Quantum dot devices for Cavity quantum electrodynamics

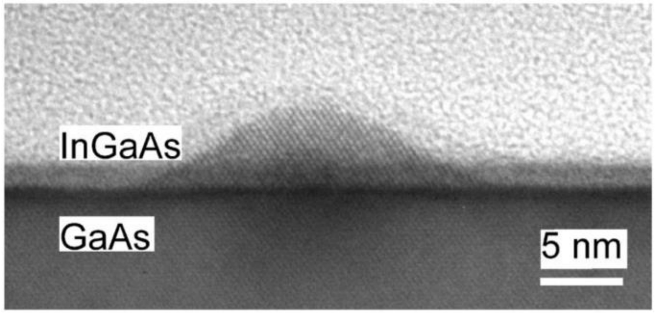
Sylvain Ravets

sylvain.ravets@c2n.upsaclay.fr

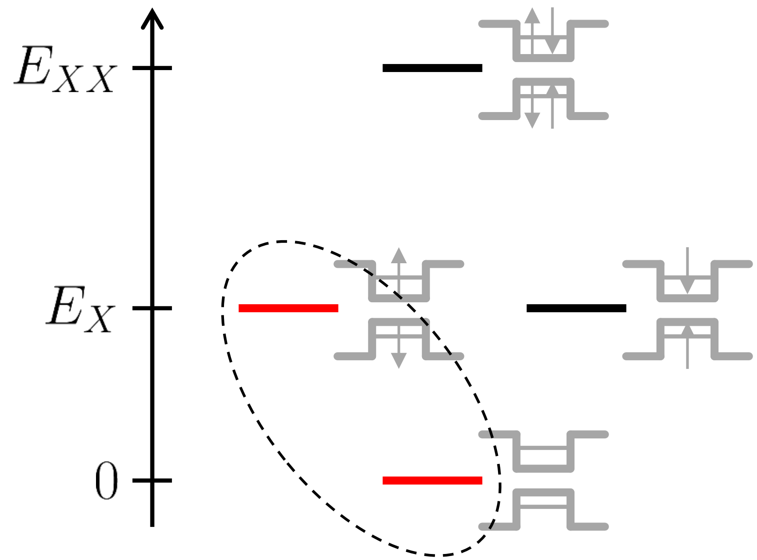
Master QLMN

24-01-2022

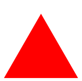
Quantum Dot (QD) as quantum light emitters



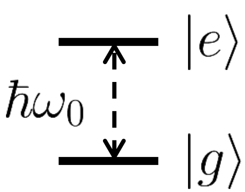
TEM image of a QD
PRB **66**, 125309 (2002)



$E_{XX} \neq E_X$ Coulomb interactions



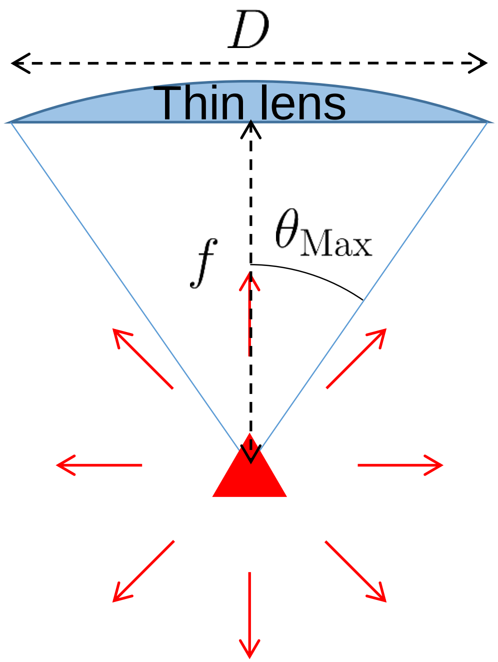
QD $\Longleftrightarrow$



Single photon emission, entanglement, quantum cryptography…

Problem: how to efficiently collect the photons?

Single photon emitter in vacuum



Numerical aperture of an optical system (lens):

$$\text{N.A.} = n\sin(\theta_{\text{Max}}) = n\sin\left[\tan^{-1}\left(\frac{D}{2f}\right)\right]$$

Let's assume an isotropic radiation pattern:

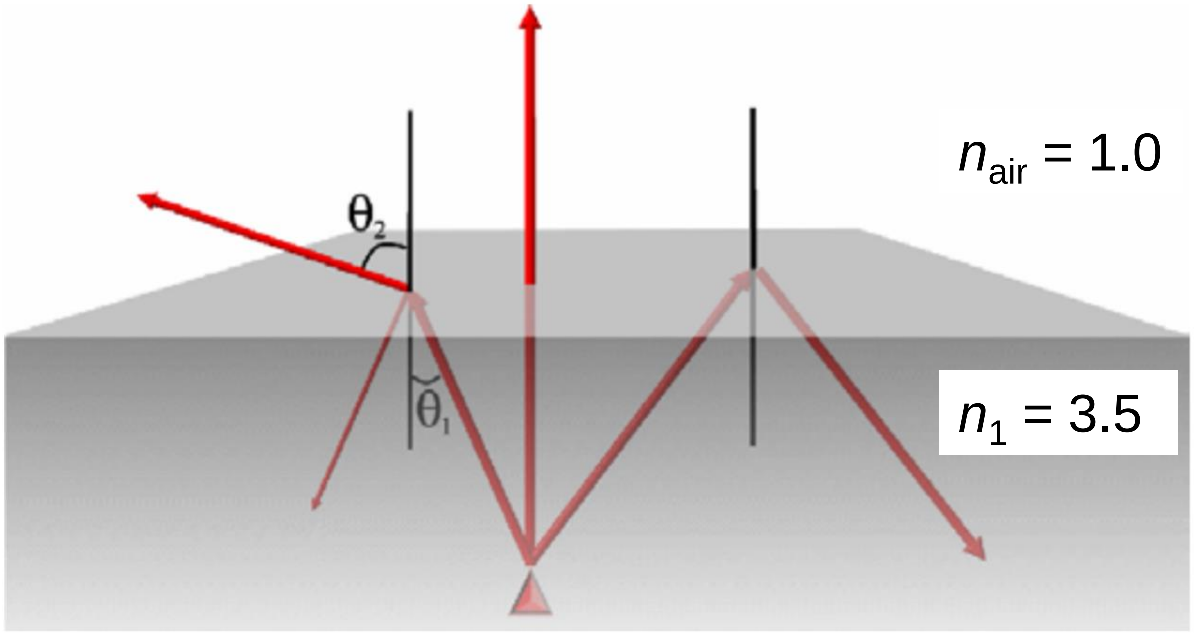
$$\frac{\Omega}{4\pi} = \frac{1}{4\pi}\int_0^{2\pi} d\phi \int_0^{\theta_{\text{Max}}} \sin\theta d\theta = \frac{1}{2}(1-\cos\theta_{\text{Max}})$$

Example: microscope objective (N.A = 0.55)

$$\theta_{\text{Max}} = 33.4^\circ$$

Up to 8% collection efficiency.

Extraction from a semiconductor material



New J. Phys. **6**, 96 (2004)

$$\sin\theta_2 = n_1 \sin\theta_1$$

Total internal reflection:

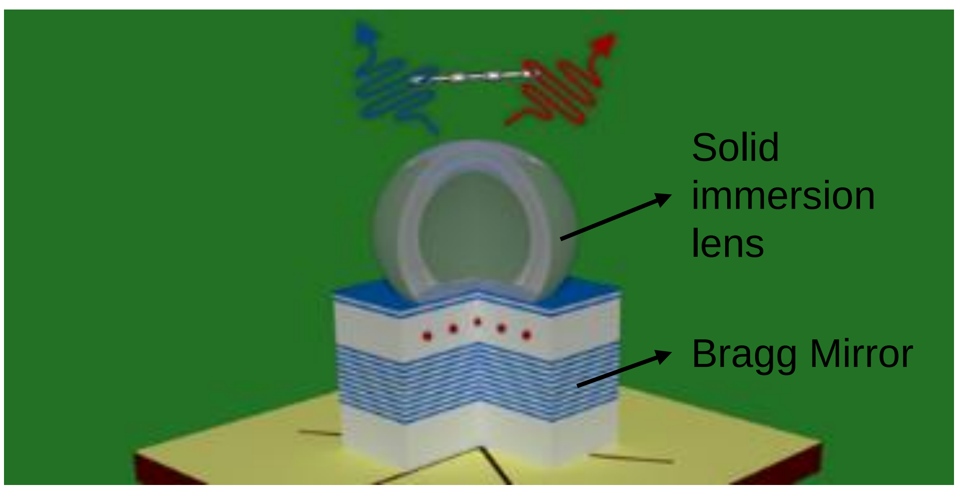
$$\theta \geq \theta_{\mathrm{Max}} = \sin^{-1}\left(\frac{1}{n_1}\right)$$

Example: θ_{Max} = 16.6°.

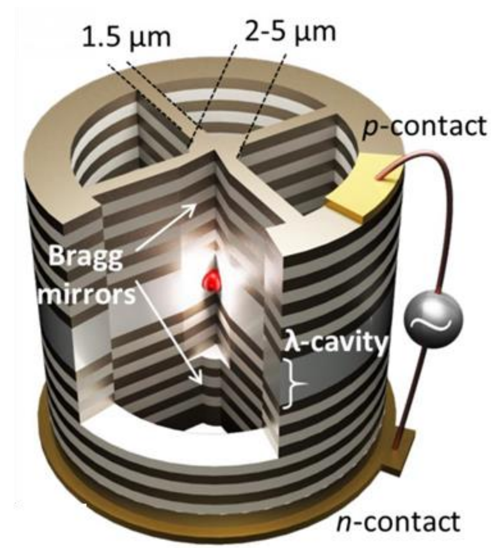
≤ 2% extraction efficiency (optimistic estimate).

Collection efficiency limited by our capacity to extract light from the material!

Integrated optics in semiconductor materials

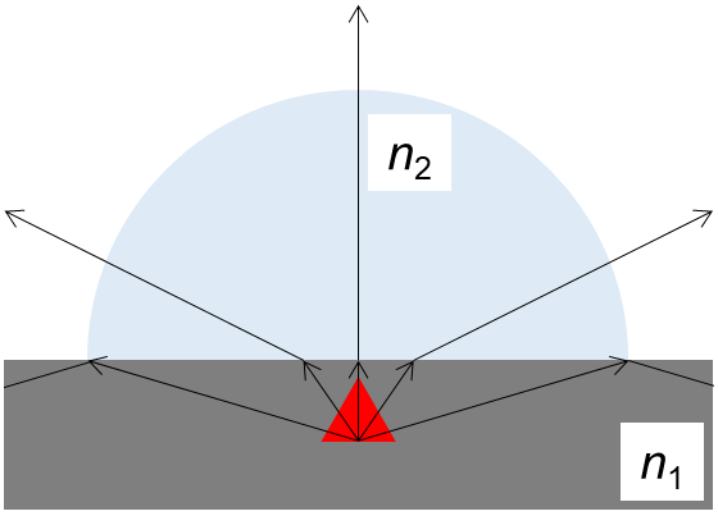


R. Trotta, Sapienza University (Italy)



P. Senellart, C2N (France)

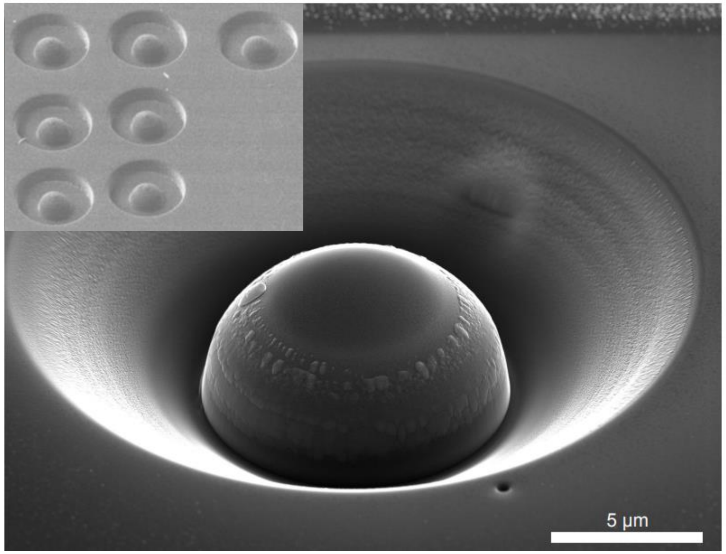
Solid immersion lens (SIL)



Add hemisphere ($1 \leq n_1 \leq n_2$) to modify total internal reflection condition. Light extraction possible for:

$$\theta \leq \theta_{\mathrm{Max}} = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Example: LaSFN9 glass (n_2 = 1.83)
θ_{Max} = 31° and ≈ 7.4 % extraction efficiency.



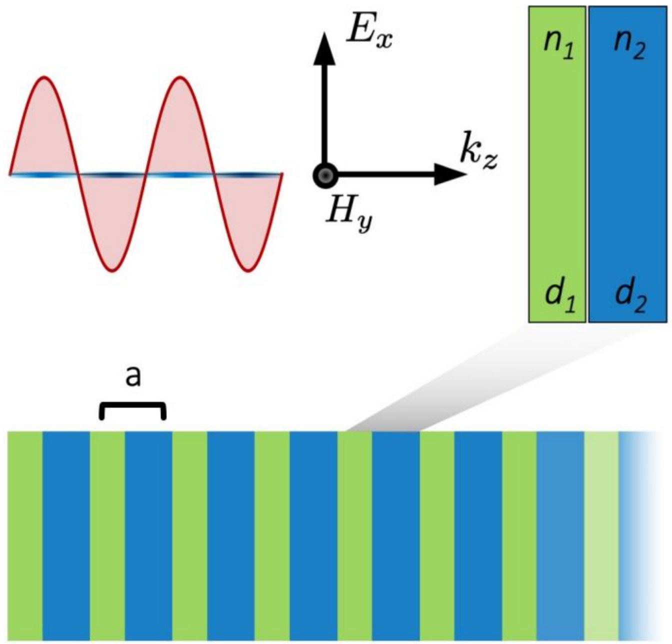
Ultimately, carve the lens directly into GaAs (focused ion beam milling): $n_1 \leq n_2$.

θ_{Max} = 90°.

50% of the light is still lost ⇒ add a mirror?

Integrated mirrors

General ideal: Stack different materials generate wave interference



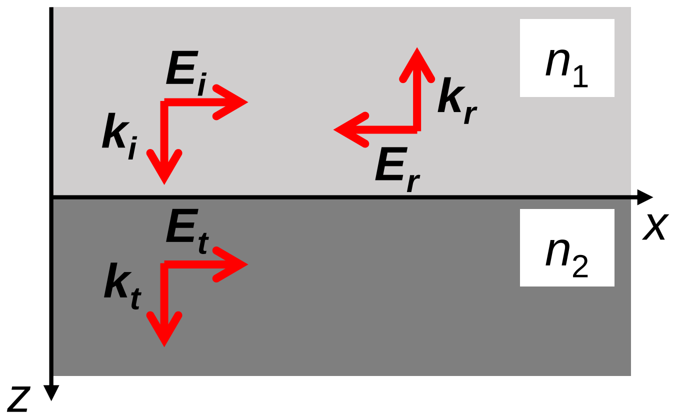
N. Carlon Zambon thesis (C2N, 2020)

Notion of “photonic crystal”.

Reflection and transmission coefficients at an interface

Semiconductor materials with different indices of refraction ⇒ Fresnel reflection.

Normal incidence



Continuity of tangential components for ***E***:

$$E_i + E_r = E_t$$

Continuity of tangential components for ***B***:

$$\frac{n_1}{c}E_i - \frac{n_1}{c}E_r = \frac{n_2}{c}E_t$$

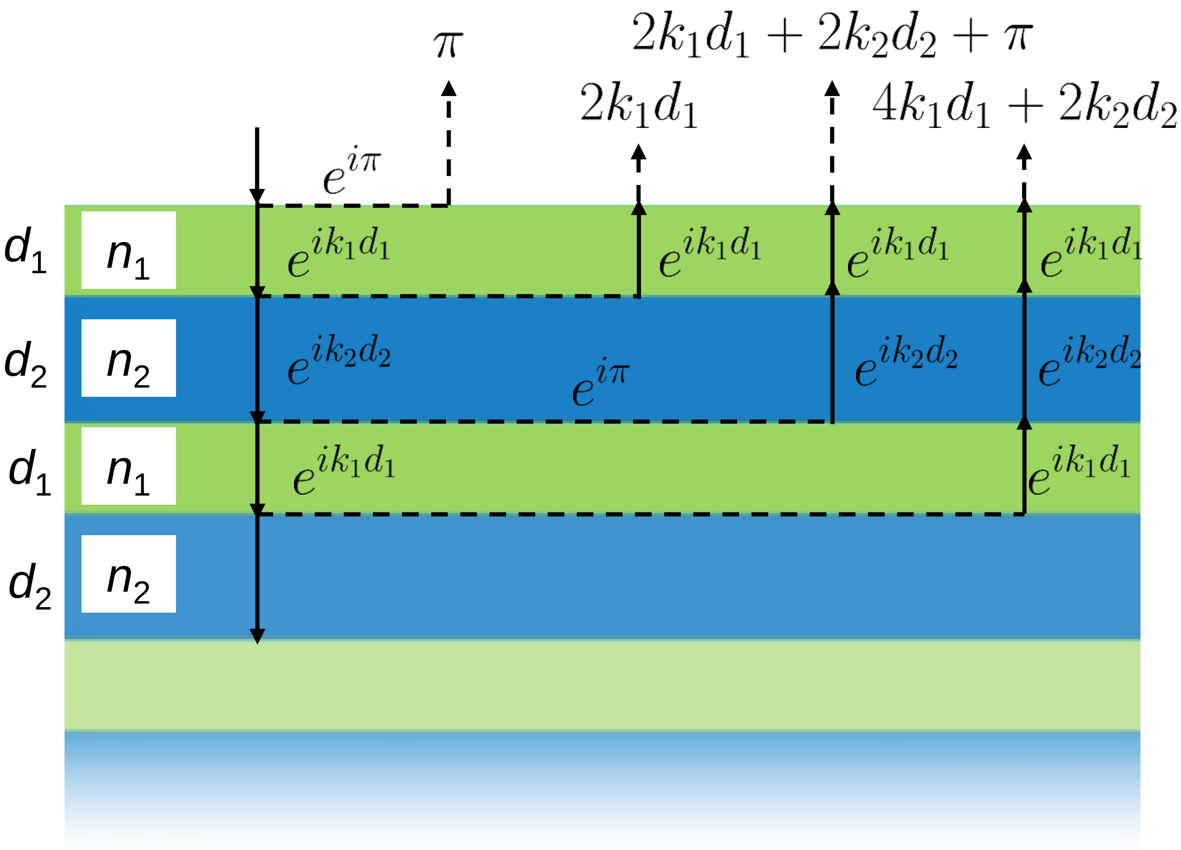
Reflection coefficient: $$r = \frac{E_r}{E_i} = \frac{n_1 - n_2}{n_1 + n_2}$$

Transmission coefficient: $$t = \frac{E_t}{E_i} = \frac{2n_1}{n_1 + n_2}$$

Homework: redo the calculation for any incidence angle.

Distributed Bragg Reflector (DBR)

General ideal: Use Fresnel reflections ($n_1 > n_2$) to generate wave interference



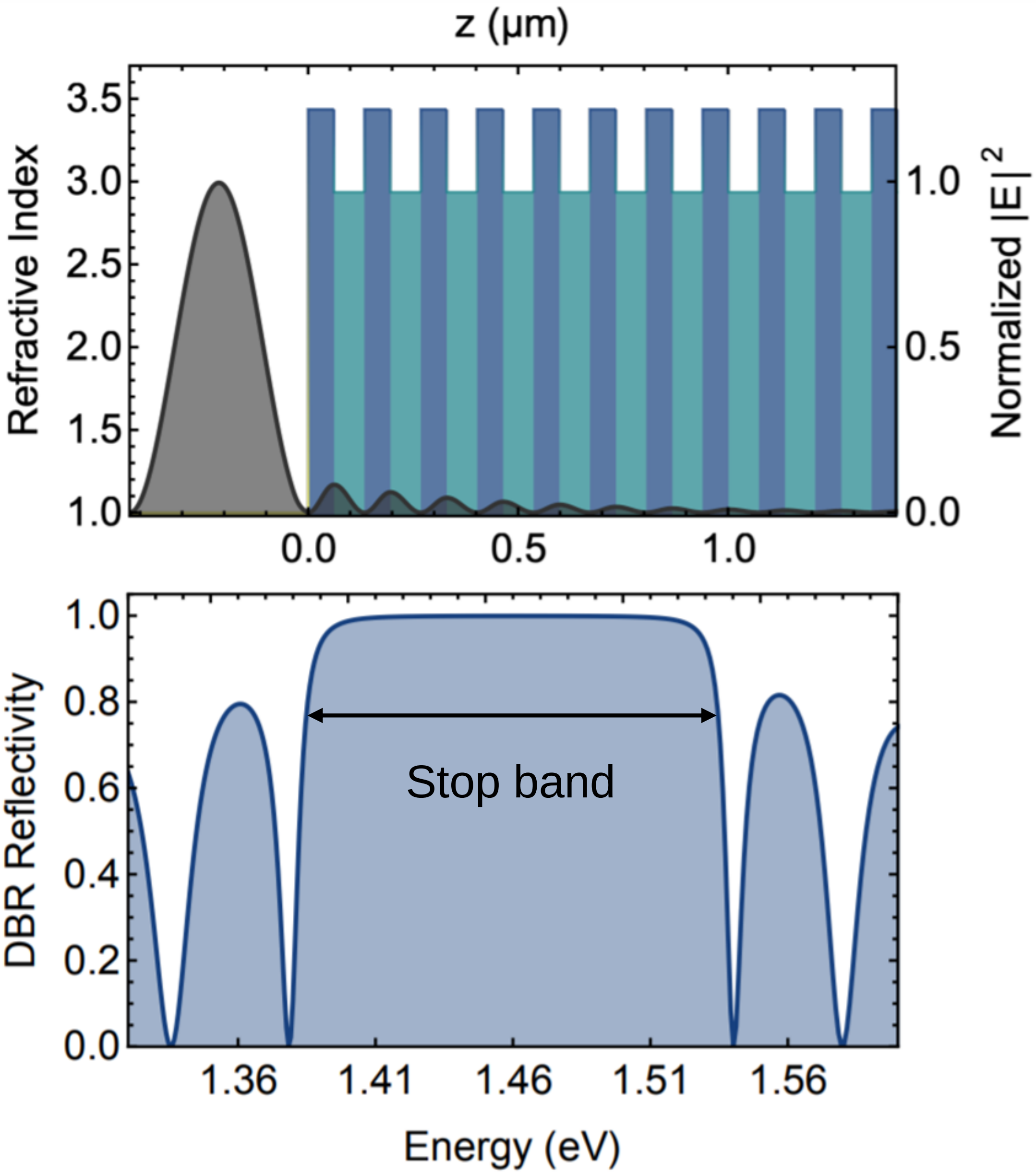
Constructive interference:

$$\begin{cases} 2k_1d_1 = \pi \\ 2k_2d_2 + 2k_1d_1 + \pi = \pi \end{cases}$$

$$\begin{cases} 4\pi n_1d_1/\lambda_0 = \pi \\ 4\pi n_2d_2/\lambda_0 + 2\pi = \pi \end{cases}$$

Optical path $\lambda_0/4$ for every layer $\Rightarrow$ strong reflection coefficient (mirror).

Distributed Bragg Reflector (DBR)



$$R(\lambda_0) \simeq 1 - 4\left(\frac{n_2}{n_1}\right)^{2N}$$

Example:
n_1 = 3.5 (GaAs)
n_2 = 2.9 (AlAs)
N = 30 pairs
λ_0 = 850 nm

d_1 = 60.7 nm
d_2 = 73.3 nm
R(λ_0) ≈ 0.99995

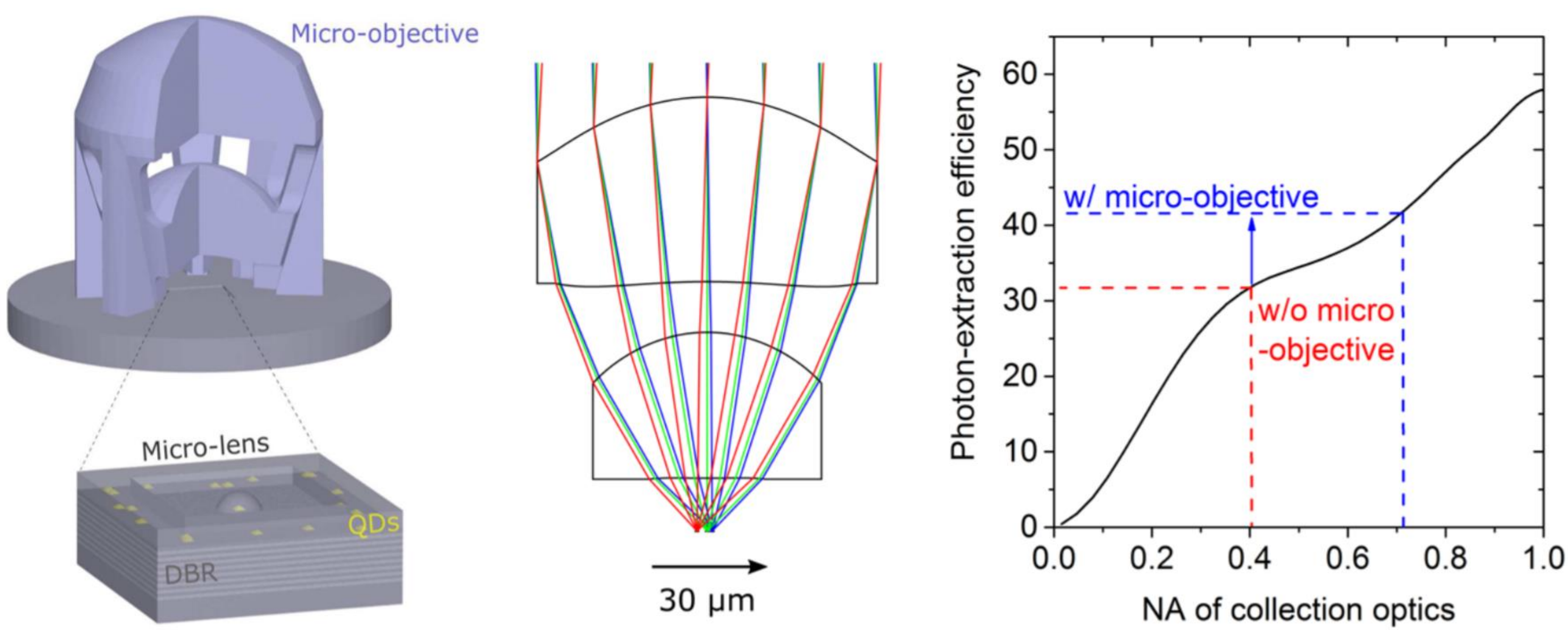
ACS Photonics **4**, 1327 (2017)

Letter

pubs.acs.org/journal/apchd5

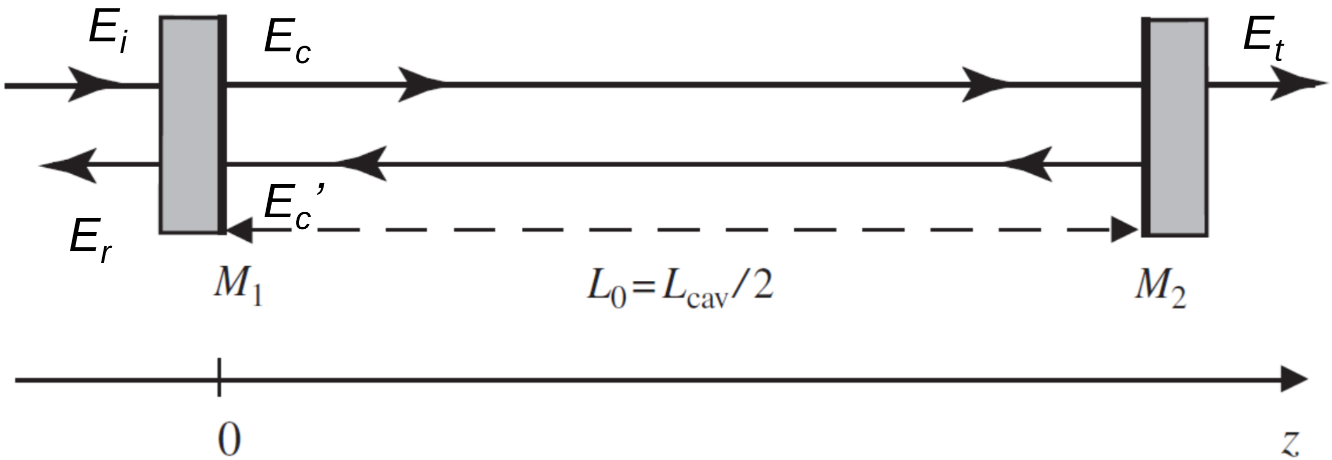
Single Quantum Dot with Microlens and 3D-Printed Micro-objective as Integrated Bright Single-Photon Source

Sarah Fischbach,[†] Alexander Schlehahn,[†] Alexander Thoma,[†] Nicole Srocka,[†] Timo Gissibl,[‡] Simon Ristok,[‡] Simon Thiele,[§] Arsenty Kaganskiy,[†] André Strittmatter,[†,⊥] Tobias Heindel,[†] Sven Rodt,[†] Alois Herkommer,[§] Harald Giessen,[‡] and Stephan Reitzenstein*,[†]



Light trapping in an optical microcavity

Fabry Pérot resonator



$$\begin{cases} E_c = t_1 E_i - r_1 E_c' \\ E_r = r_1 E_i + t_1 E_c' \end{cases}$$

$$\begin{cases} E_t = t_2 E_c e^{ikL_0} \\ E_c' = -r_2 E_c e^{2ikL_0} \end{cases}$$

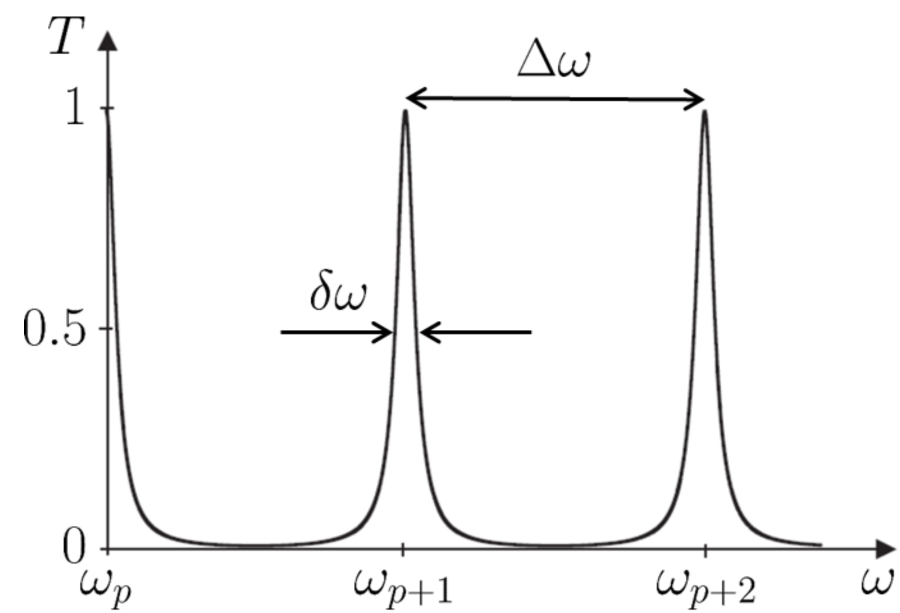
$$\left|\frac{E_t}{E_i}\right|^2 = \frac{T_1 T_2}{1 + R_1 R_2 - 2\sqrt{R_1 R_2}\cos(2kL_0)}$$

$$= \frac{T_1 T_2/(1-\sqrt{R_1 R_2})^2}{1 + \frac{4\sqrt{R_1 R_2}}{(1-\sqrt{R_1 R_2})^2}\sin^2 kL_0}$$

T Maximum when: $k_p L_0 = p\pi$

$$\boxed{\omega_p = p\frac{\pi c}{L_0}}$$

$$\boxed{\Delta\omega = \frac{\pi c}{L}}$$



Quality factor

Full width half max:

$$k_0^{\pm} = \pm\frac{1}{L_0}\frac{1}{2(R_1R_2)^{1/4}}(1-\sqrt{R_1R_2})$$

$$\Rightarrow \quad \delta\omega = \frac{1}{\pi}\frac{1-R}{\sqrt{R}}\Delta\omega$$

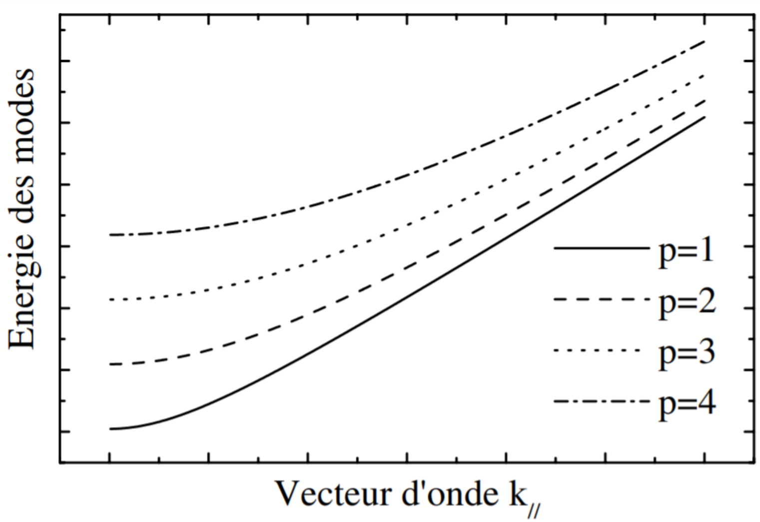
Quality factor: $\boxed{Q = \frac{\omega_0}{\delta\omega} = \frac{2L_0}{\lambda_0}\frac{\pi\sqrt{R}}{1-R}}$

Photon lifetime: $\boxed{\tau_{\mathrm{cav}} = \frac{Q}{\omega_0}}$

What about oblique incidence? $\left|\vec{k}\right| = \frac{\omega}{c}$

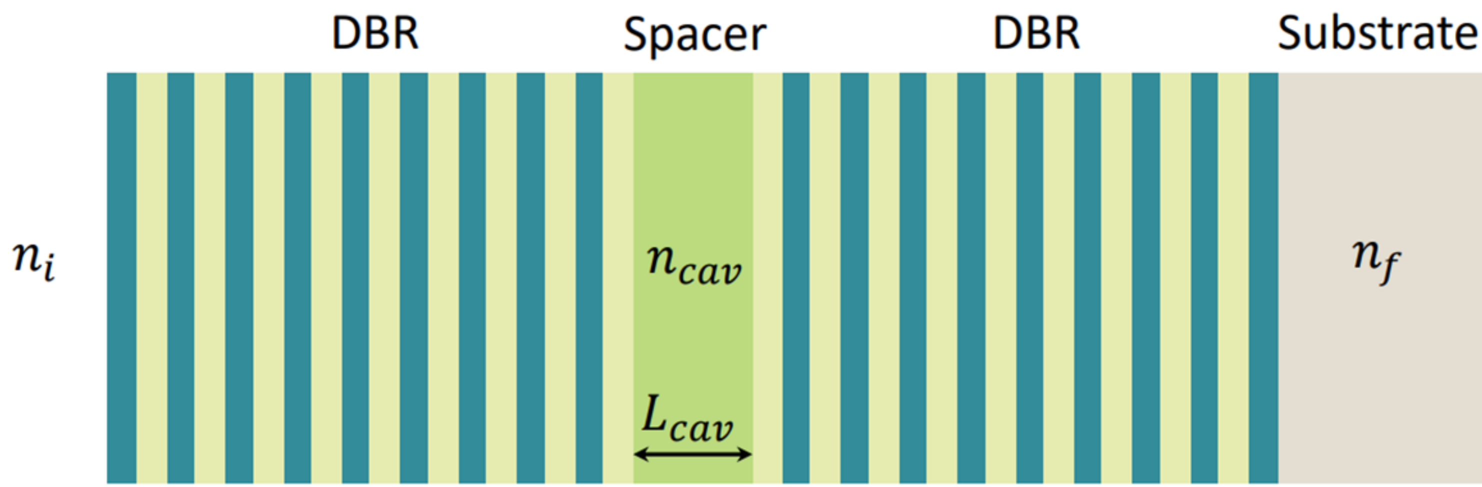
$$E(\vec{k}) = \hbar c\sqrt{\left(\frac{p\pi}{L_0}\right)^2 + k_\parallel^2}$$

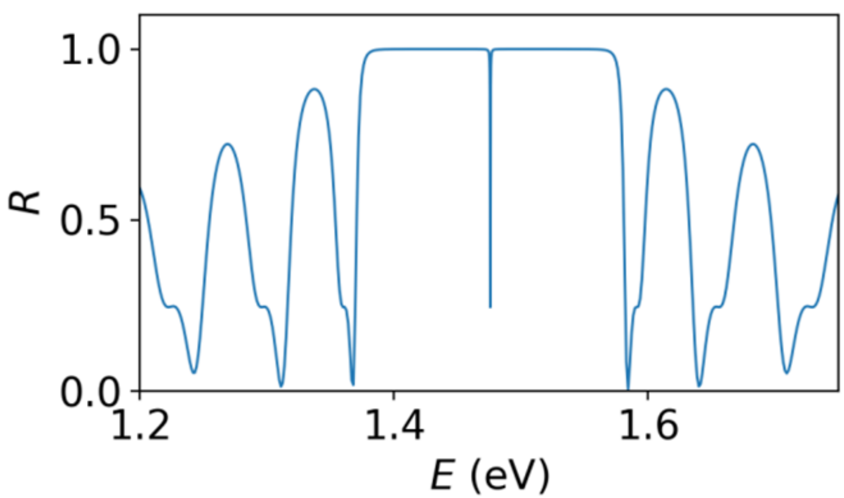
$$\simeq E_0 + \frac{\hbar^2 k_\parallel^2}{2m_{\mathrm{eff}}}$$

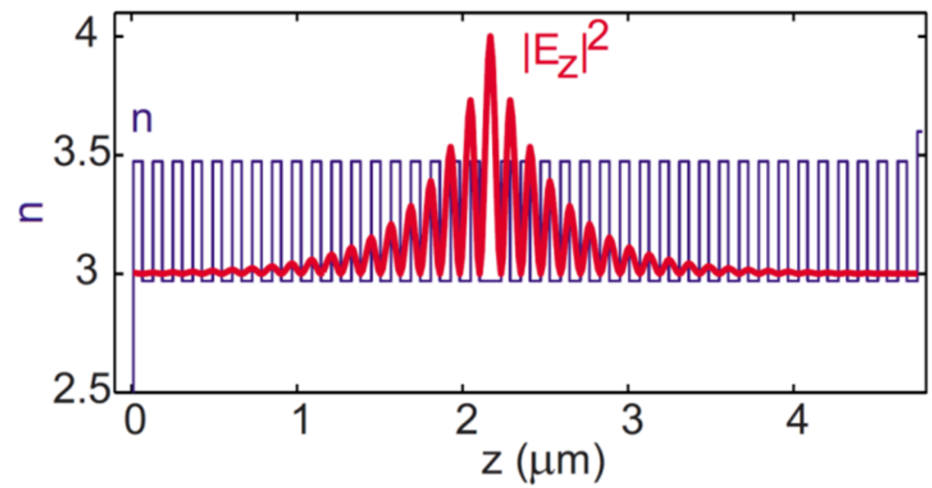


$\Rightarrow$ **Parabolic** dispersion relation.
Effective mass for the photon.

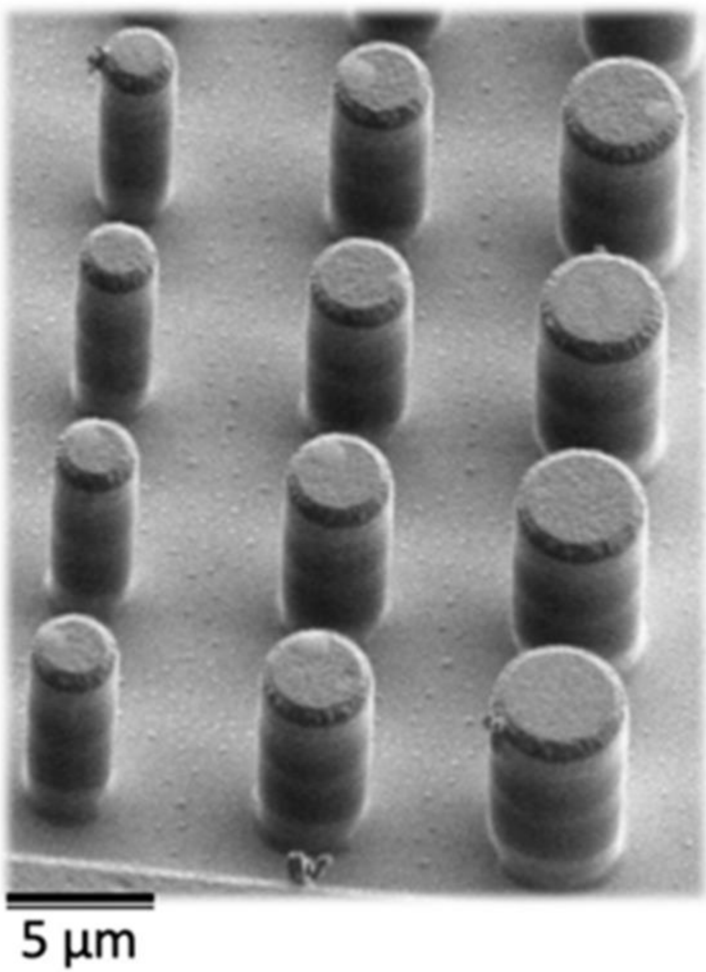
Semiconductor microcavities

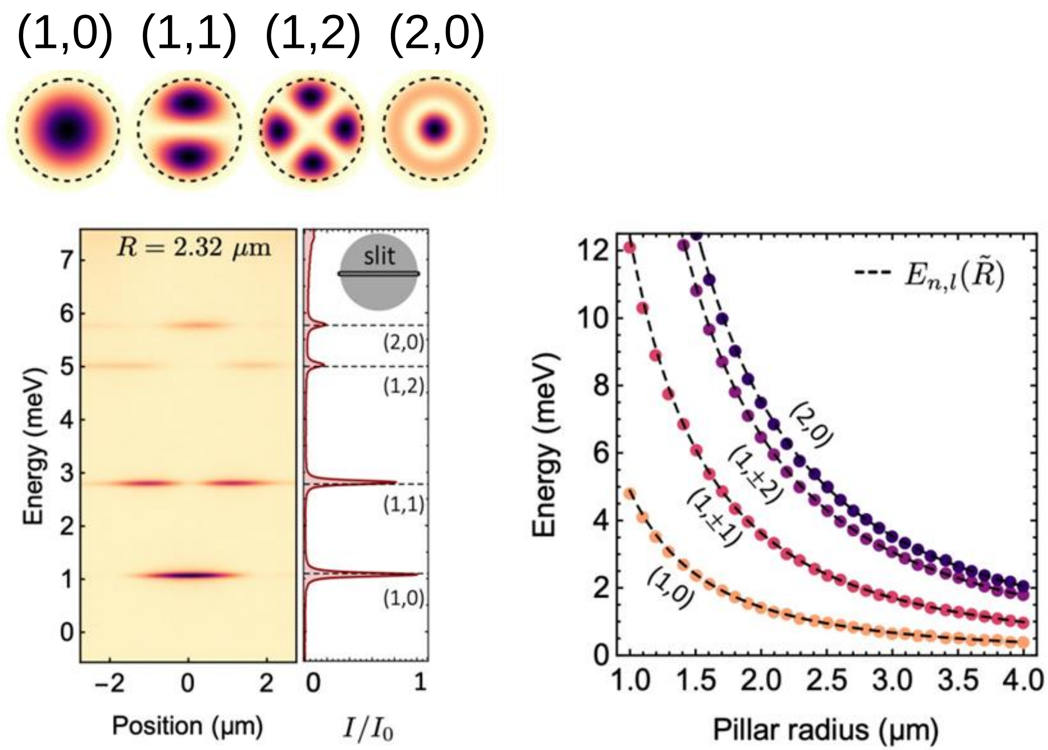






Semiconductor “photonic dots”

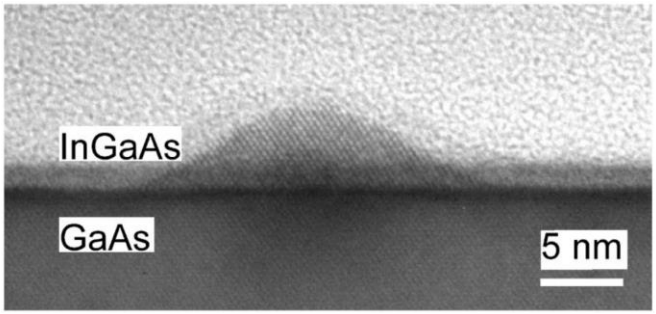




Two-level system coupled to a single mode of the electromagnetic field

The model

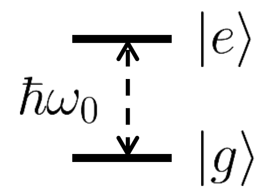
Quantum dot



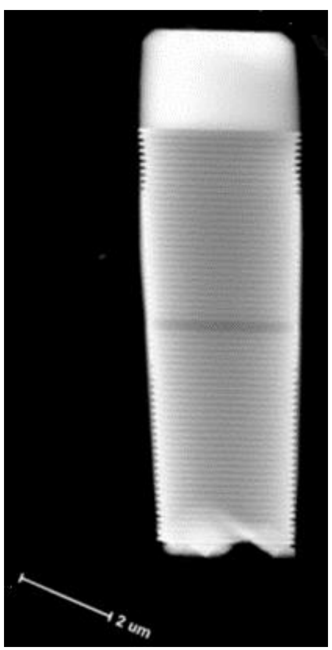
QD

$\Longleftrightarrow$

Two-level system

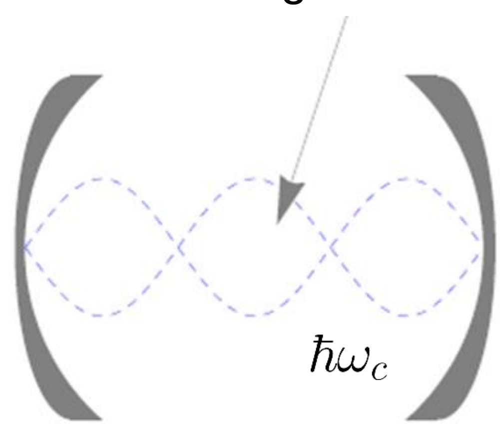


Microcavity

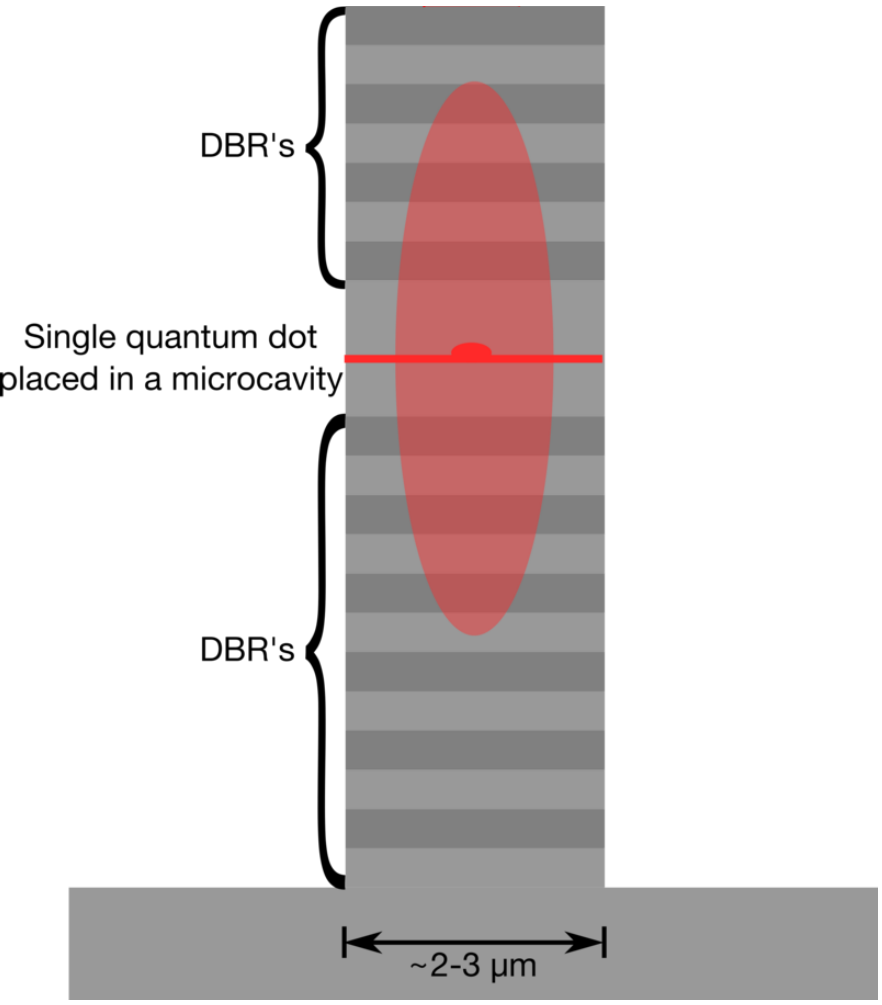


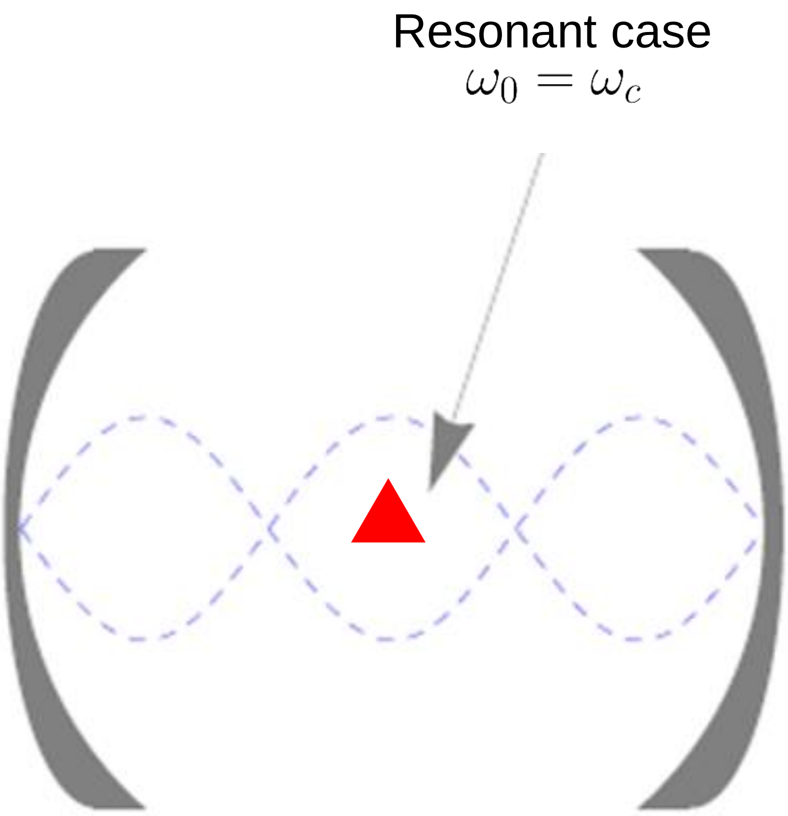
$\Longleftrightarrow$

Single mode of the electromagnetic field



The model


DBR's
Single quantum dot
placed in a microcavity
DBR's
~2-3 μm


Resonant case
$\omega_0 = \omega_c$

Jaynes-Cummings model

QD basis: $\{|g\rangle\,;|e\rangle\}$

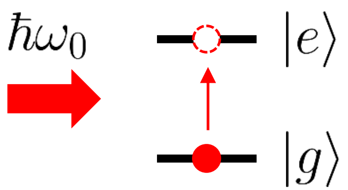
Photon number state basis: $\{|n\rangle\}$

Coupled system: tensor product

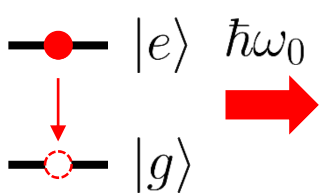
$$\{|g\rangle\,;|e\rangle\}\otimes\{|n\rangle\}$$

Hamiltonian: $$\hat{H}=\hbar\omega_0\,|e\rangle\,\langle e|+\hbar\omega_0\hat{a}^\dagger\hat{a}+\hat{H}_{\rm int}$$

Guess for the interaction Hamiltonian:



$$\hat{H}_{\rm int}=\hbar\Omega\left(|e\rangle\,\langle g|\otimes\hat{a}+|g\rangle\,\langle e|\otimes\hat{a}^\dagger\right)$$



Interaction Hamiltonian

$$\left.\begin{aligned}\hat{H}_{\text{int}} &= -\frac{q}{m}\hat{\vec{p}}\cdot\hat{\vec{A}}\\ \hat{\vec{A}} &= \sqrt{\frac{\hbar}{2\epsilon_0\omega V}}\vec{\epsilon}(\hat{a}^\dagger+\hat{a})\end{aligned}\right\}\quad \hat{H}_{\text{int}} = -\frac{q}{m}\sqrt{\frac{\hbar}{2\epsilon_0\omega V}}\hat{\vec{p}}\cdot\vec{\epsilon}\otimes(\hat{a}^\dagger+\hat{a})$$

Momentum operator:

$\langle g|\,\hat{\vec{p}}\cdot\vec{\epsilon}\,|g\rangle = \langle e|\,\hat{\vec{p}}\cdot\vec{\epsilon}\,|e\rangle = 0$ (integral of an odd function).

$$\hat{\vec{p}}\cdot\vec{\epsilon} = \langle e|\,\hat{\vec{p}}\cdot\vec{\epsilon}\,|g\rangle\,[|e\rangle\langle g| + |g\rangle\langle e|]$$

$$\Longrightarrow\quad \boxed{\hat{H}_{\text{int}} = -\frac{q}{m}\sqrt{\frac{\hbar}{2\epsilon_0\omega V}}\,\langle e|\,\hat{\vec{p}}\cdot\vec{\epsilon}\,|g\rangle\,(|e\rangle\langle g| + |g\rangle\langle e|)\otimes(\hat{a}^\dagger+\hat{a})}$$

$\hat{H}_{\text{int}} = \hbar\Omega\left(|e\rangle\langle g|\otimes\hat{a} + |g\rangle\langle e|\otimes\hat{a}^\dagger\right)$ (resonant terms only).

Matrix elements

$$\hat{a}^\dagger |n\rangle = \sqrt{n+1}\,|n+1\rangle$$
$$\hat{a}\,|n\rangle = \sqrt{n}\,|n-1\rangle$$

$$\langle g, n|\,\hat{H}_{\text{int}}\,|g, n'\rangle = 0$$

$$\langle e, n|\,\hat{H}_{\text{int}}\,|e, n'\rangle = 0$$

$$\begin{aligned}\langle g, n|\,\hat{H}_{\text{int}}\,|e, n'\rangle &= \hbar\Omega\left(\langle g|e\rangle\,\langle g|e\rangle\,\langle n|\hat{a}|n'\rangle + \langle g|g\rangle\,\langle e|e\rangle\left\langle n|\hat{a}^\dagger|n'\right\rangle\right)\\ &= \hbar\Omega\sqrt{n'+1}\,\langle n|n'+1\rangle\\ &= \hbar\Omega\sqrt{n}\delta_{n,n'+1}\end{aligned}$$

$$\langle e, n'|\,\hat{H}_{\text{int}}\,|g, n\rangle = \hbar\Omega\sqrt{n}\delta_{n,n'+1}$$

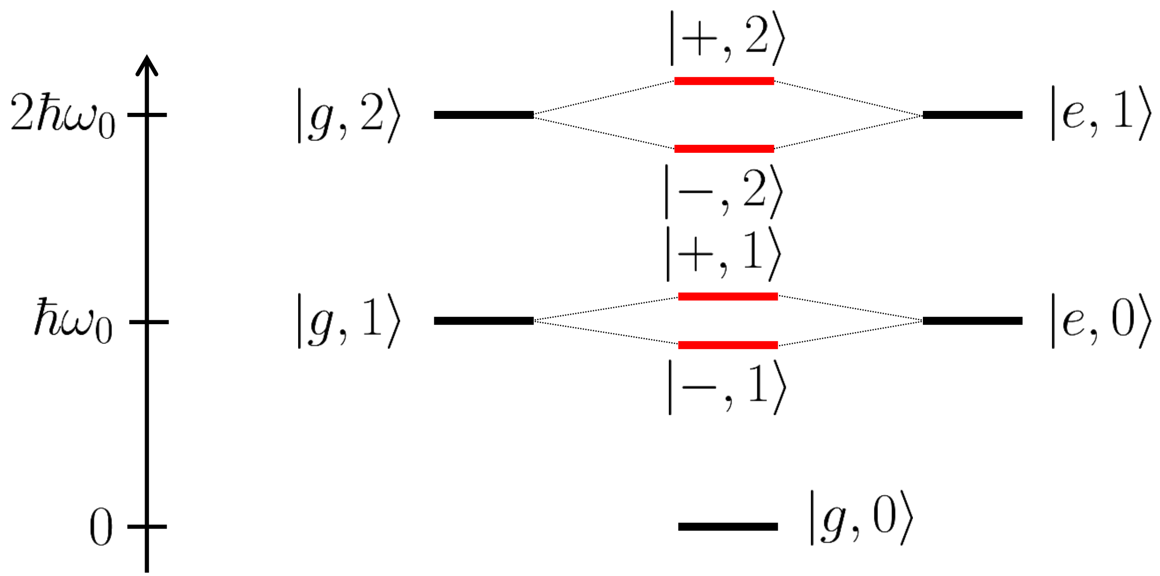
	$\lvert g,0\rangle$	$\lvert e,0\rangle$	$\lvert g,1\rangle$	$\lvert e,1\rangle$	$\lvert g,2\rangle$		$\lvert e,n-1\rangle$	$\lvert g,n\rangle$	
$\lvert g,0\rangle$	0								
$\lvert e,0\rangle$		$\hbar\omega_0$	$\hbar\Omega$						
$\lvert g,1\rangle$		$\hbar\Omega$	$\hbar\omega_0$						
$\lvert e,1\rangle$				$2\hbar\omega_0$	$\hbar\Omega\sqrt{2}$				
$\lvert g,2\rangle$				$\hbar\Omega\sqrt{2}$	$2\hbar\omega_0$				
						$\ddots$			
$\lvert e,n-1\rangle$							$n\hbar\omega_0$	$\hbar\Omega\sqrt{n}$	
$\lvert g,n\rangle$							$\hbar\Omega\sqrt{n}$	$n\hbar\omega_0$	
									$\ddots$

Diagonalization of the Hamiltonian

Diagonalization of the 2x2 Hamiltonian: $\hat{H}_n = \begin{pmatrix} n\hbar\omega_0 & \hbar\Omega\sqrt{n} \\ \hbar\Omega\sqrt{n} & n\hbar\omega_0 \end{pmatrix}$

Eigenstates and eigenvalues:

$$\begin{cases} \lambda_+ = n\hbar\omega_0 + \hbar\Omega\sqrt{n} \\ \lambda_- = n\hbar\omega_0 - \hbar\Omega\sqrt{n} \end{cases} \qquad \begin{cases} |+,n\rangle = \left(|g,n\rangle + |e,n-1\rangle\right)/\sqrt{2} \\ |-,n\rangle = \left(|g,n\rangle - |e,n-1\rangle\right)/\sqrt{2} \end{cases}$$



A gated quantum dot strongly coupled to an optical microcavity

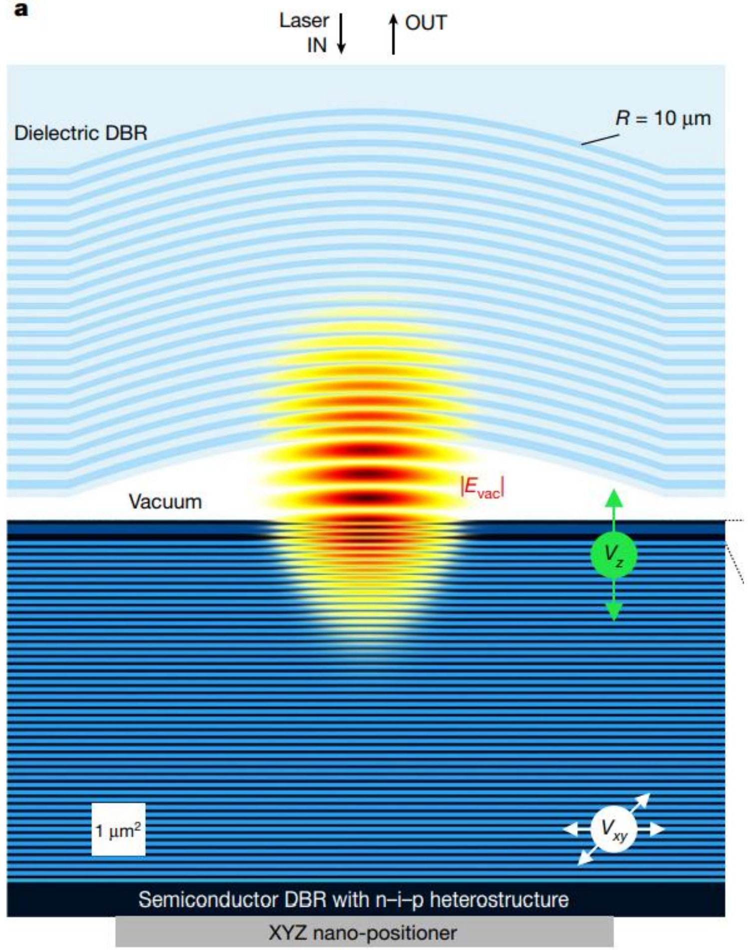
https://doi.org/10.1038/s41586-019-1709-y

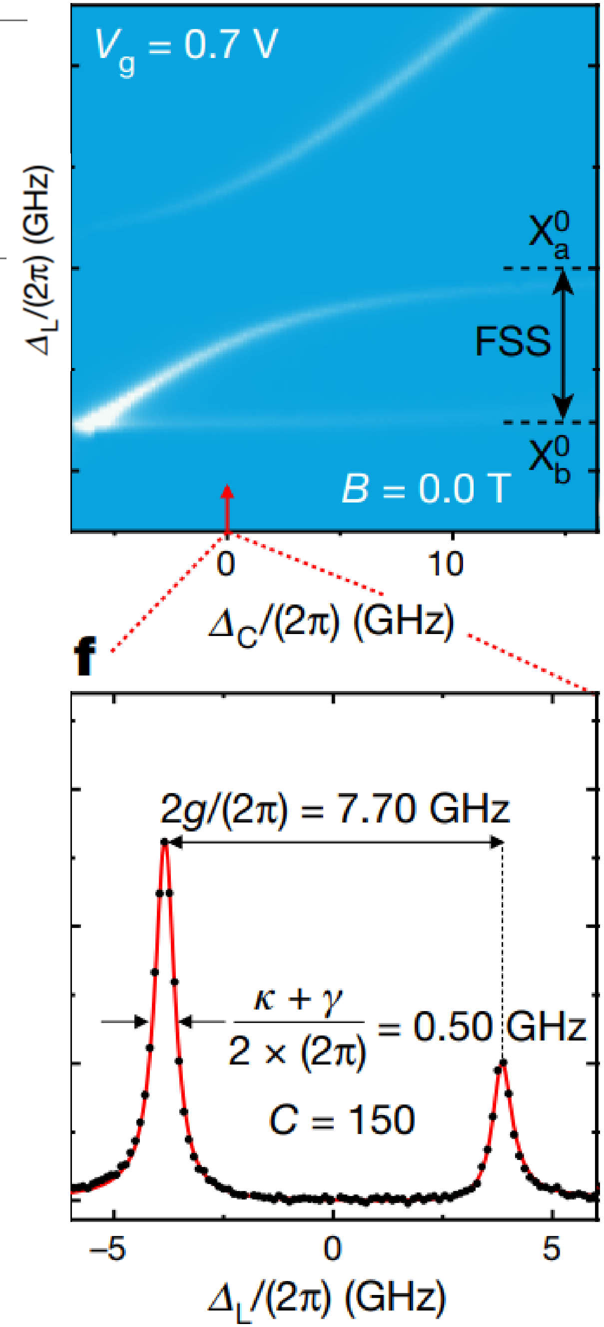
Received: 20 December 2018

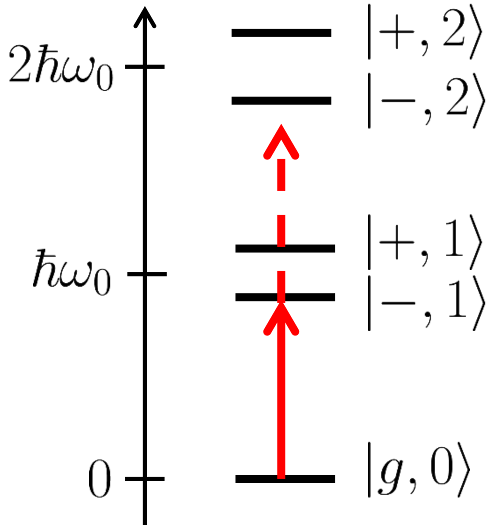
Accepted: 9 August 2019

Daniel Najer[1]*, Immo Söllner[1], Pavel Sekatski[1], Vincent Dolique[2], Matthias C. Löbl[1], Daniel Riedel[1], Rüdiger Schott[3], Sebastian Starosielec[1], Sascha R. Valentin[3], Andreas D. Wieck[3], Nicolas Sangouard[1], Arne Ludwig[3] & Richard J. Warburton[1]

a

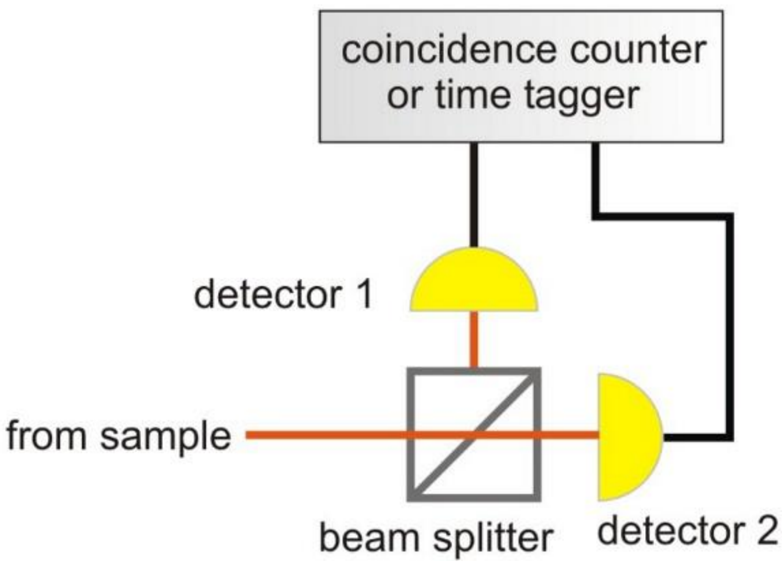


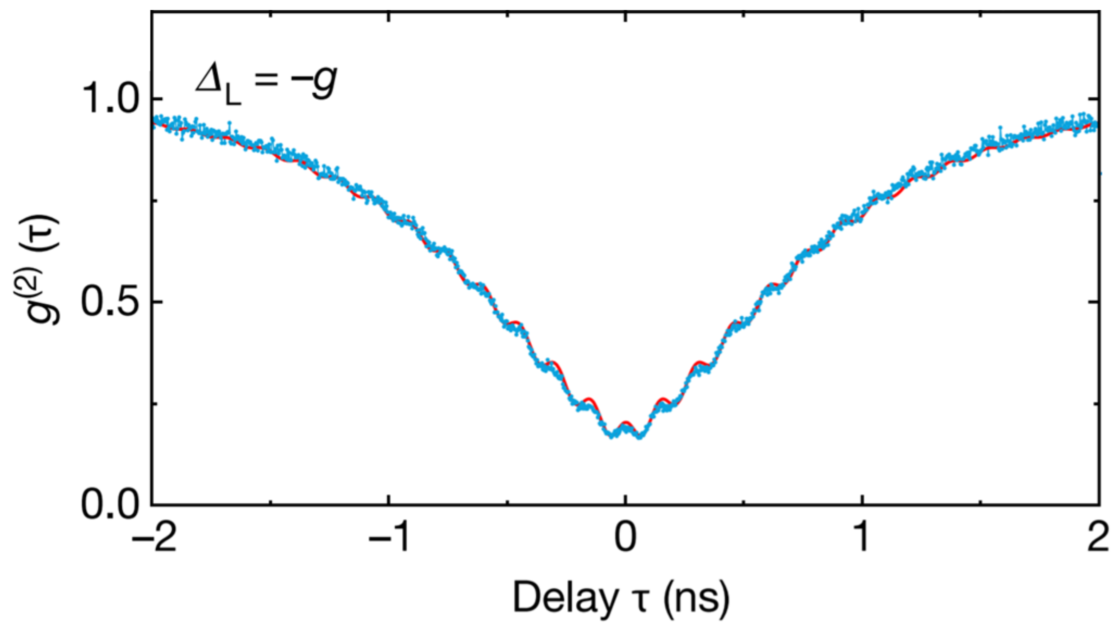




Photon blockade

Interaction with the two-level system
⇒ **Anharmonic** energy ladder





Laser resonant with $|-,1\rangle$ ⇒ quantum statistics (photon antibunching).

Dynamics of the coupled system

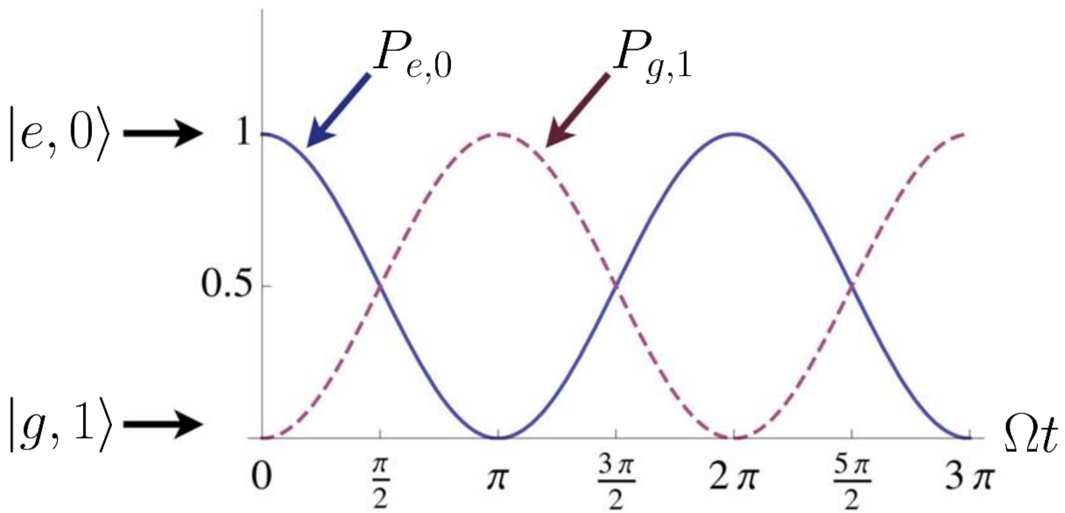
How does the excited quantum dot decays into an empty cavity?

Initial state: $|i\rangle = |e,0\rangle = \frac{1}{\sqrt{2}}\left(|+,1\rangle - |-,1\rangle\right)$

After time *t*: $$|f\rangle = \frac{1}{\sqrt{2}}\left(|+,1\rangle\, e^{-i(\hbar\omega_0+\hbar\Omega)t/\hbar} - |-,1\rangle\, e^{-i(\hbar\omega_0-\hbar\Omega)t/\hbar}\right)$$
$$= \frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{2}}(|g,1\rangle + |e,0\rangle)e^{-i\Omega t} - \frac{1}{\sqrt{2}}((|g,1\rangle - |e,0\rangle))e^{i\Omega t}\right) e^{-i\omega_0 t}$$
$$= \left(-i\,|g,1\rangle \sin\Omega t + |e,0\rangle \cos\Omega t\right) e^{-i\omega_0 t}$$

$$\Longrightarrow P_e(t) = |\cos^2\Omega t|$$

No decay, but periodic exchange of energy between atom and cavity: "**Rabi oscillation**".



Article 622 | Nature | Vol 575 | 28 November 2019

A gated quantum dot strongly coupled to an optical microcavity

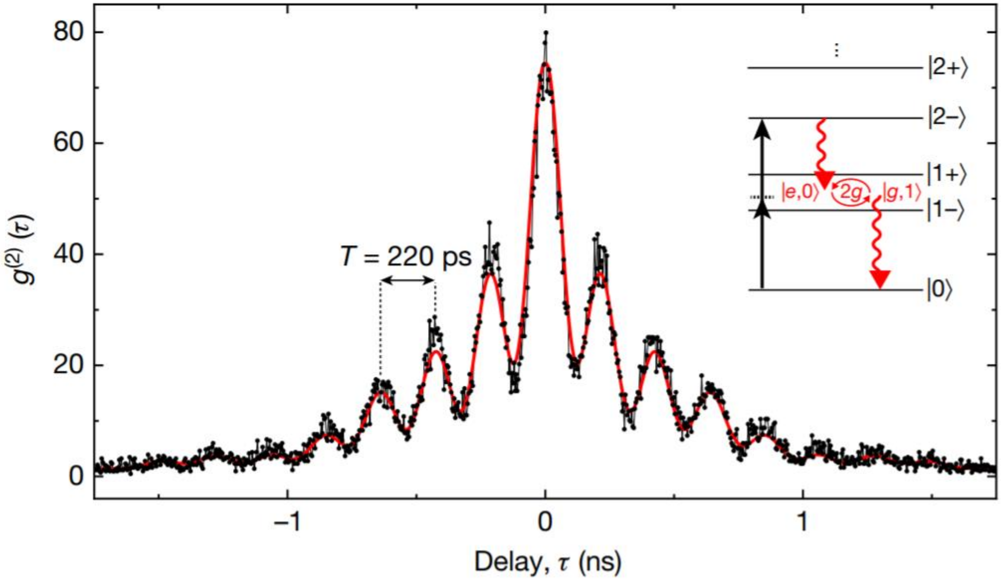


Fig. 3 | Time-resolved vacuum Rabi oscillations. Intensity autocorrelation

Initial state:

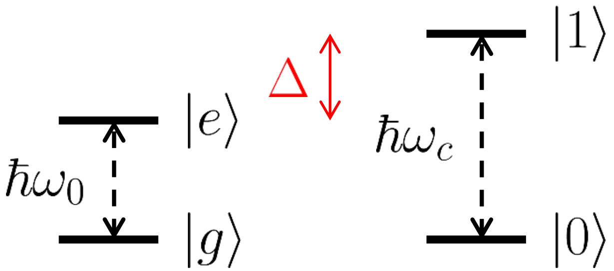
$$|i\rangle = |2,-\rangle = \frac{1}{\sqrt{2}}\left(|g,2\rangle - |e,1\rangle\right)$$

Destruction of one photon at t=0$^+$: $$\frac{\hat{a}\,|i\rangle}{||\hat{a}\,|i\rangle\,||} = \frac{1}{\sqrt{3}}\left(\frac{\sqrt{2}-1}{\sqrt{2}}\,|+,1\rangle + \frac{\sqrt{2}+1}{\sqrt{2}}\,|+,1\rangle\right)$$

At time t: $$|f\rangle = \frac{1}{\sqrt{3}}e^{-i\omega_0 t}\left[(\sqrt{2}\cos\Omega t + i\sin\Omega t)\,|g,1\rangle - (cos\Omega t + i\sqrt{2}\sin\Omega t)\,|e,0\rangle\right]$$

Probability of photon Destruction at time t: $$P(t) = |\hat{a}\,|f\rangle\,|^2 = \frac{1}{3}(1+\cos^2\Omega t)$$

Generalization to the case of a detuned cavity



$$\hat{H}_n = \begin{pmatrix} n\hbar\omega_0 & \hbar\Omega\sqrt{n} \\ \hbar\Omega\sqrt{n} & n\hbar\omega_0 + \Delta \end{pmatrix}$$

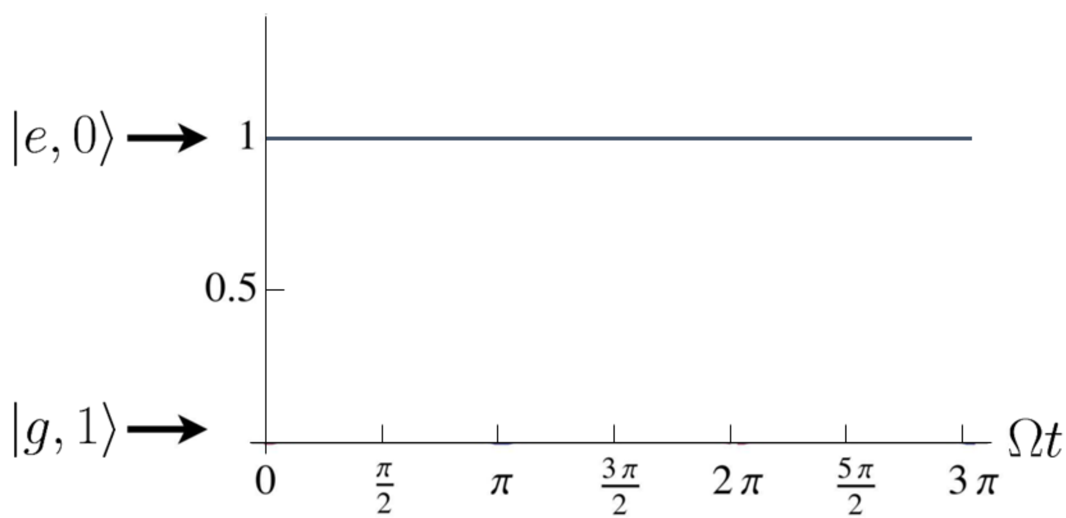
Exercise: Calculate the corresponding eigenvalues and eigenvectors.

$$P_e(t) = 1 - \frac{4\Omega^2}{\Delta^2 + 4\Omega^2} \sin^2\left(\sqrt{\Delta^2 + 4\Omega^2}\frac{t}{2}\right)$$

Limiting case $\Delta \gg \Omega$

$\Longrightarrow$ $P_e(t) \simeq 1$

No available mode for emission to occur.



Intermediate conclusions

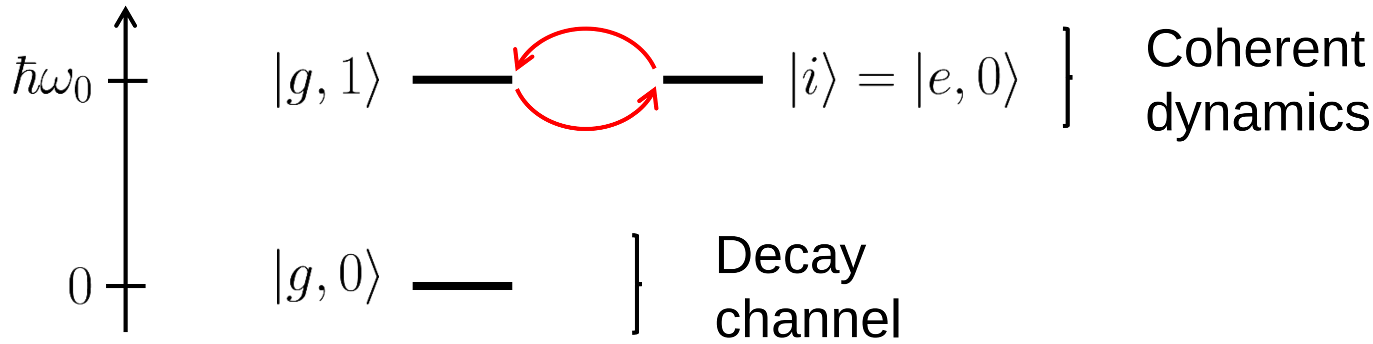
- Quantum dot coupling a **single mode** of the electromagnetic field leads to:
  - New (entangled) states for the coupled system,
  - **Anharmonic** energy spectrum (antibunching),
  - **Modified emission** (Rabi oscillations, …).

- Ideal model. Not a realistic situation:
  - What about losses? Coupling to the environment?
  - How does the system decay?

Effect of the cavity losses, Purcell effect

Master equation

Three state model:



Master equation for the density matrix, including damping:

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}\left[\hat{H}_1, \hat{\rho}\right] - \frac{\kappa}{2}(\hat{a}^\dagger\hat{a}\hat{\rho} + \hat{\rho}\hat{a}^\dagger\hat{a}) + \kappa\hat{a}\hat{\rho}\hat{a}^\dagger$$

$$\kappa = \tau_c^{-1} = \omega_0/Q$$

Exercise: show that:

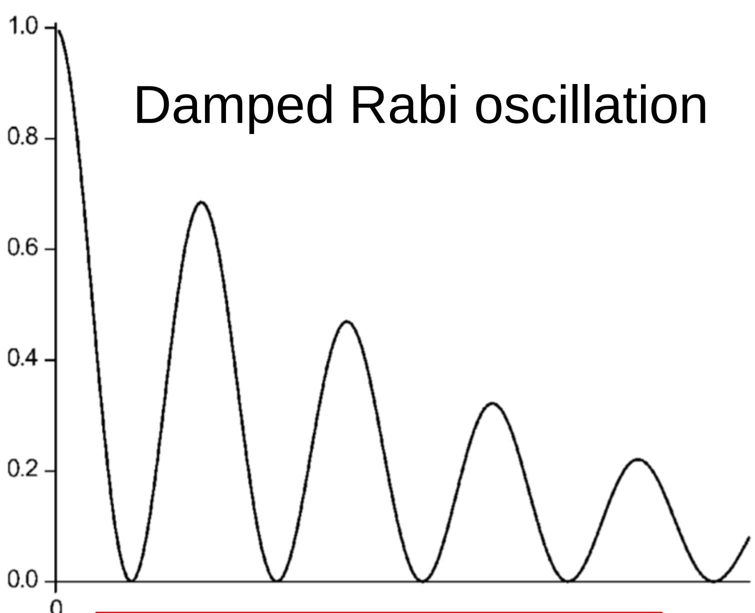
$$\frac{d}{dt}\begin{bmatrix} \rho_{11} \\ \rho_{22} \\ \rho_{12} - \rho_{21} \end{bmatrix} = \begin{bmatrix} 0 & 0 & i\Omega \\ 0 & -\kappa & -i\Omega \\ 2i\Omega & -2i\Omega & -\kappa/2 \end{bmatrix} \begin{bmatrix} \rho_{11} \\ \rho_{22} \\ \rho_{12} - \rho_{21} \end{bmatrix}$$

Master equation

Eigen-frequencies equation for the system: $\left(\Lambda + \frac{\kappa}{2}\right)\left(\Lambda^2 + \kappa\Lambda + 4\Omega^2\right)$

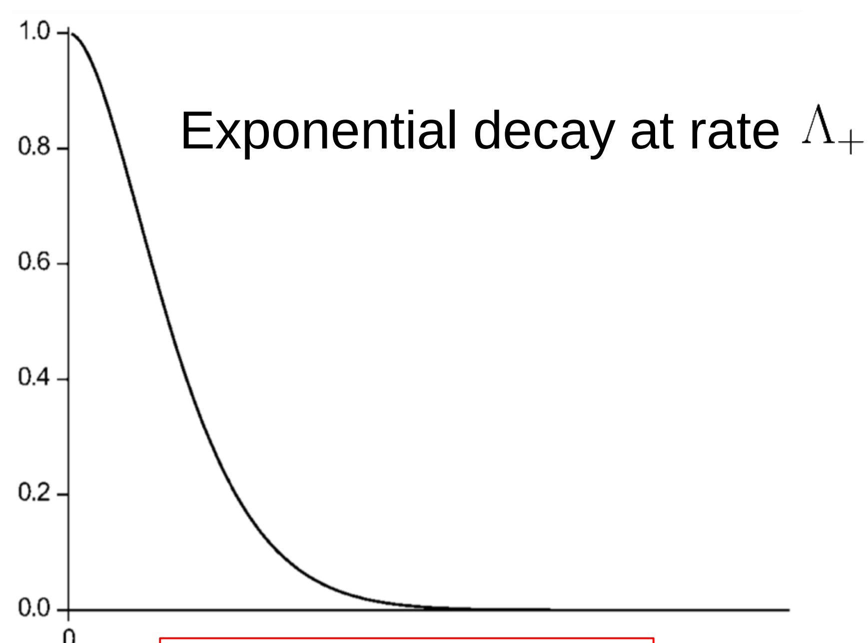
Three eigenvalues: $\Lambda_0 = -\frac{\kappa}{2} = -\frac{\omega_0}{2Q}$ $\quad \Lambda_\pm = -\frac{\omega_0}{2Q} \pm \frac{\omega_0}{2Q}\left(1 - 16\frac{\Omega^2 Q^2}{\omega_0^2}\right)^{1/2}$

Case: $4\Omega > \frac{\omega_0}{Q}$



STRONG COUPLING

Case: $4\Omega < \frac{\omega_0}{Q}$



WEAK COUPLING

Cavity decay rate

$$\Gamma_{\text{cav}} = |\Lambda_+| \simeq 4\Omega^2 \frac{Q}{\omega_0}$$

With Ω defined in: $\hat{H}_{\text{int}} = -\frac{q}{m}\sqrt{\frac{\hbar}{2\epsilon_0 \omega V}} \langle e| \hat{\vec{p}} \cdot \vec{\epsilon} |g\rangle \left(|e\rangle \langle g| + |g\rangle \langle e|\right) \otimes \left(\hat{a}^\dagger + \hat{a}\right)$

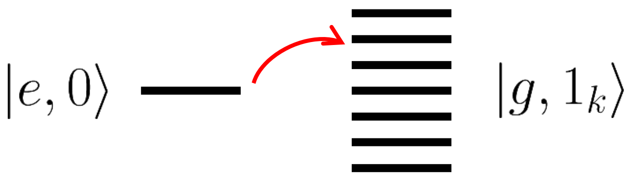
One obtains: $\boxed{\Gamma_{\text{cav}} = 2\frac{q^2}{m^2} \frac{\left|\langle e| \hat{\vec{p}} \cdot \vec{\epsilon} |g\rangle\right|^2}{\epsilon_0 \hbar} \frac{Q}{V\omega_0^2}}$

To be compared to: $\Gamma_{\text{vac}} = \frac{1}{3\pi} \frac{q^2}{m^2} \frac{\left|\langle e| \hat{\vec{p}} \cdot \vec{\epsilon} |g\rangle\right|^2}{\epsilon_0 \hbar} \frac{\omega_0}{c^3}$

$$\boxed{\frac{\Gamma_{\text{cav}}}{\Gamma_{\text{vac}}} = \frac{3}{4\pi^2} \frac{\lambda_0^3 Q}{V}}$$

⇨ Modification of the emission rate by the cavity: **PURCELL EFFECT**.

Fermi golden rule



Excited state coupled to a continuum of radiation modes:

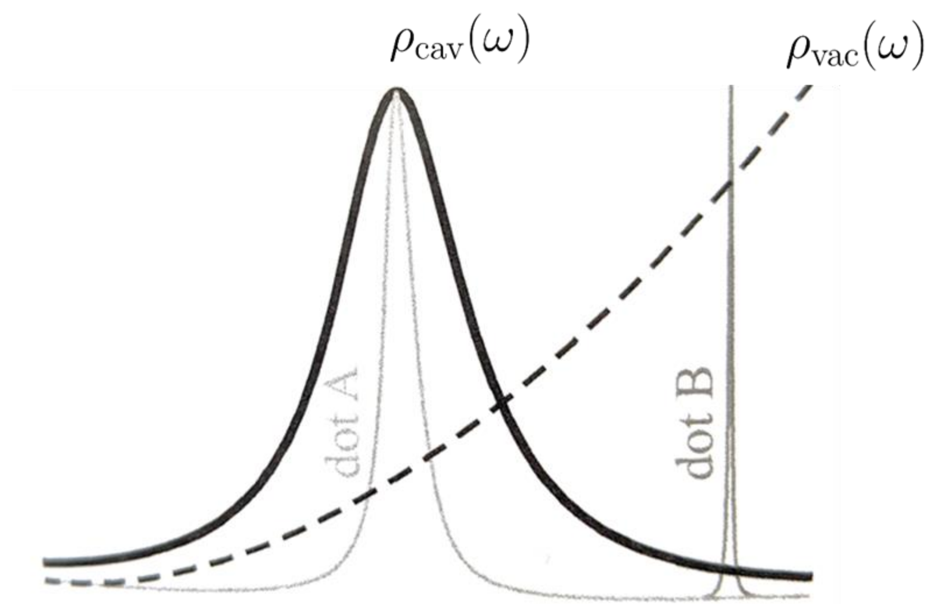
$\Rightarrow$ Fermi golden rule.

Transition probability: $\Gamma = \frac{2\pi}{\hbar^2} \left| \langle g, 1_k | \hat{H}_{\mathrm{int}} | e, 0 \rangle \right|^2 \rho(\omega)$

$$\rho_{\mathrm{vac}}(\omega) = \frac{\omega^2 V}{\pi^2 c^3}$$

$$\rho_{\mathrm{cav}}(\omega) = \frac{2}{\pi} \frac{\omega_0/Q}{(\omega_0/Q)^2 + 4(\omega - \omega_0)^2}$$

$$\boxed{\frac{\Gamma_{\mathrm{cav}}}{\Gamma_{\mathrm{vac}}} \propto \frac{\rho_{\mathrm{cav}}(\omega)}{\rho_{\mathrm{vac}}(\omega)} \underset{\omega \simeq \omega_0}{=} \frac{1}{4\pi^2} \frac{\lambda_0^3 Q}{V}}$$



Emission rate and directionality enhanced at resonance.

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

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

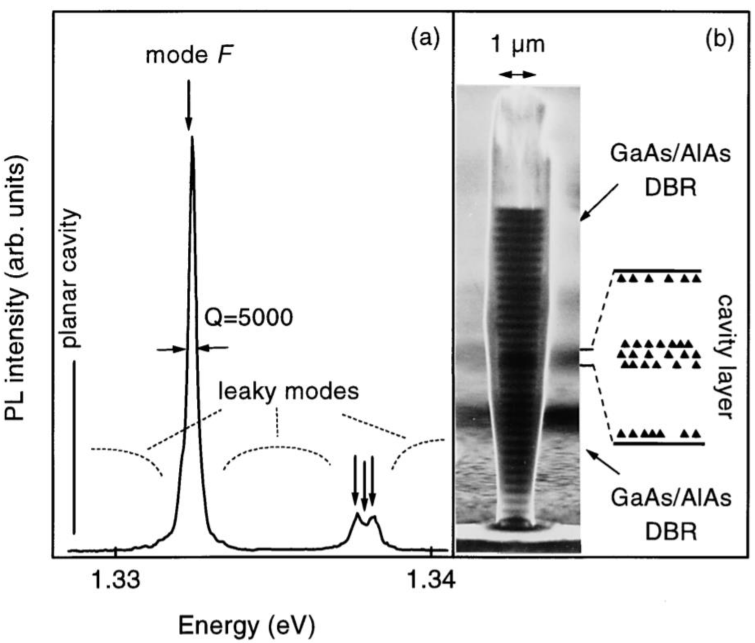
is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for $\nu = 10^7$ sec.$^{-1}$, $\mu = 1$ nuclear magneton, the corresponding relaxation time would be 5×10^{21} seconds! However, for a system coupled to a resonant electrical 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 $f = 3Q\lambda^3/4\pi^2V$, 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.$^{-1}$.

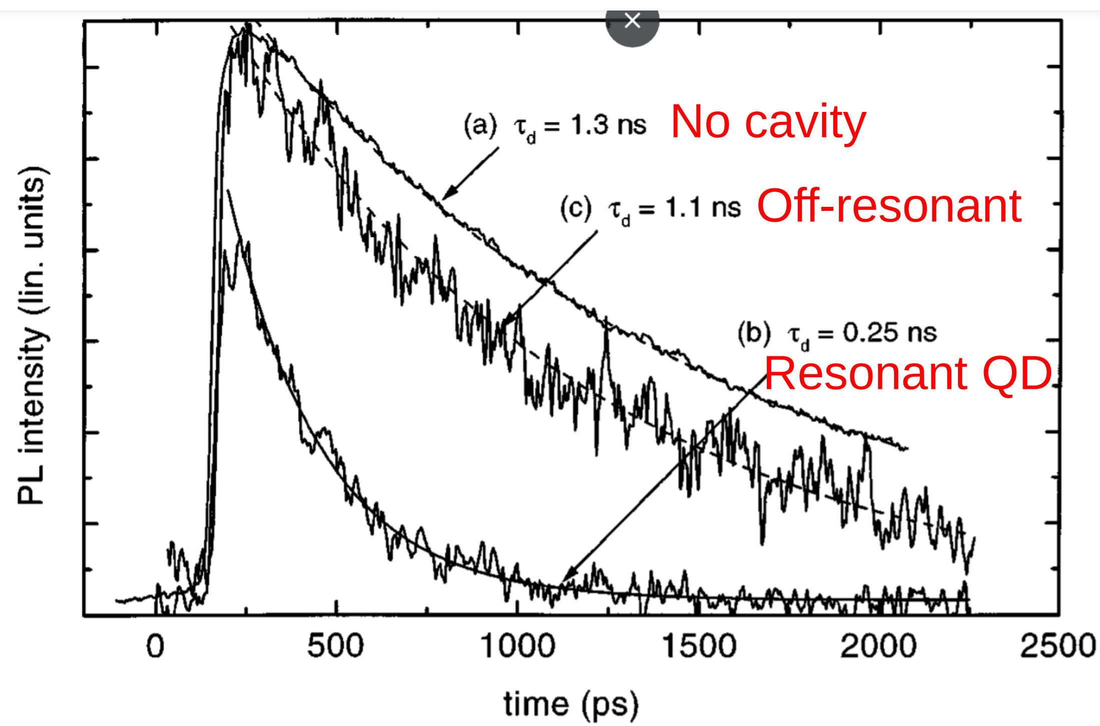
First demonstration with InAs quantum dots

VOLUME 81, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1998

Enhanced Spontaneous Emission by Quantum Boxes in a Monolithic Optical Microcavity

J. M. Gérard,* B. Sermage, B. Gayral, B. Legrand, E. Costard,† and V. Thierry-Mieg‡
France Télécom/CNET/DTD/CDP, 196 avenue H. Ravera, F-92220 Bagneux, France
(Received 3 April 1998)





nature nanotechnology

LETTERS

https://doi.org/10.1038/s41565-020-00831-x

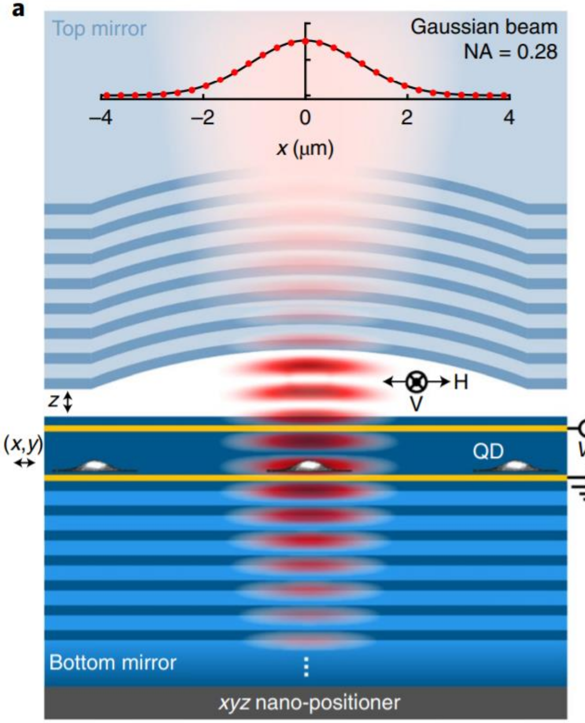
Check for updates

A bright and fast source of coherent single photons

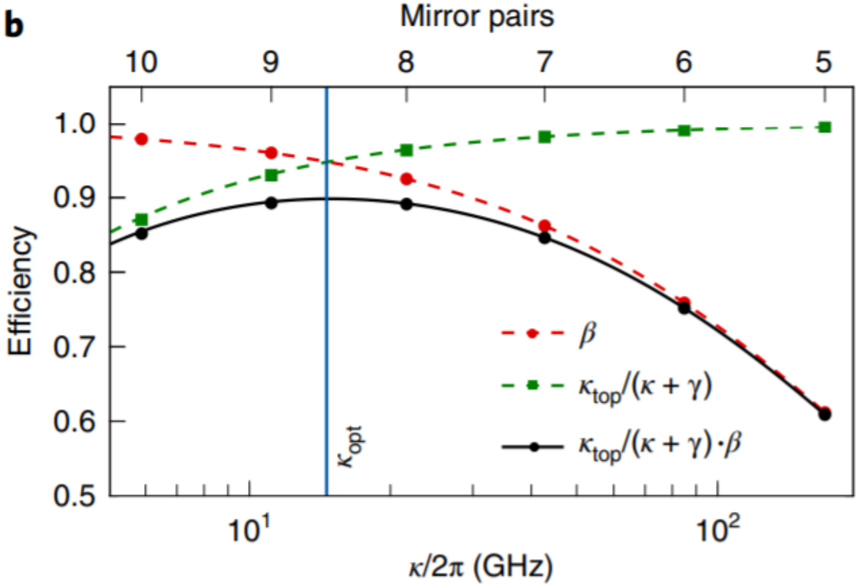
Natasha Tomm[1,3], Alisa Javadi[1,3] ✉, Nadia Olympia Antoniadis[1], Daniel Najer[1], Matthias Christian Löbl[1], Alexander Rolf Korsch[1,2], Rüdiger Schott[2], Sascha René Valentin[2], Andreas Dirk Wieck[2], Arne Ludwig[2] and Richard John Warburton[1]

A single-photon source is an enabling technology in device-independent quantum communication[1], quantum simulation[2,3], and linear optics-based[4] and measurement-based quantum computing[5]. These applications employ many photons and place stringent requirements on the efficiency of single-photon creation. The scaling on efficiency is typically an exponential function of the number of photons. Schemes taking full advantage of quantum superpositions also depend sensitively on the coherence of the photons, that is, their indistinguishability[6]. Here, we report a single-photon source with a high end-to-end efficiency. We employ gated quantum dots in an open, tunable microcavity[7]. The gating provides control of the charge and electrical tuning of the emission frequency; the high-quality material ensures low noise; and the tunability of the microcavity compensates for the lack of control in quantum dot position and emission frequency. Transmission through the top mirror is the dominant escape route for photons from the microcavity, and this output is well matched to a single-mode fibre. With this design, we can create a single photon at the output of the final optical fibre on-demand with a probability of up to 57% and with an average two-photon interference visibility of 97.5%. Coherence persists in trains of thousands of photons with single-photon creation at a repetition rate of 1 GHz.

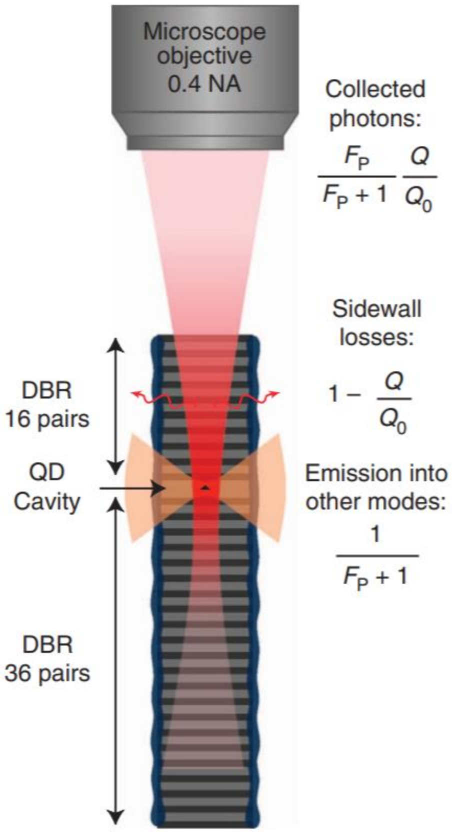
a

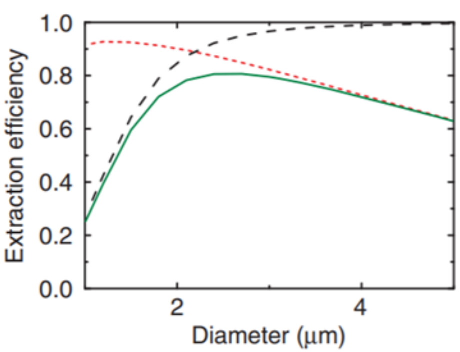


b



Micropillar sources for quantum technologies





Micropillar sources developed in P. Senellart's group (C2N):

- **2014:** extraction efficiencies ≈ 53 %

nature COMMUNICATIONS

ARTICLE

Received 14 Aug 2013 | Accepted 10 Jan 2014 | Published 5 Feb 2014 DOI: 10.1038/ncomms4240 OPEN

Deterministic and electrically tunable bright single-photon source

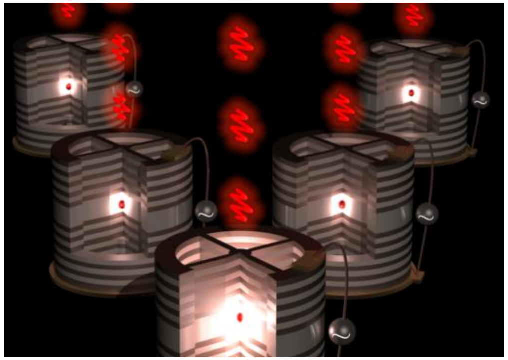
- **2016:** extraction efficiency ≈ 65 %

ARTICLES
PUBLISHED ONLINE: 7 MARCH 2016 | DOI: 10.1038/NPHOTON.2016.23
nature photonics

Near-optimal single-photon sources in the solid state

- **2017:** Commercially available

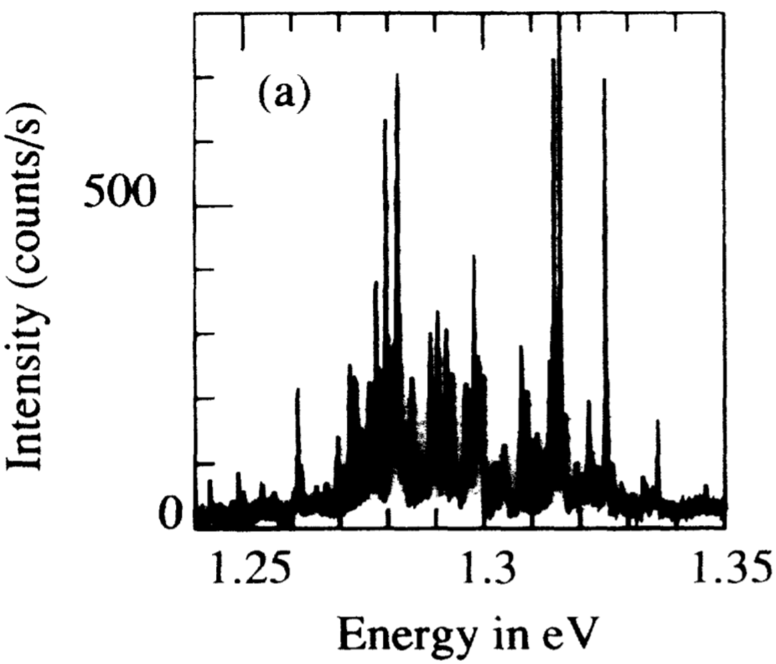
QUANDELA



The problem of scalability

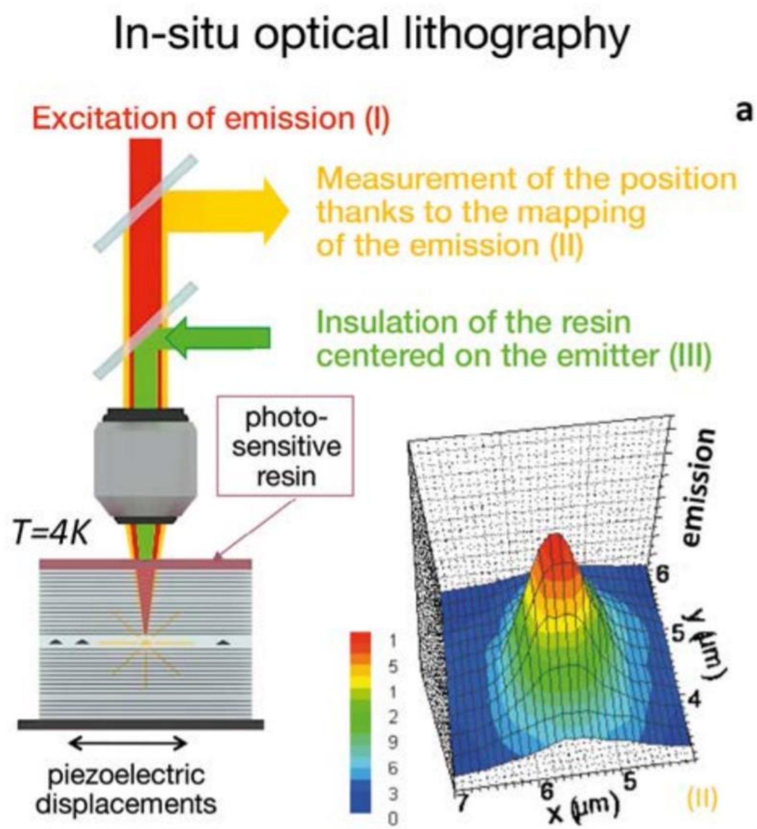
Random assembling, positioning of quantum dots during fabrication:

⇨ Inhomogeneous broadening



PRL **73**, 216 (1994)

Solution for 1 single photon source:



PRL **101**, 267404 (2008)

No existing technologies for arrays of identical single photon sources!

Conclusion

- Using **integrated optics** to solve the photon extraction issue.
- Most efficient way to extract photons: quantum dot in cavity.
- **Jaynes Cummings** model: description of light-matter coupling in an idealistic scenario.
- **Coupling to the environment** needs to be added to describe emission properties.
- Nearly **optimal single photon** sources available today.
- **Scalability issue**: work on the technology? Use 2D active materials?