CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

INSTITUT d'OPTIQUE GRADUATE SCHOOL

UNIVERSITÉ PARIS-SUD 11

Nano-antenne plasmonique pour l'émission de photons uniques

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Co-Auteurs

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- C. Javaux, B. Dubertret

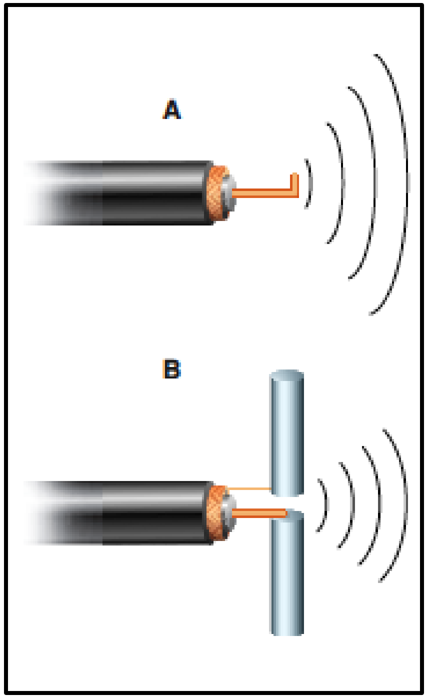
Goal of an antenna

Increase the coupling between :

a localized source/detector

and

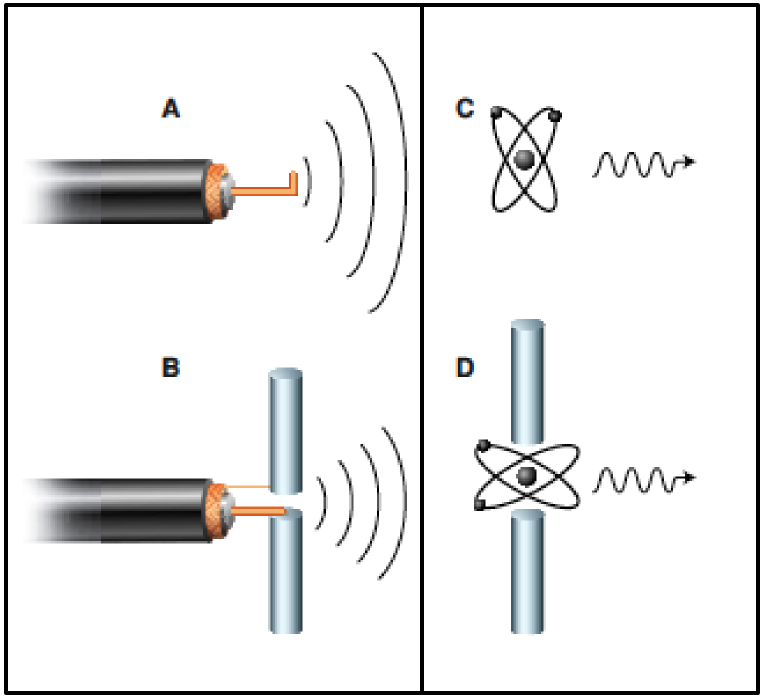
propagating waves



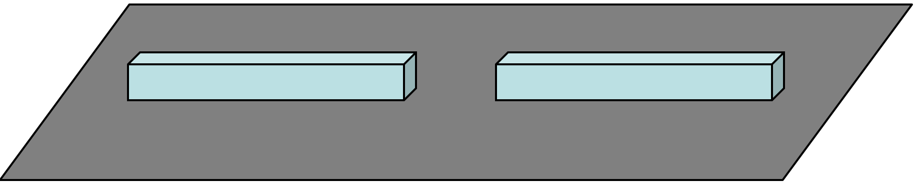
Goal of an antenna for single photon emission

Reduce the decay time

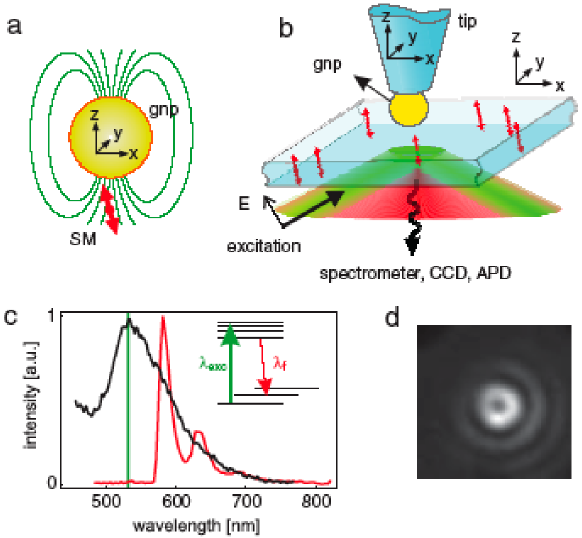
Collect all the emitted photons



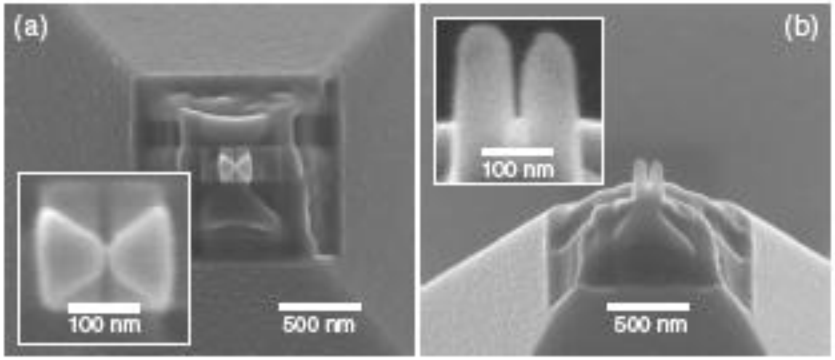
Nanoantennas



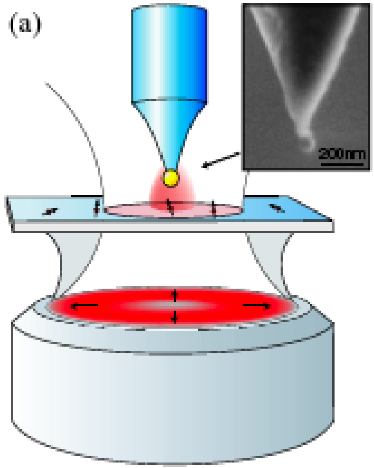
Mühlschlegel et al. Science 308 p 1607 (2005)



Kühn et al. PRL 97, 017402 (2006)



Farahani et al., PRL 95, 017402 (2005)

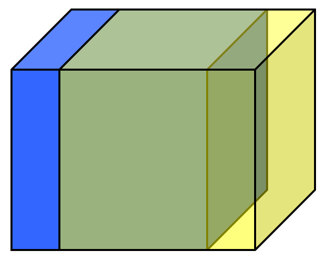


Anger et al., PRL 96, 113002 (2006)

What is a plasmon ?

Exemple : thin metallic film

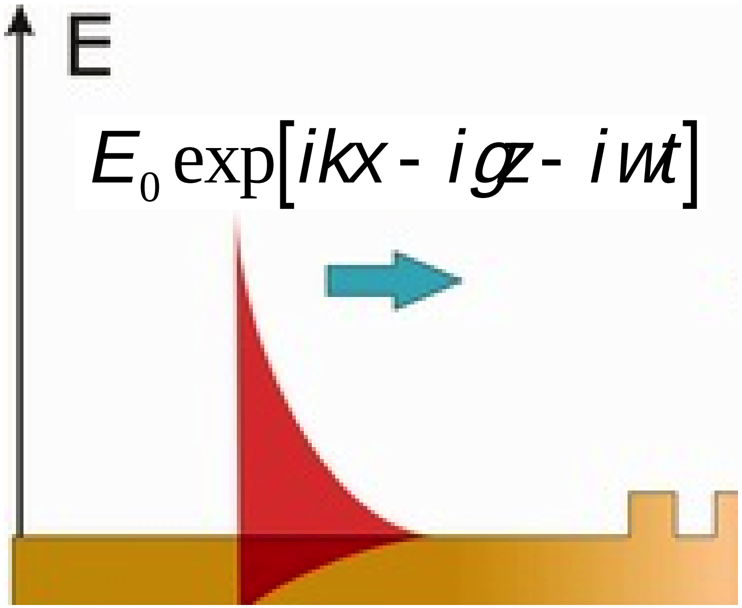
collective oscillation mode of the electrons

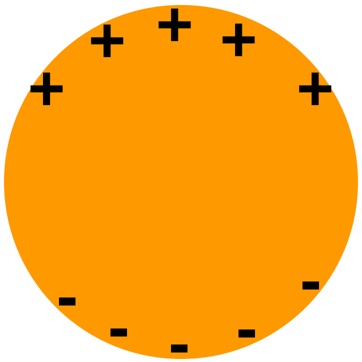


$$\omega_p^2 = \frac{ne^2}{m\varepsilon_0}$$

$$m\ddot{x} = -eE - \gamma m\dot{x} = -n\frac{e^2}{\varepsilon_0}x - \gamma m\dot{x}$$

Qu'est-ce qu'un plasmon de surface?





$$r_F = \frac{\varepsilon_2 k_{z1} - \varepsilon_1 k_{z2}}{\varepsilon_2 k_{z1} + \varepsilon_1 k_{z2}}$$

$$\alpha = 4\pi a^3 \frac{\varepsilon_m(\omega) - 1}{\varepsilon_m(\omega) + 2}$$

$$\varepsilon_2 k_{z1} + \varepsilon_1 k_{z2} = 0$$

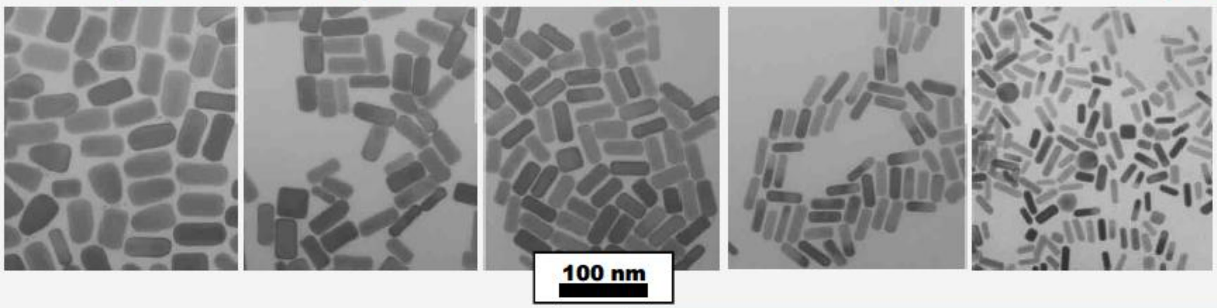
$$\varepsilon_m(\omega) + 2 = 0$$

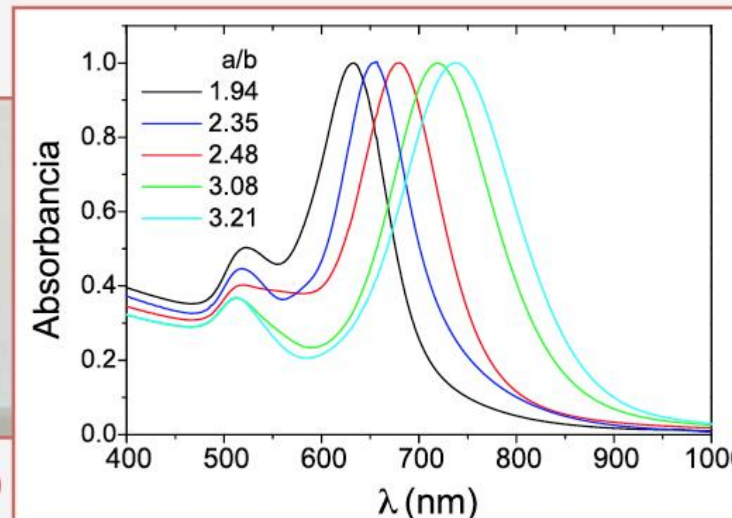
Tuning the electrostatic resonance

Plasmons in metallic nanoparticles

The colors of gold nanorods

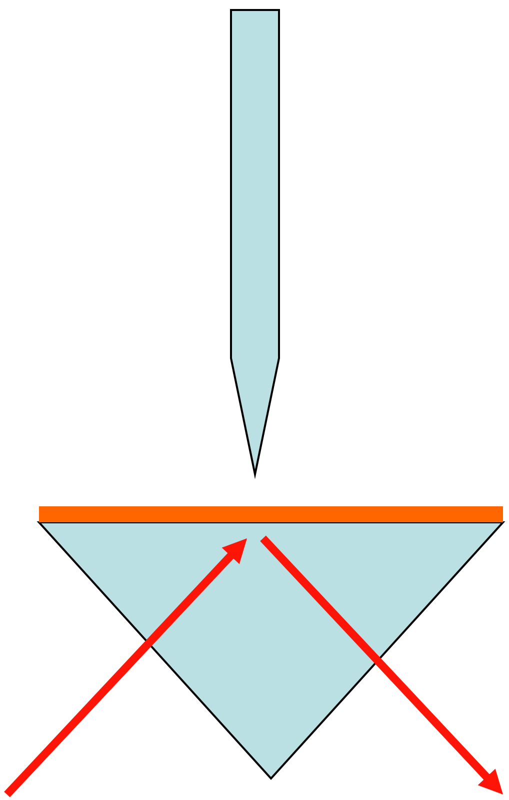
AR 1,94 2,35 2,48 3,08 3,21

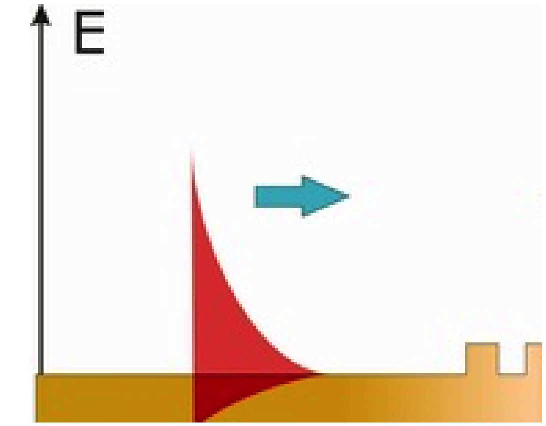




J. Pérez-Juste *et al.*, Appl. Surf. Sci. (2004)

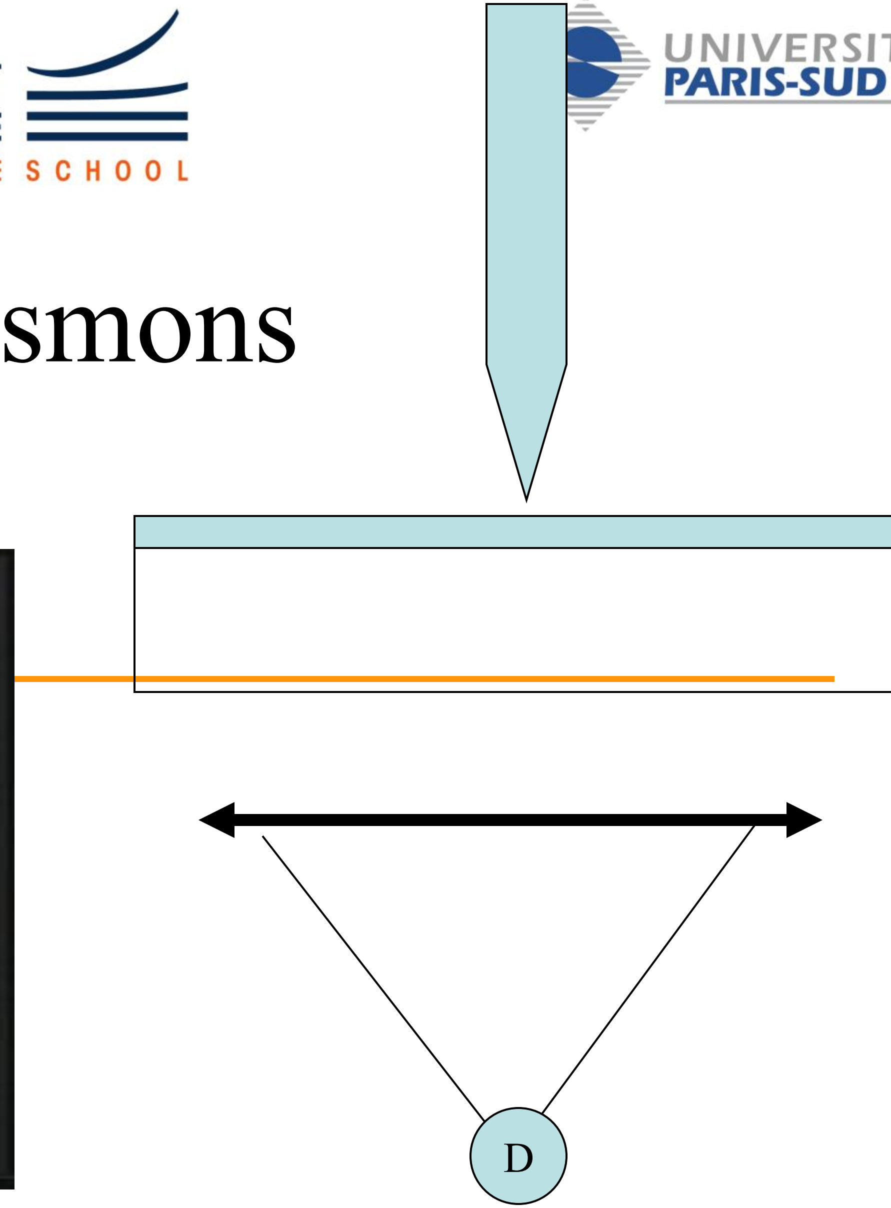
Image d'un plasmon de surface





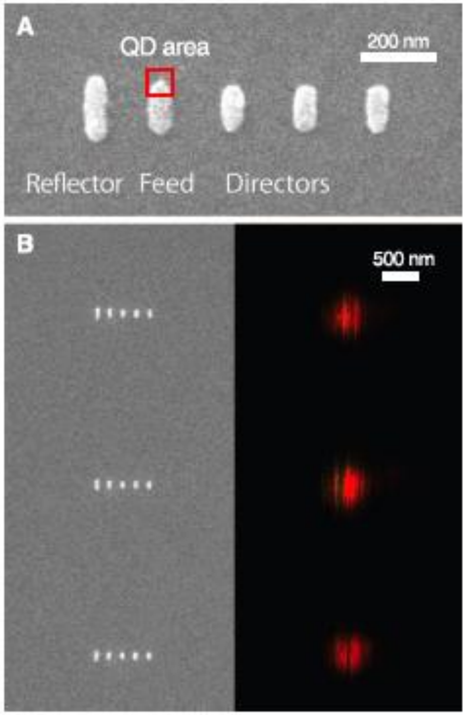
$$E_x \exp[ikx - i\gamma z - i\omega t]$$

Seeing Surface plasmons



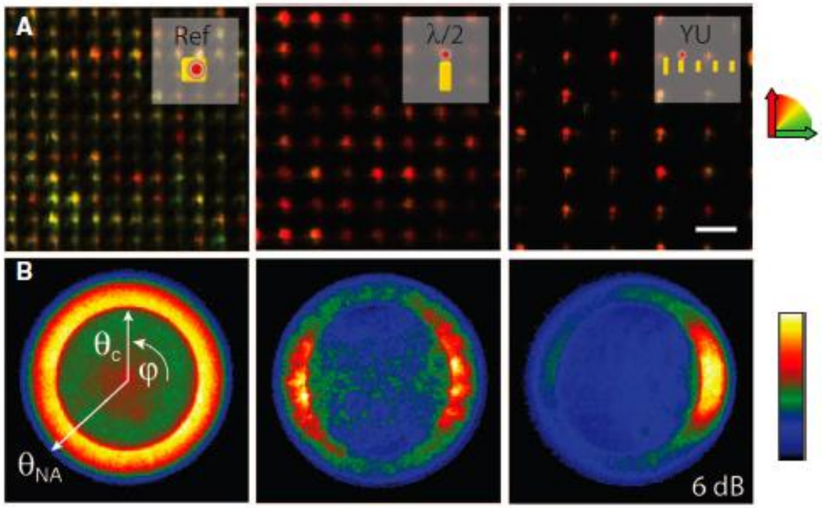
Courtesy: Alexandre Bouhelier

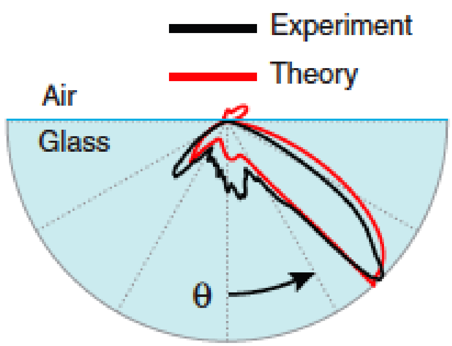
Controlling the direction (1)



Unidirectional Emission of a Quantum Dot Coupled to a Nanoantenna

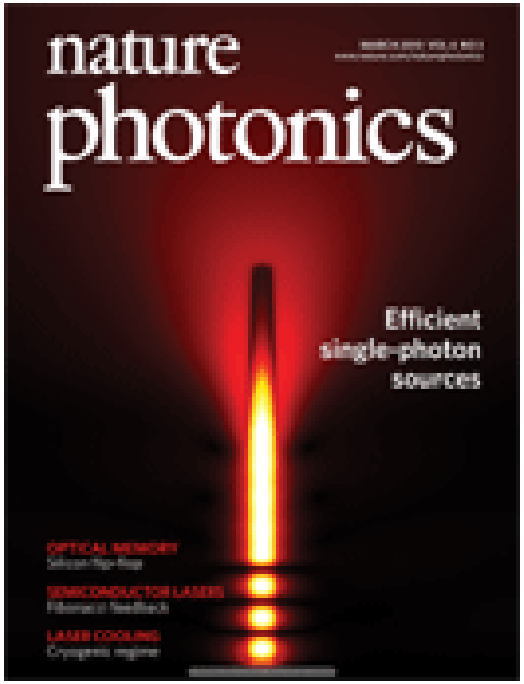
Alberto G. Curto,[1] Giorgio Volpe,[1] Tim H. Taminiau,[1] Mark P. Kreuzer,[1] Romain Quidant,[1,2] Niek F. van Hulst[1,2]*





Science **329**, 930 (2010)

Controlling the direction (2)



Key idea : no Purcell effect but funneling the energy into a single mode

Broad spectrum and good coupling.

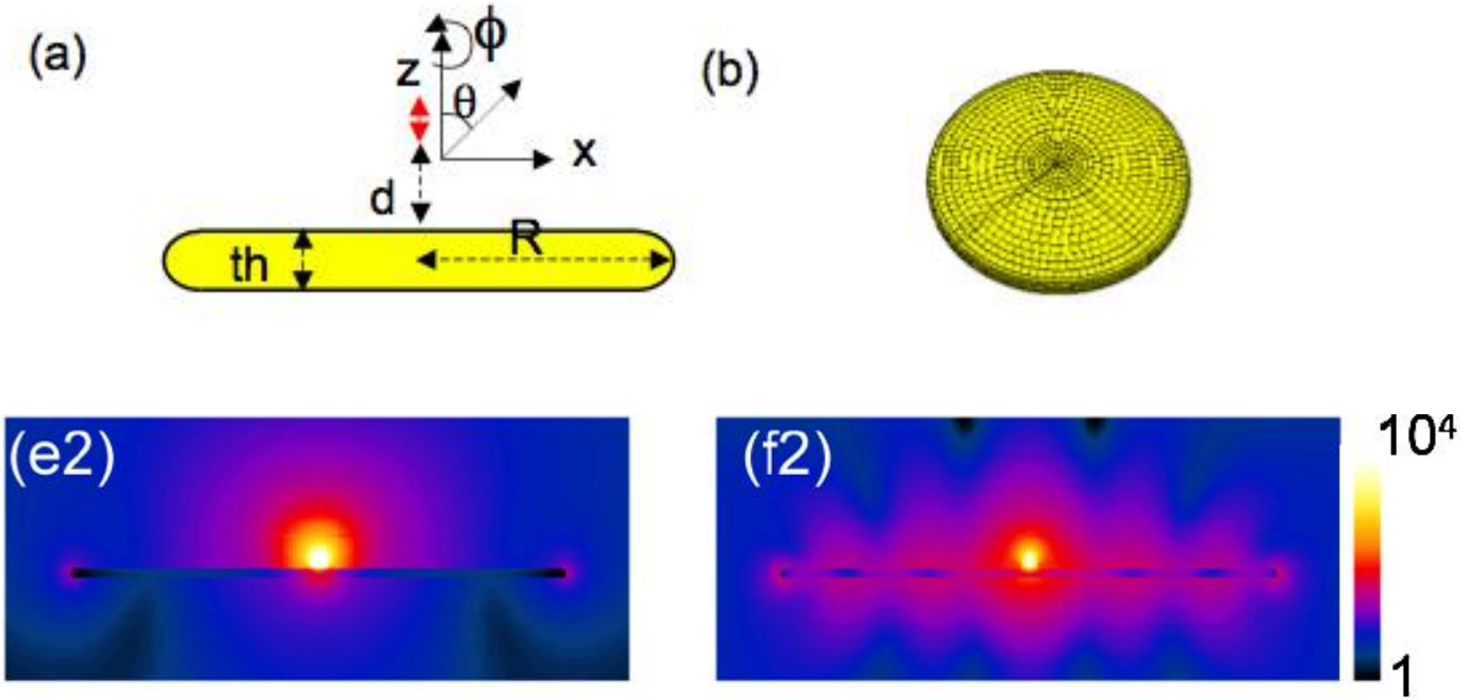
Motivation

Design and *fabricate deterministically* a plasmonic antenna in order to

- *accelerate* spontaneous emission,
- *control* the angular emission

over a *broad band*.

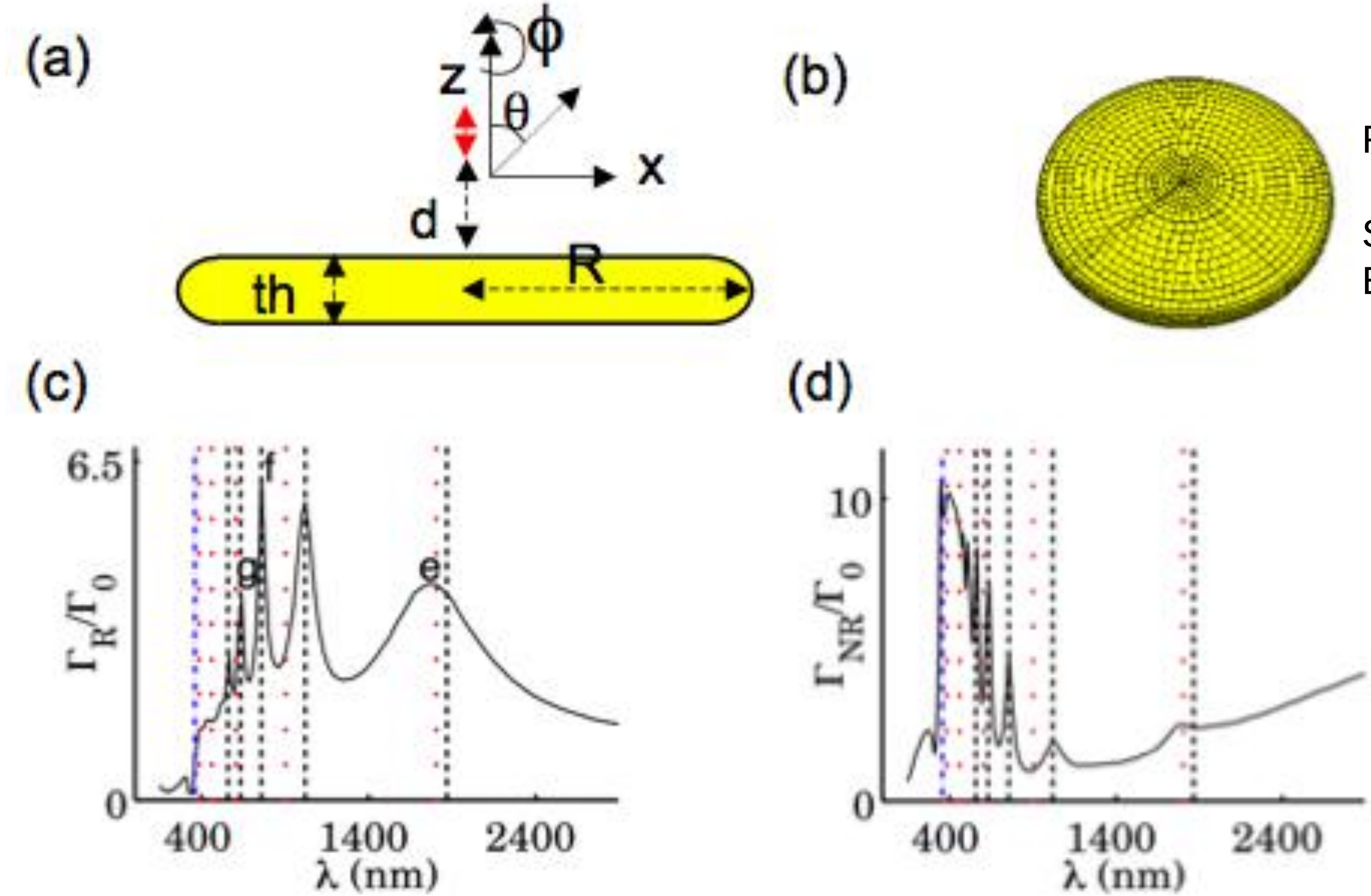
Surface plasmon microcavity



Emission mechanism

Phys.Rev.Lett. 104, 026802 (2010)

Surface plasmon microcavity

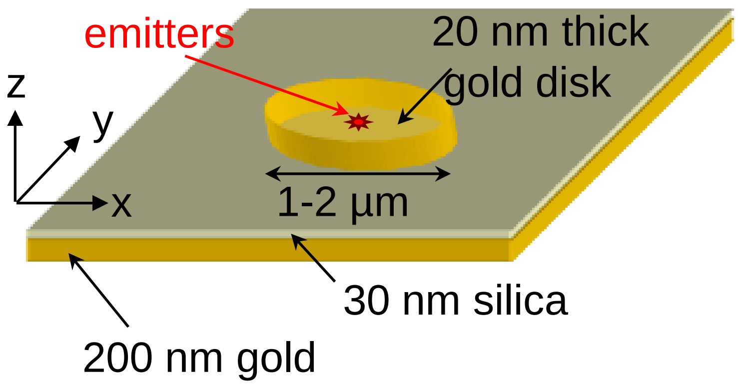


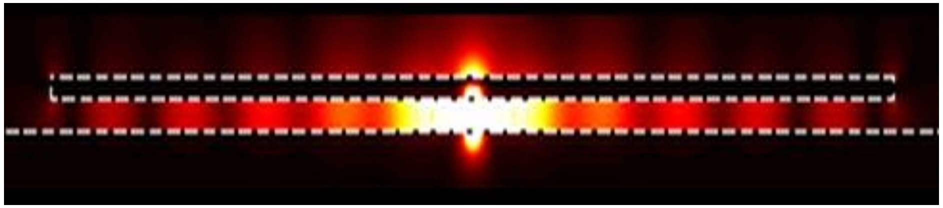
R=600 nm

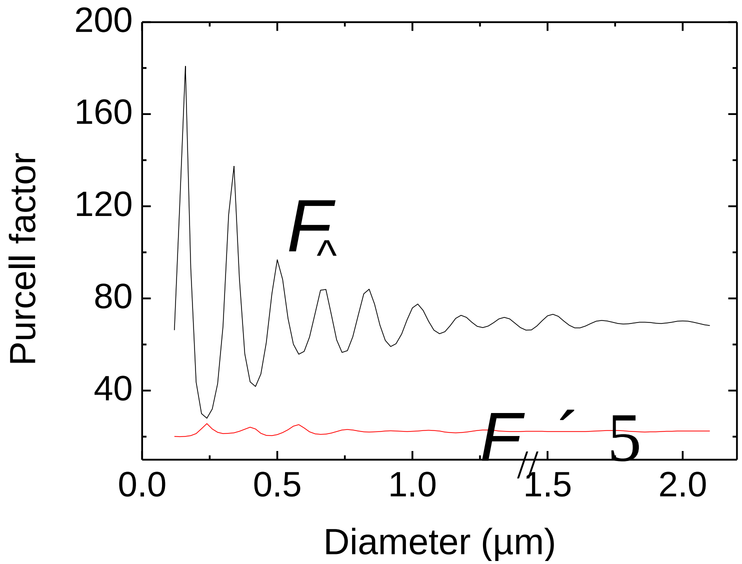
Silver disk
Embedded in glass

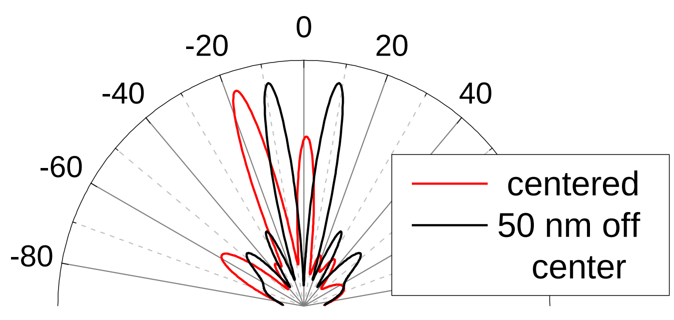
Phys.Rev.Lett. 104, 026802 (2010)

Patch Antenna





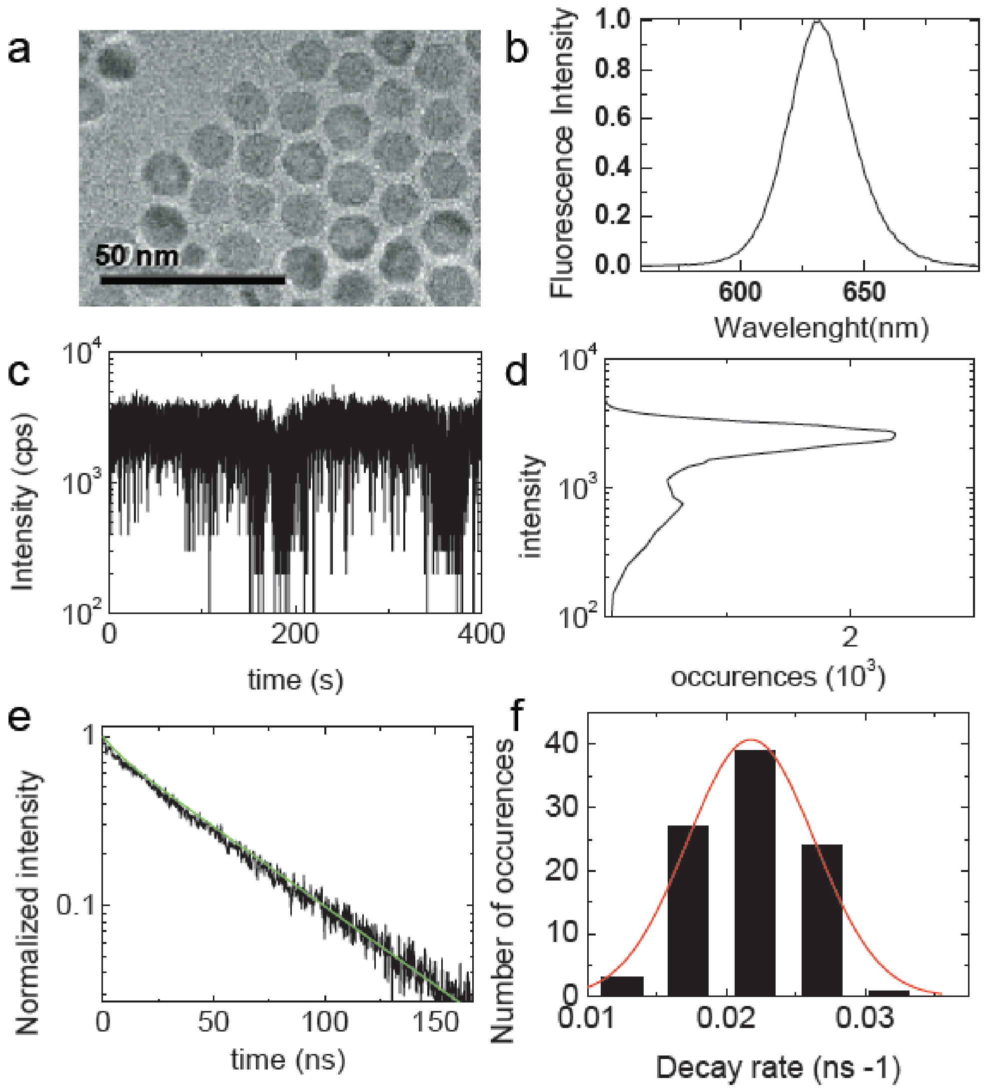




Diameter 1.5 µm

*Belacel et al. NanoLetters **13**, p 1516 (2013)*

Quantum dots characterization

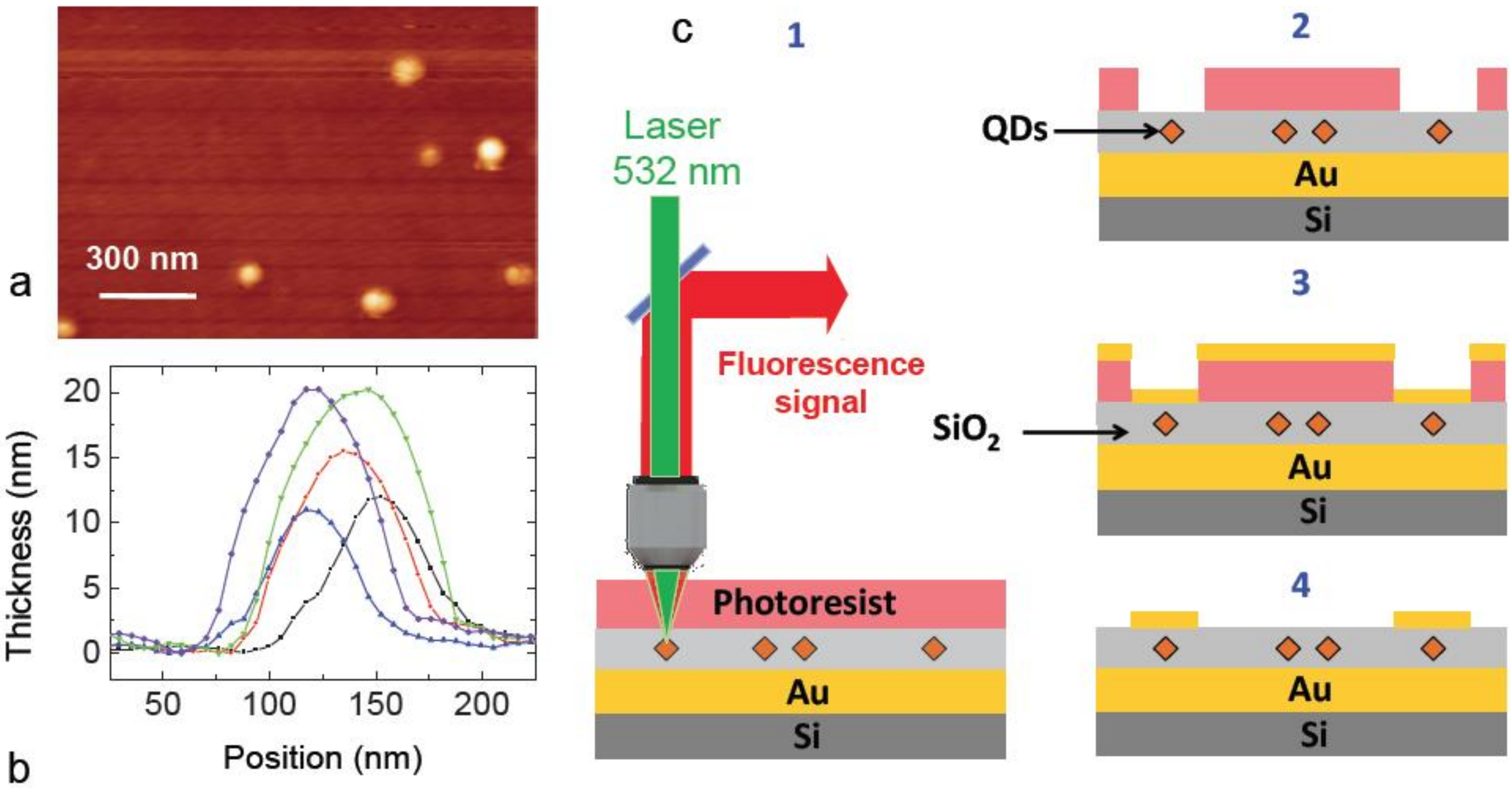


CdSe/CdS quantum dots
core diameter: 3 nm
QD diameter : 13 nm

87% photons emitted in bright state, 13% In the grey state.

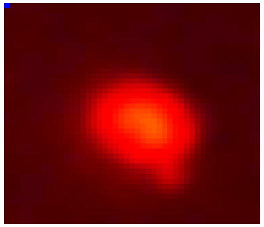
*Belacel et al. NanoLetters **13**, p 1516 (2013)*

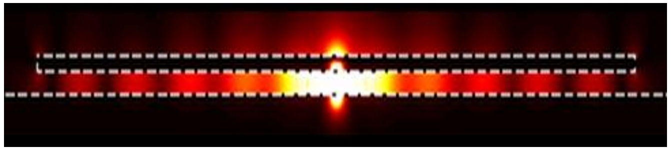
Patch Antenna Fabrication

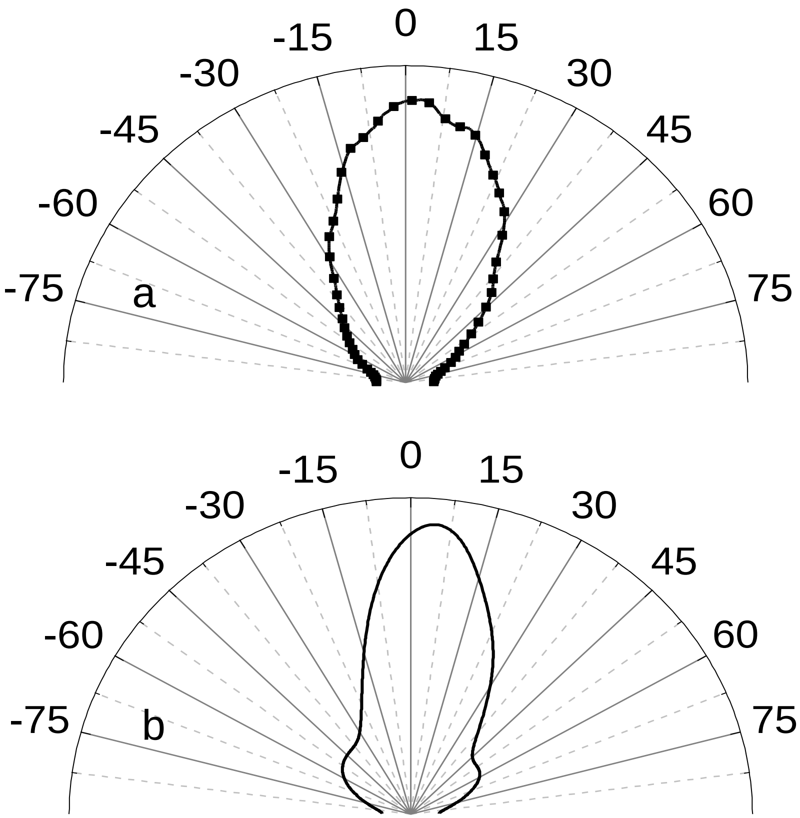


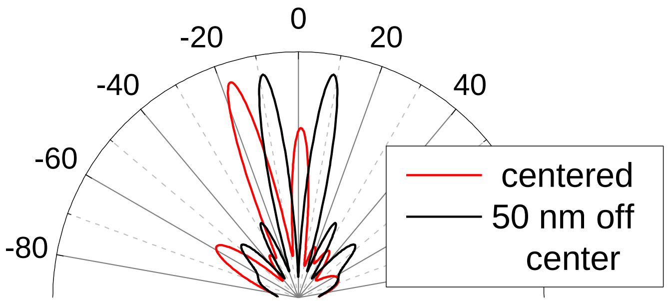
Collaboration with Attocube (now commercially available)

Controlling the angular emission



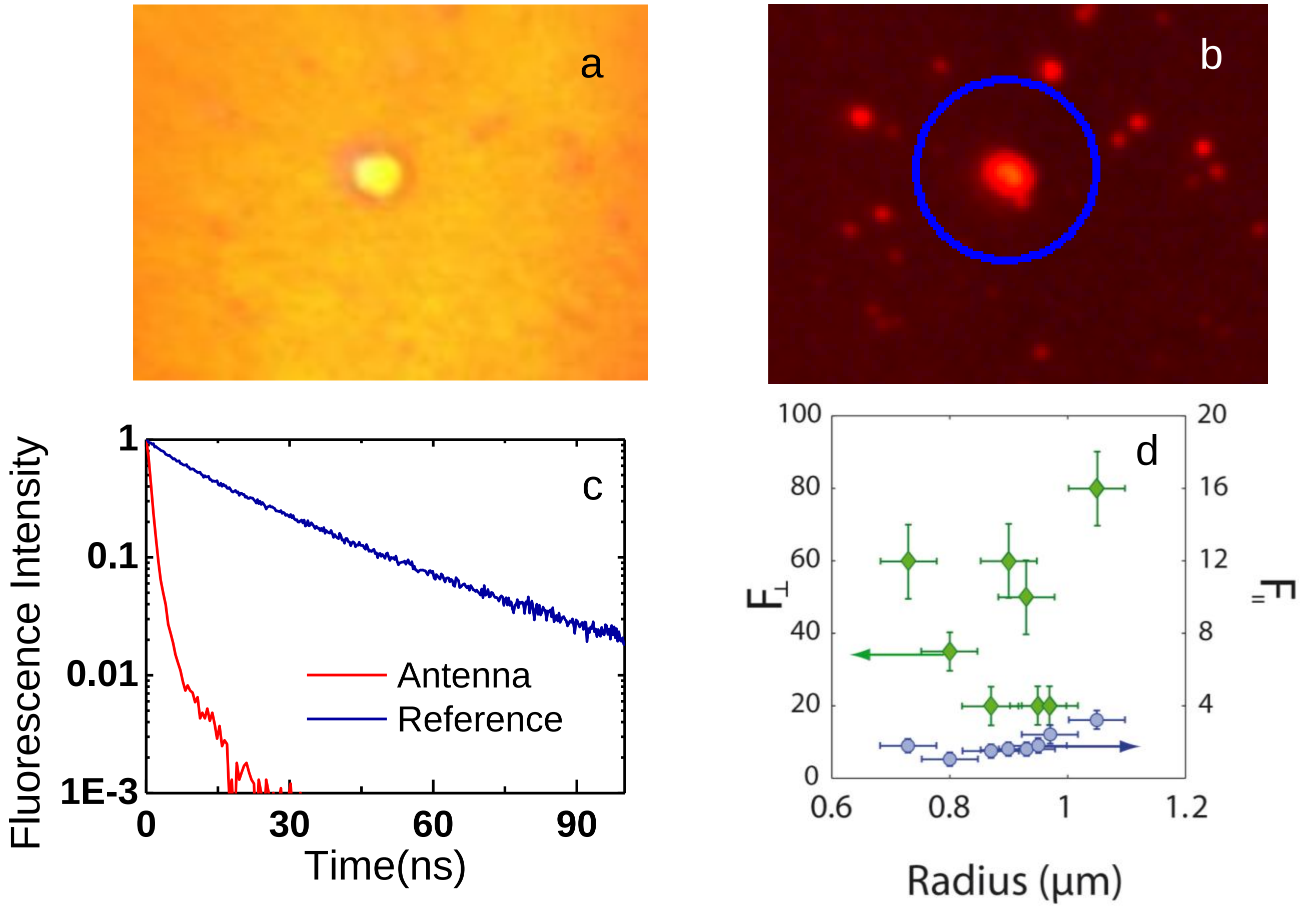






*Belacel et al. NanoLetters **13**, p 1516 (2013)*

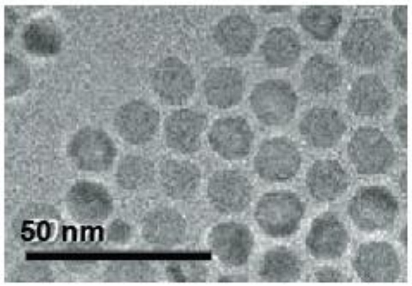
Accelerating spontaneous Emission

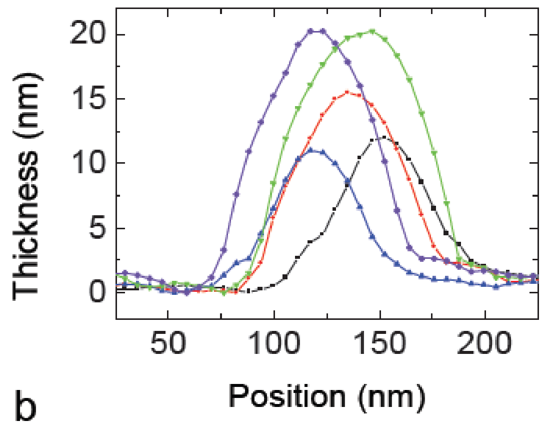


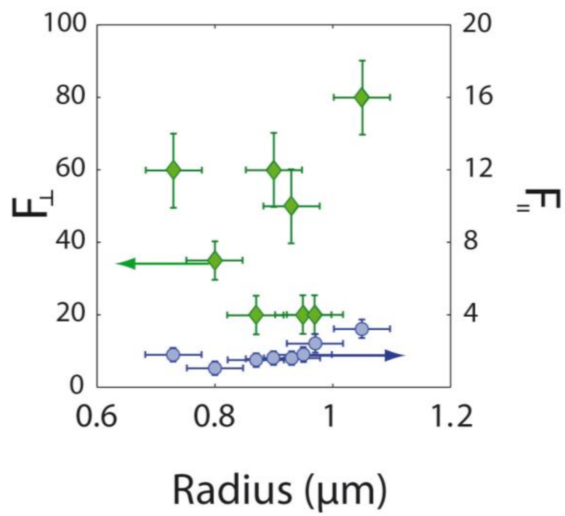
*Belacel et al. NanoLetters **13**, p 1516 (2013)*

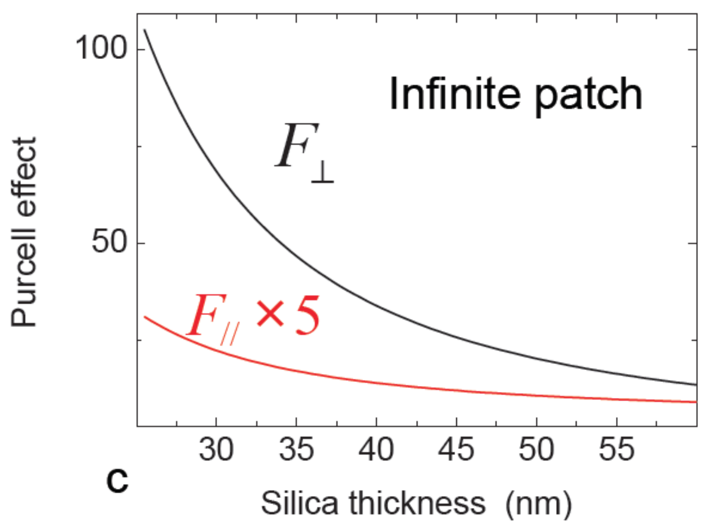
Origin of the Purcell fluctuations

The QD cluster thickness fluctuates.



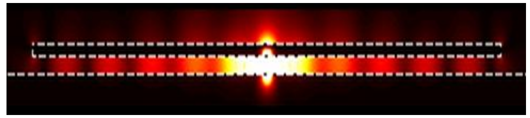






Quenching or photon emission ?

Quenching or SPP emission ?

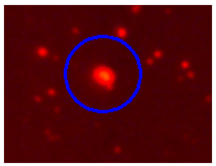


Photon (5%)

Joule losses

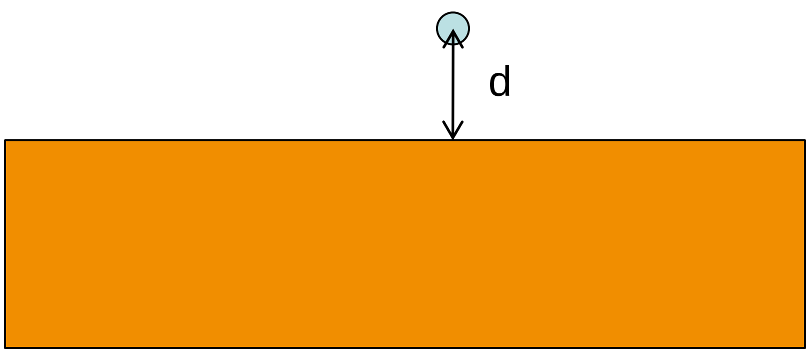
Antenna modes spontaneous emission

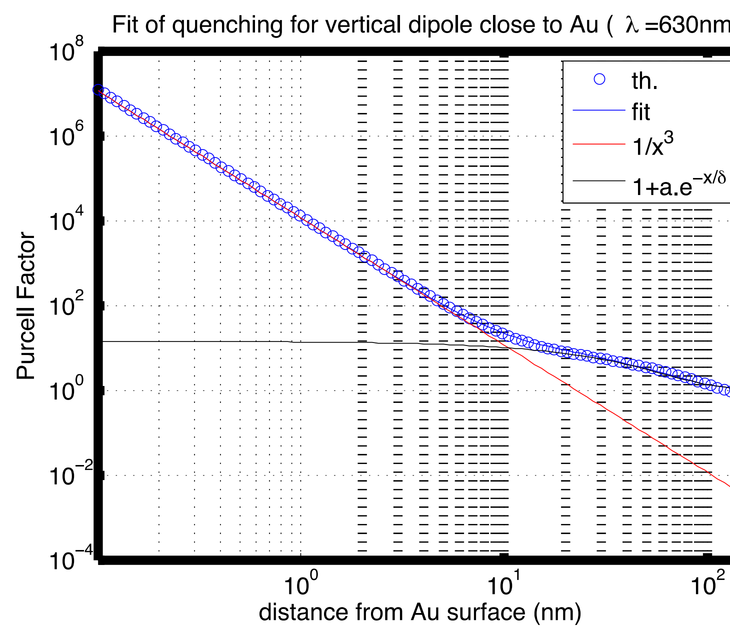
Excited QD



Quenching

5%





Efficiency

i) Current efficiency : <5%

ii) Going to NIR (1.3 µm) and reducing the antenna size (0.32 µm), the efficiency increases to 42%.

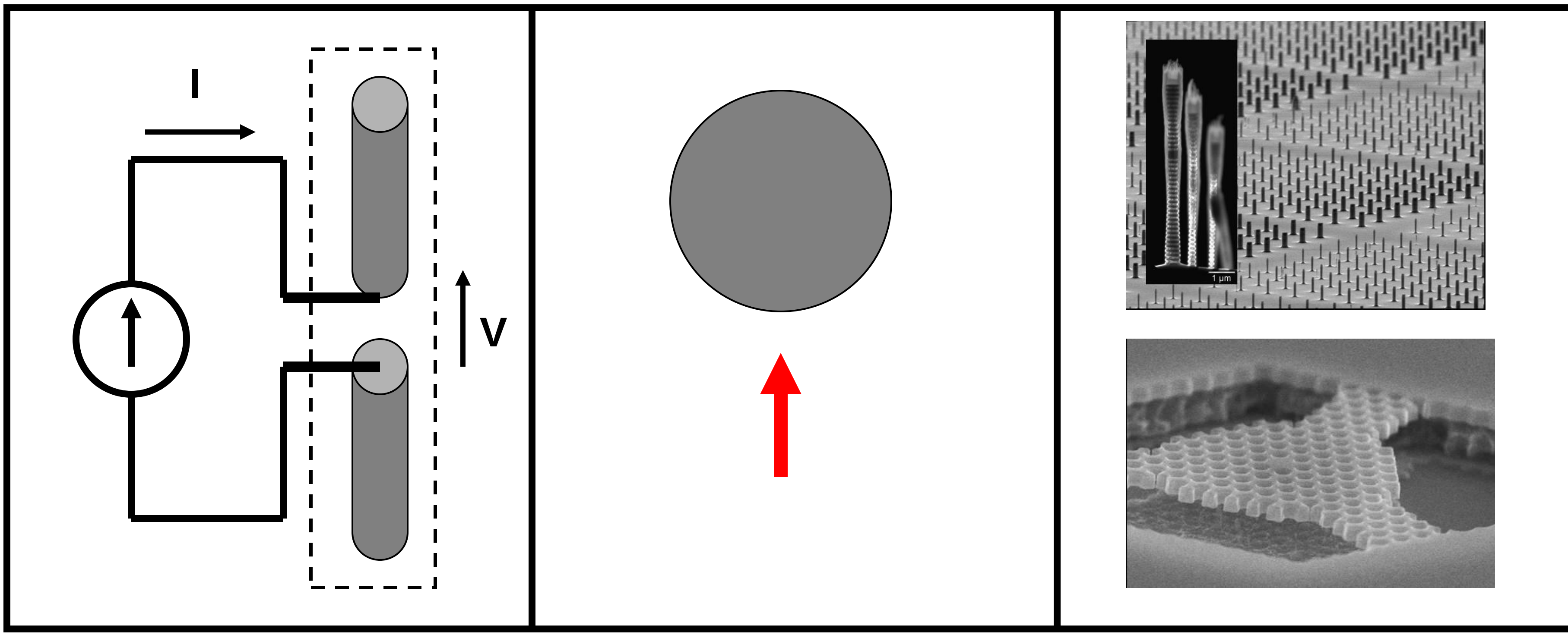
iii) Further improvement of the antenna design using metallo-dielectric structures can provide over 80% efficiency.

Key issue

Can we unify our description of the electron/photon interaction ?

Emission figures of merit

Antennas | **Nanoantenna** | **Microcavity**



Antennas: Z, G

Impedance
Radiation resistance

Nanoantenna: Γ_R, Γ_{NR}

Classical dipole radiation
No feedback on the source

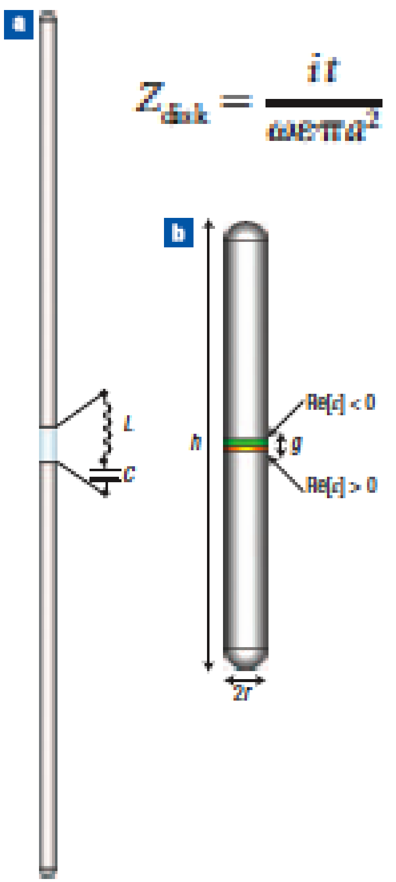
Microcavity: F_P, Ω_R

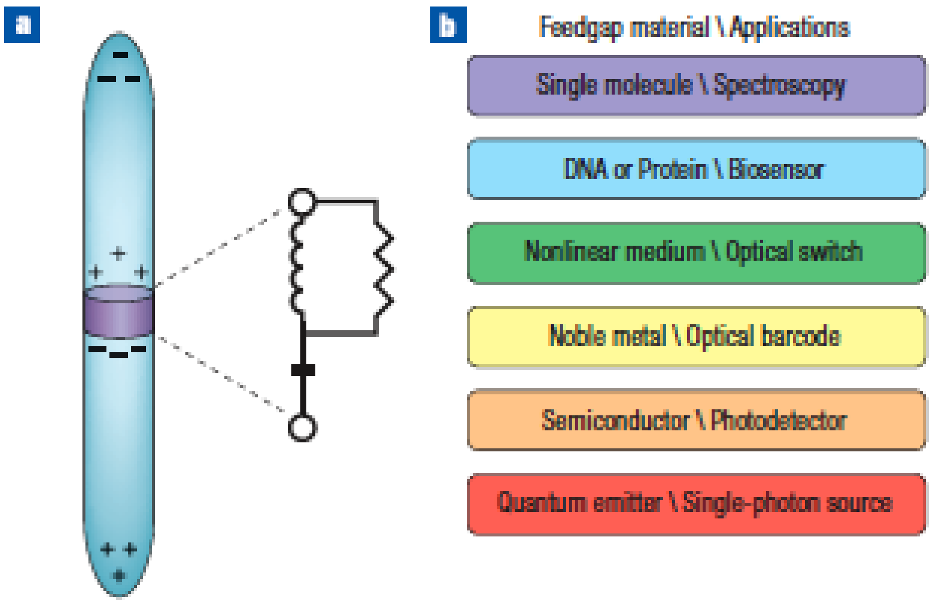
Fermi golden rule
LDOS

Antenna impedance

Tuning the scattering response of optical nanoantennas with nanocircuit loads

ANDREA ALÙ AND NADER ENGHETA*





Mark L. Brongersma

nature photonics | VOL 2 | MAY 2008 |

nature photonics | VOL 2 | MAY 2008 |

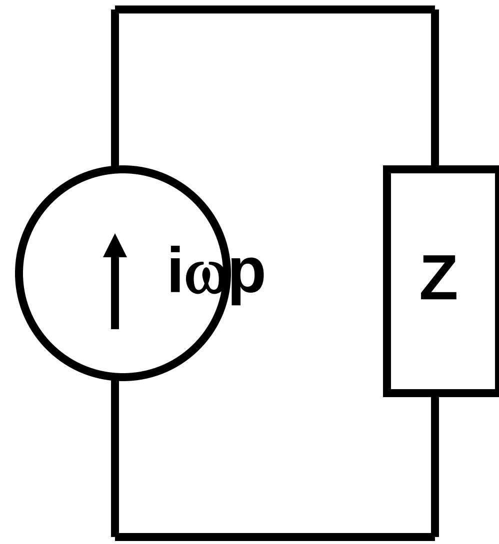
Nanoantenna Impedance definition

$$P = \frac{1}{2}\,\mathrm{Re}\left[i\omega p_z E_z^*\right]$$

$$P = \frac{1}{2}\,\mathrm{Re}\left[I U^*\right]$$

$- E_z$ ⟷ U

$-i\omega p_z$ ⟷ I



Greffet et al. Phys.Rev.Lett. 105, 117701 (2010)

Nanoantenna Impedance definition

$$P = \frac{1}{2}\,\mathrm{Re}\left[i\omega p_z E_z^*\right]$$

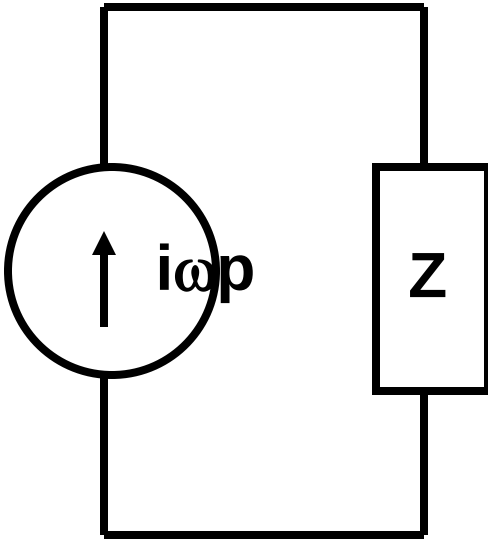
$$P = \frac{1}{2}\,\mathrm{Re}\left[I U^*\right]$$

$-E_z$ ⟷ **U**

$-i\omega p_z$ ⟷ **I**

$$E_z = G_{zz}\, p_z$$

$U = ZI$



Greffet et al. Phys.Rev.Lett. 105, 117701 (2010)

Nanoantenna Impedance definition

$$P = \frac{1}{2}\,\mathrm{Re}\left[i\omega p_z E_z^*\right]$$

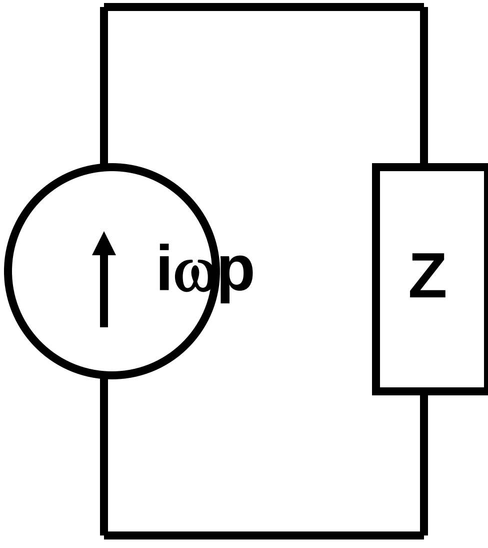
$-\mathbf{E}_z$ ↔ **U**

$-i\omega \mathbf{p}_z$ ↔ **I**

$$-E_z = \left[\frac{G_{zz}}{i\omega}\right]\left(-i\omega p_z\right)$$

$$P = \frac{1}{2}\,\mathrm{Re}\left[I U^*\right]$$

U=ZI



$$Z = \frac{G_{zz}(\mathbf{r},\mathbf{r})}{i\omega}$$

Greffet et al. Phys.Rev.Lett. 105, 117701 (2010)

Physical meaning of Re(Z)

Electrical engineering point of view :

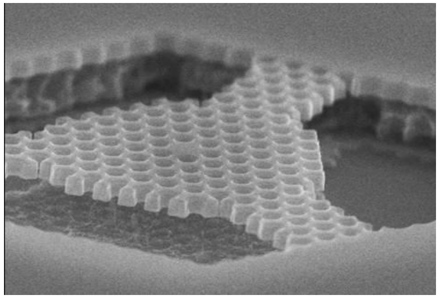
Radiation resistance α Im(G)

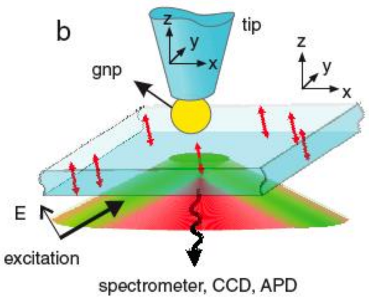
Quantum optics point of view :

LDOS α Im(G)

$$P = \frac{1}{2} \, \mathrm{Re}\left[i\omega p_z E_z^* \right]$$

Microcavity versus nanoantenna

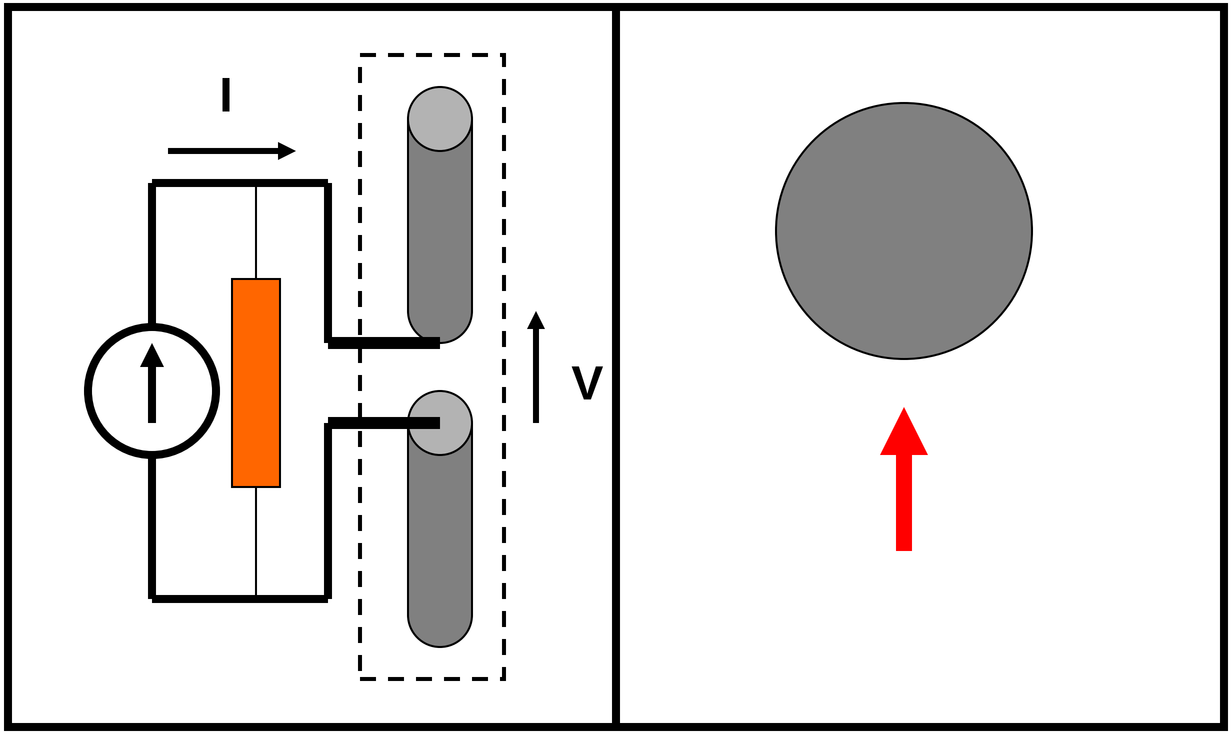




	Microcavity	Nanoantenna
Spatial confinment	$(\lambda/2n)^3$	$\pi z^6/a^3$
Quality factor	10^3-10^6	**10-1000**
		Broadband
Waves	$K < n\,\omega/c$	**Evanescent waves/ polaritons**

Source-antenna coupling

Antennas | **Nanoantenna**



Z, G | Γ_R, Γ_{NR}

Impedance matching | **Multiple scattering**

Quantum emitter impedance

What is the internal impedance of a quantum emitter ?

$$p_z = \alpha\varepsilon_0 E_z \quad \Rightarrow \quad -i\omega p_z = (-i\omega\alpha\varepsilon_0)(E_z)$$

$$Z_{in} = \frac{i}{\omega\alpha\epsilon_0}.$$

Greffet et al. Phys.Rev.Lett. 105, 117701 (2010)

Atom : a RLC series circuit !

Two-level system polarisability

$$\alpha(\omega) = \alpha_0/[\omega_0^2 - \omega^2 - i\gamma\omega]$$

(without the rotating wave approximation)

$$\alpha_0\epsilon_0 = (e^2/m)f$$

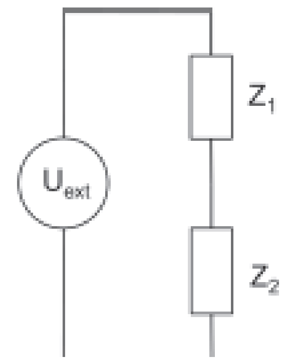
$$Z_{in} = \frac{Z_0}{\sigma}\left(1 + iQ\frac{\omega_0}{\omega} - iQ\frac{\omega}{\omega_0}\right)$$

Greffet et al. Phys.Rev.Lett. 105, 117701 (2010)

Addition d'impédances et diffusion multiple

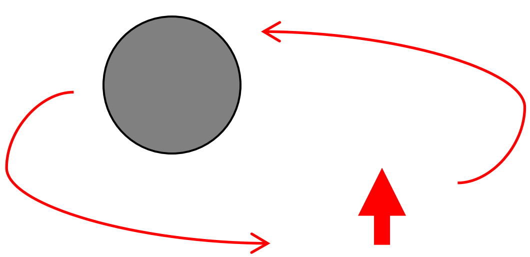
$$p_z = \alpha\epsilon_0[E_{\rm ext} + G_{zz}p_z]. \qquad p_z = \frac{\alpha\epsilon_0}{1-\alpha\epsilon_0 G_{zz}}E_{\rm ext}.$$

Addition d'impédances



$$p_z = \left[\frac{1}{-\mathrm{i}\omega}\right]\frac{1}{\mathrm{i}/\omega\alpha\epsilon_0 - \mathrm{i}G_{zz}/\omega}E_{\rm ext} = \left[\frac{1}{-\mathrm{i}\omega}\right]\frac{E_{\rm ext}}{Z_1(\omega)+Z_2(\omega)}.$$

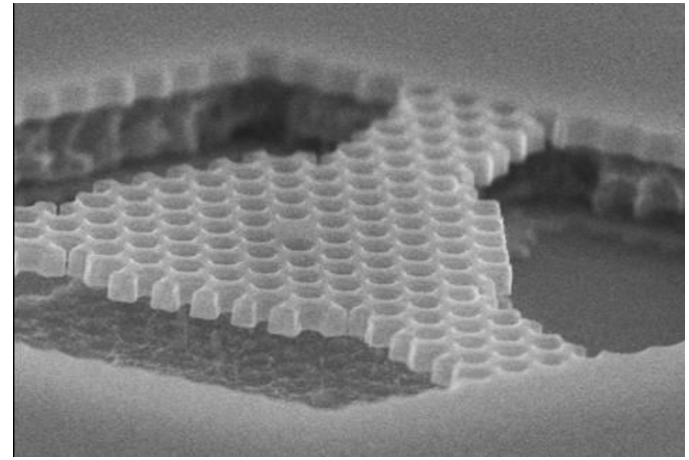
Diffusion multiple



$$p_z = \alpha\epsilon_0[1 + \alpha\epsilon_0 G_{zz} + (\alpha\epsilon_0 G_{zz})^2 + (\alpha\epsilon_0 G_{zz})^3 + \ldots]E_{\rm ext},$$

Example 1: a microcavity

$$G_{zz}(r,r',\omega) = \frac{E_z(r)E_z^*(r')}{\omega_0^2(1 - i/Q) - \omega^2}\,\frac{\omega^2}{\varepsilon_0}$$



$$\frac{1}{Z} = \frac{i\omega}{G_{zz}(r,r)} = \frac{1}{R} + i\left(C\omega - \frac{1}{L\omega}\right)$$

$C = \varepsilon_0 V_{eff}$

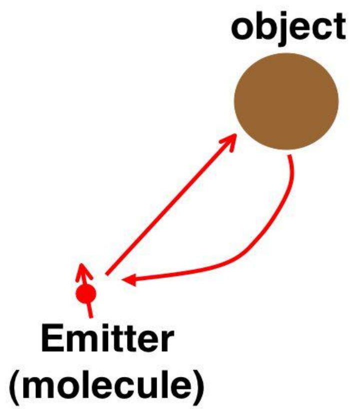
$1/L = \varepsilon_0 V_{eff}\,\omega_0^2$

$R = QL\omega$

Microcavity = RLC parallel circuit = notch filter

Example 2: a metallic nanosphere

$$F_p = \frac{\mathrm{Im}(G)}{\mathrm{Im}(G_0)} = 1 + \frac{6 p e_0 c^3}{w^3}\,\mathrm{Im}\left[\mathbf{u} \times S(\mathbf{r},\mathbf{r},w)\,\mathbf{u}\right]$$



$$F_p = 1 + \frac{3Q}{4p^2}\;\frac{a^3 / ^3}{p\;\; z^6}$$

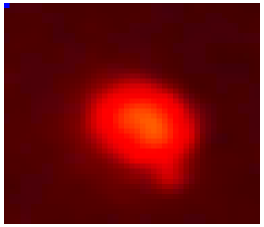
$$\mathbf{E}(\mathbf{r},w) = \mathbf{G}_0(\mathbf{r},\mathbf{r},w)\,\mathbf{p} + S(\mathbf{r},\mathbf{r},w)\,\mathbf{p}$$

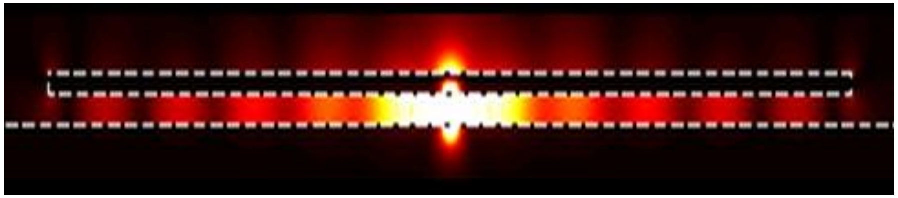
$$V_{eff} = \frac{p\;\; z^6}{a^3}$$

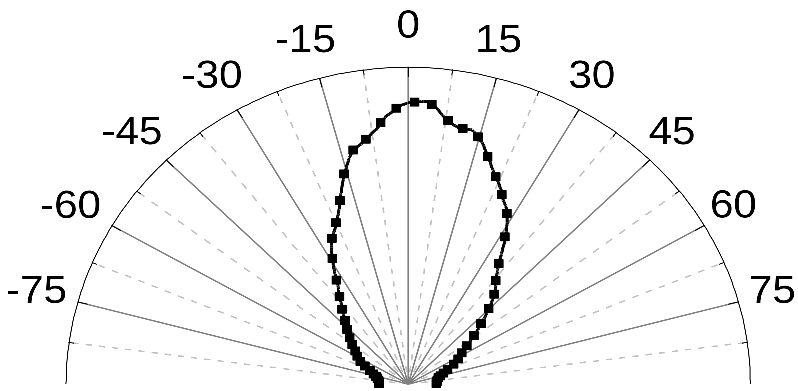
The nanoantenna achieves a *large Purcell factor* over a *broad spectrum*

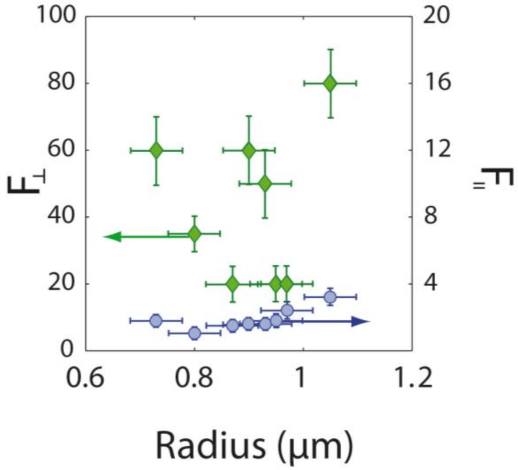
Greffet et al. Phys.Rev.Lett. 105, 117701 (2010)

Summary









$$Z = \frac{G_{zz}(\mathbf{r},\mathbf{r})}{i w}$$

$$Z_{in} = \frac{i}{\omega \alpha \epsilon_0}.$$