COLLÈGE DE FRANCE
1530

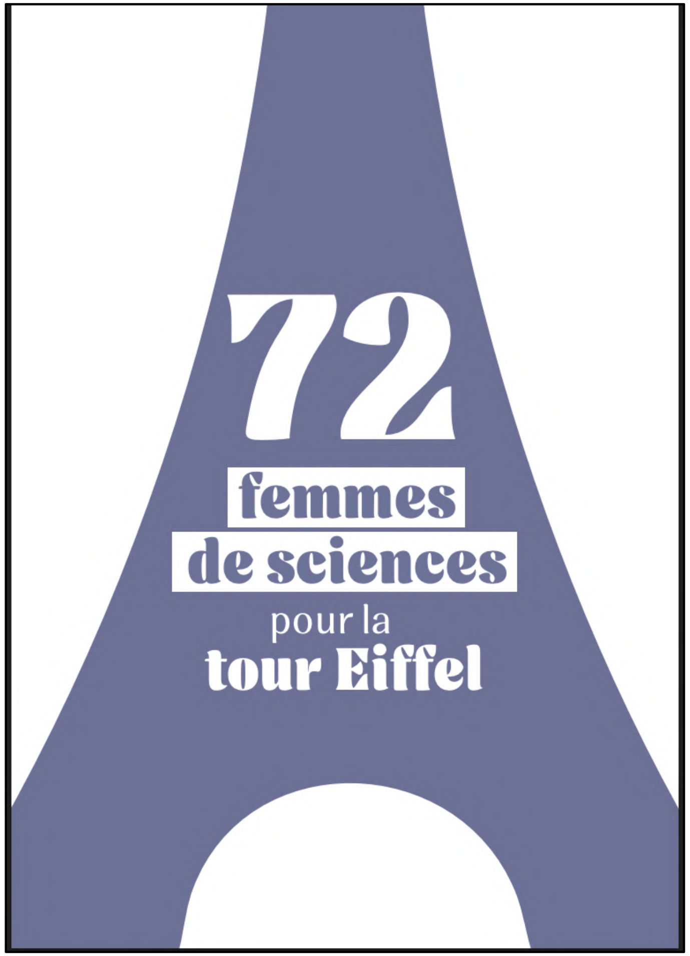
COMMUNIQUÉ

Marie Curie, Sophie Germain, Agnès Ullmann... : Découvrez la liste complète des 72 noms de femmes scientifiques proposés pour rejoindre la frise des savants sur la Tour Eiffel !

Mise à jour le 26/01/2026 à 16h59

INFORMATICIENNE
Rose Dieng
1956-2008

PHYSICIENNE
Claudine Hermann
1945-2021



https://cdn.paris.fr/presse/2026/01/26/774679514eb0328c2fcd8fd9bd994eed.pdf

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Technologies quantiques émergentes

Pascale Senellart

27 Janvier 2026

Sources de photons

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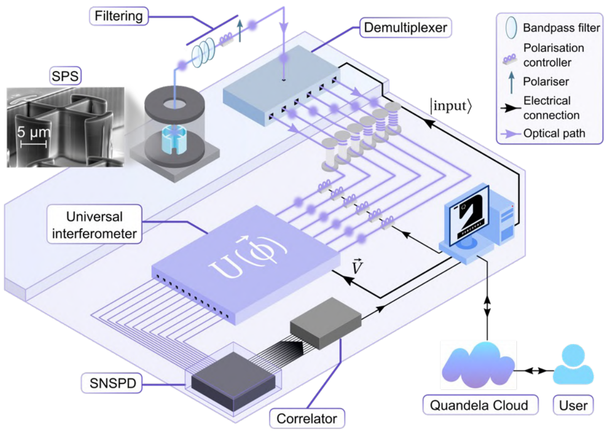
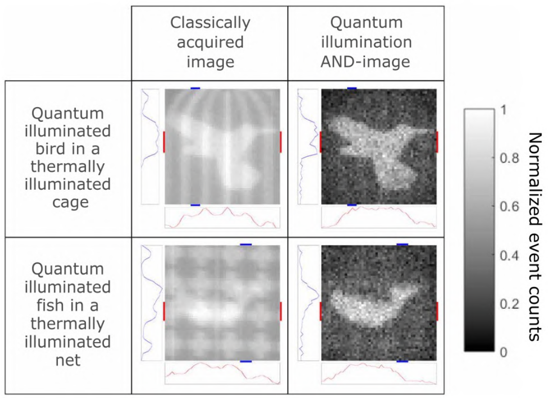
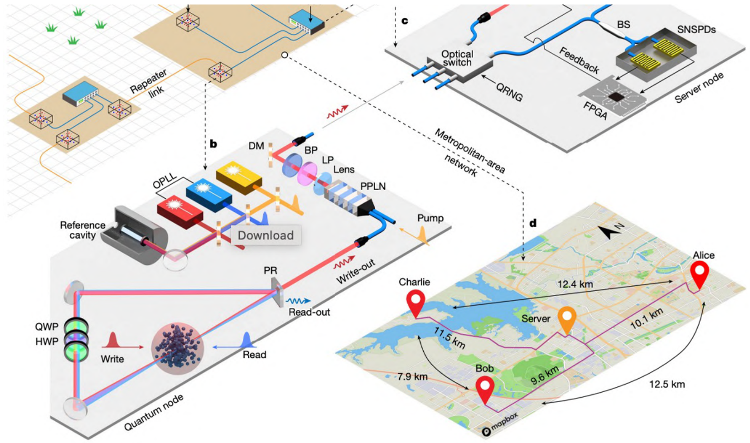
Des photons pour les technologies quantiques



Nature Photonics 18, 603 (2024)



Sci. Adv.6,eaay2652(2020).



Nature 629, 579 (2024)

Rappel cours 2 – quantification du champ électromagnétique

Hamiltonien

$$\hat{H} = \sum_{\ell} \hbar\omega_\ell \left(\hat{a}_\ell^\dagger \hat{a}_\ell + \tfrac{1}{2} \right).$$

$$\hat{a}_\ell = \frac{1}{\sqrt{2}} \left(\sqrt{\frac{\varepsilon_0 \omega_\ell}{\hbar L^3}} \hat{\mathbf{A}}_{\perp\ell} - i \sqrt{\frac{\varepsilon_0}{\hbar\omega_\ell L^3}} \hat{\mathbf{E}}_{\perp\ell} \right)$$

$$\hat{a}_\ell^\dagger = \frac{1}{\sqrt{2}} \left(\sqrt{\frac{\varepsilon_0 \omega_\ell}{\hbar L^3}} \hat{\mathbf{A}}^\dagger_{\perp\ell} - i \sqrt{\frac{\varepsilon_0}{\hbar\omega_\ell L^3}} \hat{\mathbf{E}}^\dagger_{\perp\ell} \right)$$

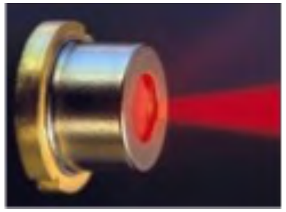
Etats propres

$$|n_1, n_2, \ldots, n_\ell \ldots\rangle = \frac{(\hat{a}_1^+)^{n_1} (\hat{a}_2^+)^{n_2} \ldots (\hat{a}_\ell^+)^{n_\ell} \ldots}{\sqrt{n_1! n_2! \ldots n_\ell! \ldots}} |0\rangle$$

Etat quelconque

$$|\psi\rangle = \sum_{n=(n_1,\ldots,n_\ell,\ldots)} C_n \, |n_1, \ldots, n_\ell, \ldots\rangle \quad \text{with} \quad \sum_n |C_n|^2 = 1$$

Etats quantiques de la lumière : état cohérent



Etat quasi classique

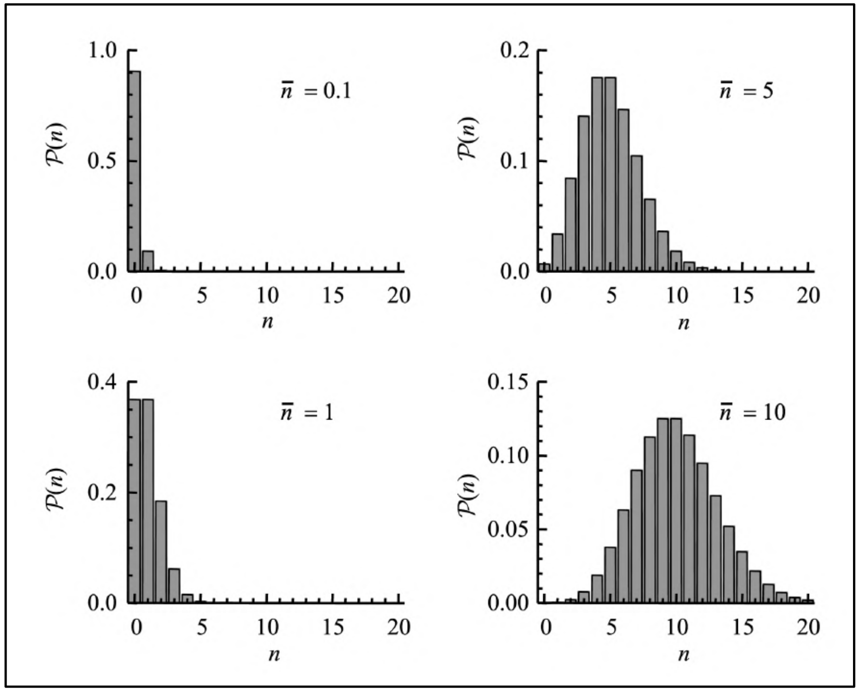
Etat cohérent $|\alpha\rangle$ - définition :

$$\hat{a}\,|\alpha\rangle = \alpha\,|\alpha\rangle\,, \qquad \alpha \in \mathbb{C}.$$

On montre que :

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}}\,|n\rangle\,,$$

Statistique de photons de Poisson de moyenne $\bar{n} = |\alpha|^2$.

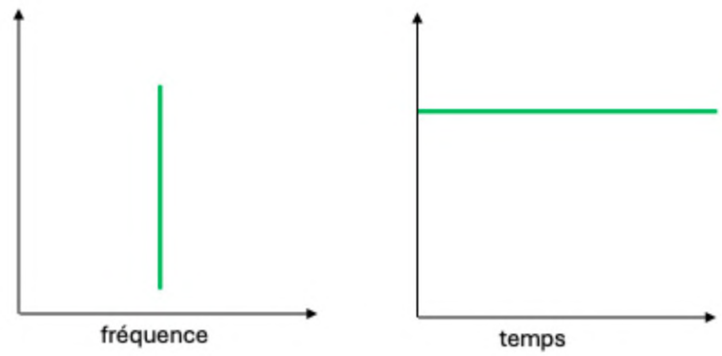


Description d'un état à un photon en seconde quantification

Etat à un photon
$\hat{N}|1\rangle = |1\rangle$

Cas monomode

$$|\psi\rangle = |1_\ell\rangle$$



Description d'un état à un photon en seconde quantification

- Rappels

Etat à un photon

$\hat{N}\,|1\rangle = |1\rangle$

Cas monomode

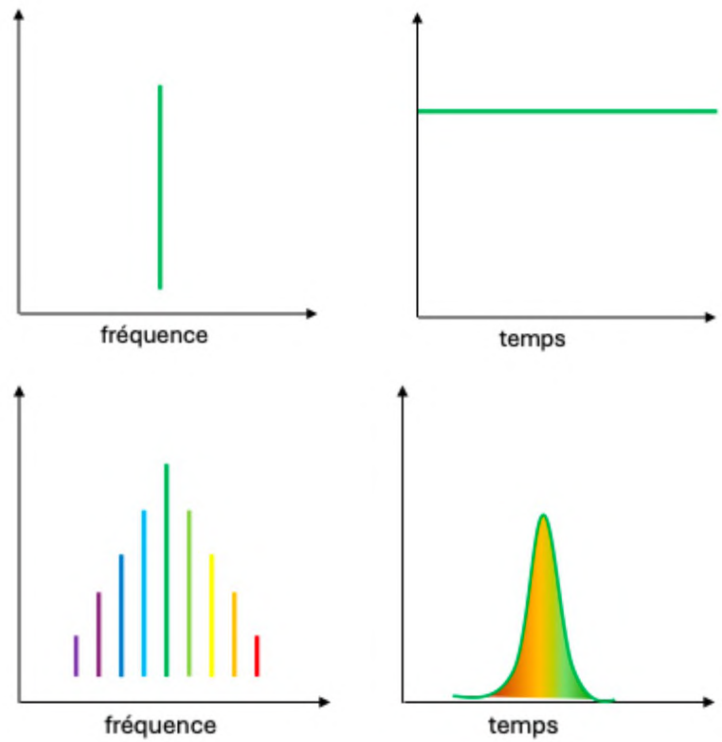
$$|\psi\rangle = |1_\ell\rangle$$

Impulsion à un photon

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

avec

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



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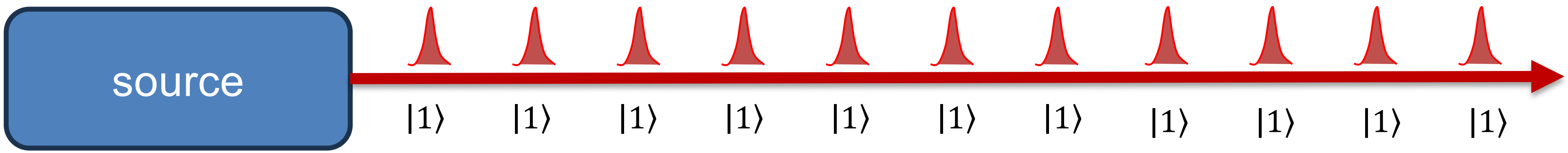
Source de photon unique idéale



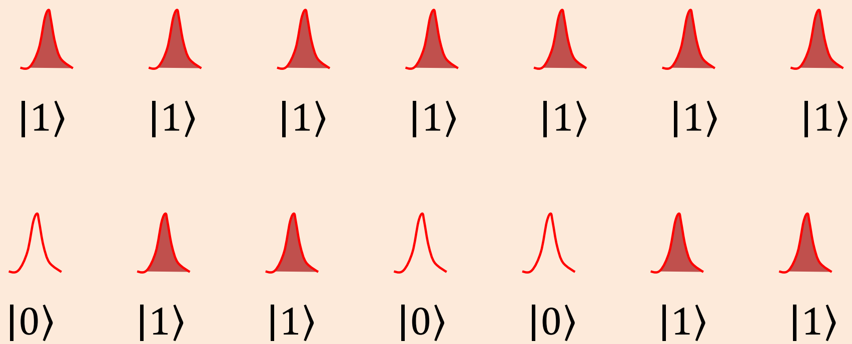
Caractéristiques clés:

- Source impulsionnelle
- Exactement 1 photon par impulsion
- Horloge rapide

Métriques pour décrire une source de photons uniques

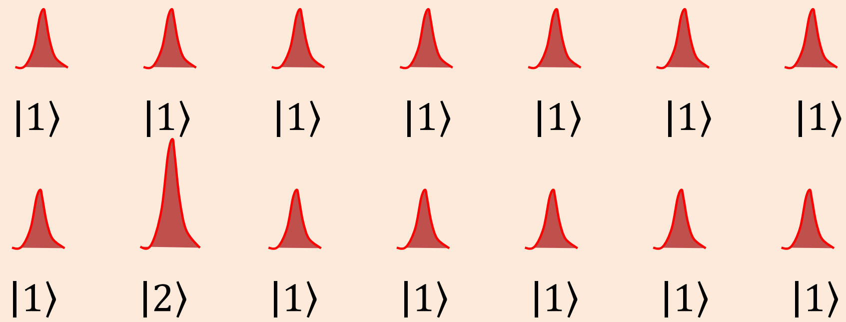
"Brillance" B

Probabilité d'avoir un photon par impulsion

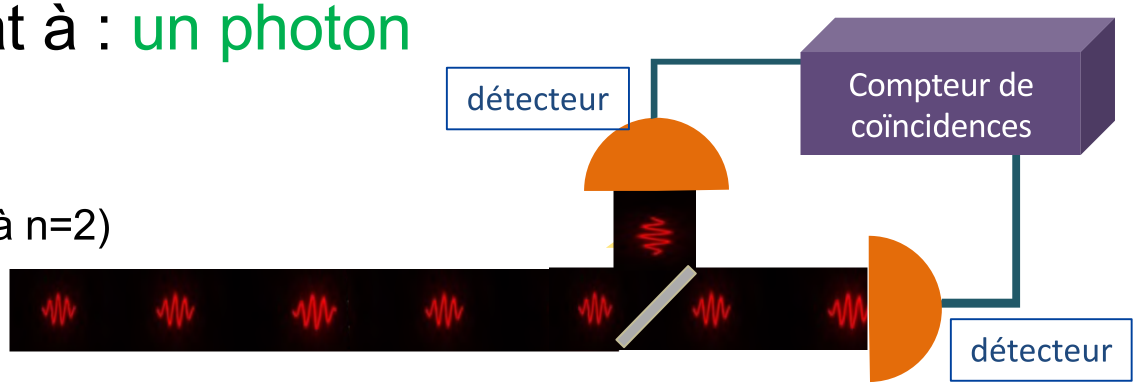


Pureté à 1 photon. P_1

Probabilité d'avoir maximum un photon par impulsion $P_1 = 1 - g^2(0)$



Caractériser un état à : un photon



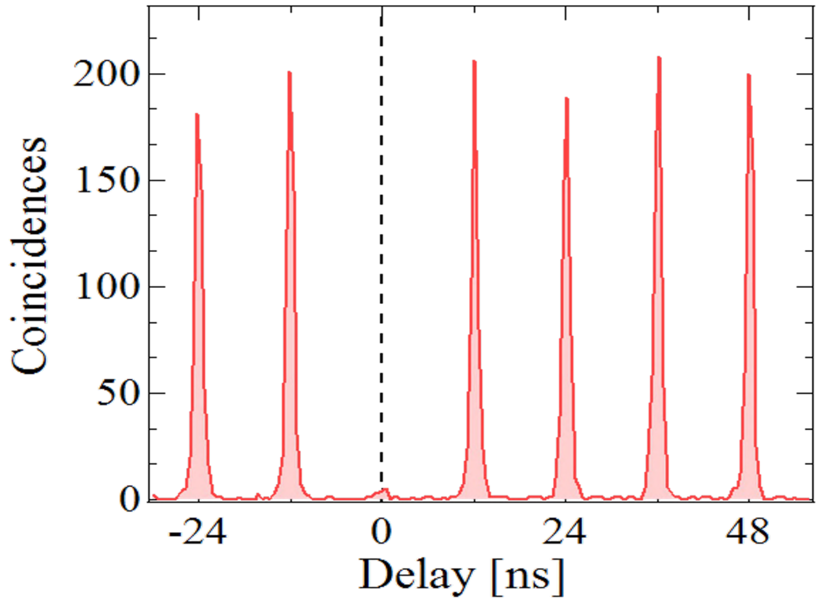
Corrélations de photons :

Accéder à la distribution de photons (jusqu'à n=2)

- **Auto-corrélations en intensité :**

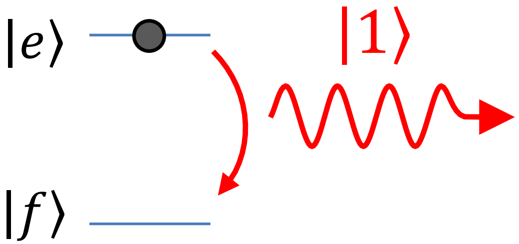
Cas d'un état monomode :

$$g^{(2)}(\tau = 0) = \frac{\sum_{n\geq 2} n(n-1)\, P(n)}{\left(\sum_{n\geq 1} n\, P(n)\right)^2}$$

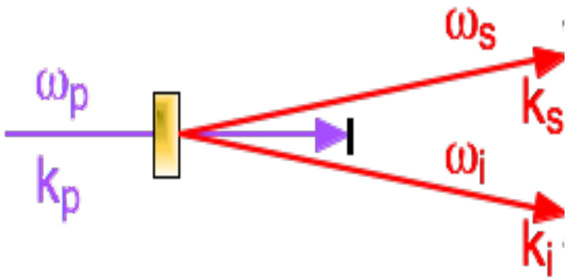


Deux catégories de sources

Sources basées sur un émetteur quantique

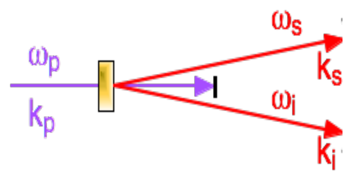


Sources basées sur la conversion de fréquence

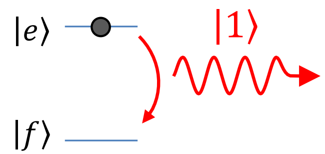


Sources de photons uniques

Sources de photons annoncées



Sources de photons à la demande



Contrôle de l'émission spontanée

Sources de photons à boîtes quantiques semiconductrces

Photons uniques

Photons intriqués

Du laboratoire au produit

Séminaire Audrey Bienfait

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Sources de photons annoncées

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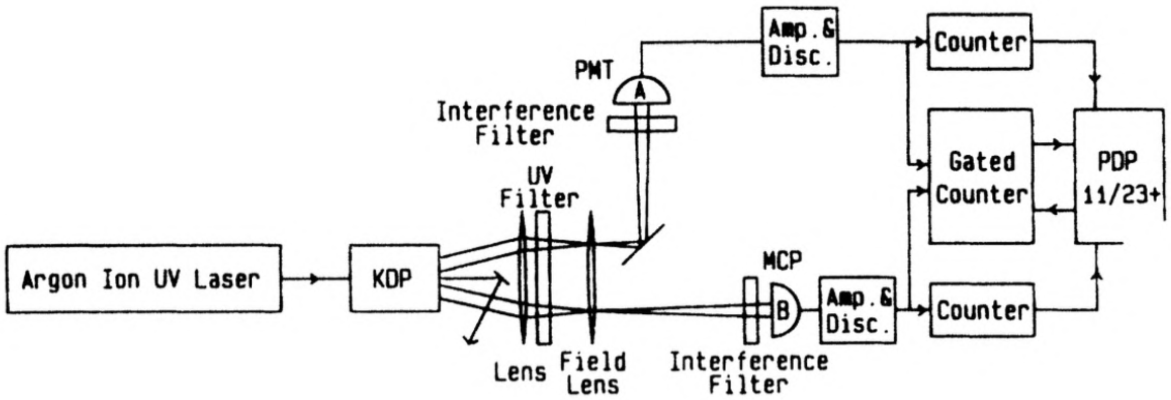
Sources de photons uniques annoncées



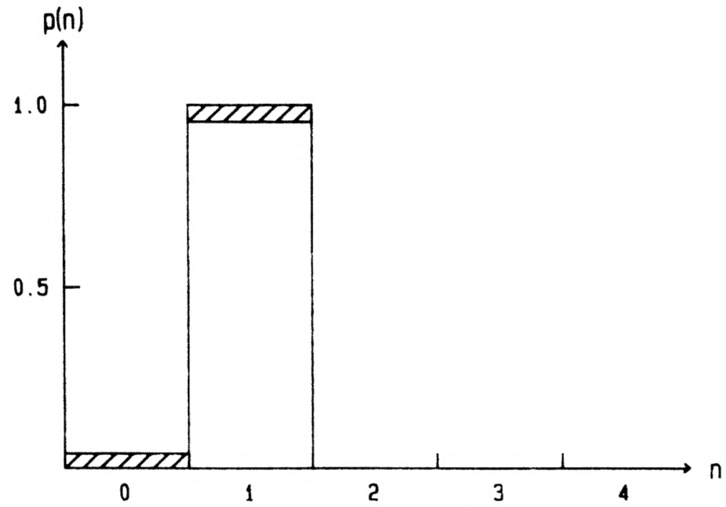
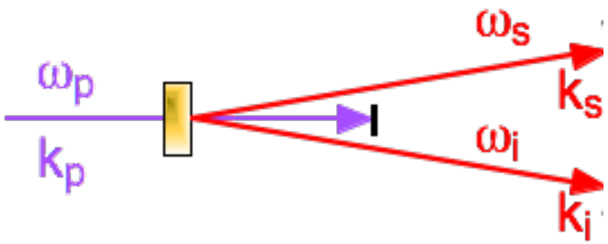


FIG. 2. The derived photon probability $p(n)$ conditioned on the detection of a signal photon. The cross-hatched regions indicate the uncertainties of $p(n)$.

Cf. cours 2

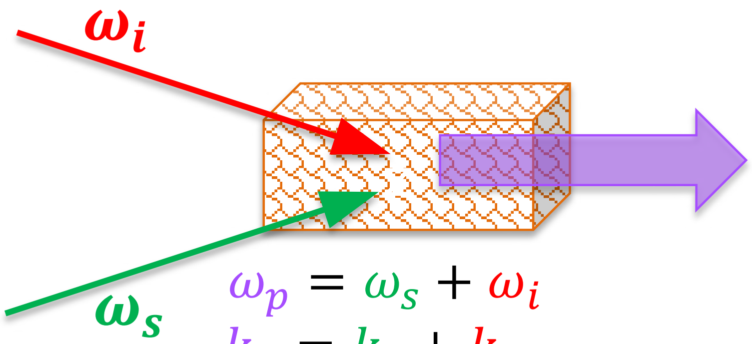
$\omega_p = \omega_s + \omega_i$

$k_p = k_s + k_i$



Phys. Rev. Lett. 56, 58 (1986)

Optique non linéaire - rappels



$$\omega_p = \omega_s + \omega_i$$
$$k_p = k_s + k_i$$

$$P^{\mathrm{NL}}(t) = \frac{\varepsilon_0 \chi^{(2)}}{4}\Big[E_1^2 e^{-i2\omega_1 t} + E_2^2 e^{-i2\omega_2 t} + 2E_1 E_2 e^{-i(\omega_1+\omega_2)t} + 2E_1 E_2^* e^{-i(\omega_1-\omega_2)t} + \left(|E_1|^2 + |E_2|^2\right) + \mathrm{c.c.}\Big]$$

Equation d'onde avec source non-linéaire

$$\nabla^2 \mathbf{E} - \frac{n^2}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = \frac{1}{\varepsilon_0 c^2}\frac{\partial^2 \mathbf{P}^{\mathrm{NL}}}{\partial t^2}$$

$$\mathbf{P}^{\mathrm{NL}}(t) = \varepsilon_0 \chi^{(2)} \mathbf{E}^2(t)$$

$$E(t) = \frac{1}{2}E_1 e^{-i\omega_1 t} + \frac{1}{2}E_2 e^{-i\omega_2 t} + \mathrm{c.c.}$$

Fréquences générées

- $2\omega_1,\ 2\omega_2$: secondes harmoniques
- $\omega_1 + \omega_2$: somme de fréquences
- $\omega_1 - \omega_2$: différence de fréquences

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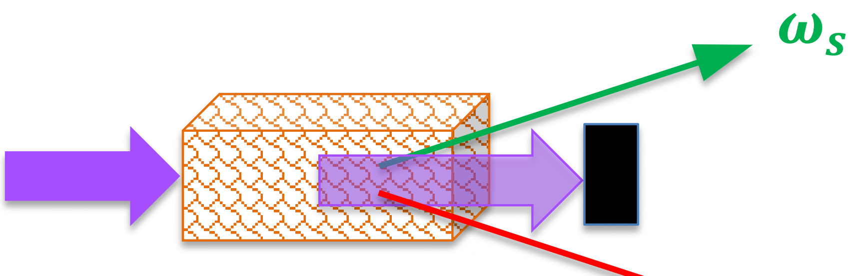
Conversion de fréquence quantique – conversion paramétrique

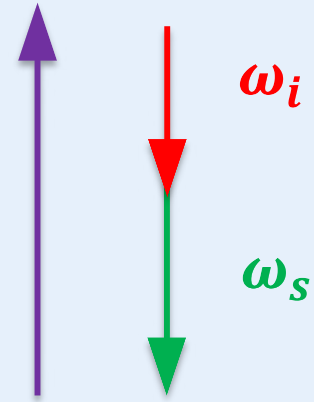


$\omega_p = \omega_s + \omega_i$

$k_p = k_s + k_i$

Conversion spontanée

$\omega_p = \omega_s + \omega_i$



$$\hat{H}_{\text{int}} = \hbar g \left(\hat{a}_p \, \hat{a}_s^\dagger \hat{a}_i^\dagger + \hat{a}_p^\dagger \, \hat{a}_s \hat{a}_i \right)$$

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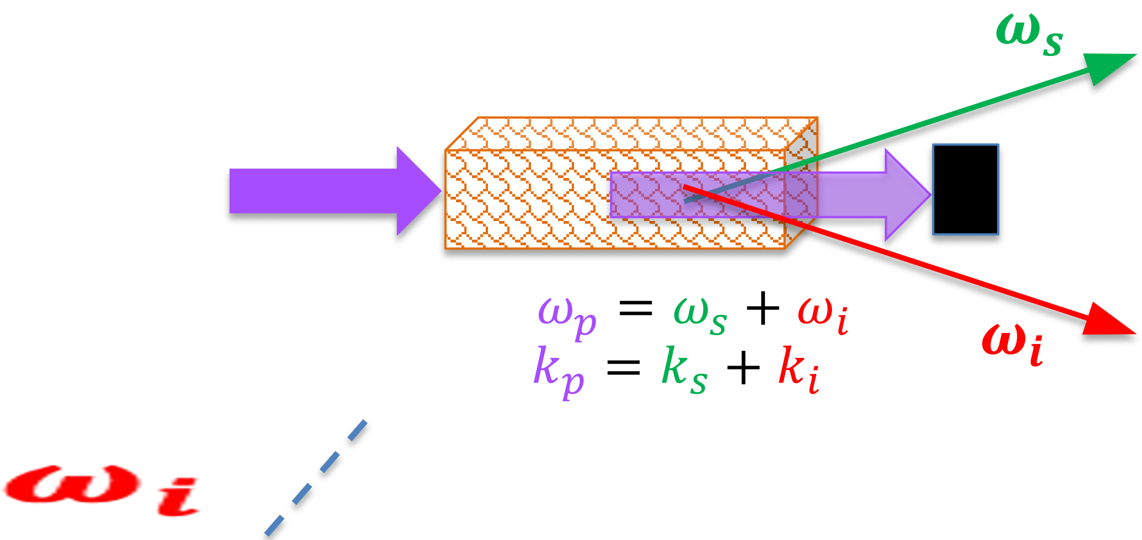
Sources de photons uniques annoncées

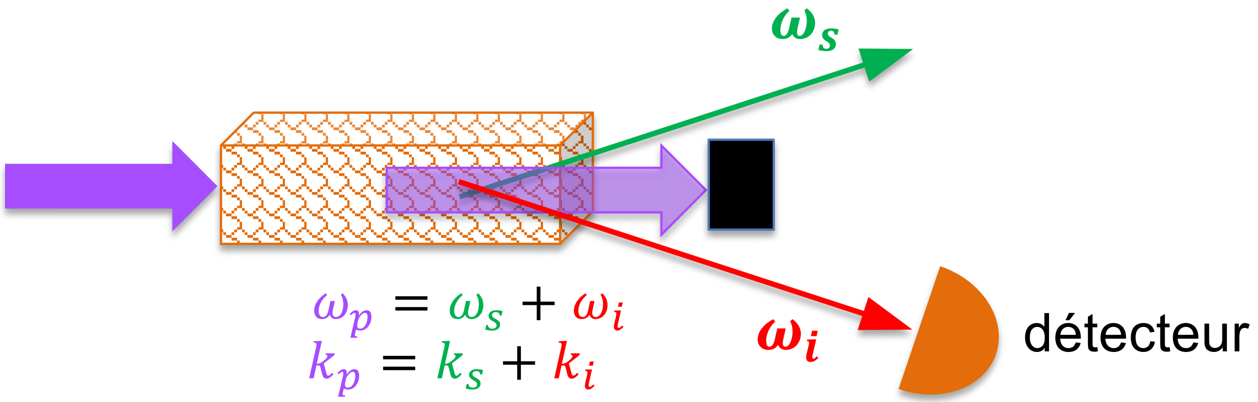


Source de photons annoncées

Au seuil de la conversion de fréquence : $|\eta|^2 \ll 1$

$$
\begin{aligned}
|\psi\rangle &= \left(1 - \frac{|\eta|^2}{2}\right) |0_s, 0_j\rangle + \eta\, |1_s, 1_j\rangle + \eta^2\, |2_s, 2_j\rangle \\
&\approx |0_s, 0_j\rangle + \eta\, |1_s, 1_j\rangle + \eta^2\, |2_s, 2_j\rangle
\end{aligned}
$$

Sources de photons uniques annoncées



Source de photons annoncées

Au seuil de la conversion de fréquence : $|\eta|^2 \ll 1$

$$\begin{aligned} |\psi\rangle &= \left(1 - \frac{|\eta|^2}{2}\right)|0_s, 0_j\rangle + \eta\,|1_s, 1_j\rangle + \eta^2\,|2_s, 2_j\rangle \\ &\approx |0_s, 0_j\rangle + \eta\,|1_s, 1_j\rangle + \eta^2\,|2_s, 2_j\rangle \end{aligned}$$

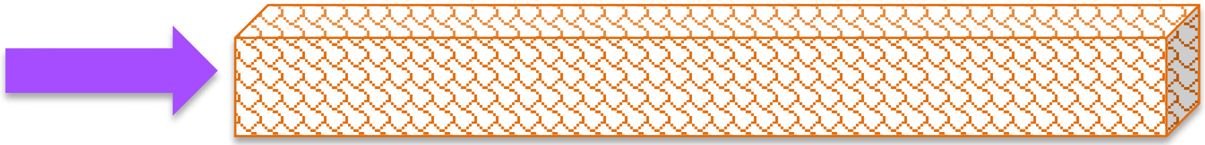
Après détection côté photons jumeaux

$$\begin{aligned} |\psi_h\rangle &= \frac{1}{|\eta|}\left(\eta\,|1_s\rangle + \eta^2\,|2_s\rangle\right) \\ &\approx |1_s\rangle + \eta\,|2_s\rangle \end{aligned}$$

Sources de photons uniques annoncées

Accord de phase

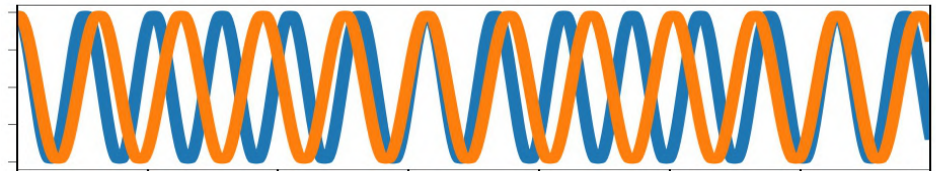
$\Delta k = k_3 - (k_1 + k_2) = 0$



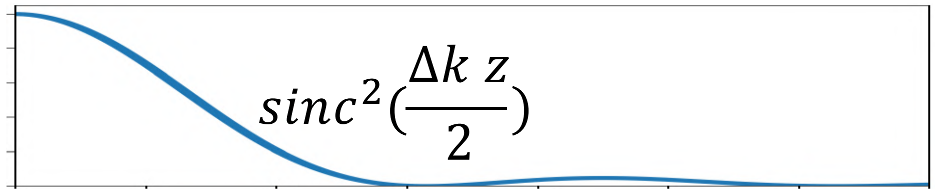
$$E_3(z,t) = A_3(z)\, e^{i(k_3 z - \omega_3 t)} + \text{c.c.}$$

$$\frac{dA_3}{dz} = i\,\kappa\, A_1 A_2\, e^{i\Delta k z},$$

$$A_3(L) = i\,\kappa\, A_1 A_2 \int_0^L e^{i\Delta k z}\, dz$$
$$= \kappa\, A_1 A_2\, L\, \mathrm{sinc}\left(\frac{\Delta k L}{2}\right) e^{i\Delta k L/2}$$



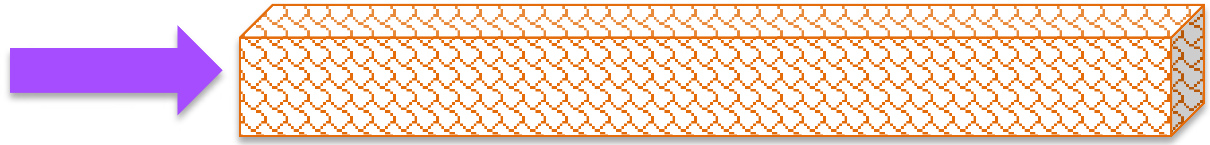
Facteur d'accord de phase



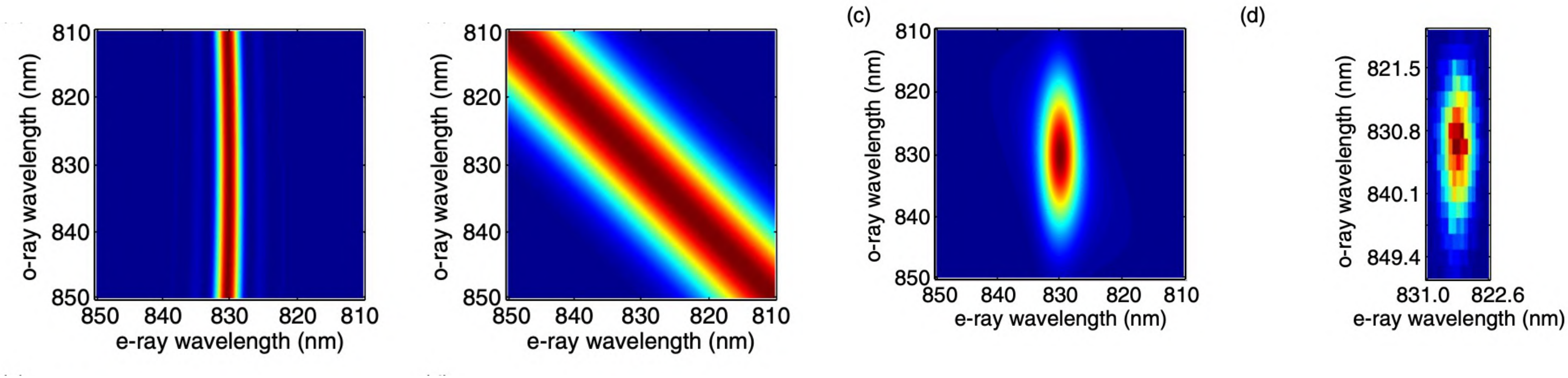
Sources de photons uniques annoncées

Accord de phase

$$\Delta k = k_3 - (k_1 + k_2) = 0$$

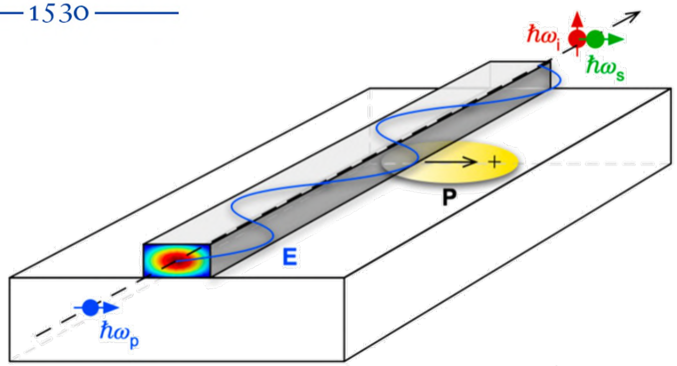


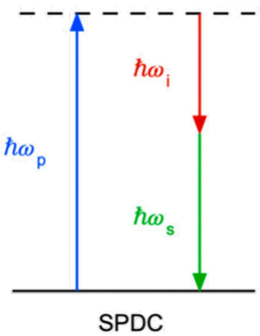
Accord de phase　　Conservation énergie　　Densité spectrale jointe



KDP crystal and an ultrafast pump centered at 415 nm - Phys. Rev. Lett. 100, 133601 (2008)

Sources de photons uniques annoncées





$$\omega_p = \omega_s + \omega_i$$
$$k_p = k_s + k_i$$

Mélange à 3 ondes, χ^2

Appl. Phys. Rev. 8, 011314 (2021)

Efficacité de génération (sortie du guide)

valeur du tenseur de non-linéarité

puissance de pompe

$$r_{\mathrm{SPDC}} \propto \frac{4 d_{\mathrm{eff}}^2 P_{\mathrm{p}} L^2}{9 \varepsilon_0^2 c^2 A_{\mathrm{eff}}} \operatorname{sinc}^2\left(\frac{\Delta k L}{2}\right)$$

surface d'interaction

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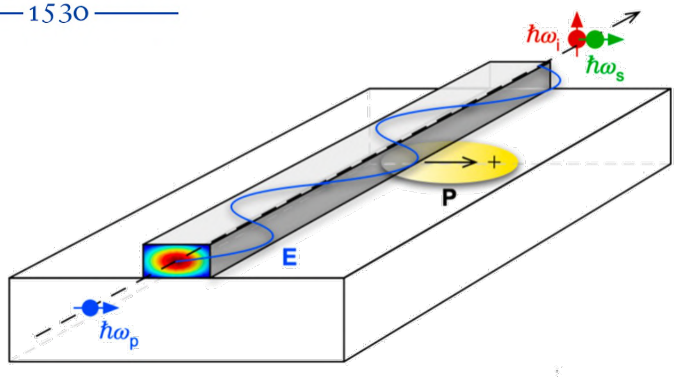
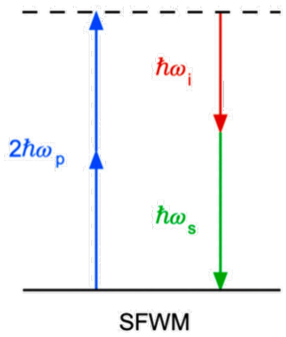
Sources de photons uniques annoncées





Mélange à 4 ondes, χ^3

Appl. Phys. Rev. 8, 011314 (2021)

Efficacité de génération

indice optique non-linéaire

puissance de pompe

$$r_{\mathrm{SFWM}} \propto \left| \frac{2\omega_p n_2}{c A_{\mathrm{eff}}} P_p L \right|^2$$

surface d'interaction

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Sources de photons uniques annoncées

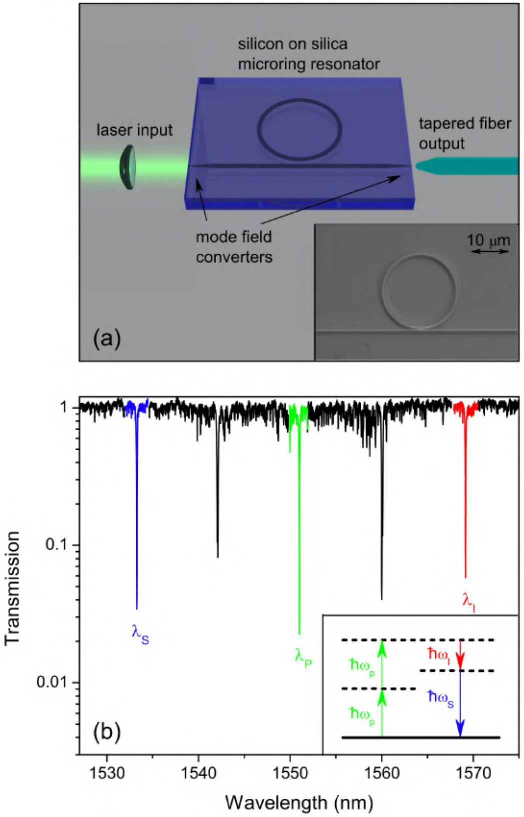
TABLE I. Related properties of common materials for integrated photon pair sources. Values are at 1.55 μm if not specified. The nonlinear susceptibilities, d_{max}, are the largest reported values for the corresponding orientation. The waveguide losses are the lowest values reported in the literature.

Material	n	d_{max} [pm/V]	n_2 [m^2W^{-1}]	Transparency [μm]	Propagation loss [dB/cm]
Si	3.8	15 ($\chi^{(2)}_{xxz}$ of strained-Si)[29]	4.5×10^{-18},[50]	1.1–9	0.02653
Si_3N_4	2	—	2.6×10^{-19},[44]	0.4–4	0.01[45]
GaAs	3.4	170 (d_{36} at 1 μm)[52]	1.6×10^{-17},[50]	1.0–10	<1[53]
AlN	2.1	23.2 (d_{33} at 1 μm)[54]	2.3×10^{-19},[55]	0.2–5	0.6[56]
$LiNbO_3$	2.21	25.2 (d_{33} at 1 μm)[52]	9.1×10^{-20},[57]	0.5–4	0.6[58]
Silica	1.44	—	2.7×10^{-20},[59]	0.2–2	2×10^{-6}
Hydex	1.5 – 1.9	—	1.15×10^{-19},[60]	0.2–2	0.06[60]

Appl. Phys. Rev. 8, 011314 (2021)

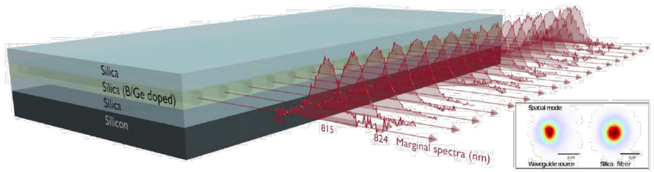
Sources de photons uniques annoncées

silicium



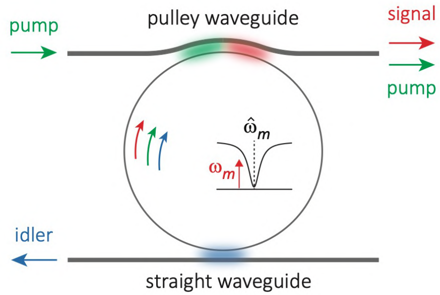
Optica 2, 88 (2015)

silice



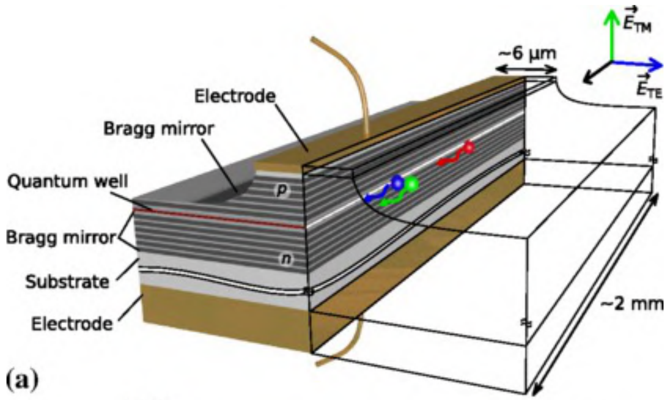
Optica 1, 90 (2017)

nitrure de silicium

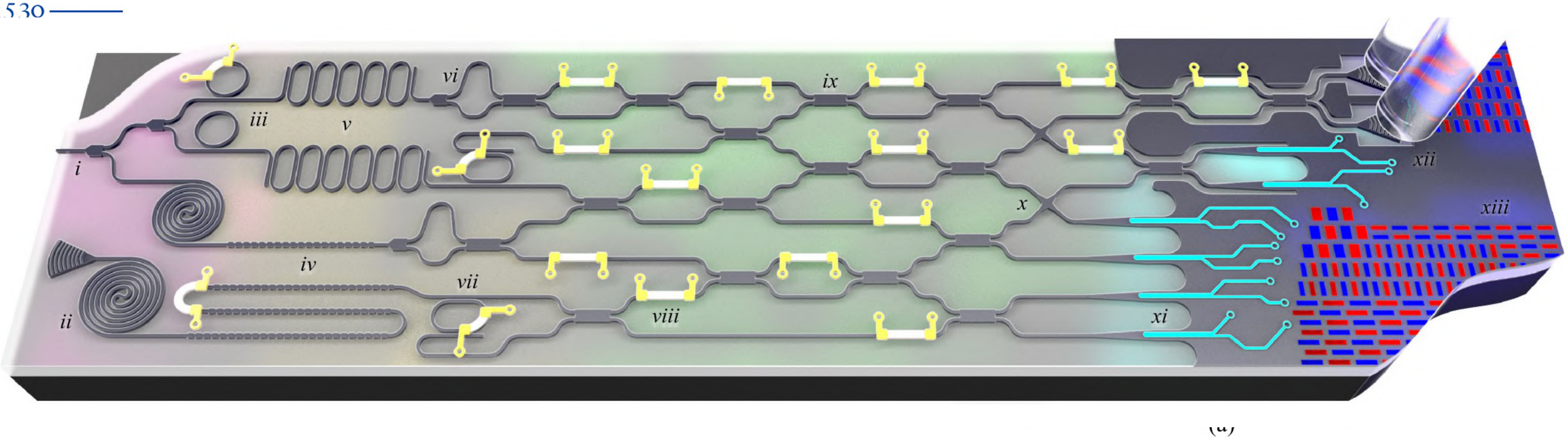


Nature Physics, 15, 373 (2019)

GaAs/AlAs



Phys. Rev. Lett. 112, 183901 (2014)


i
ii
iii
iv
v
vi
vii
viii
ix
x
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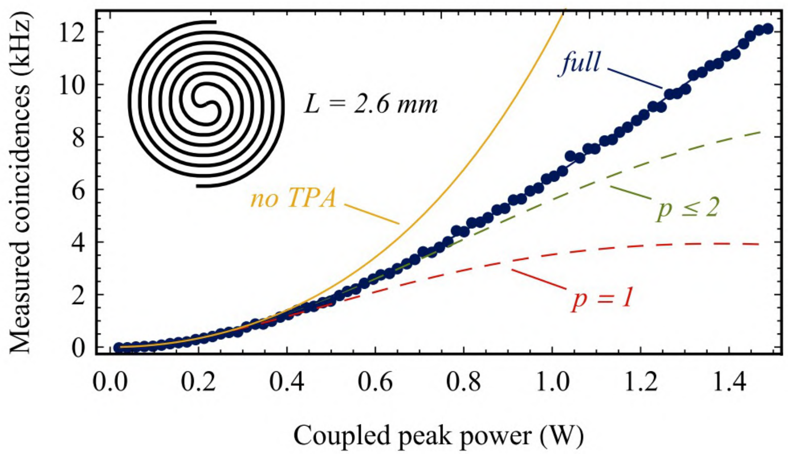
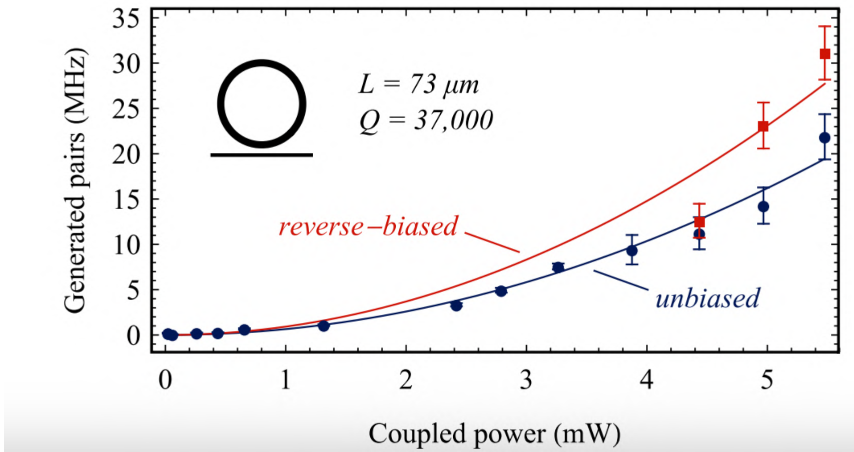
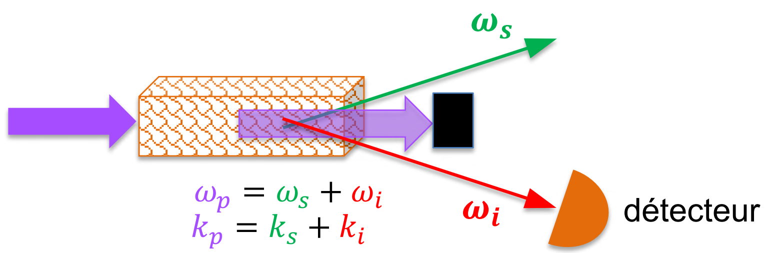
xii
xiii


Measured coincidences (kHz)
Coupled peak power (W)
L = 2.6 mm
full
no TPA
p ≤ 2
p = 1
0
2
4
6
8
10
12
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4


Generated pairs (MHz)
Coupled power (mW)
L = 73 µm
Q = 37,000
reverse−biased
unbiased
0
5
10
15
20
25
30
35
0
1
2
3
4
5

Sources de photons uniques annoncées

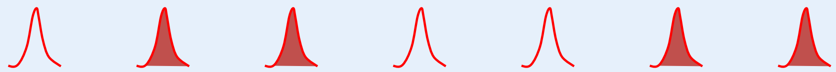


Source de photons annoncées

Après détection côté photons jumeaux

$$|\psi_h\rangle = \frac{1}{|\eta|}\left(\eta\,|1_s\rangle + \eta^2\,|2_s\rangle\right)$$
$$\approx |1_s\rangle + \eta\,|2_s\rangle$$

Brillance : Probabilité d'avoir un photon par impulsion



$|0\rangle$ $|1\rangle$ $|1\rangle$ $|0\rangle$ $|0\rangle$ $|1\rangle$ $|1\rangle$

$$B = |\eta|^2$$

Pureté à 1 photon : $P_1 = 1 - g^2(0)$

$|1\rangle$ $|2\rangle$ $|1\rangle$ $|1\rangle$ $|1\rangle$ $|1\rangle$ $|1\rangle$

$$P_1 = 1 - 2|\eta|^2$$

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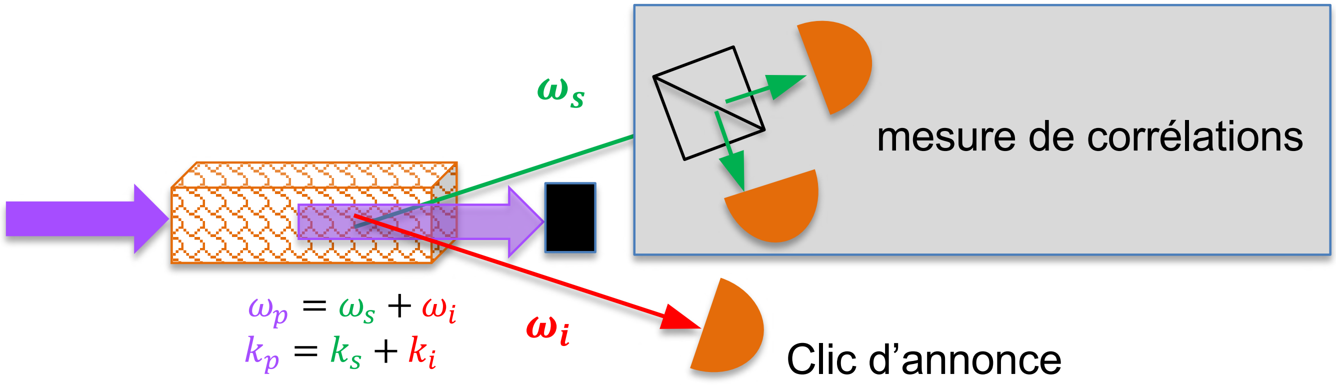
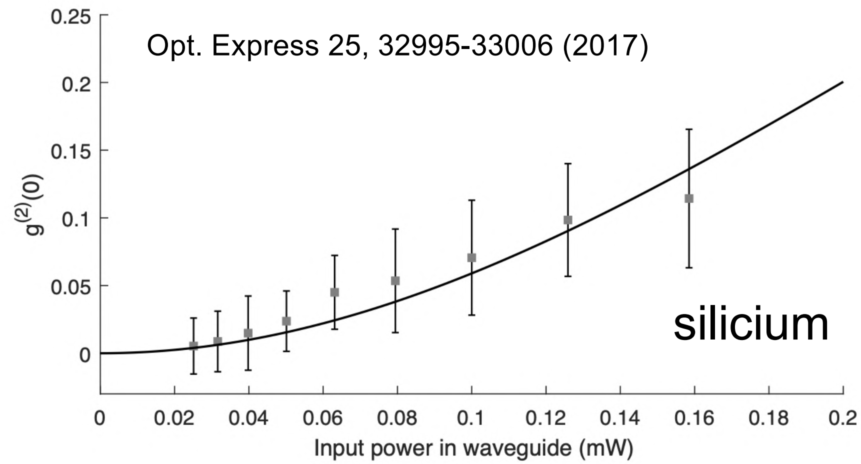
Sources de photons uniques annoncées





Source de photons annoncées

Après détection côté photons jumeaux

$$|\psi_h\rangle = \frac{1}{|\eta|}\left(\eta\,|1_s\rangle + \eta^2\,|2_s\rangle\right)$$
$$\approx |1_s\rangle + \eta\,|2_s\rangle$$

$|\eta|^2 \ll 1$ Limitation fondamentale : compromis brillance - pureté

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Une source annoncée brillante ?

(12) **United States Patent**
Cable

(10) **Patent No.: US 11,984,933 B2**
(45) **Date of Patent: May 14, 2024**

(54) **SYSTEMS AND METHODS FOR PHOTONIC MULTIPLEXING**

(71) Applicant: **Psiquantum, Corp.**, Palo Alto, CA (US)

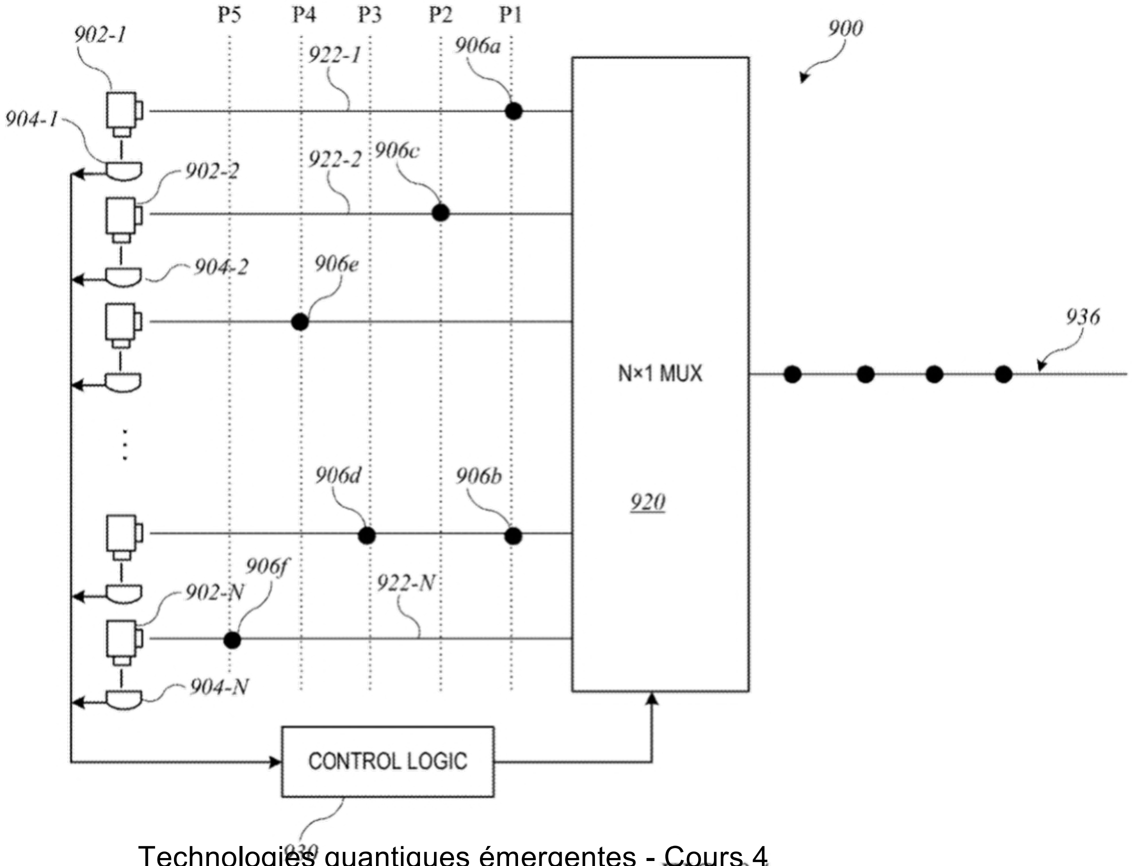
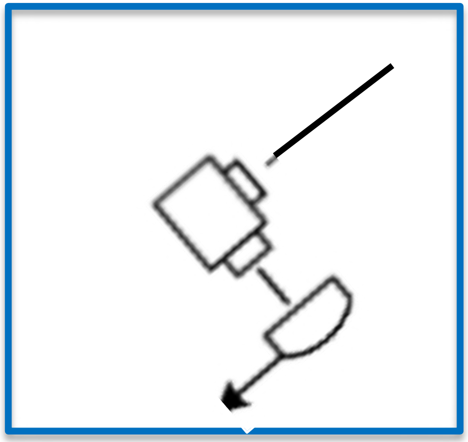


FIG. 9A

Ψ PsiQuantum

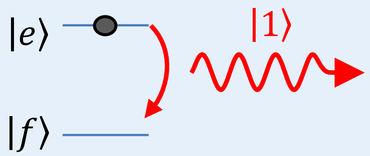
Source annoncée



Sources de photons à la demande

Sources de photons uniques à émetteur quantique

Atome à deux niveaux



Atome à deux niveaux $\{|g\rangle, |e\rangle\}$

$$\hat{H}_{\rm at} = \frac{\hbar\omega_0}{2}\,\hat{\sigma}_z \qquad (\hat{\sigma}_z = |e\rangle\langle e| - |g\rangle\langle g|)$$

Opérateur dipôle

$$\hat{\mathbf{d}} = \mathbf{d}_{eg}\,\hat{\sigma}_- + \mathbf{d}_{ge}\,\hat{\sigma}_+ \qquad (\hat{\sigma}_- = |g\rangle\langle e|)$$

Champ electromagnétique

Champ électromagnétique quantifié (modes ℓ)

$$\hat{H}_{\rm em} = \sum_\ell \hbar\omega_\ell \left(\hat{a}_\ell^\dagger \hat{a}_\ell + \frac{1}{2}\right)$$

Interaction

Interaction dipolaire (approx. dipôle électrique)

$$\hat{H}_{\rm int} = -\hat{\mathbf{d}}\cdot\hat{\mathbf{E}}(\mathbf{r}_0)$$

Champ électrique en opérateurs de création/annihilation

$$\hat{\mathbf{E}}(\mathbf{r}_0, t) = i\sum_\ell \sqrt{\frac{\hbar\omega_\ell}{2\varepsilon_0 V}}\,\mathbf{e}_\ell(\mathbf{r}_0)\left(\hat{a}_\ell e^{-i\omega_\ell t} - \hat{a}_\ell^\dagger e^{+i\omega_\ell t}\right)$$

Couplage (cas $\omega_\ell \approx \omega_0$)

$$\hat{H}_{\rm int} = \hbar\sum_\ell \left(g_\ell\,\hat{a}_\ell^\dagger\hat{\sigma}_- + g_\ell^*\,\hat{a}_\ell\hat{\sigma}_+\right)$$

Interaction avec un photon à la fois

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Sources de photons uniques à base d'émetteur quantiques

- Premières observations expérimentales – nuage d'atomes

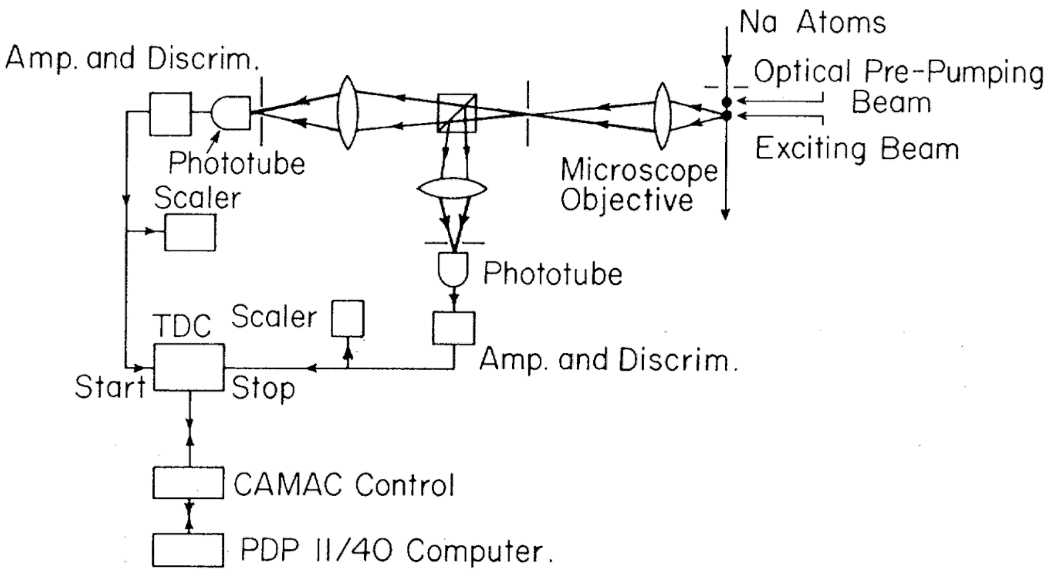
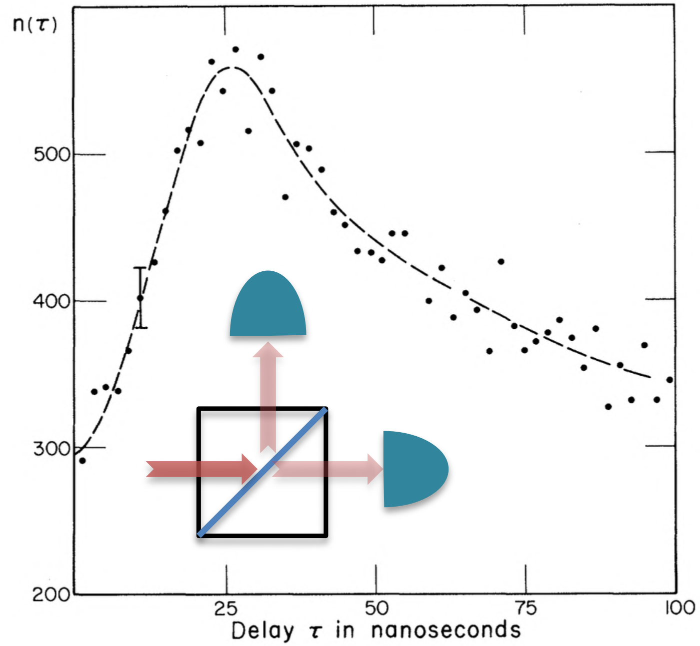


FIG. 1. Outline of the principal elements of the experiment.

Phys. Rev. Lett. 39, 691 (1977)

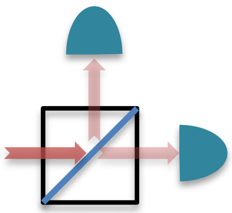
Double "clics"

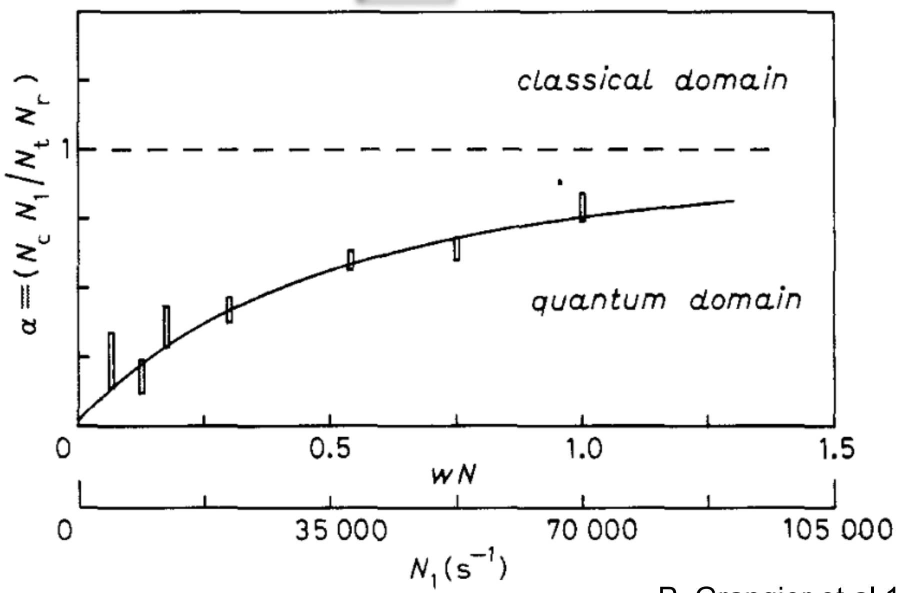


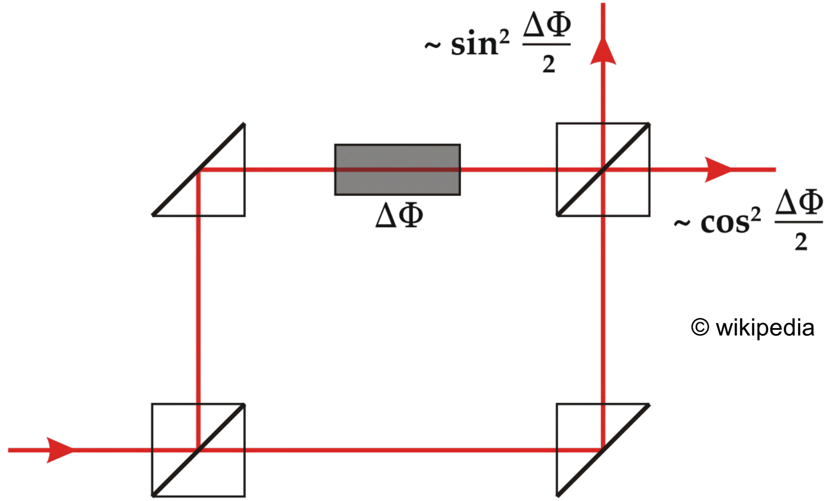
Sources de photons uniques à base d'émetteur quantiques

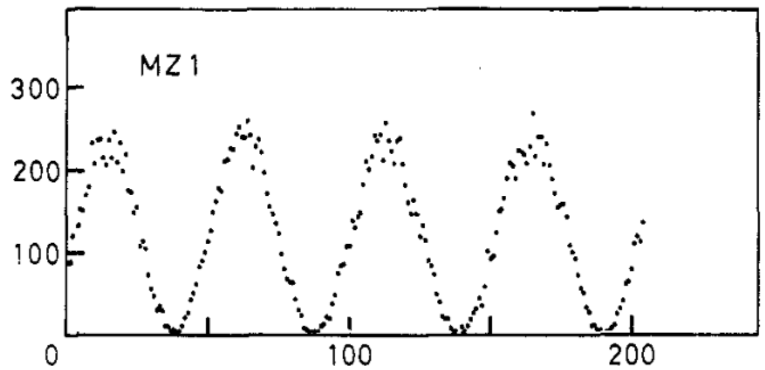
- Premières observations expérimentales : nuage d'atomes

Double “clics”







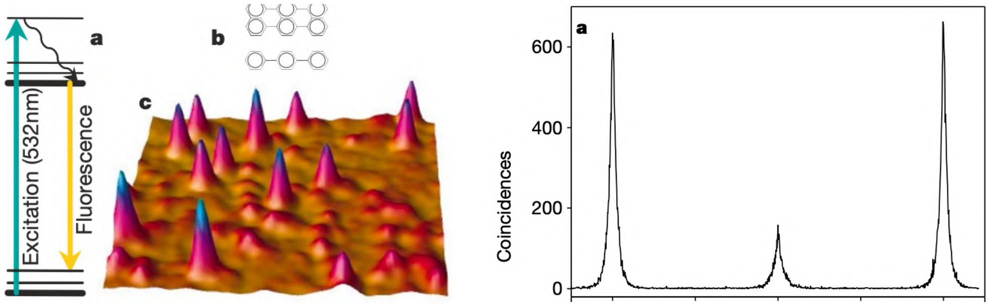


P. Grangier et al 1986 EPL 1 173

Sources à la demande : premières démonstrations

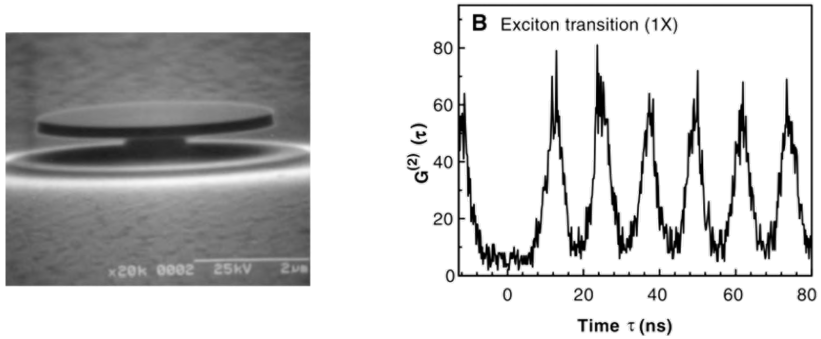
Molécule unique

Nature 407,491 (2000)



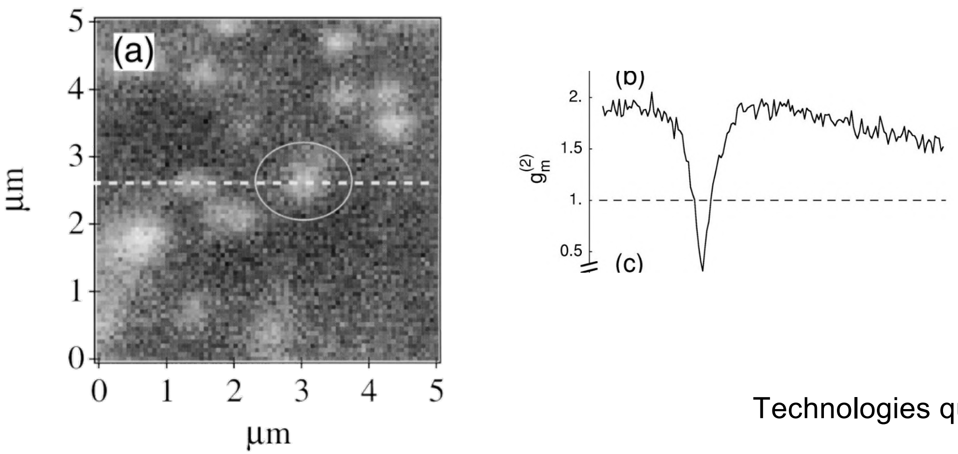
Boîte quantique semiconductrice

Nature 406, 968 (2000).
Science 290, 2822 (2000)



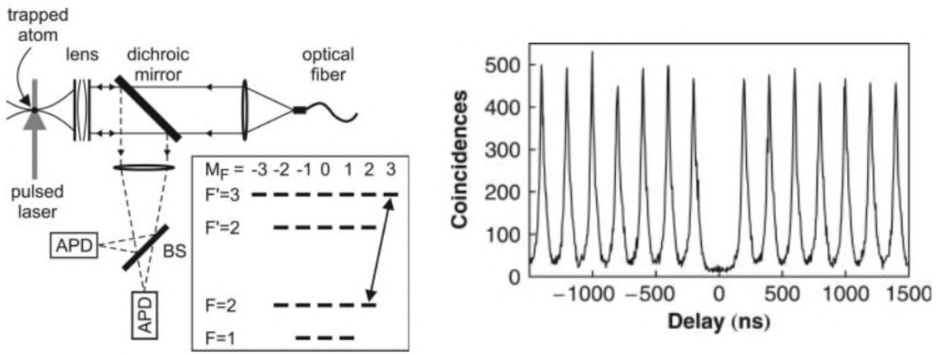
Centre NV dans le diamant

Phys. Rev. Lett. 85, 290 (2000).
Opt. Lett. 25, 1294 (2000)

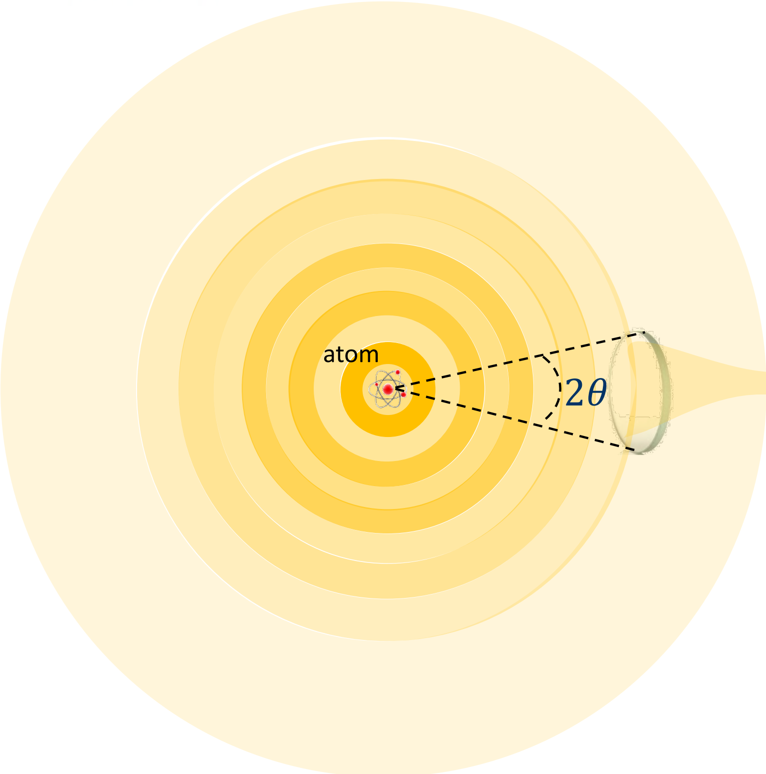


Atome unique

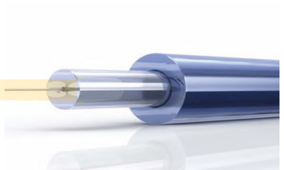
Science **3**09,454-456(2005)



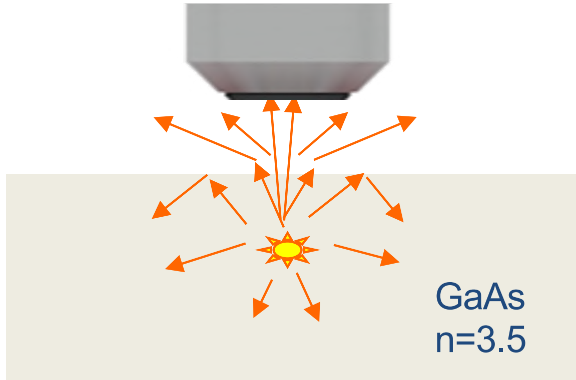
Sources à la demande : collection des photons



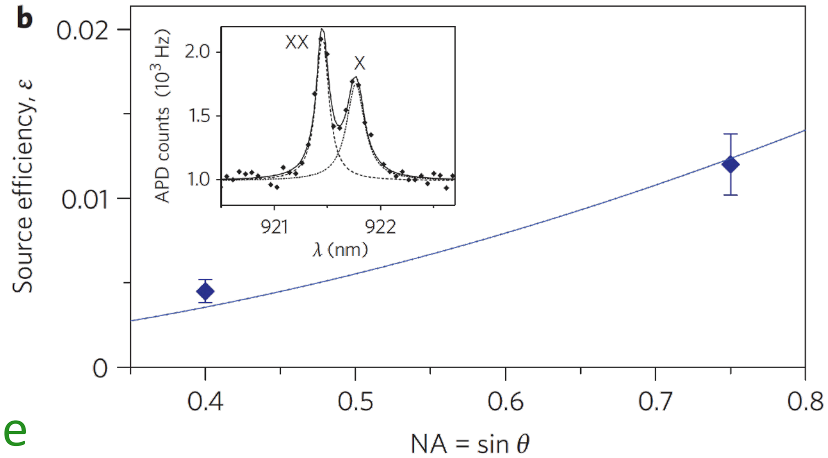
Fraction collectée $\approx \dfrac{\pi\theta^2}{4\pi}$



Optical fiber



Nature Photonics **4**, 174 - 177 (2010)



Une source de photons uniques très inefficace

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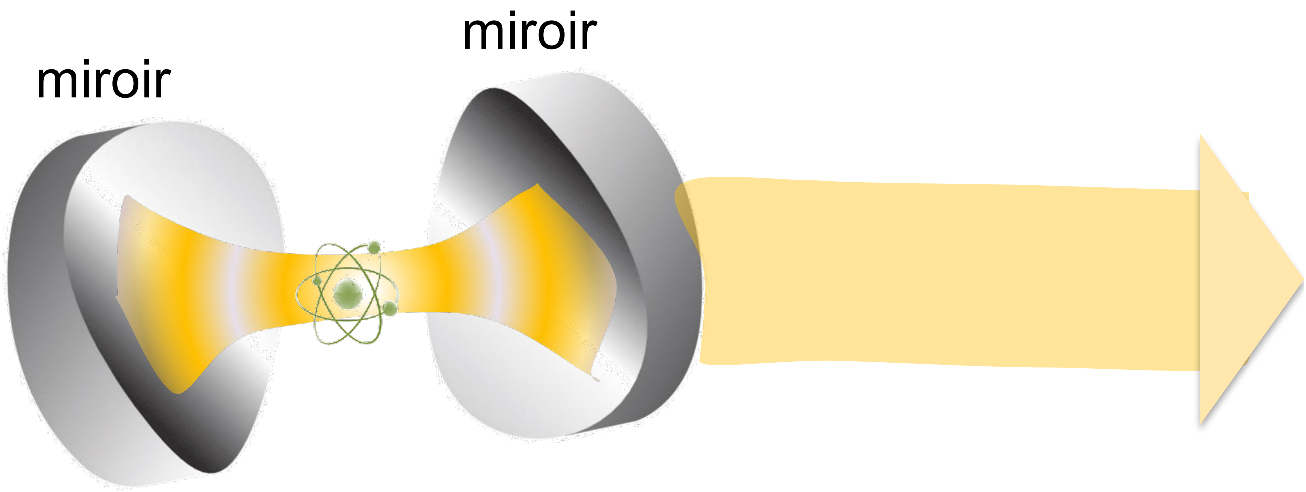
Sources à la demande : collection des photons



B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. PURCELL, *Harvard University*.—For nuclear magnetic moment transitions at radio frequencies the probability of spontaneous emission, computed from

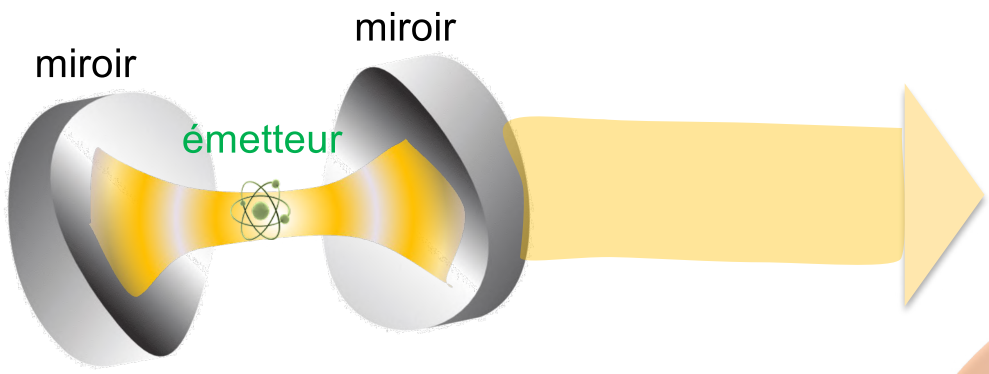
$$A_\nu = (8\pi\nu^2/c^3)h\nu(8\pi^3\mu^2/3h^2)\ \mathrm{sec.}^{-1},$$

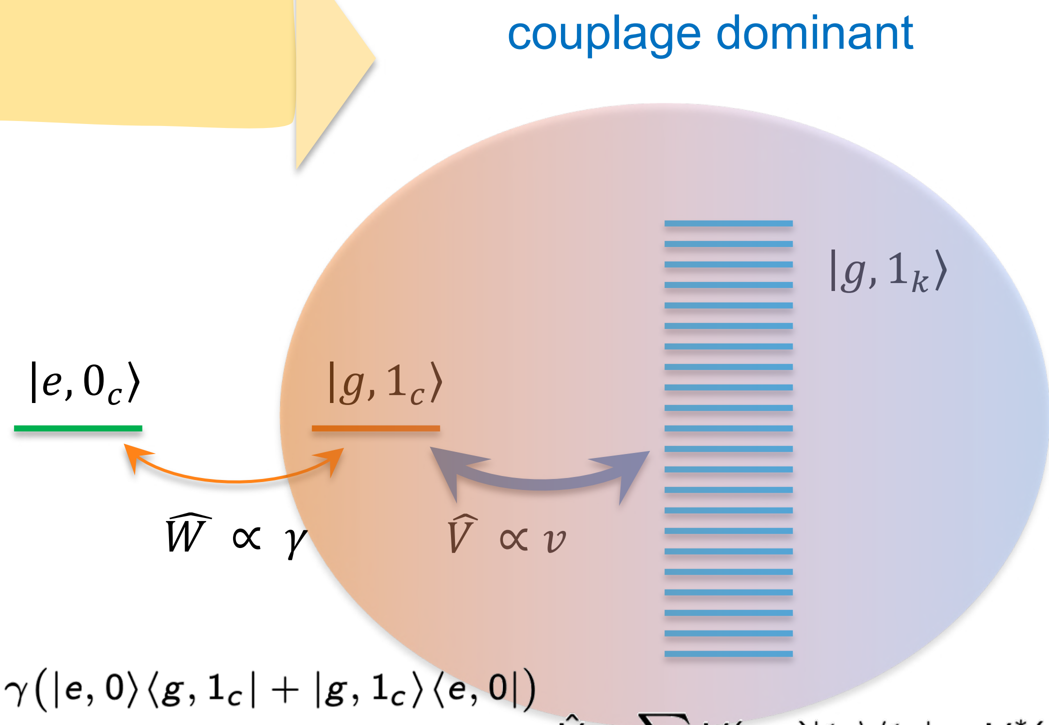
is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for $\nu = 10^7$ sec.$^{-1}$, $\mu = 1$ nuclear magneton, the corresponding relaxation time would be 5×10^{21} seconds! However, for a system coupled to a resonant electrical circuit, the factor $8\pi\nu^2/c^3$ no longer gives correctly the number of radiation oscillators per unit volume, in unit frequency range, there being now *one* oscillator in the frequency range ν/Q associated with the circuit. The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor $f = 3Q\lambda^3/4\pi^2 V$, where V is the volume of the resonator. If a is a dimension characteristic of the circuit so that $V \sim a^3$, and if δ is the skin-depth at frequency ν, $f \sim \lambda^3/a^2\delta$. For a non-resonant circuit $f \sim \lambda^3/a^3$, and for $a < \delta$ it can be shown that $f \sim \lambda^3/a\delta^2$. If small metallic particles, of diameter 10^{-3} cm are mixed with a nuclear-magnetic medium at room temperature, spontaneous emission should establish thermal equilibrium in a time of the order of minutes, for $\nu = 10^7$ sec.$^{-1}$.

E. M. Purcell - Phys. Rev. 69, 681 (1946)

Interface atome-photon
Interface spin-photon
Interface qubit stationnaire – qubit volant

Contrôle de l'émission spontanée : effet Purcell

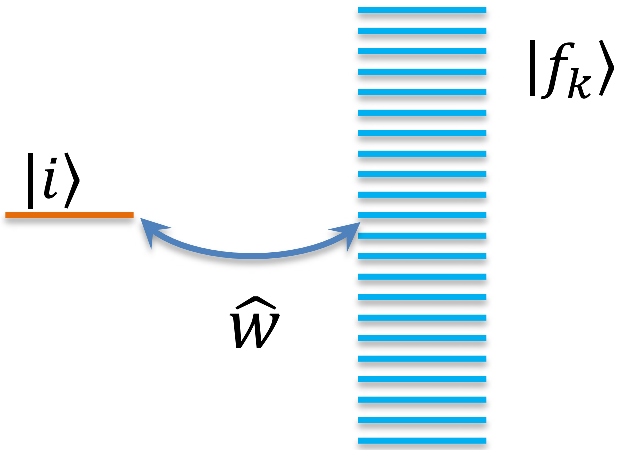




$$\hat{W} = \gamma\big(|e,0\rangle\langle g,1_c| + |g,1_c\rangle\langle e,0|\big)$$

$$\hat{V} = \sum_k V(\omega_{kc})|1_c\rangle\langle 1_k| + V^*(\omega_{kc})|1_k\rangle\langle 1_c|$$

Règle d'Or de Fermi

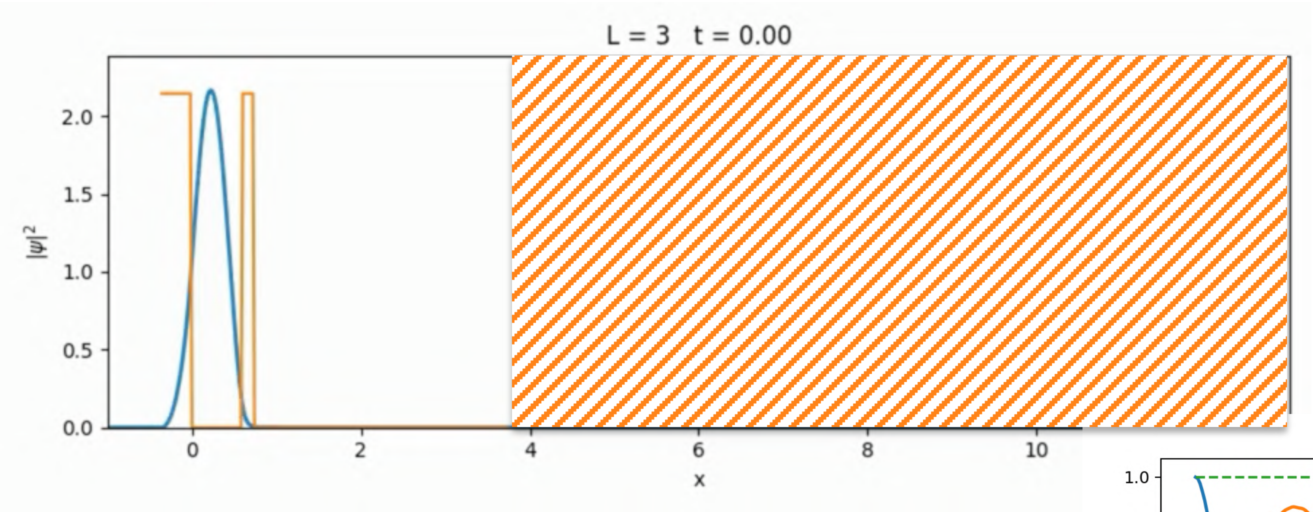


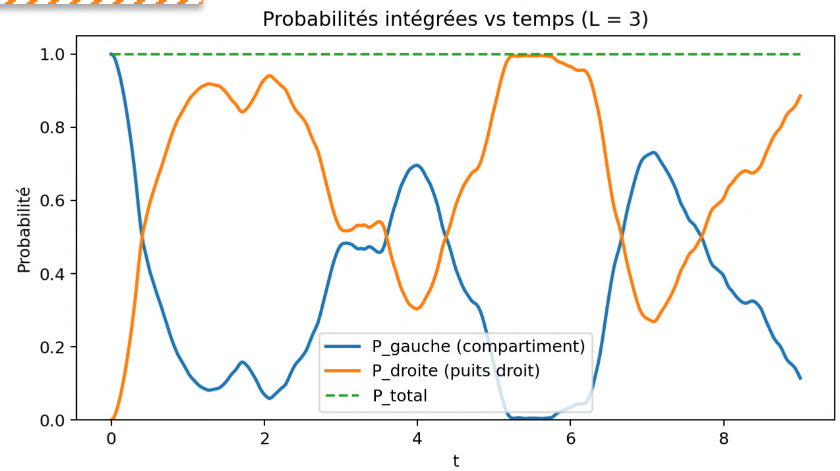
$$\hat{W} = \sum_k W(E_{ki})|i\rangle\langle f_k| + W^*(E_{ki})|f_k\rangle\langle i|$$

À $t = 0$: $|\psi\rangle = |i\rangle$.

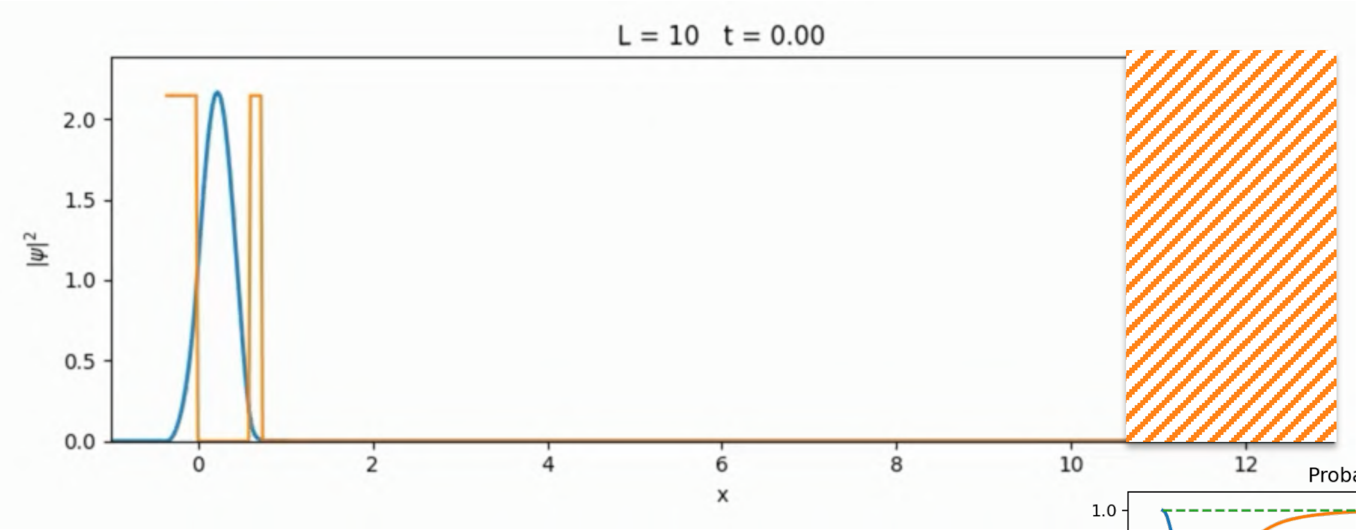
$P_i(t)$: Probabilité $|\psi\rangle = |i\rangle$ à l'instant t

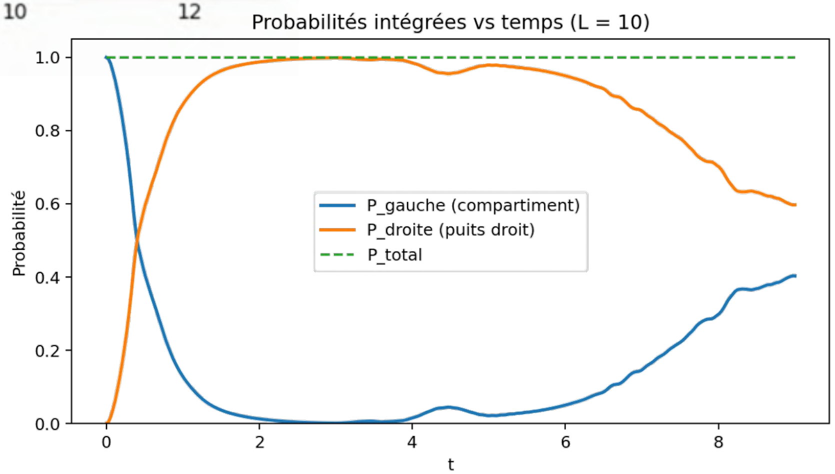
Règle d’Or de Fermi : intuition



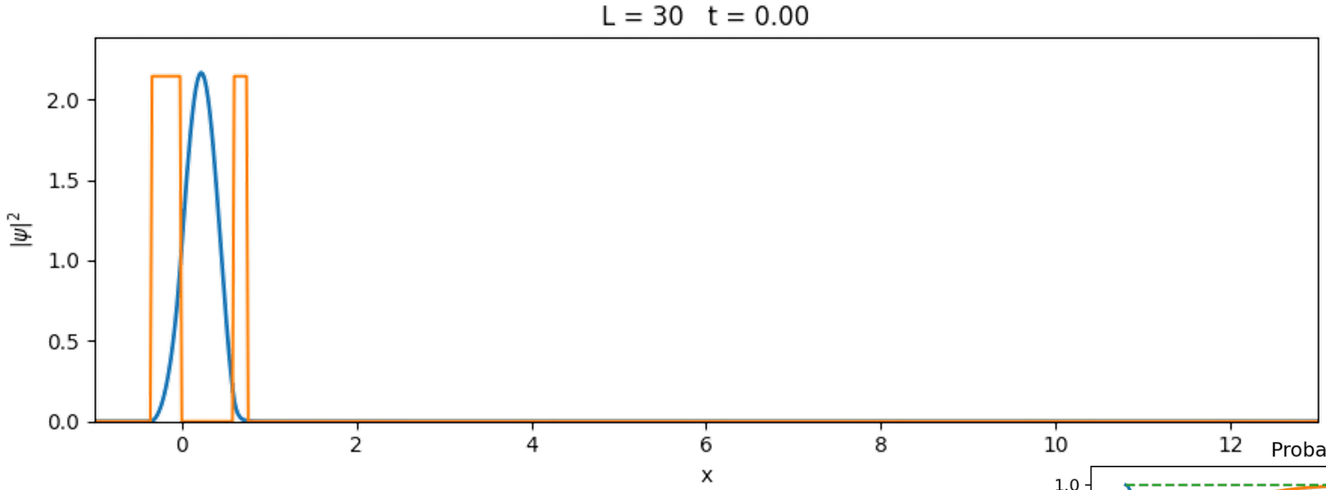


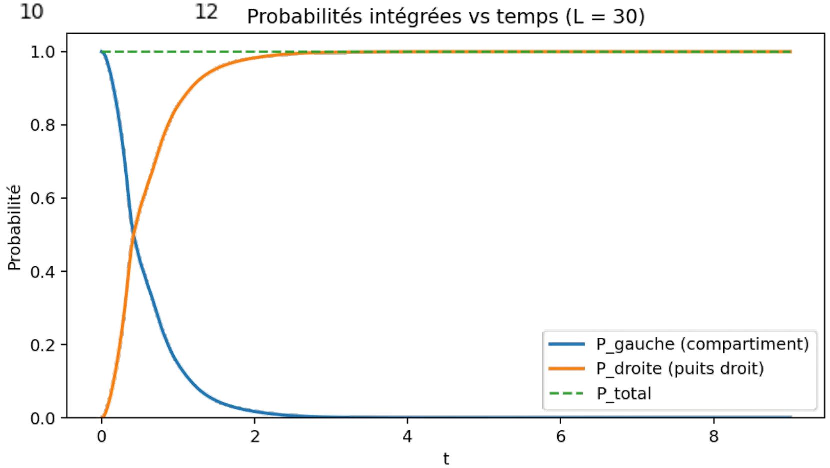
Règle d'Or de Fermi : intuition





Règle d'Or de Fermi : intuition





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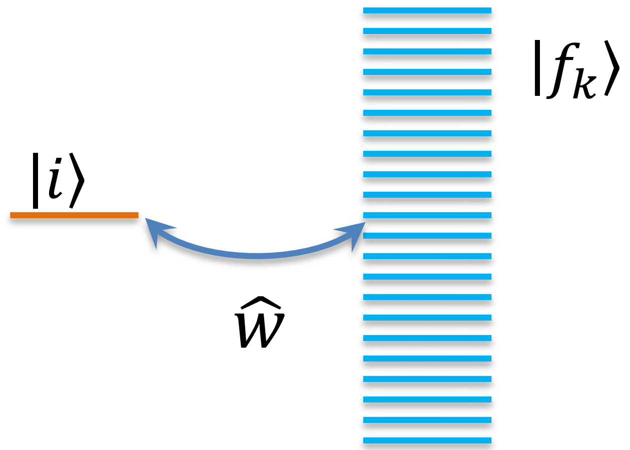
Règle d'Or de Fermi



$$\hat{W} = \sum_k W(E_{ki})|i\rangle\langle f_k| + W^*(E_{ki})|f_k\rangle\langle i|$$

À $t = 0$: $|\psi\rangle = |i\rangle$.

$P_i(t)$: Probabilité $|\psi\rangle = |i\rangle$ à l'instant t

Règle d'or de Fermi

$$P(t) = e^{-\Gamma t}$$

$$\Gamma = \frac{2\pi}{\hbar} |\hat{W}(E_f = E_i)|^2 \rho(E_f = E_i)$$

Densité d'états $\rho(E)\delta E$: Nombre d'états $|k_f\rangle$ sur δE

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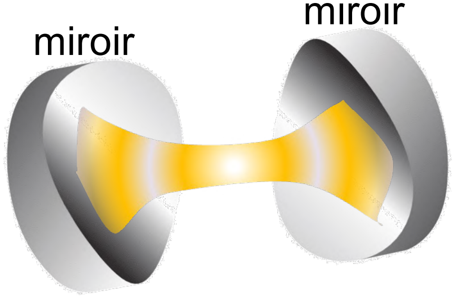
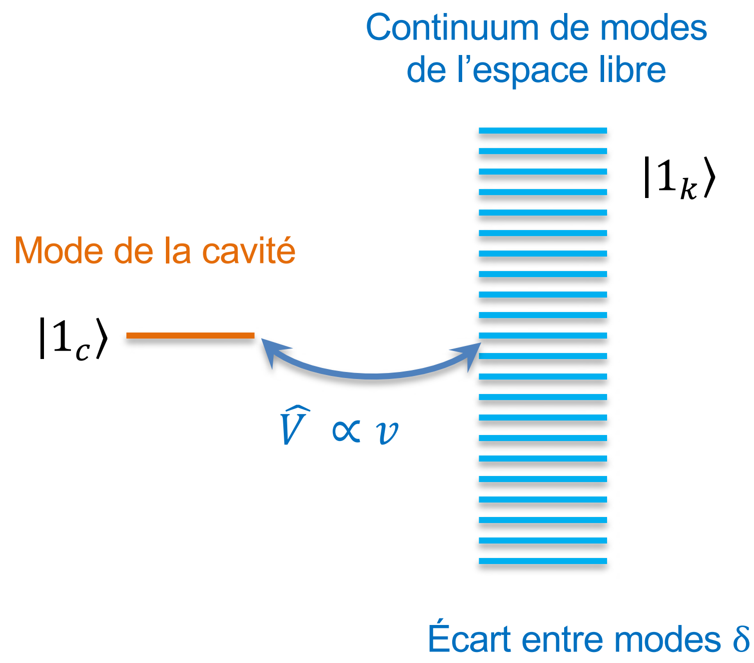
Temps de vie d'un photon dans une cavité





- $|1_c\rangle$: un photon dans la cavité, $E_c = \hbar\omega_c$
- $|1_k\rangle$: un photon dans les modes extérieurs, $E_k = \hbar\omega_k = E_c + k\delta,\ k \in \mathbb{Z},\ \delta \ll E_c$

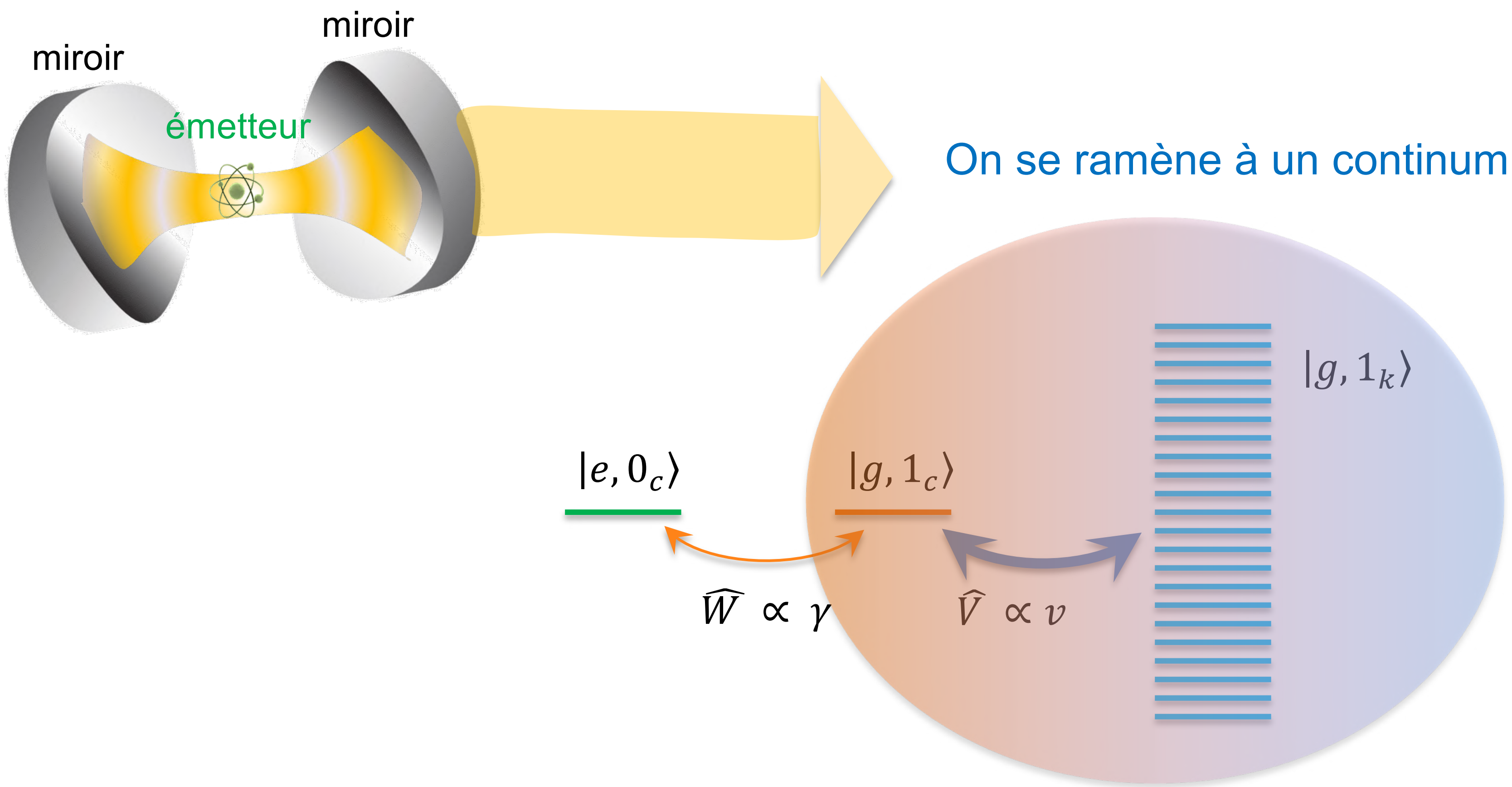
Couplage

$$\hat{V} = \sum_k V(\omega_{kc})|1_c\rangle\langle 1_k| + V^*(\omega_{kc})|1_k\rangle\langle 1_c|$$

Taux d'échappement du photon hors de la cavité

$$\Gamma_c = \frac{2\pi v^2}{\hbar\delta}$$

Contrôle de l'émission spontanée : effet Purcell



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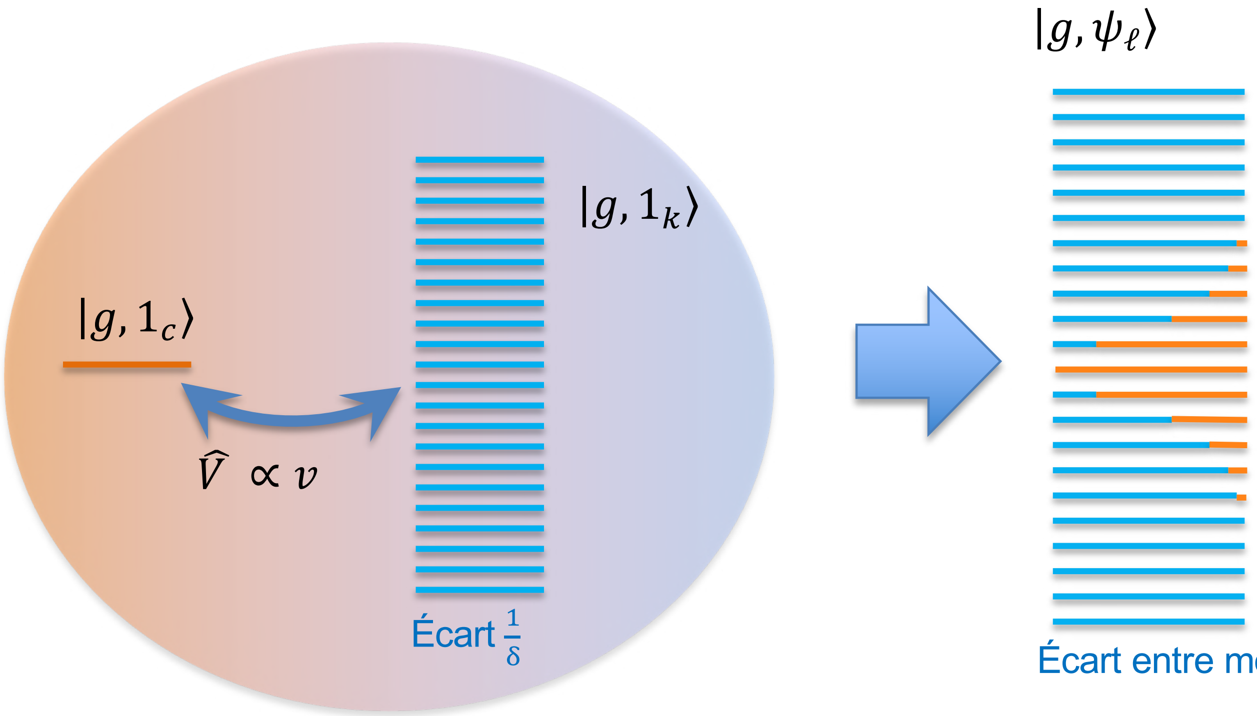
Contrôle de l'émission spontanée : effet Purcell

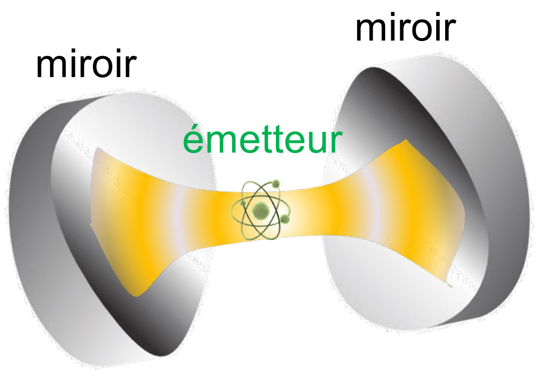
On diagonalise

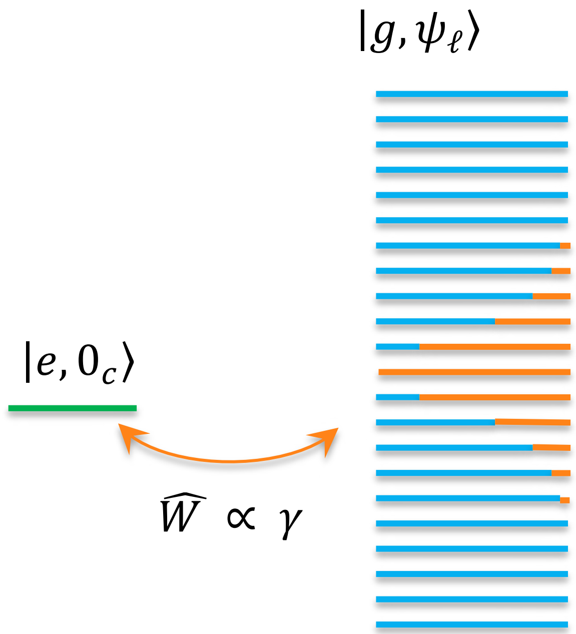


$$|\psi_\ell\rangle = \alpha_\ell \, |1_c\rangle + \sum_k \beta_{\ell,k} \, |1_k\rangle$$

$$\langle 1_c | \psi_\ell \rangle = \left(1 + \frac{\pi^2 v^2}{\delta^2} + \frac{(E_\ell - E_c)^2}{v^2} \right)^{-1/2}$$

Contrôle de l'émission spontanée : effet Purcell





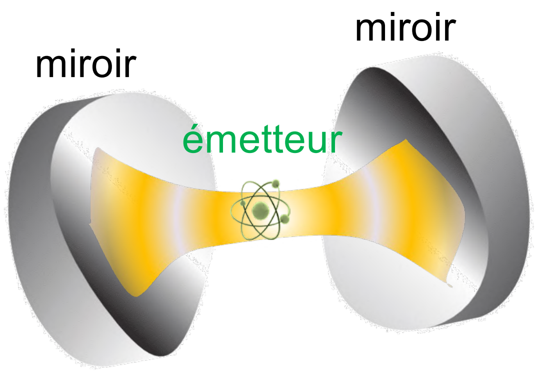
$$|\psi_\ell\rangle = \alpha_\ell \, |1_c\rangle + \sum_k \beta_{\ell,k} \, |1_k\rangle$$

$$\langle 1_c|\psi_\ell\rangle = \left(1 + \frac{\pi^2 v^2}{\delta^2} + \frac{(E_\ell - E_c)^2}{v^2}\right)^{-1/2}$$

Taux d'émission spontanée de l'atome dans la cavité

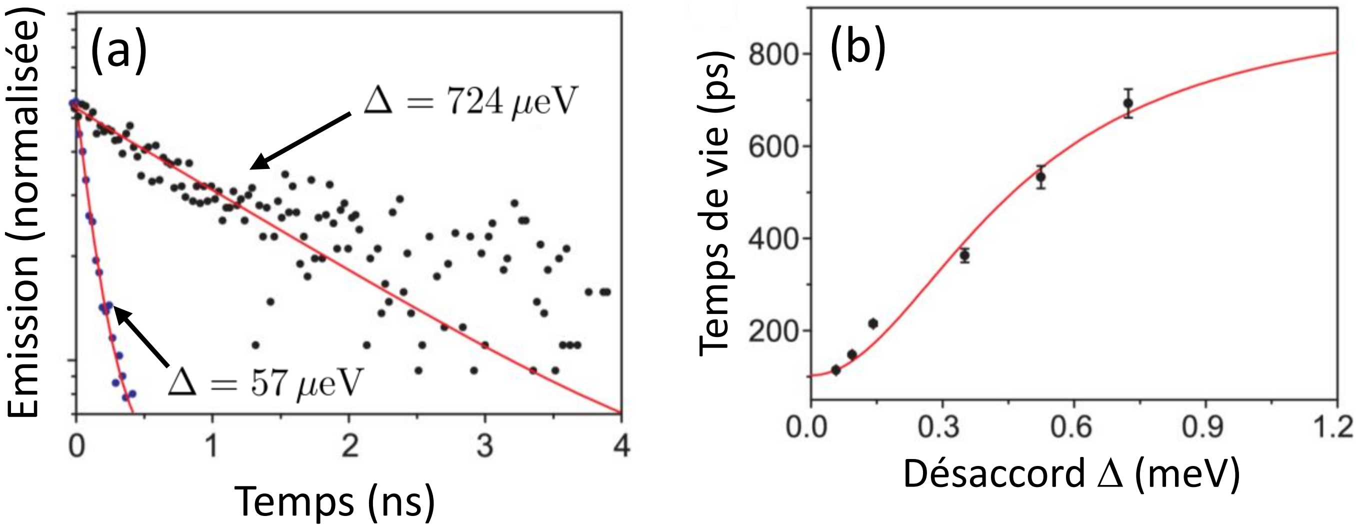
$$\Gamma_e = \frac{\gamma^2 \, \Gamma_c}{(E_e - E_c)^2 + \left(\frac{\hbar \Gamma_c}{2}\right)^2}.$$

Contrôle de l'émission spontanée : effet Purcell



Taux d'émission spontanée de l'atome dans la cavité

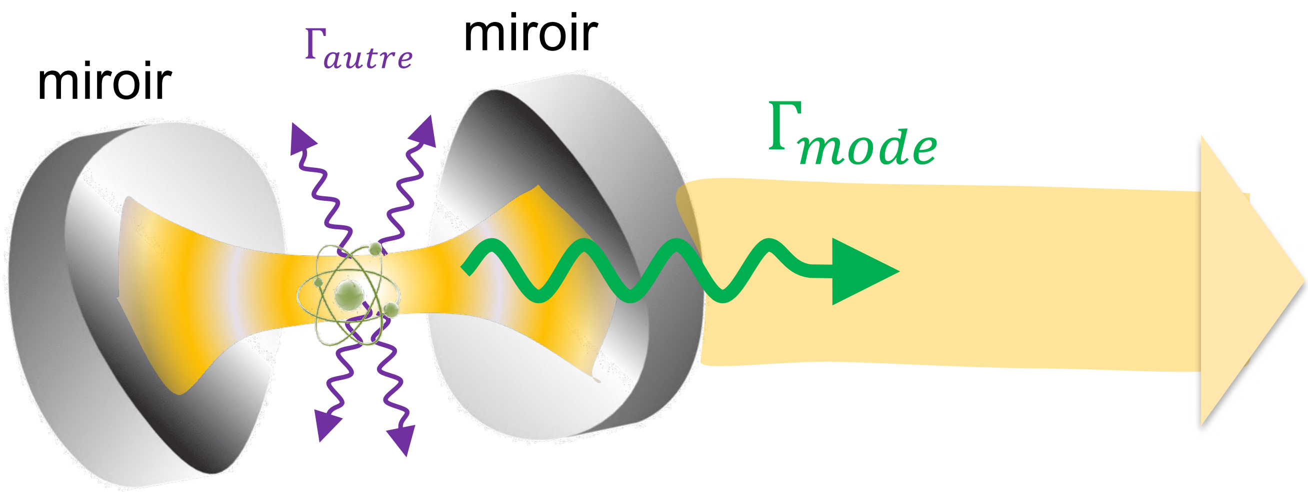
$$\Gamma_e = \frac{\gamma^2 \Gamma}{\Delta^2 + \left(\frac{\hbar \Gamma_C}{2}\right)^2} \qquad \Delta = E_e - E_c$$



Y.-M. He et al., Optica 4, 802 (2017)

Sources à la demande : collection des photons

$$\Gamma_{total} = \Gamma_{mode} + \Gamma_{autre}$$



Fraction émise dans le mode de cavité

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

E. M. Purcell - Phys. Rev. 69, 681 (1946)

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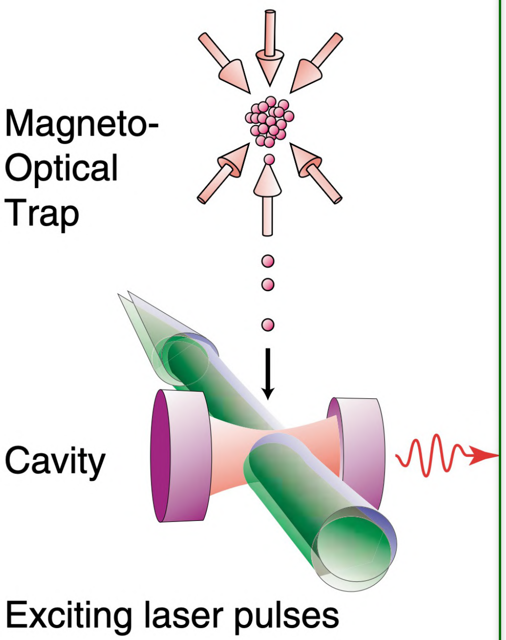
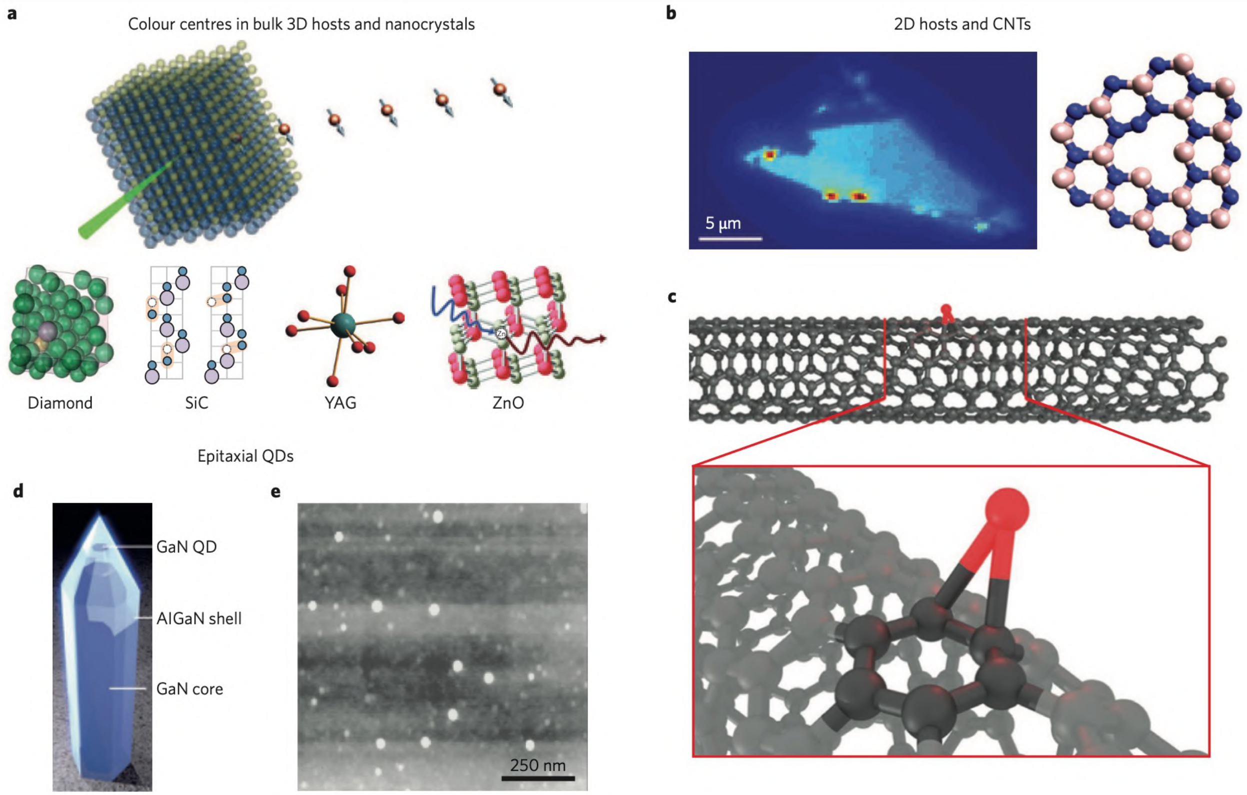
Sources de photons uniques : émetteurs

Atomes



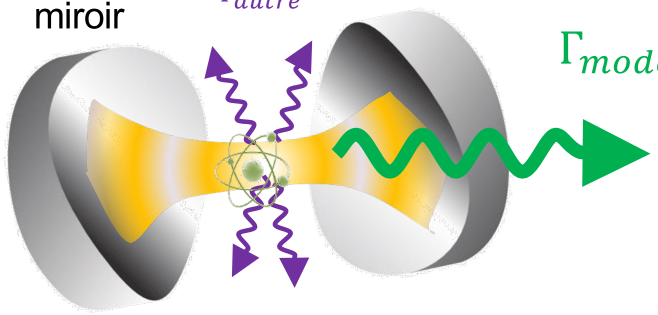
Phys. Rev. Lett. 89, 067901 (2002)

Atomes artificiels



Nature Photonics 10, 631–641 (2016)

Sources de photons uniques : cavité



Facteur de Purcell

Facteur de Purcell

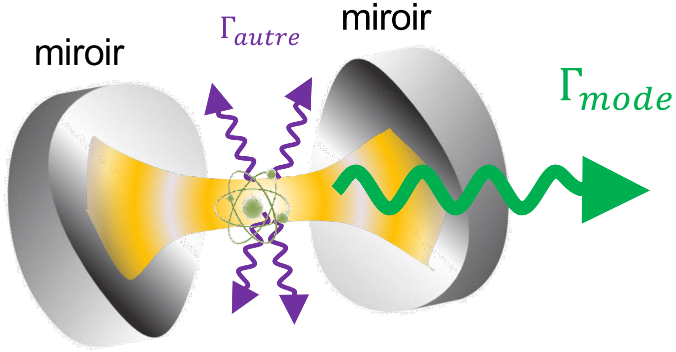
$$F_P = \frac{\Gamma_{\text{mode}}}{\Gamma_{\text{sans cavité}}} = \frac{3}{4\pi^2}\frac{Q}{V_{\text{eff}}}\left(\frac{\lambda}{n}\right)^3$$

facteur de qualité $Q \propto \frac{1}{\Gamma_c}$

volume effectif V_{eff}

E. M. Purcell - Phys. Rev. 69, 681 (1946)

Sources à la demande : resonance atome-cavité



Facteur de Purcell

Facteur de Purcell

$$F_P = \frac{\Gamma_{\text{mode}}}{\Gamma_{\text{sans cavité}}} = \frac{3}{4\pi^2}\frac{Q}{V_{\text{eff}}}\left(\frac{\lambda}{n}\right)^3$$

Dépendence spatiale et spectrale

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

E. M. Purcell - Phys. Rev. 69, 681 (1946)

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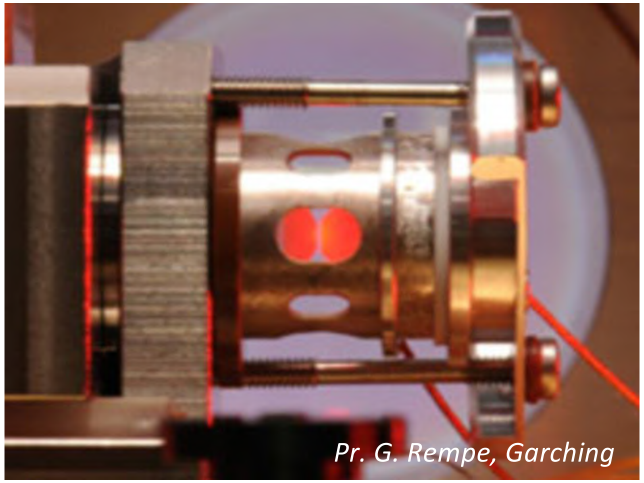
Source de photons uniques brillantes

Deux systèmes à la pointe*

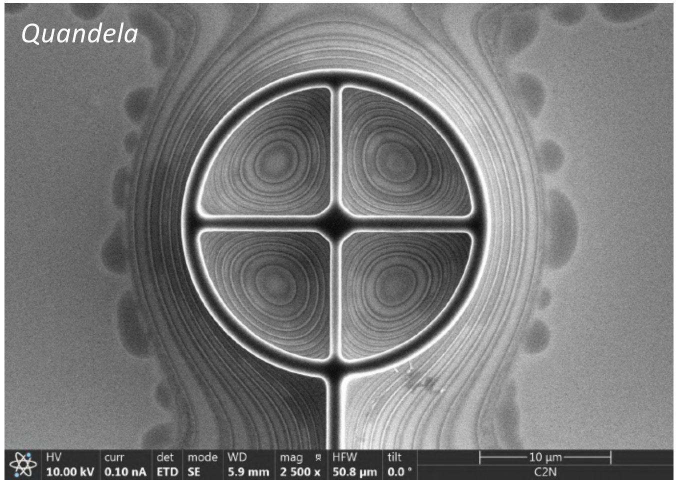
Atomes piégés en cavité



2-4 cm

Cf. cours 5 : piégeage
Séminaire 3 février Pr. Rempe

Boites quantiques en microcavités



40 µm

*source de photons uniques et indiscernables

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Sources de photons à boîtes quantiques semiconductrices

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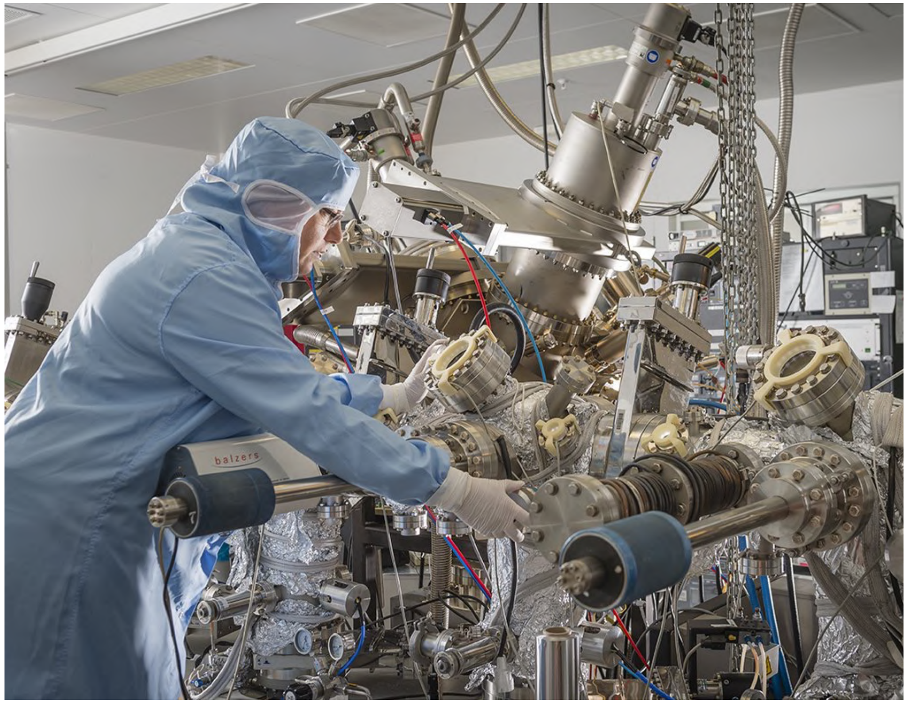
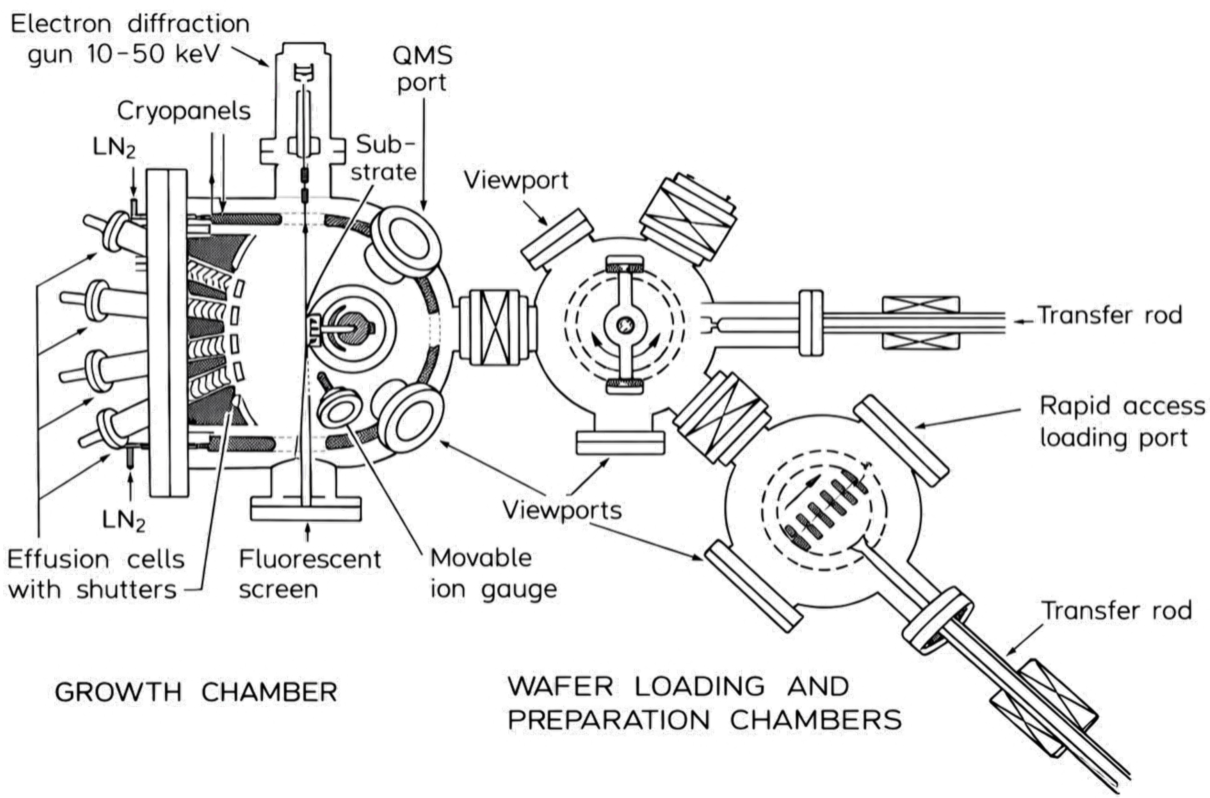
Atomes artificiels semiconducteurs

Croissance par épitaxie par jet moléculaire





Physics, Fabrication, and Applications of Multilayered Structures
P. Dhez, C. Weisbuch 1988, pp 93-110, Tsuneo Sakamoto

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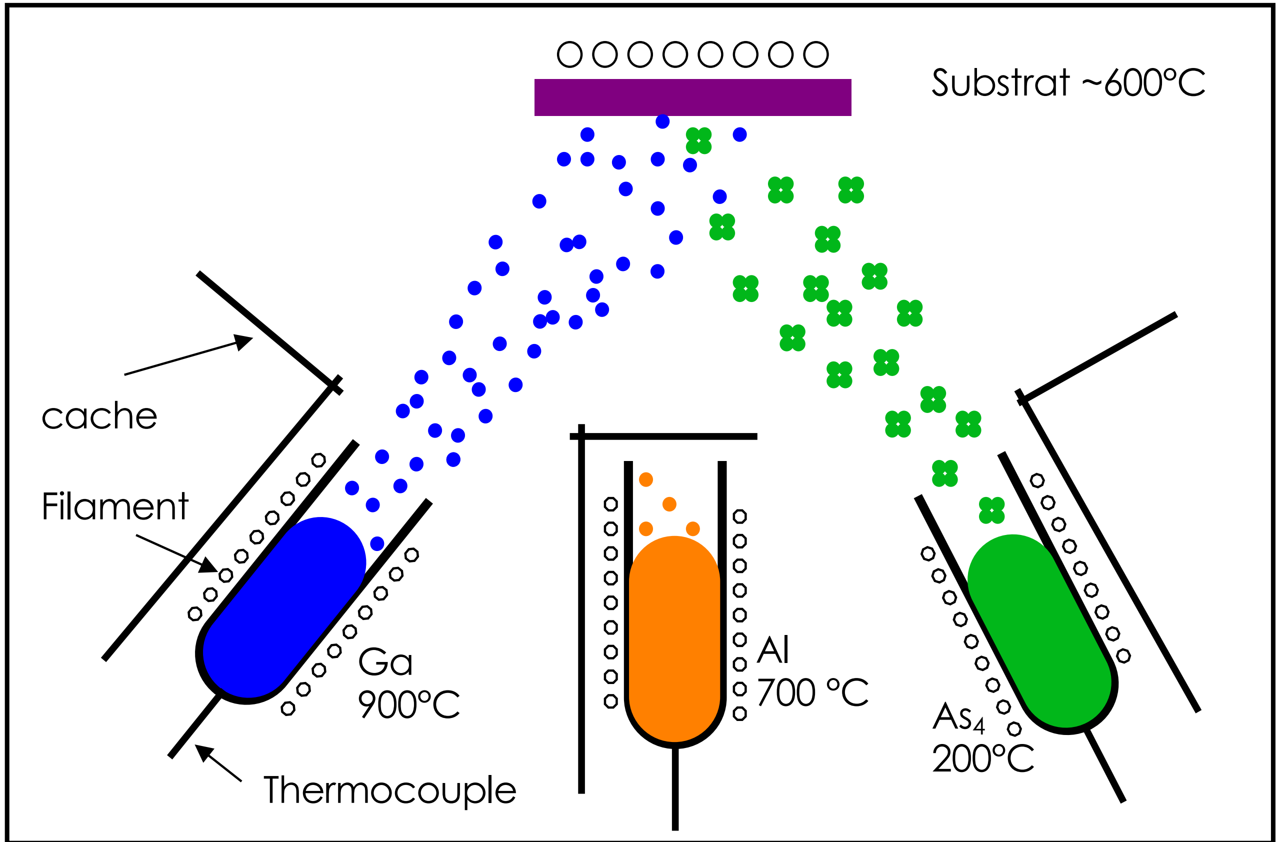
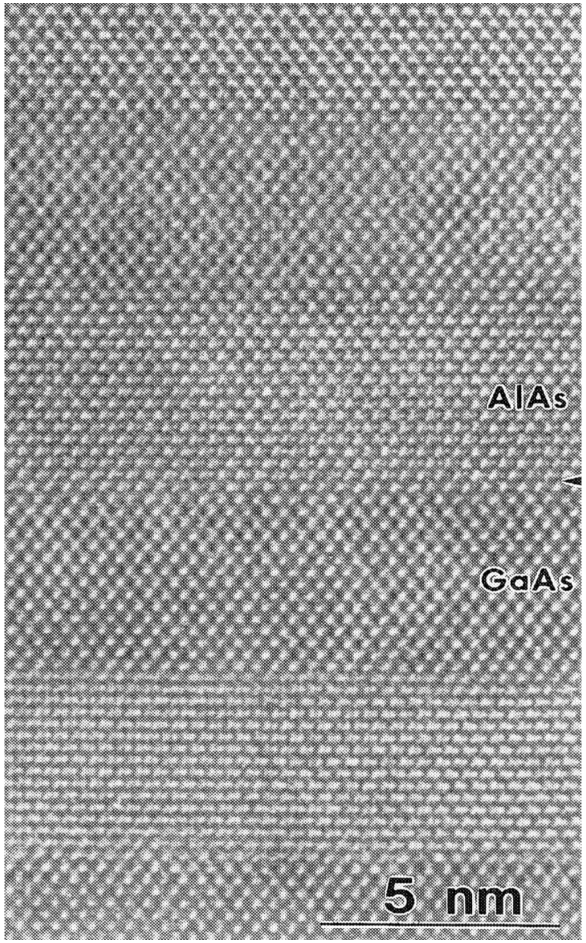
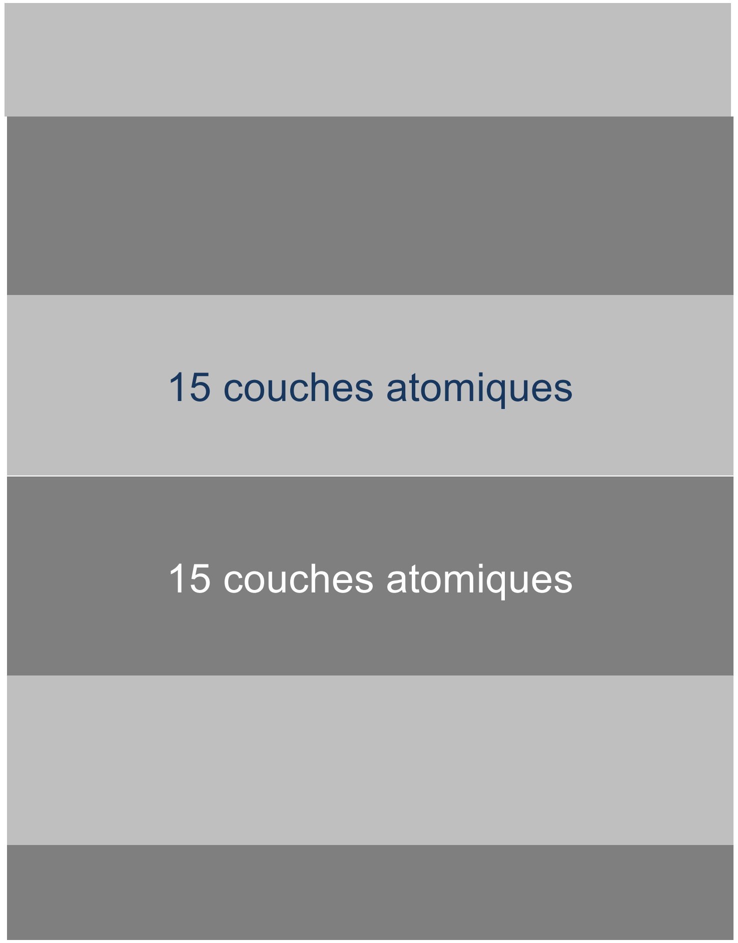
Croissance par épitaxie par jet moléculaire



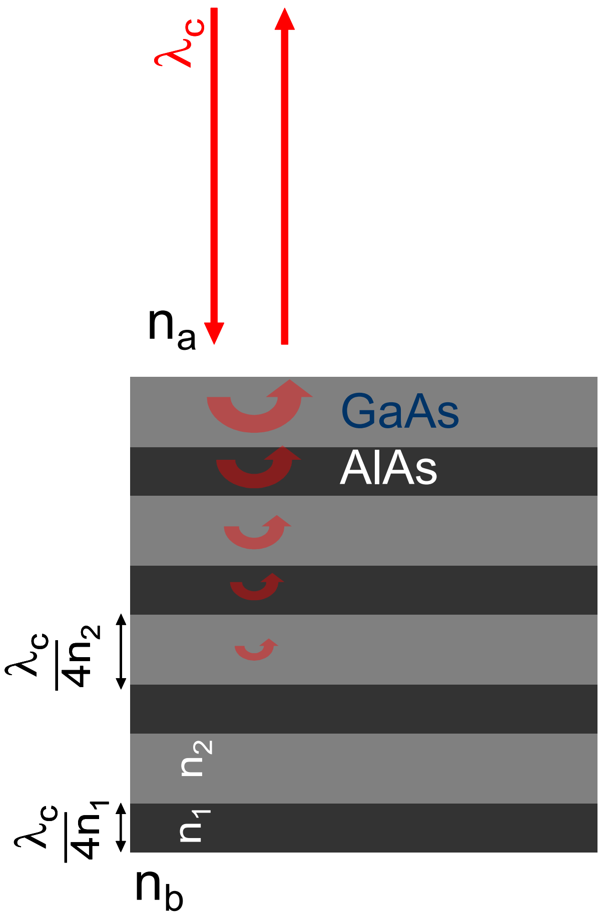
Ultra vide
P ~ 10^{-10} Torr

Croissance par épitaxie par jet moléculaire

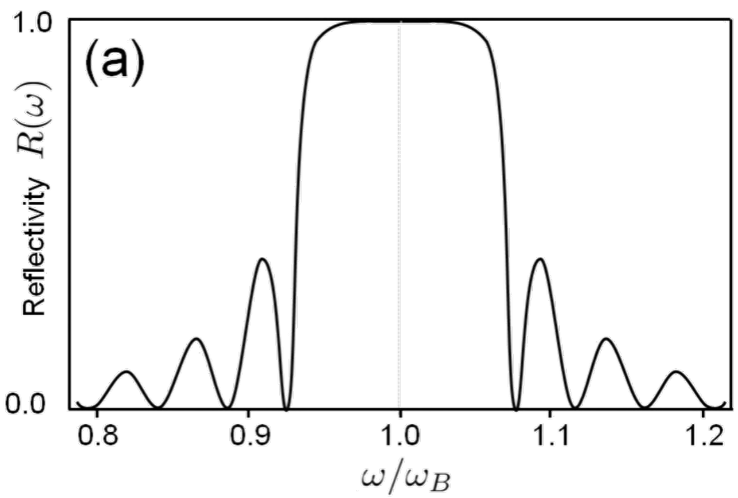




Confiner la lumière : miroirs de grande réflectivité



Miroirs interférentiels



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

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

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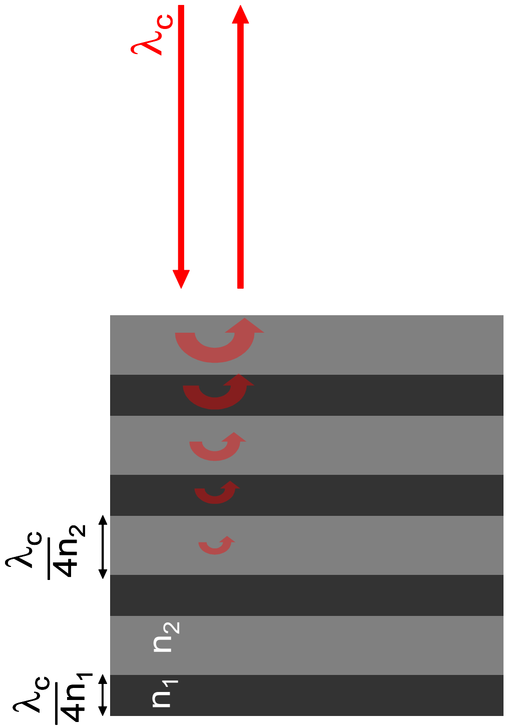
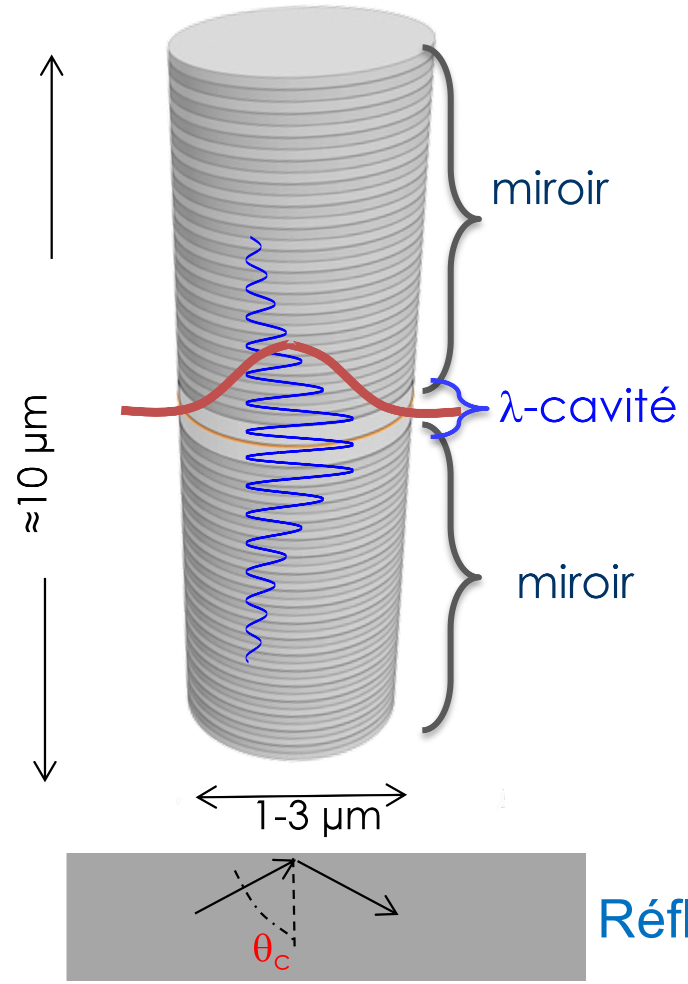
Exemple de micro-cavité : micropiliers



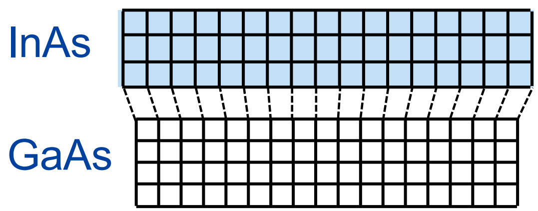
Miroirs interférentiels

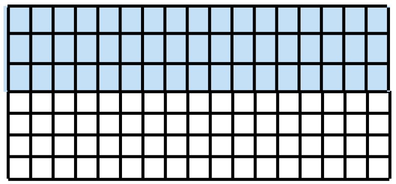
GaAs

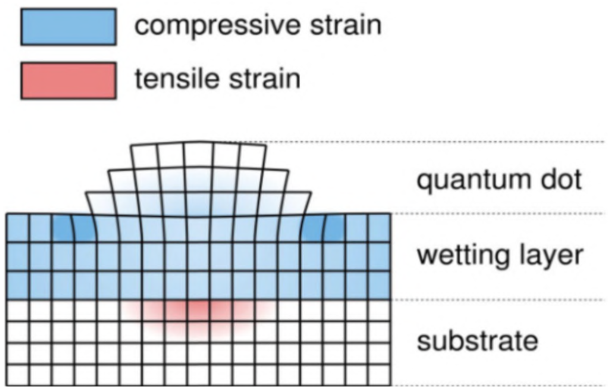


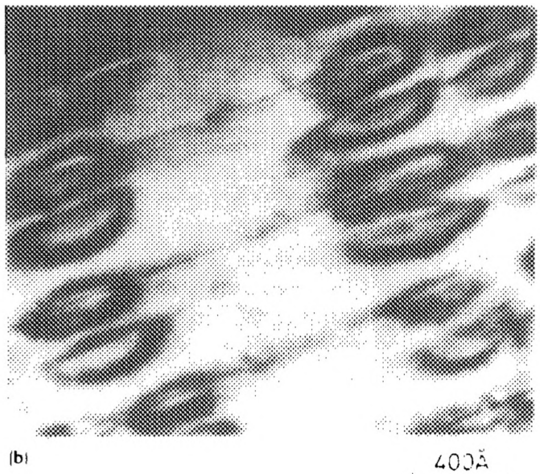
Réflexion totale

Synthèse des boîtes quantiques semiconductrices

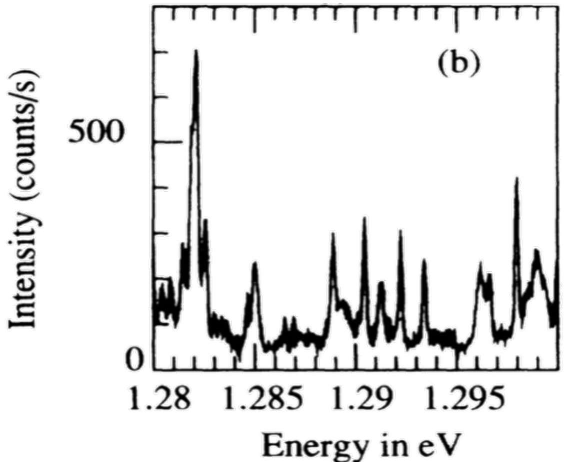




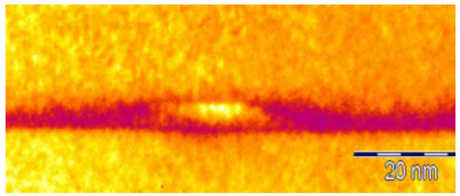




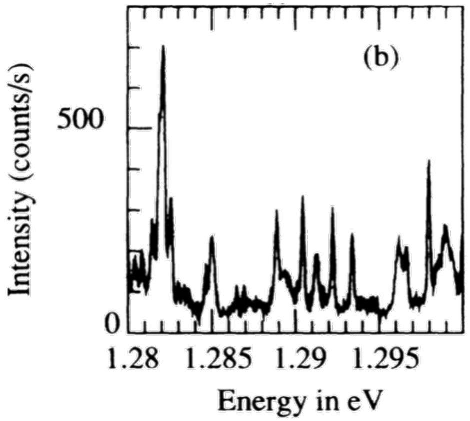
Appl. Phys. Lett. 47, 1099 (1985)



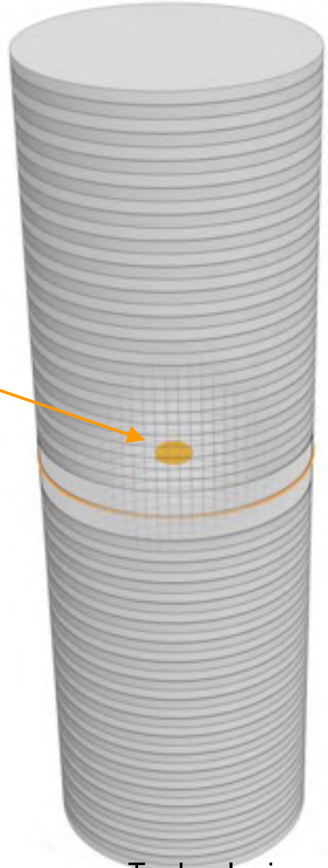
Phys. Rev. Lett. 73, 716 (1994)

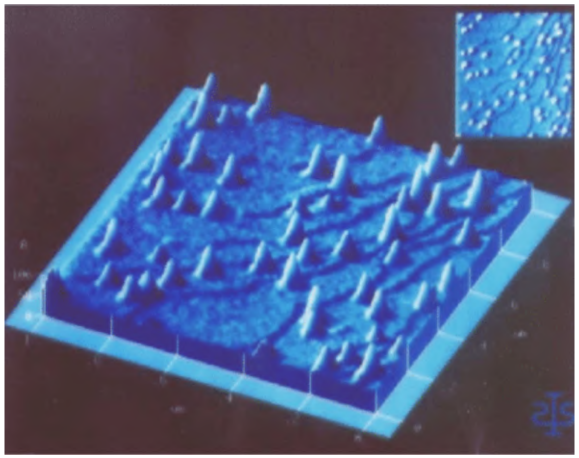


Défi technologique



Boîte quantique





Facteur de Purcell

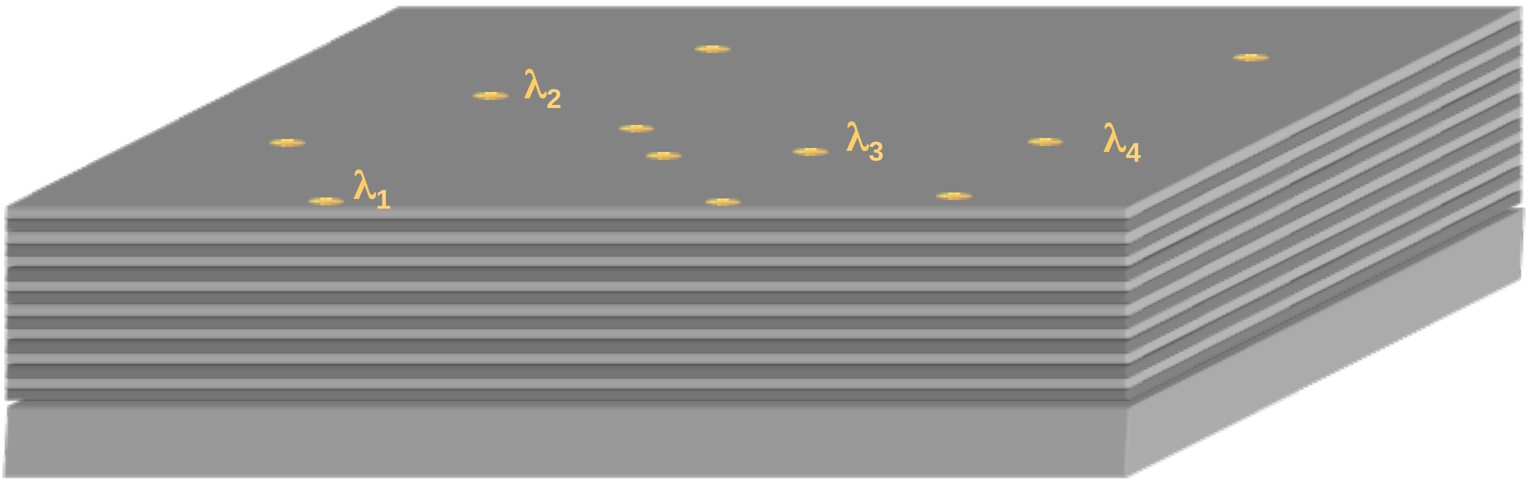
Facteur de Purcell

$$F_P = \frac{\Gamma_{\text{mode}}}{\Gamma_{\text{sans cavité}}} = \frac{3}{4\pi^2}\frac{Q}{V_{\text{eff}}}\left(\frac{\lambda}{n}\right)^3$$

Dépendence spatiale et spectrale

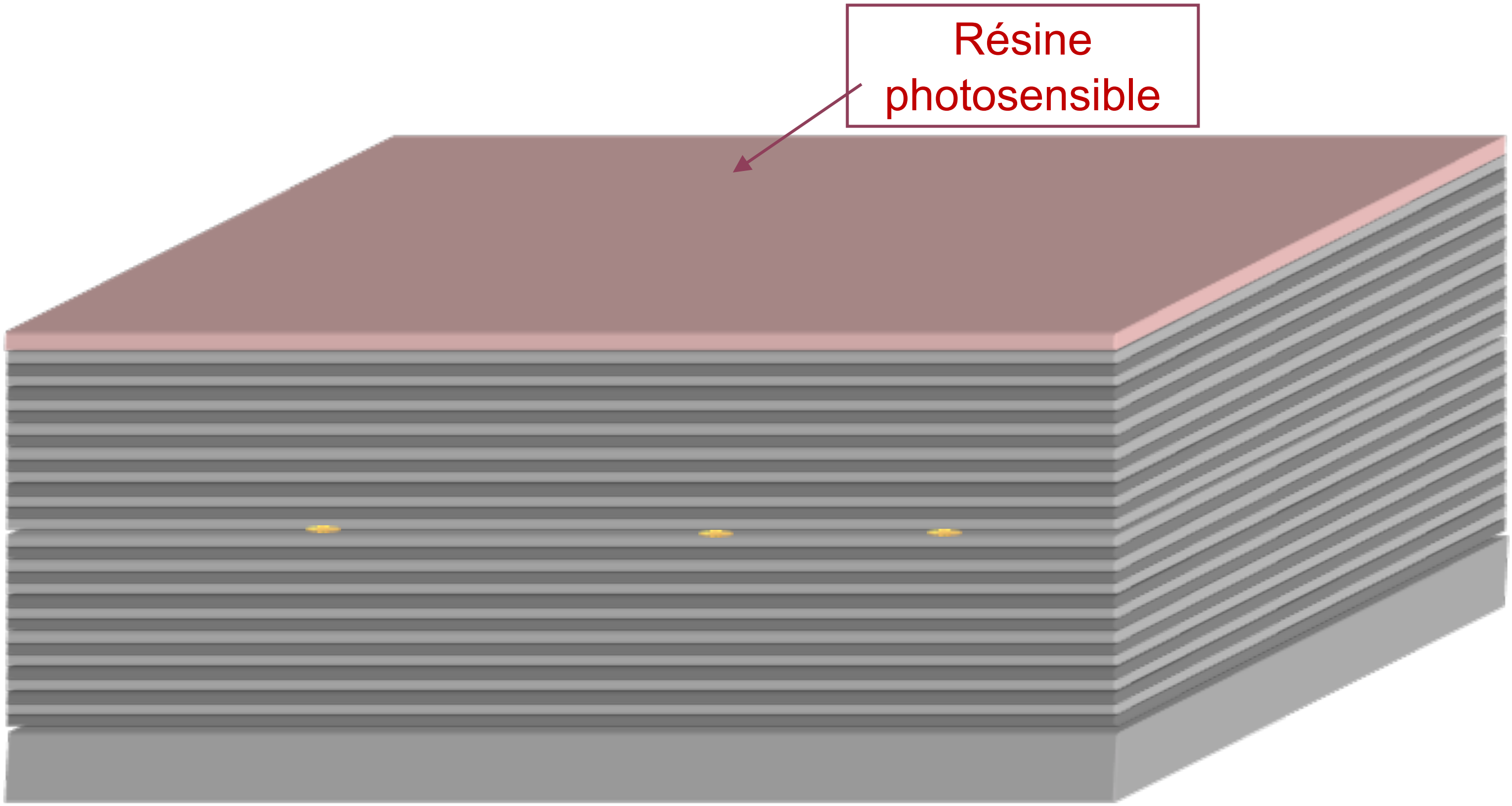
$$F = F_P \frac{\left|\langle e\,|\,\mathbf{d}\cdot\mathbf{u}(\mathbf{r}_{QD})\,|\,g\rangle\right|^2}{\left|\langle e\,|\,\mathbf{d}\,|\,g\rangle\right|^2}\frac{1}{1+\left(\frac{2Q}{\hbar\omega_c}\right)^2(\hbar\omega_{eg}-\hbar\omega_c)^2}$$

Contrôle du couplage émetteur-cavité : lithographie in-situ

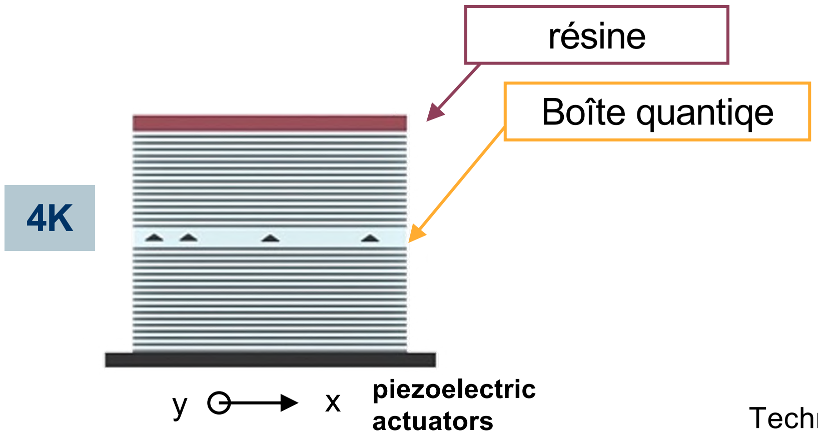


Contrôle du couplage émetteur-cavité : lithographie in-situ

Contrôle du couplage émetteur-cavité : lithographie in-situ



Contrôle du couplage émetteur-cavité : lithographie in-situ



Phys. Rev. lett. 101, 267404 (2008)

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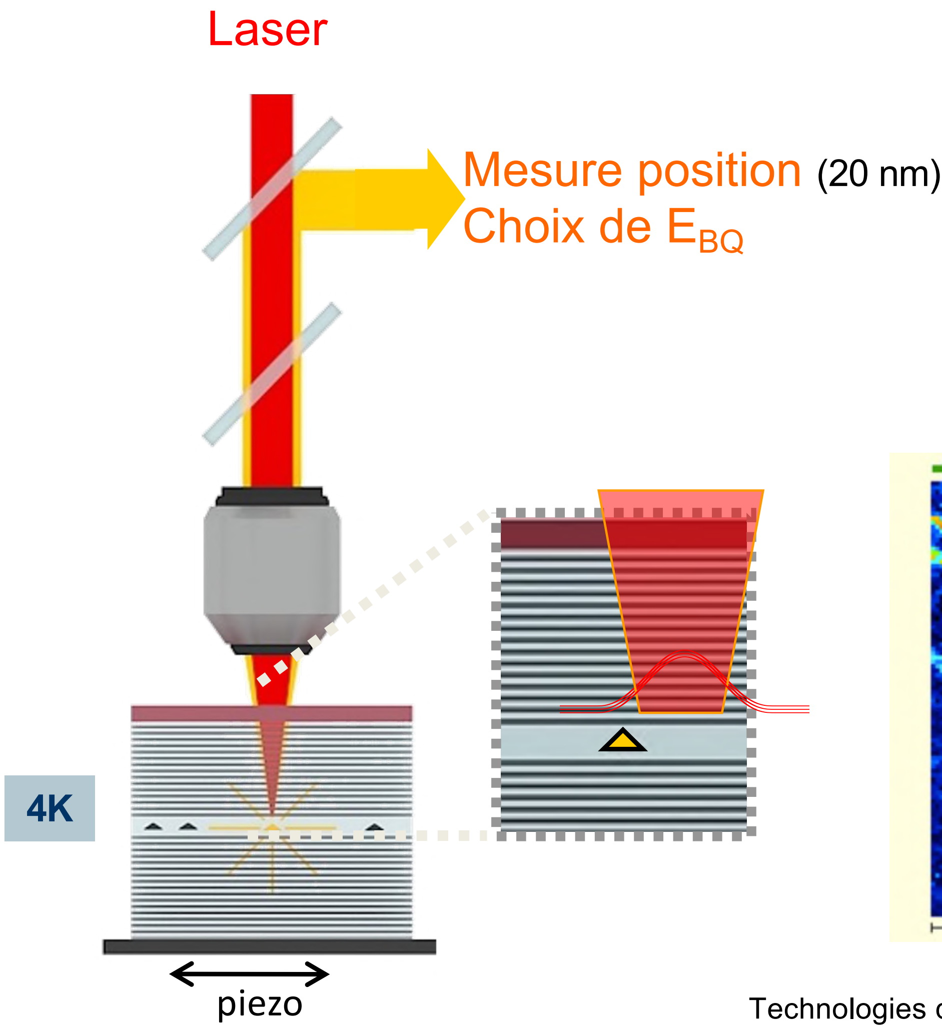
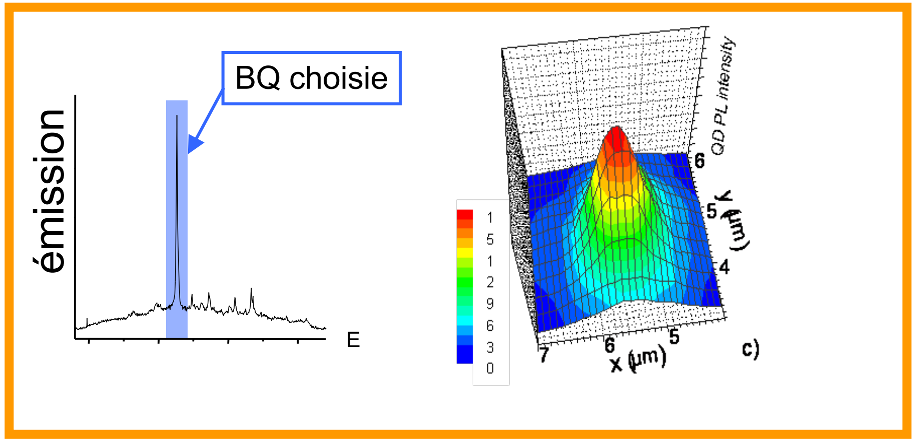
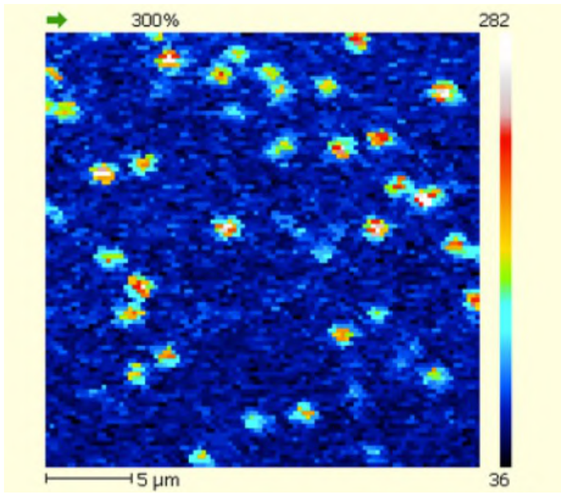
Contrôle du couplage émetteur-cavité : lithographie in-situ

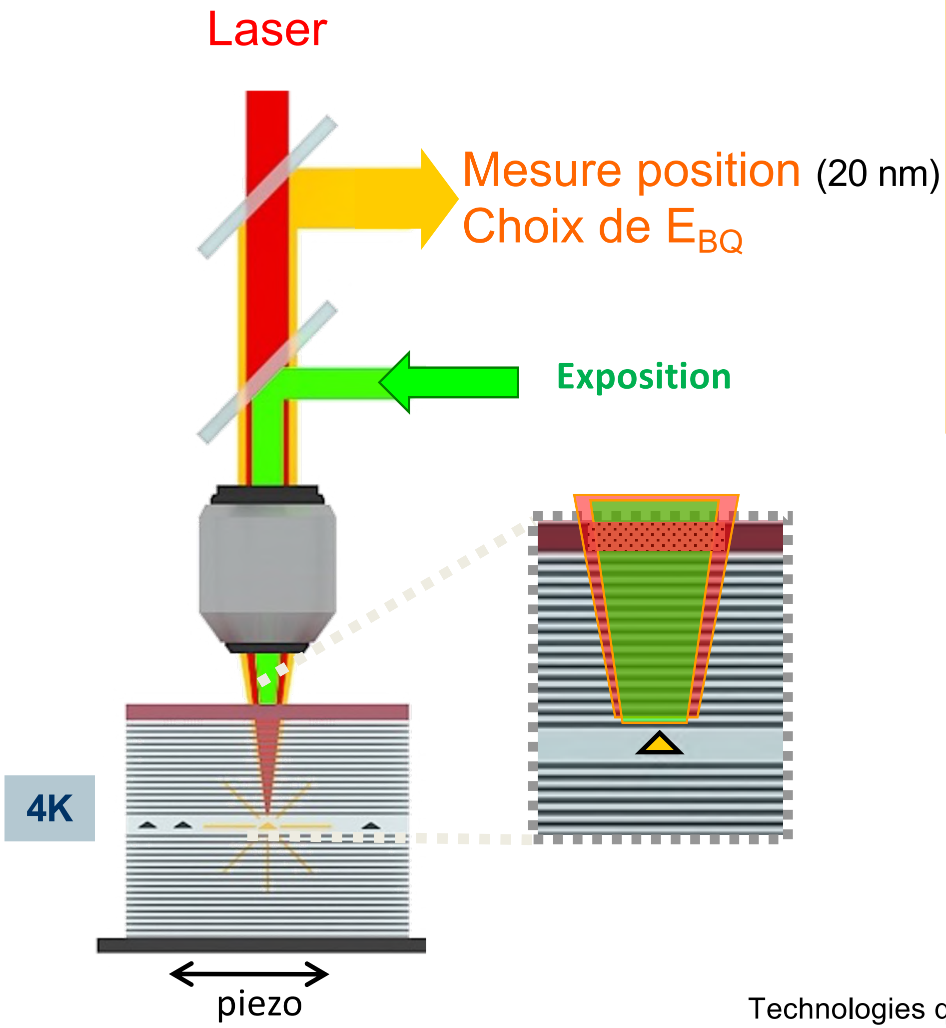


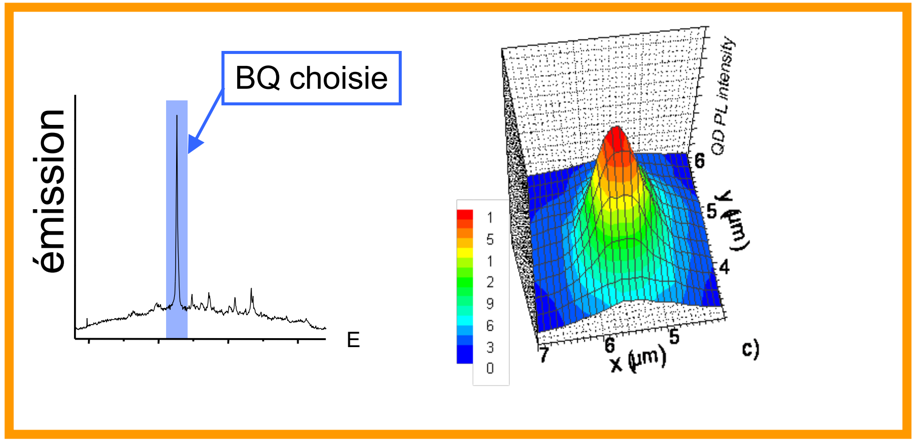




Phys. Rev. lett. 101, 267404 (2008)

Contrôle du couplage émetteur-cavité : lithographie in-situ





Phys. Rev. lett. 101, 267404 (2008)

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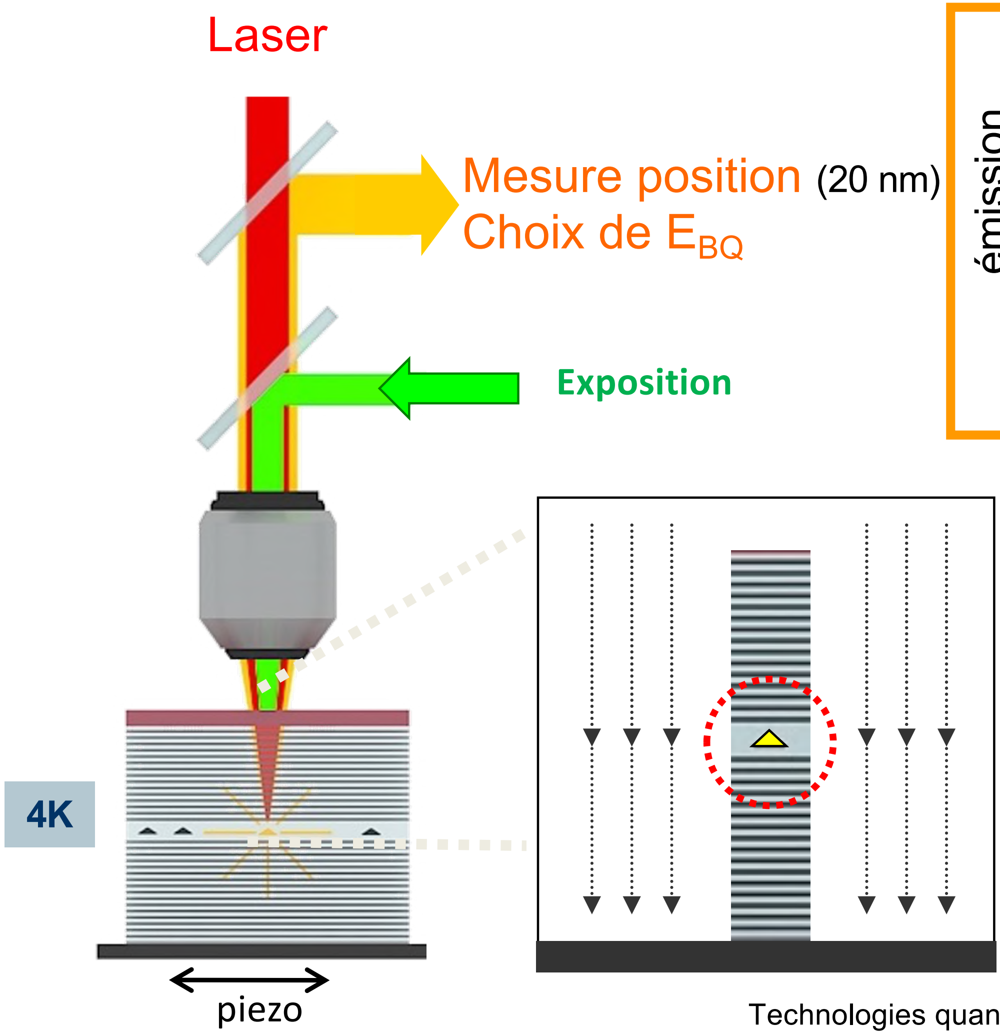
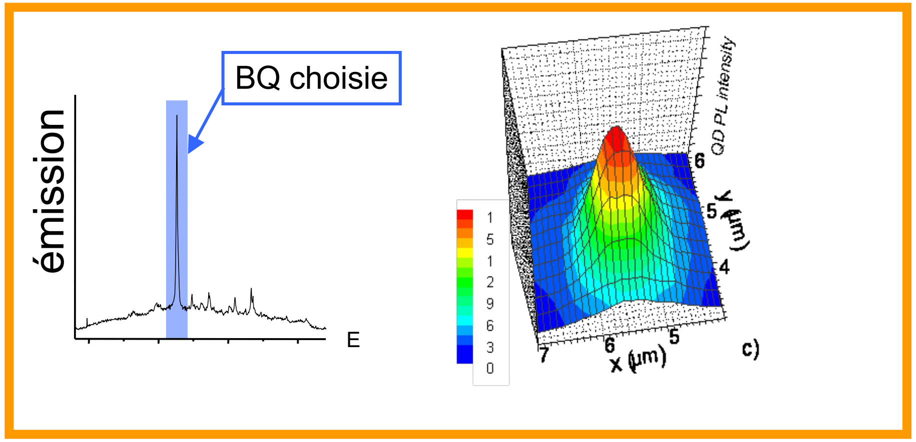
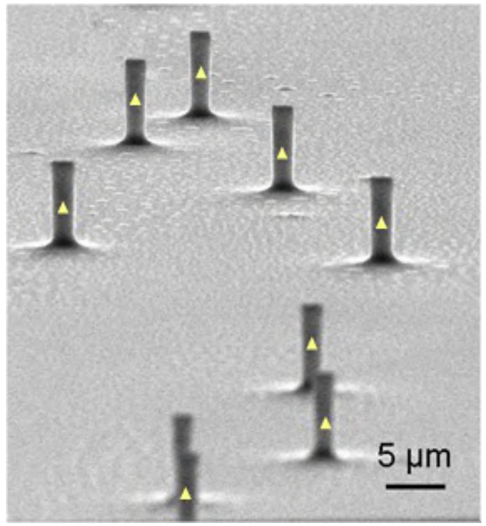
Contrôle du couplage émetteur-cavité : lithographie in-situ

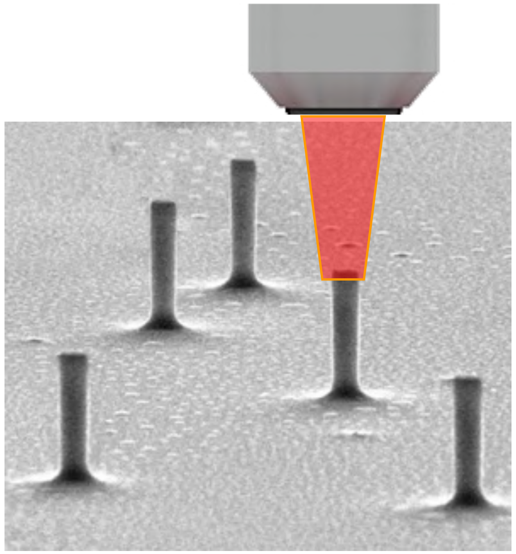


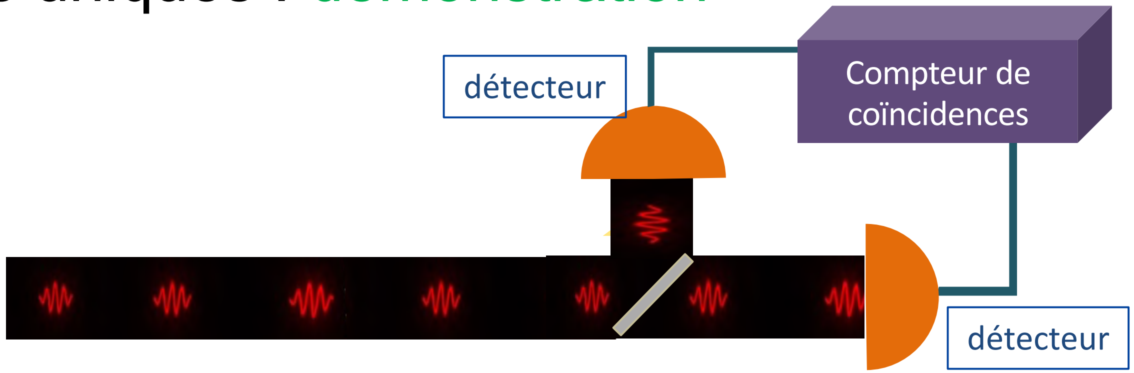


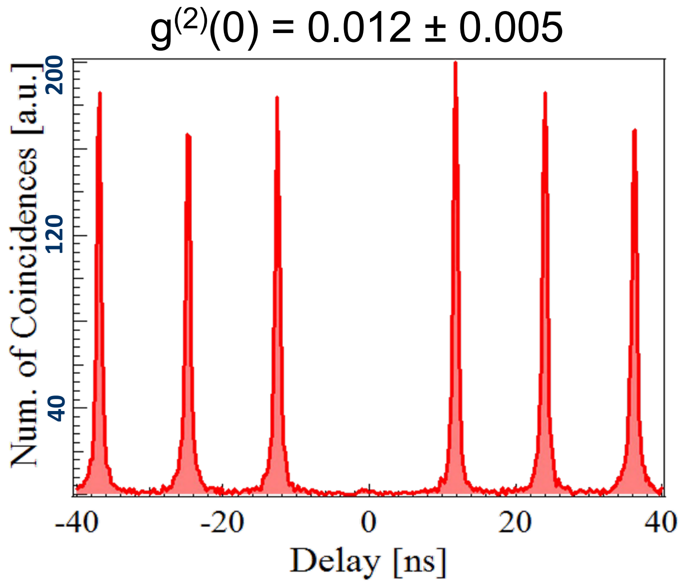


Phys. Rev. lett. 101, 267404 (2008)

Emission de photons uniques : démonstration

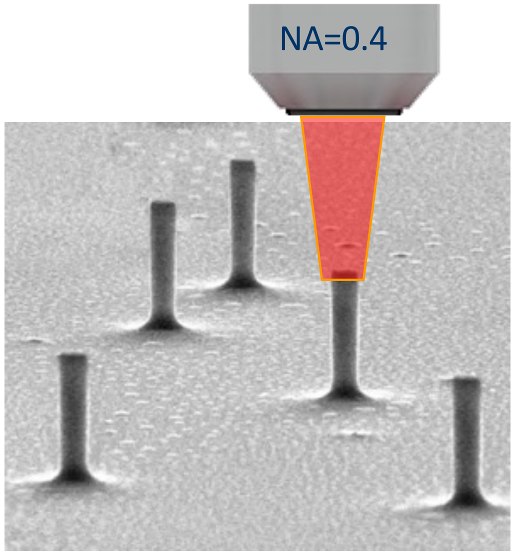


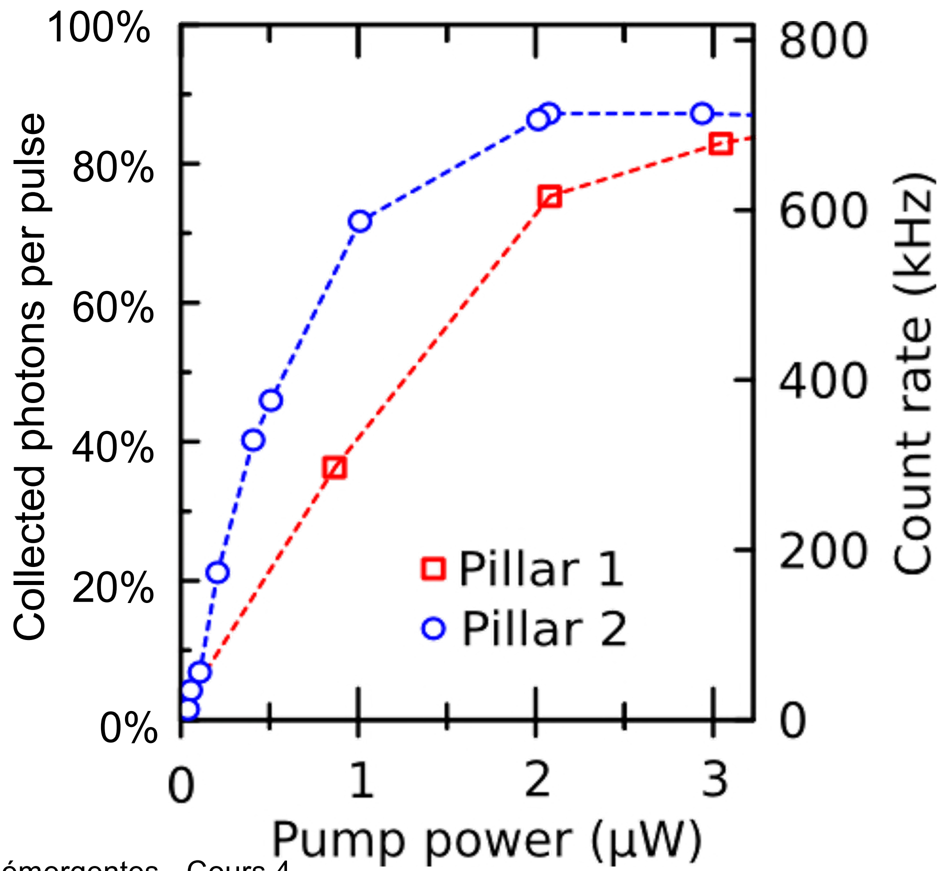




Mesure de la brillance : méthode

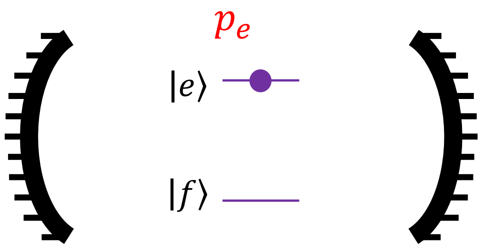
$$C = \nu_{laser} * \eta_{setup} * \mathrm{B}$$



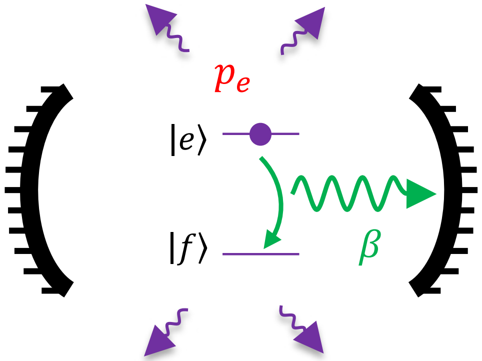


Nature Communications 4, 1425 (2013)

Paramètres contrôlant la brillance d'une source

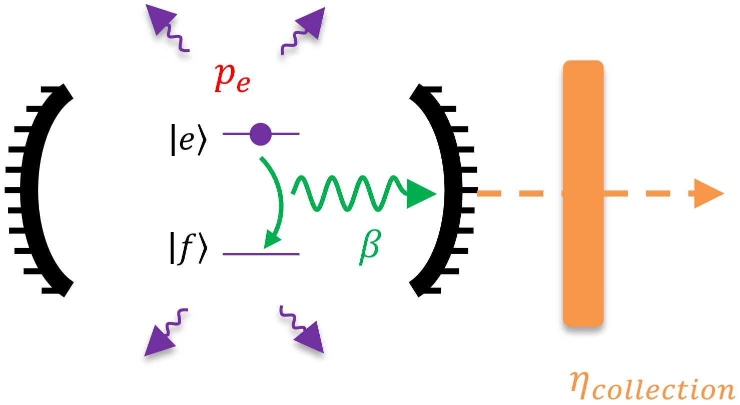


Paramètres contrôlant la brillance d'une source

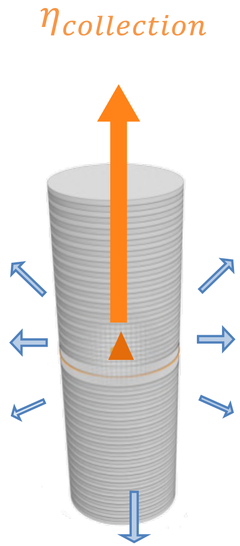


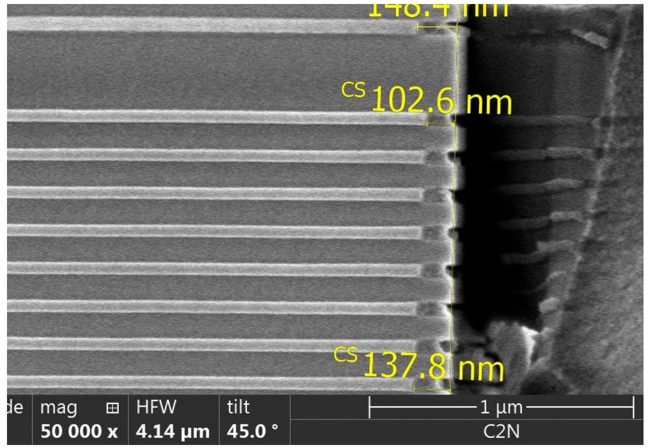
$$\beta = \frac{\Gamma_{mode}}{\Gamma_{mode} + \Gamma_{autre}}$$

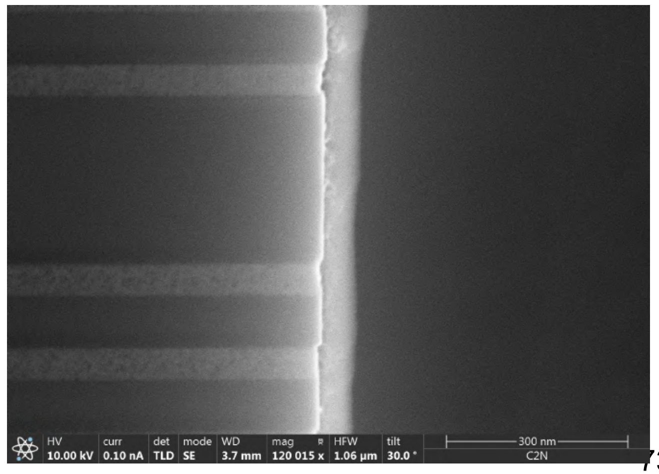
Paramètres contrôlant la brillance d'une source



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







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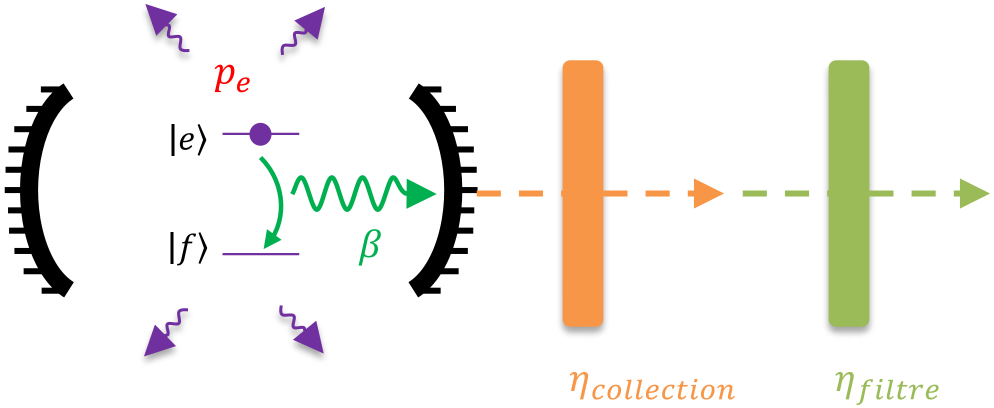
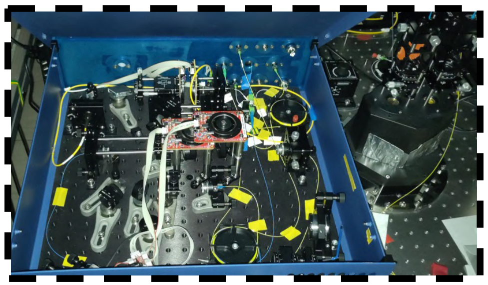
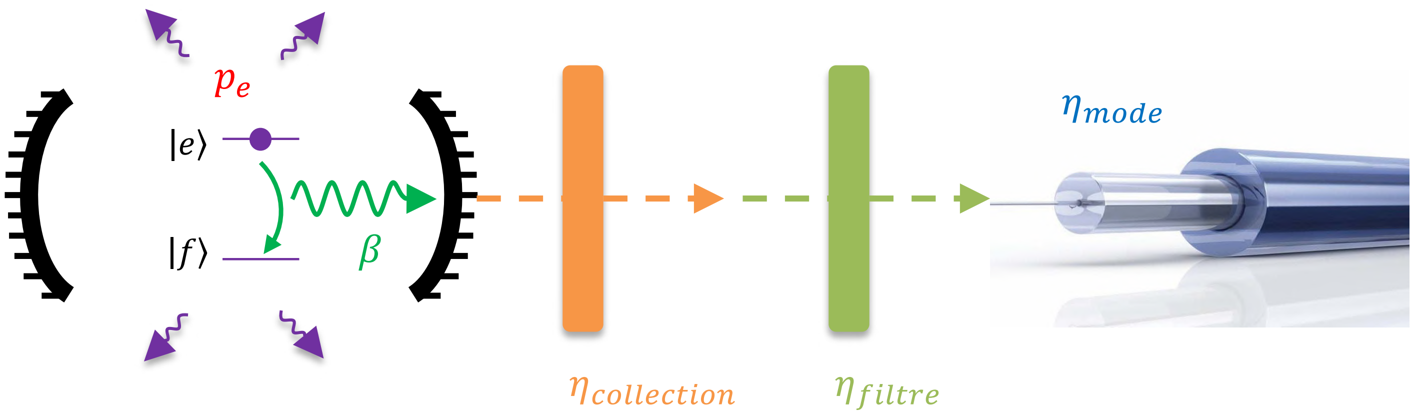
Paramètres contrôlant la brillance d'une source



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



Paramètres contrôlant la brillance d'une source



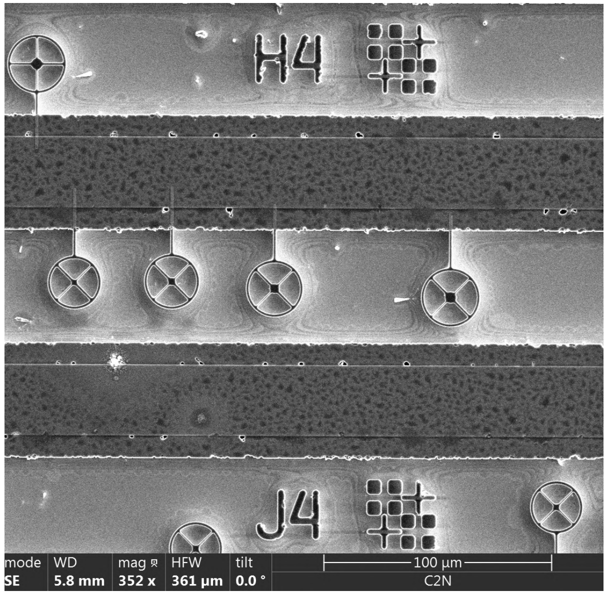
$$\beta = \frac{\Gamma_{mode}}{\Gamma_{mode} + \Gamma_{autre}}$$

Brillance utile

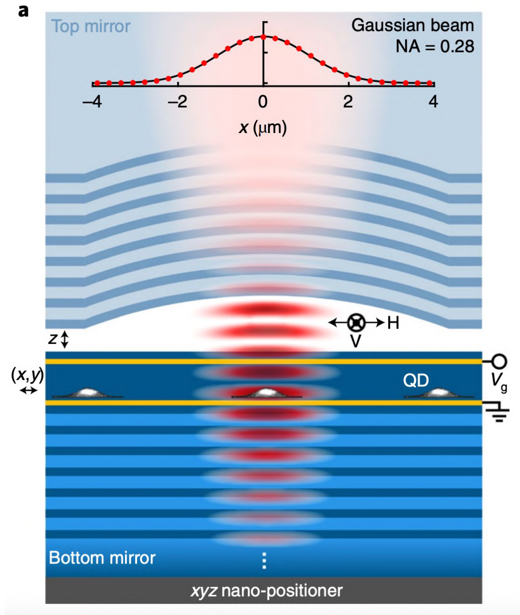
$$B = p_e \; \beta \; \eta_{collection} \; \eta_{filtre} \; \eta_{mode}$$

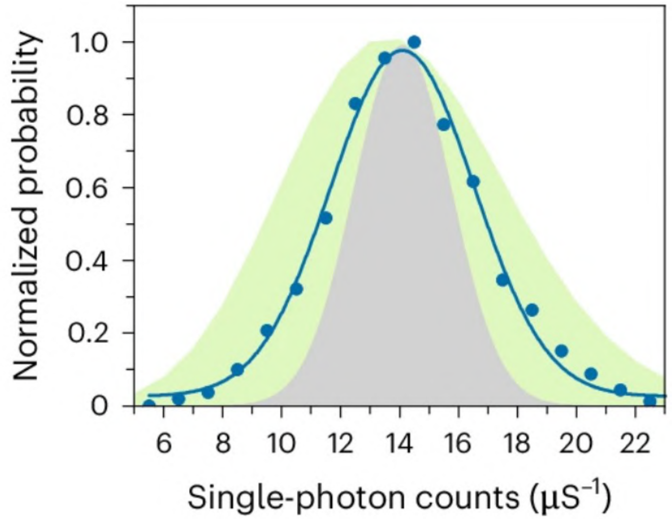
Sources de photons uniques efficaces : état de l'art

Micropiliers



Cavités ouvertes





Pulse area (π)

Brillance utile

$B = 60\ \%$

$B = 57\ \%$

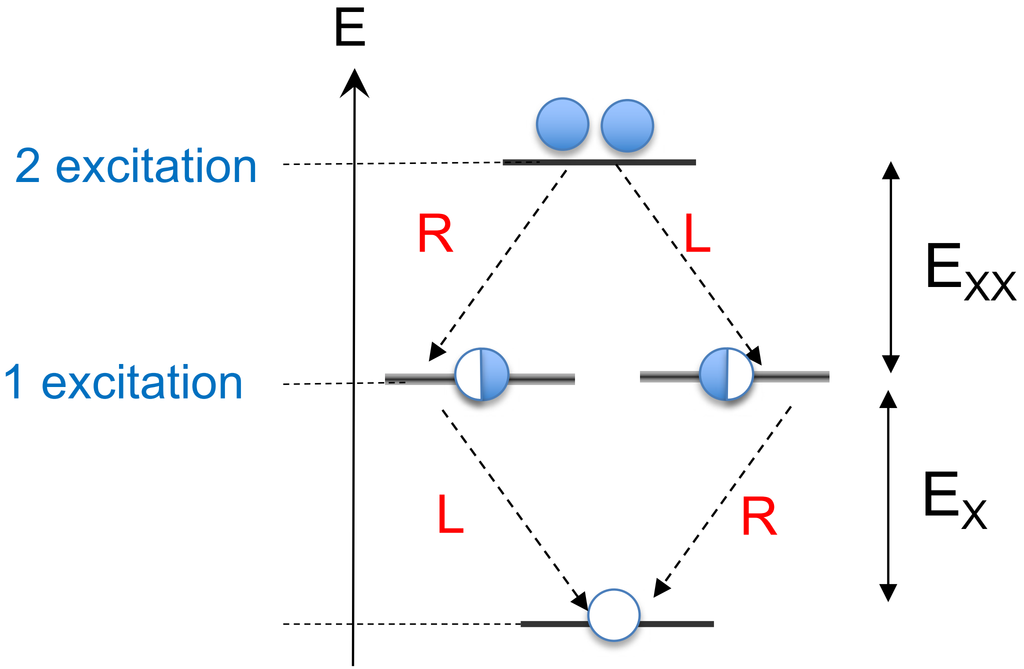
$B = 71\ \%$

Quandela, en préparation

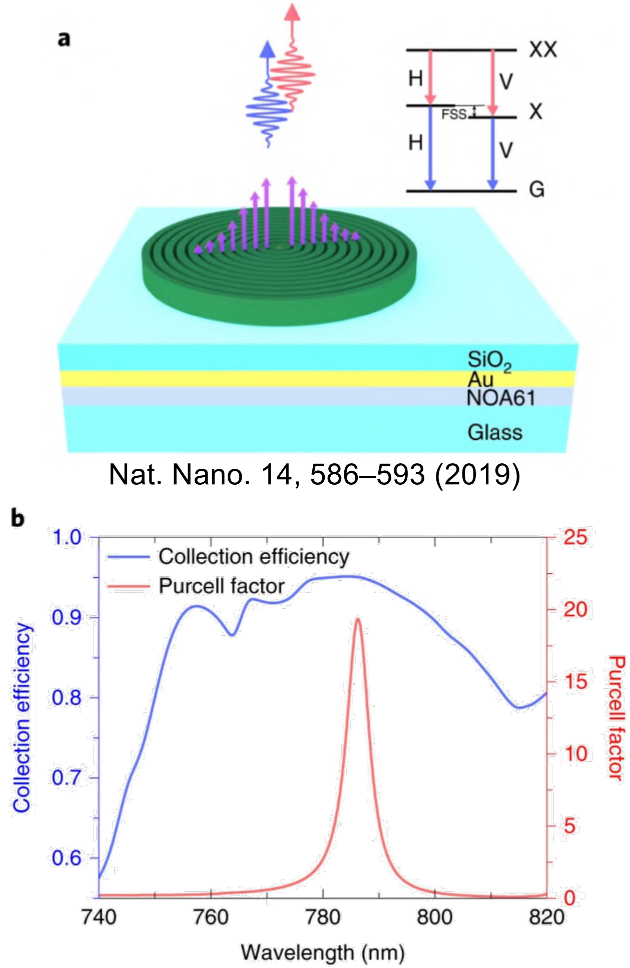
Nature Nanotechnology 16, 399 (2021)

Nature Photonics 19, 387–391 (2025)

Boites quantiques : génération de photons intriqués



$$|\psi_+\rangle = \frac{|R_{XX}L_X\rangle + |L_{XX}R_X\rangle}{\sqrt{2}}$$



Nat. Nano. 14, 586–593 (2019)

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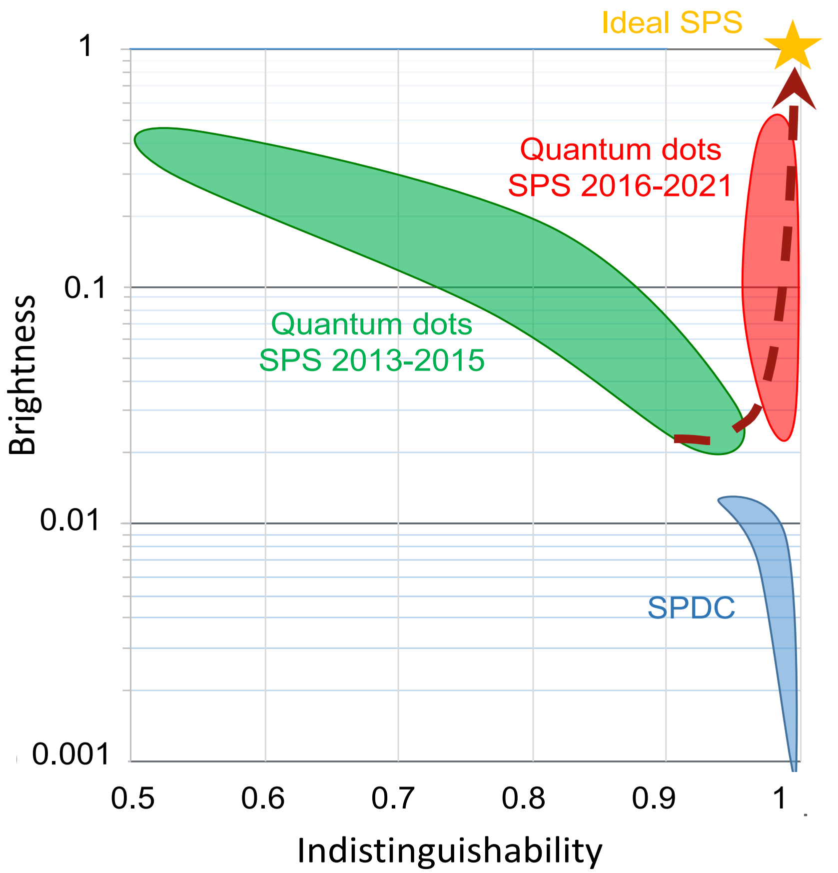
Du laboratoire au produit

Commercialisation de sources de photons uniques



Photoniques 107 (2021) 40-43

Taux de generation de N qubits photoniques

$$\nu_{N\,qubits} = B^{N}\,\nu_{horloge}$$

SPARROW QUANTUM 2016

QUANDELA 2017

aegiq 2019

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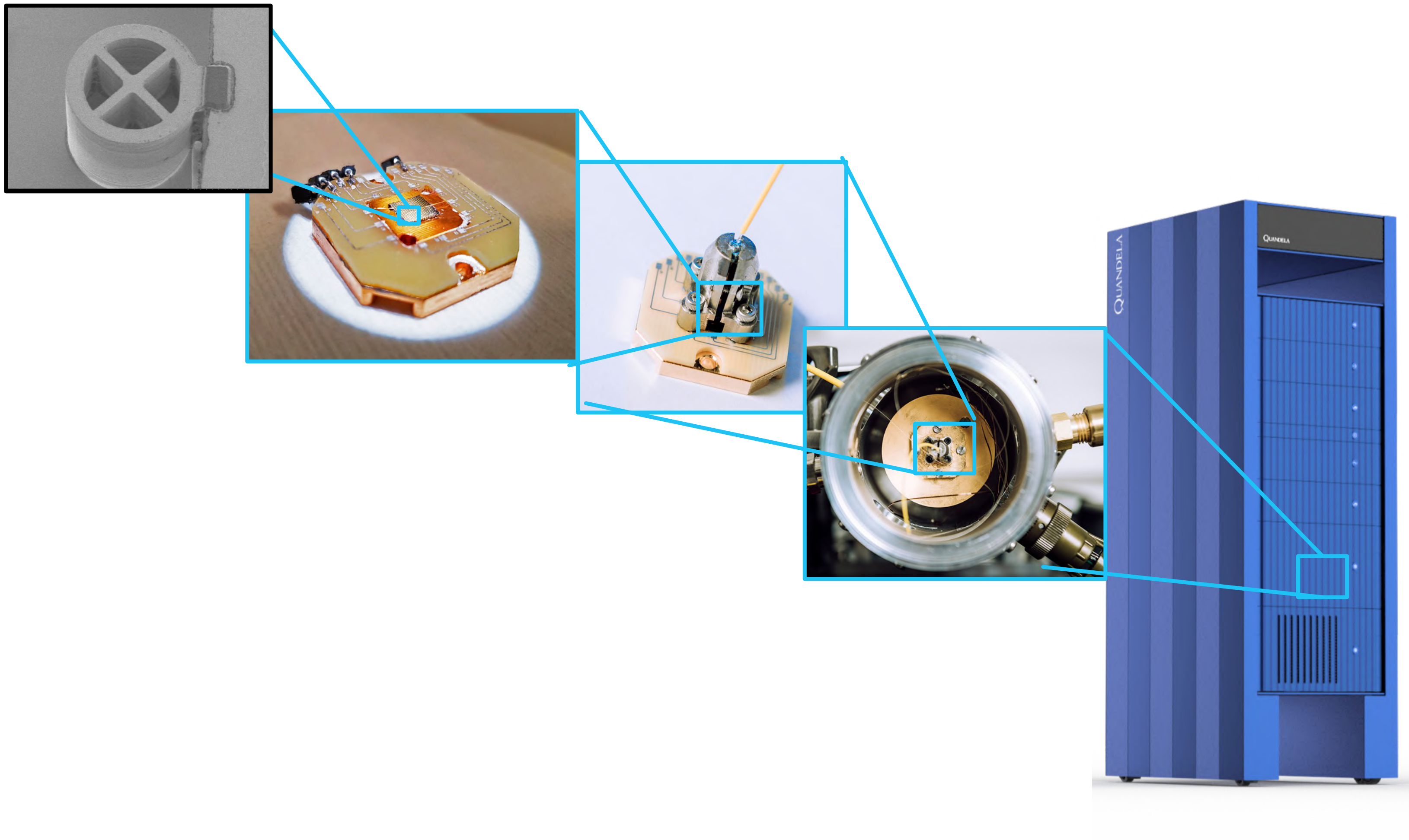
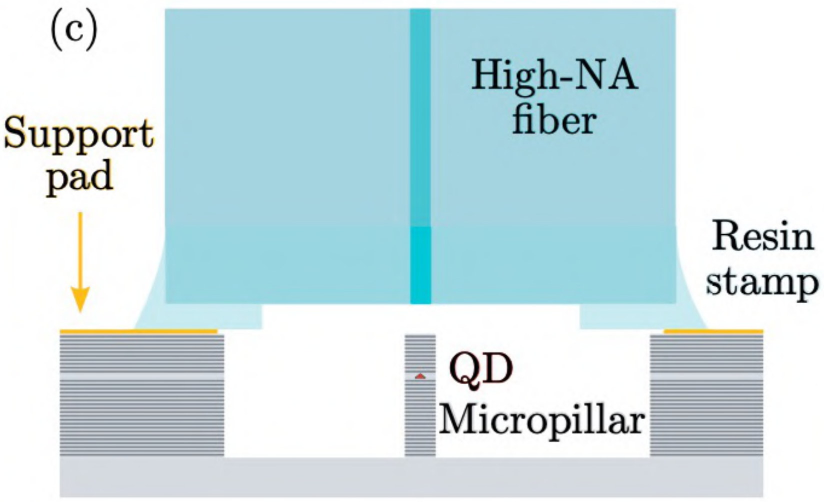
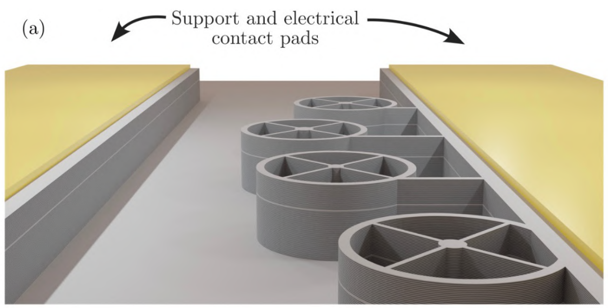
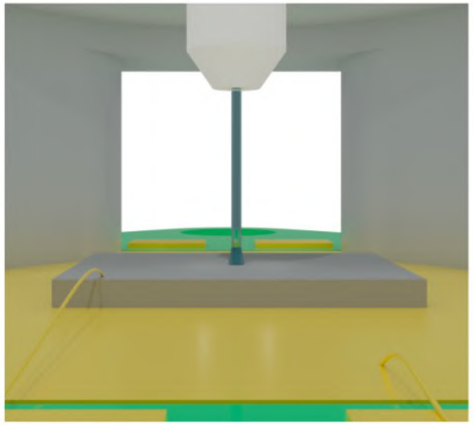
Source de photons uniques : premiers produits

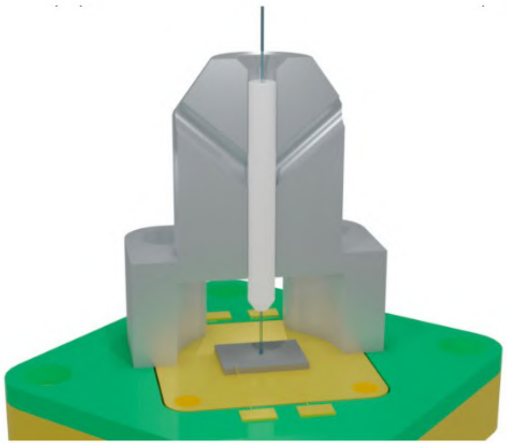


Source de photons uniques : premiers produits

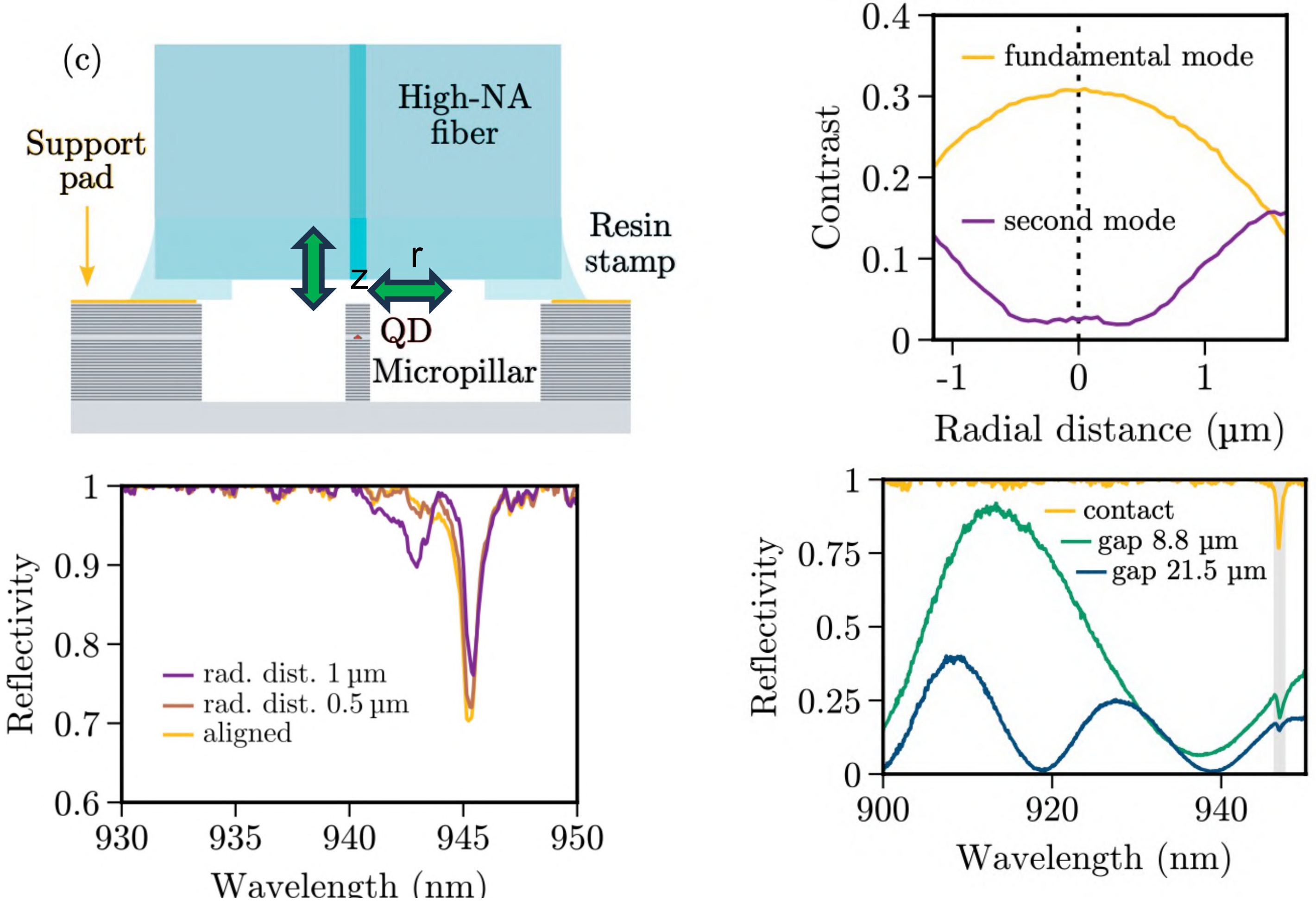




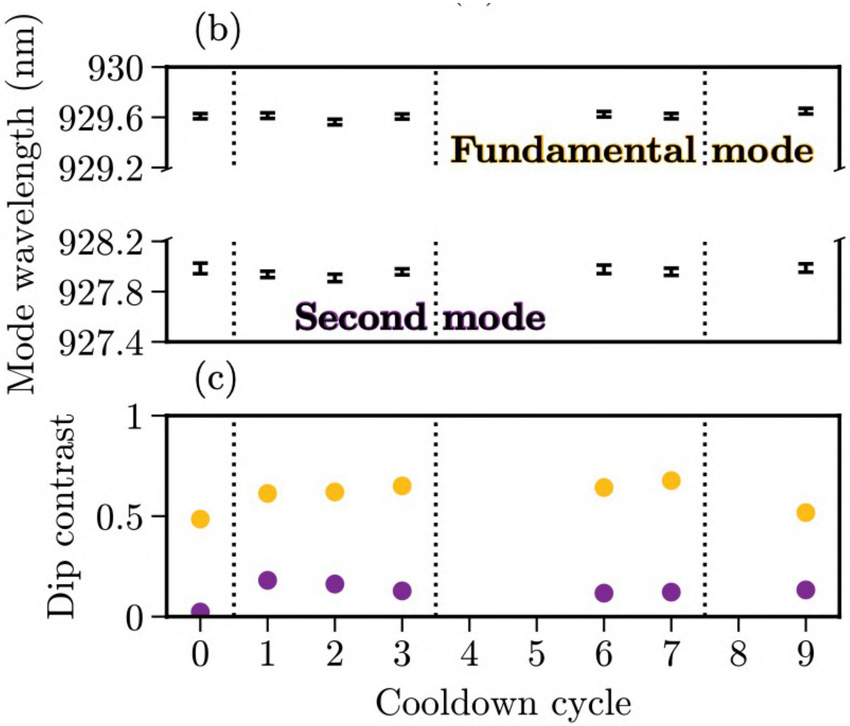


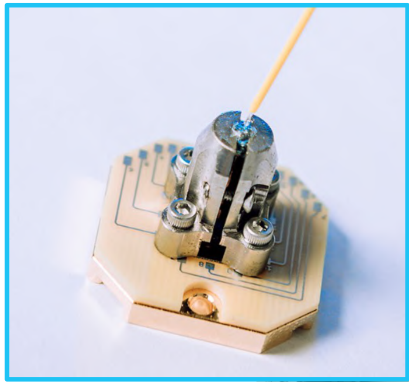


Source de photons uniques : premiers produits



Source de photons uniques : premiers produits





Cryostat à circuit fermé (4K)

Source de photons uniques : premiers produits