Controlling spontaneous emission with surface waves

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Nanophotonics in a nutshell

1) Large electric field

$$\frac{\varepsilon_0 E^2}{2} V = \frac{\hbar\omega}{2} \quad \rightarrow \quad E = \sqrt{\frac{\hbar\omega}{\varepsilon_0 V}}$$

2) Overlap of electrons and photons in a tiny volume

Heterostructures : Alferov

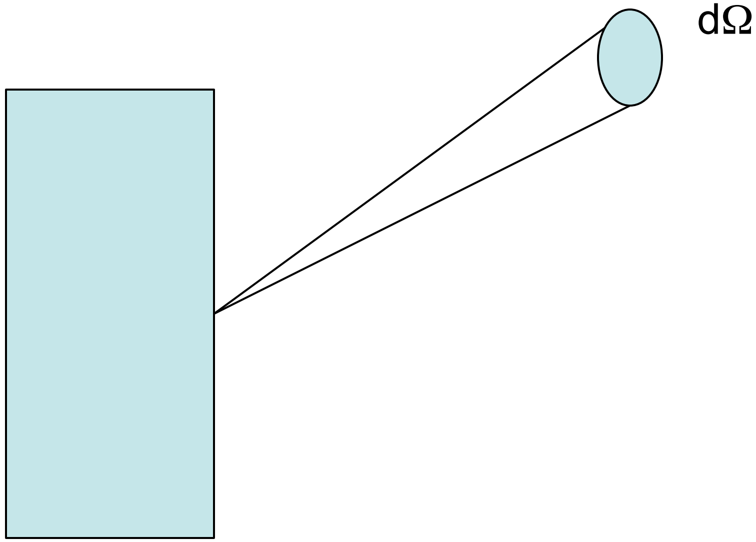
Nanoantennas for
Smart IR incandescent sources

Infrared sources

Available IR sources ?

1. LEDs : low efficiency in the IR
2. Quantum Cascade Lasers
3. OPO
4. Incandescent sources : globars, hot membranes.

A key concept : Kirchhoff's law



$$d\Phi = I_\lambda dS \cos\theta d\Omega$$

$$I_\lambda = \varepsilon_\lambda(\theta) I_\lambda^o(T)$$

$$\varepsilon_\lambda = \alpha_\lambda = 1 - R_\lambda = T_\lambda$$

J. Opt. Soc. Am. A. ***10****, 2735 (1998)*

Incandescent IR sources

(Bad) Features of thermal sources

Low brightness

Narrow spectrum

Directional emission

Improved efficiency

Fast modulation

Smart Incandescent IR sources

(Bad) Features of thermal sources

Low brightness

Narrow spectrum

Directional emission

Improved efficiency

Fast modulation

Low brightness

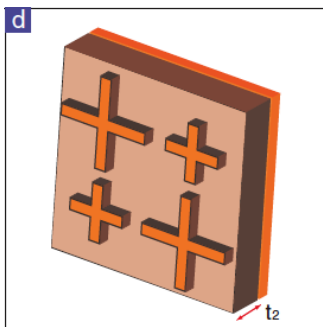
Broad spectrum (low temporal coherence)

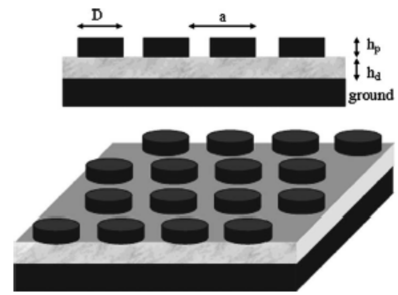
Quasi-isotropic (low spatial coherence)

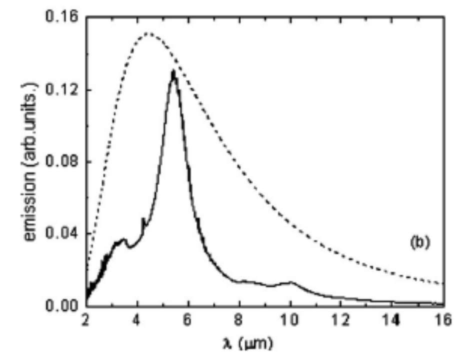
Low efficiency

Slow modulation

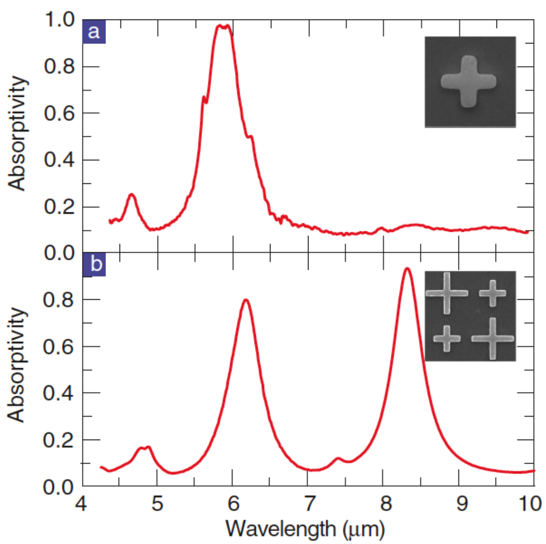
Narrow Spectrum (temporal coherence)

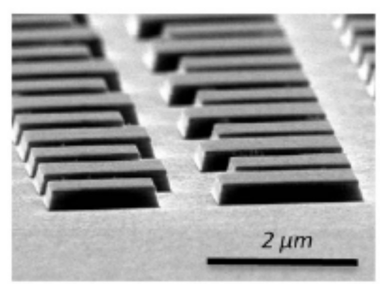


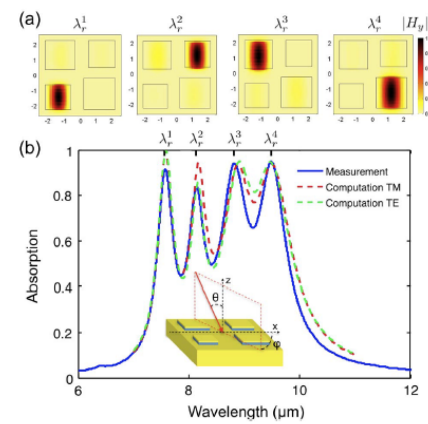




Puscasu, *Appl.Phys.Lett.* **92**, 233102 (2008)



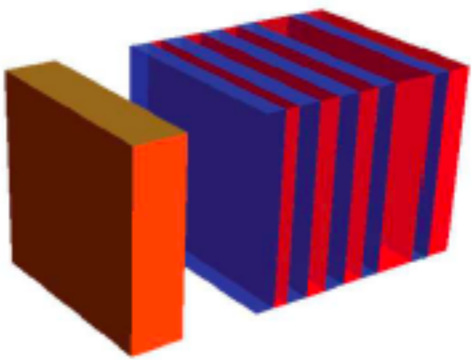


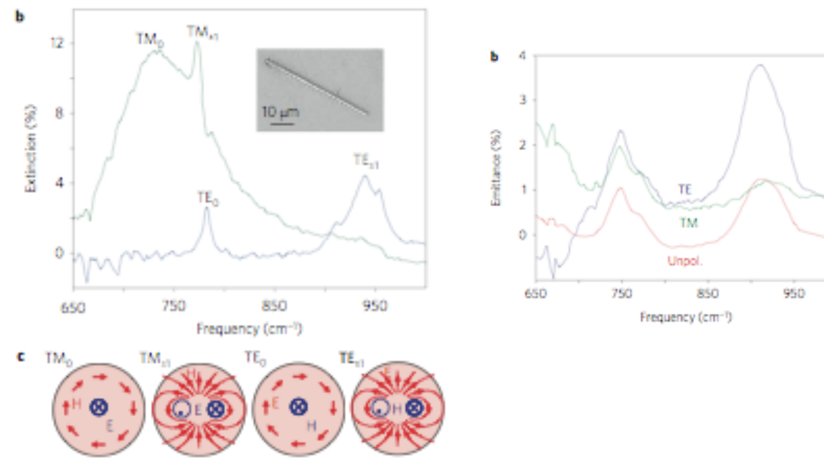


*Liu et al. Phys.Rev.Lett.***107***, 045901, (2011)*

Bouchon et al., Opt.Lett. **37**, 1038 (2012)

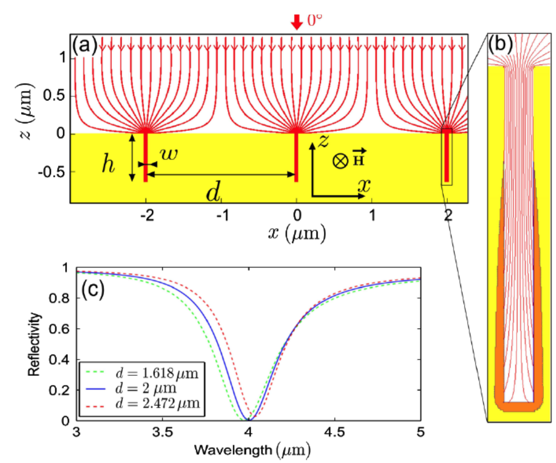
Narrow Spectrum (temporal coherence)





J. Schuller et al. Nature Photonics 3, 658 (2009)

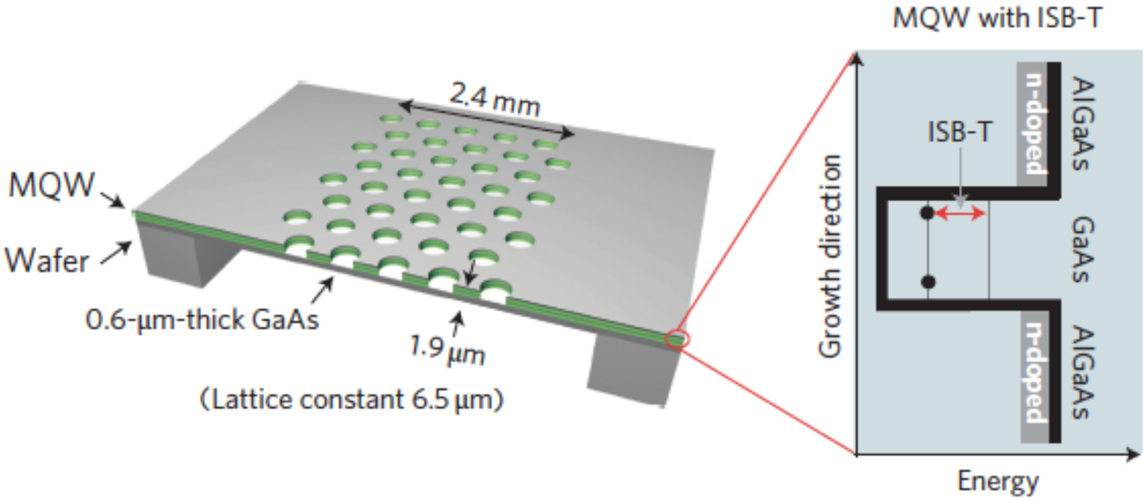
Dielectric stack on a tungsten substrate
to filter the emission

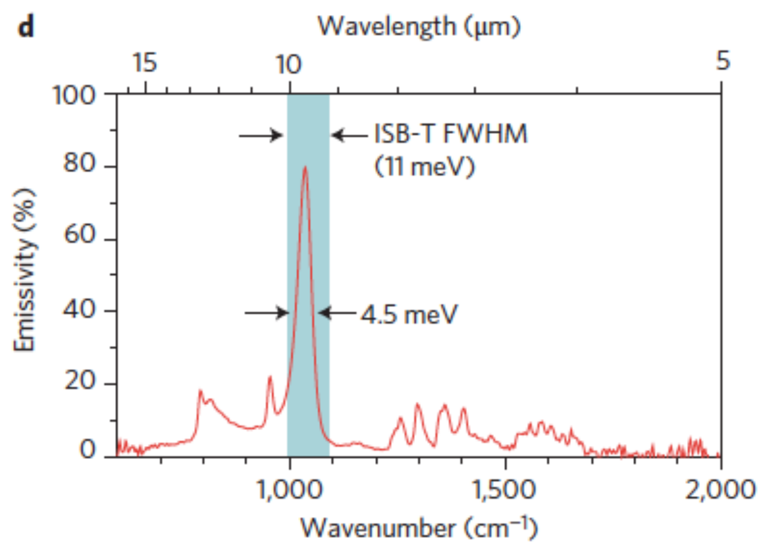


E. Rephaeli, Opt.Express 17, 15145 (2009)

Pardo et al. Phys.Rev.Lett.107, 093902, (2011)

Narrow Spectrum (temporal coherence)





De Zoysa et al. Nature Photonics 6, 535 (2012)

Low brightness

Broad spectrum (low temporal coherence)

Quasi-isotropic (low spatial coherence)

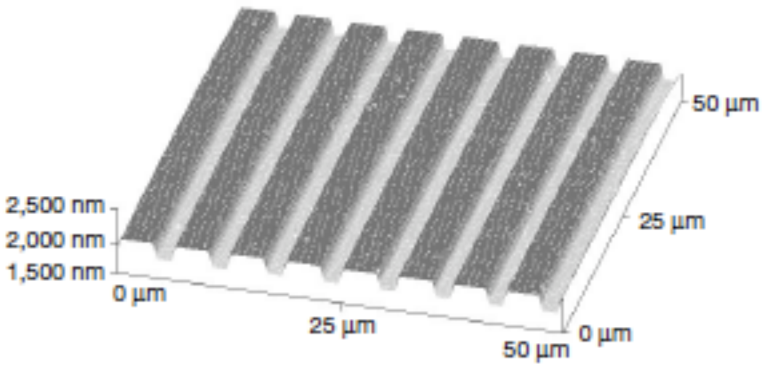
Low efficiency

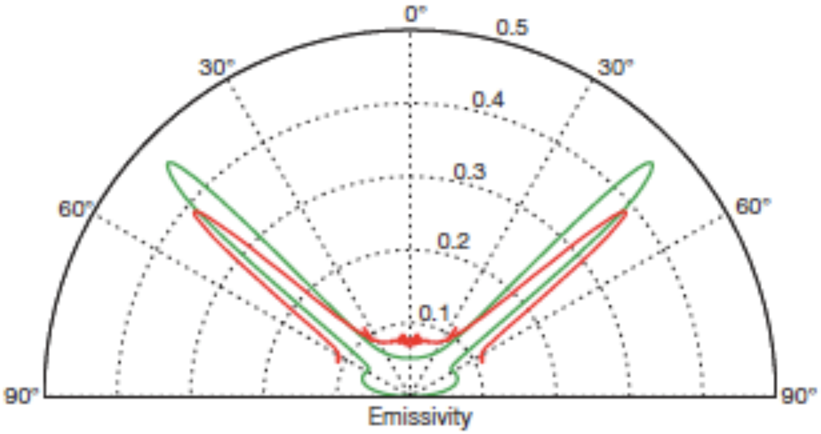
Slow modulation

Design strategies :

1. Use resonant absorption by a surface wave
2. Design a directional transmission filter

Directivity (spatial coherence)

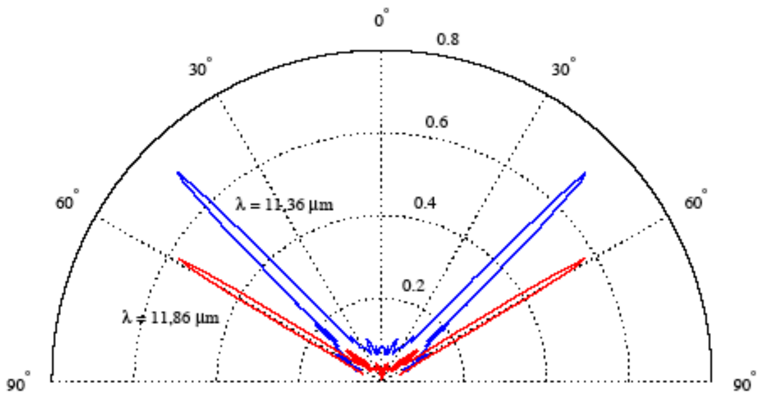


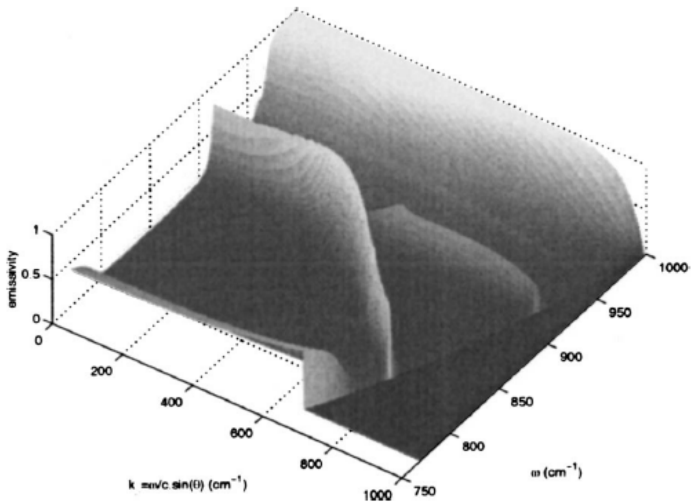


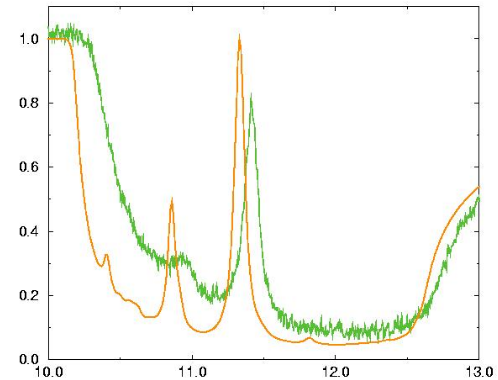
Coherent emission of light by thermal sources

Jean-Jacques Greffet*¶, Rémi Carminati*, Karl Joulain*, Jean-Philippe Mulet*, Stéphane Mainguy† & Yong Chen‡

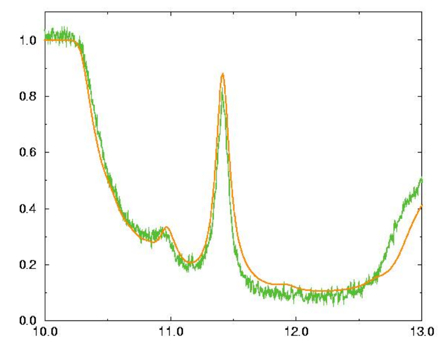
NATURE | VOL 416 | 7 MARCH 2002 | www.nature.com







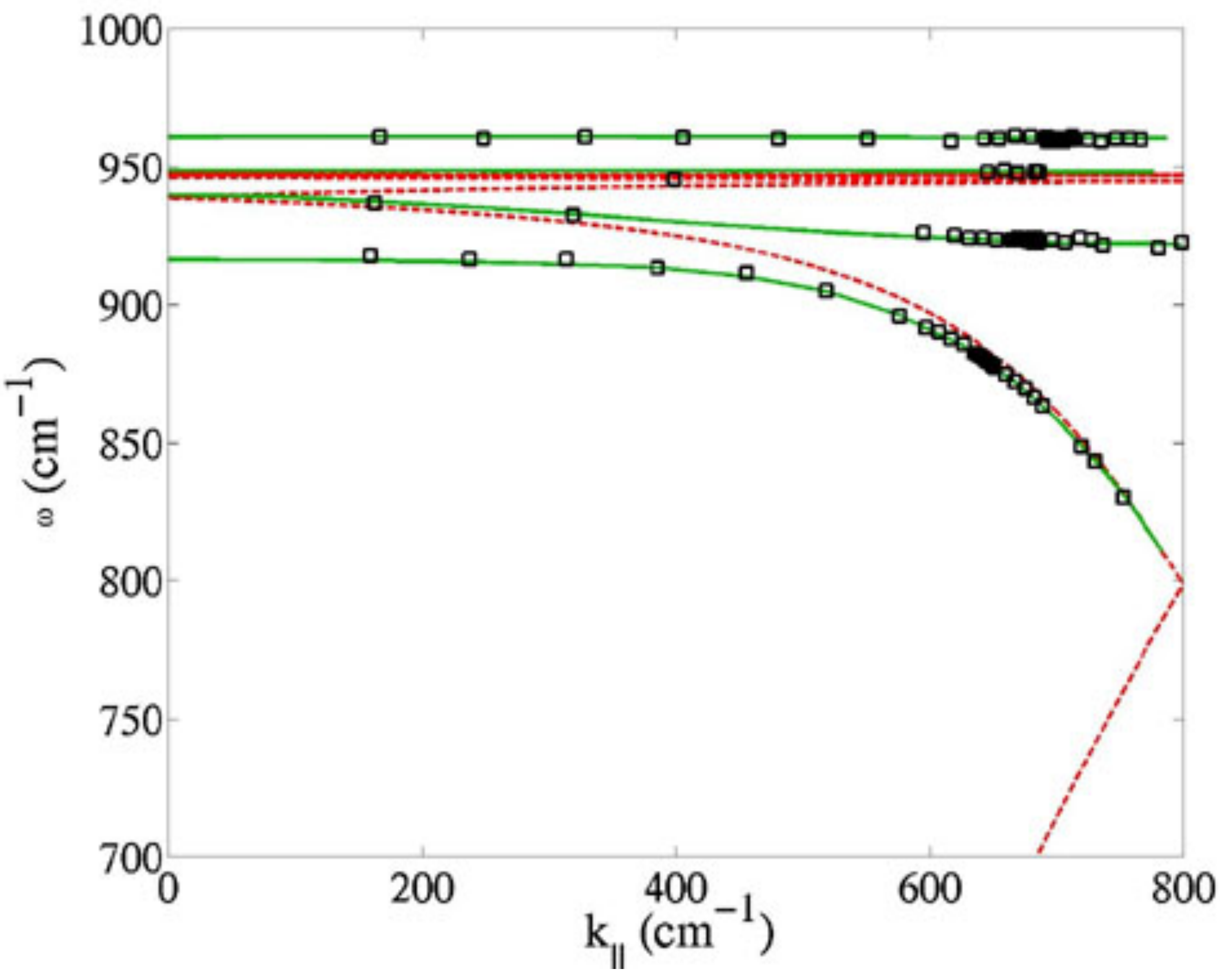
Calculation with optical data at 300 K



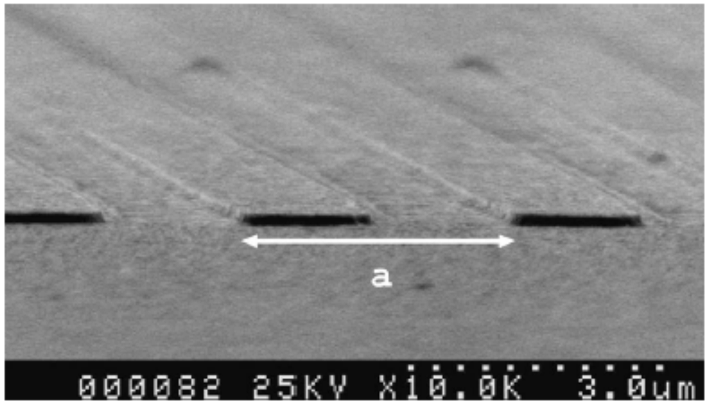
Calculation with optical data at 800 K

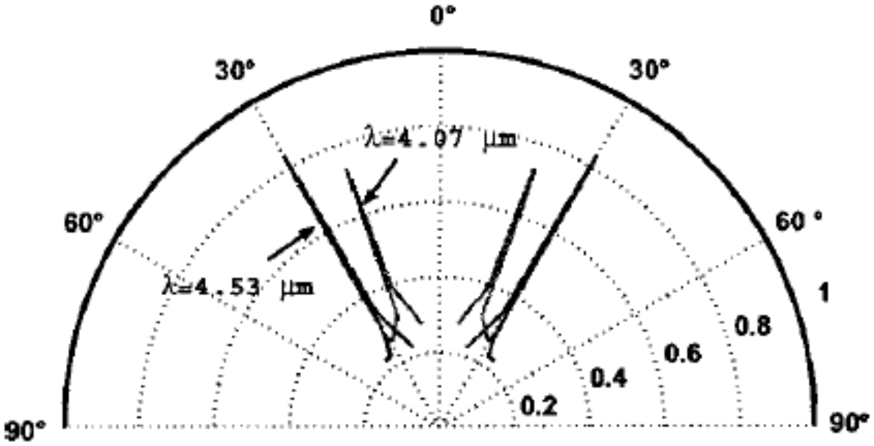
*F. Marquier et al. Phys.Rev.B **69**, p 155412 (2004)*

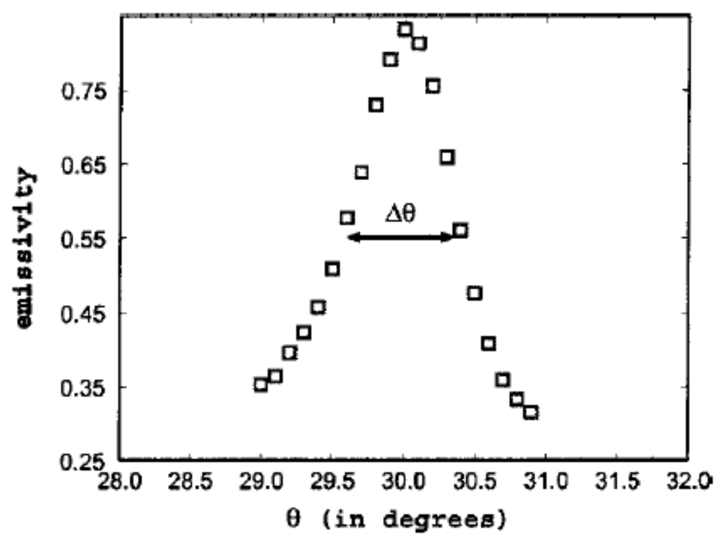
SPhP Dispersion relation



Highly directional thermal emission

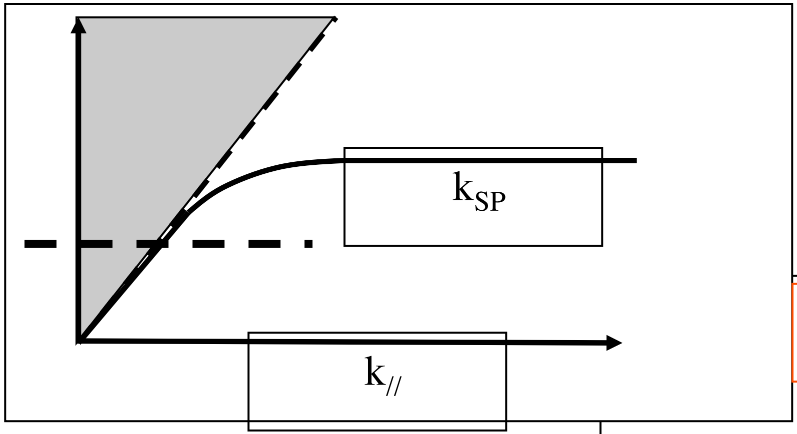


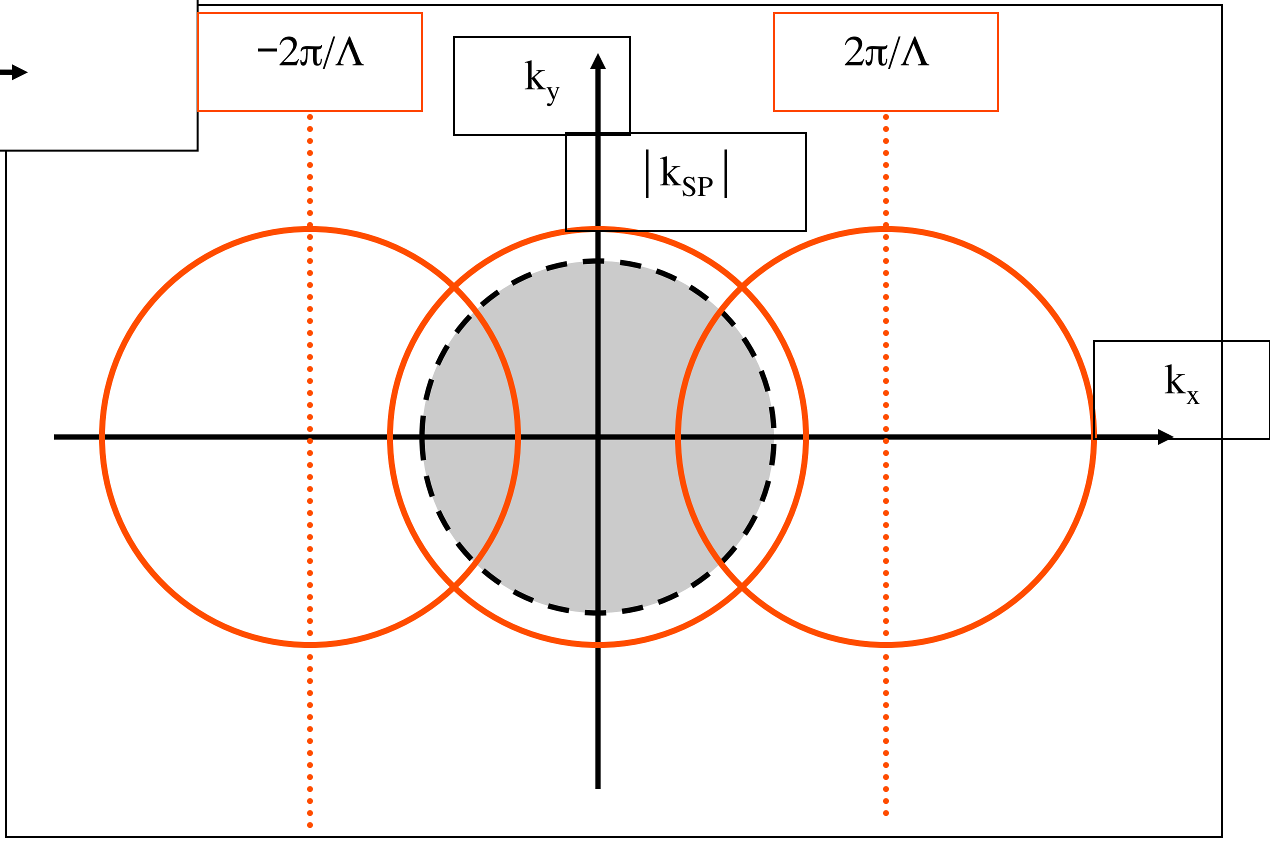




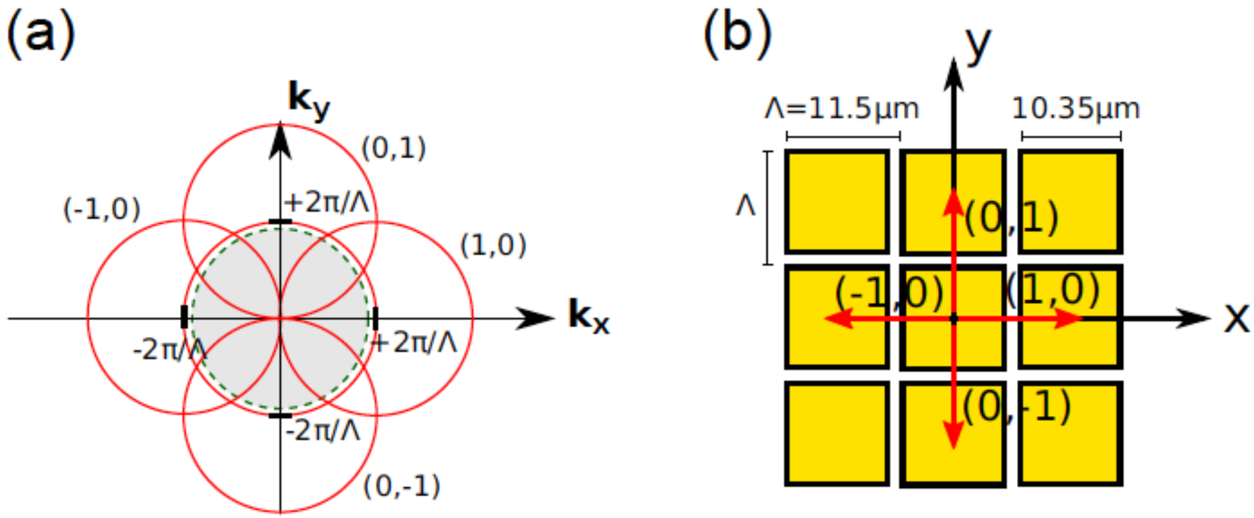
M. Laroche et al. Opt.Lett. ***19****, p 2623 (2005)*

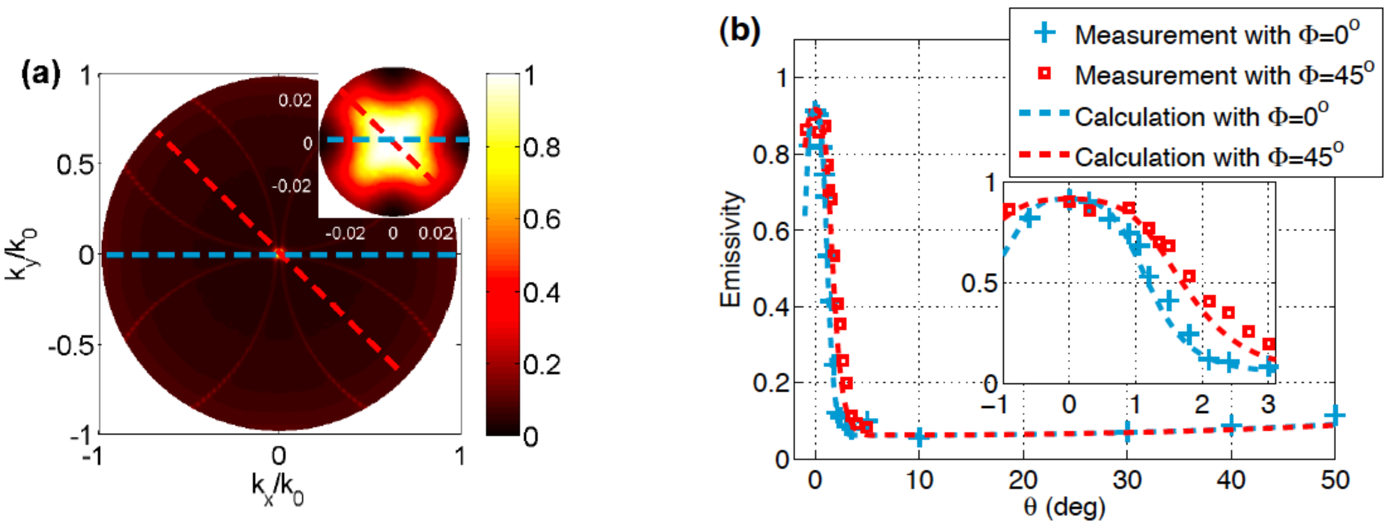
Dispersion relation





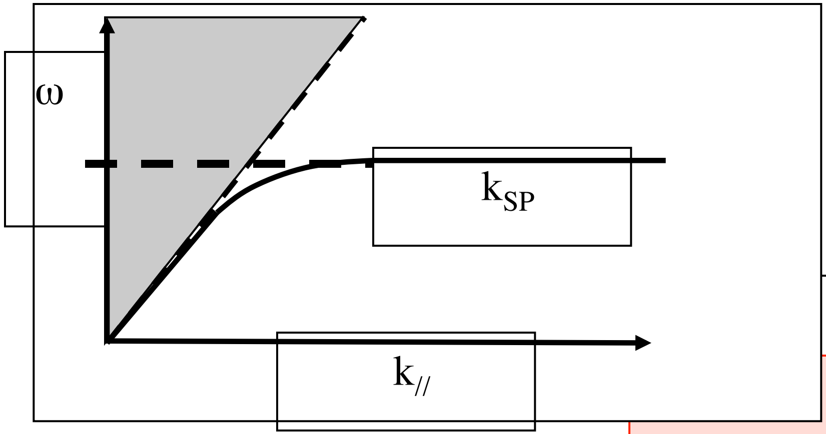
Vertical emission

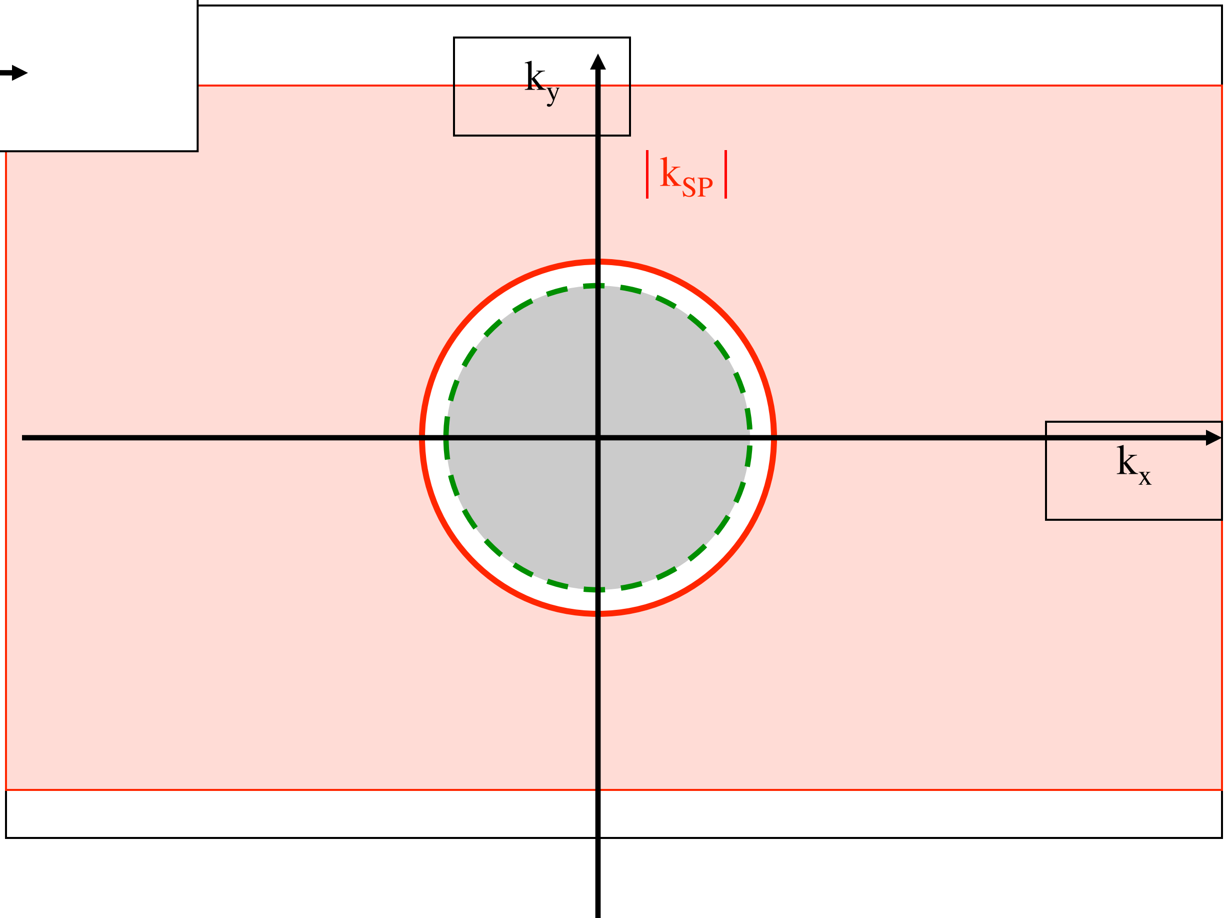




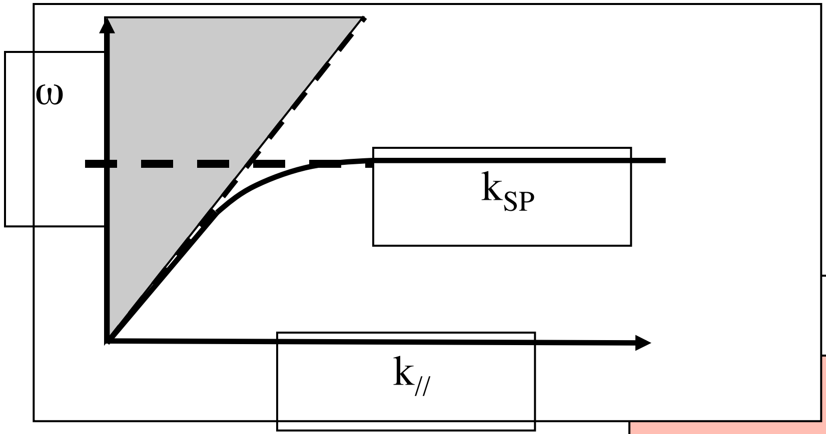
C. Arnold et al., Phys.Rev.B ***86****, 035316 (2012)*

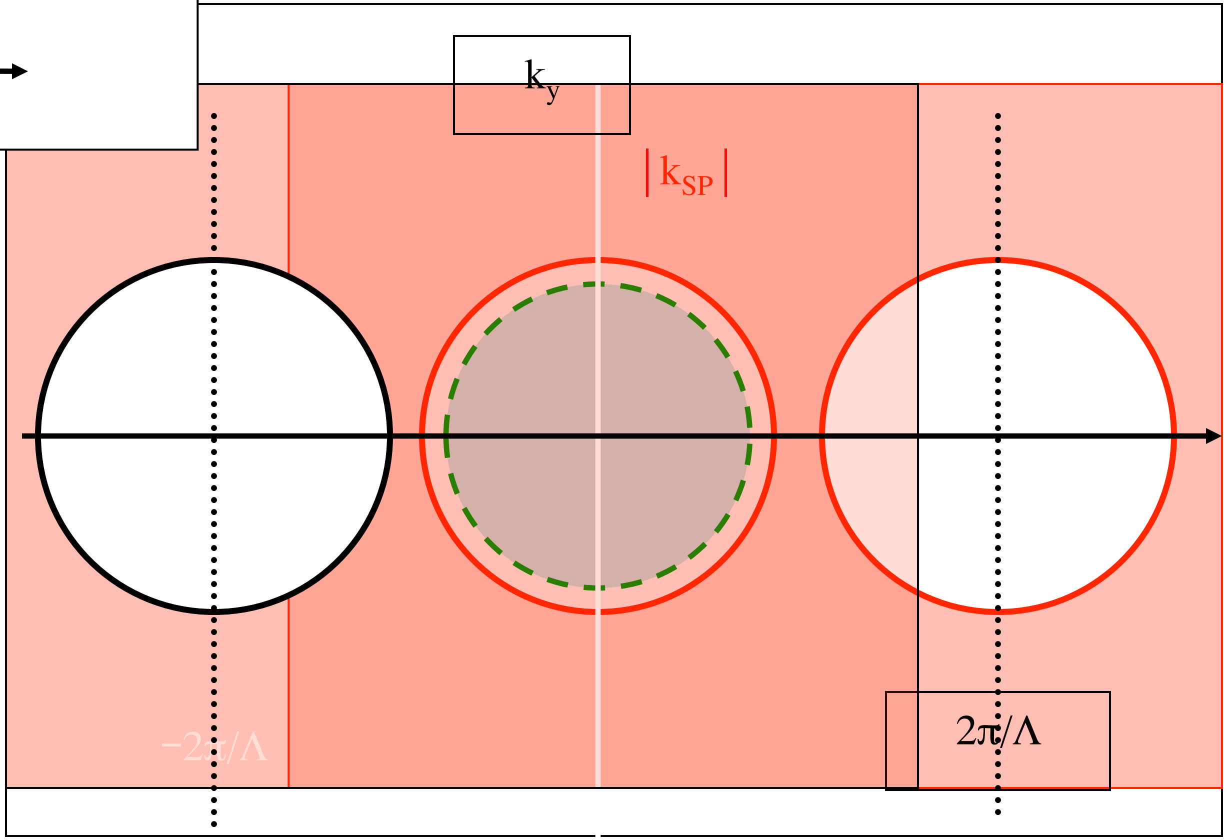
Dispersion relation



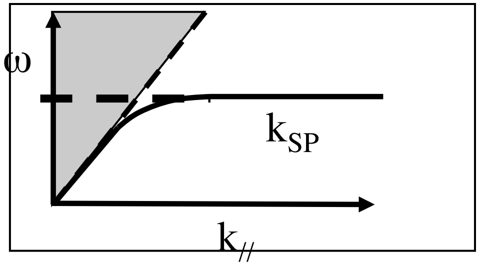


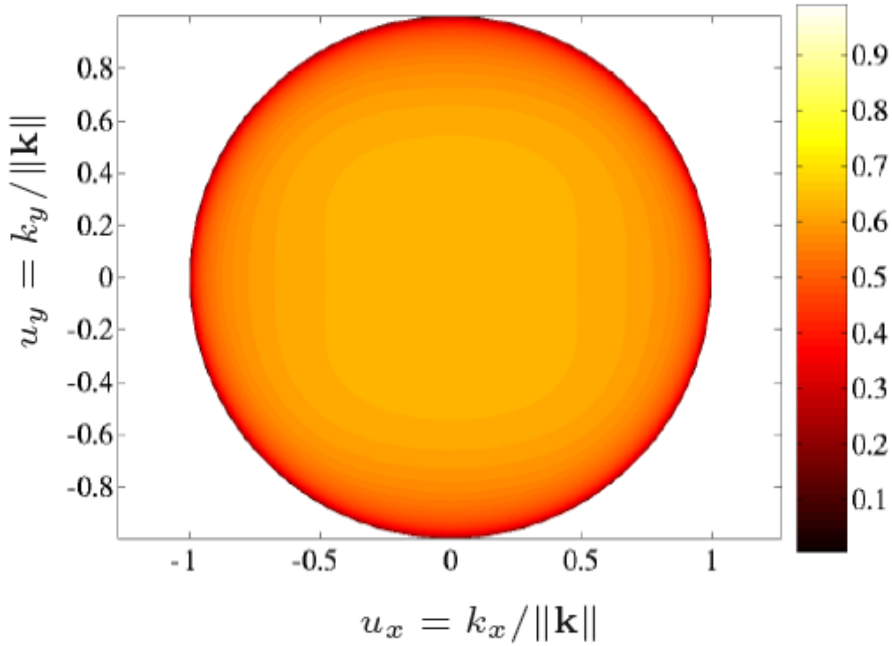
Dispersion relation





Absorption / emission pattern





average emissivity in both p- and s-polarization
(λ=10.9μm)

Low brightness

Broad spectrum (low temporal coherence)

Quasi-isotropic (low spatial coherence)

Low efficiency

Slow modulation

Slow modulation

$$d\Phi = I_\lambda dS \cos\theta d\Omega$$

$$I_\lambda = \varepsilon_\lambda(\theta) I_\lambda^o(T)$$

Modulation is obtained by modulating the temperature.
The cooling dynamics limits the modulation to a few Hz.

Can we solve this problem ?

Slow modulation

$$d\Phi = I_\lambda dS \cos\theta d\Omega$$

$$I_\lambda = \varepsilon_\lambda(\theta) I_\lambda^o(T)$$

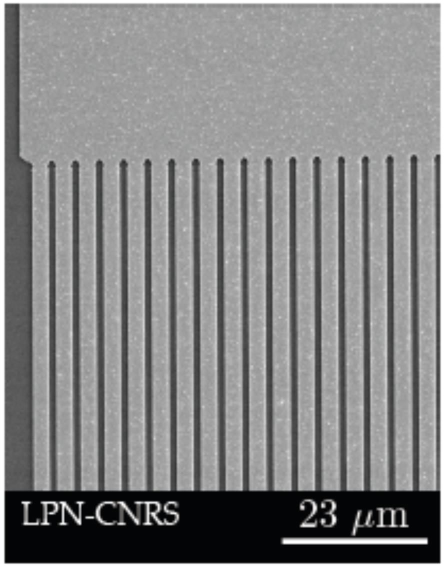
Design strategy :

1.Design a structure with *actively controlled* resonant absorption,

JJG, Nature 478, 191 (2011)

Smart incandescent emitters

Controlling electrically the emissivity with surface waves

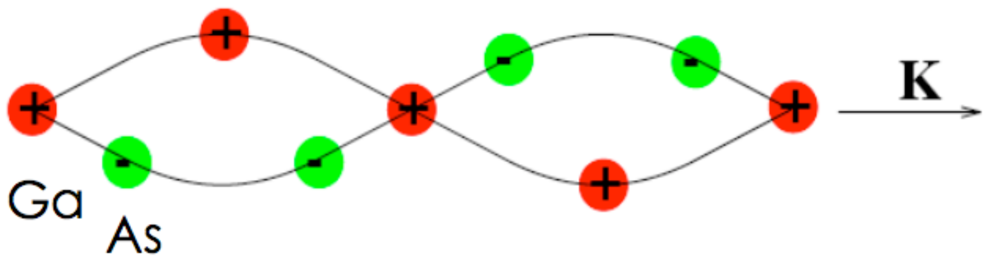


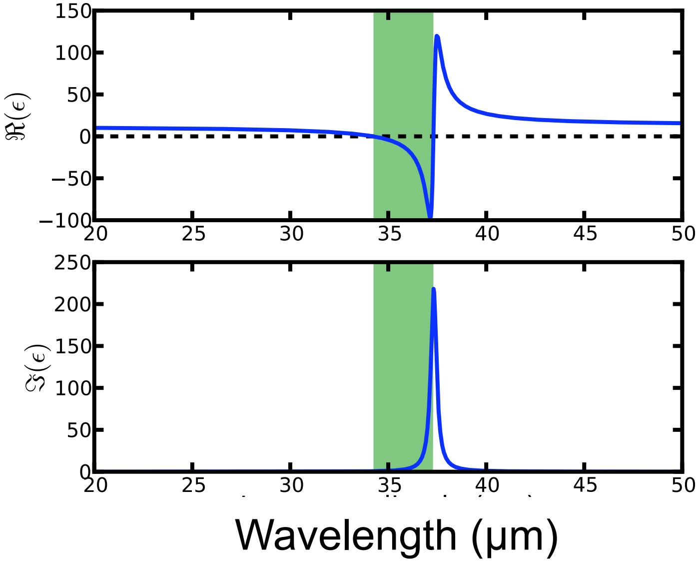
Simon Vassant, Jean-Luc Pelouard, Fabrice Pardo
LPN, CNRS

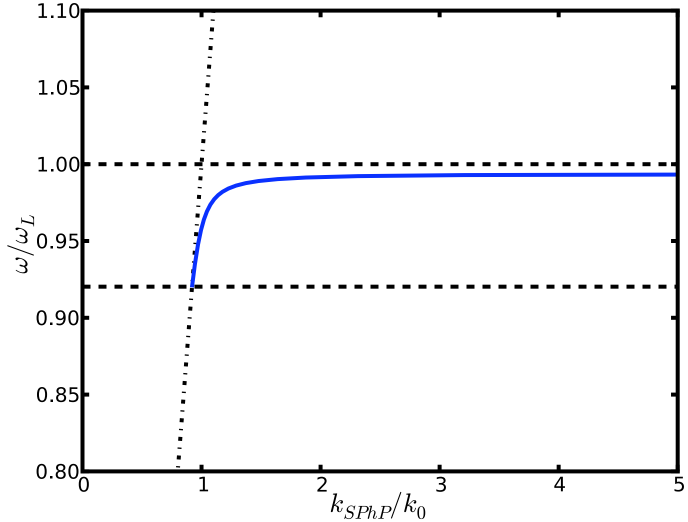
François Marquier

Phys.Rev.Lett. ***109,*** *237401 (2012)*

Surface phonon polaritons



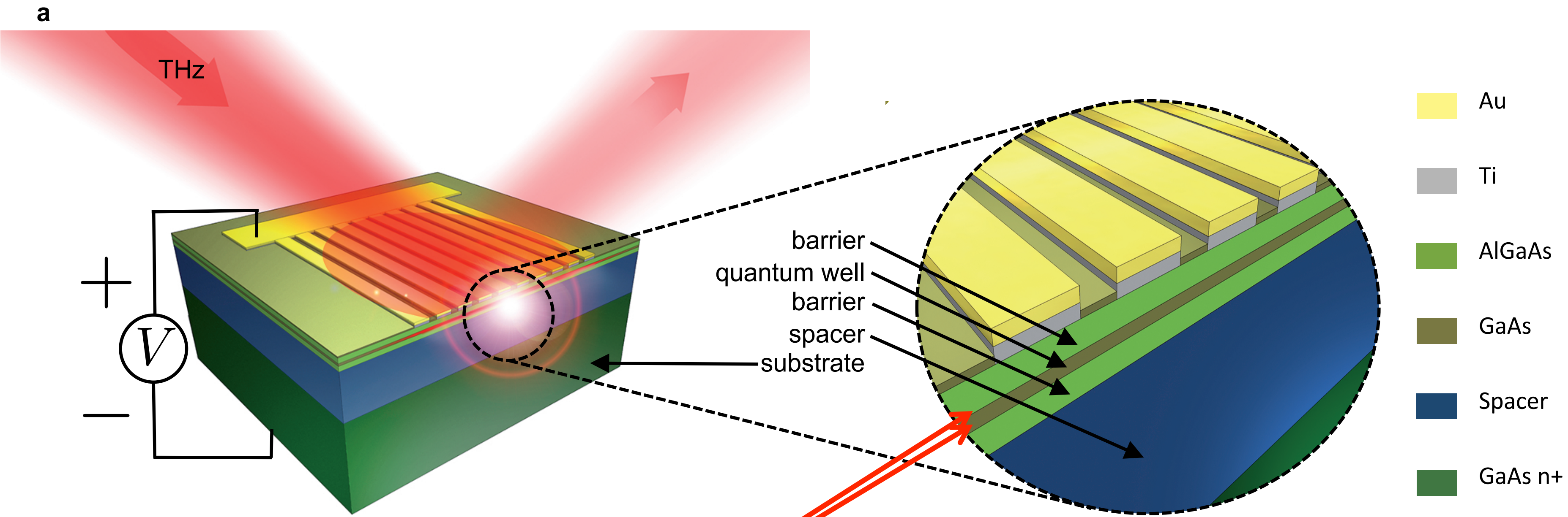




Dielectric constant

Surface phonon polariton dispersion relation

Electrical modulation of reflectivity



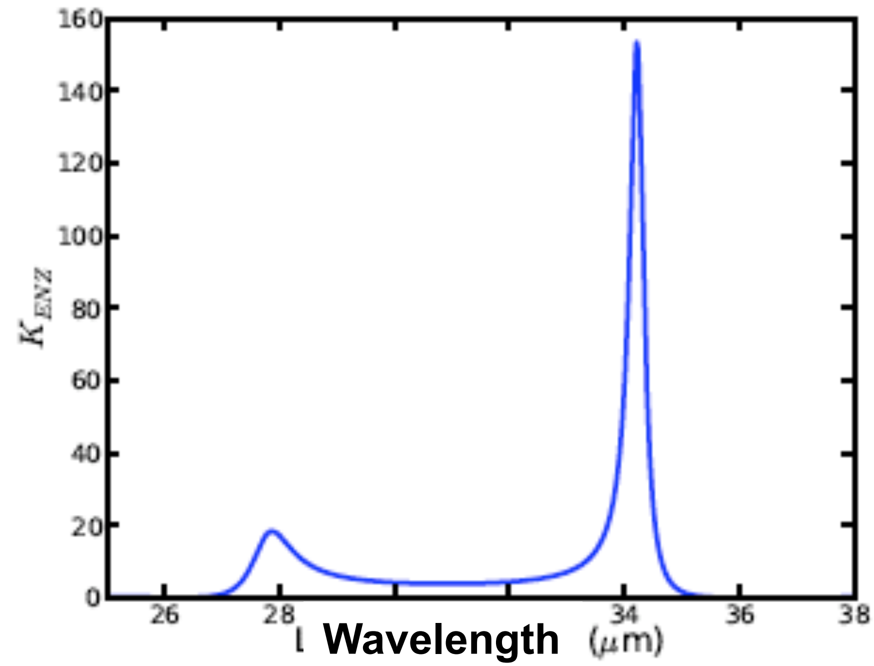
1. **Surface mode at the Quantum well interfaces**
2. **Grating coupler**
3. **Resonant Intersub-band transitions to control the refractive index in the Quantum well**

S. Vassant et al. PRL ***109****, 237401 (2012)*

The Epsilon Near Zero effect

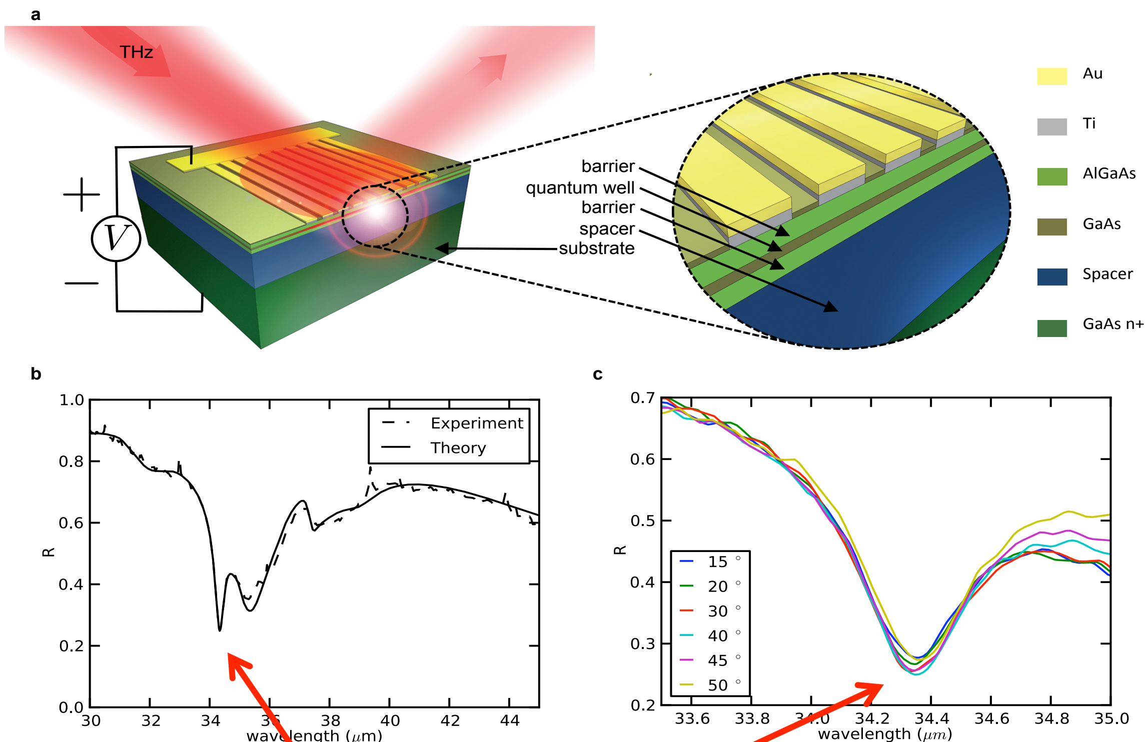
$$|E_{zGaAs}|^2 = \left|\frac{\epsilon_{zAlGaAs}}{\epsilon_{zGaAs}}\right|^2 |E_{zAlGaAs}|^2$$

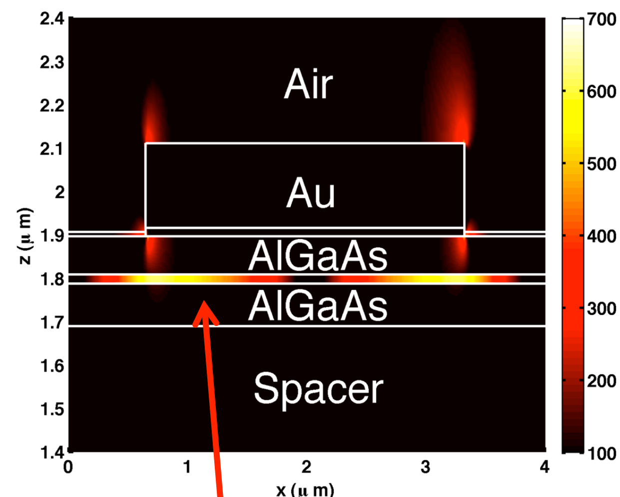
$$= K_{ENZ} \quad |E_{zAlGaAs}|^2$$



S. Vassant et al. PRL **109**, 237401 (2012)

Resonant absorption by a single QW



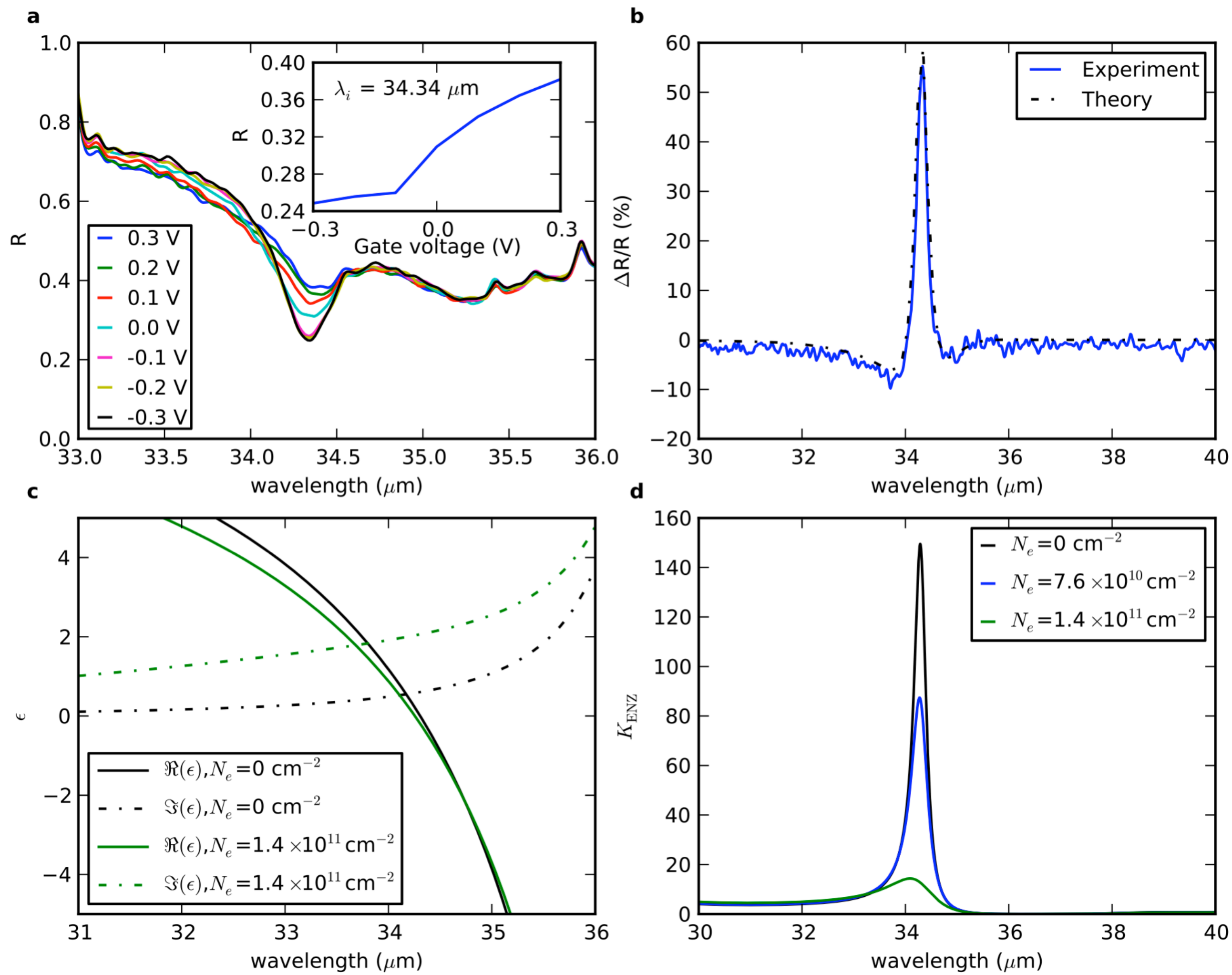


76% of the incident energy is absorbed
45% of the incident energy is absobed *in the QW*

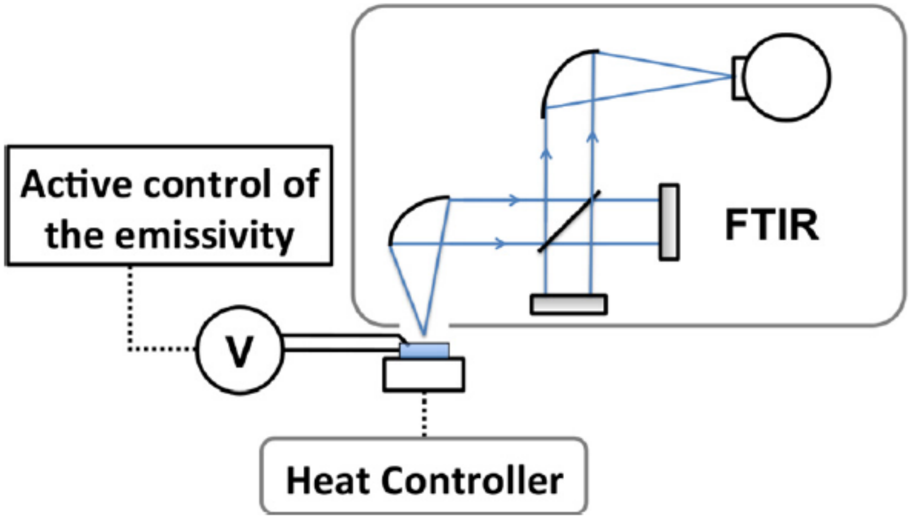
*S. Vassant et al. PRL **109**, 237401 (2012)*

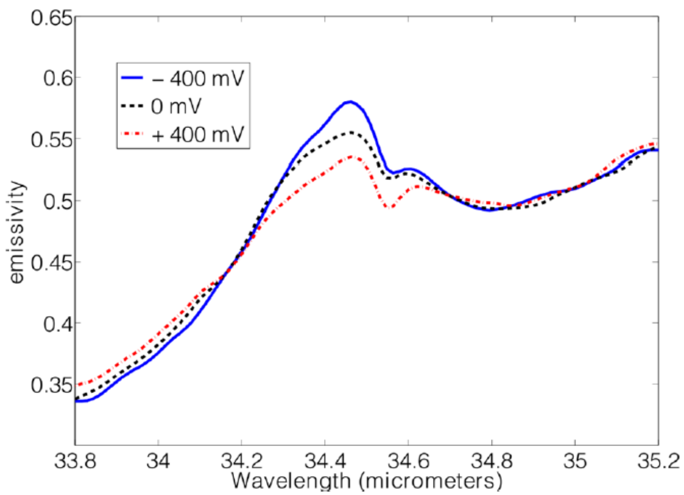
Using electrons to control phonon absorption

$$\varepsilon_{zz} = \varepsilon_{GaAs} - \sum_{n,n'} \varepsilon_{\infty} \frac{f_{nn'}\omega_p'^2}{\omega^2 - \omega_{nn'}^2 + i\gamma_{isb}\omega} \qquad \omega_p'^2 = \frac{(N_n - N_{n'})e^2}{\varepsilon_0 m^*}$$



Electrically modulated emissivity





S. Vassant et al., Appl.Phys.Lett. ***102****, 081125 (2013)*

Plasmonic nanoantennas for single photon emission

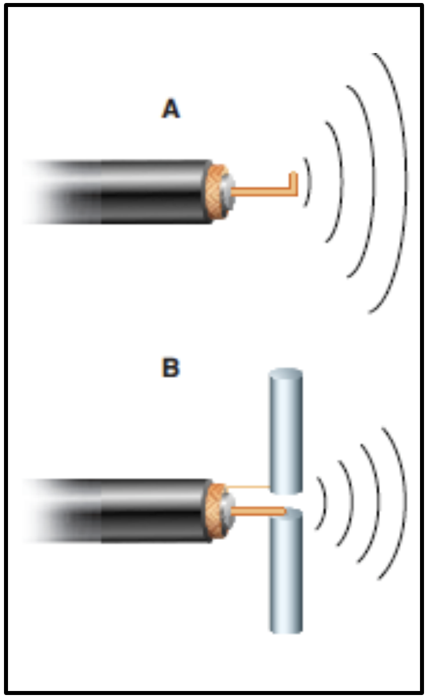
Goal of an antenna

Increase the coupling between :

a localized source/ detector

and

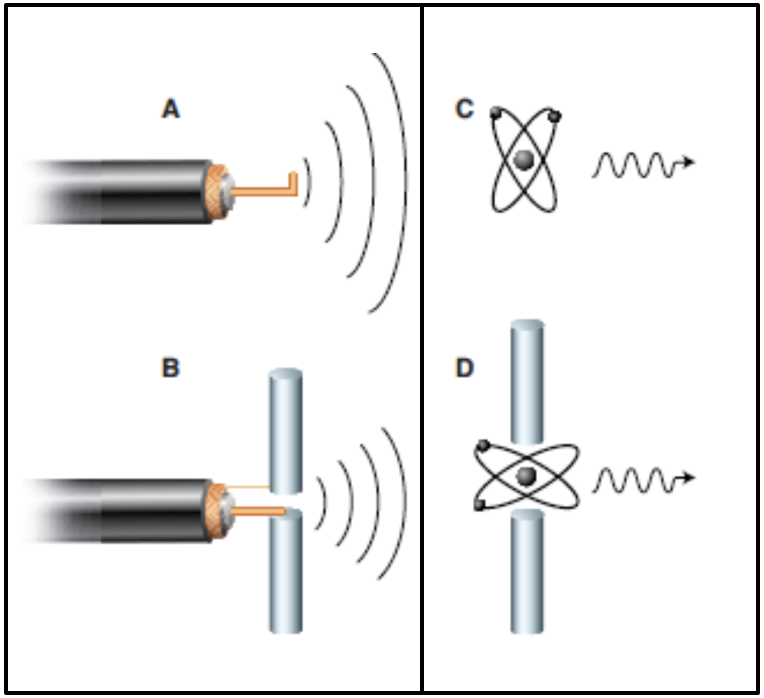
propagating waves



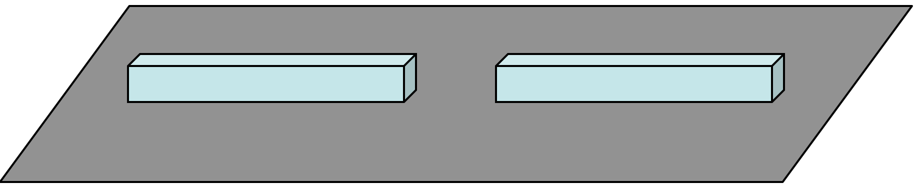
Goal of an antenna for single photon emission

Reduce the decay time

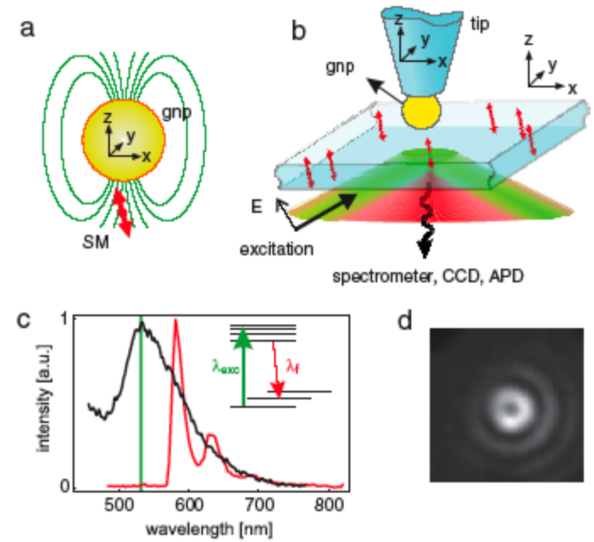
Collect all the emitted photons



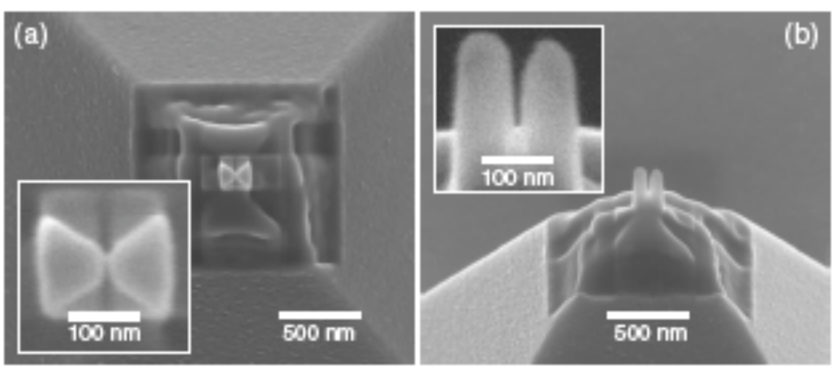
Nanoantennas



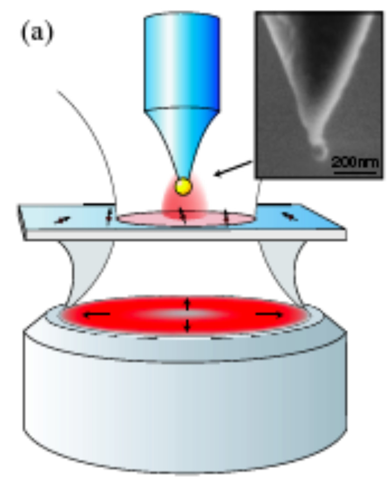
Mühlschlegel et al. Science 308 p 1607 (2005)



Kühn et al. PRL 97, 017402 (2006)

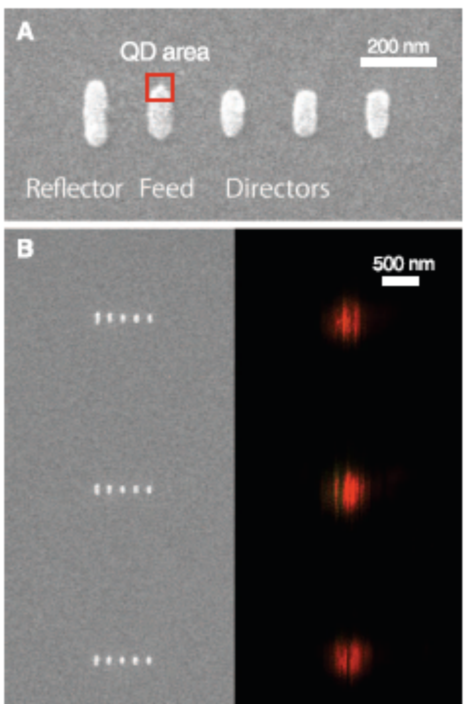


Farahani et al., PRL 95, 017402 (2005)



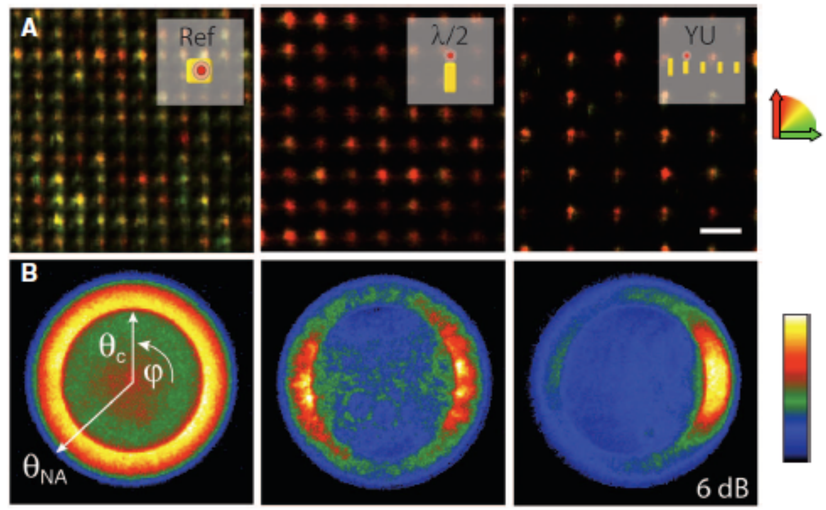
Anger et al., PRL 96, 113002 (2006)

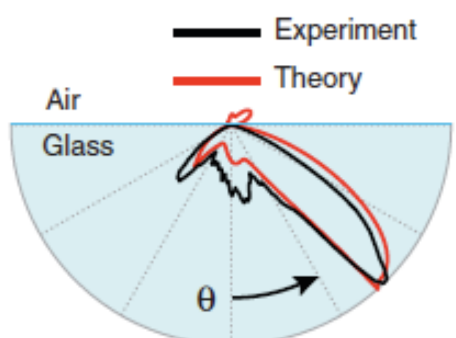
Controlling the direction (1)



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)

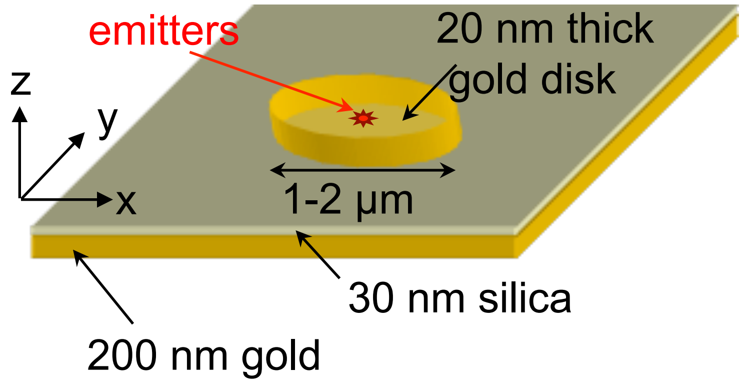
Motivation

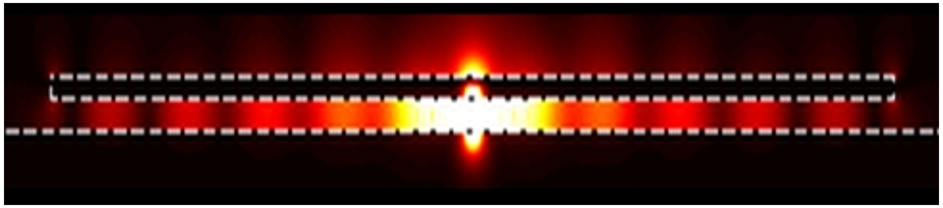
Design and *fabricate deterministically* a plasmonic antenna in order to

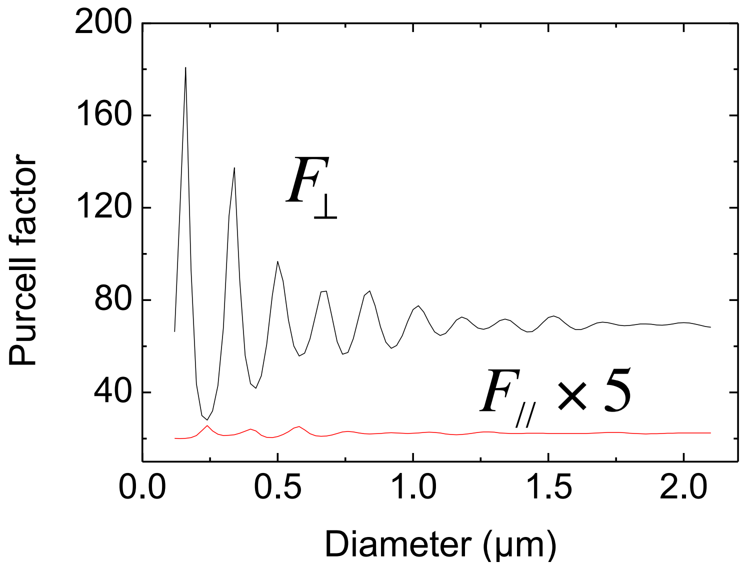
- *accelerate* spontaneous emission,
- *control* the angular emission

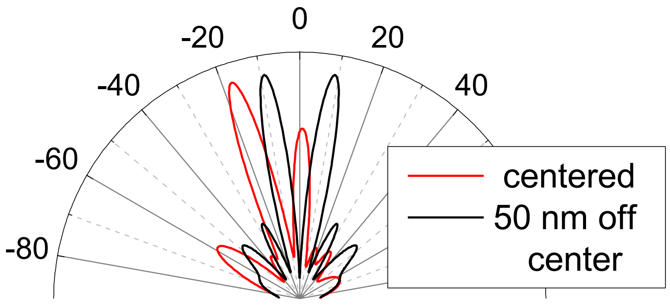
over a *broad band*.

Patch Antenna



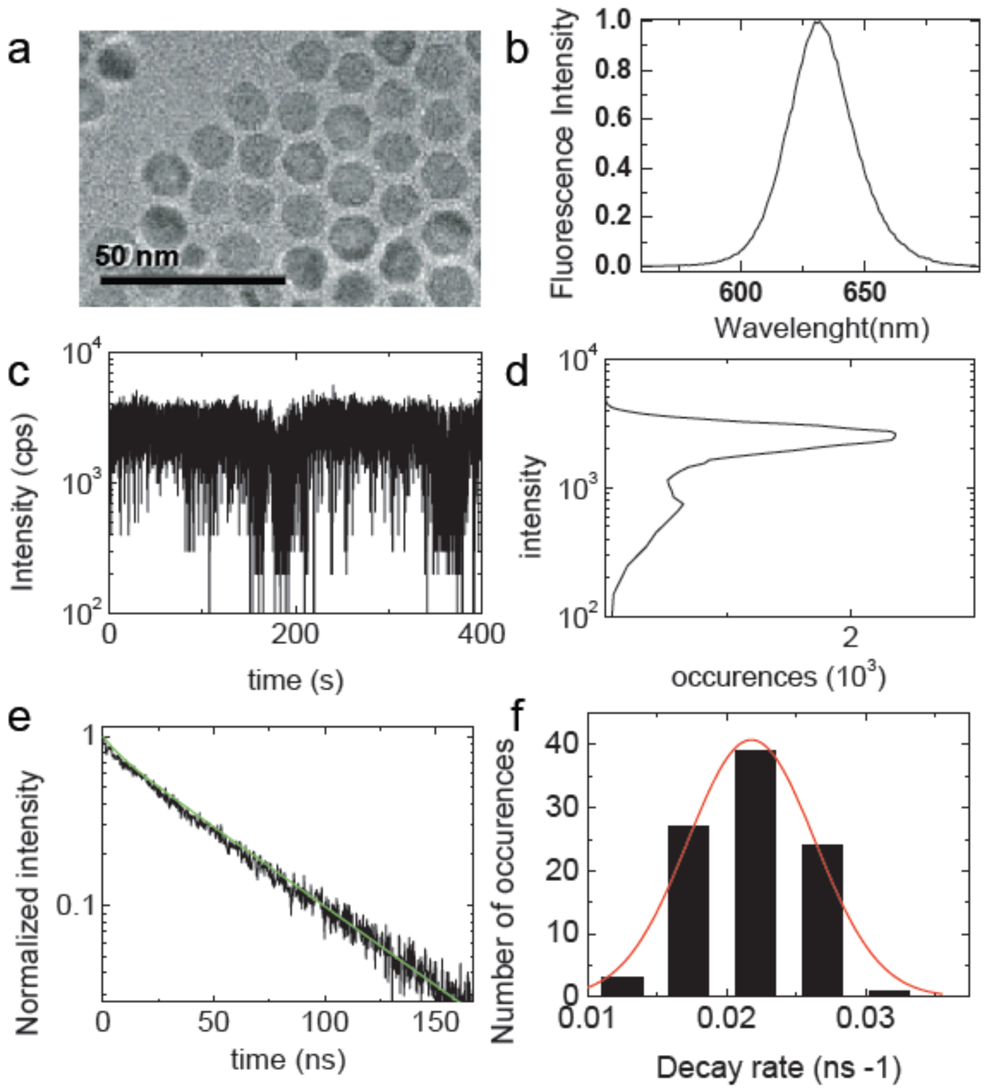






Diameter 1.5 µm

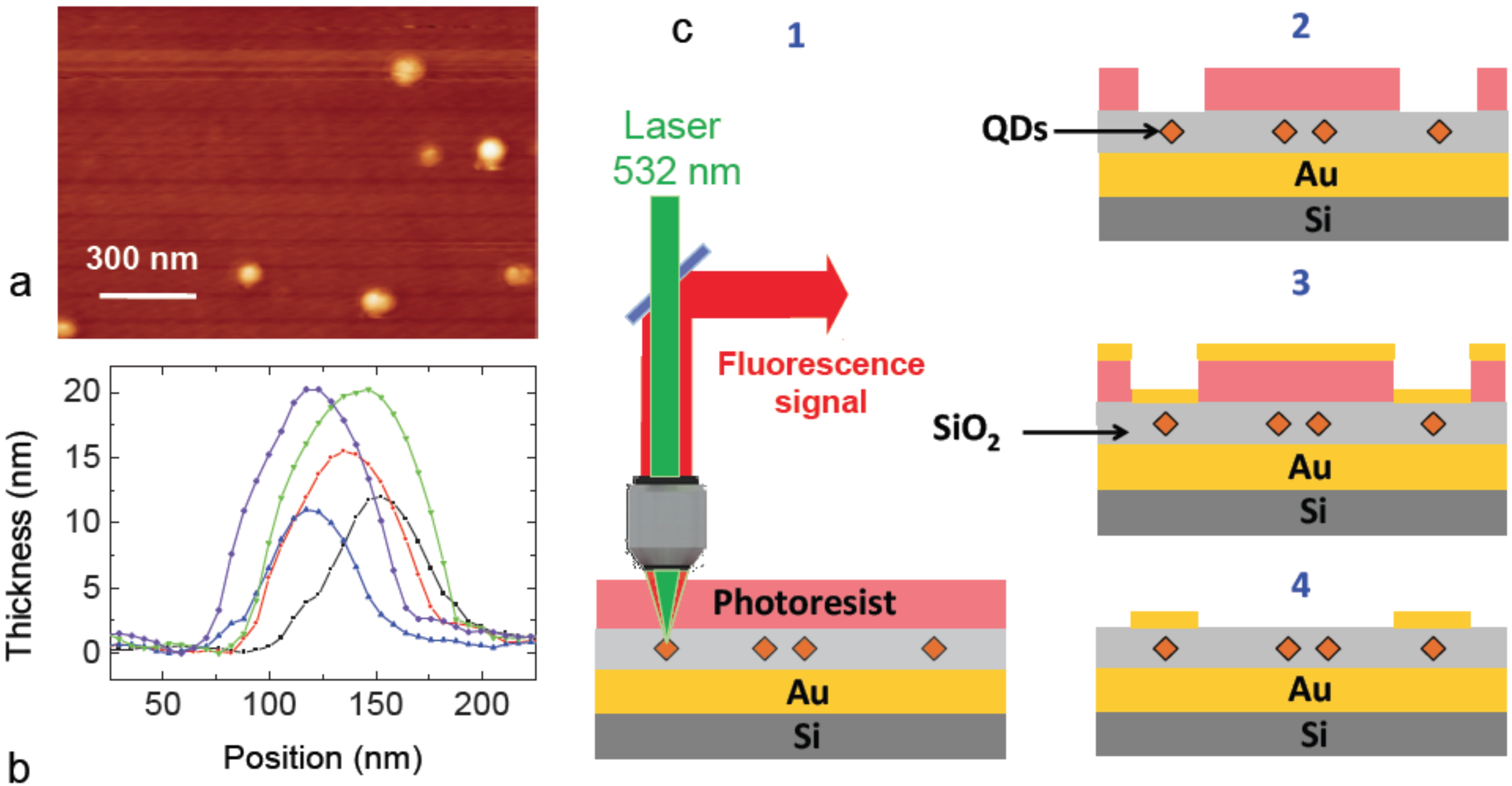
Quantum dots characterization



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

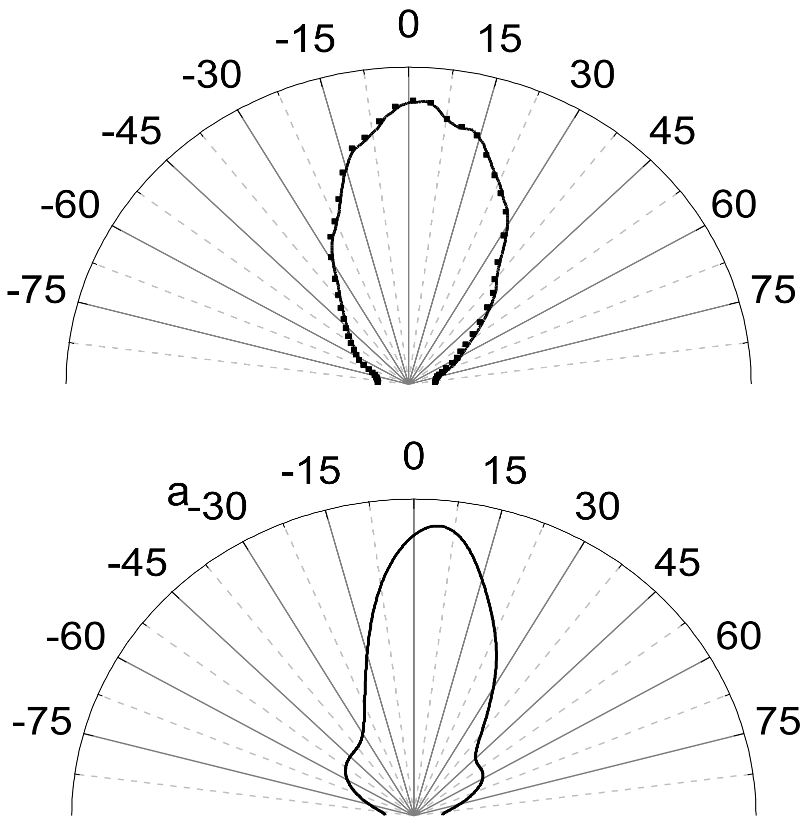
87% photons emitted in bright state, 13% In the grey state.

Patch Antenna Fabrication

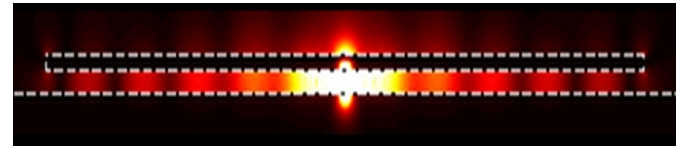


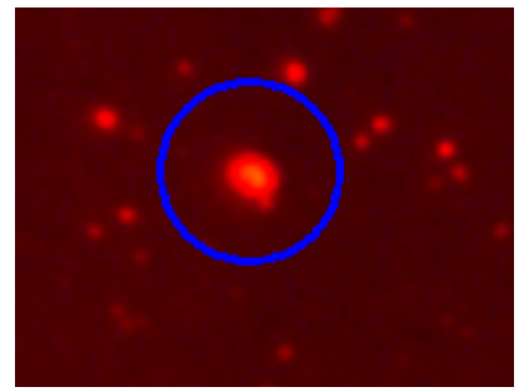
Collaboration LPN/Attocube (now commercially available)

Controlling the angular emission

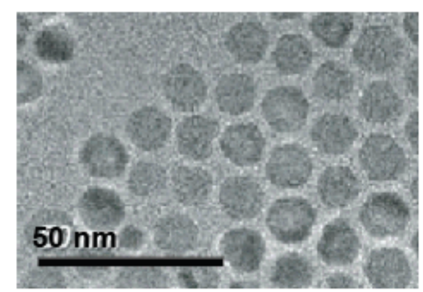


b

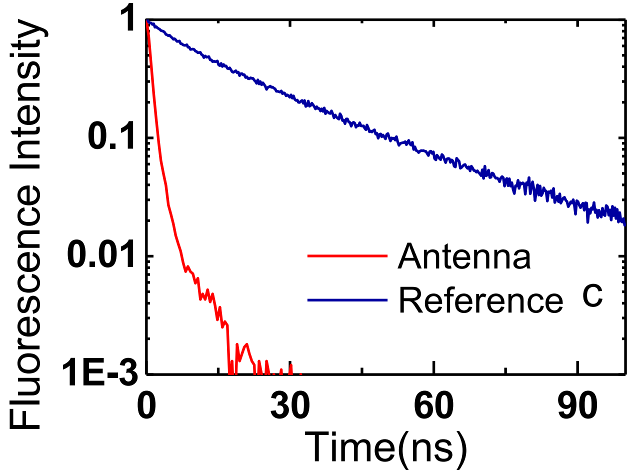


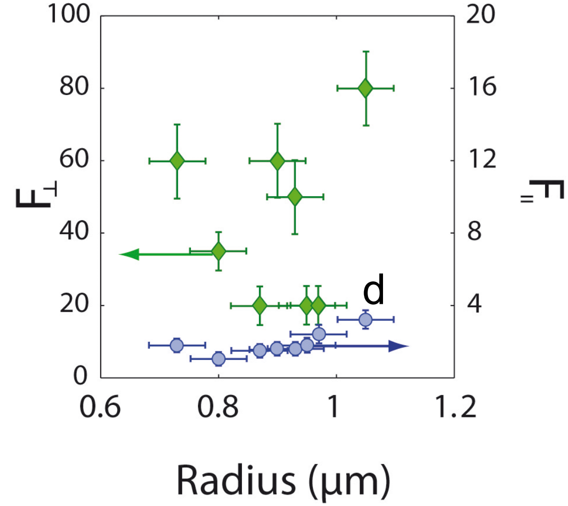


a



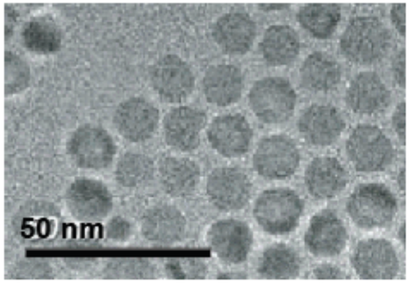
Accelerating spontaneous Emission

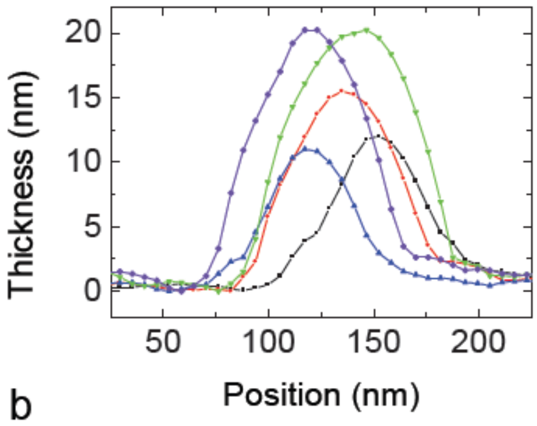


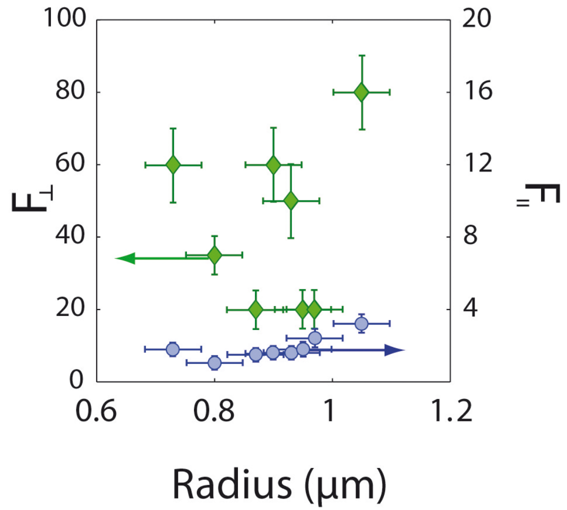


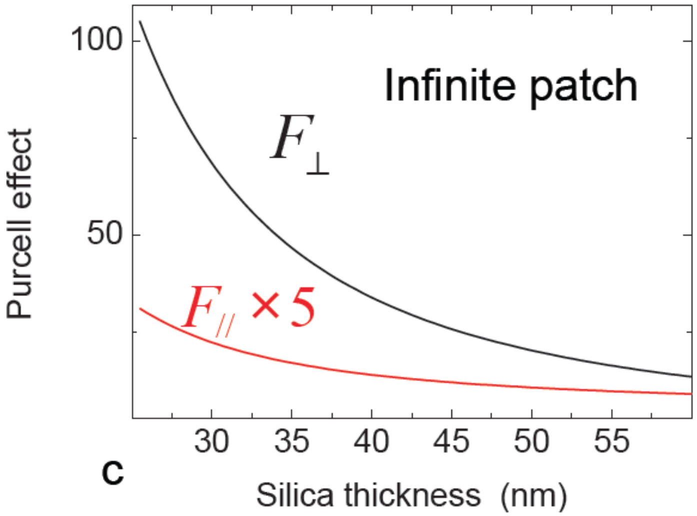
Origin of the Purcell fluctuations

The QD cluster thickness fluctuates.

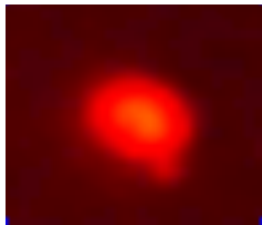


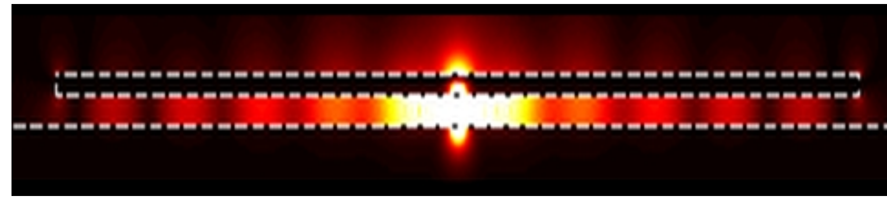


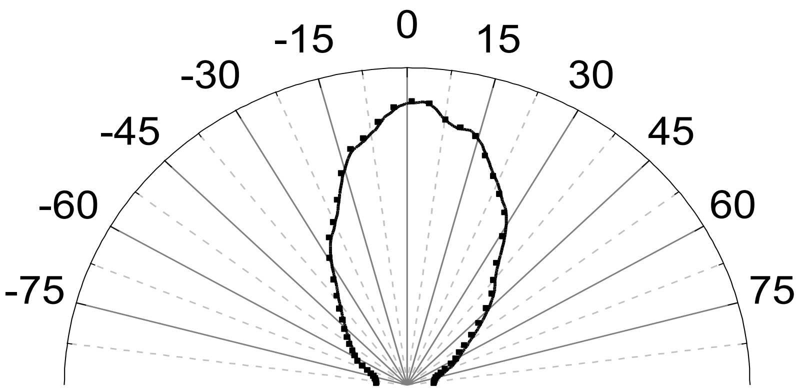


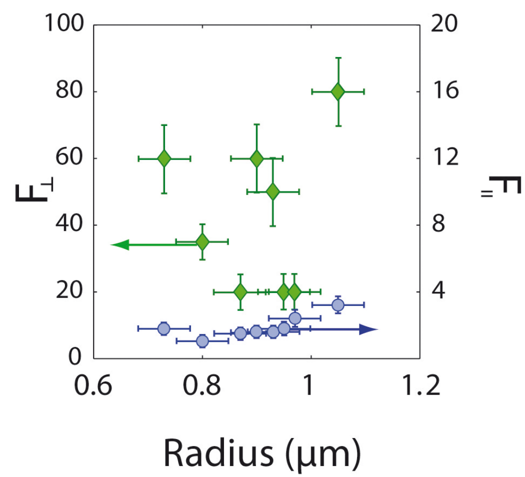


Summary





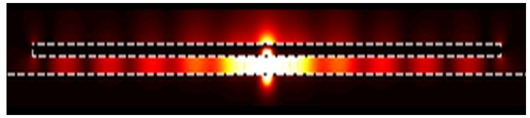




- **Promising solution for single photon sources at 1.5 µm.**

Quenching or photon emission ?

Quenching or SPP emission ?

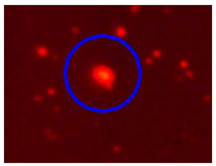


Photon (5%)

Joule losses

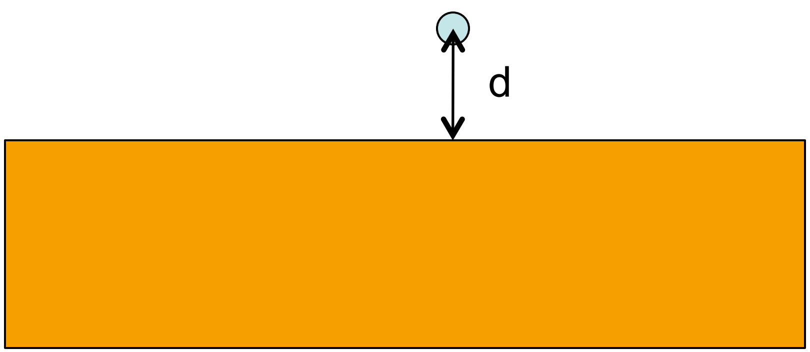
Antenna modes spontaneous emission

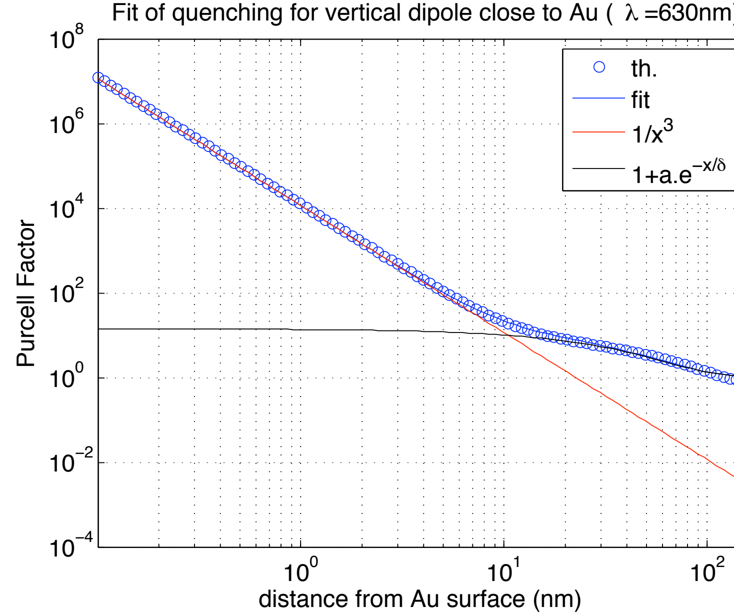
Excited QD



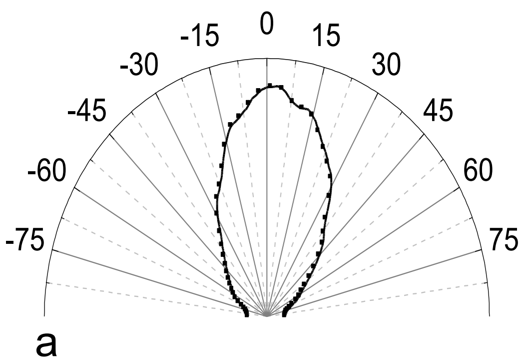
Quenching

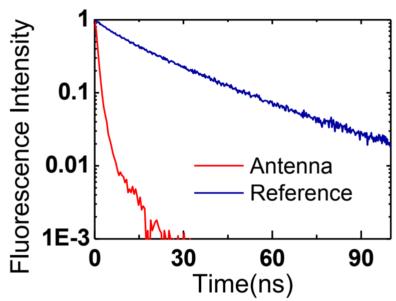
5%

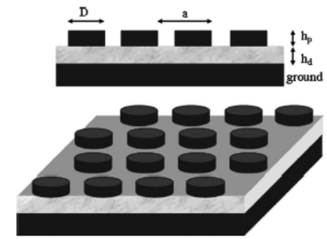


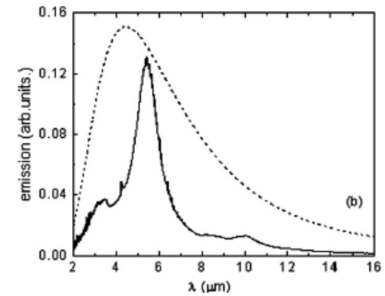


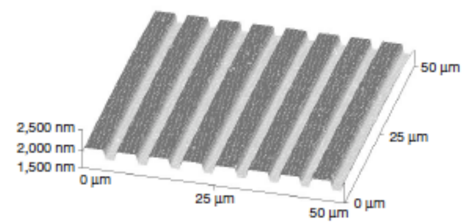
Summary

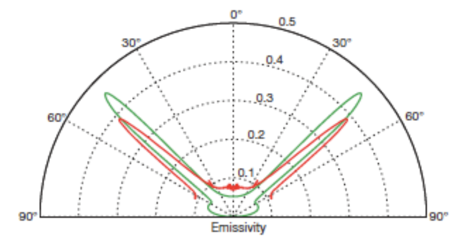

0
15
30
45
60
75
-15
-30
-45
-60
-75
a

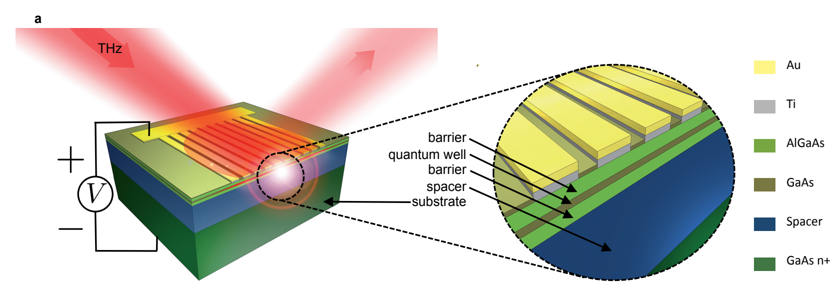

Fluorescence Intensity
1
0.1
0.01
1E-3
0
30
60
90
Time(ns)
Antenna
Reference


D
a
ground


emission (arb.units.)
0.16
0.12
0.08
0.04
0.00
2
4
6
8
10
12
14
16
λ (µm)
(b)


50 µm
25 µm
0 µm
2,500 nm
2,000 nm
1,500 nm
0 µm
25 µm
50 µm


0°
30°
30°
60°
60°
90°
90°
0.5
0.4
0.3
0.2
0.1
Emissivity


a
THz
V
barrier
quantum well
barrier
spacer
substrate
Au
Ti
AlGaAs
GaAs
Spacer
GaAs n+