Spontaneous and stimulated emission control in Confined Tamm-Plasmon structures

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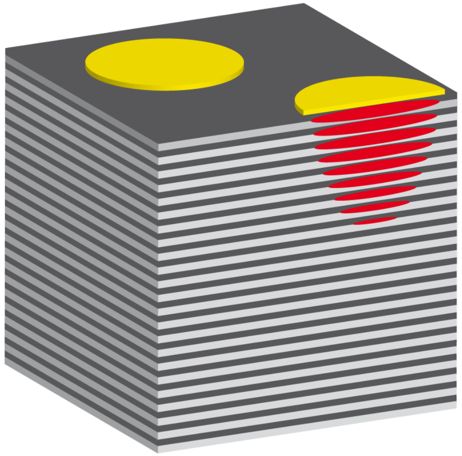
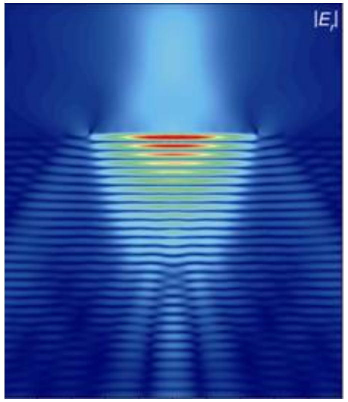
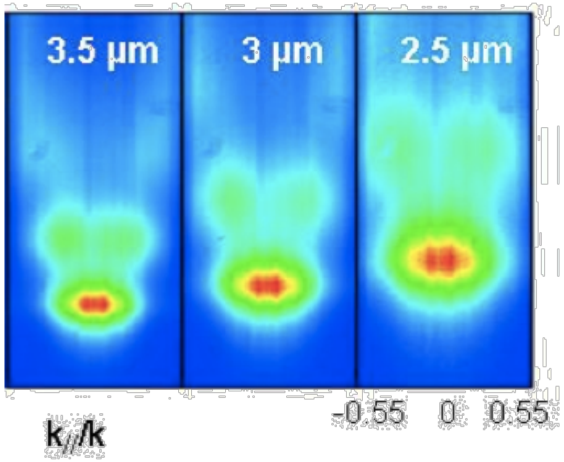






Motivations

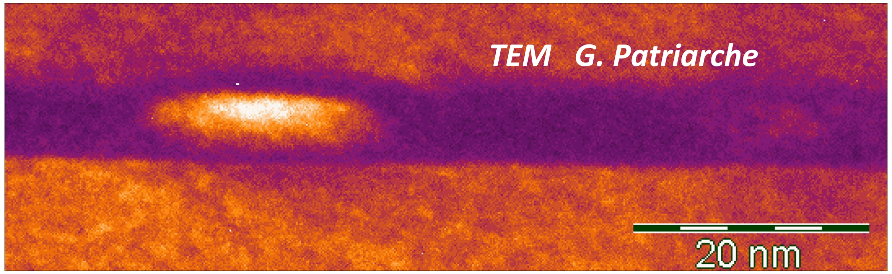
Increase light-matter interaction

↓

- **Light extraction**
  - *Efficient single photon sources*
- **Larger optical non linearities**
  - *Low-threshold Lasers*

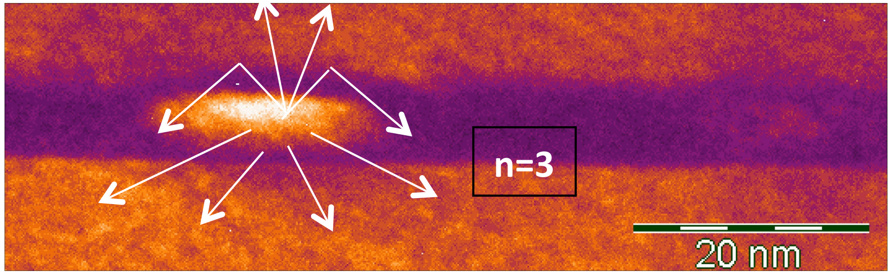
Single quantum dots for single photon sources

InAs/GaAs self assembled QD



Quantum efficiency ~ 1

n=1

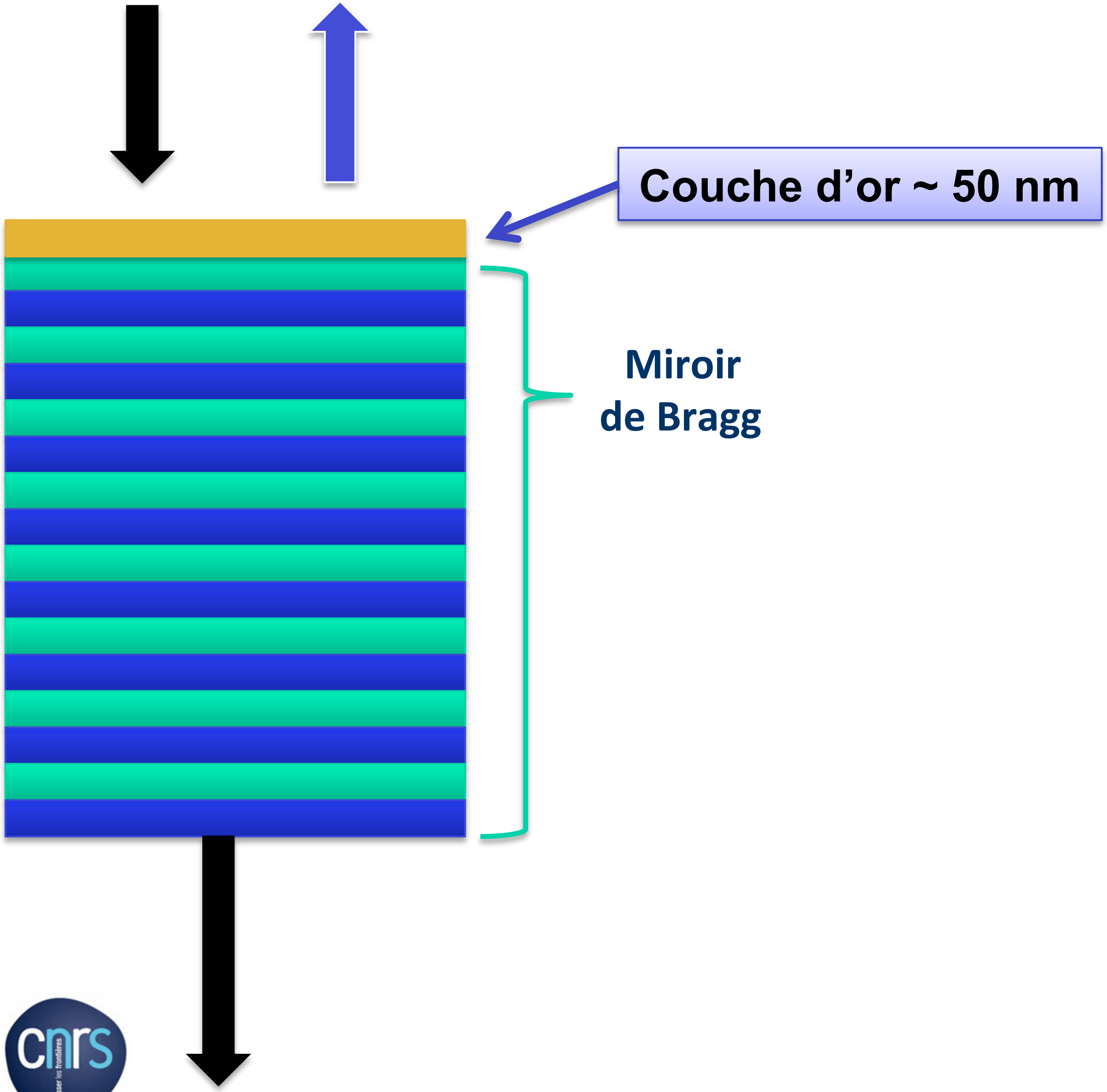


Only 1-5 % photon can be collected!

Modes de Tamm plasmon 2D

M. Kaliteevski et al Physical Review B 76, no. 16 (2007)

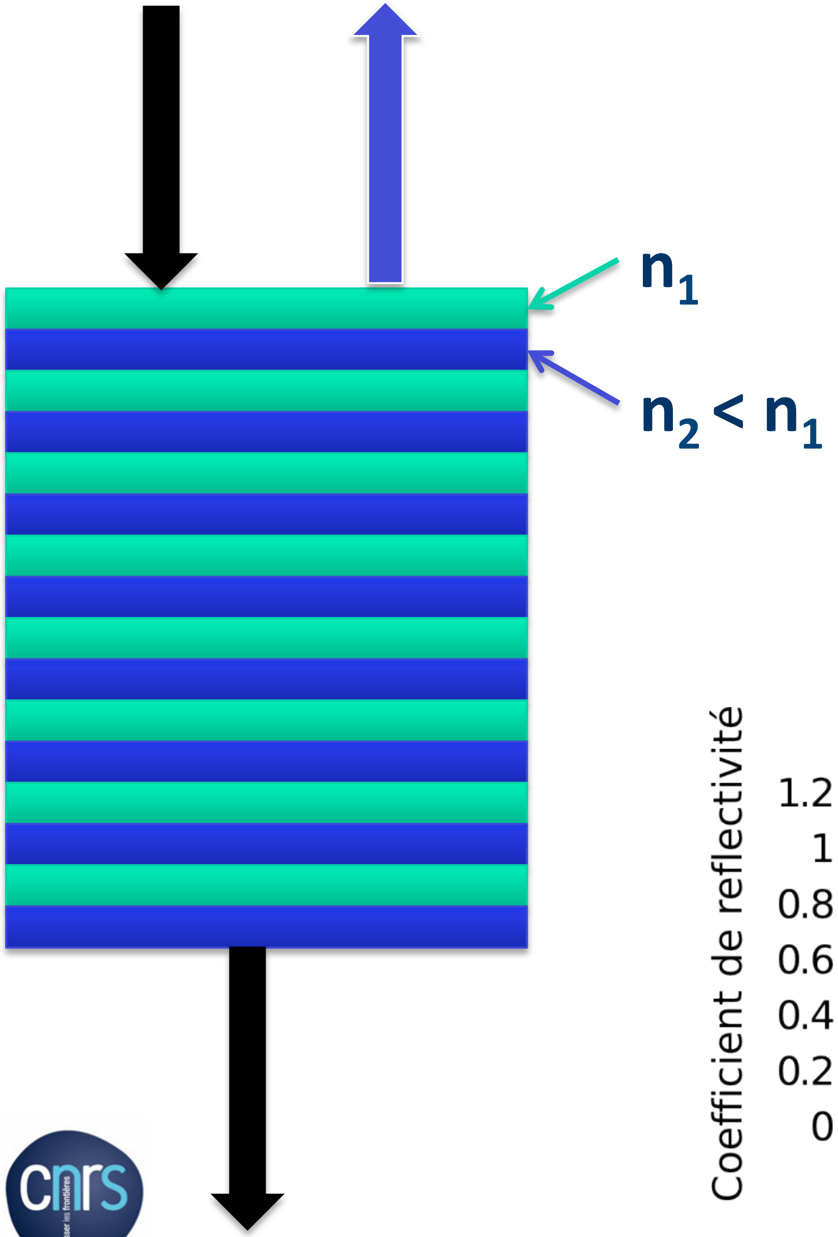
Modes de Tamm plasmon 2D



Couche d'or ~ 50 nm

Miroir de Bragg

Modes de Tamm plasmon 2D

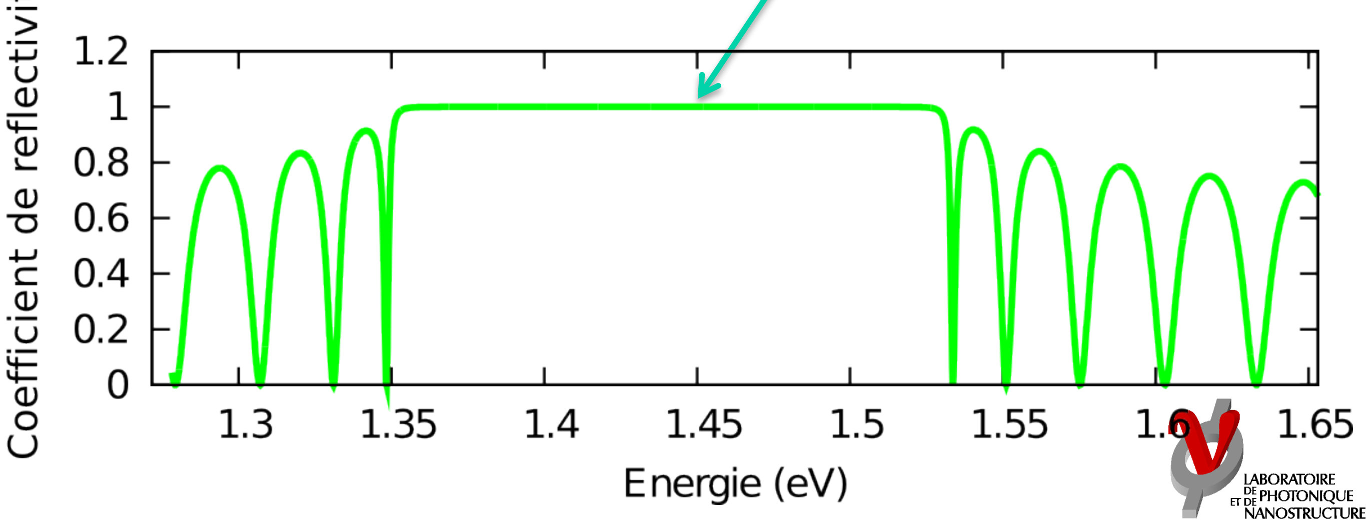


n_1

$n_2 < n_1$

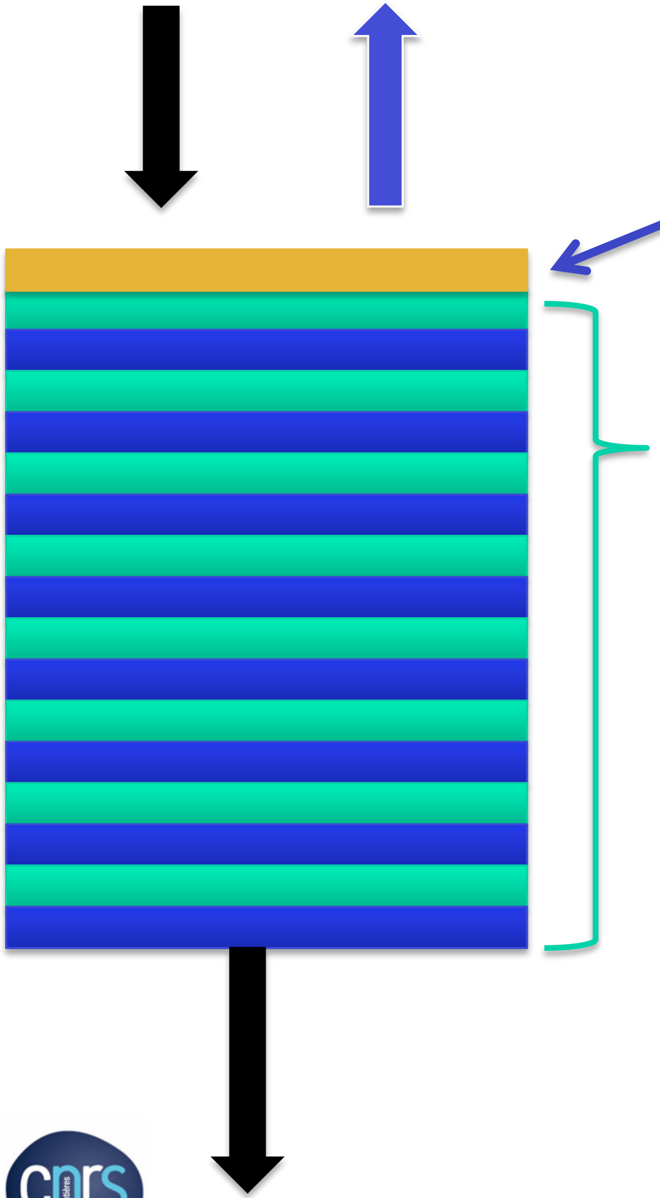
Conditions :

$$n_1 \cdot e_1 = n_2 \cdot e_2 = \frac{\lambda}{4}$$



Réfection totale

Modes de Tamm plasmon 2D

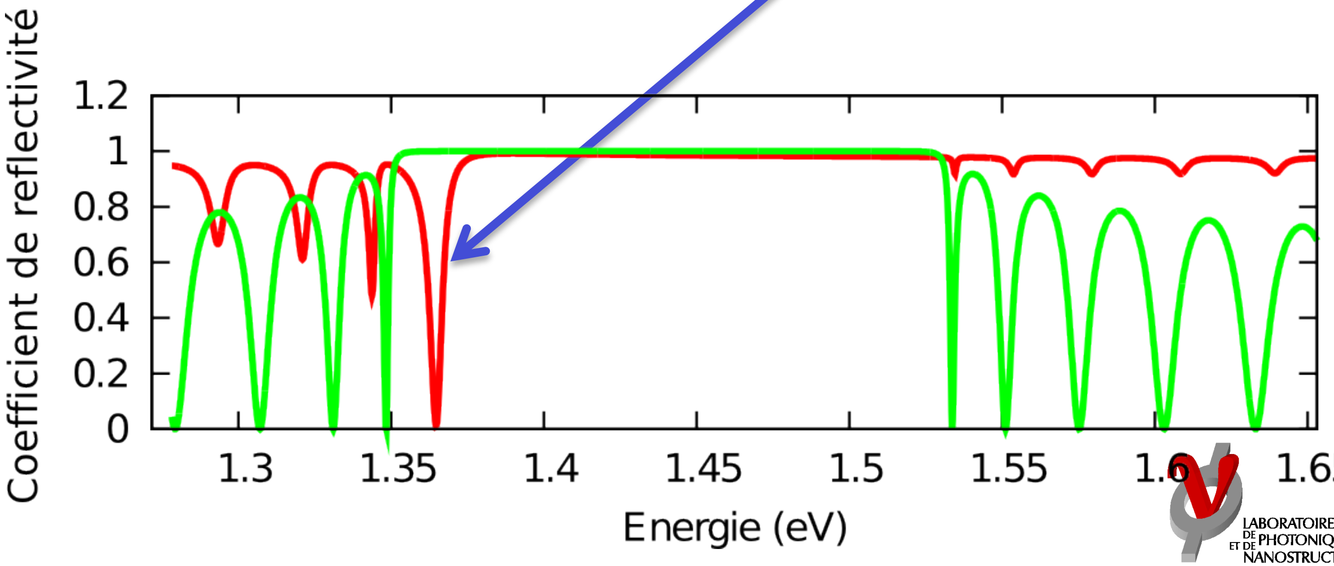


Couche d’or ~ 50 nm

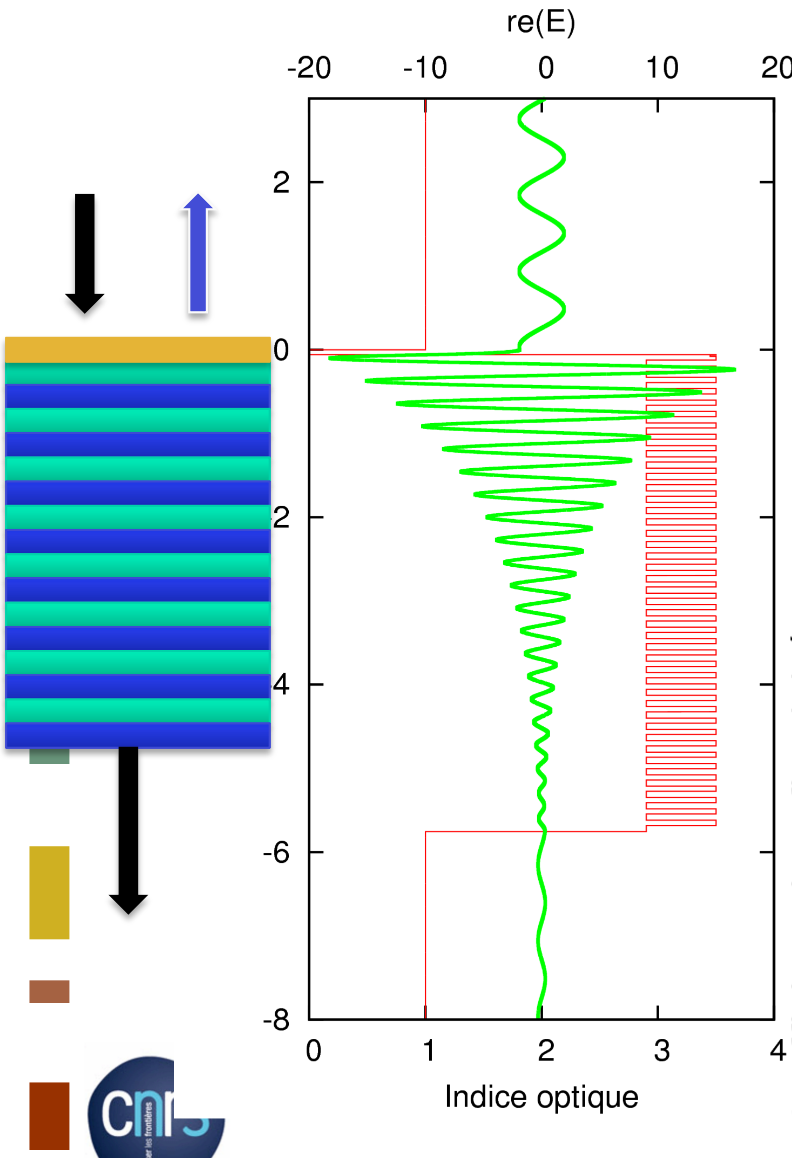
Miroir de Bragg

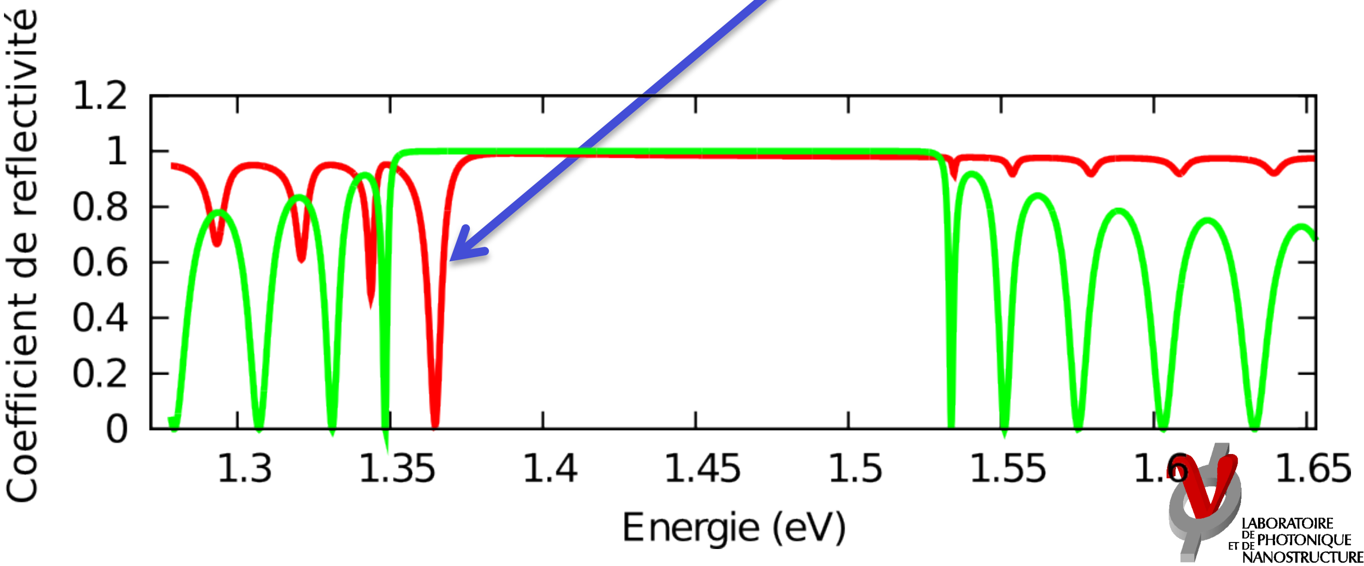
Mode de Tamm plasmonique :

Etat confiné entre le miroir de Bragg et le métal



Modes de Tamm plasmon 2D

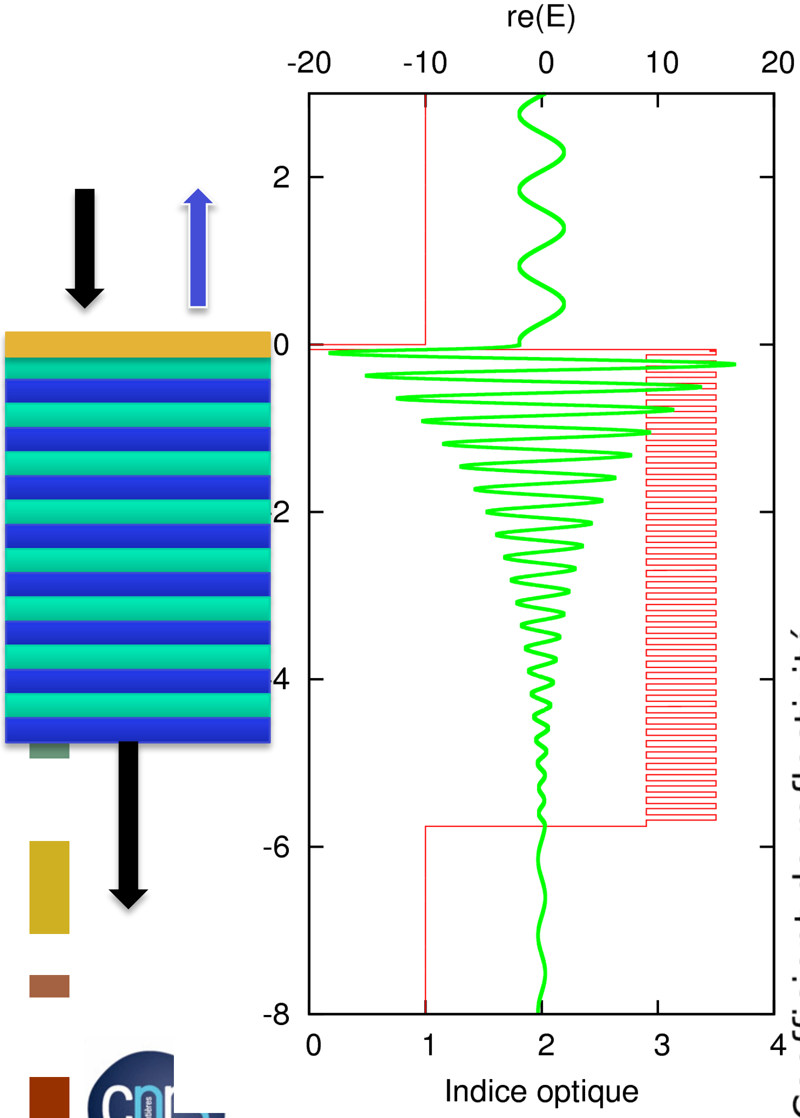




Mode de Tamm plasmonique :

Etat confiné entre le miroir de Bragg et le métal

Modes de Tamm plasmon 2D

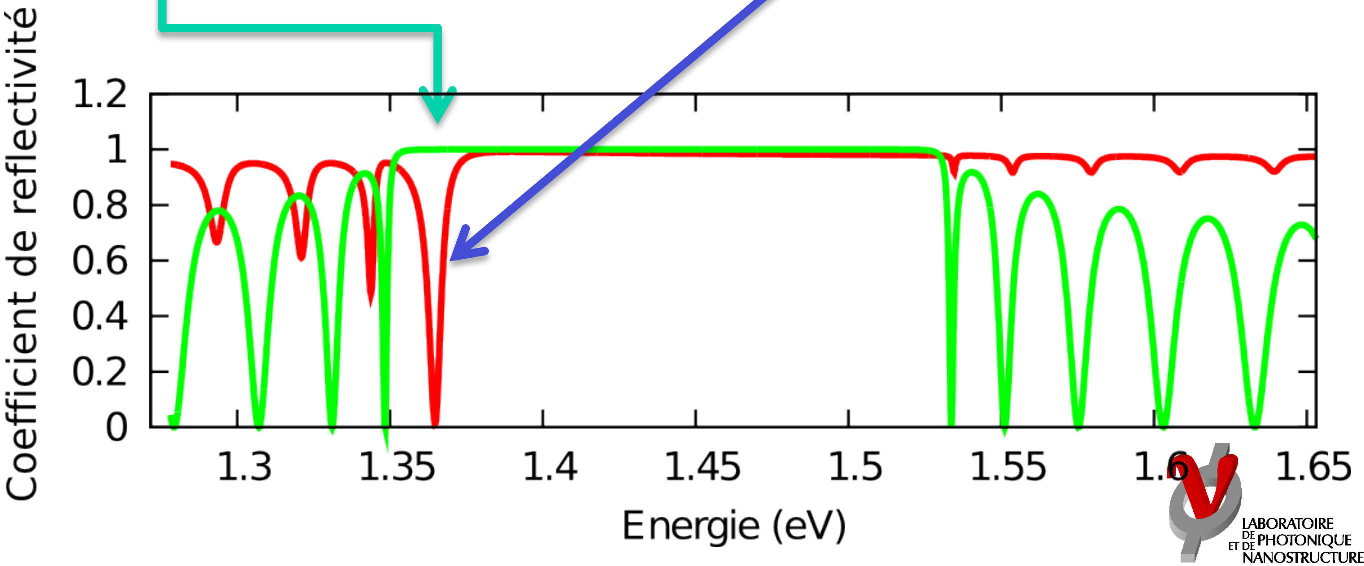


$$\omega_{\mathrm{Tamm}} = \frac{\omega_0}{1 + \frac{2 n_1 \omega_0}{\beta \omega_p}}$$

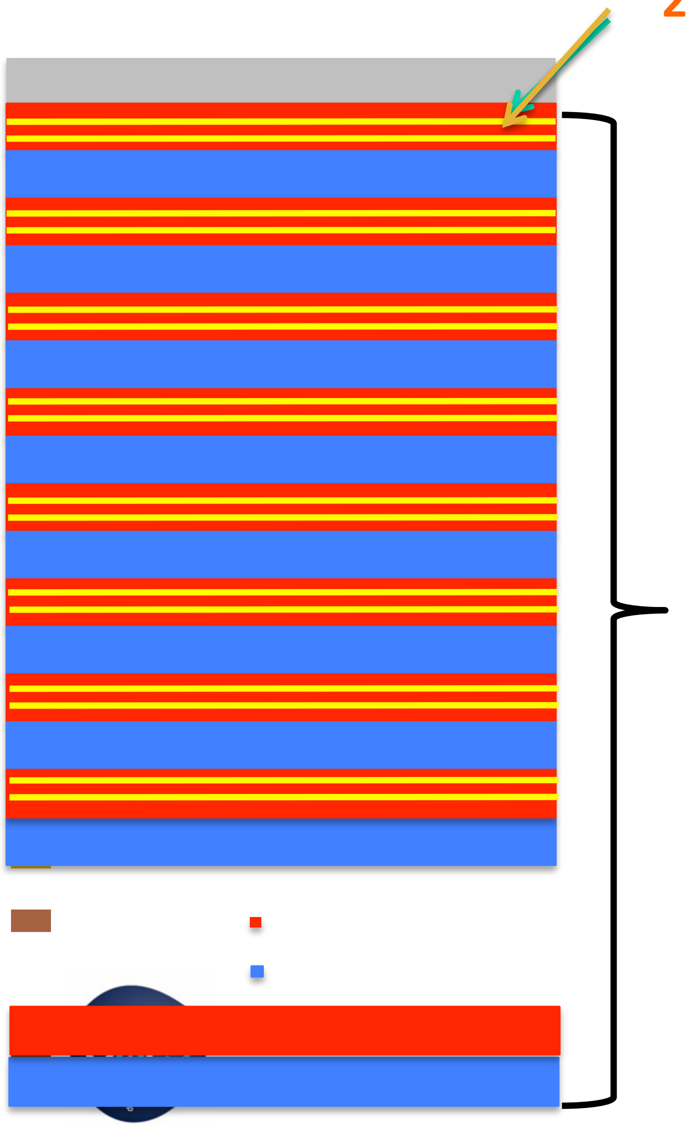
Fréquence plasma du métal

Mode de Tamm plasmonique :

Etat confiné entre le miroir de Bragg et le métal



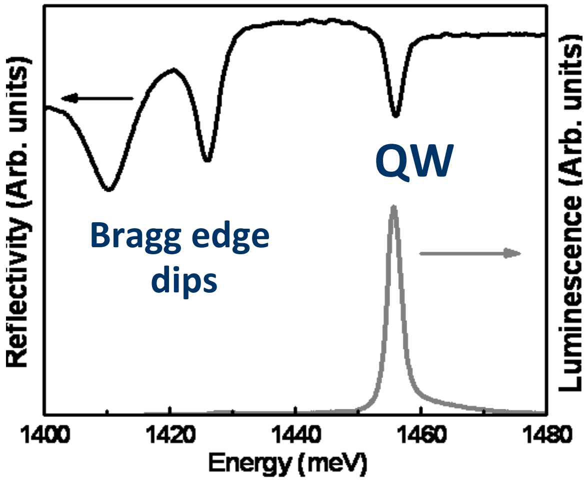
Strong coupling regime: Tamm-plasmon exciton polaritons

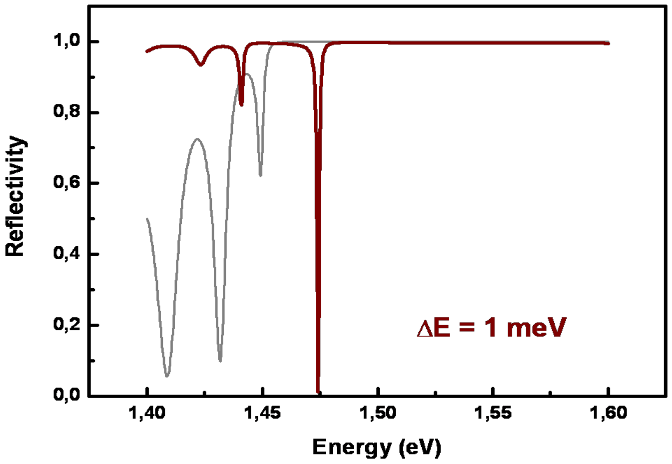


60 nm thick silver film

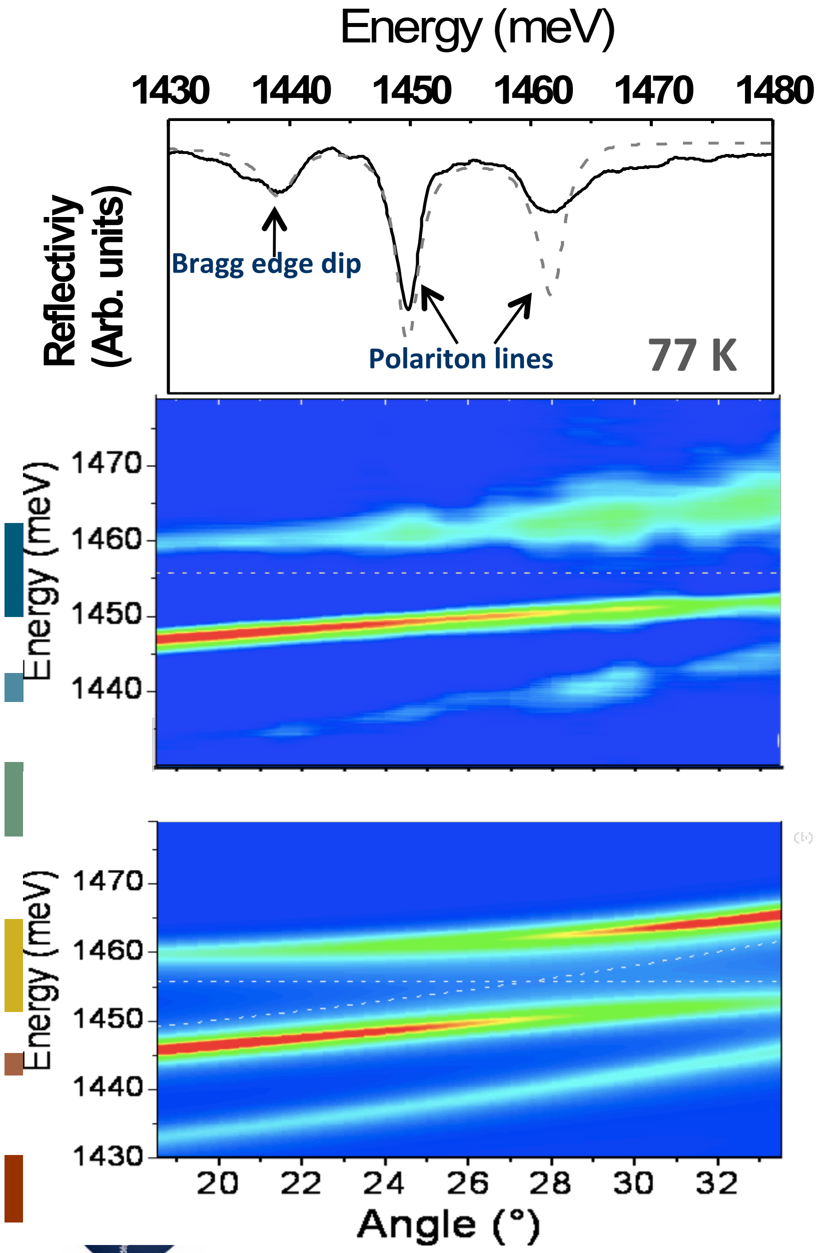
2 InGaAs/AlGaAs QWs in each 15 last high refractive index layers

45x $Al_{0.05}GaAs$/AlAs λ/4 pairs





Reflectometry experiments



➡ Strong coupling Tamm plasmon/exciton

- **Rabi splitting : 12 meV**
- **Thin polariton lines compared to splitting**
- **Simulations with a transfer matrix method**

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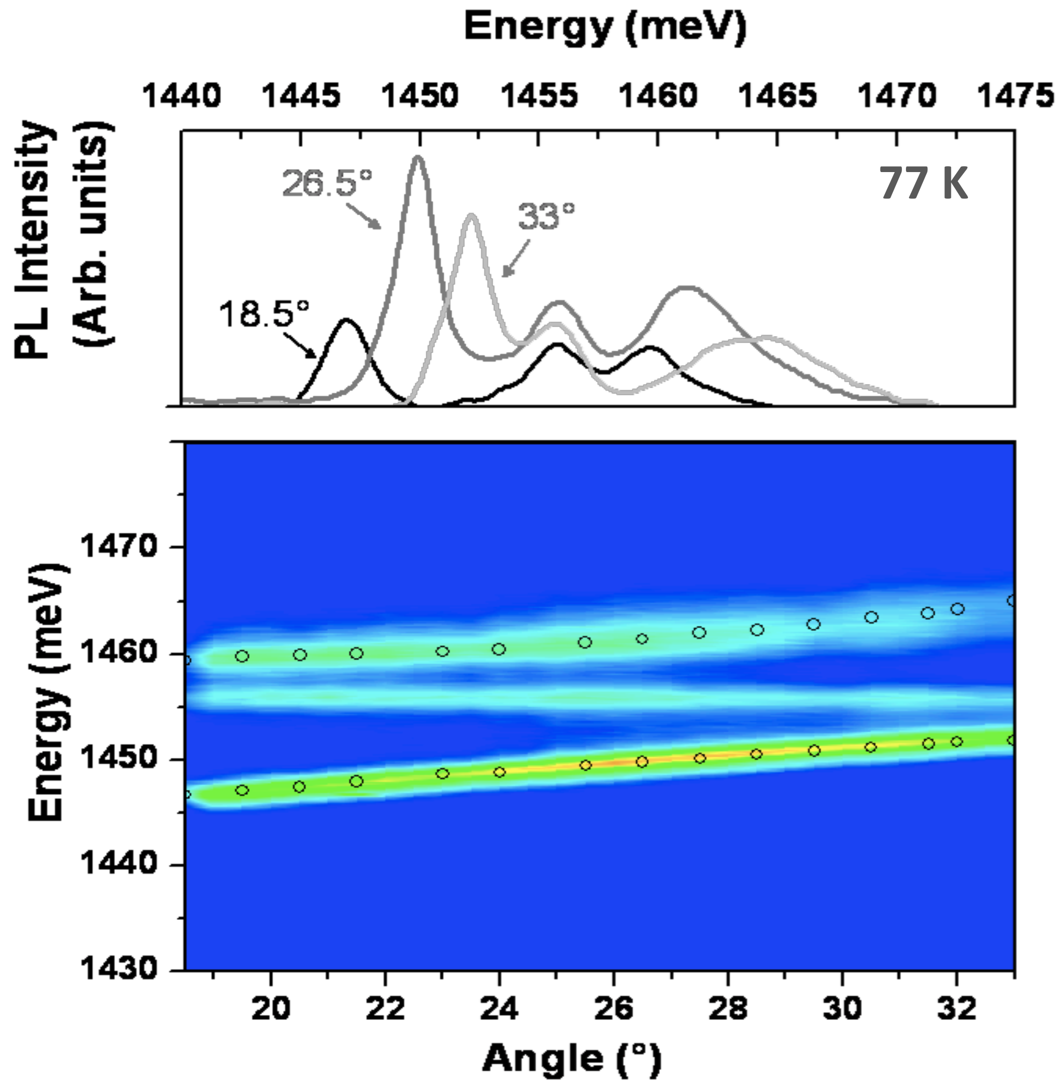
Hybrid state luminescence



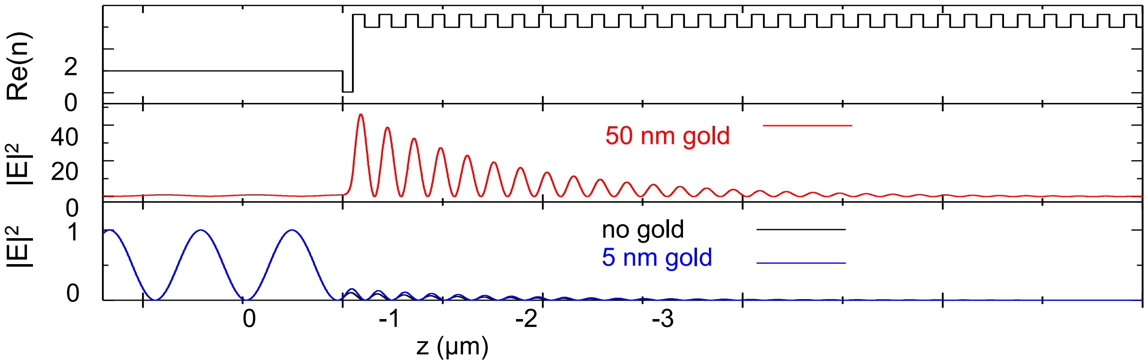
- ➡ **Strong polaritonic emission**
  - ▶ **Emission in TE and TM**

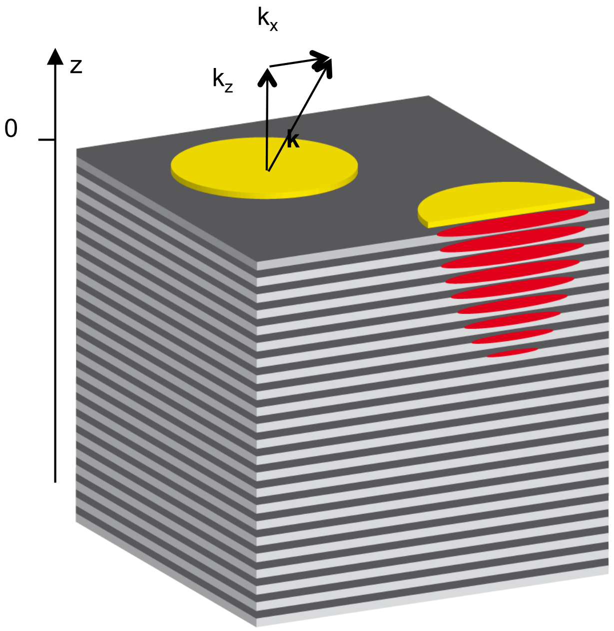
- **Dispersion relation**
- **Polaritonic emission**

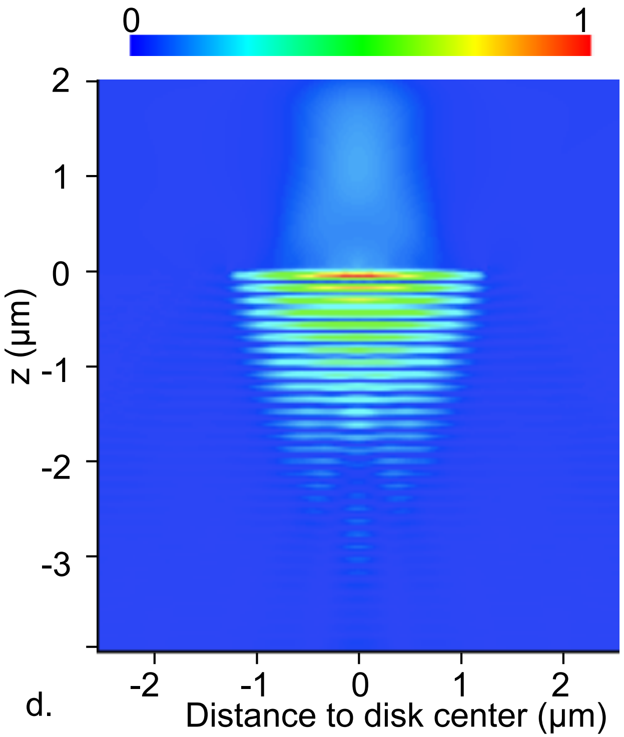
➡ **Possible polaritonic non linearities**

APL 95, 151114 (2009)

0D Tamm plasmon modes







3D FDTD Calculcation

Collaboration J. Bellessa

LPMCN – Lyon - France

Brevet n°1003881 2010

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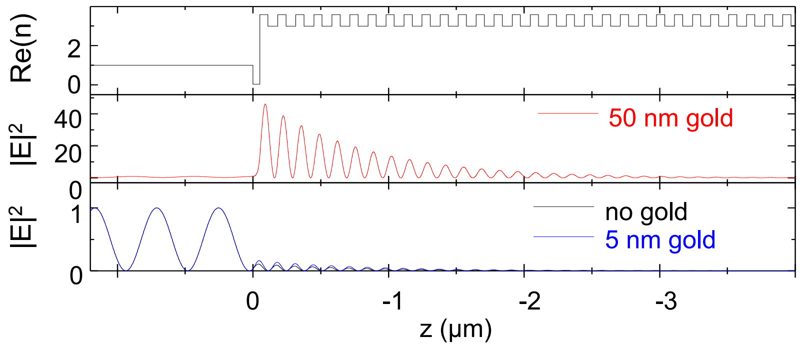
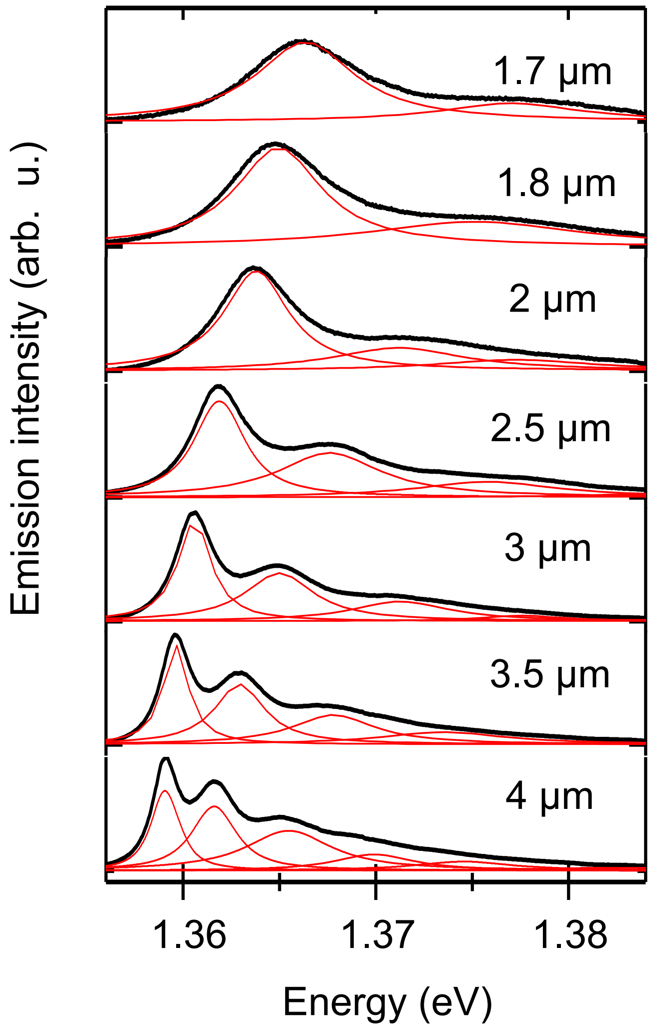
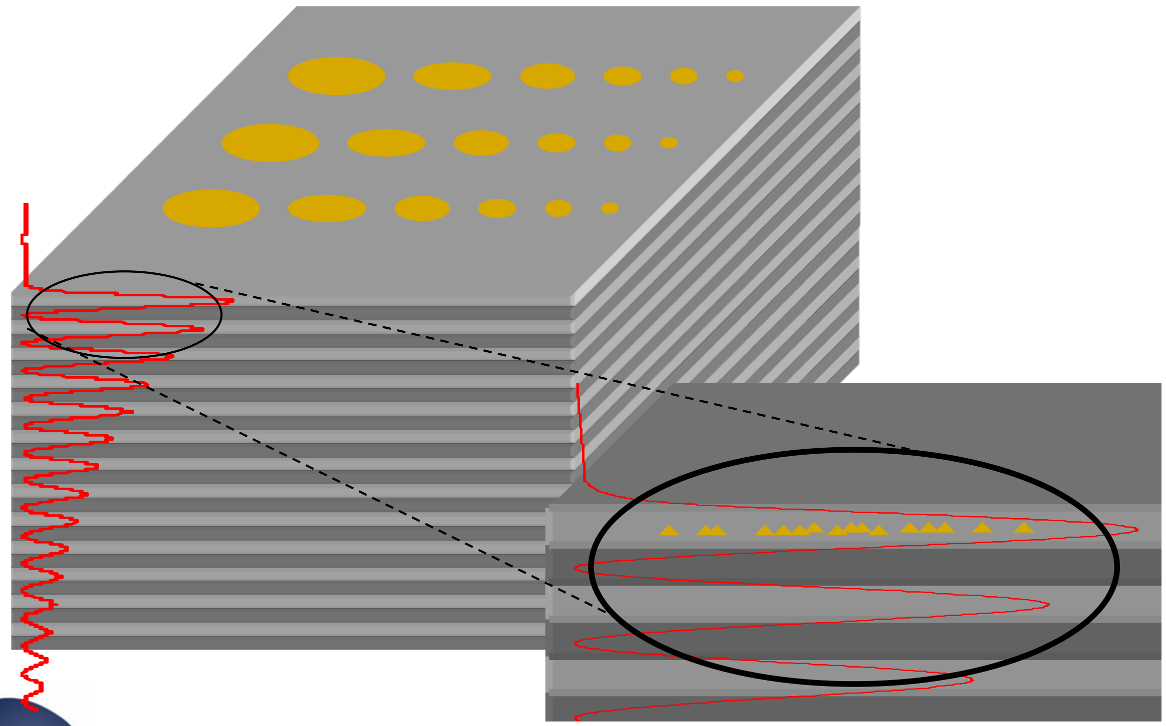
0D Tamm plasmon modes: experimental evidence

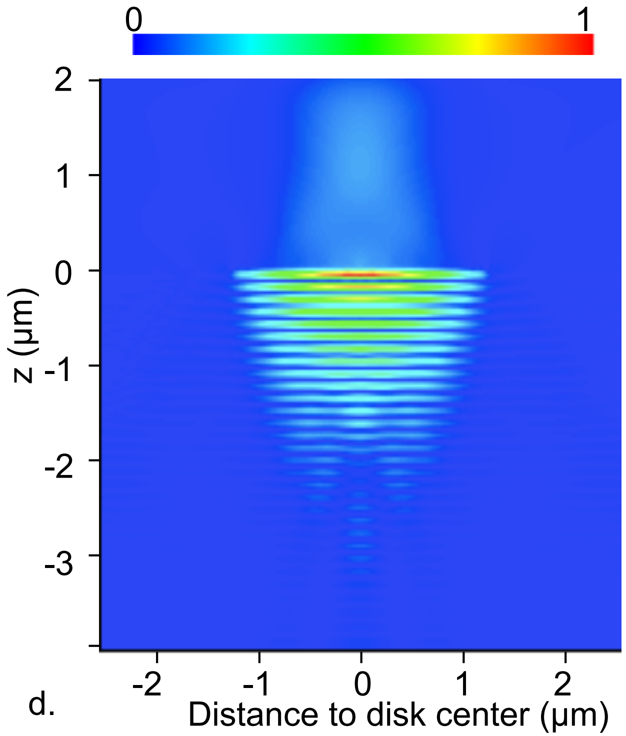


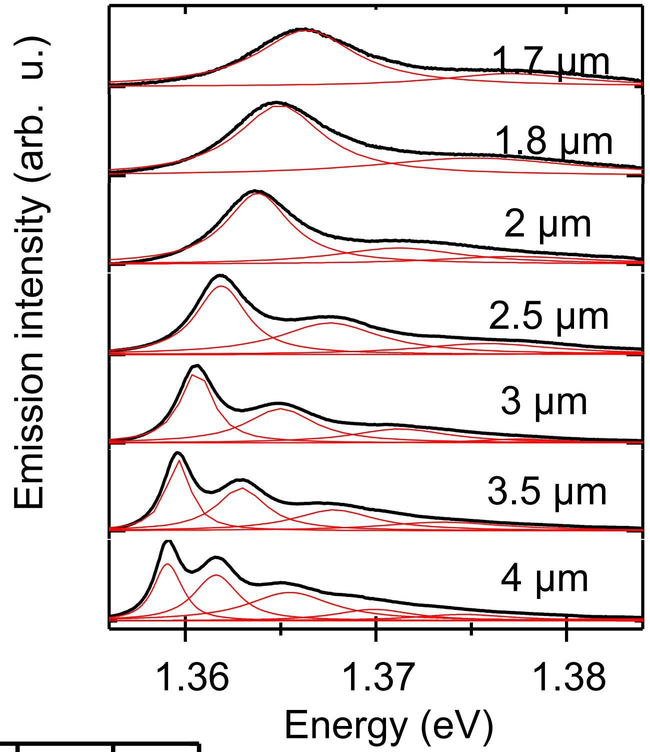


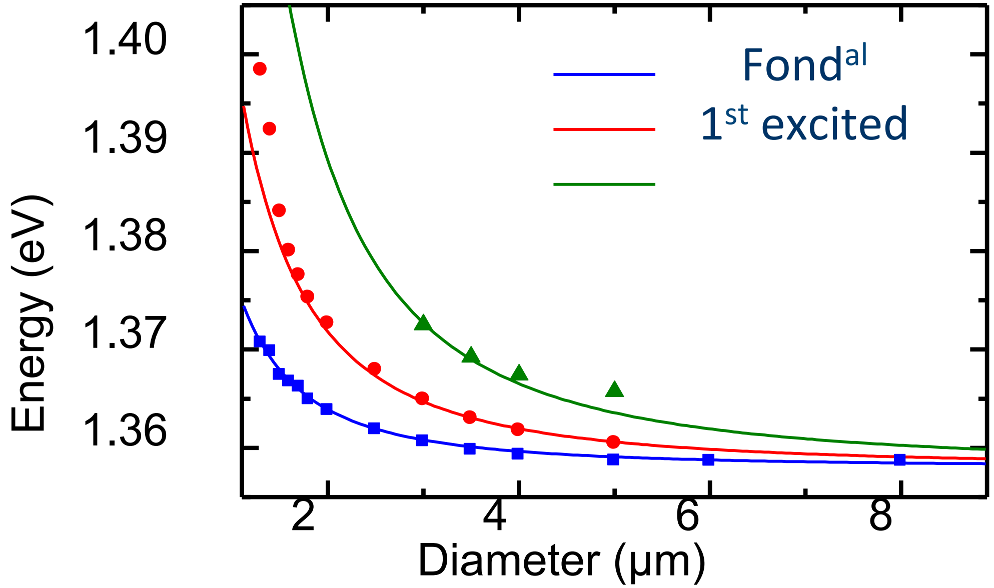


Broadband light source: a dense array of InAs quantum dots

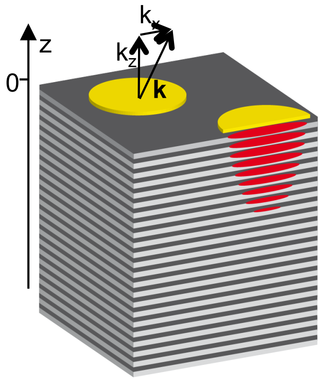
0D Tamm plasmon modes: experimental evidence

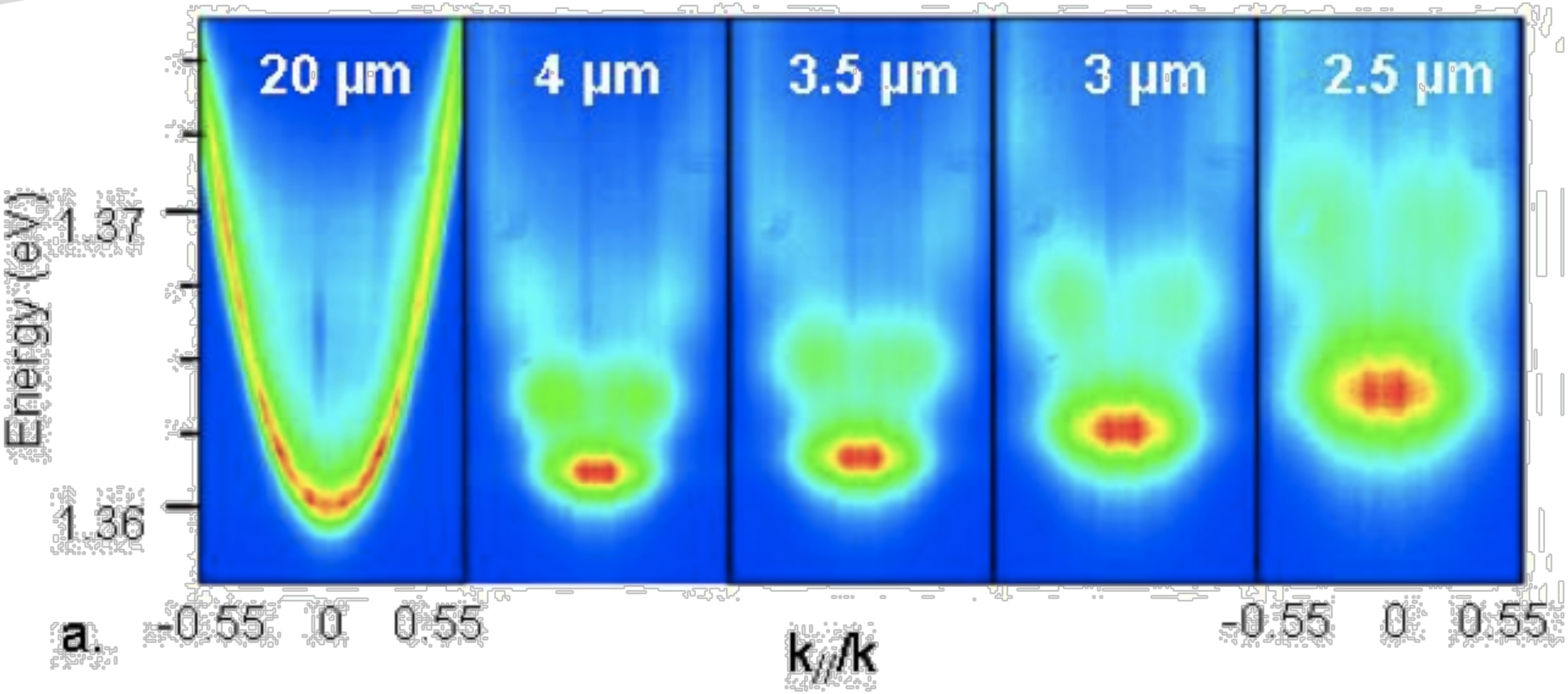




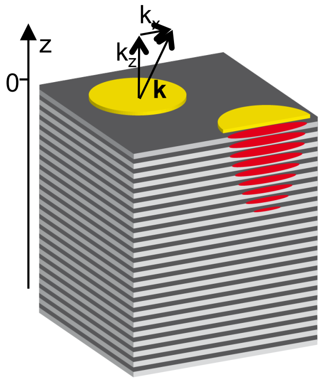


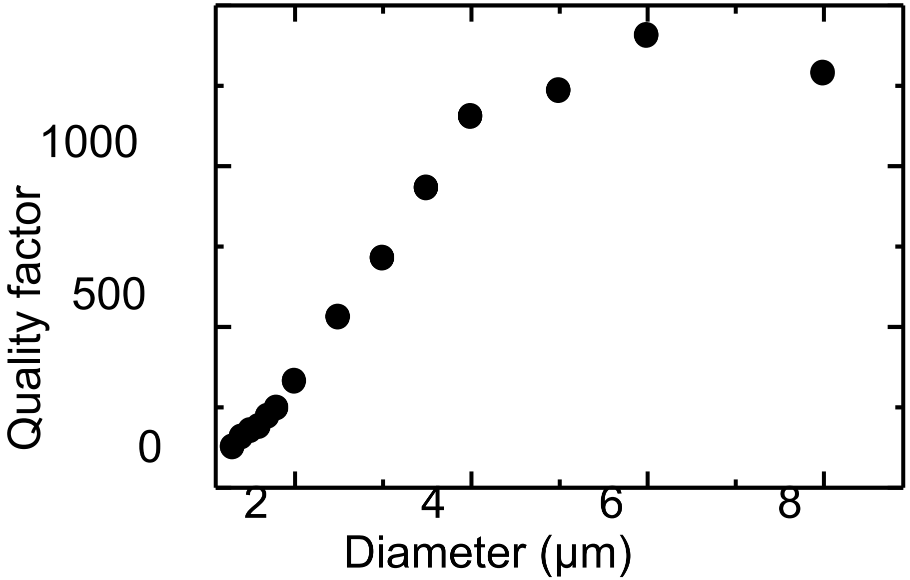
0D Tamm plasmon modes: radiation patterns

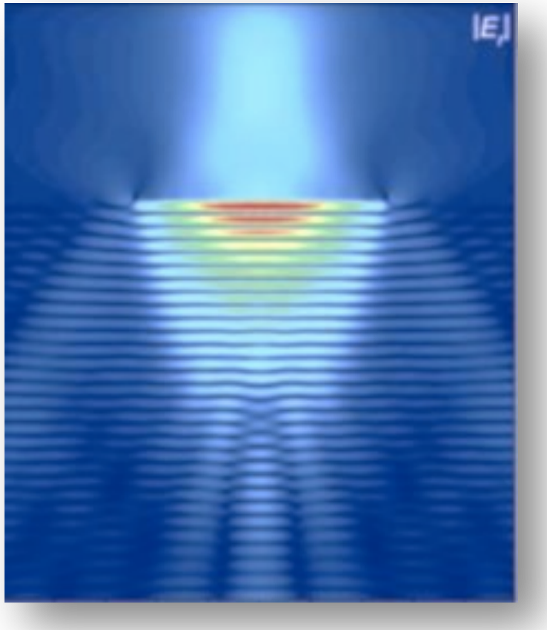




0D Tamm plasmon modes: experimental evidence





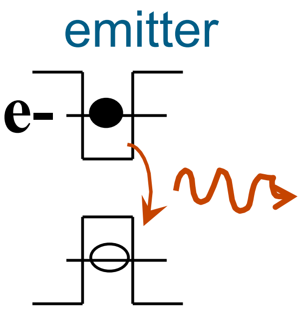


Confined photon-plasmon modes, Q=1200

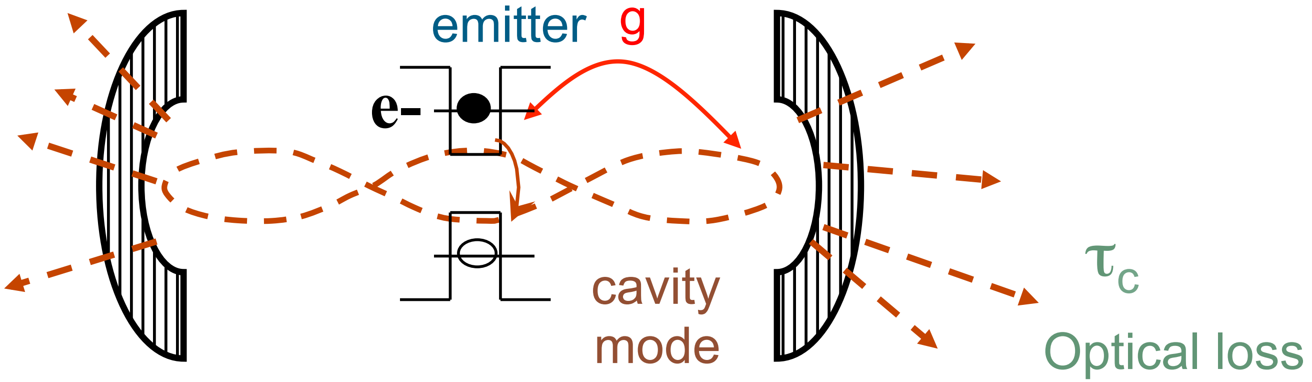
Controlling spontaneous emission with Confined Tamm plasmon modes

LABORATOIRE
DE PHOTONIQUE
ET DE NANOSTRUCTURES

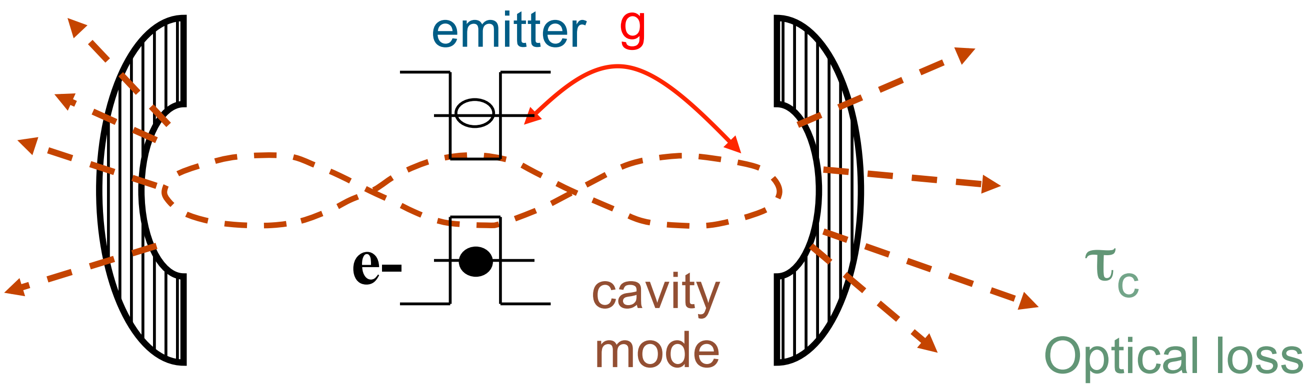
Controlling spontaneous emission



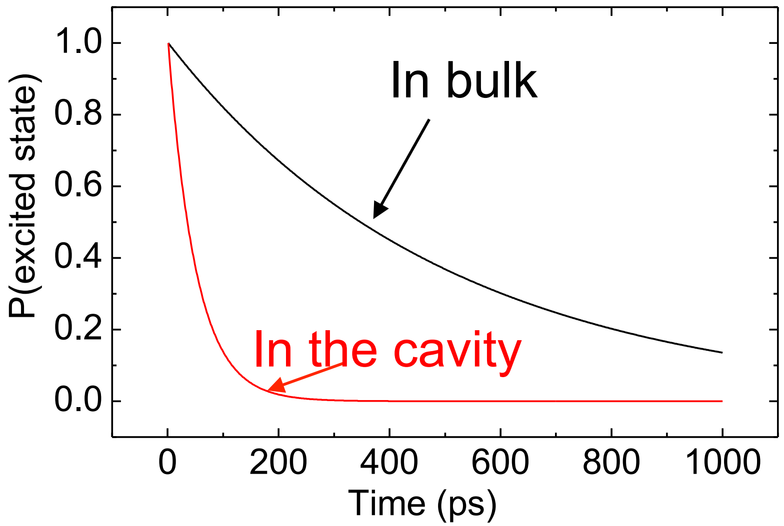
Controlling spontaneous emission



Controlling spontaneous emission



$g \ll \tau_c$



Weak coupling regime

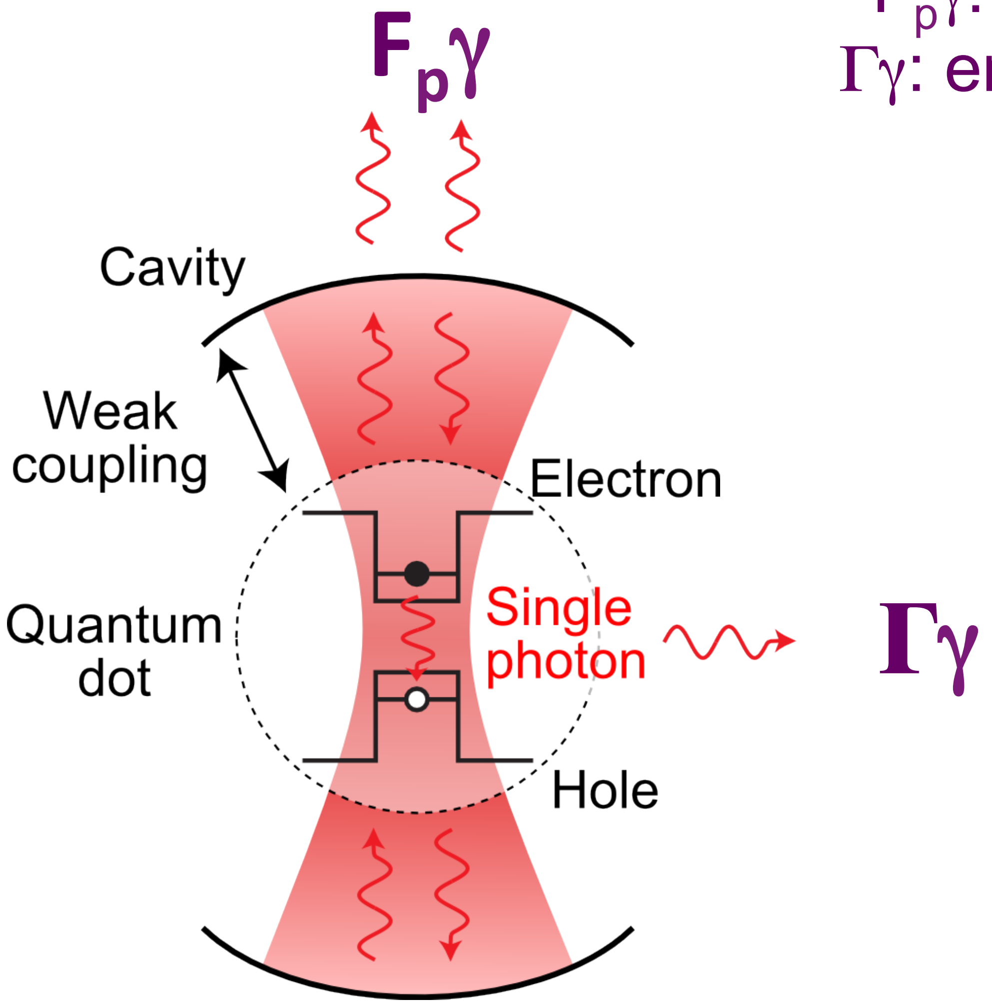
Enhanced spontaneous emission

Purcell Effect

Purcell factor F_P

$$F_P \propto \frac{Q}{V}$$

Light extraction using Purcell effect

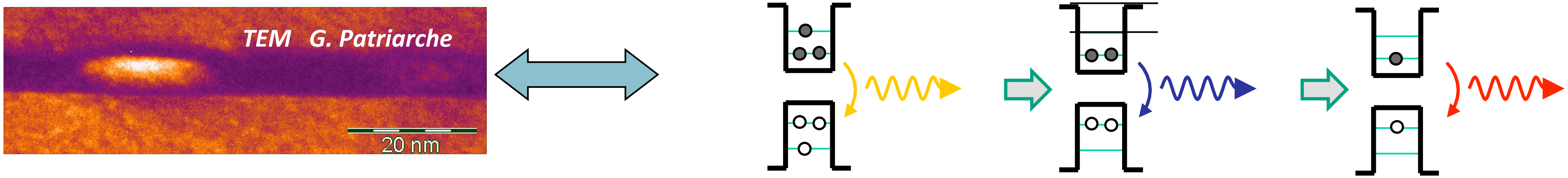


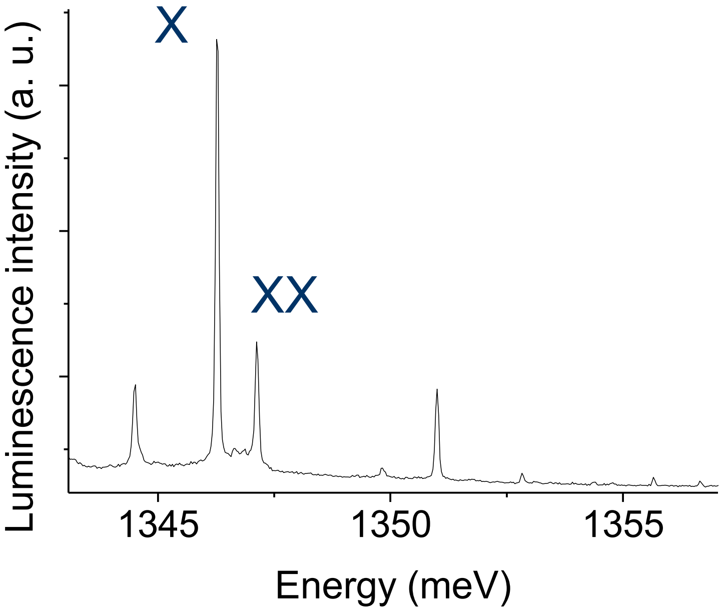
$F_p\gamma$: emission rate into the mode
$\Gamma\gamma$: emission rate into other modes

Coupling to the mode

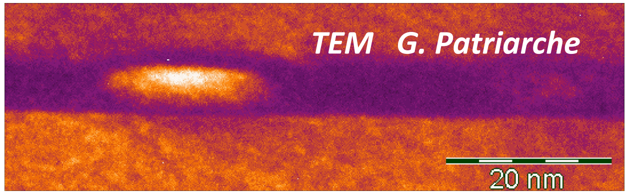
$$\beta = \frac{F_P}{F_P + \Gamma}$$

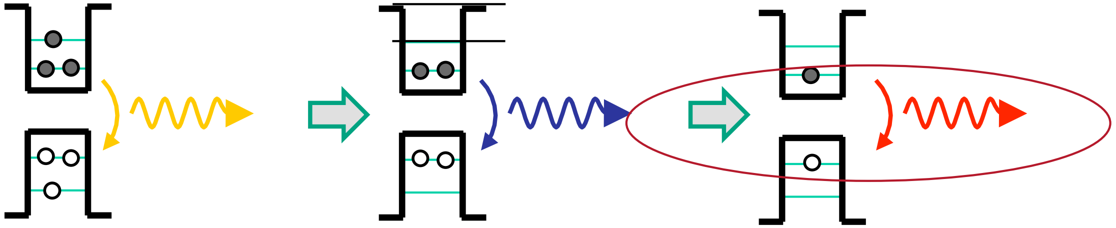
Single quantum dots for single photon sources

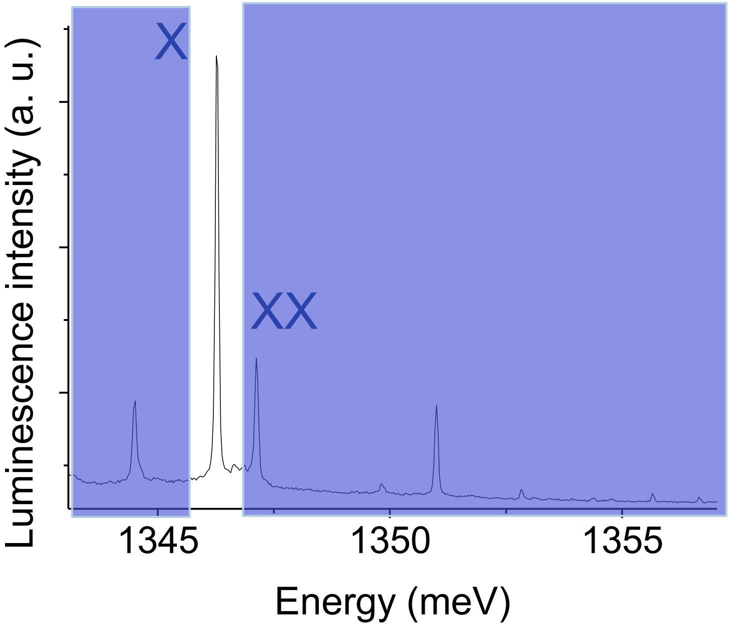


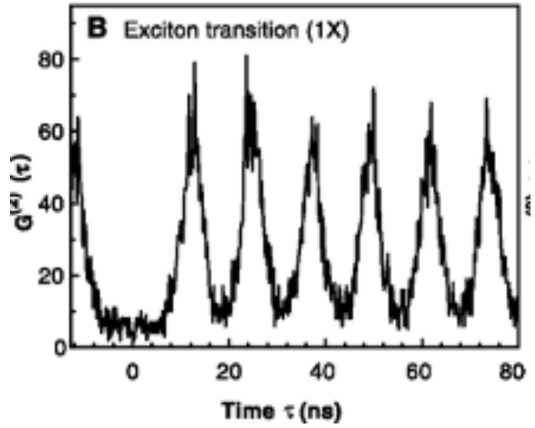


Single quantum dots for single photon sources





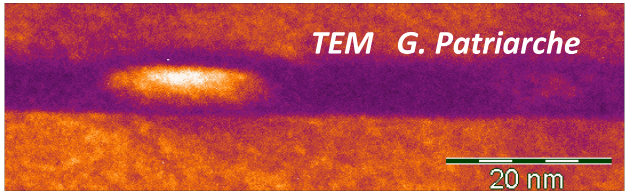


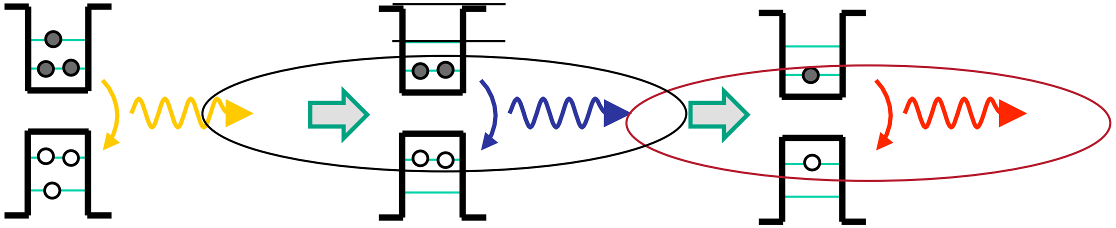


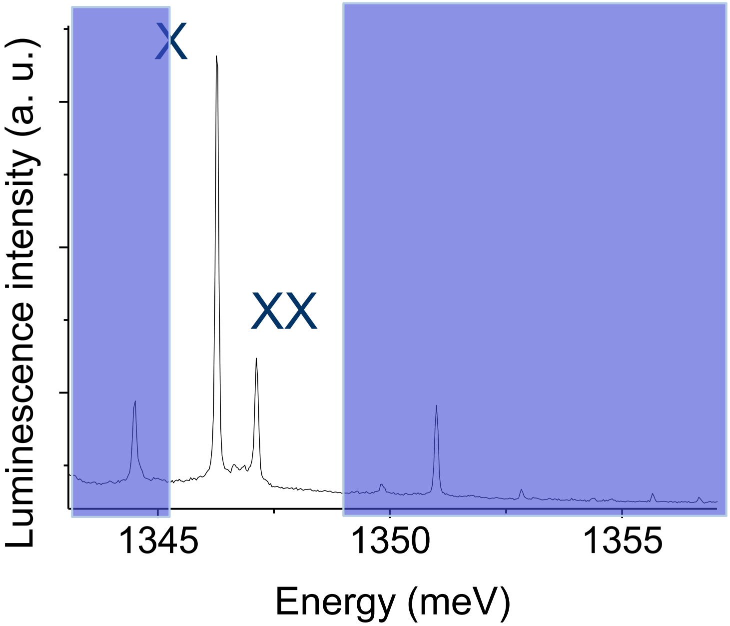
Single photon emission

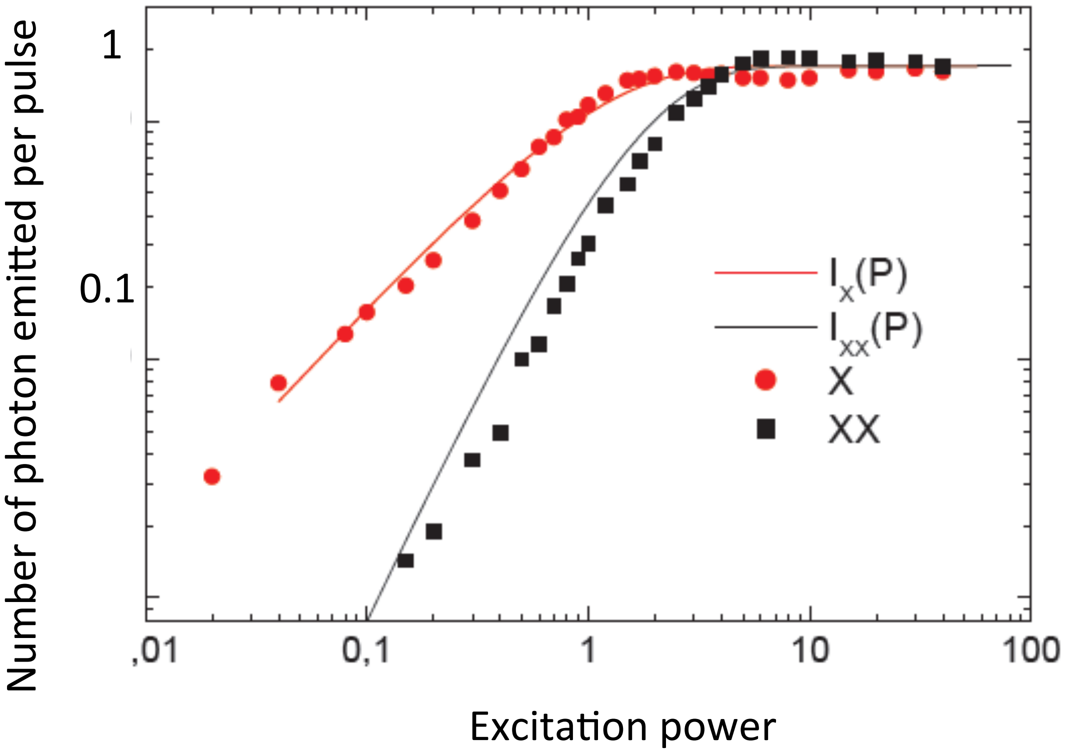
Science 290, *2282 (2000)*

Single quantum dots for single photon sources



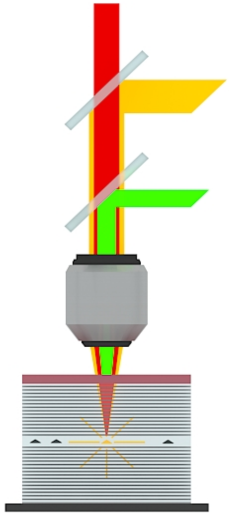






Maximum creation rate P(1) = 1

0D Tamm plasmon modes: control of spontaneous emission



Deterministic coupling

Spatial coupling
Energy coupling

<u>Gold disk :</u>

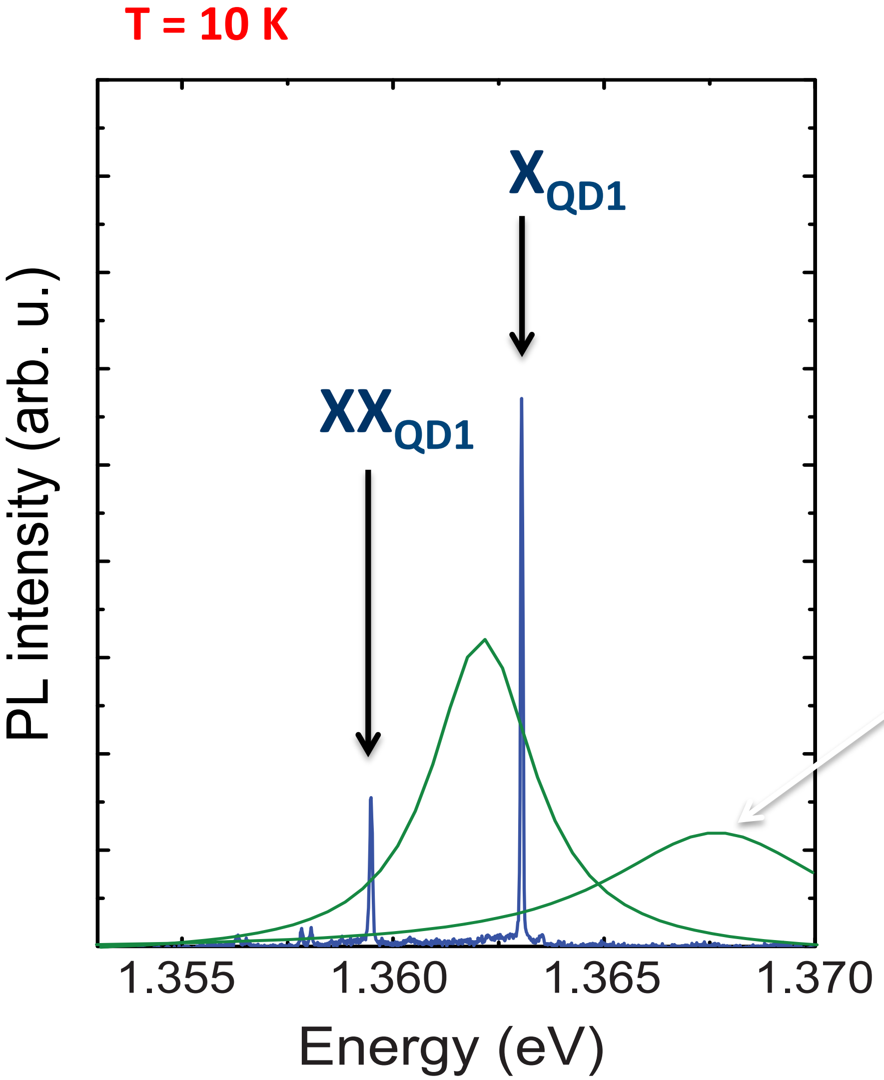
- Thickness : 50nm
- Diameter : 2.5µm
- Quality factor : 490

<u>QD / gold disk distance :</u>
44nm

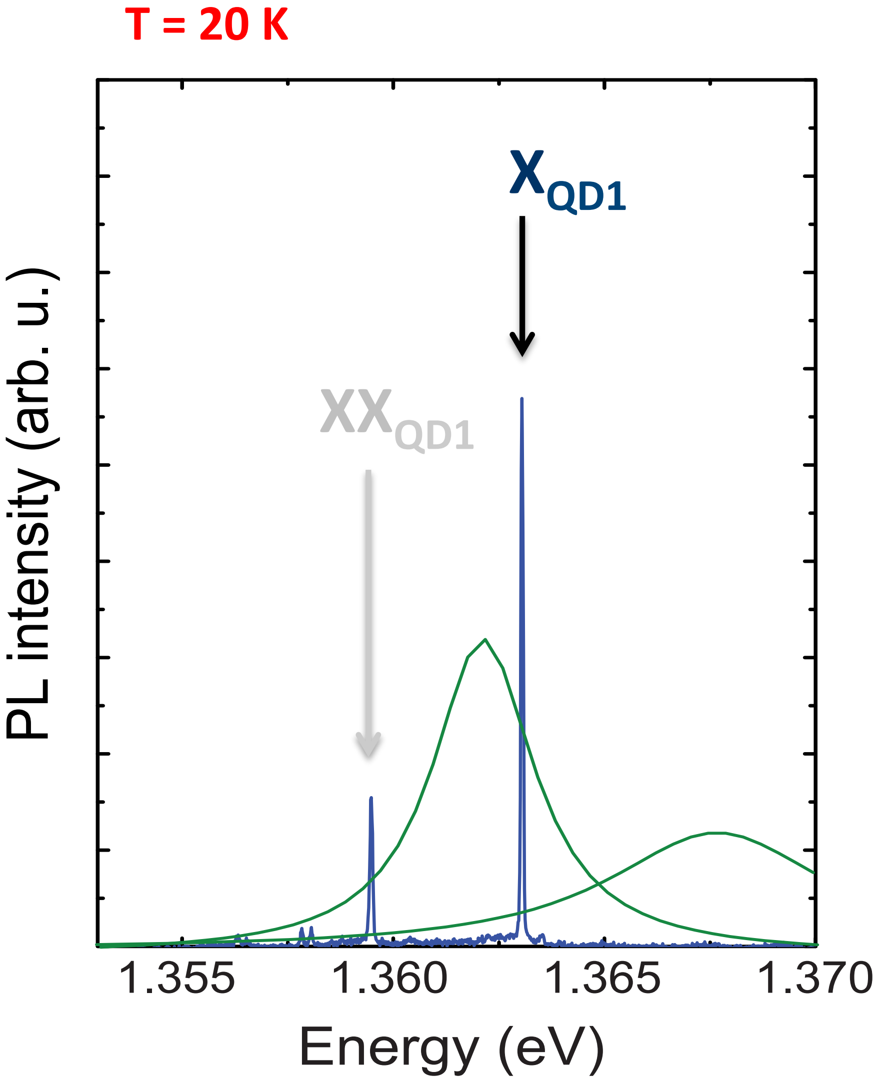
<u>QD1-QD2 distance :</u>
~300nm

Reference QDs

Lifetime **1.3 ns**



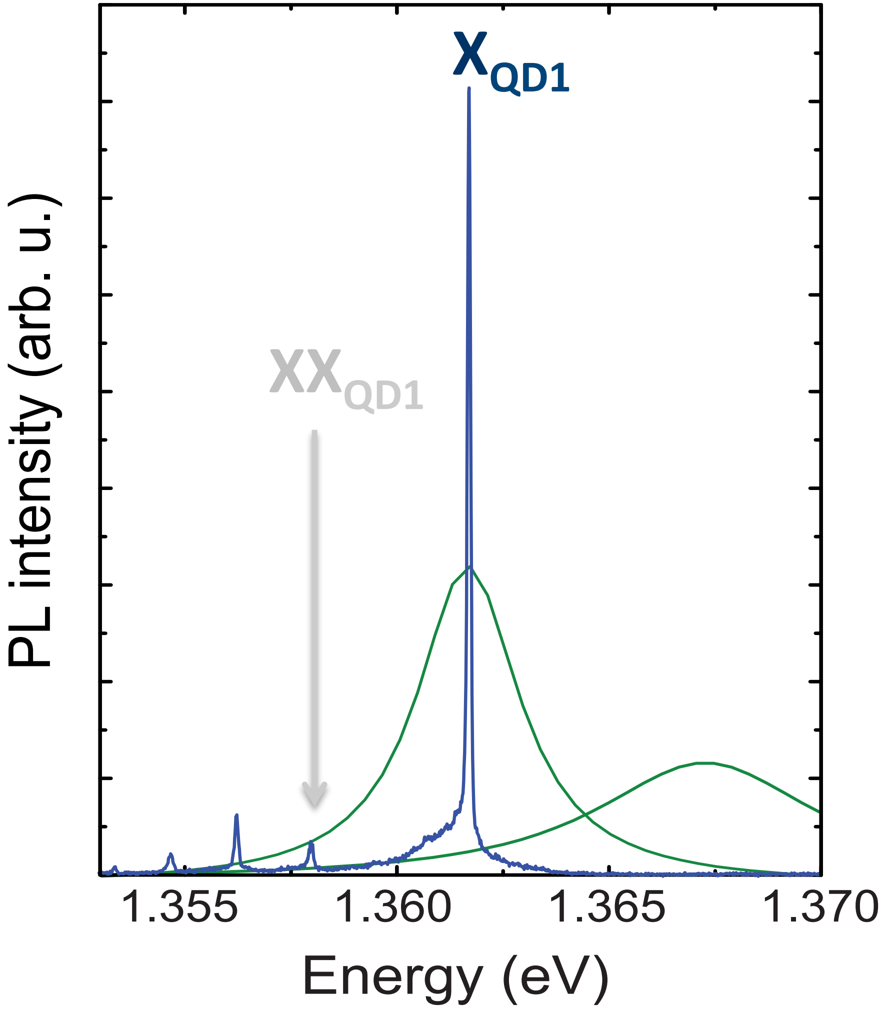
First two modes of a confined TP for a 2.5 µm microdisk



Reference QDs — Lifetime **1.3 ns**

X_{QD1} (T=20K) — Lifetime **700 ps**

T = 40 K



Reference QDs	Lifetime **1.3 ns**
X_{QD1} (T=20K)	Lifetime **700 ps**
X_{QD1} (T=40K)	Lifetime **400 ps**
Acceleration	**Purcell factor F_P = 2.8**

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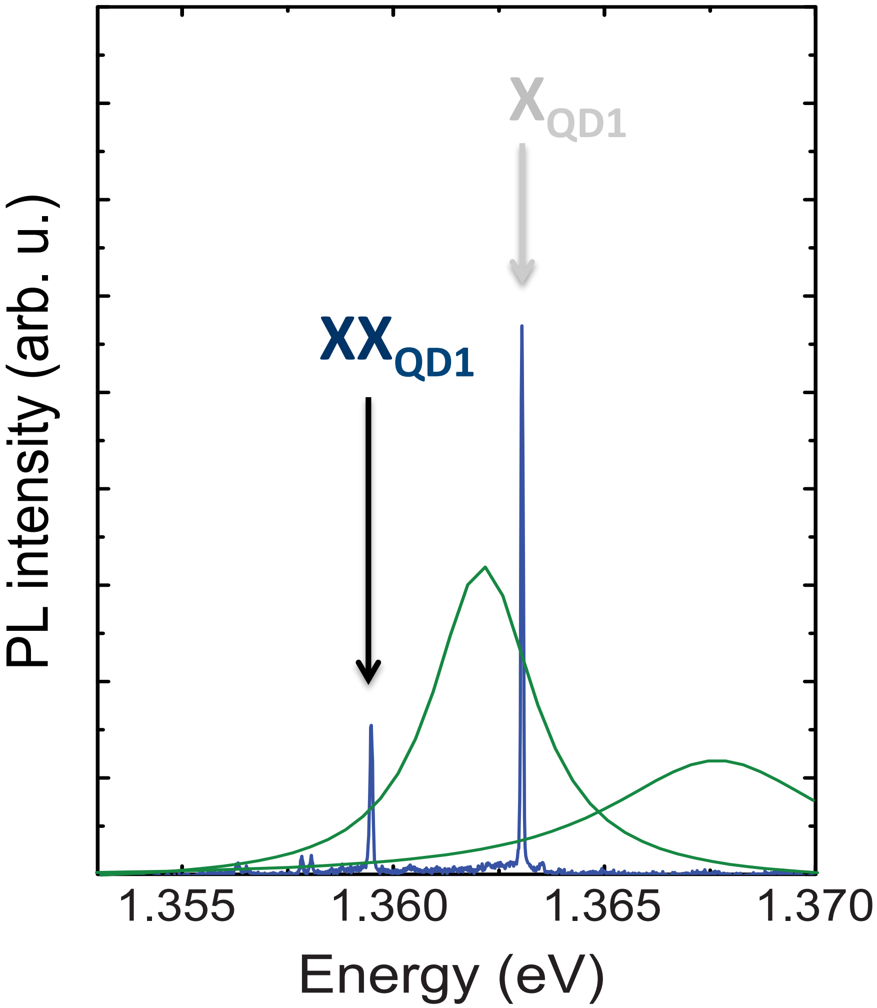
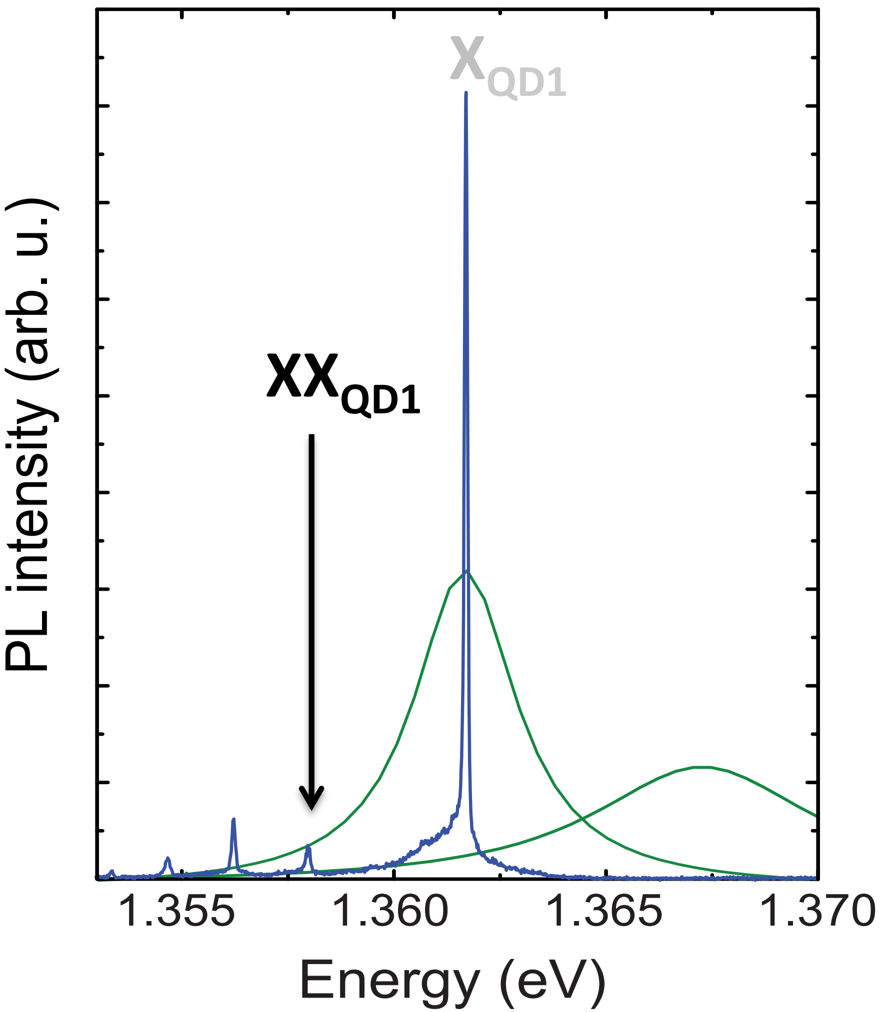
T = 20 K



Reference QDs	Lifetime **1.3 ns**
X_{QD1} (T=20K)	Lifetime **700 ps**
X_{QD1} (T=40K)	Lifetime **400 ps**
Acceleration	**Purcell factor F_P = 2.8**
XX_{QD1} (T=20K)	Lifetime **5.8 ns**

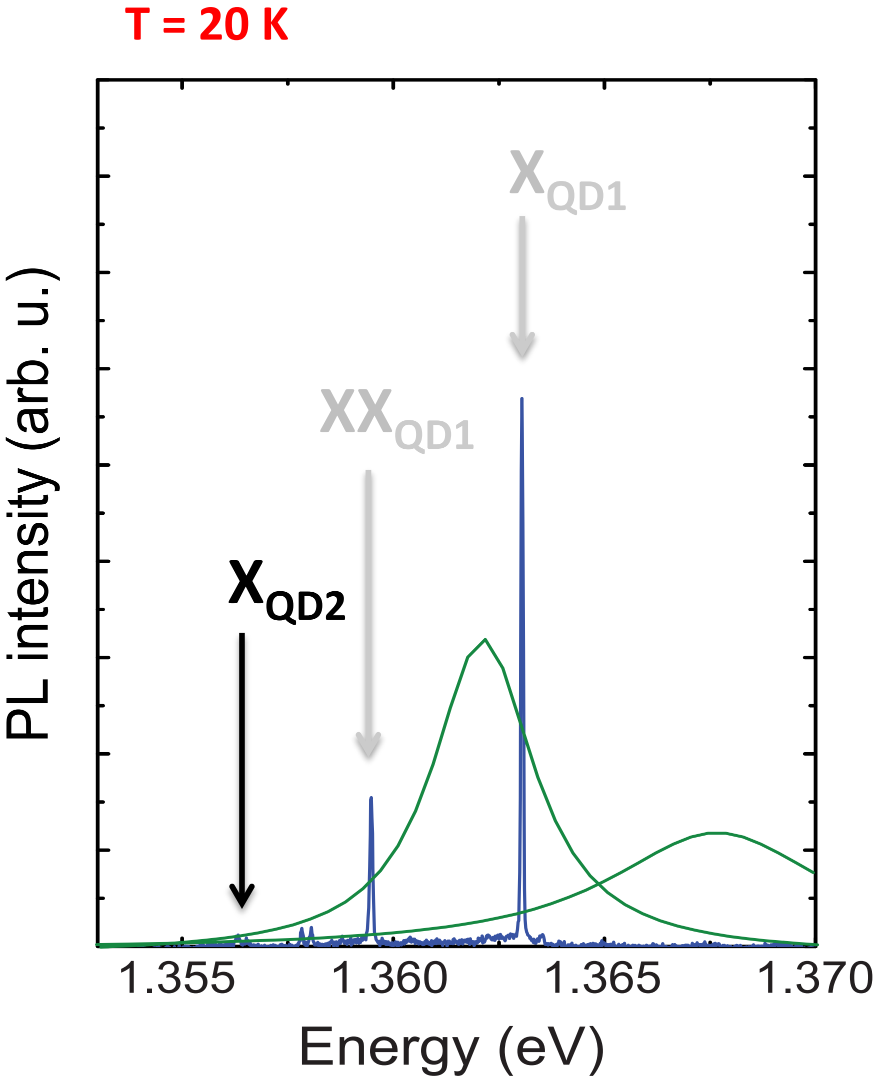
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

T = 40 K



Reference QDs	Lifetime **1.3 ns**
X_{QD1} (T=20K)	Lifetime **700 ps**
X_{QD1} (T=40K)	Lifetime **400 ps**
Acceleration	**Purcell factor F_P = 2.8**
XX_{QD1} (T=20K)	Lifetime **5.8 ns**
XX_{QD1} (T=40K)	Lifetime **17 ns**

Frequency tuning by temperature



Reference QDs	Lifetime **1.3 ns**
X_{QD1} (T=20K)	Lifetime **700 ps**
X_{QD1} (T=40K)	Lifetime **400 ps**
Acceleration	**Purcell factor F_P = 2.8**
XX_{QD1} (T=20K)	Lifetime **5.8 ns**
XX_{QD1} (T=40K)	Lifetime **17 ns**
X_{QD2} (T=20K)	Lifetime **52 ns**
Strong inhibition of a factor up to 40!	**Emission factor into all other modes Γ = 0.03**

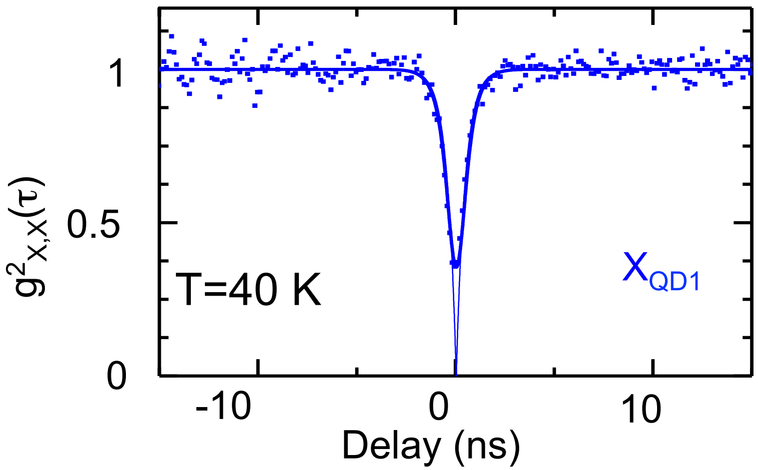
Control of spontaneous emission over 2 orders of magnitude

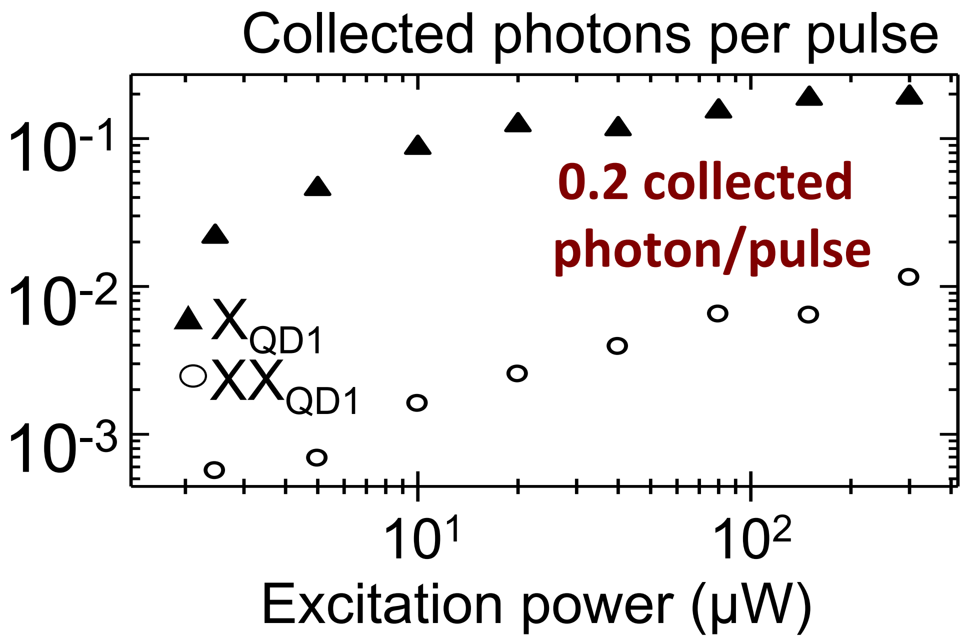
O. Gazzano, et al Phys. Rev. Lett. 107, 247402 (2011).

Single photon source ?

O. Gazzano, et al.
Appl. Phys. Lett. 100, 232111 (2012)

0D Tamm plasmon modes: single photon source



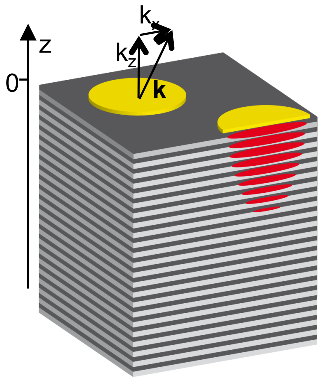


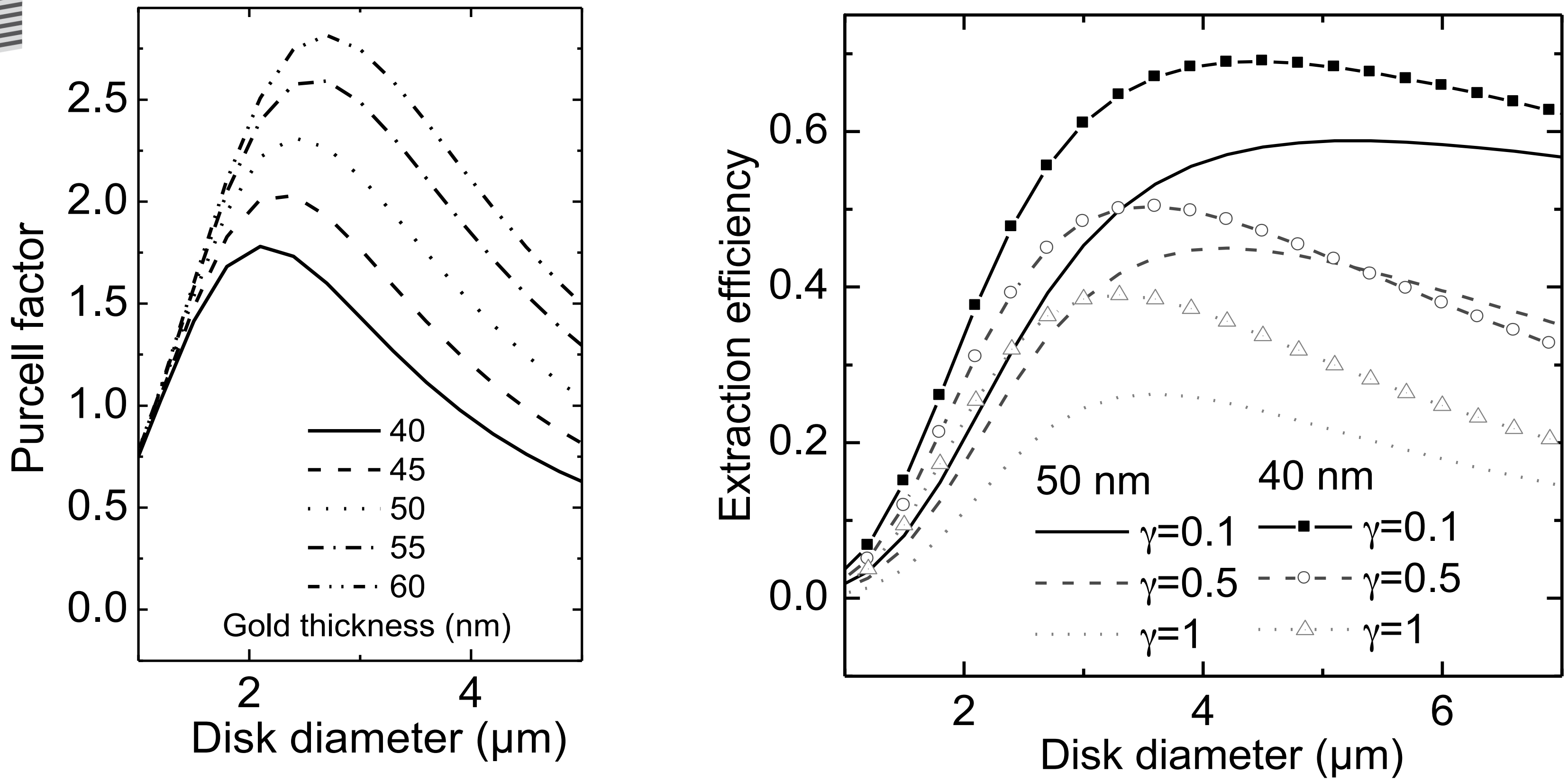
0.2 collected photon/pulse

$$\eta = \underbrace{\frac{F_P}{F_p + G_{other}}}_{\approx 1} \underbrace{\frac{Q}{Q_0}}_{\approx 450/1200 = 0.35} \underbrace{(1-\alpha)}_{\approx 0.67} = 0.25$$

O. Gazzano, et al.
Appl. Phys. Lett. 100, 232111 (2012)

Extraction in optimized structures





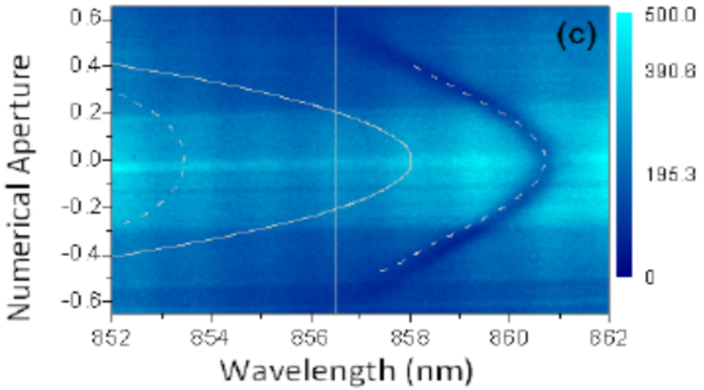
O. Gazzano, et al.
Appl. Phys. Lett. 100, 232111 (2012)

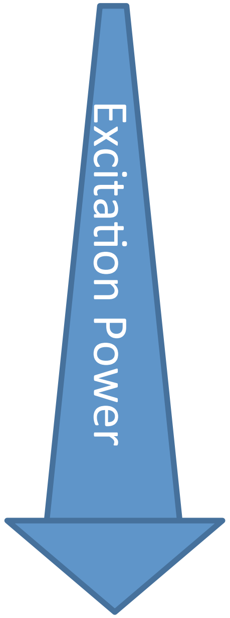
Controlling stimulated emission with Confined Tamm plasmon modes

LABORATOIRE
DE PHOTONIQUE
ET DE NANOSTRUCTURES

Lasing in 2D Tamm

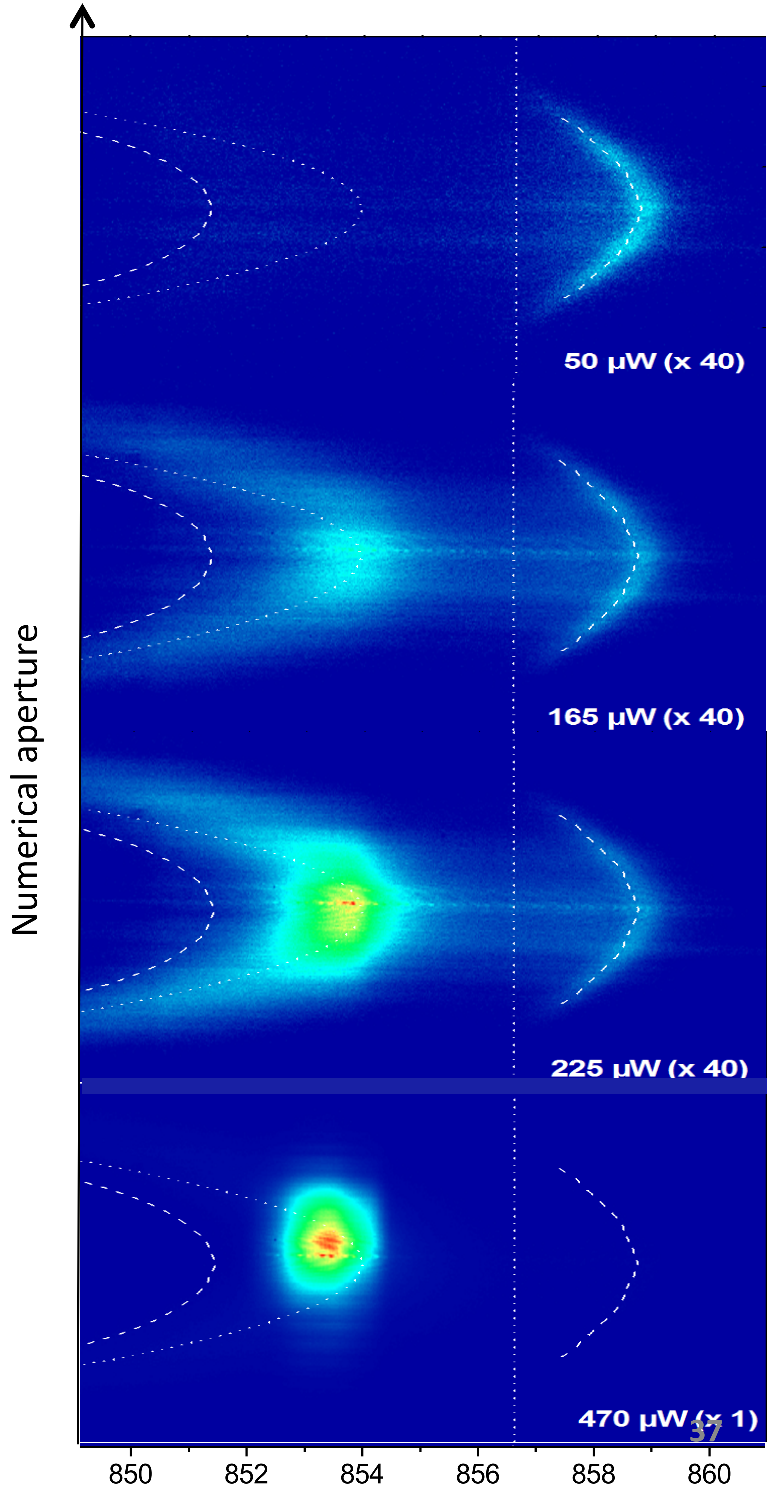
Tamm dispersion relation (Reflectivity)





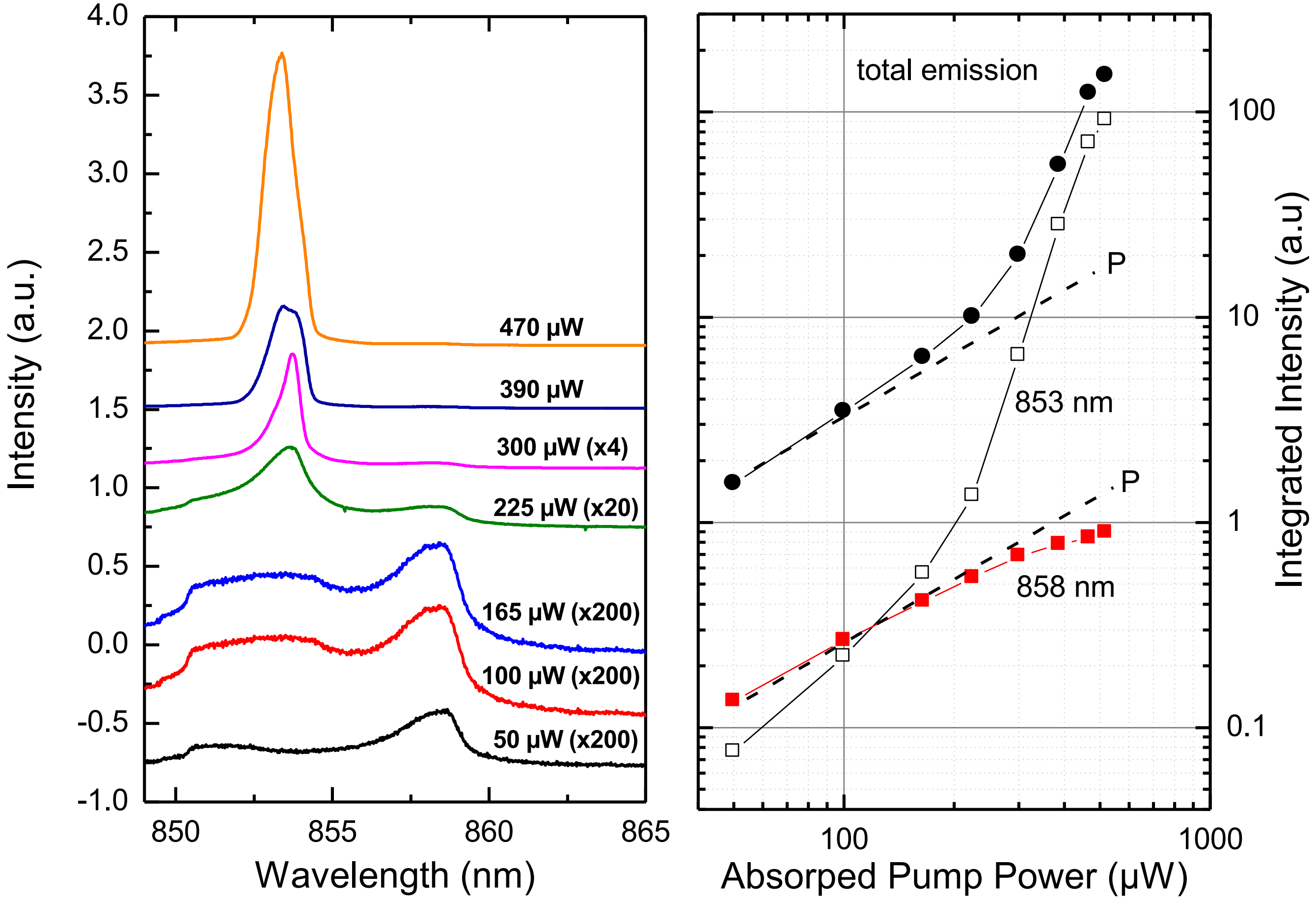
- Low power
  polaritonic emission
- Screening of the strong coupling
  emission at
  bare Tamm energy
- High excitation
  intense emission at k=0

C. Symonds et al., APL mars 2012



Non linear emission

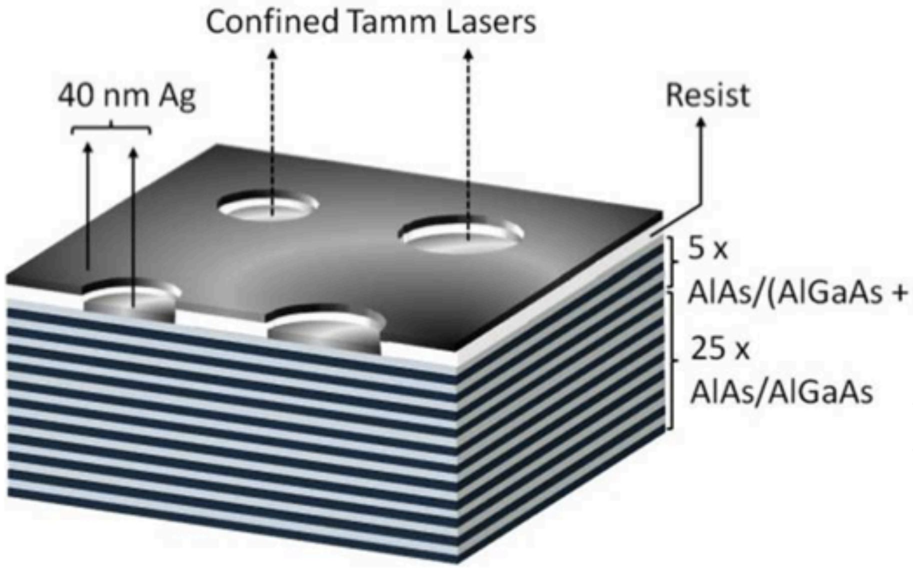
- Pulsed excitation
- polaritonic emission
  linear
- bare Tamm
  super linear
- Linewidth 1,3nm
- Threshold XX



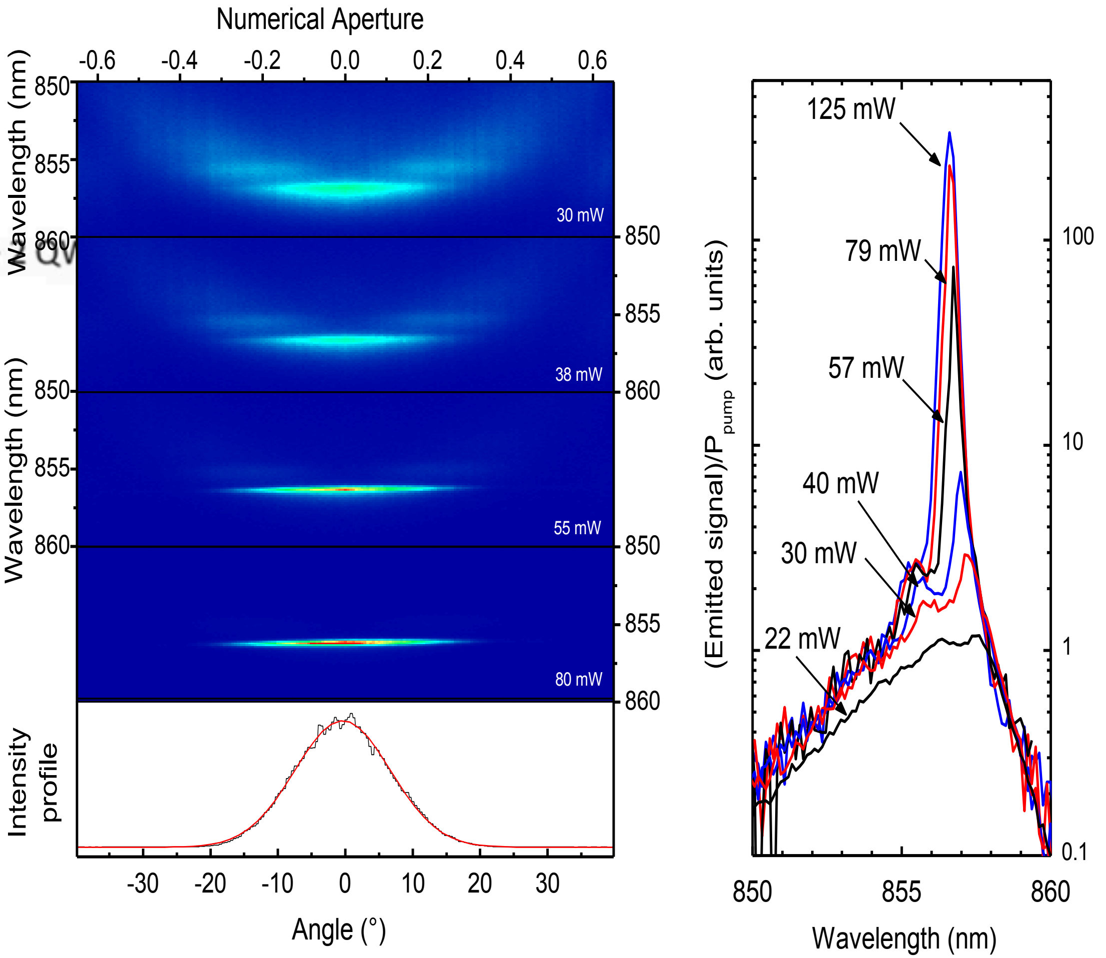
C. Symonds et al., APL mars 2012

Lasing in confined Tamm states

- Disk diameters 1⟺10µm



4µm diameter

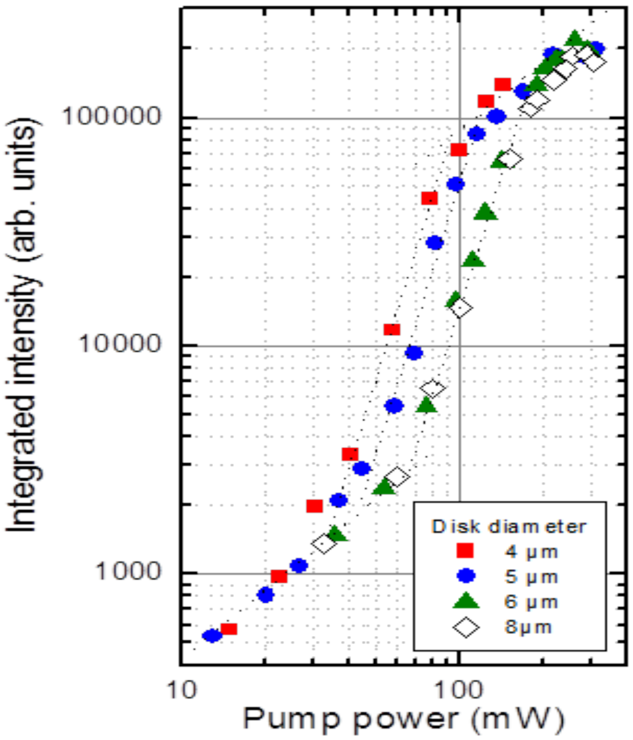


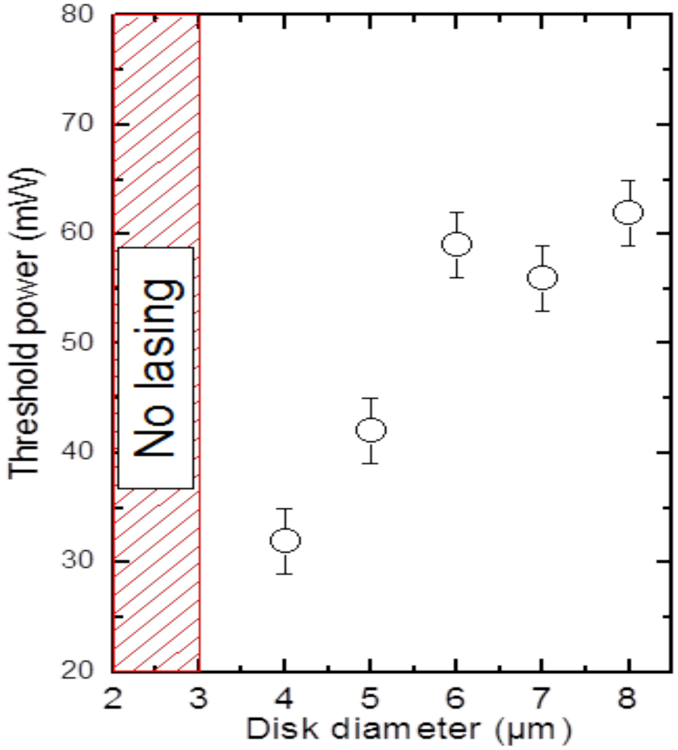
- Large excitation spot

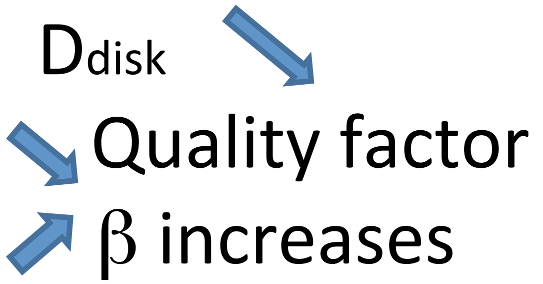
Lasing from lower energy mode

Reduction of the threshold

- Threshold decreases with disk diameter







Ddisk

Quality factor

β increases

- Lower threshold

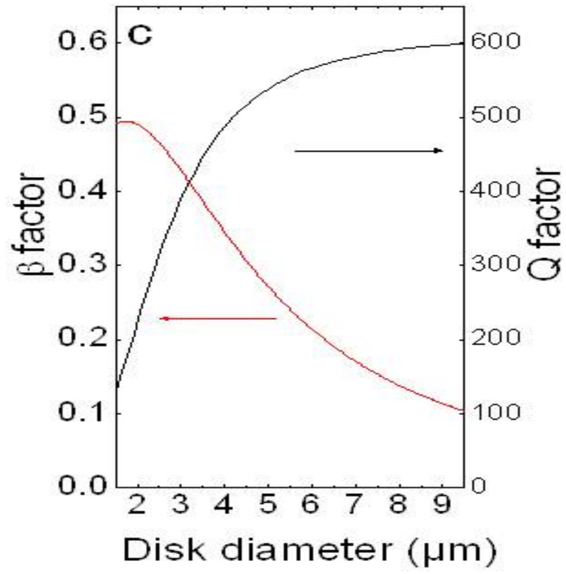
  for 4µm

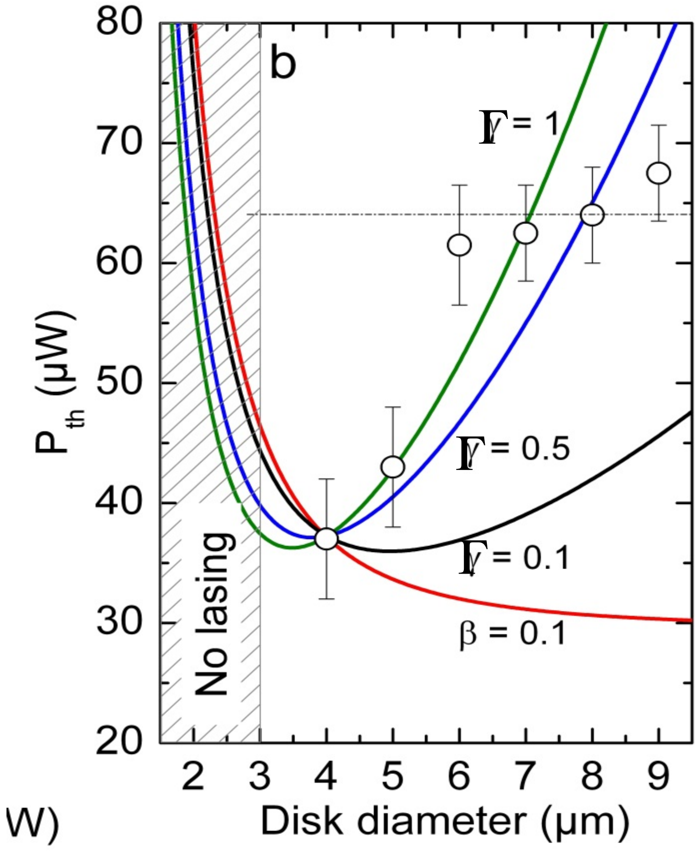
Reduction of the threshold

- Threshold decreases with disk diameter

$$P_{th} \propto \frac{1}{\beta Q}$$

Björk et al. PRA 93

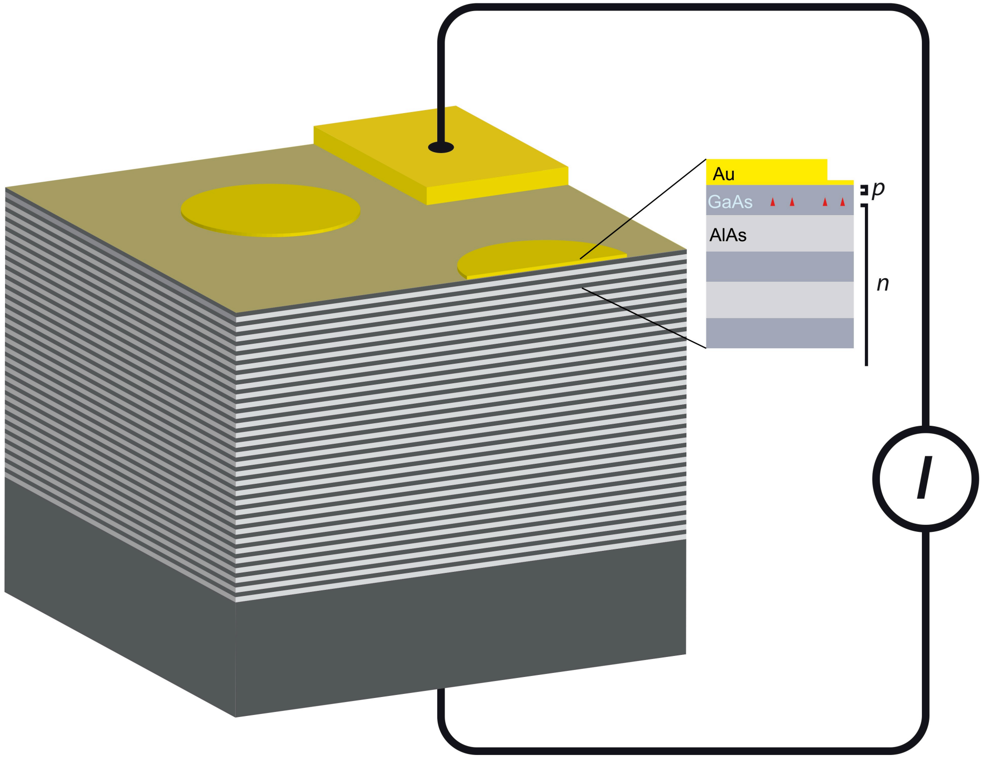




- Minimum at 4µm

Accepted in Nano Letters

Electric control compatibility



Easy electrical control

Conclusions

Confined Tamm-plasmon modes

Easy implementation

Highly customizable: think of new lateral confinement geometries !

High extraction efficiency

Electrical pumping