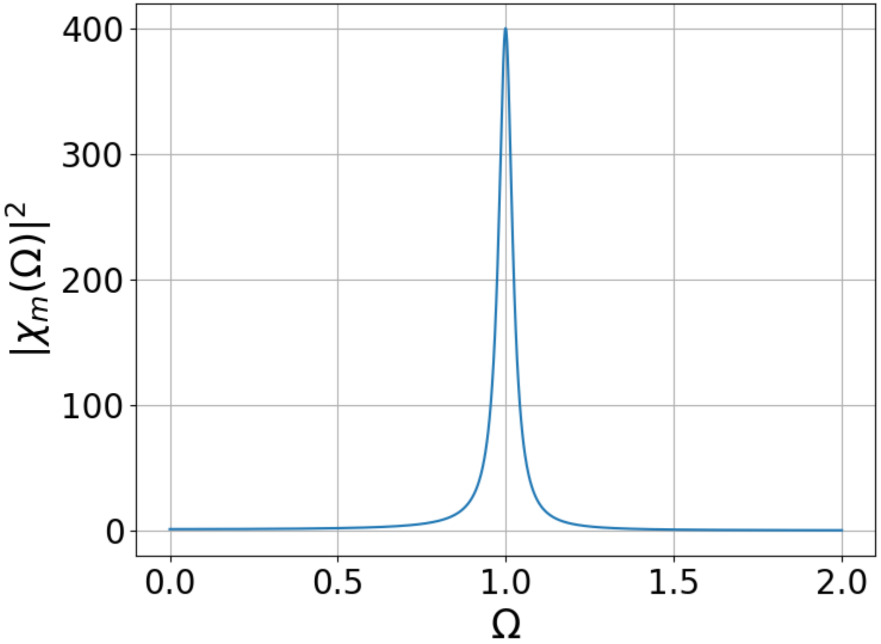
Résonateur mécanique : description classique



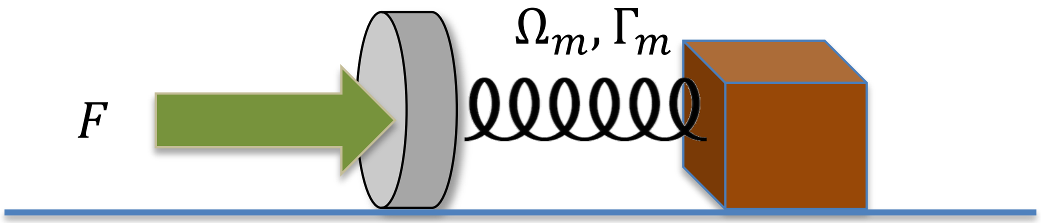
$$m\ddot{x} + m\Gamma_m\dot{x} + m\Omega_m^2 x = F(t)$$

$$x(\Omega) = \chi_m(\Omega)\, F(\Omega)$$

$$\chi_m(\Omega) = \frac{1}{m(\Omega_m^2 - \Omega^2 - i\Gamma_m\Omega)}$$



Résonateur mécanique : description classique



$$m\ddot{x} + m\Gamma_m \dot{x} + m\Omega_m^2 x = F(t)$$

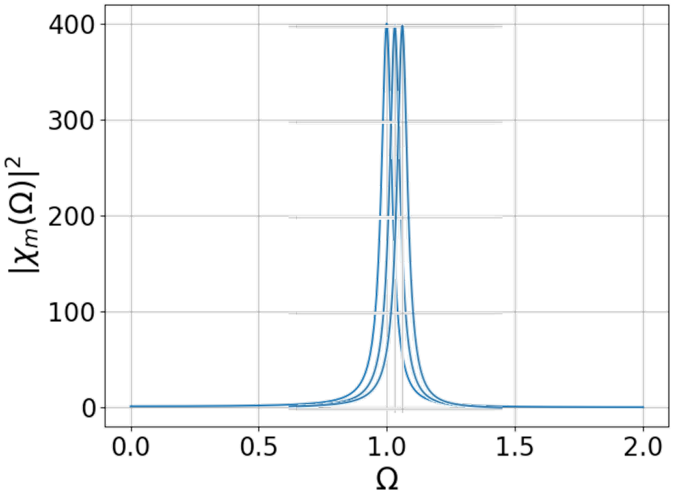
$$x(\Omega) = \chi_m(\Omega)\, F(\Omega)$$

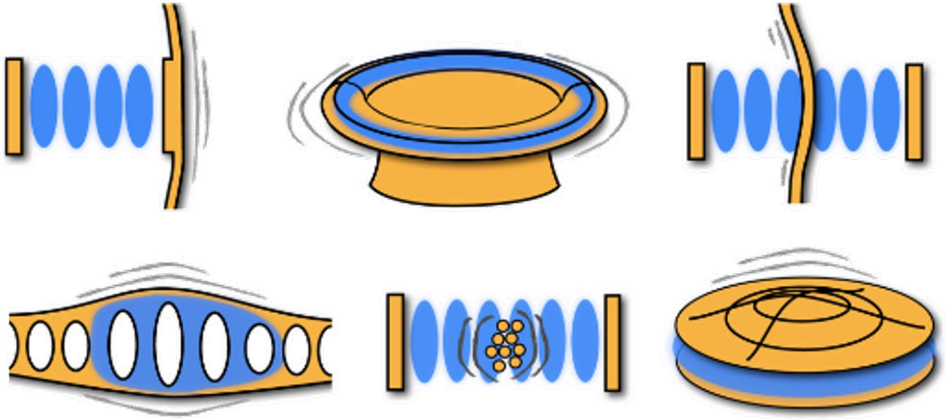
$$\chi_m(\Omega) = \frac{1}{m(\Omega_m^2 - \Omega^2 - i\Gamma_m \Omega)}$$

Amortissement ?

- Anélasticité interne / friction interne (défauts, dislocations, impuretés, …)
- Pertes par ancrages
- Amortissement par le gaz
- Damping visqueux
- Amortissement optique

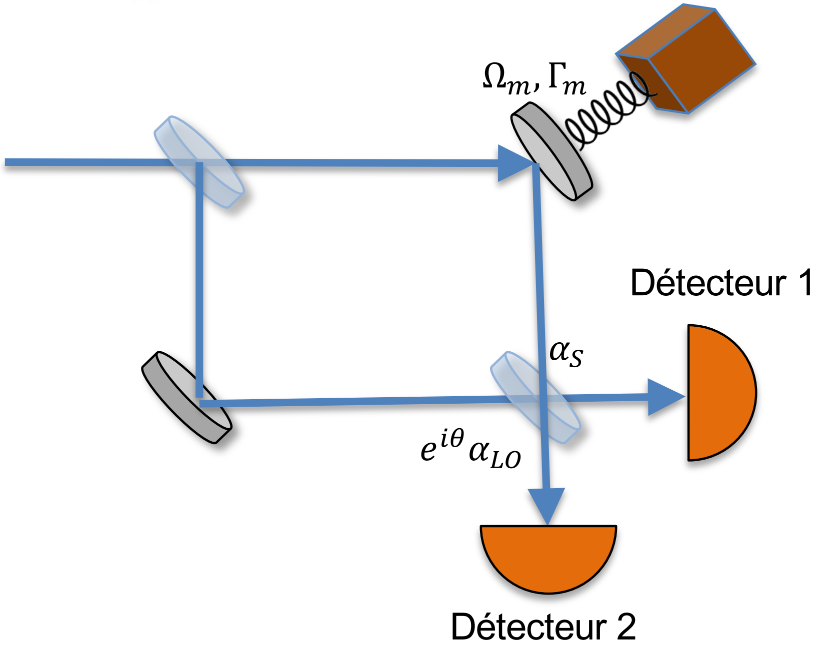
Couplage optomécanique?





- Pression de radiation
- Déformation mécanique
- Déformation Thermique
- Effet piezo electrique : (contrainte $\propto \vec{E} \rightarrow \Delta n \propto |E|$)
- Effet d'électrostriction : (contrainte $\propto |E|^2 \rightarrow \Delta n \propto |E|^2$)

Mesure des modes mécaniques : detection homodyne



Signal : $E_s(t)$, Référence $E_{LO}(t) = \alpha_{LO} e^{i\theta}$

$$E_{1,2}(t) = \frac{1}{\sqrt{2}}\left(E_s(t) \pm E_{LO}(t)\right).$$

$$\delta E_S = \frac{\partial H}{\partial \phi}\delta\phi \bar{E}_S \Rightarrow \delta\phi(t) = G_\phi\, x(t), \quad G_\phi = \frac{4\pi n}{\lambda}$$

$$E_s(t) \simeq \bar{E}_s + G_E\, x(t)$$

Photocourants (efficacité η) :

$$i_{1,2}(t) = \eta \mid E_{1,2}(t) \mid^2.$$

Courant différentiel :

$$\boxed{\delta i(t) \equiv i_1 - i_2 \;\simeq\; 2\eta\, \Re e\left[E_{LO}^*(t)\,\delta E_s(t)\right] = K\, x(t)}$$

→ On mesure le spectre de bruit de $\delta i(t)$

Réponse Fabry-Pérot

$$H(\phi) \equiv \frac{E_t}{E_i} = \frac{t_1 t_2}{1 - r_1 r_2 e^{i\phi}}$$

$$\phi = \frac{4\pi n L_c}{\lambda}$$

Parenthèse : spectres de bruit

Pour un signal réel A(t) (courant, tension, position…)

Spectre est défini par

$$S_{AA}(\Omega) \equiv \int_{-\infty}^{+\infty} \langle A(t)A(0)\rangle \, e^{i\Omega t} \, dt \qquad [A^2/\mathrm{Hz}]$$

Bruit blanc

$$\langle A(t)A(0)\rangle \propto \delta(t) \quad \Rightarrow \quad S_{AA}(\Omega) = \text{const.}$$

Oscillateur amorti

$$\langle A(t)A(0)\rangle \sim e^{-\Gamma|t|} \cos(\Omega_m t)$$

$$\Rightarrow \quad S_{AA}(\Omega) = \text{Lorentzien centré en } \Omega_m$$

$$\langle A^2\rangle = \int_{-\infty}^{+\infty} \frac{d\Omega}{2\pi} S_{AA}(\Omega)$$

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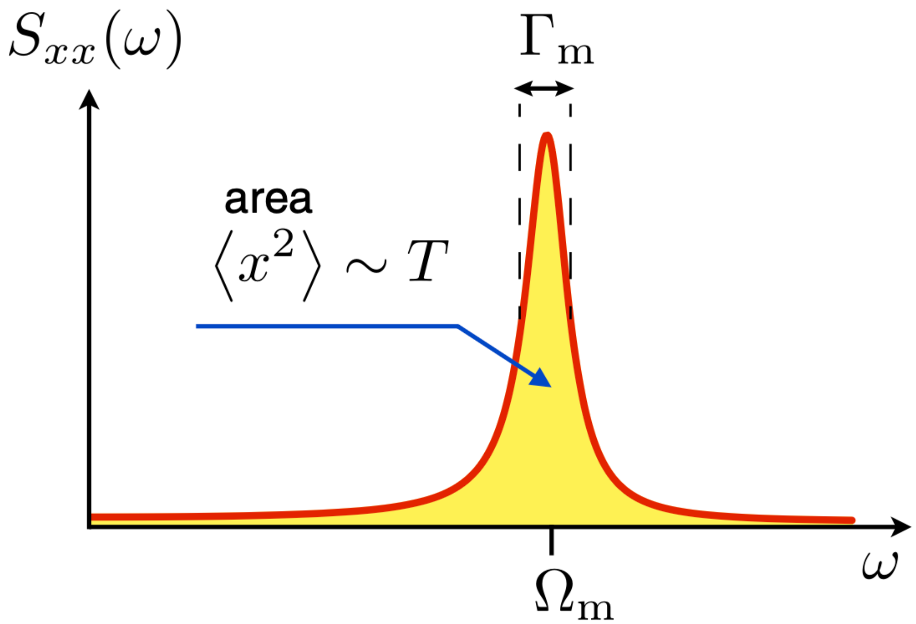
Mesure des modes mécaniques : detection homodyne

$$S_{ii}(\Omega) = \int_{-\infty}^{+\infty} d\tau\, e^{i\Omega\tau} \langle \delta i(t+\tau)\, \delta i(t) \rangle$$

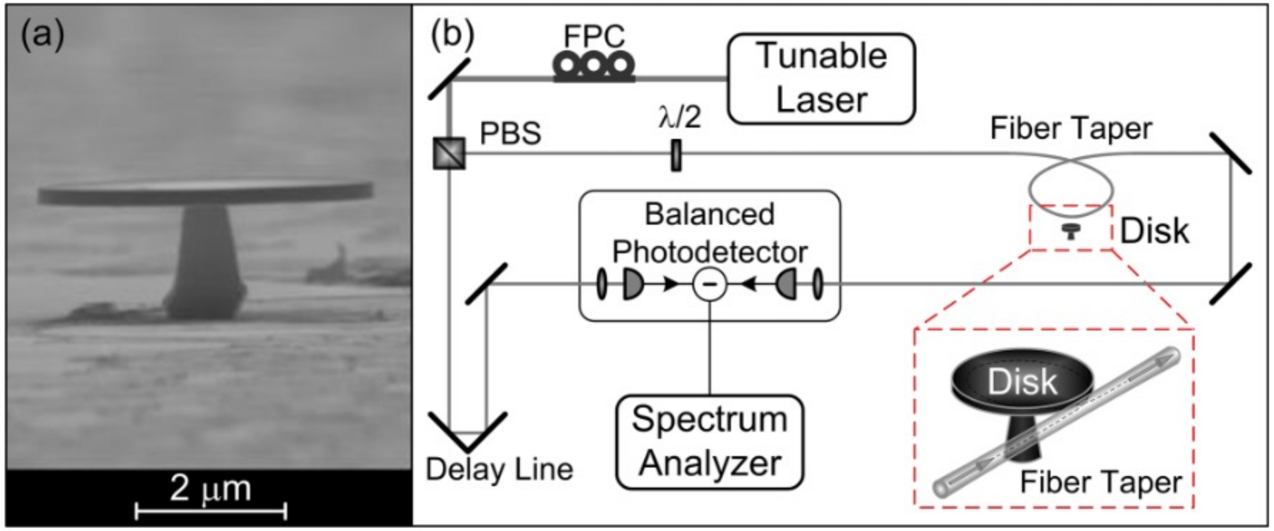
$$\hat{i}(t) = K\, x(t) + \hat{i}_{\mathrm{SN}}(t) + \hat{i}_{\mathrm{tech}}(t)$$

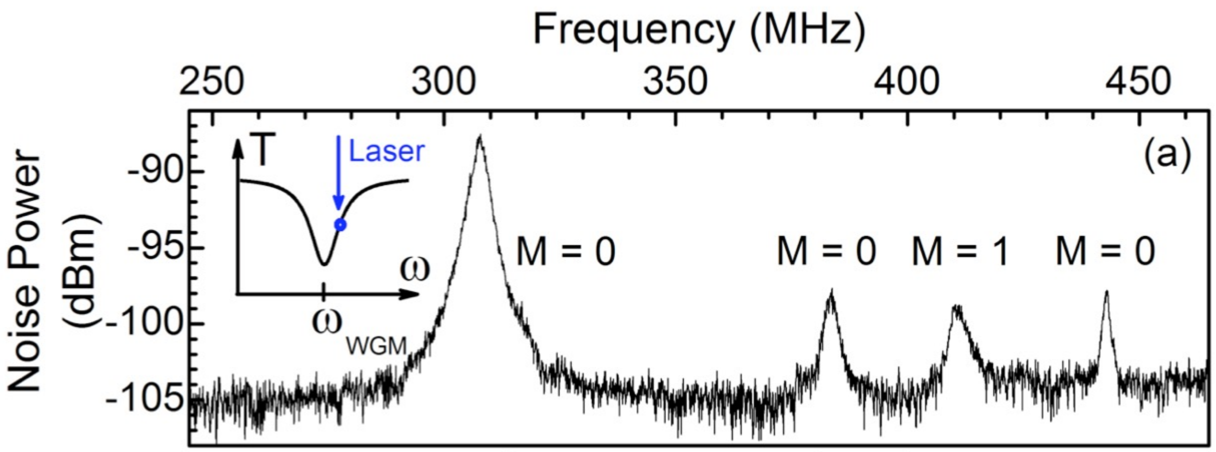
$$S_{ii}(\Omega) = S_{ii}^{\mathrm{bg}}(\Omega) + |K|^2 S_{xx}(\Omega),$$



Rev. Mod. Phys. 86, 1391 (2014).

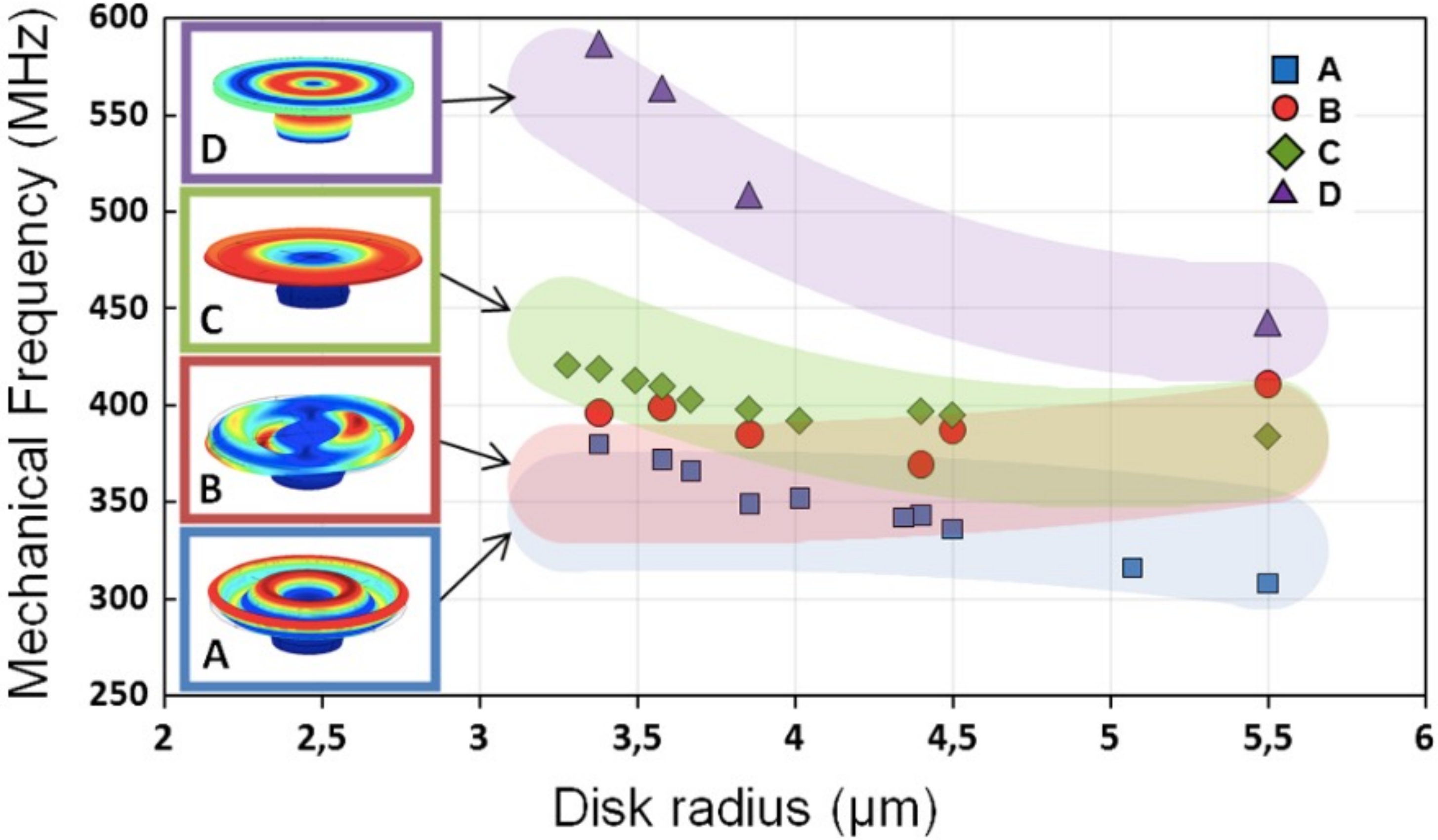
Résonateurs opto-mécaniques microdisques





Physical Review Letter 105, 263903 (2010)

Résonateurs opto-mécaniques microdisques



Physical Review Letter 105, 263903 (2010)

capteurs optomécaniques

Quelques éléments de nanofabrication

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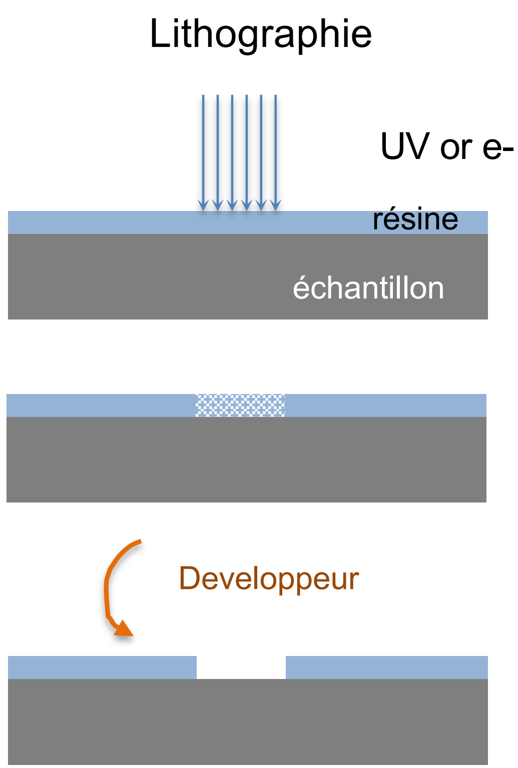
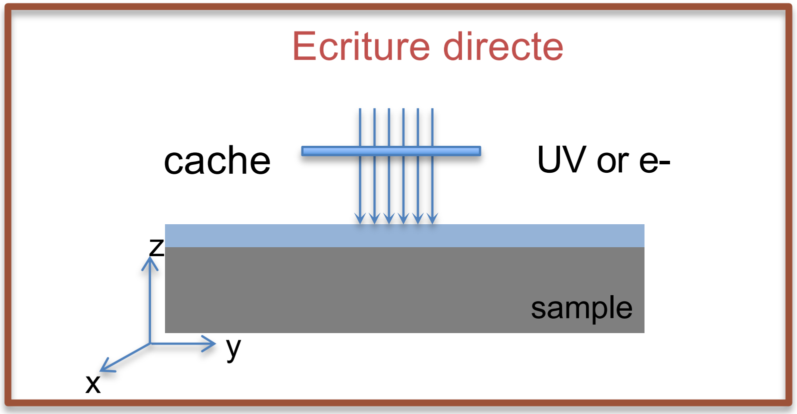
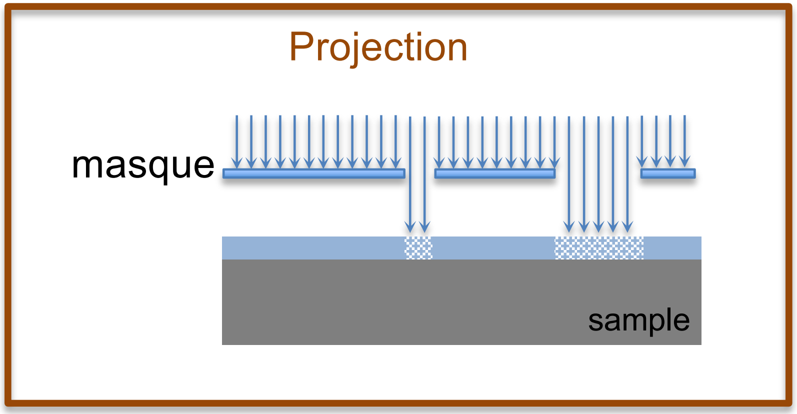
Eléments de nanofabrication : salles blanches

- ✓ Une filtration permanente de l'air
- ✓ Un flux d'air contrôlé
- ✓ Une surpression
- ✓ Des règles strictes d'habillage
- ✓ Un contrôle de l'environnement

Eléments de nanofabrication : lithographie







Résolution:
10 nm lithographie électronique
500-800 nm lithographie optique

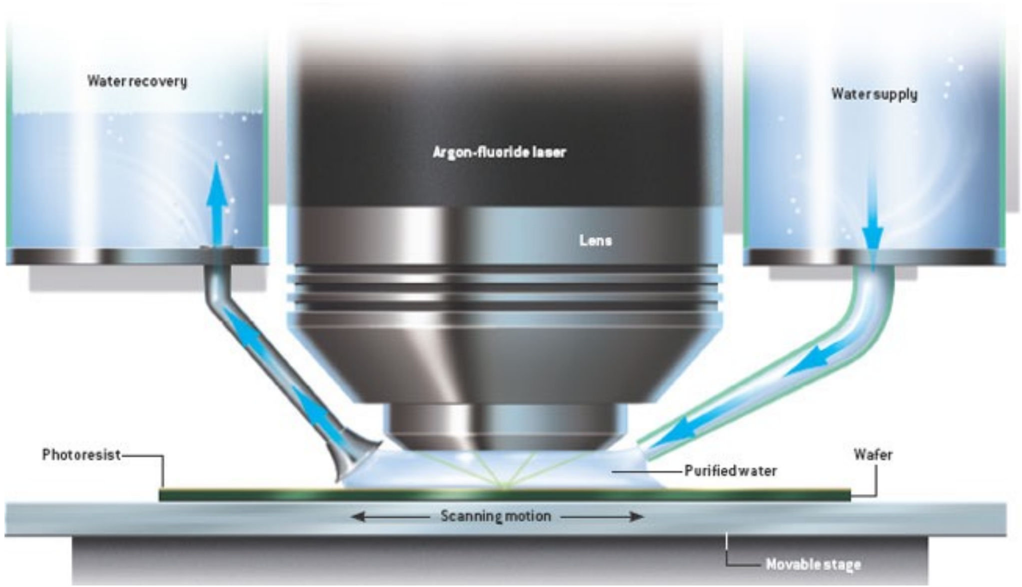
Lithographie optique à ses limites

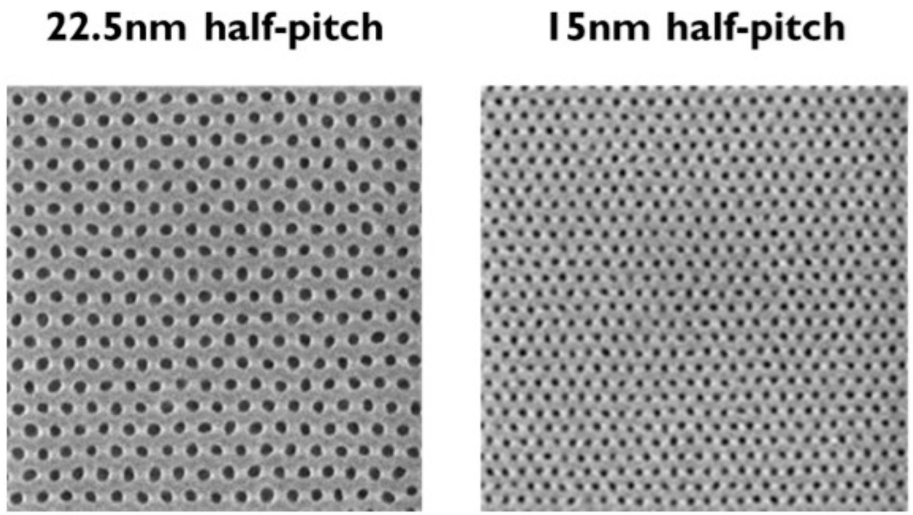
Shrinking Circuits with Water
Gary Stix
Scientific American **293**, 64 - 67 (2005)
doi:10.1038/scientificamerican0705-64

Imec Reports Breakthrough Results on Directed Self-Assembly at SPIE Advanced Lithography 2015

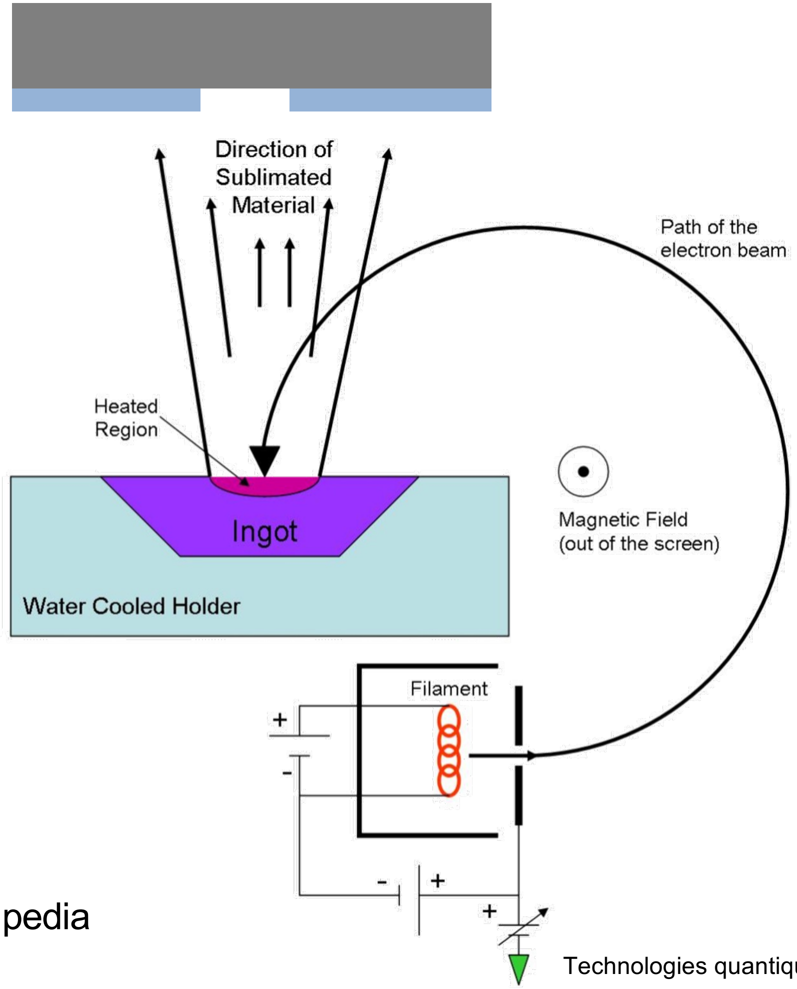
19/2/2015

Developments Pave the Way to DSA Extending 193nm Immersion Lithography Towards the 7nm Node





Eléments de nanofabrication : transfert de masque



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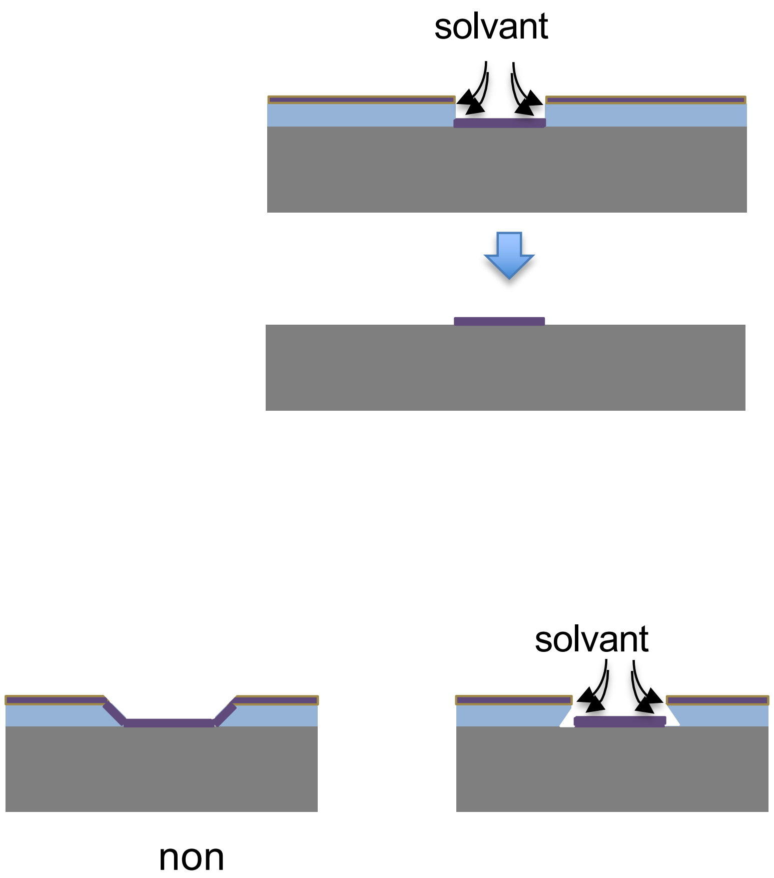
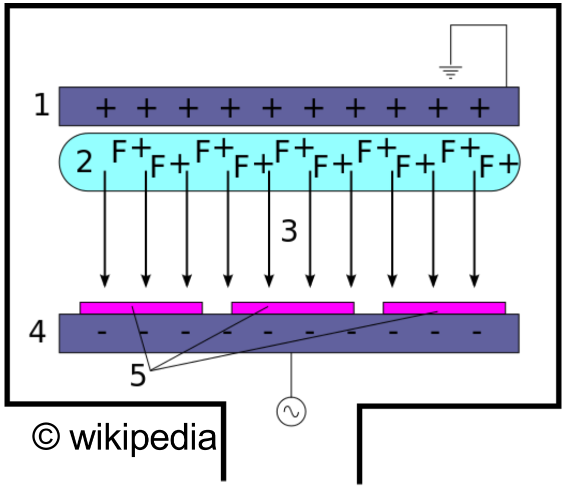


Eléments de nanofabrication : gravure

Gravure sèche



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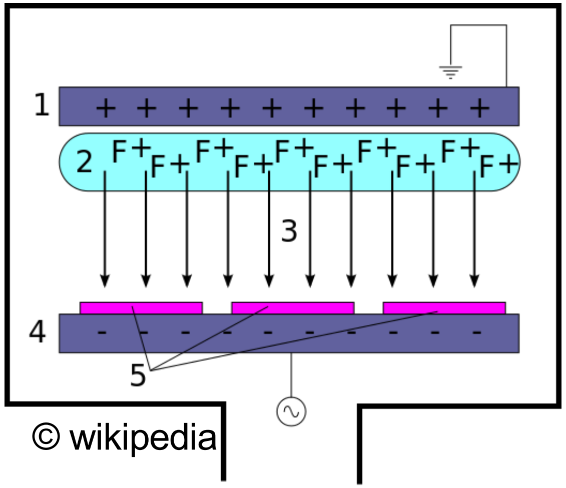
Anisotropic etching

Eléments de nanofabrication : gravure

Gravure sèche

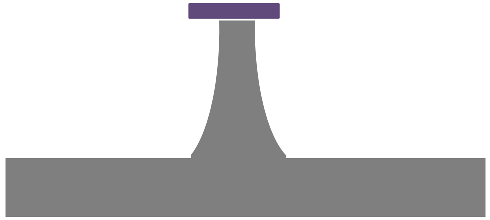


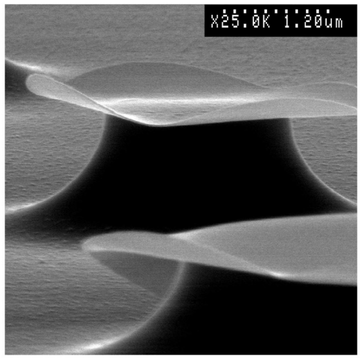
© wikipedia

Anisotropic etching

Gravure humide

Gravure isotrope





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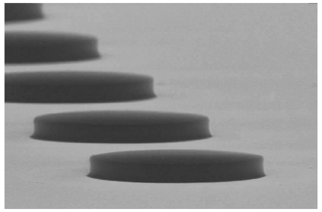
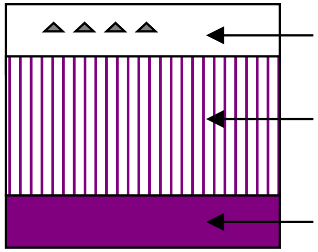
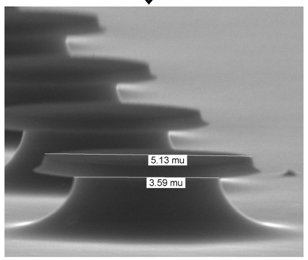
Exemple de nano-fabrication : microdisque

Lithographie électronique négative

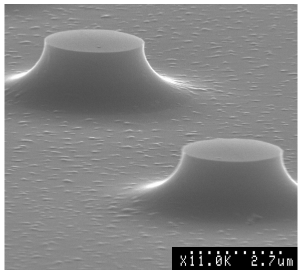




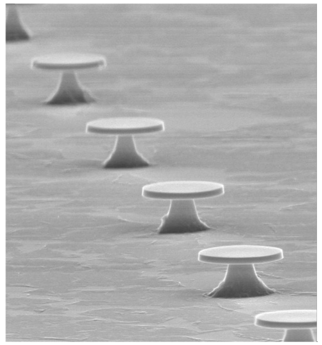
Gravure humide non sélective



Retrait résine



Gravure humide sélective



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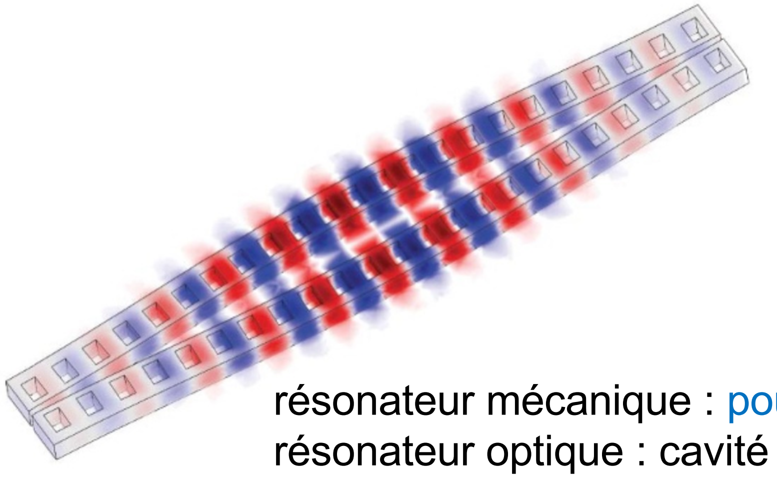
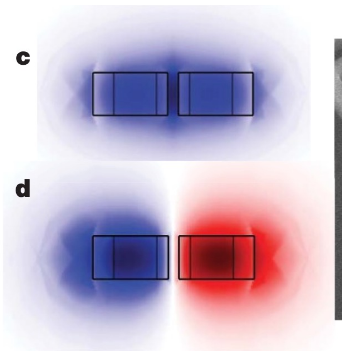
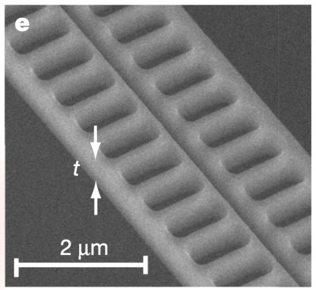
Exemple : le résonateur “fermeture éclair”

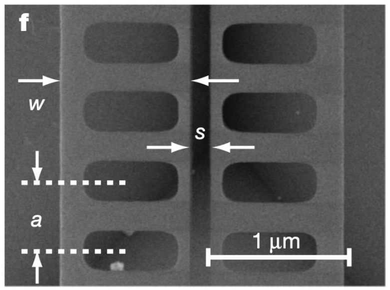
Nature 459, 550 (2009)

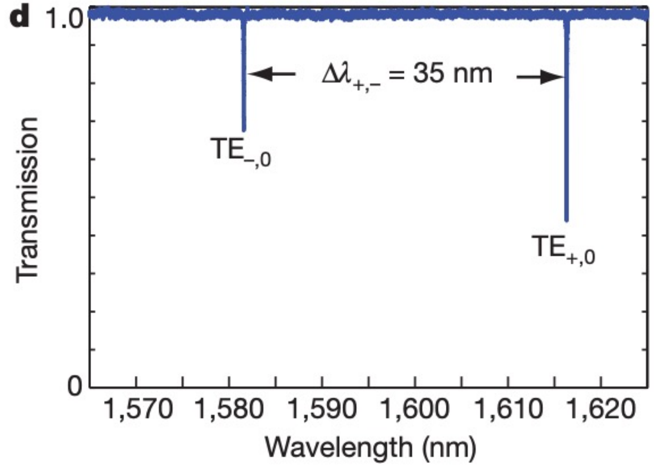


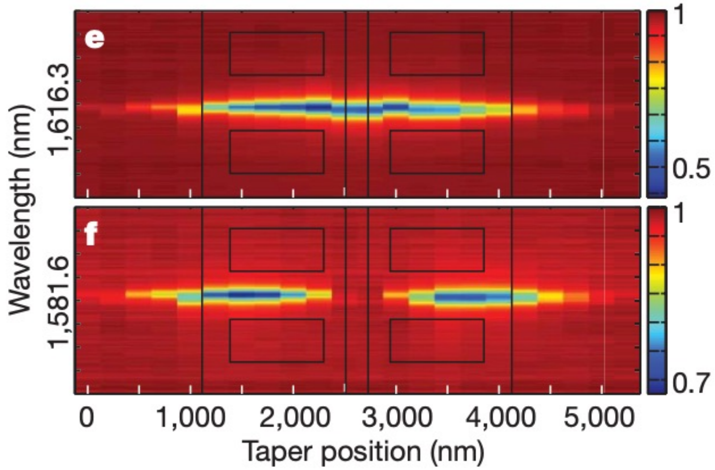
résonateur mécanique : poutres couplées
résonateur optique : cavité à cristal photonique











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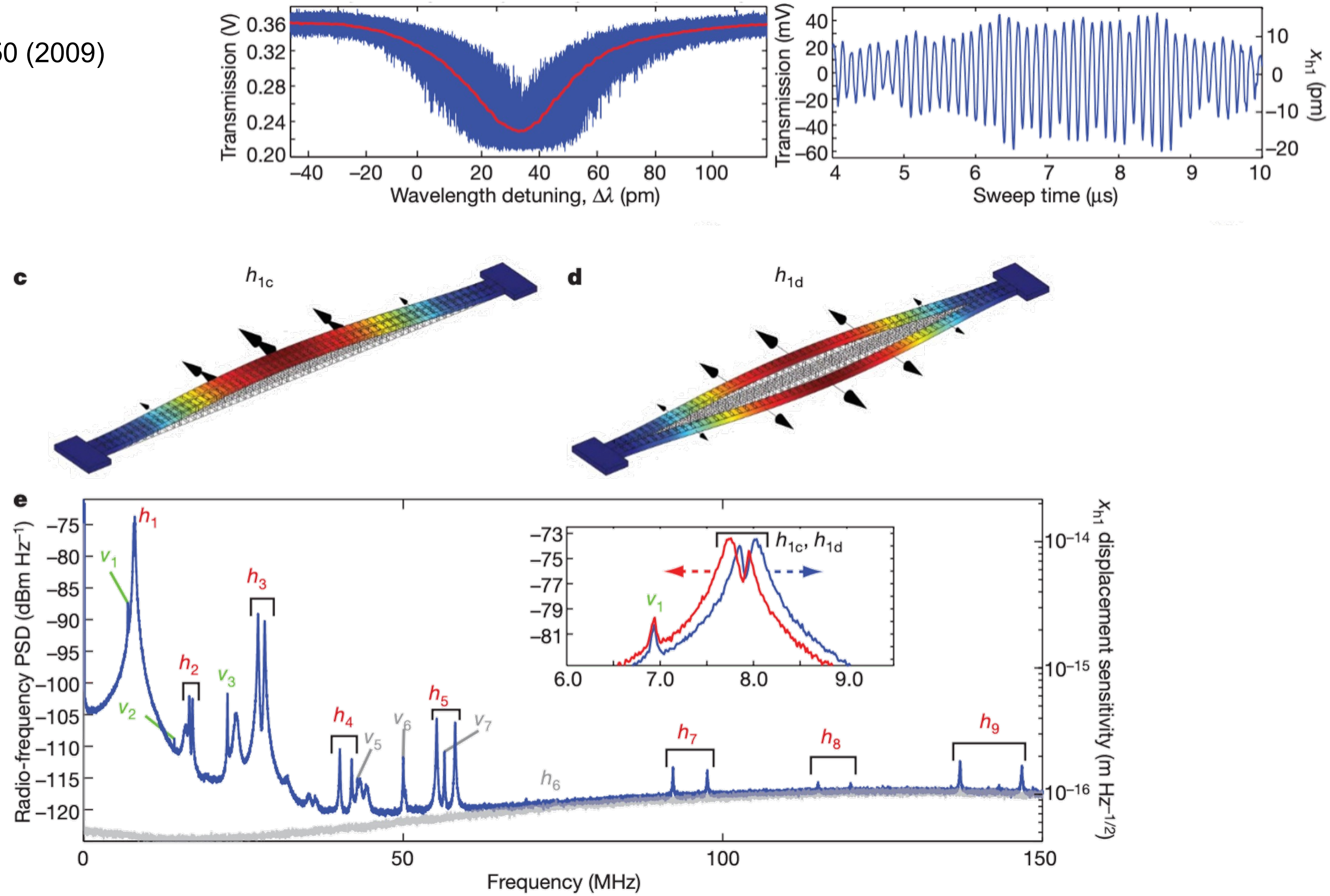
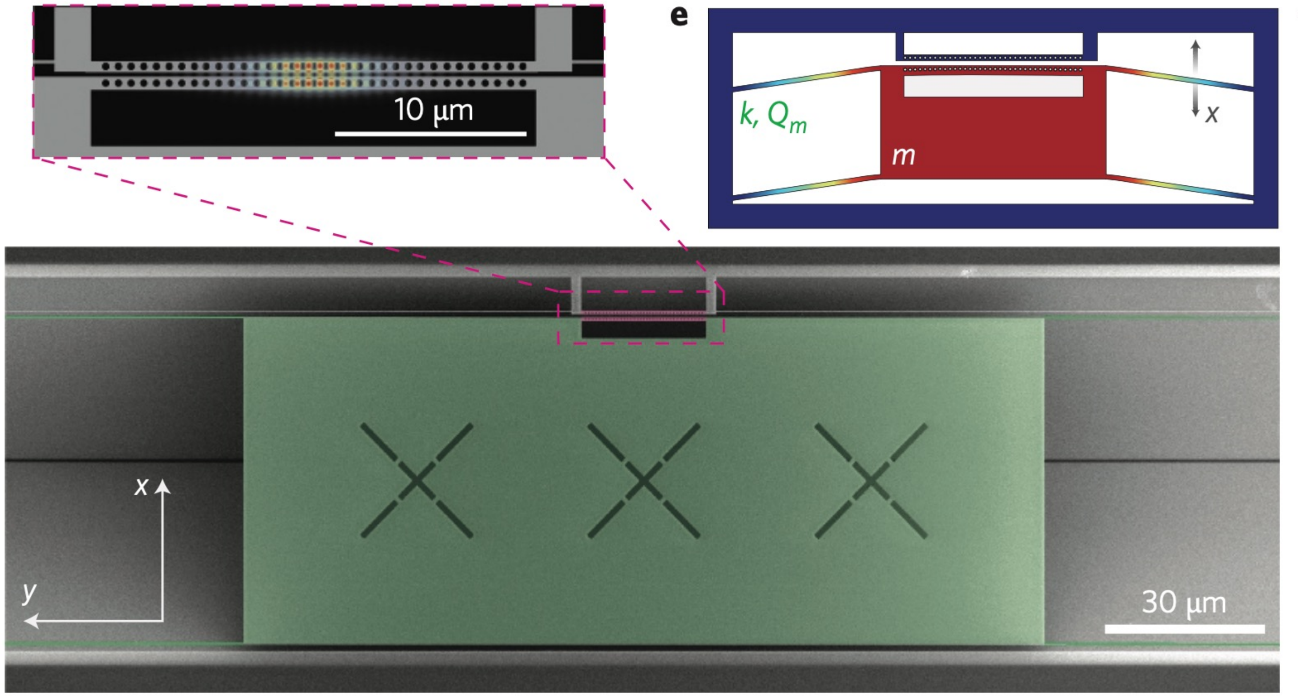
Le résonateur “fermeture éclair”

Nature 459, 550 (2009)



Capteur optomécanique : accéléromètre

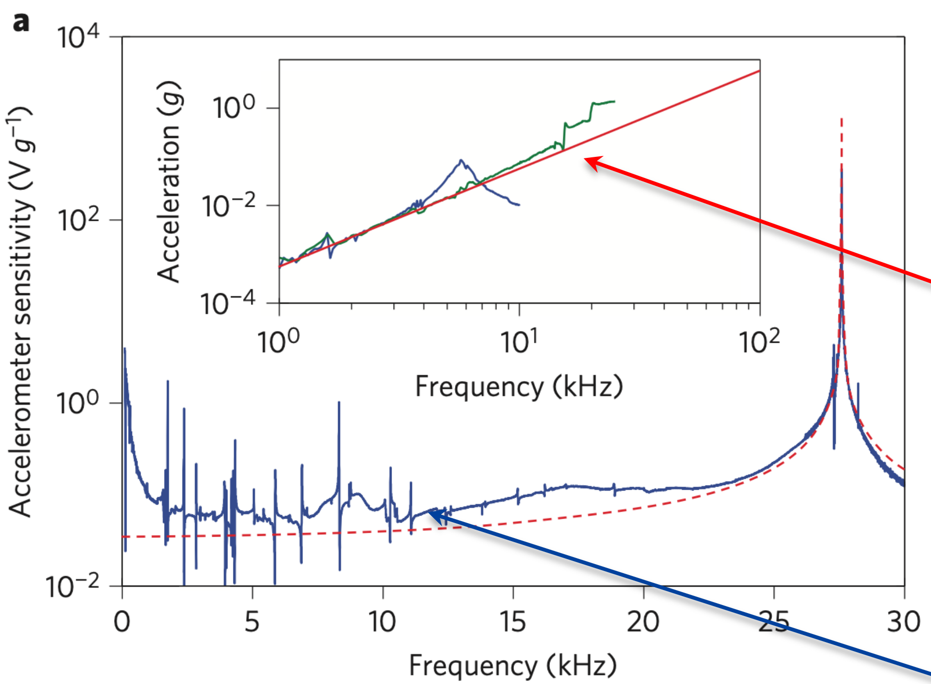


Nature Photonics 6, 768–772 (2012)

Capteur optomécanique : accéléromètre

susceptibilité mécanique en accélération

$\chi(\omega) = \frac{x(\omega)}{a(\omega)}$ et $\chi(\omega) = \frac{1}{\omega_m^2 - \omega^2 + i\omega\Gamma_m}$



Sans contre-reaction optique

Pour $\omega \ll \omega_m$: $\frac{x}{a} \approx \frac{1}{\omega_m^2}$

Plus petite acceleration détectable

$a_{min}(\omega) = \frac{\text{bruit de lecture en } x}{x/a} \propto \omega_m^2$

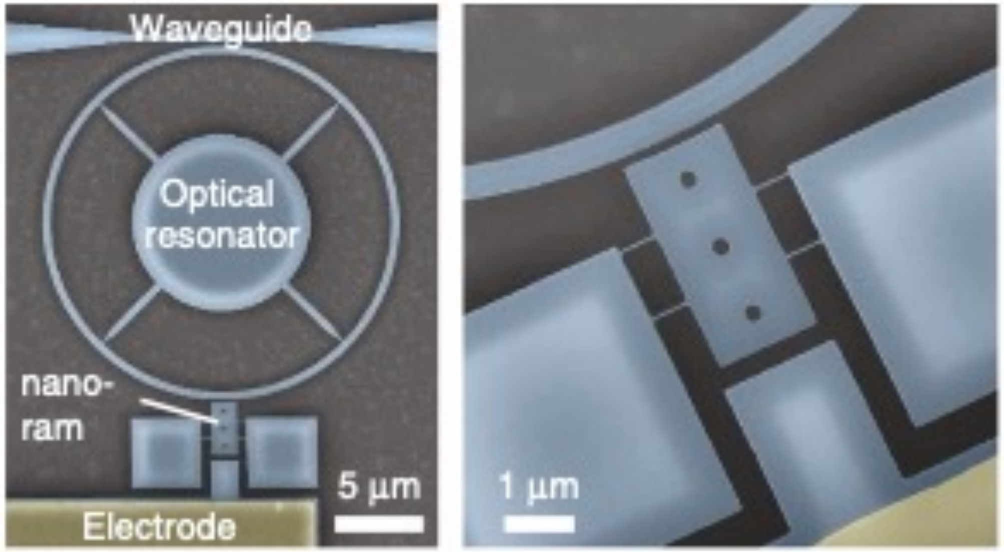
Réponse opto-mécanique

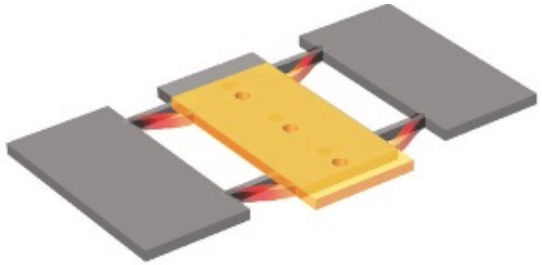
$a_{min}(\omega) \approx$ constante

Sur grande gamme de fréquences

Nature Photonics 6, 768–772 (2012)

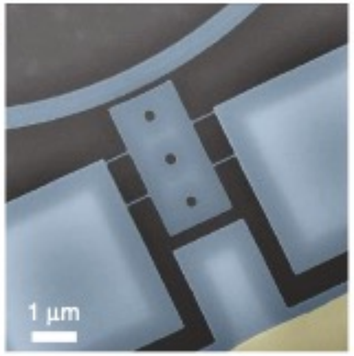
Capteur optomécanique : spectroscopie de masse

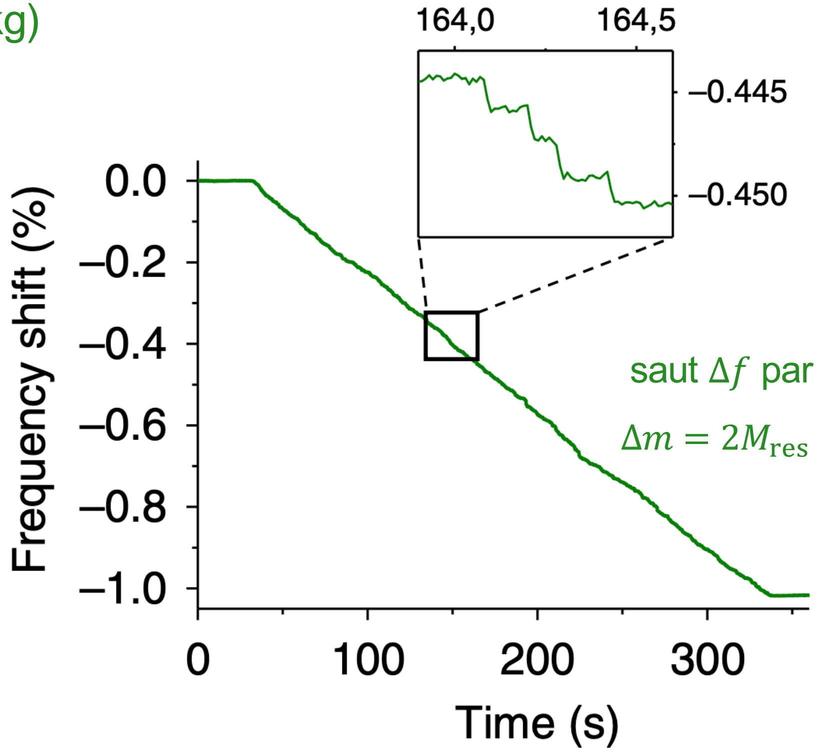




Nature Communications 11, 3781 (2020)

Dépot de particules de masse 5.7 Mda
(1MDa≈1.6605×10^{-21}kg)





saut Δf par particule déposée

$$\Delta m = 2M_{\mathrm{res}} \frac{\Delta f}{f_0}$$

$$\delta m_{\min} \approx 0{,}7\ \mathrm{MDa}$$

Nature Communications 11, 3781 (2020)

Régime quantique

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Résonateurs optiques et mécaniques : description quantique

Mode de cavité

$$\hat{H}_c = \hbar\hat{\omega}_c \hat{c}^+ \hat{c}$$

Mode mécanique

$$\hat{H}_m = \hbar\hat{\Omega}_m \hat{b}^+ \hat{b}$$

$$\hat{x} = x_{zpf}\left(\hat{b}^+ + \hat{b}\right)$$

$$\hat{p} = -i\, m\, \Omega_m x_{zpf}\left(\hat{b} - \hat{b}^+\right)$$

$$x_{zpf} = \sqrt{\frac{\hbar}{2\, m\, \Omega_m}}$$

$$x_{zpf}^2 = \langle 0|\hat{x}^2|0\rangle$$

Hamiltonien total : $\hat{H}_{tot} = \hbar\hat{\omega}_c \hat{c}^+ \hat{c} + \hbar\hat{\Omega}_m \hat{b}^+ \hat{b}$

Rev. Mod. Phys. 86, 1391 (2014).

Résonateurs optiques et mécaniques : description quantique

Hamiltonien total : $\hat{H}_0 = \hbar\hat{\omega}_c \hat{c}^+\hat{c} + \hbar\hat{\Omega}_m \hat{b}^+\hat{b}$

Fréquence de la cavité

$$\omega_c(x) \approx \omega_c + x\frac{\partial \omega_c}{\partial x} + \cdots \qquad G = -\frac{\partial \omega_c}{\partial x}$$

Pour une cavité simple longueur L, $G = \frac{\omega_c}{L}$

$$\hat{H}_{tot} = \hat{H}_0 + \hat{H}_{int} + \hat{H}_{drive}$$

$$\hat{H}_{int} = -\hbar g_0\, \hat{c}^+\hat{c}\, (\hat{b} + \hat{b}^+)$$

$$g_0 = G x_{zpf}$$

$$\hat{H}_{drive} = \hbar\mathcal{E}(\hat{c}e^{-i\omega_\ell t} + h.c.)$$

Rev. Mod. Phys. 86, 1391 (2014).

Résonateurs optiques et mécaniques : description quantique

$$\hat{H}_{tot} = \hbar\hat{\omega}_c\hat{c}^+\hat{c} + \hbar\hat{\Omega}_m\hat{b}^+\hat{b} + -\hbar g_0\,\hat{c}^+\hat{c}\,(\hat{b} + \hat{b}^+) + \hbar\mathcal{E}(\hat{c}e^{-i\omega_\ell t} + h.c.)$$

Dans le référentiel tournant à ω_ℓ

$$\hbar\omega_c\hat{c}^\dagger\hat{c} \;\rightarrow\; -\hbar\Delta\,\hat{c}^\dagger\hat{c} \qquad \text{avec } \Delta = \omega_\ell - \omega_c$$

$$\hbar\mathcal{E}\left(\hat{c}^\dagger e^{-i\omega_d t} - \hat{c}e^{i\omega_d t}\right) \;\rightarrow\; i\hbar\mathcal{E}\left(\hat{c}^\dagger + \hat{c}\right)$$

Hypothèse : champ optique intense $\boxed{\hat{c} = \alpha + \hat{a}}$ (linéarisation), avec $\alpha \in \mathbb{R}$,
(choisi pour supprimer les termes linéaires)

$$\hbar g_0\left(\hat{b} + \hat{b}^\dagger\right)\hat{c}^\dagger\hat{c} = \hbar g_0\left(\hat{b} + \hat{b}^\dagger\right)\left(|\,\alpha\,|^2 + \alpha^*\hat{a} + \alpha\hat{a}^\dagger + \hat{a}^\dagger\hat{a}\right) \approx \hbar g_0\alpha(\hat{b} + \hat{b}^\dagger)(\hat{a} + \hat{a}^\dagger)$$

Représentation d'interaction : $\hat{a}_I(t) = \hat{a}\,e^{+i\Delta t}, \hat{b}_I(t) = \hat{b}\,e^{-i\omega_m t}$

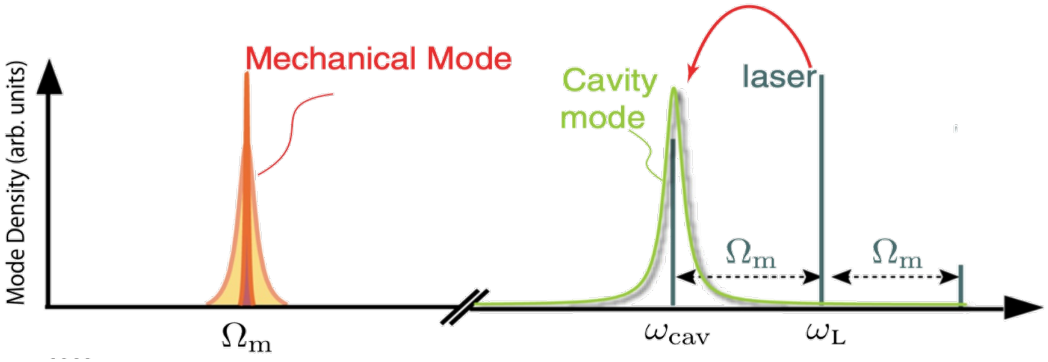
$$\hat{V}_I(t) = \hbar G\left[\hat{a}\hat{b}\,e^{i(\Delta-\omega_m)t} + \hat{a}\hat{b}^\dagger\,e^{i(\Delta+\omega_m)t} + \hat{a}^\dagger\hat{b}\,e^{-i(\Delta+\omega_m)t} + \hat{a}^\dagger\hat{b}^\dagger\,e^{-i(\Delta-\omega_m)t}\right]$$

Rev. Mod. Phys. 86, 1391 (2014).

Excitation optique d'un mode mécanique

$$\hat{V}_I(t) = \hbar G\left[\hat{a}\hat{b}\, e^{i(\Delta-\omega_m)t} + \hat{a}\hat{b}^\dagger\, e^{i(\Delta+\omega_m)t} + \hat{a}^\dagger\hat{b}\, e^{-i(\Delta+\omega_m)t} + \hat{a}^\dagger\hat{b}^\dagger\, e^{-i(\Delta-\omega_m)t}\right]$$

Si $\hat{\Omega}_m \gg \kappa$



Si $\Delta = \omega_m$, alors $\boxed{\hat{V}_I = \hbar G(\hat{a}\hat{b} + \hat{a}^\dagger\hat{b}^\dagger).}$

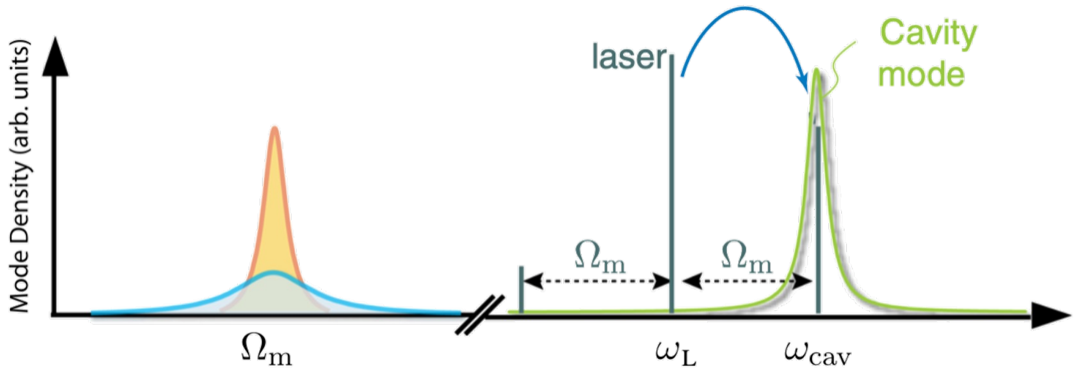
Création de paires (photon cavité –phonon Ω_m)

Rev. Mod. Phys. 86, 1391 (2014).

Refroidissement optique d'un mode mécanique

$$\hat{V}_I(t) = \hbar G\left[\hat{a}\hat{b}\, e^{i(\Delta-\omega_m)t} + \hat{a}\hat{b}^\dagger\, e^{i(\Delta+\omega_m)t} + \hat{a}^\dagger\hat{b}\, e^{-i(\Delta+\omega_m)t} + \hat{a}^\dagger\hat{b}^\dagger\, e^{-i(\Delta-\omega_m)t}\right]$$

Si $\hat{\Omega}_m \gg \kappa$



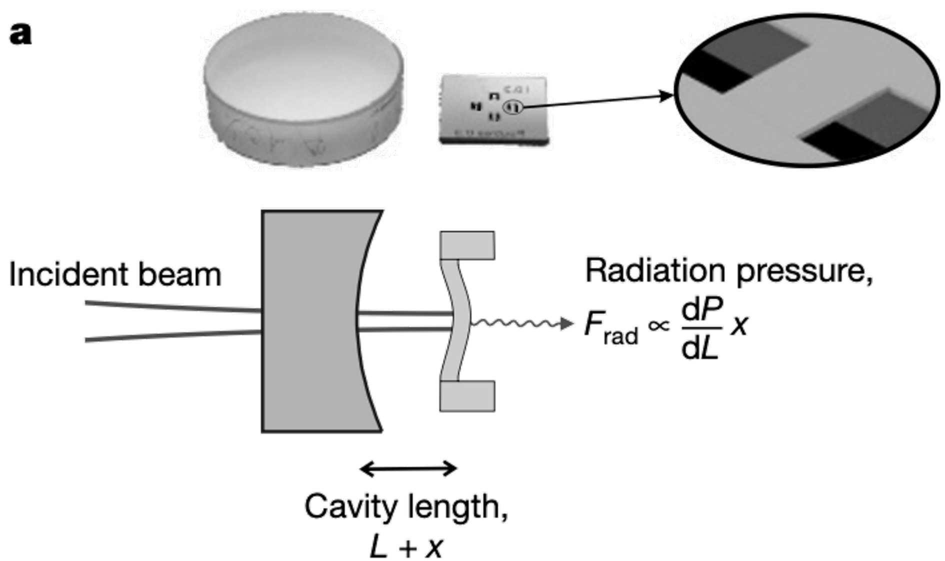
Si $\Delta = -\omega_m$, alors $\boxed{\hat{V}_I = \hbar G(\hat{a}\hat{b}^\dagger + \hat{a}^\dagger\hat{b}).}$

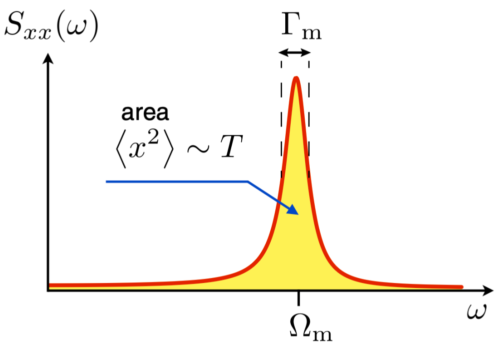
Suppression d'un phonon pour obtenir un photon du mode de cavité

Rev. Mod. Phys. 86, 1391 (2014).

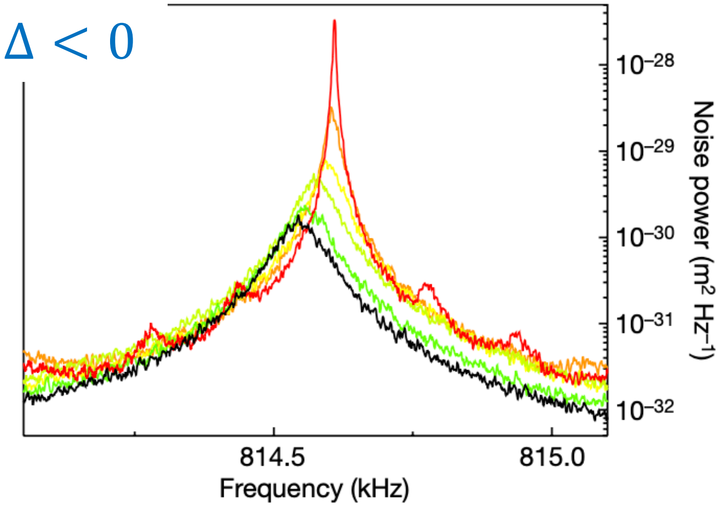
Contrôle optique de la temperature d'un résonateur

Nature 444, 71–74 (2006)

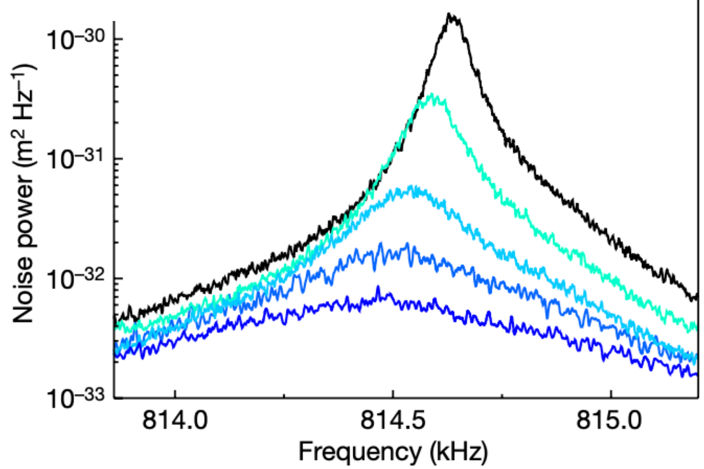




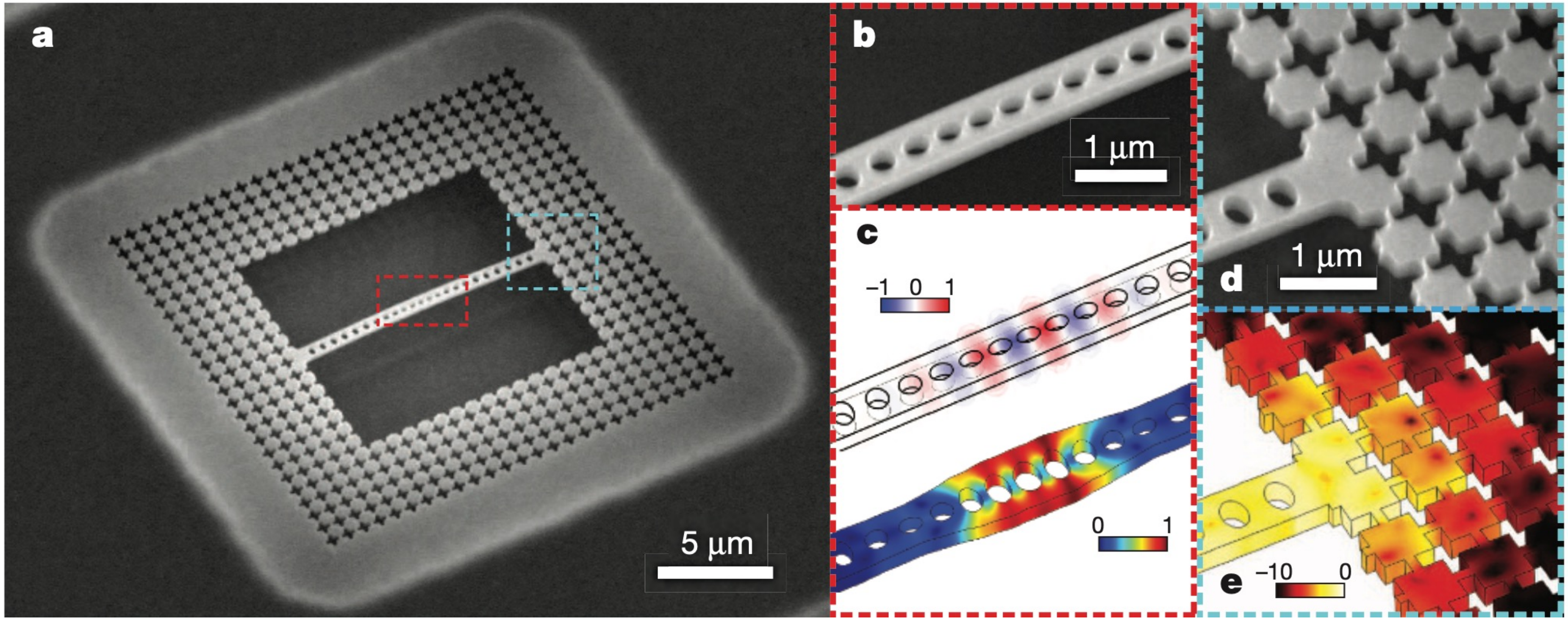
$\Delta < 0$



$\Delta < 0$

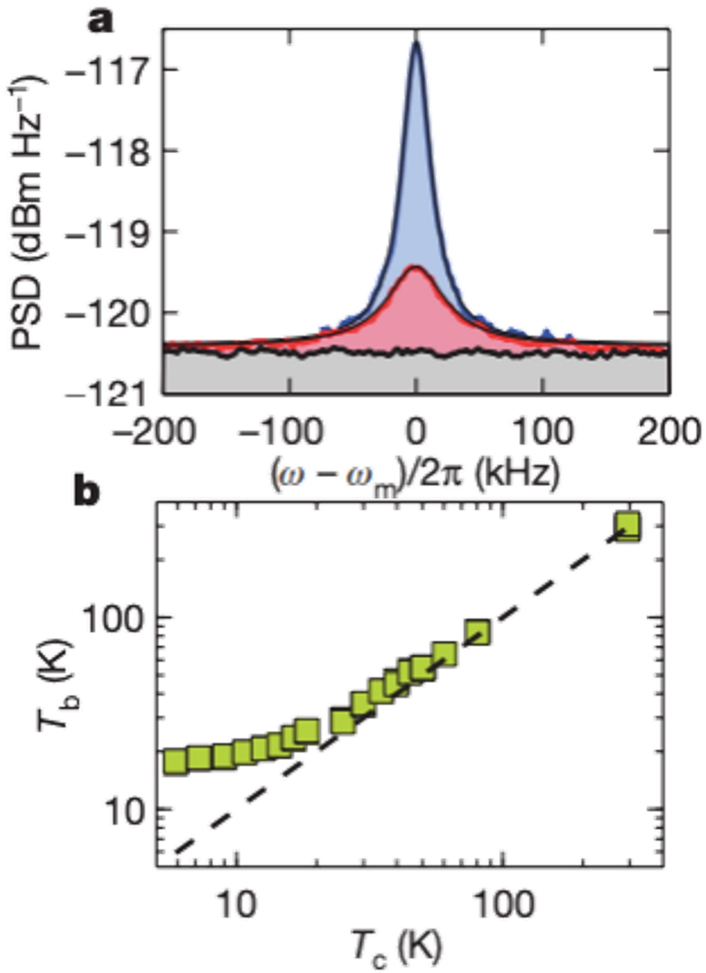


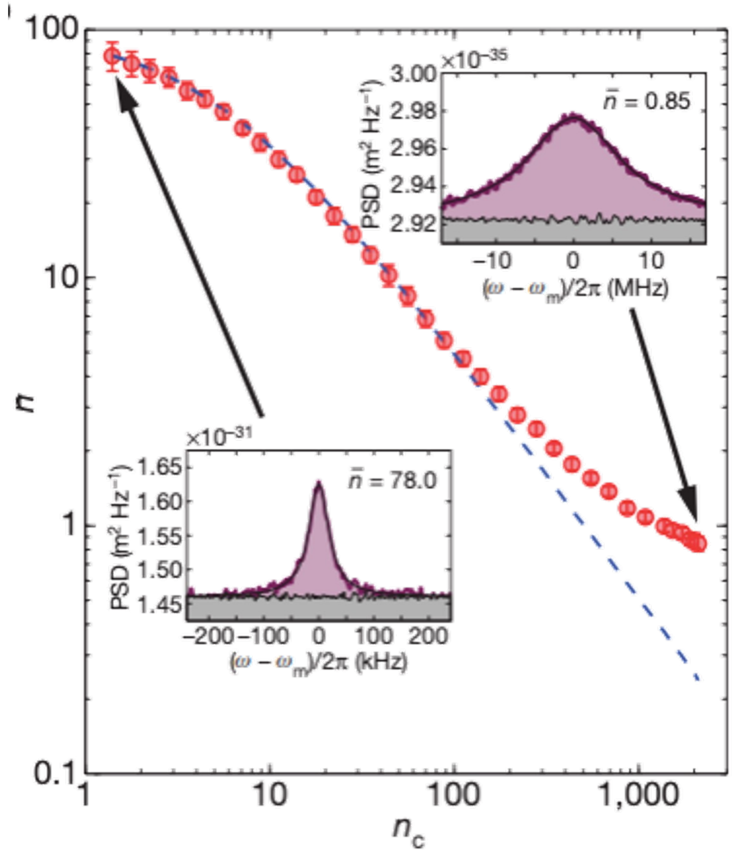
Refroidissement d'un mode mécanique : régime quantique



Nature 478, 89. (2011)

Refroidissement d'un mode mécanique : régime quantique

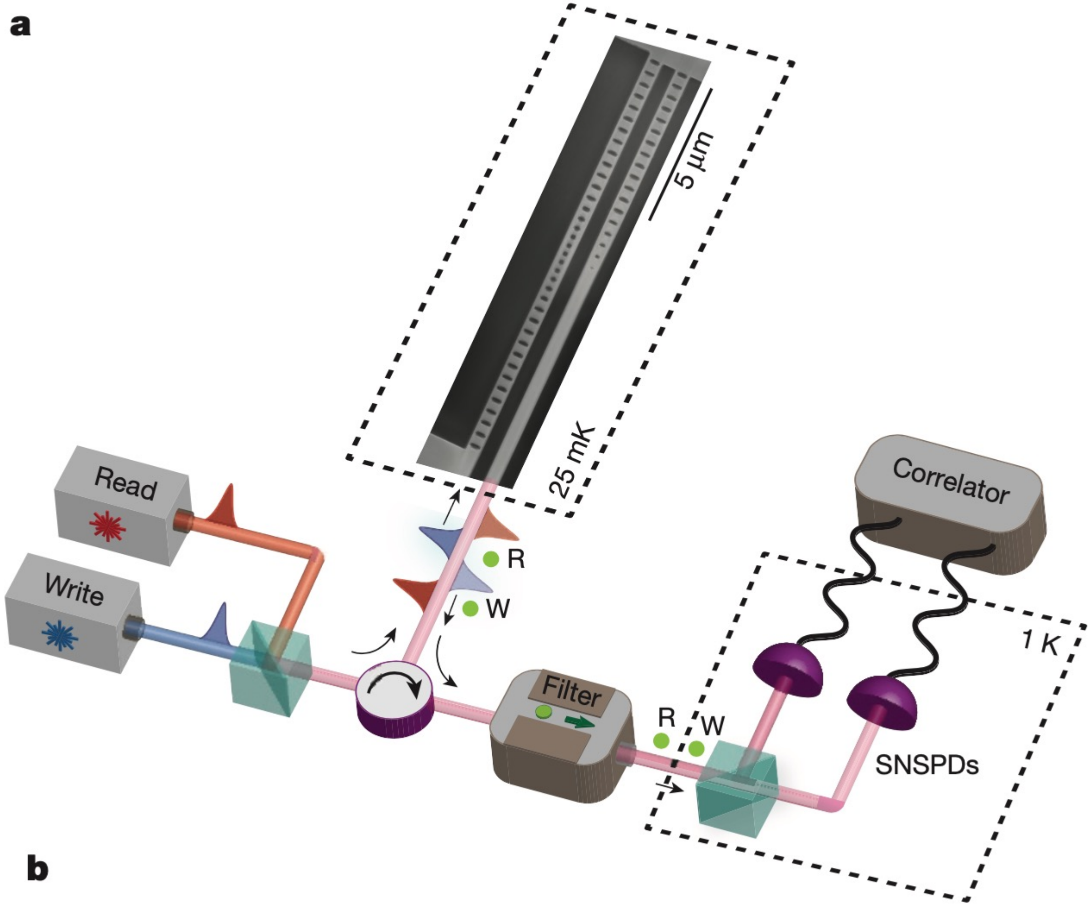




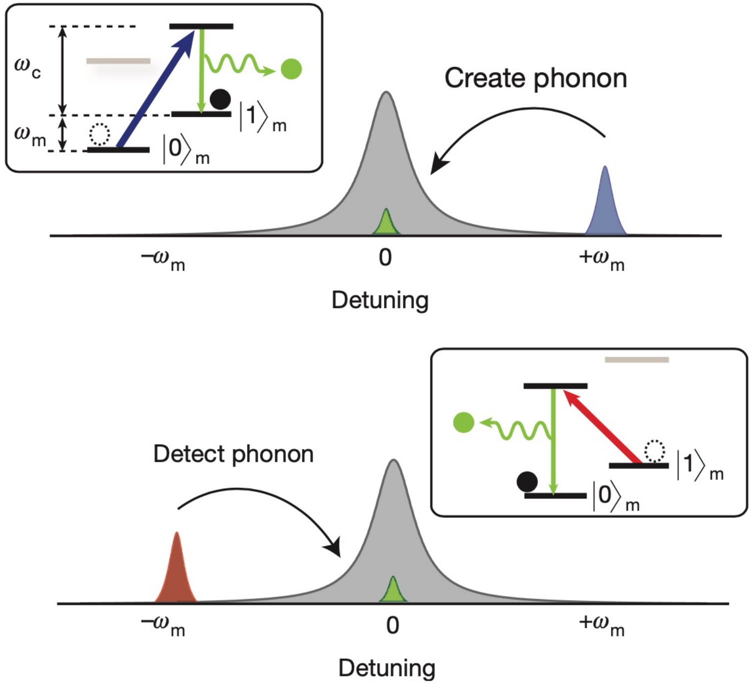
Nature 478, 89. (2011)

Génération de paires photon – phonon : protocole

a



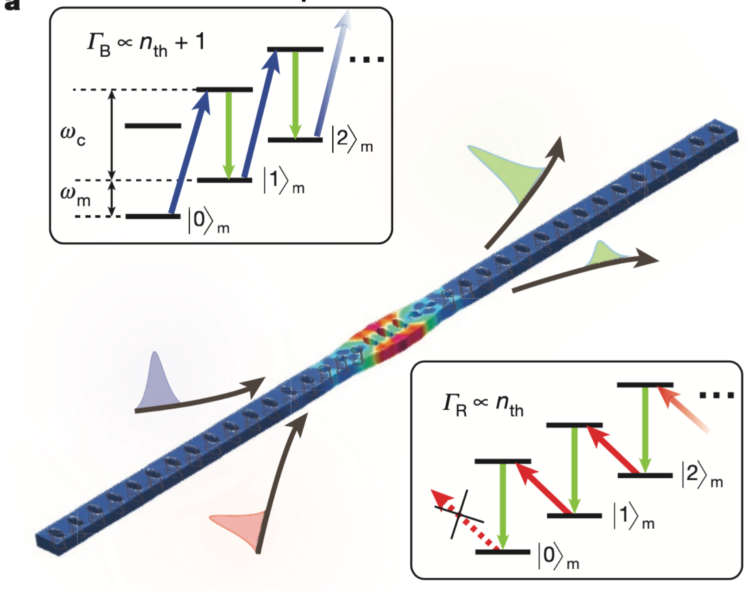
b



Nature 530, 313–316 (2016)

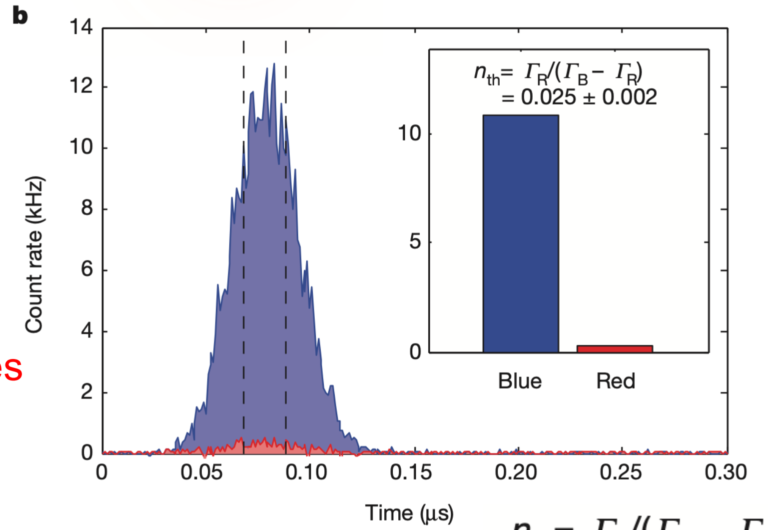
Génération de paires photon – phonon : refroidissement

Raman Stokes processes



Raman anti-Stokes processes

dilution refrigerator 25 mK
=> quantum ground state of motion.



$$n_{th} = \Gamma_R/(\Gamma_B - \Gamma_R) = 0.025 \pm 0.002$$

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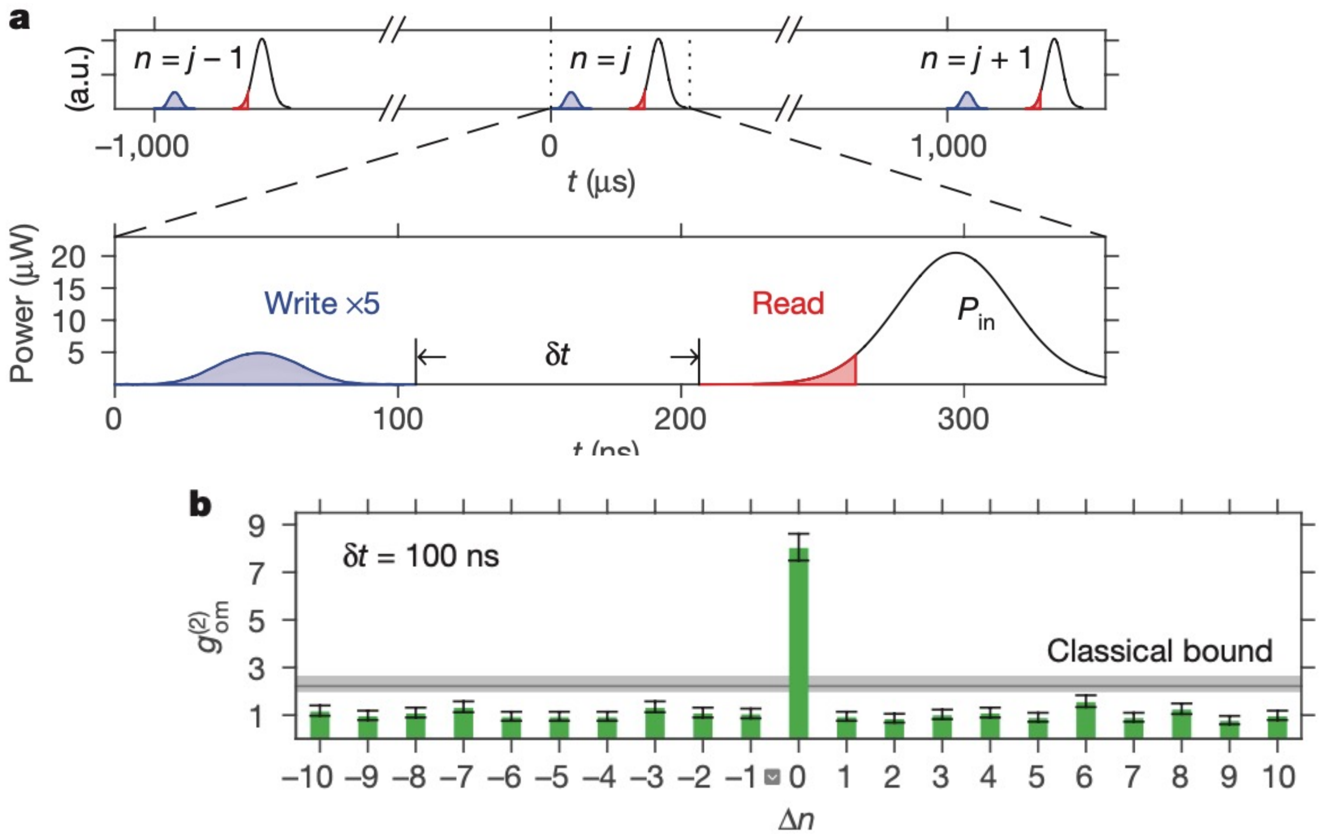
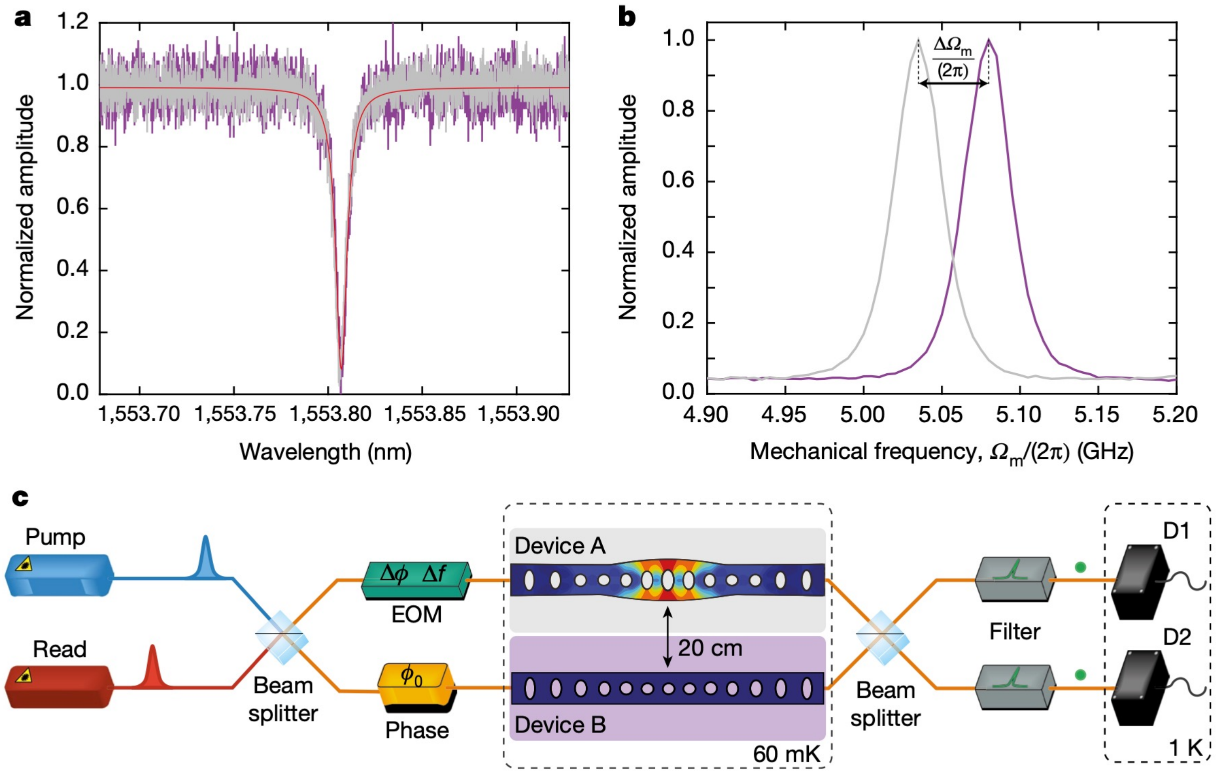
Génération de paires photon – phonon : corrélations



Nature 530, 313–316 (2016)

Intrication de deux résonateurs optomécaniques



Voir protocole leçon 8

Nature 556, 73–477 (2018)