Microcavity Quantum Electrodynamics:

From atoms to quantum dots

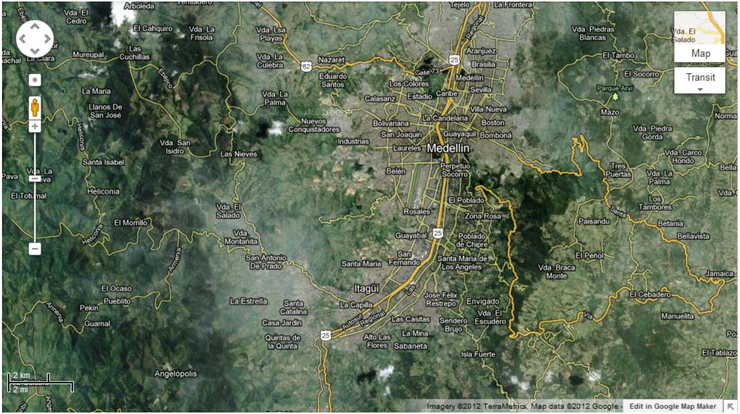
Boris Anghelo Rodríguez Rey

Grupo de Física Atómica y Molecular
Instituto de Física, Universidad de Antioquia

September 26, IWQCD 2012
Universidad del Valle

Universidad de Antioquia

Universidad de Antioquia



Universidad de Antioquia

Our purpose

Microcavity quantum electrodynamics (μCQED), the interplay between quantum optics and solid state systems, has recently emerged as one of the most active and promising research fields. A single quantum emitter, a qdot or a qwell, coupled to one confined light mode in a photonic crystal or a micropillar-cavity is one of these μCQED systems with more perspectives for device applications such as single photon sources and quantum information processing. Furthermore, this system exhibits fundamental physical phenomena such as weak and strong coupling, Purcell effect, non-classical light, and polariton laser (non-equilibrium BEC).
In this talk I will give a short review on the subject.

Outline

Microcavity QED: Matter–ligth coupling

Polariton Physics and SC Phenomena

Model and results

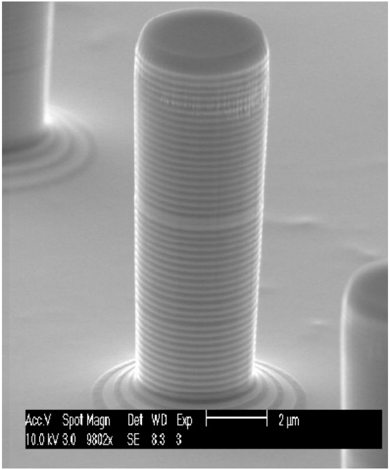
Outline

Microcavity QED: Matter–ligth coupling

Polariton Physics and SC Phenomena

Model and results

Semiconductor Micropillars

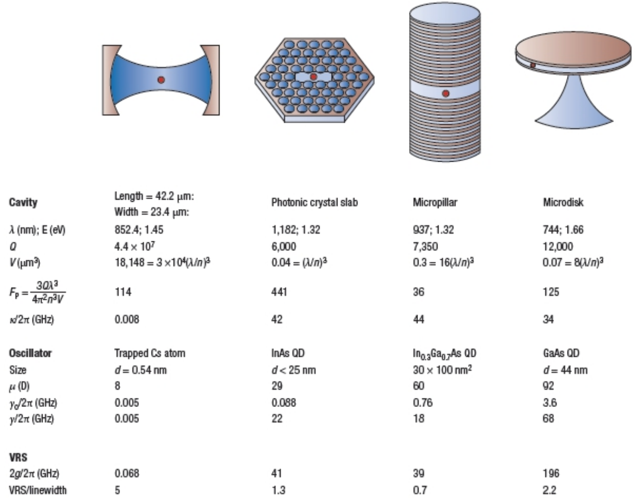


2 μm micropillar, Sheffield.

Properties

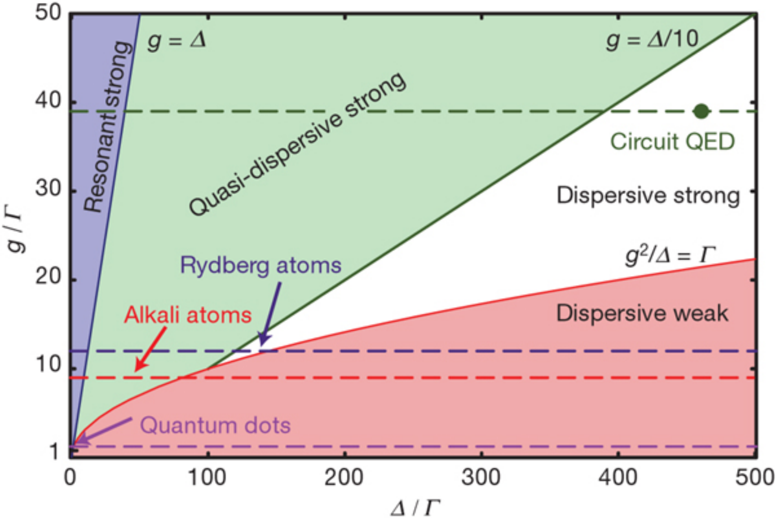
- Eliptic and circular geometry.
- Layers of GaAs and AlGaAs periodically distributed with $\lambda/4$–thick.
- High-Q cavity, $Q \approx 10^4$, embedded with active medium (quantum dots).
- Narrow emission spectrum.

μ–n CQED; G. Khitrova *et al.*, Nature Physics 2, 81 (2006)

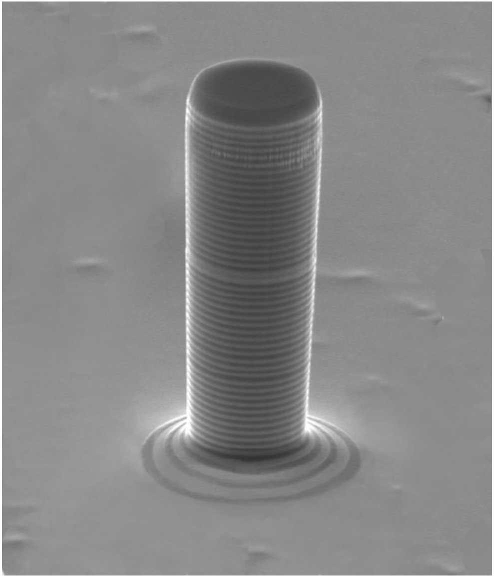


Cavity	Length = 42.2 μm: Width = 23.4 μm:	Photonic crystal slab	Micropillar	Microdisk
λ (nm); E (eV)	852.4; 1.45	1,182; 1.32	937; 1.32	744; 1.66
Q	4.4×10^7	6,000	7,350	12,000
V (μm^3)	$18{,}148 = 3 \times 10^4(\lambda/n)^3$	$0.04 = (\lambda/n)^3$	$0.3 = 16(\lambda/n)^3$	$0.07 = 8(\lambda/n)^3$
$F_P = \dfrac{3Q\lambda^3}{4\pi^2 n^3 V}$	114	441	36	125
$\kappa/2\pi$ (GHz)	0.008	42	44	34
Oscillator	Trapped Cs atom	InAs QD	$In_{0.3}Ga_{0.7}As$ QD	GaAs QD
Size	$d = 0.54$ nm	$d < 25$ nm	30×100 nm^2	$d = 44$ nm
μ (D)	8	29	60	92
$\gamma_0/2\pi$ (GHz)	0.005	0.088	0.76	3.6
$\gamma/2\pi$ (GHz)	0.005	22	18	68
VRS				
$2g/2\pi$ (GHz)	0.068	41	39	196
VRS/linewidth	5	1.3	0.7	2.2

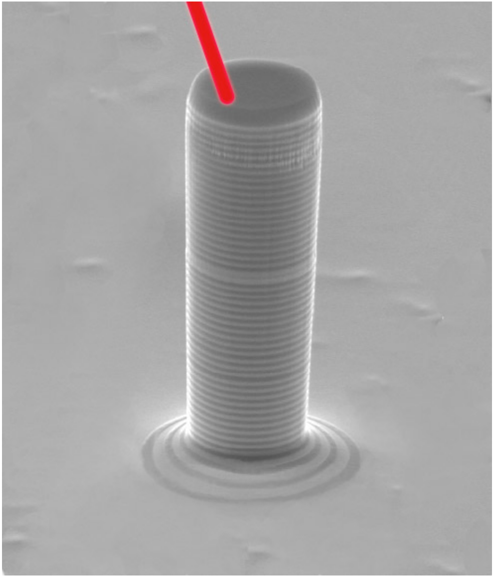
Coupling regimes; D. I. Schuster *et al.*, Nature 445, 515 (2007)



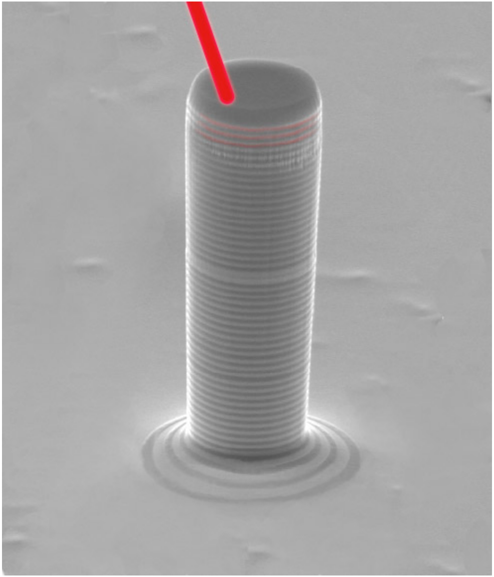
Polariton: Exciton–Photon Interaction



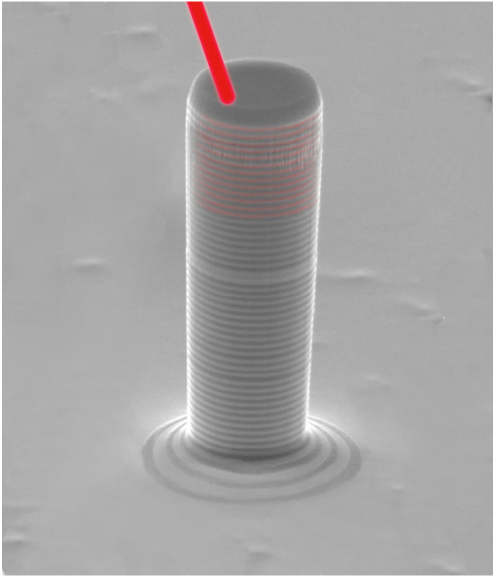
Polariton: Exciton–Photon Interaction



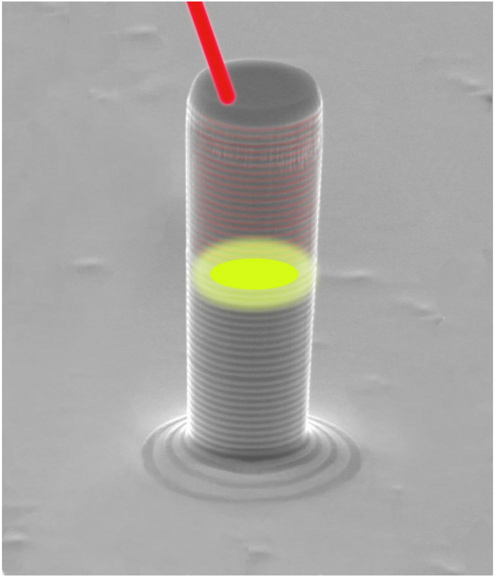
Polariton: Exciton–Photon Interaction



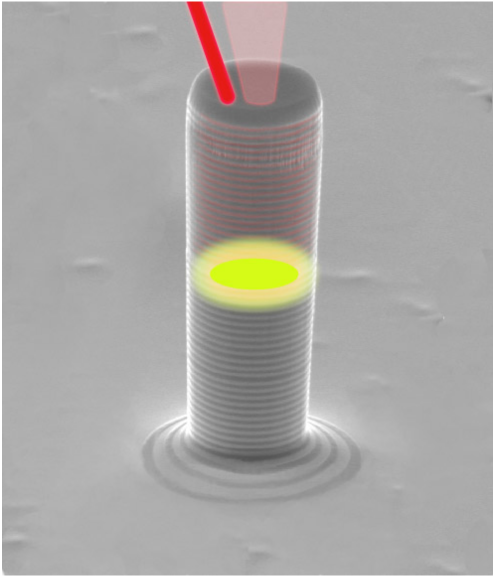
Polariton: Exciton–Photon Interaction



Polariton: Exciton–Photon Interaction



Polariton: Exciton–Photon Interaction



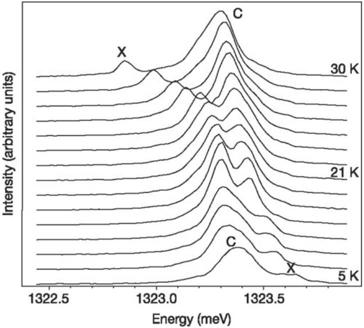
Outline

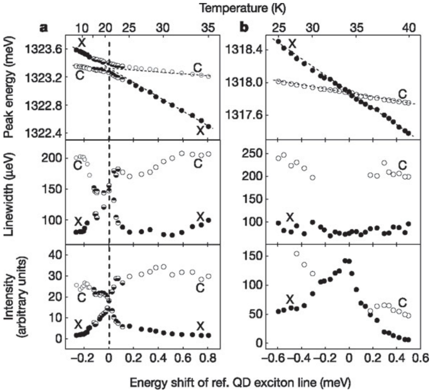
Microcavity QED: Matter–ligth coupling

Polariton Physics and SC Phenomena

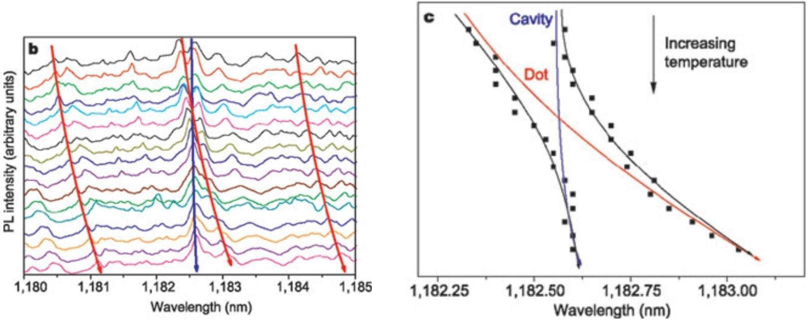
Model and results

Strong and Weak Coupling; J. P. Reithmaier *et al.*, Nature 432, 197 (2004)





Anti–crossing; T. Yoshie *et al.*, Nature 432, 200 (2004)



But . . . ; F. P. Laussy *et al.*, PRL 101, 083601 (2008)

. . . the anticrossing is not always the hallmark of the SC!

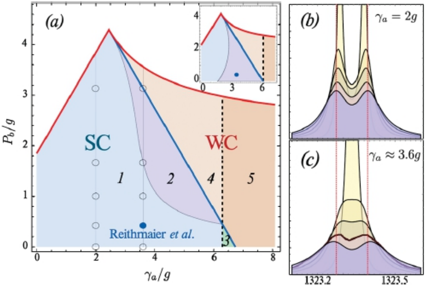
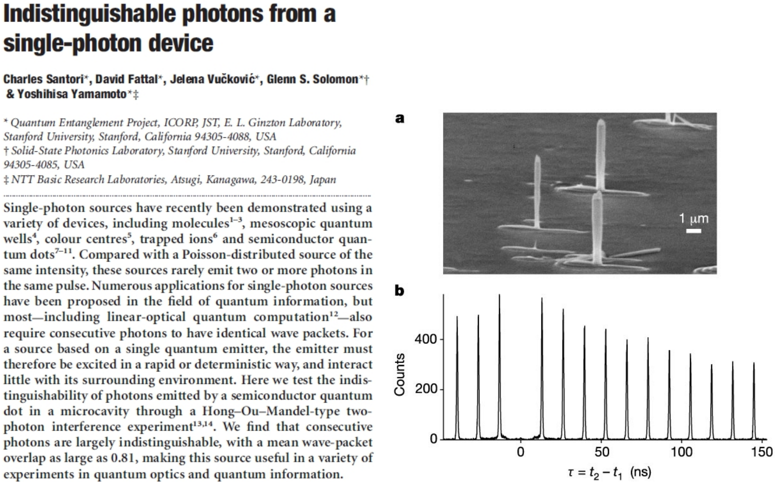


FIG. 2 (color). (a) Regions of strong (blue) and weak (red) coupling at resonance in the space of parameters (γ_a, P_b), with $\gamma_b \approx 2.3g$ and $P_a \approx 0.12\gamma_a$ fitting the experiment of Reithmaier *et al.* [3], marked by a plain blue point. Region 1 exhibits line splitting, while in the darker area 2, although still in SC, the splitting cannot be resolved. The dashed vertical line marks the criterion for SC in absence of pumping, giving rise to region 3, where SC is recovered (with line splitting) thanks to pumping, and region 4, where it is lost because of it. In the inset, the same but for $P_a = 0$, in which case the line splitting of [3] would not be resolved. (b),(c) Spectra of emission with increasing exciton pumping P_b marked by the hollow points in (a). For $\gamma_a = 2g$ in (b), SC is retained throughout and made more visible. For the best fit parameter, $\gamma_a \approx 3.6g$ in (c), line splitting is lost increasing pumping, first because it is not resolved [region 2 of (a)], then because the system goes into WC [region 4 of (a)].

Single Photon Sources (WC); C. Santori *et al.*, Nature 419, 594 (2000)



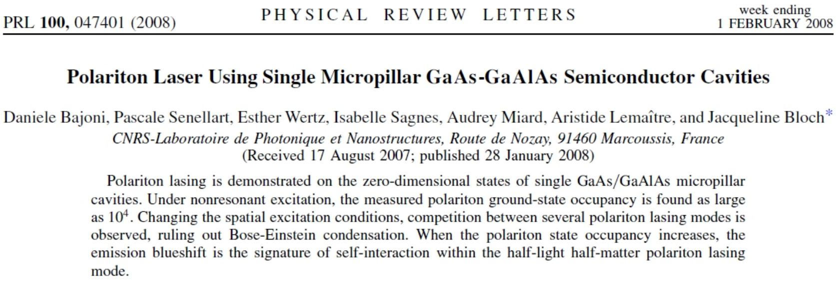
Indistinguishable photons from a single-photon device

Charles Santori*, David Fattal*, Jelena Vučković*, Glenn S. Solomon*† & Yoshihisa Yamamoto*‡

* *Quantum Entanglement Project, ICORP, JST, E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305-4088, USA*
† *Solid-State Photonics Laboratory, Stanford University, Stanford, California 94305-4085, USA*
‡ *NTT Basic Research Laboratories, Atsugi, Kanagawa, 243-0198, Japan*

Single-photon sources have recently been demonstrated using a variety of devices, including molecules[1–3], mesoscopic quantum wells[4], colour centres[5], trapped ions[6] and semiconductor quantum dots[7–11]. Compared with a Poisson-distributed source of the same intensity, these sources rarely emit two or more photons in the same pulse. Numerous applications for single-photon sources have been proposed in the field of quantum information, but most—including linear-optical quantum computation[12]—also require consecutive photons to have identical wave packets. For a source based on a single quantum emitter, the emitter must therefore be excited in a rapid or deterministic way, and interact little with its surrounding environment. Here we test the indistinguishability of photons emitted by a semiconductor quantum dot in a microcavity through a Hong–Ou–Mandel-type two-photon interference experiment[13,14]. We find that consecutive photons are largely indistinguishable, with a mean wave-packet overlap as large as 0.81, making this source useful in a variety of experiments in quantum optics and quantum information.

Micropillars (QWs); D. Bajoni *et al.*, PRL 100, 047401 (2008)



PRL **100,** 047401 (2008) PHYSICAL REVIEW LETTERS week ending 1 FEBRUARY 2008

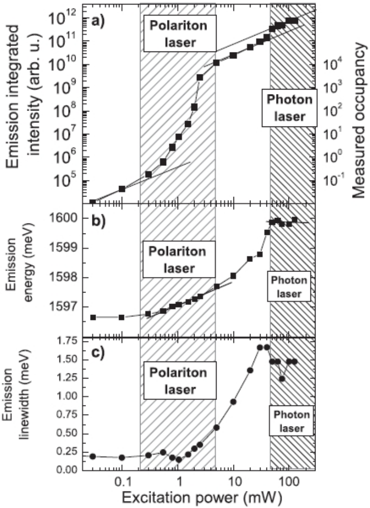
Polariton Laser Using Single Micropillar GaAs-GaAlAs Semiconductor Cavities

Daniele Bajoni, Pascale Senellart, Esther Wertz, Isabelle Sagnes, Audrey Miard, Aristide Lemaître, and Jacqueline Bloch*
CNRS-Laboratoire de Photonique et Nanostructures, Route de Nozay, 91460 Marcoussis, France

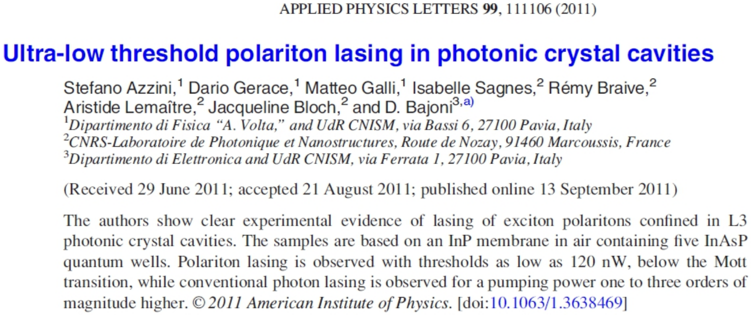
(Received 17 August 2007; published 28 January 2008)

Polariton lasing is demonstrated on the zero-dimensional states of single GaAs/GaAlAs micropillar cavities. Under nonresonant excitation, the measured polariton ground-state occupancy is found as large as 10^4. Changing the spatial excitation conditions, competition between several polariton lasing modes is observed, ruling out Bose-Einstein condensation. When the polariton state occupancy increases, the emission blueshift is the signature of self-interaction within the half-light half-matter polariton lasing mode.

Micropillars (QWs); D. Bajoni *et al.*, PRL 100, 047401 (2008)



Photonic Crystal (QWs); S. Azzini *et al.*,APL 99, 111106 (2011)



APPLIED PHYSICS LETTERS **99**, 111106 (2011)

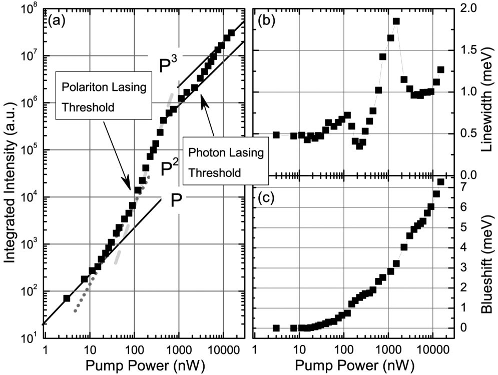
Ultra-low threshold polariton lasing in photonic crystal cavities

Stefano Azzini,[1] Dario Gerace,[1] Matteo Galli,[1] Isabelle Sagnes,[2] Rémy Braive,[2]
Aristide Lemaître,[2] Jacqueline Bloch,[2] and D. Bajoni[3,a)]
[1]*Dipartimento di Fisica "A. Volta," and UdR CNISM, via Bassi 6, 27100 Pavia, Italy*
[2]*CNRS-Laboratoire de Photonique et Nanostructures, Route de Nozay, 91460 Marcoussis, France*
[3]*Dipartimento di Elettronica and UdR CNISM, via Ferrata 1, 27100 Pavia, Italy*

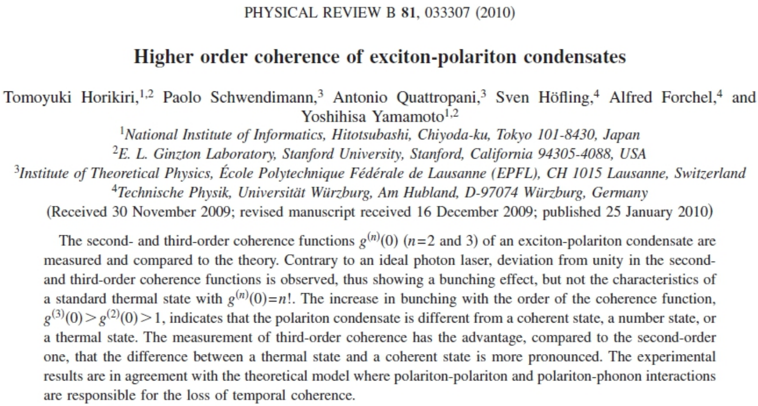
(Received 29 June 2011; accepted 21 August 2011; published online 13 September 2011)

The authors show clear experimental evidence of lasing of exciton polaritons confined in L3 photonic crystal cavities. The samples are based on an InP membrane in air containing five InAsP quantum wells. Polariton lasing is observed with thresholds as low as 120 nW, below the Mott transition, while conventional photon lasing is observed for a pumping power one to three orders of magnitude higher. © *2011 American Institute of Physics*. [doi:10.1063/1.3638469]

Photonic Crystal (QWs); S. Azzini *et al.*, APL 99, 111106 (2011)



Coherence functions (QWs); T. Horikiri *et al.*, PRB 81, 033307 (2010)



PHYSICAL REVIEW B **81**, 033307 (2010)

Higher order coherence of exciton-polariton condensates

Tomoyuki Horikiri,[1,2] Paolo Schwendimann,[3] Antonio Quattropani,[3] Sven Höfling,[4] Alfred Forchel,[4] and Yoshihisa Yamamoto[1,2]
[1]*National Institute of Informatics, Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan*
[2]*E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305-4088, USA*
[3]*Institute of Theoretical Physics, École Polytechnique Fédérale de Lausanne (EPFL), CH 1015 Lausanne, Switzerland*
[4]*Technische Physik, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany*

(Received 30 November 2009; revised manuscript received 16 December 2009; published 25 January 2010)

The second- and third-order coherence functions $g^{(n)}(0)$ ($n=2$ and 3) of an exciton-polariton condensate are measured and compared to the theory. Contrary to an ideal photon laser, deviation from unity in the second- and third-order coherence functions is observed, thus showing a bunching effect, but not the characteristics of a standard thermal state with $g^{(n)}(0)=n!$. The increase in bunching with the order of the coherence function, $g^{(3)}(0)>g^{(2)}(0)>1$, indicates that the polariton condensate is different from a coherent state, a number state, or a thermal state. The measurement of third-order coherence has the advantage, compared to the second-order one, that the difference between a thermal state and a coherent state is more pronounced. The experimental results are in agreement with the theoretical model where polariton-polariton and polariton-phonon interactions are responsible for the loss of temporal coherence.

Coherence functions (QWs); T. Horikiri *et al.*, PRB 81, 033307 (2010)

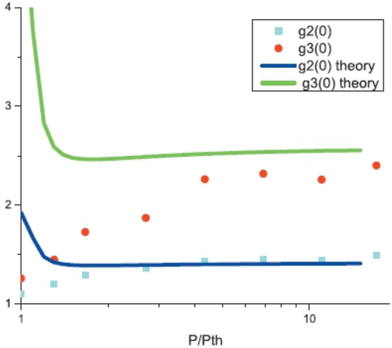


FIG. 3. (Color) Pump intensity dependence of $g^{(2)}(0)$ and $g^{(3)}(0)$. $P_{\rm th}$ is threshold power. Square: $g^{(2)}(0)$ and circle: $g3(0)$. Two curves are calculated coherence functions whose theoretical model is described in Ref. 9.

Coherence functions (QWs); T. Horikiri *et al.*, PRB 81, 033307 (2010)

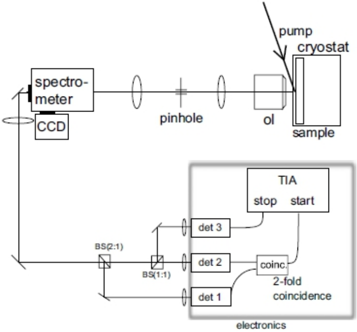
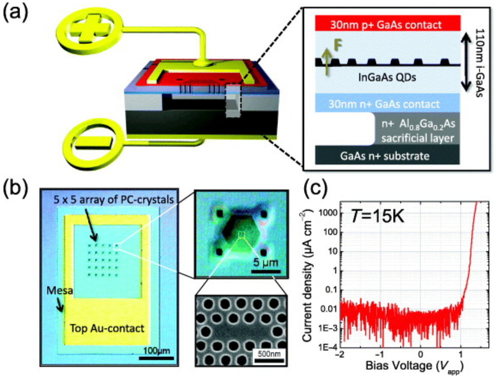


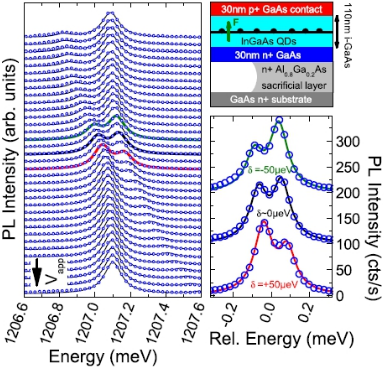
FIG. 1. Experimental setup pump: mode-locked Ti:Sa laser with 76 MHz repetition rate and 4 ps pulse width. GaAs QW microcavity sample is hold in a cryostat which keeps the sample temperature at 10 K during experiment. ol is an objective lens with 4 mm focal length and 0.55 NA. Momentum distribution is imaged at the entrance slit of the spectrometer by the ol and the following two lenses. Thus, dispersion curve of LP can be directly observed by the attached CCD camera and LP ground-state emission is spectrally selected. When the signal goes through the other exit, it enters HBT setup. First two beam splitters [BS(2:1) and BS(1:1)] splits the signal into three paths with roughly equal intensities for maximizing threefold coincidence. Electronics consists of electrical processing units for taking twofold or threefold coincidences, i.e., single photon detectors (det 1 to det 3), delay units for timing adjustments, discriminator (delay units and discriminator are not shown in the figure), coincidence unit, and TIA.

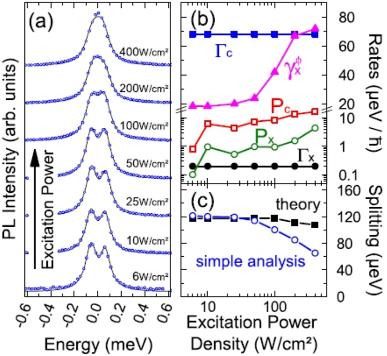
PC Nanocavities; A. Laucht *et al.*, New J. Phys. 11, 023034 (2009)



Electrically tunable single-QD PC nanocavities. (a) Schematic representation and layer sequence of the active region. (b) Microscope image showing the 5 × 5 array of PCs and image depicting a single PC. Scanning electron microscope image showing one of the L3 cavites at the center of each PC. (c) Current–voltage characteristic without illumination.

Emission spectrum: th. and exp.; A. Laucht *et al.*, PRL 103, 087405 (2009)





Outline

Microcavity QED: Matter–ligth coupling

Polariton Physics and SC Phenomena

Model and results

Quantum Open Systems

Master Equation: Born-Markov & $T = 0$

$$\frac{d\hat{\rho}}{dt} = i\left[\hat{\rho}, \hat{H}\right] + \kappa\mathcal{L}_{\hat{a}}\{\hat{\rho}\} + \gamma\mathcal{L}_{\hat{\sigma}}\{\hat{\rho}\} + P\mathcal{L}_{\hat{\sigma}^\dagger}\{\hat{\rho}\} + \dots$$

$$\mathcal{L}_{\hat{O}} \equiv \frac{1}{2}\left(2\hat{O}\hat{\rho}\hat{O}^\dagger - \hat{O}^\dagger\hat{O}\hat{\rho} - \hat{\rho}\hat{O}^\dagger\hat{O}\right)$$

- Weak coupling between the system and its reservoirs (Born).
- Disentangled system–bath density operator (Initial condition).
- No memory effects (Markov).
- QRT ⇒ Photoluminescence spectrum.

Master Equation

Main terms

- $[H, \rho]$ Jaynes-Cummings (JC): Free exciton and field mode hamiltonians $+$ Dipolar interaction in RWA.
- $\kappa \mathcal{L}_a\{\rho\}(P_a \mathcal{L}_{(a^\dagger)}\{\rho\})$ Coherent photon losses (gain).
- $\gamma \mathcal{L}_\sigma\{\rho\}$ Spontaneous emission (exciton losses).
- $P \mathcal{L}_{\sigma^\dagger}\{\rho\}$ Exciton incoherent pumping.
- Other terms: *gain or loss of polaritons* (P_P, γ_P), dephasing $\gamma_\phi, \cdots$

Master Equation

Main terms

- $[H, \rho]$ Jaynes-Cummings (JC): Free exciton and field mode hamiltonians $+$ Dipolar interaction in RWA.
- $\kappa\mathcal{L}_a\{\rho\}(P_a\mathcal{L}_{(a^\dagger)}\{\rho\})$ Coherent photon losses (gain).
- $\gamma\mathcal{L}_\sigma\{\rho\}$ Spontaneous emission (exciton losses).
- $P\mathcal{L}_{\sigma^\dagger}\{\rho\}$ Exciton incoherent pumping.
- Other terms: *gain or loss of polaritons* (P_P, γ_P), dephasing $\gamma_\phi, \cdots$

Master Equation

Main terms

- $[H, \rho]$ Jaynes-Cummings (JC): Free exciton and field mode hamiltonians $+$ Dipolar interaction in RWA.
- $\kappa\mathcal{L}_a\{\rho\}(P_a\mathcal{L}_{(a^\dagger)}\{\rho\})$ Coherent photon losses (gain).
- $\gamma\mathcal{L}_\sigma\{\rho\}$ Spontaneous emission (exciton losses).
- $P\mathcal{L}_{\sigma^\dagger}\{\rho\}$ Exciton incoherent pumping.
- Other terms: *gain or loss of polaritons* ($P_P,\ \gamma_P$), dephasing γ_ϕ, $\ldots$

Timescales and coupling regime

J. Phys.: Condens. Matter 21, 395603 (2009)

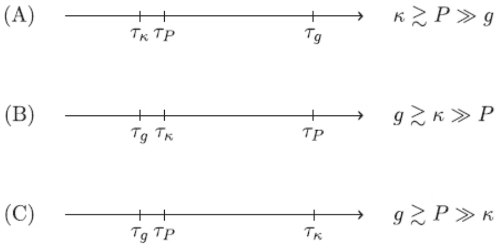
Including only coherent emission κ, γ and exciton pumping P:

$$\frac{d\rho}{dt} = i[\rho, H] + \frac{P}{2}(2\sigma_+\rho\sigma_- - \sigma_-\sigma_+\rho - \rho\sigma_-\sigma_+) \\ + \frac{\gamma}{2}(2\sigma_-\rho\sigma_+ - \sigma_+\sigma_-\rho - \rho\sigma_+\sigma_-) + \frac{\kappa}{2}(2a\rho a^\dagger - a^\dagger a\rho - \rho a^\dagger a).$$

Two regimes can be achieved as loss and pump rates are modified

Timescales and coupling regime

J. Phys.: Condens. Matter 21, 395603 (2009)



(A) Weak Coupling and linear physics (First excitation manifold).

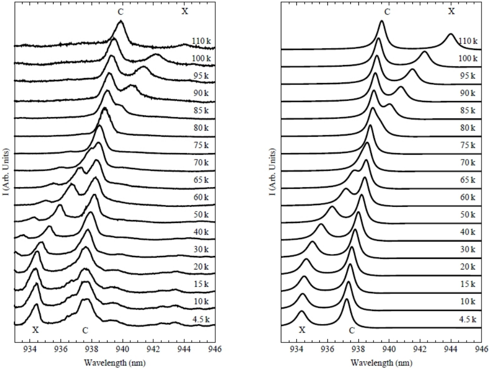
(B) Strong Coupling and linear physics (First excitation manifold).

(C) Strong Coupling and non-linear physics (Beyond the first excitation manifold).

Weak Coupling; J. Phys.: Condens. Matter 21, 395603 (2009)

In the weak coupling regime—PRL **101**, 083601 (2008)—:

$$16g^2 < (\kappa + P - \gamma)^2$$

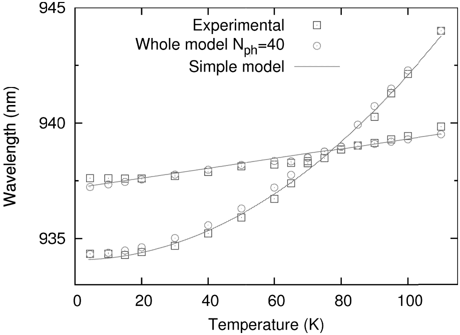


Where $g = 0.2$ meV, $\gamma = 0.2$ meV, $\kappa = 0.9$ meV, $Q \approx 1000$, $\lambda_C = 937.59$ nm y $P = 1$ meV.

Weak Coupling; J. Phys.: Condens. Matter 21, 395603 (2009)

In the weak coupling regime—PRL **101**, 083601 (2008)—:

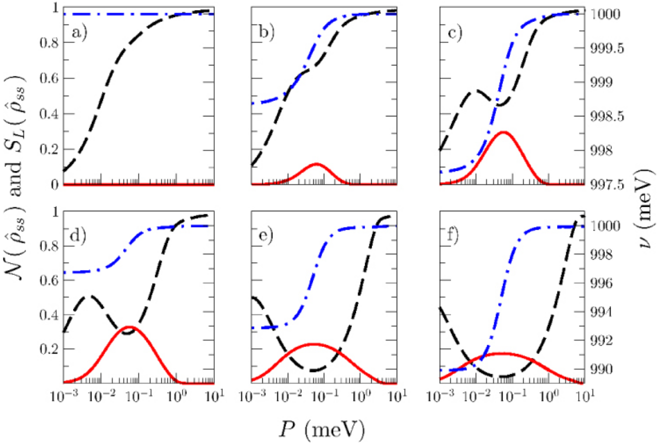
$$16g^2 < (\kappa + P - \gamma)^2$$



Where $g = 0.2$ meV, $\gamma = 0.2$ meV, $\kappa = 0.9$ meV, $Q \approx 1000$, $\lambda_C = 937.59$ nm y $P = 1$ meV.

Polariton Lasing in a QD: Quantum Properties

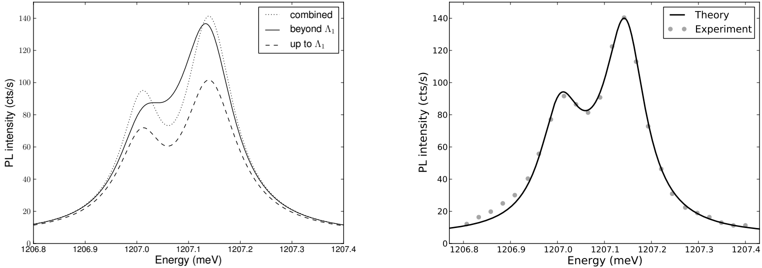
arXiv:1205.2719 G. Cipagauta talk at 15:00 tomorrow



$\mathcal{N}(\hat{\rho})$ (continuous red line), $S_L(\hat{\rho})$ (dashed black line) and ν (dashed-dotted blue line) for $\kappa = 5 \times 10^{-2}$meV and

(a) $\Delta = 0$, (b) $\Delta = 1$meV, (c) $\Delta = 2$meV, (d) $\Delta = 3$meV, (e) $\Delta = 7$meV and (f) $\Delta = 10$meV.

Polariton bath ; arXiv:1206.5193



LEFT: Emission spectra calculated for the parameters reported by Finley and co-workers. The continuous line is the PL spectrum computed with the exact expansion beyond Λ_1. Dashed and doted lines correspond to the spectrum calculated up to Λ_1 by Carmichael and Finley approximations, respectively. RIGHT: Best theoretical fit of the experimental emission spectrum. The fundamental mode frequency and detuning are fixed in $\omega_c = 1207.1$ meV$/\hbar$ and $\Delta = -50\ \mu$eV$/\hbar$, respectively.

Polariton pumping and loss rates!

$P_p = 0.02$	$P_a = 2.27$	$P_\sigma = 2.32$	$g = 67.93$
$\gamma_p = 8.96$	$\gamma_a = 31.82$	$\gamma_\sigma = 10.12$	$\gamma_\phi = 7.40$

Fitting parameters in units of $\mu\text{eV}/\hbar$. The fitting was made implementing a *"simulated annealing"* algorithm. The cost function was the sum of squared differences $S^2 = \sum_i (X_{\text{exp},i} - X_{\text{th},i})^2$ over the available experimental data. The fit shown gives $S = 12.6$ cts/s.

$P_a = 4.5$	$P_\sigma = 0.5$	$g = 59.0$
$\gamma_a = 68.0$	$\gamma_\sigma = 0.2$	$\gamma_\phi = 19.9$

Finley et al. parameters

COLLABORATORS

Polariton Laser

- Daniel G. Suárez, (B.Sc.), UNAL
- Gustavo Cipagauta, (M.Sc.), UNAL
- Karen M. Fonseca, UNAL
- Herbert Vinck Posada, UNAL

Polariton bath

- Nicolás Moure (B.Sc. UdeA) USC
- Herbert Vinck Posada, UNAL

Others

- Juliana Restrepo, UAN
- Augusto González, ICIMAF, Cuba
- Paulo S. S. Guimarães, UFMG, Brazil
- Jhonny Castrillon (M.Sc, UdeA) ⇒ poster
- Juan Pablo Ramírez (M.Sc. UdeA) ⇒ poster
- ⋮

Thank you!