Quantum optics with microcavity polaritons

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Physique quantique et applications

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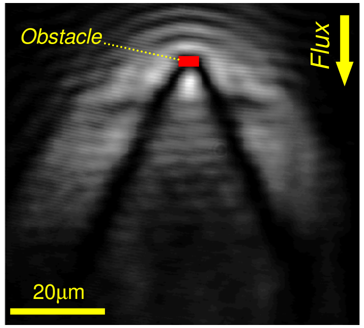
Macroscopic quantum coherence of polariton gases

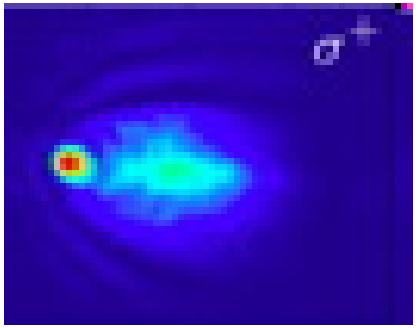
⇒ An ideal system to study out of equilibrium quantum fluids



Superfludity, hydrodynamic dark solitons and vortices in polaritons superfluids (*Nature Physics 2009, Science 2011, Nature Photonics 2011*)

Polariton Non Linear Spin Dynamics

⇒ Towards integrated optoelectronic devices

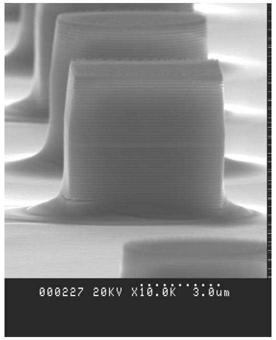


Logic gates, All Optical Spin Switches, polariton transistor

(Nature Physics 2007, PRL 2007, Nature Photonics 2010, PRL 2011,PRL2012, Nature Communications 2013)

Quantum Effects in semiconductor nano and microcavities in strong coupling regime

⇒ Towards a compact, integrable nano- source of entangled beams



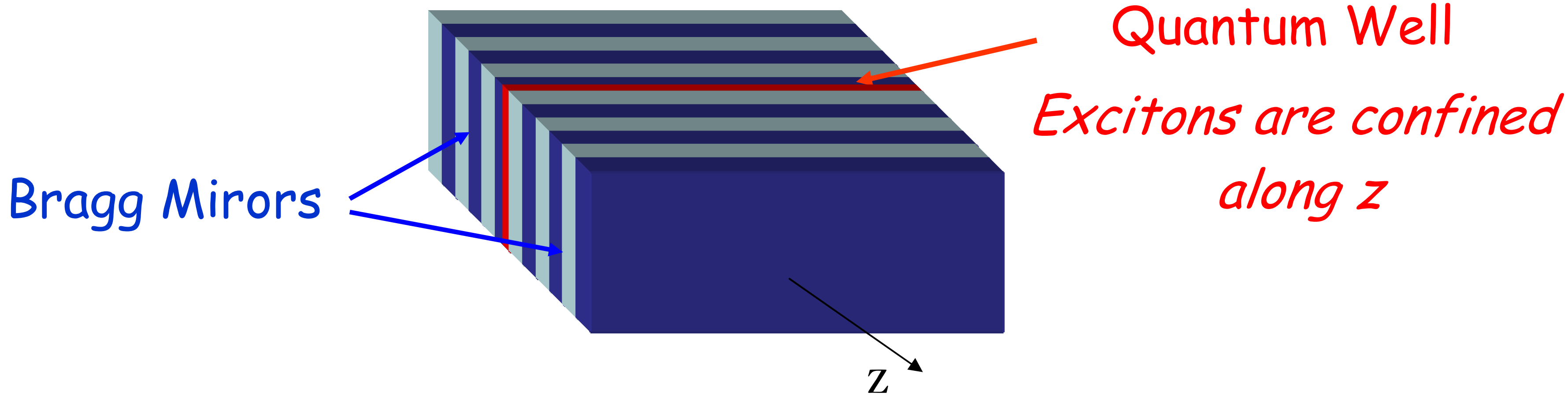
Micropillars, quantum wires, micropillars

(PRL 2007, APL 2010,PRB 2011)

Contents

1. Introduction
2. Non degenerate Four wave mixing: correlated polariton modes
3. Degenerate Four-Wave Mixing: intensity squeezing
4. Conclusion and perspectives

Quantum Well in a Optical Cavity



Quantification condition: $k_{z,photon} = 2\pi n_c / \lambda_0$

Excitonic state $\mathbf{K}_{//}$
coupled to a unique mode of the intracavity field
with wave vector $\mathbf{k} = (\mathbf{K}_{//}, k_z)$

$\Rightarrow$ Reversible evolution : Rabi oscillations

Strong Coupling Regime: Cavity Polaritons

Exciton-photon linear coupling:

$$H_k = \mathrm{E}_{cav}(\mathrm{k})\hat{\mathrm{a}}_\mathrm{k}^\dagger\hat{\mathrm{a}}_\mathrm{k} + \mathrm{E}_{exc}(\mathrm{k})\hat{\mathrm{b}}_\mathrm{k}^\dagger\hat{\mathrm{b}}_\mathrm{k} + \frac{\Omega_R}{2}(\hat{\mathrm{a}}_\mathrm{k}^\dagger\hat{\mathrm{b}}_\mathrm{k} + \hat{\mathrm{b}}_\mathrm{k}^\dagger\hat{\mathrm{a}}_\mathrm{k})$$

Strong coupling regime $\Omega_R >> \gamma_a, \gamma_b$

$\Omega_R = 5.1$ meV

$\gamma_a, \gamma_b \approx 0.1$ meV ≈ 25 Ghz

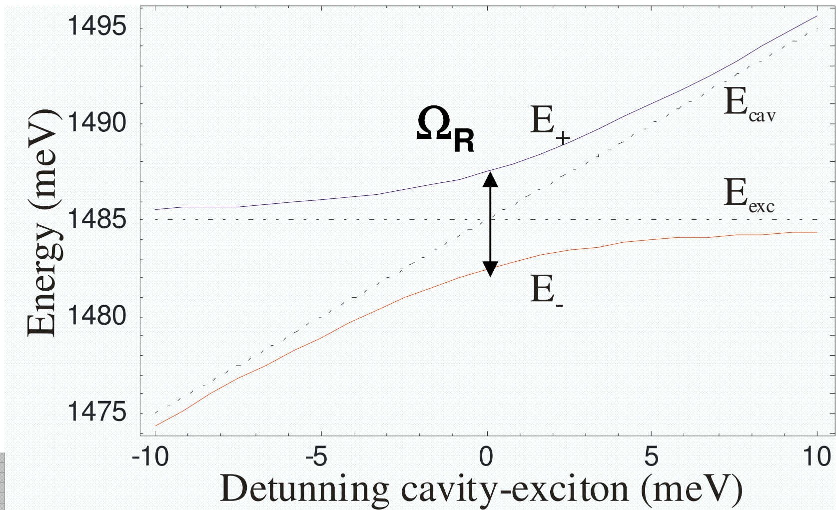
Normal modes: Cavity polaritons

$$\hat{p}_k = -C_k\hat{a}_k + X_k\hat{b}_k$$

$$\hat{q}_k = X_k\hat{a}_k + C_k\hat{b}_k$$

$$H_k = \mathrm{E}_{LP}(\mathrm{k})\hat{\mathrm{p}}_\mathrm{k}^\dagger\hat{\mathrm{p}}_\mathrm{k} + \mathrm{E}_{UP}(\mathrm{k})\hat{\mathrm{q}}_\mathrm{k}^\dagger\hat{\mathrm{q}}_\mathrm{k}$$

Energies anticrossing



Polaritons Nonlinear Properties

When the exciton density rises (strong excitation), coulombian interaction between excitons are large.

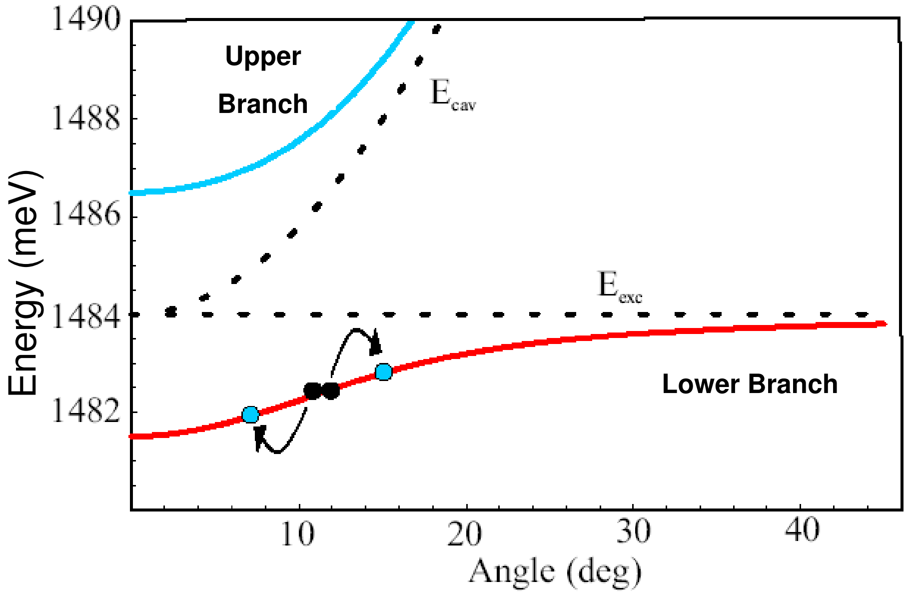
Hamiltonien for the lower polariton branch:

$$\boxed{H = H_{lin} + H_{PP}^{eff}}$$

$$\boxed{H_{PP}^{eff} = \frac{1}{2}\sum_{k,k',q} V_{k,k',q}^{PP} p_{k+q}^{\dagger} p_{k'-q}^{\dagger} p_k p_{k'}}$$

Polaritons four-wave mixing

$\{k_p , k_p\} \rightarrow \{k_p+q , k_p-q\}$



Motivations

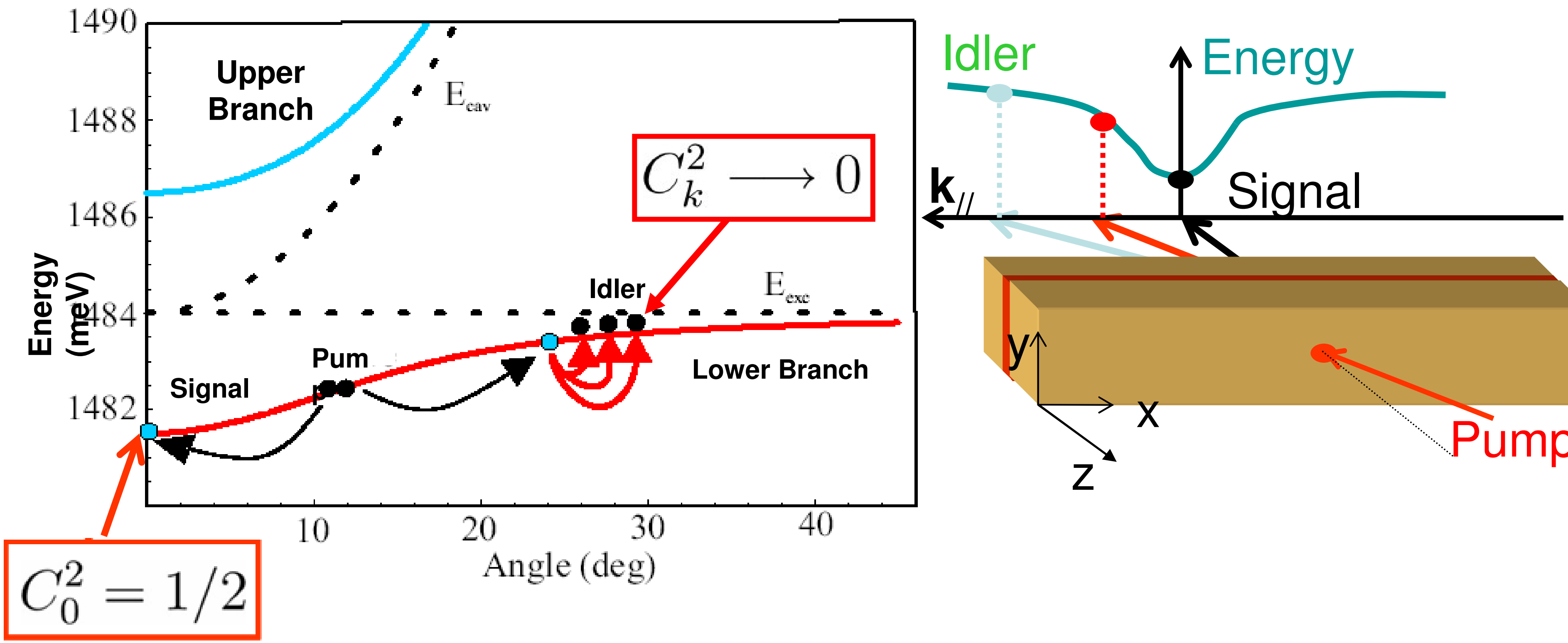
Study of nonlinear interactions between polaritons

Generation non-classical state of ligth with a semiconductor microcavity

μOPO

Generation of two distinct quantum correlated polariton modes

Parametric generation : quantum correlations between signal and idler?

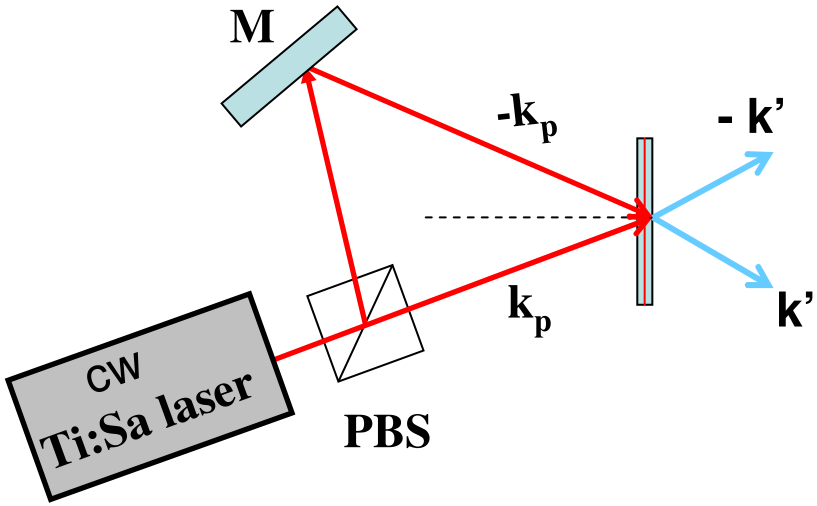


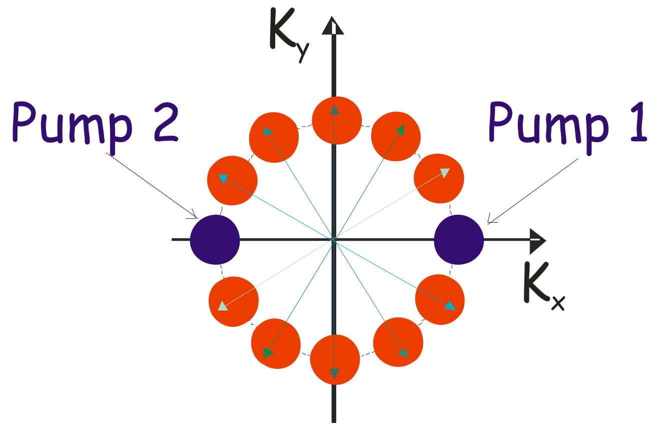
One pump with k≠0 : large asymmetry between signal and idler: the photonic fraction of the idler mode is very small

Savvidis *et al.* Phys.Rev.Lett **84**, 1547 (2000); Ciuti *et al.* Phys.Rev.B **62** R4825 (2000)

Geometry

Two pumps resonant excitation





Momentum Conservation

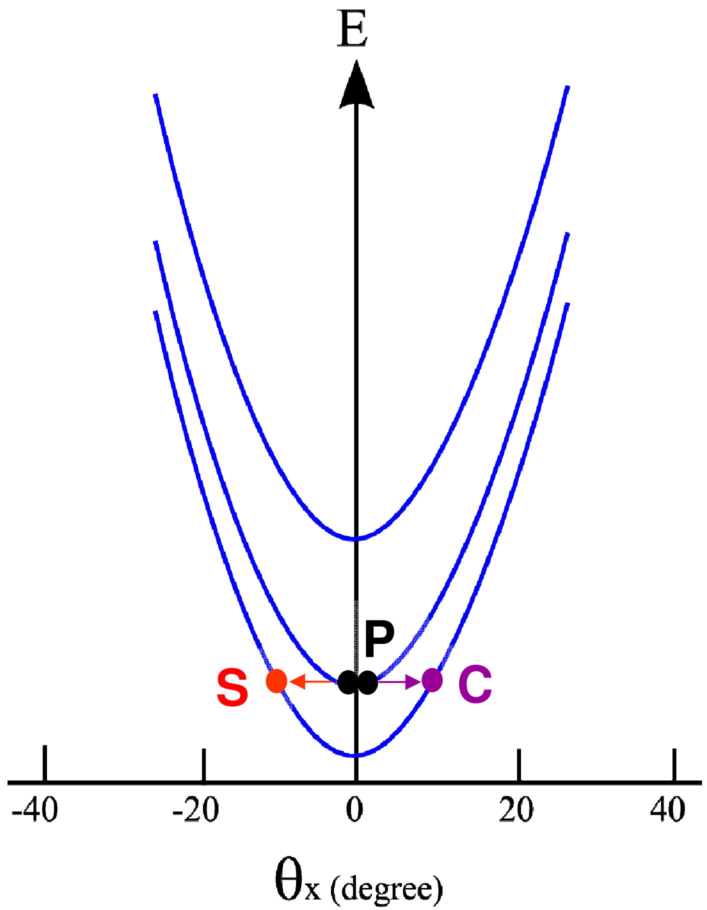
$\{-k_p, k_p\} \longrightarrow \{-k', k'\}$

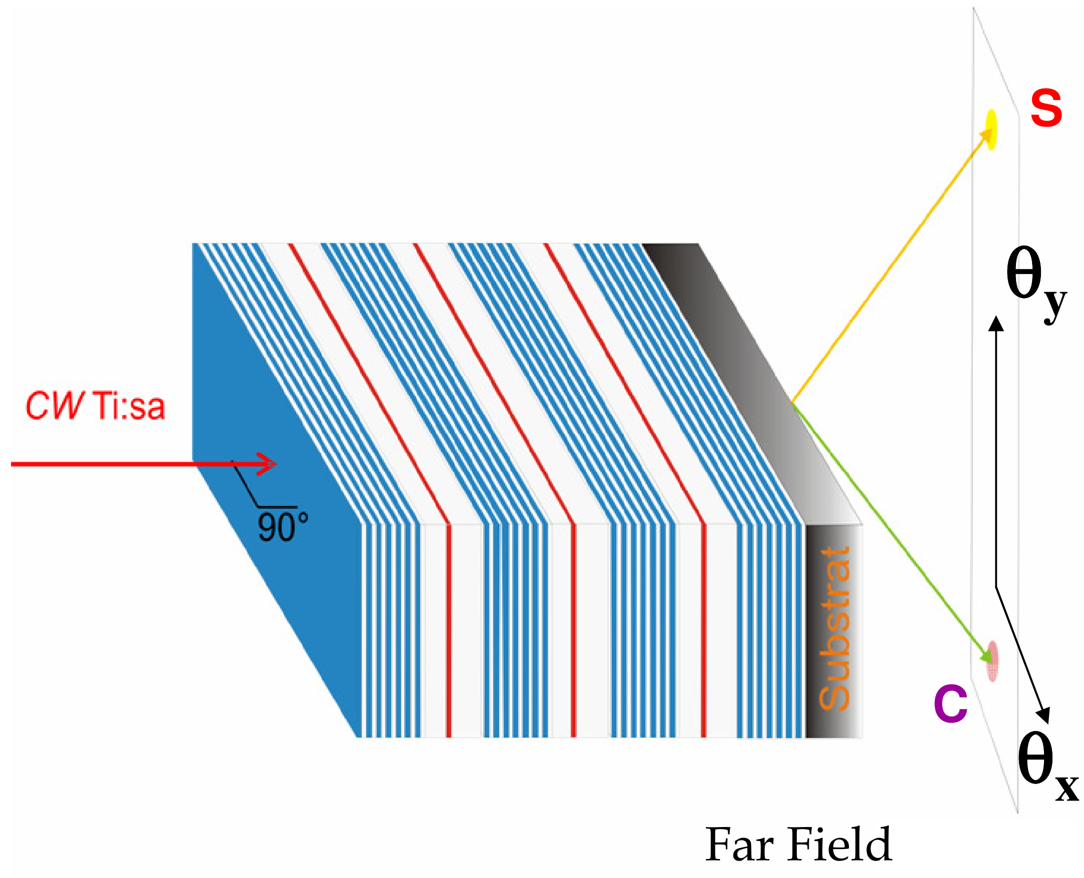
Energy conservation

$|k_p| = |k'|$

- Symmetry between signal and idler
- Large photon component

Triple microcavities: horizontal Parametric Process



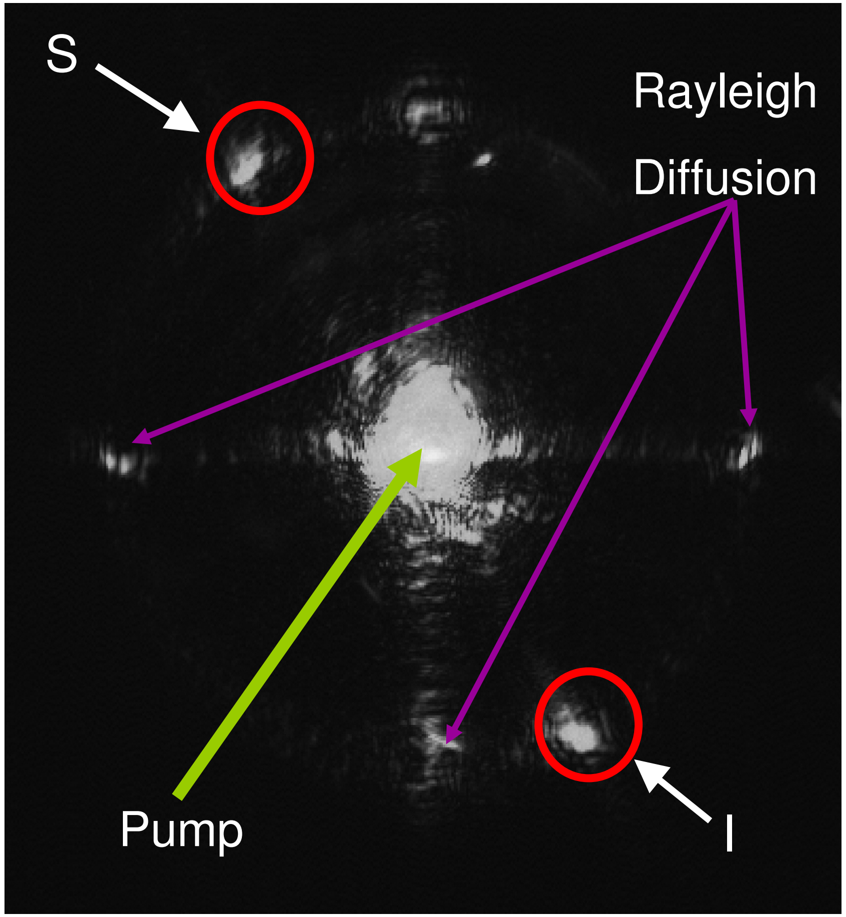


Collaborations: C. Diedrichs, J. Tignon & C. Delalande, *Laboratoire Pierre Aigrain*, ENS

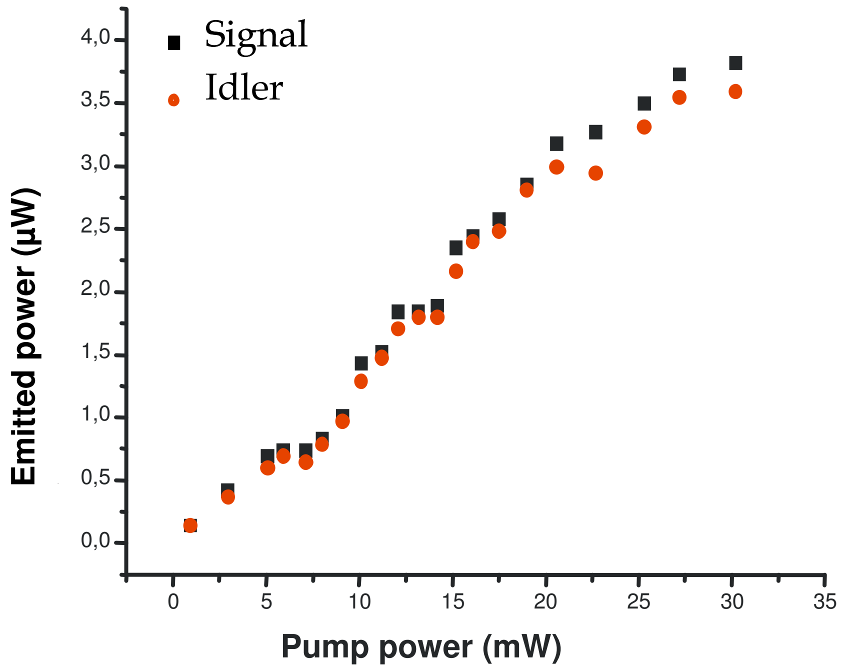
A. Lemaître & J. Bloch, *Laboratoire Photonique et Nanostructure*, CNRS

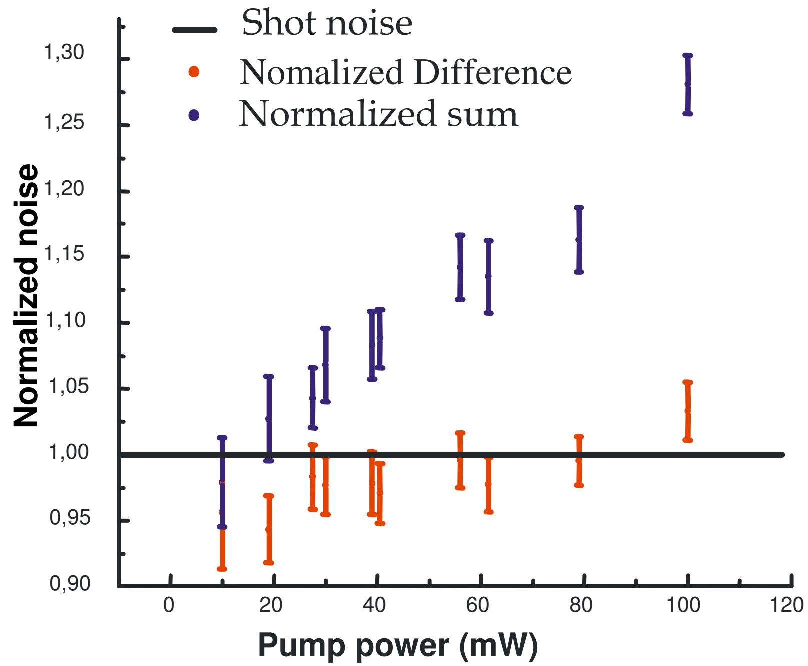
Strong coupling under resonant excitation

Far Field Emission



Experimental results





negative detuning

The intensity noise on the difference of photocurrents is at the shot noise level

Conclusions

Achievements

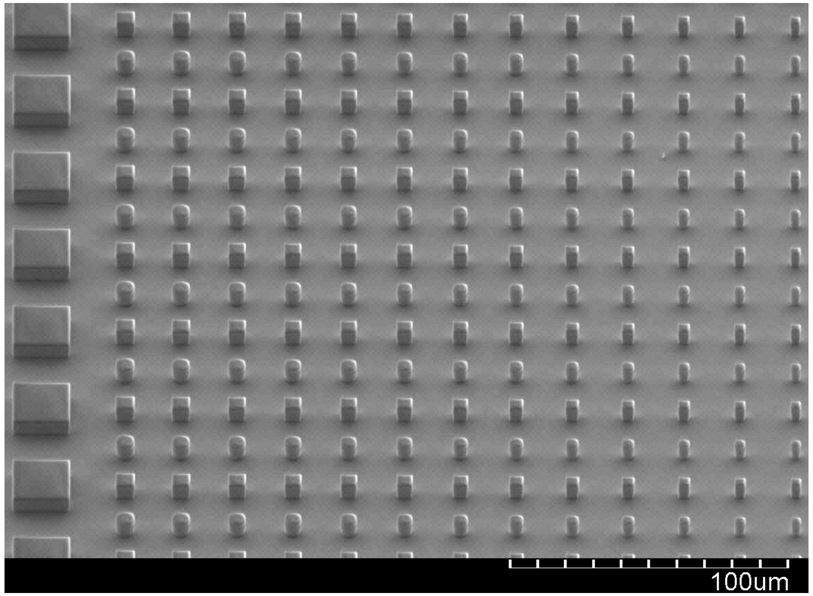
- Polariton four wave mixing: generation of correlated polariton modes

- Generation of correlated beams with a Triple Microcavity

  - simple geometry
  - equal signal / idler intensities (good for noise measurements)

- Reduction of the Noise to the Shot Noise level

Intensity squeezing in semiconductor microstructures



T. Boulier, M. Bamba, A. Amo, C. Adrados, A. Lemaitre, E. Galopin, I. Sagnes, J. Bloch, C. Ciuti, E. Giacobino and A. Bramati

ANR

CNRS

MPQ

LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

ECOLE NORMALE SUPERIEURE

UPMC SORBONNE UNIVERSITÉS

Physics OSAKA UNIVERSITY
Department of Physics, Graduate School of Science

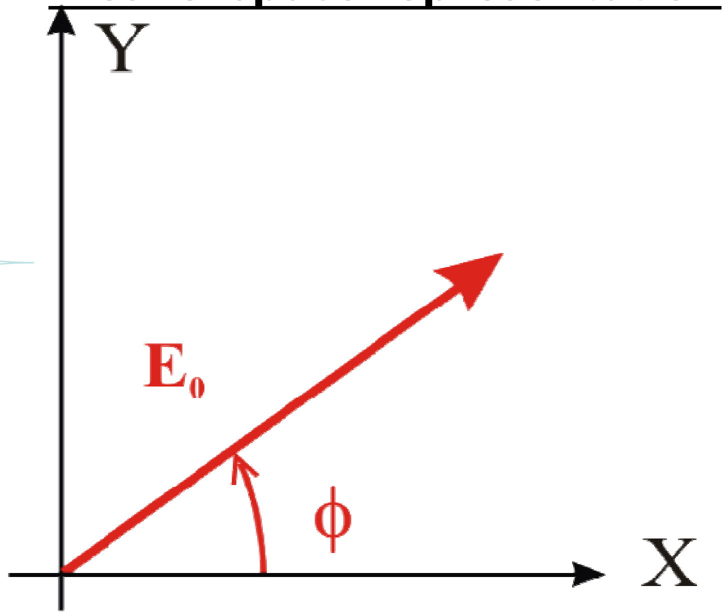
Squeezed states of light

Classically: $E = E_0 \cos(\omega t + \phi)$

$$= X\cos(\omega t) + Y\sin(\omega t)$$

Electro-magnetic wave represented by a **complex number**
=> **vector** in a 2D space, called the **Fresnel space**

Fresnel space representation



No lower limit to fluctuations: the state can be **point-like** in the Fresnel space.

Squeezed states of light

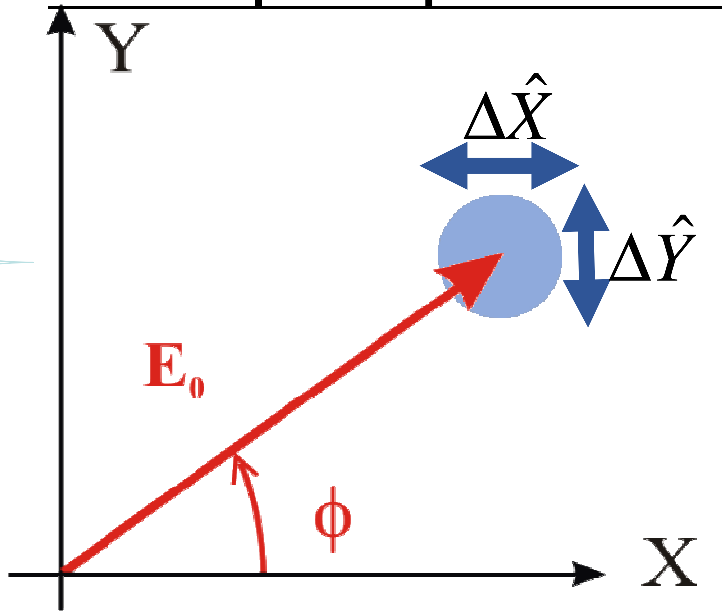
Quantum: $\hat{E} = \hat{E}_0 \cos(\omega t + \phi)$

$$= \hat{X}\cos(\omega t) + \hat{Y}\sin(\omega t)$$

X and *Y* do not commute $[\hat{X}, \hat{Y}] \neq 0$

$$\Delta\hat{X}\Delta\hat{Y} \geq 1$$

Fresnel space representation



Coherent state: **shot noise**

$$\Delta\hat{X} = \Delta\hat{Y} = 1$$

(E.g. in a laser beam)

Squeezed states of light

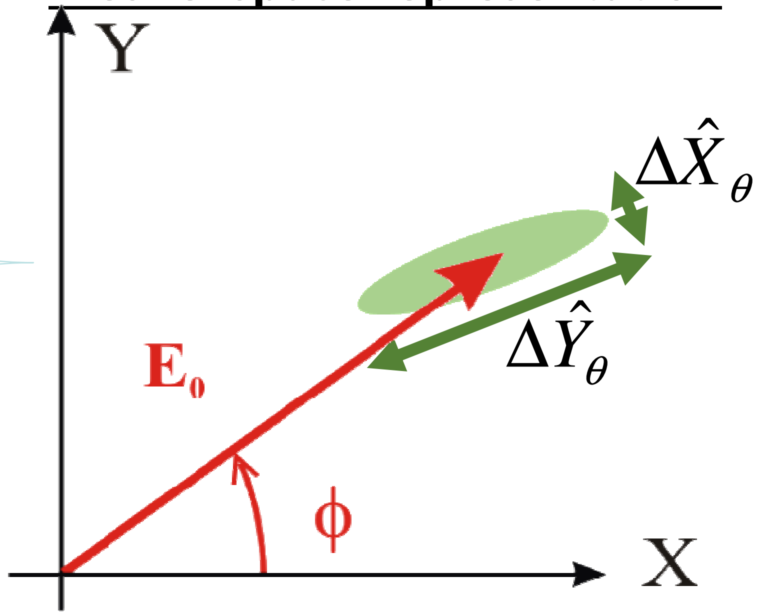
Quantum: $\hat{E} = \hat{E}_0 \cos(\omega t + \phi)$

$$= \hat{X}\cos(\omega t) + \hat{Y}\sin(\omega t)$$

X and *Y* do not commute $[\hat{X}, \hat{Y}] \neq 0$

$$\Delta\hat{X}\Delta\hat{Y} \geq 1$$

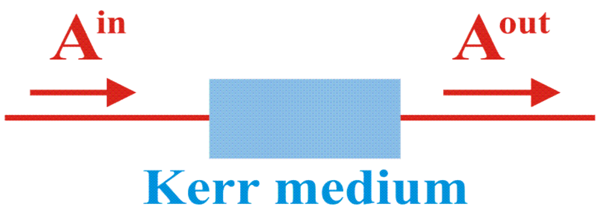
Fresnel space representation



« Squeezed » below shot noise: $\Delta\hat{X} \neq \Delta\hat{Y};\ \underline{\Delta\hat{X}\ or\ \Delta\hat{Y} < 1}$

Quadrature squeezing: $\Delta\hat{X}_\theta < 1$ **for some axis θ**; of course $\Delta\hat{Y}_\theta > 1$

Light squeezing via Kerr effect



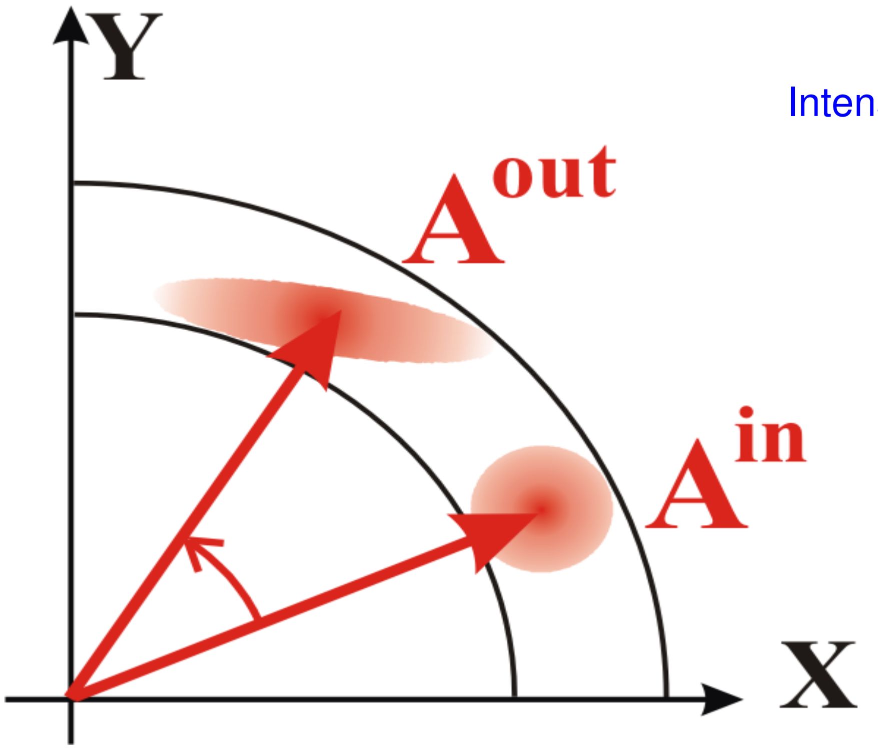
$$\boxed{n(I) = n_0 - n_2 I}$$

$$E_{in}(t) = E_{1in} + \delta E_{1in}(t) + \delta E_{2in}(t)$$

Intensity fluctuations

Effect on phase fluctuations

Modulation of the refraction index



$\Rightarrow$ ***Semiconductors***

$\Rightarrow$ ***Atomic medium***

$\Rightarrow$ ***Optical fibers***

Polaritons : Nonlinear Properties

When the exciton density rises (strong excitation), coulombian interaction between excitons are large

This generates polariton-polariton interactions

$$\boxed{H = H_{lin} + H_{\text{Non-lin}}}$$

At normal angle **(degenerate 4-wave mixing)**

Hamiltonian in the polariton basis, upper branch neglected

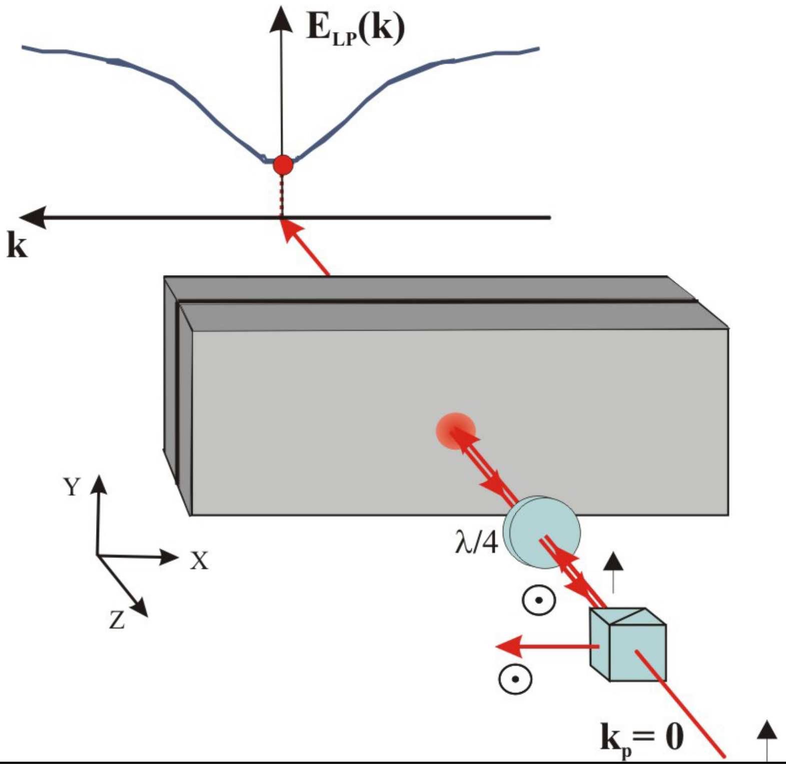
$$\boxed{H = \eta\omega_{LP}\, p^{+} p + \eta\alpha\, X^{4} p^{+} p^{+} pp}$$

Self-phase modulation term

=> Polariton Kerr effect

Savvidis, P. G. *et al., Phys. Rev. Lett.* **84**, 1547–1550 (2000); Stevenson, R. M. *et al.*, *Phys. Rev. Lett.* **85,** 3680 (2000); Messin, G. *et al.*, *Phys. Rev. Lett.* **87** (2001); Romanelli, M et al., *Phys. Rev. Lett.* **98** (2007)

Squeezing in a degenerate four wave mixing



Generation of squeezed state by degenarated four-wave mixing:

First observation of non classical states in these systems: limited squeezing , 4%

J.Ph Karr *et al*, Phys. Rev. A **69**, 031802 (R) (2004), Laboratoire Kastler Brossel, Paris

Main problem = coupling with phonon reservoir

Origin of the excess-noise ?

PRL **104,** 213604 (2010) PHYSICAL REVIEW LETTERS week ending 28 MAY 2010

Quantum Squeezing Generation versus Photon Localization in a Disordered Planar Microcavity

Motoaki Bamba,* Simon Pigeon, and Cristiano Ciuti†

Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Diderot-Paris 7 et CNRS, Bâtiment Condorcet, 10 rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France

(Received 12 February 2010; revised manuscript received 1 April 2010; published 28 May 2010)

We investigate theoretically the nonlinear dynamics induced by an intense pump field in a disordered planar microcavity. Through a self-consistent theory, we show how the generation of quantum optical noise squeezing is affected by the breaking of the in-plane translational invariance and the occurrence of photon localization. We find that the generation of single-mode Kerr squeezing for the ideal planar case can be prevented by disorder as a result of multimode nonlinear coupling, even when the other modes are in the vacuum state. However, the excess noise is a nonmonotonic function of the disorder amplitude. In the strong localization limit, we show that the system becomes protected with respect to this fundamental coupling mechanism and that the ideal quadrature squeezing generation can be obtained.

DOI: 10.1103/PhysRevLett.104.213604 PACS numbers: 42.50.Dv, 42.50.Pq, 42.65.Hw, 71.55.Jv

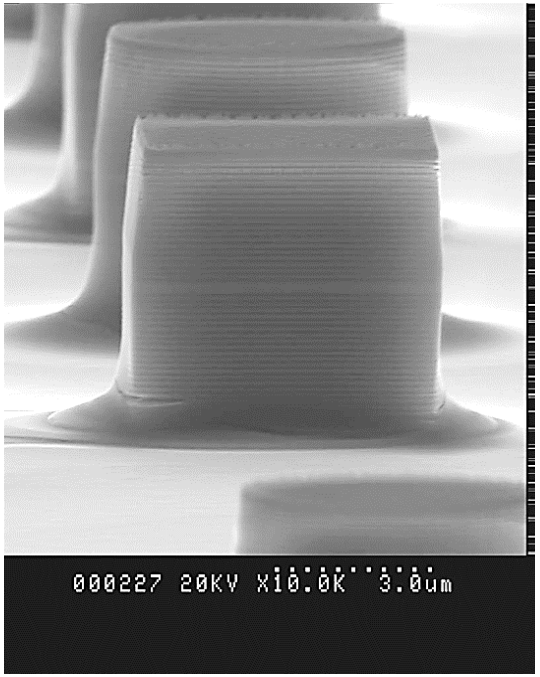
Disorder, mode coupling;

solution?

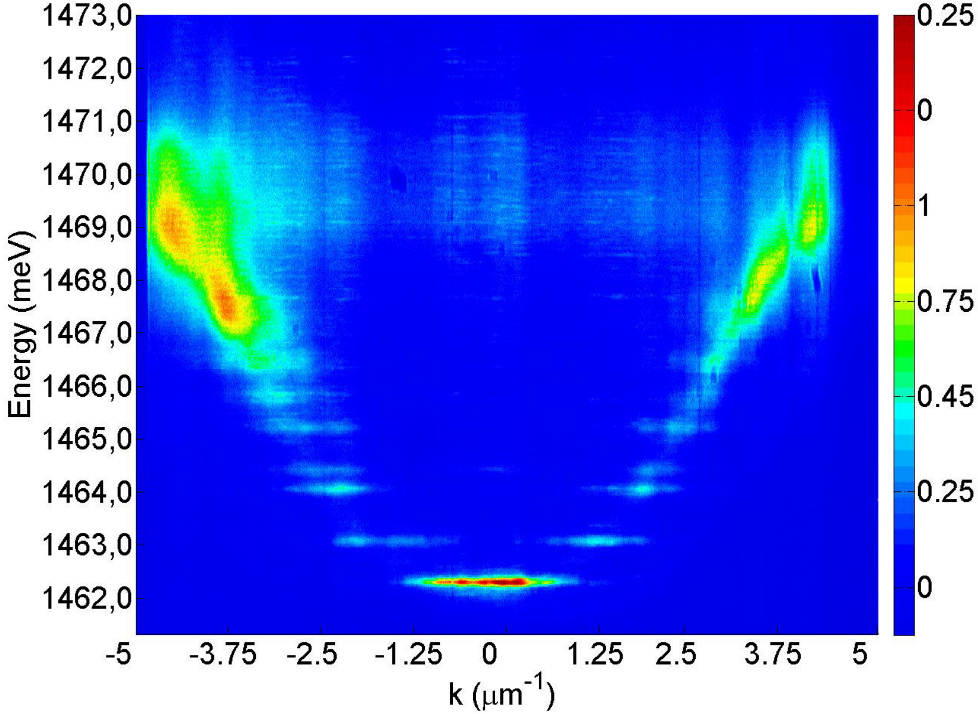
Strong confinement !

Strong confinement => discrete energy levels => limited coupling with the phonon reservoir

Beyond planar microcavities : micropillars



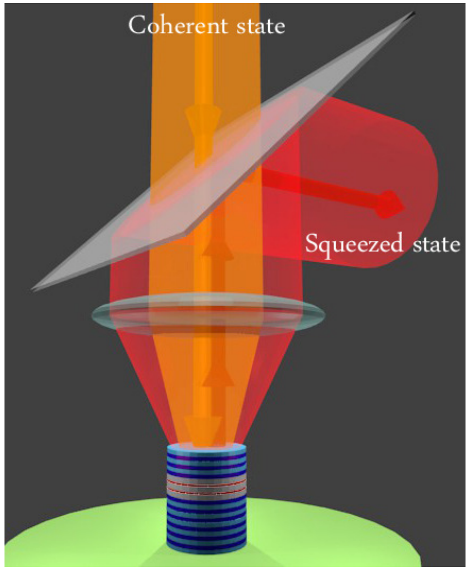
SEM bird's eye view of micropillars obtained at LPN

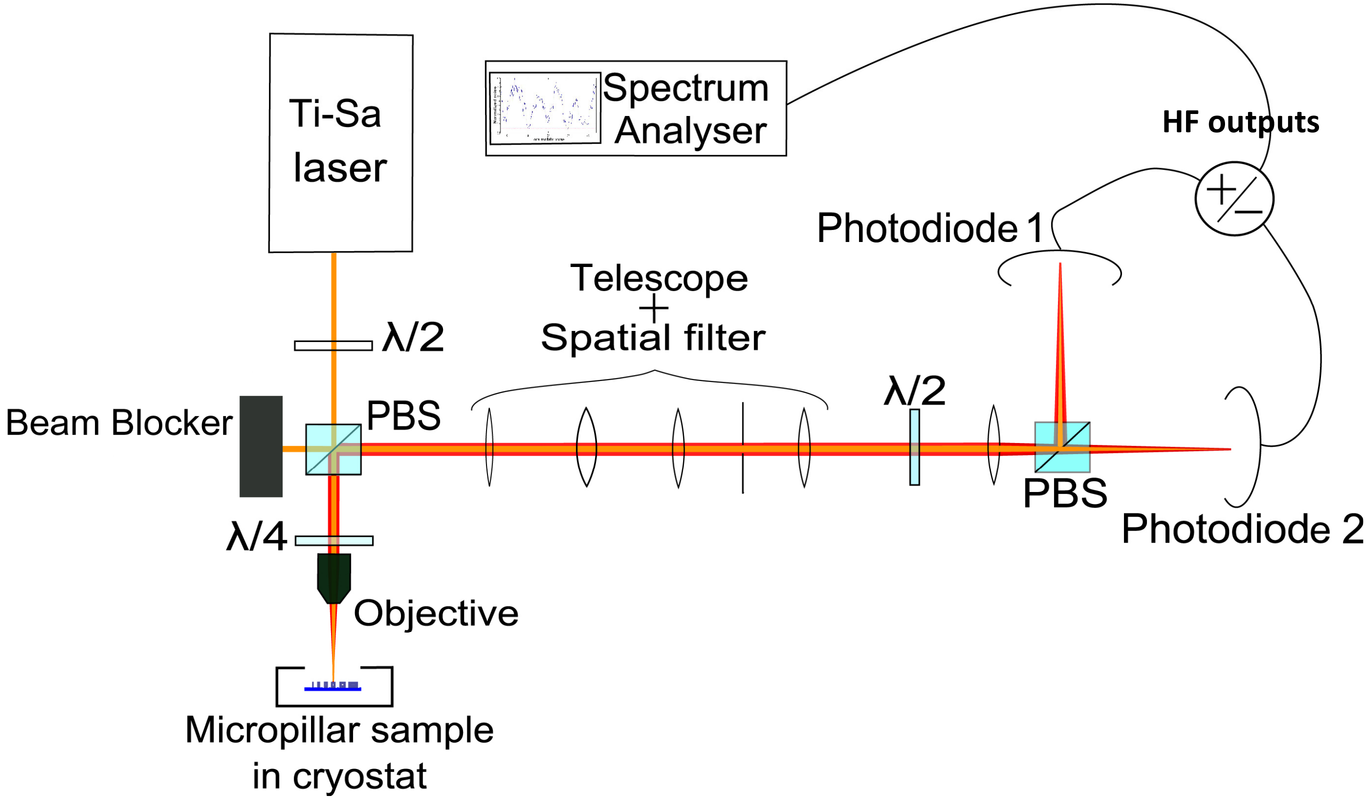


Micropillar's quantized dispersion curve

- Confinement obtained in a controlled way by etching microns-sized pillars in a planar microcavity (*typical size : 6μm*)
- Energy modes are quantized, coupling with phonon reservoir is strongly limited
- Stronger squeezing expected with respect to planar microcavity

Setup : balanced detection mesurement



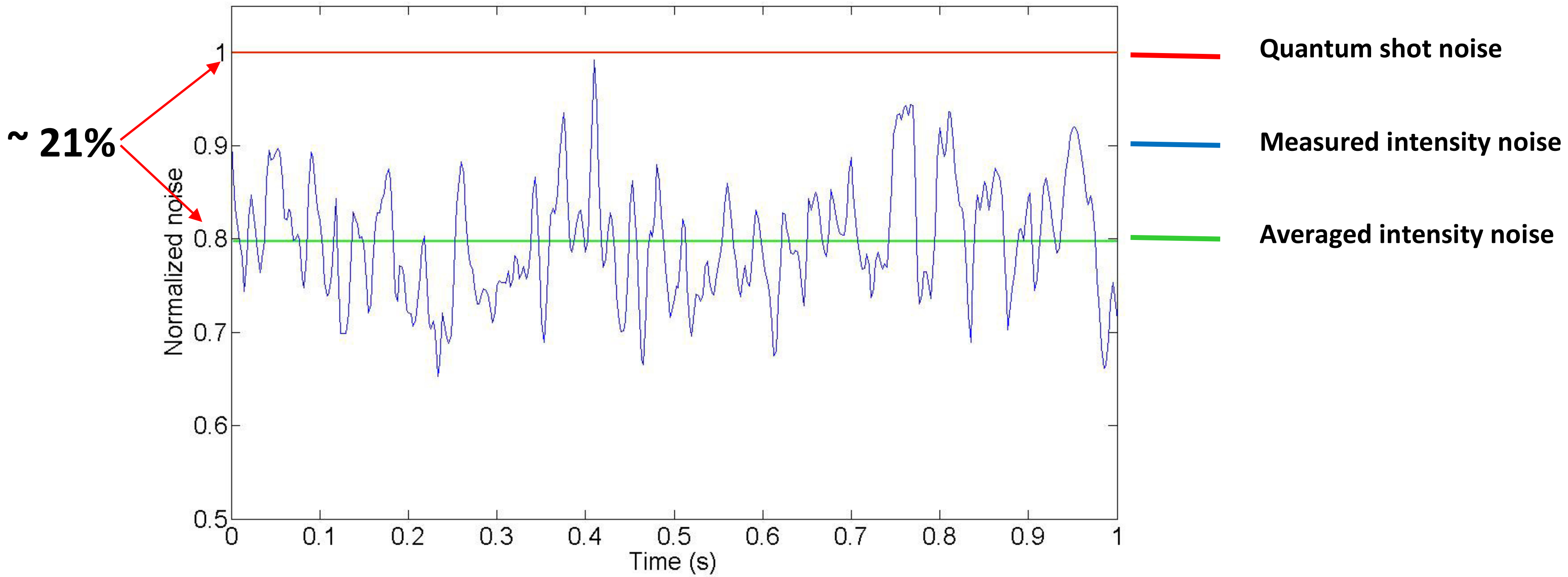


<u>**Intensity noise measurement technique**</u> : <u>balanced detection</u>

After amplification, on a *spectrum analyser* :

- **Difference** of the photodiodes' *HF outputs* gives the <u>shot noise</u>
- **Sum** of the *HF outputs* gives the <u>intensity noise</u>

Experimental results



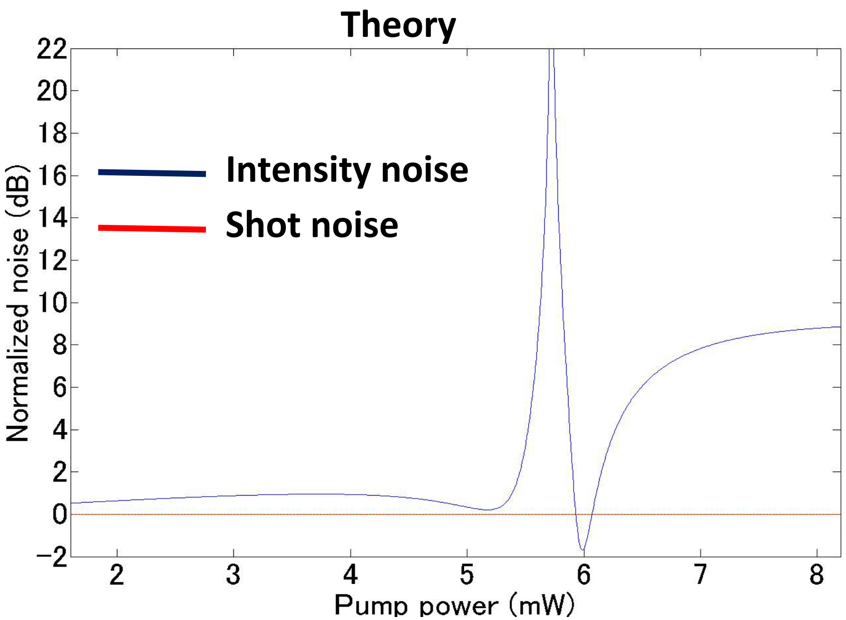
Intensity noise measurement, showing around **21%** squeezing
This is an ***order of magnitude*** better than previously

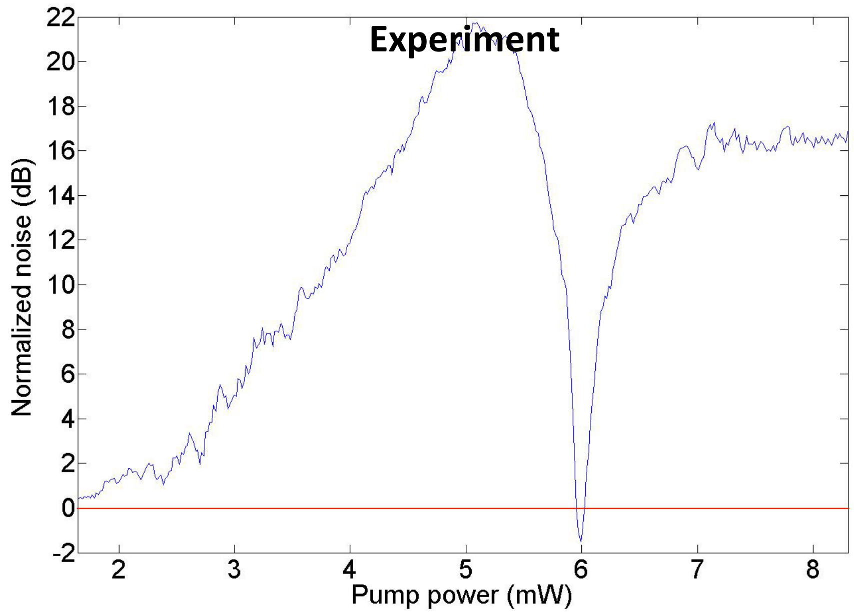
The *inferred* squeezing after correction is **37%** below the shot noise

Comparison with theory

A <u>Heisenberg-Langevin model</u> gives qualitative prediction,
especially at and beyond the turning point

<u>Intensity noise evolution with pump power:</u>





The model does not take some phenomena into account, e.g. effect of disorder

Conclusion and perspectives

Previous results were improved ***tenfold***, making this technique ***potentially useful***

•***Micrometric*** size + ***semiconductor*** structure => potential for ***integrability***

•Achievable in <u>low power</u> range *(5-10mW CW vs 200mW pulsed laser in standard NL systems)*

=> *ultra low threshold quantum devices*

<u>Perspectives</u>

•Optimisation of cavity parameters

•Quantum correlated beams