Spontaneous mirror-symmetry breaking in coupled photonic crystal nanolasers

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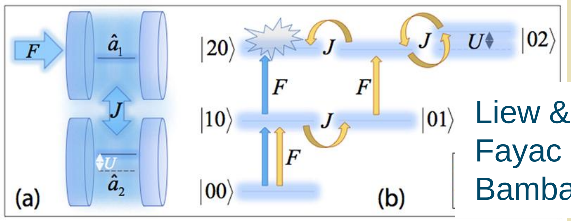
Nonlinear optical nanocavities

Nonlinear optical cavity(s)
with few photons

- **New paradigm for quantum correlations:** NL coupled cavities

- **Nonlinear optical transitions:**

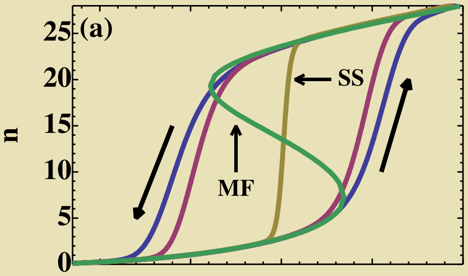
Unconventional photon blockade



Liew & Savona, PRL (2010)
Fayac *et al,* Sci. Reports (2015)
Bamba *et al*, PRA (2011)

Explanation: Quantum interferences &
weak nonlinearity

Optical bistability with few photons



Casteels *et al*, arXiv (2015)

<u>Motivation:</u> Nonlinear dynamics in nanocavities

Instabilities (bifurcations) & their statistical features with few photons

Spontaneous symmetry breaking (SSB)

- **Spontaneous Symmetry Breaking: a system with a given symmetry ends in a state with a lower symmetry**

SSB in many different systems:

- ☐ **Bose Einstein Condensates** *[Zibold et al, PRL (105) 2010]*
- ☐ **Metamaterials** *[Liu et al, Nature Com,* ***5*** *(2014)]*
- ☐ …

In Optics:

- ☐ **Spatiotemporal complexity in lasers** *[Green et al, PRL* ***65*** *(1990)]*
- ☐ **Photorefractive media** *[Kevrekidis et al, Phys. Lett. A* ***340*** *(2005)]*
- ☐ …

Malomed, B. A., *Spontaneous Symmetry Breaking, Self-Trapping, and Josephson Oscillations* (Springer, 2013).

Here: Spontaneous **mirror-symmetry** breaking in a **nanophotonic** system:
Two coupled nanolasers

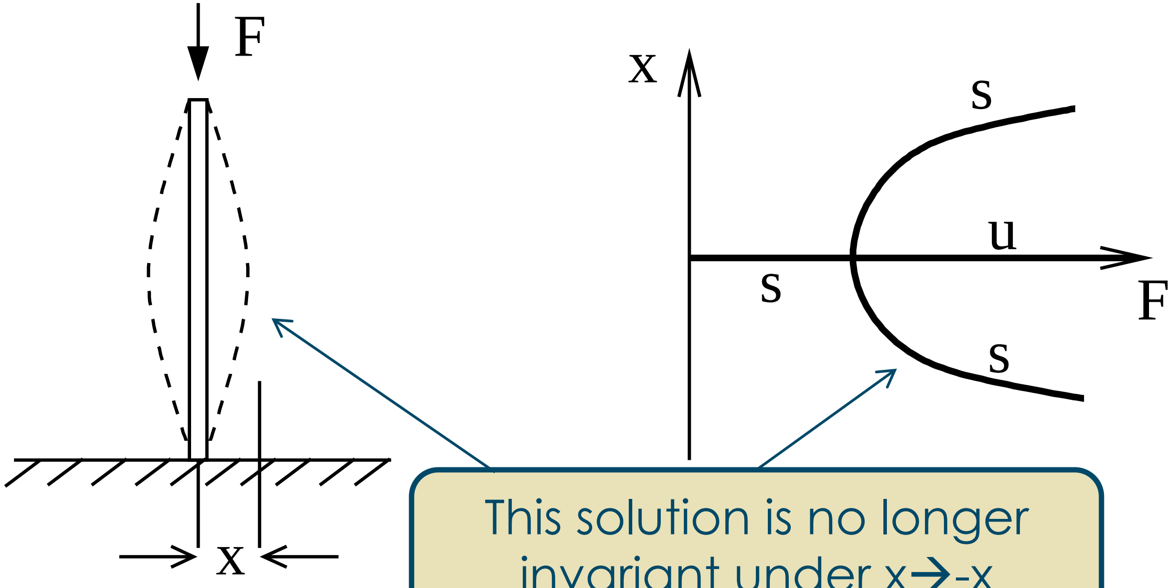
Outline

- **Introduction**
  - ☐ SSB: From double-well potentials (DWP) to photonic crystal coupled lasers
- **Photonic crystal L3 coupled nanolasers**
  - ☐ Coupling control
- **SSB demonstration**
  - ☐ Pitchfork bifurcation
  - ☐ Switching broken parity states
- **Conclusions**

Mechanical example: buckling instability

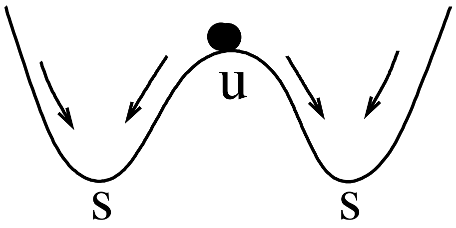
- **The Euler strut**

The system is invariant under x→-x (Z_2)



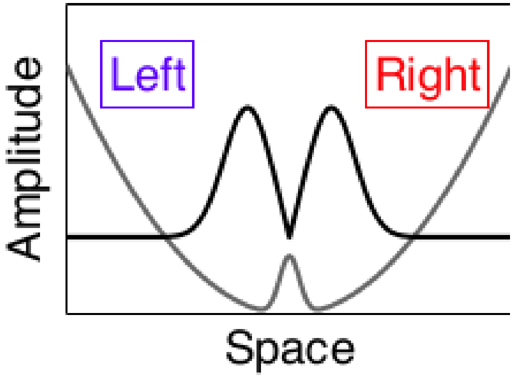
This solution is no longer invariant under x→-x

- **Equivalent to 1 classical particule in a double well potential with dissipation**



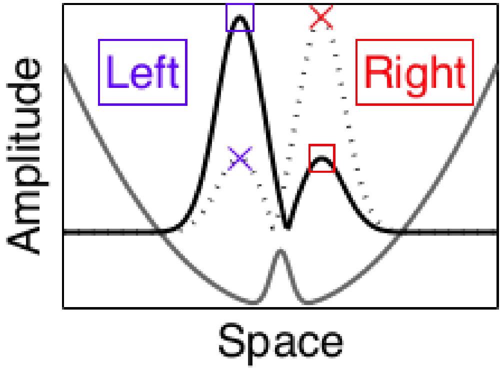
Localization in double-well potentials (DWP)

Nonlinear DWP



Delocalized state

Interactions (nonlinearity)



Localization within a well

In Bose-Einstein condensates:

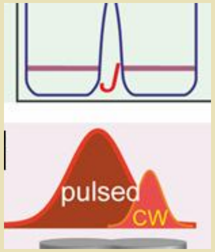
$$i\hbar \frac{d\psi_{L,R}}{dt} = U|\psi_{L,R}|^2 \psi_{L,R} - J\psi_{R,L}$$

Interaction energy

Tunneling rate

$$\boxed{J < U|\psi|^2}$$

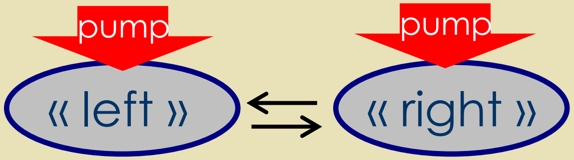
Self-trapping



Abbarchi et *al.*,
Nat. Phys. **9** (2013)

See also Raghavan *et al*, PRA 59 (1999)

Spontaneous symmetry breaking



pump

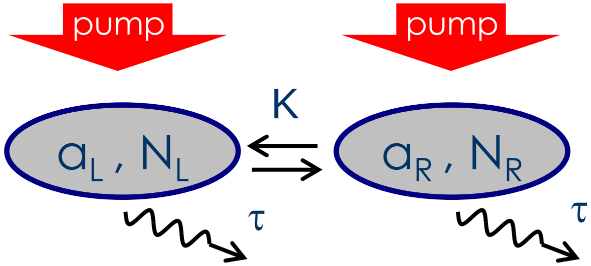
pump

« left » ⇆ « right »

- P. Coullet & N. Vandenberghe, PRE (2001)
- Rodrigues *et al*, in SSB…, Malomed Ed. (2012)
- Ohadi et al, PRX (2015)

And in coupled semiconductor lasers?

- **Coupled field amplitude equations for two semiconductor (QW) cavities:**



$$\frac{da_L}{dt} = -\left(\frac{1}{t} - iw\right)a_L + \frac{(1+ia)}{2}G(N_L)a_L + (g+iK)a_R + \text{spont}$$

$$\frac{da_R}{dt} = -\left(\frac{1}{t} - iw\right)a_R + \frac{(1+ia)}{2}G(N_R)a_R + (g+iK)a_L + \text{spont}$$

Linear cavity	Light-matter interaction	Coupling terms	Spontaneous emission
τ: cavity lifetime	G(N): gain	K: tunneling rate	
ω: resonant frequency	α: Henry factor	γ: loss split	

+ rate equations for N_L, N_R…

SSB in coupled lasers

- **Close to laser threshold** (adiabatic elimination of N):

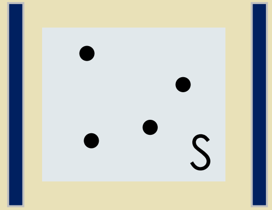
$$i\frac{d\psi_{L,R}}{dt} = U|\psi_{L,R}|^2\psi_{L,R} + K\psi_{R,L} + i\left(\frac{d\psi_{L,R}}{dt}\right)_{dis}$$

, with

- $\psi_{L,R} \equiv a^*_{L,R}\exp(i\bar{\omega}t)$
- $U = -\alpha/\tau S_{norm}$
- $S_{norm} = \gamma_{tot}/(\gamma_{\|}\beta)$

- **Why semiconductor nanolasers?**

Small V_{cav}, high β



$S \sim 1/\beta \rightarrow 1$

for $\beta \rightarrow 1$

- **SSB in coupled cavity lasers**: if **K>0 & U<0** → the antibonding state undergoes a pitchfork bifurcation for

$$K < |U||\psi|^2 \quad\Rightarrow\quad \boxed{\frac{K\tau}{\alpha} < 1}$$

- Characteristic intracavity energy: $|\psi|^2 \sim S_{norm}$

✓ Need controllable evanescent coupling (K) !!

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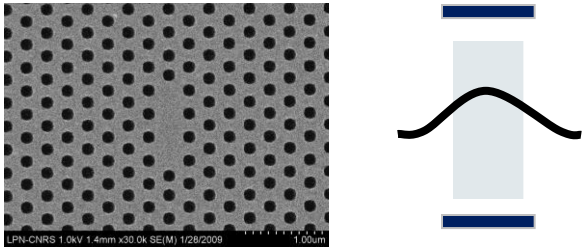
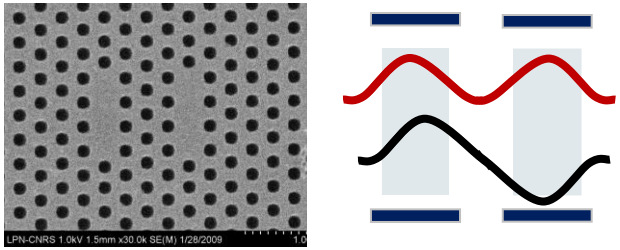
Photonic crystal coupled cavities

- **Building up a DWP: Two evanescently coupled L3 nanocavities**

Single L3 cavity

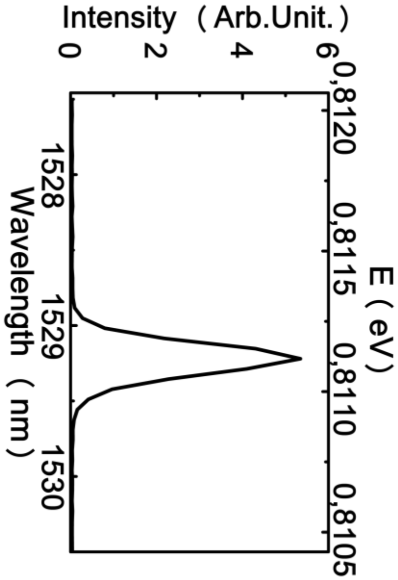


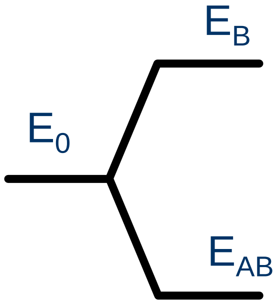
Coupled L3 cavities

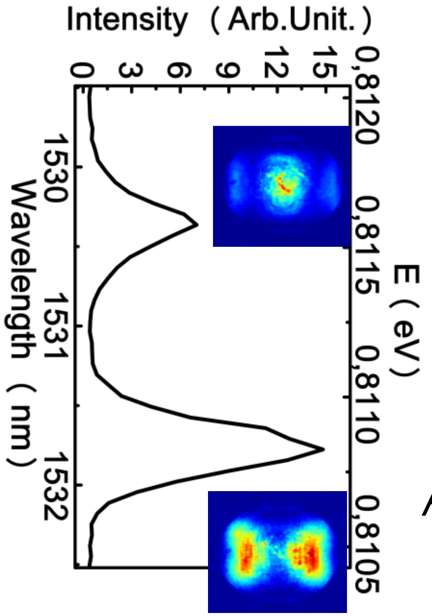


Bonding

Anti-bonding







Bonding

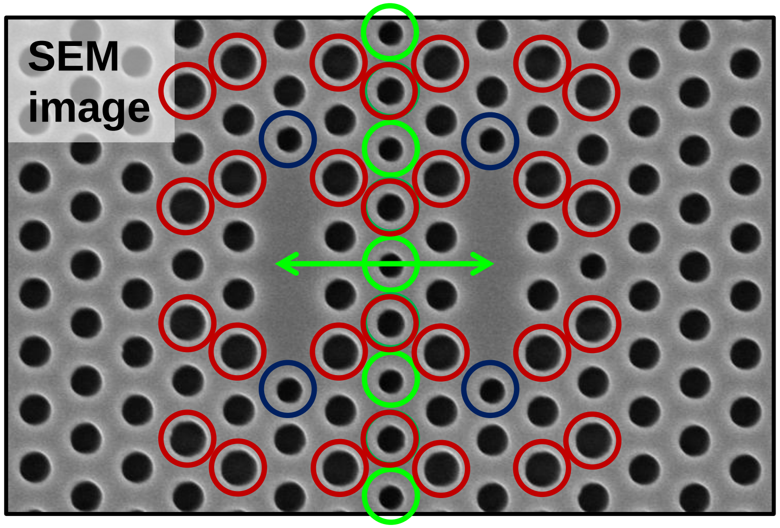
Anti-bonding

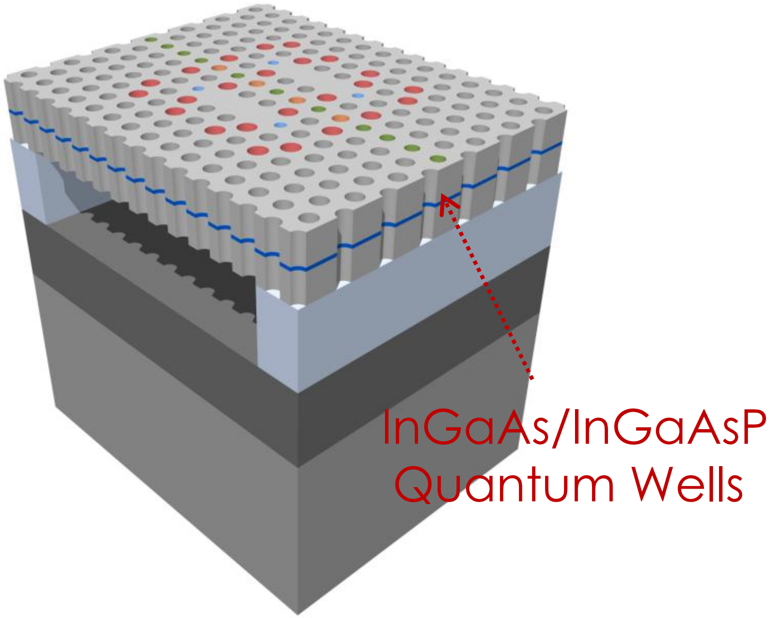
M. Brunstein et al, APL 2011; Caselli et al, PRB (2012); Haddadi et al, Opt. Exp. 2014

PhC nanocavities

Spatial coupling (Photon tunneling) VS Interactions (carrier induced frequency shift)

Evanescent coupling




InGaAs/InGaAsP Quantum Wells

- High Q-factor

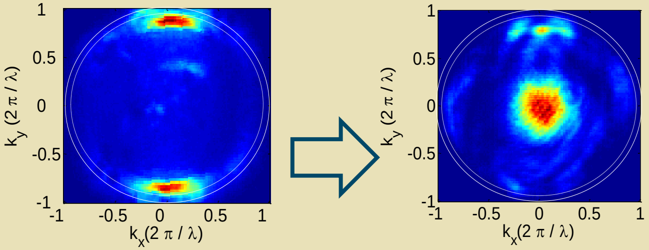
Akahane et al. Nature 2003

- Improved emission directionality

Tran et al., PRB 2009

- Controlled coupling strength

Caselli et al., Opt. Express 2014



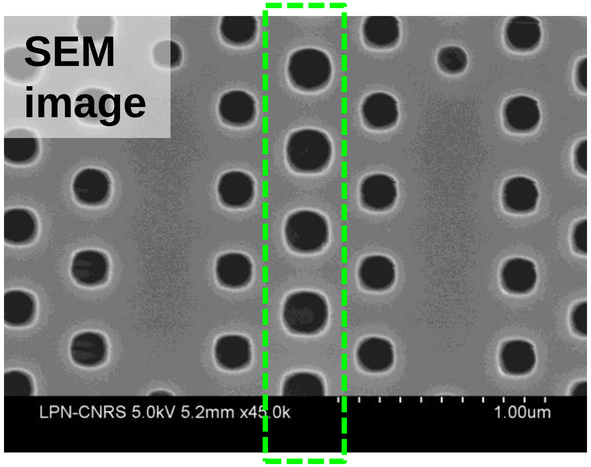
Unfolded **Band-folded**

Haddadi et al, Opt. Express 2012
Haddadi et al, APL 2013

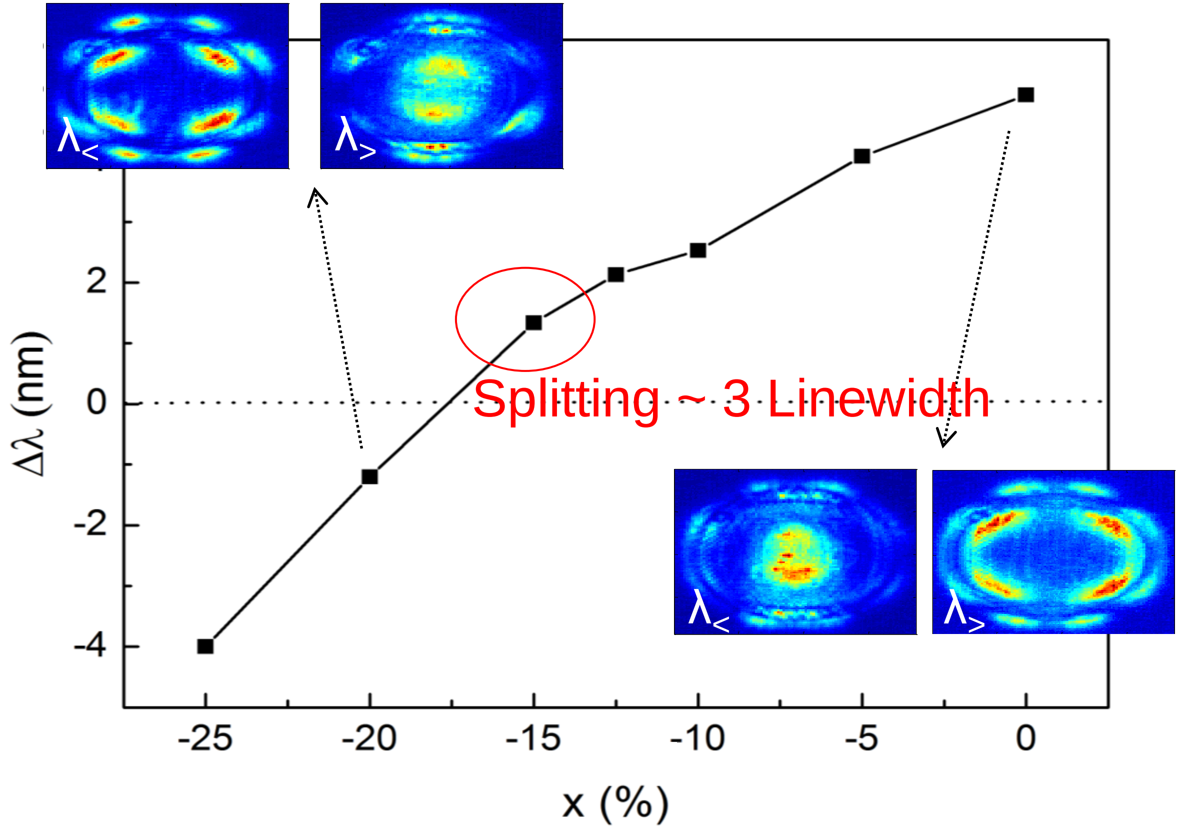
Barrier engineering

- **Controlled coupling strength: barrier engineering**

Central row
(barrier) modified



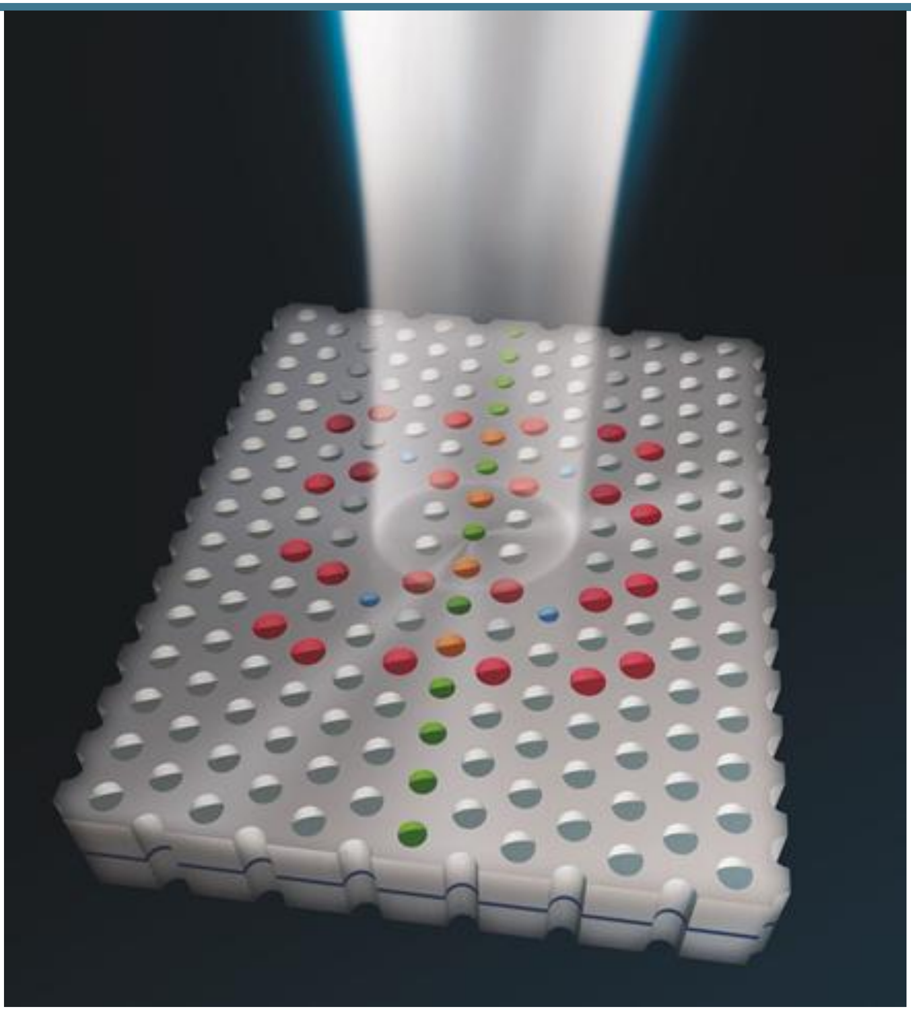
$r_{modified} = r + r\,x\%$



Splitting ~ 3 Linewidth

Haddadi et al, Opt. Exp. 2014

The PhC-coupled nanolasers



- ✓ Q-factor ~ 5000 (both low laser & SSB thresholds)
- ✓ Controlled coupling strength
- ✓ Efficient free-space coupling

Low threshold SSB condition fullfiled

$Kt\ /a < 1$

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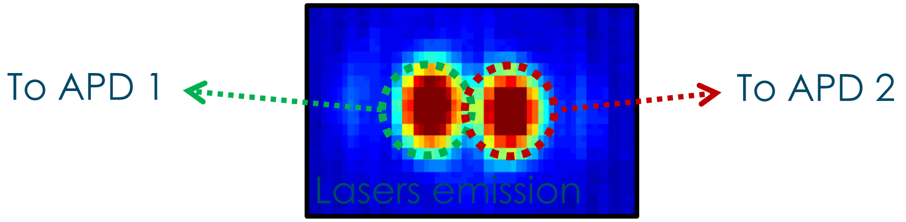
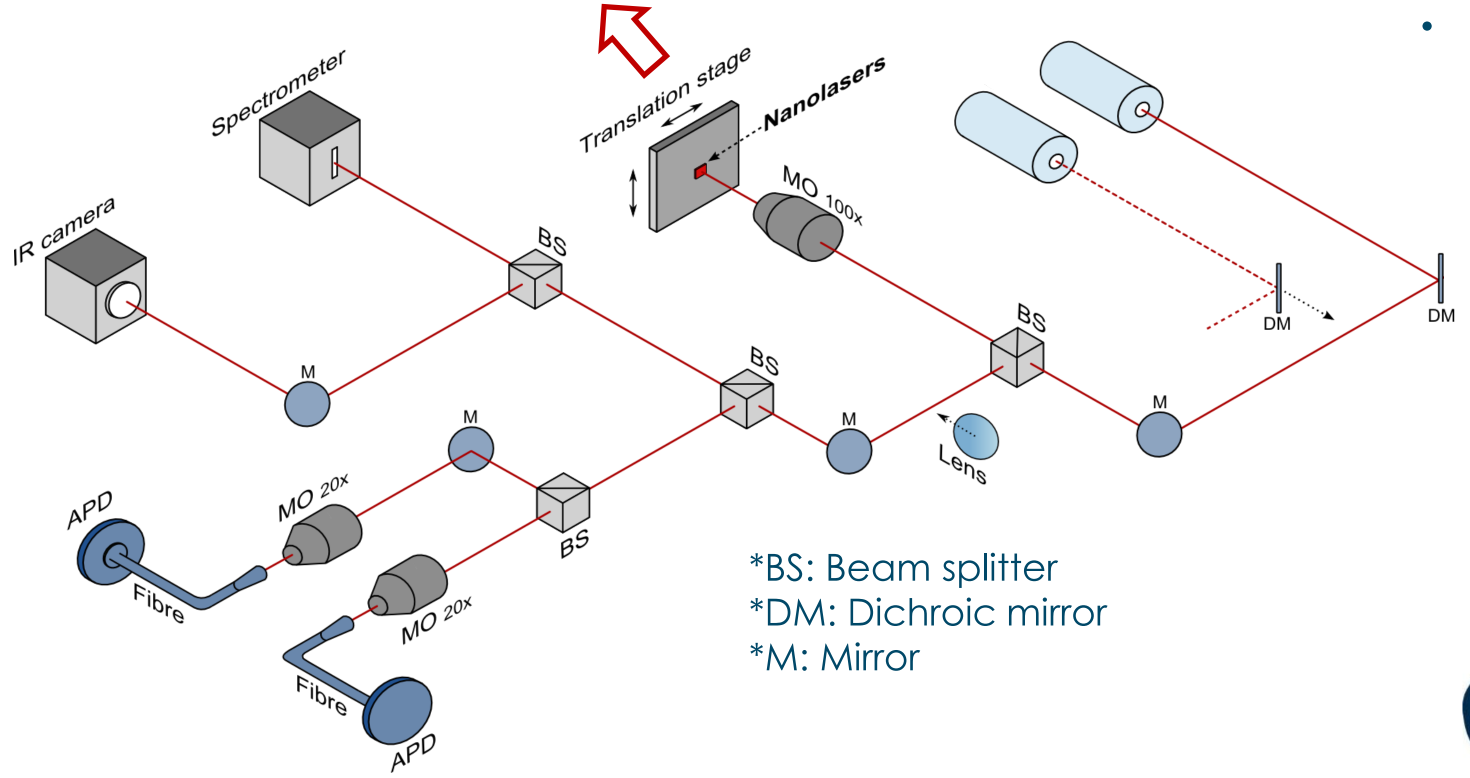
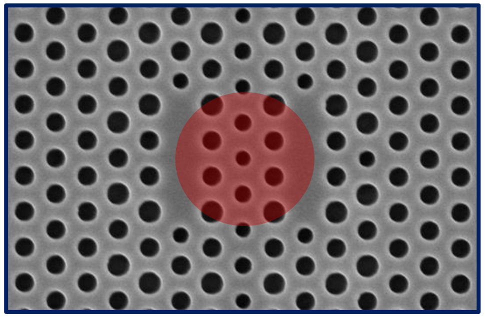
Experimental setup





*BS: Beam splitter
*DM: Dichroic mirror
*M: Mirror

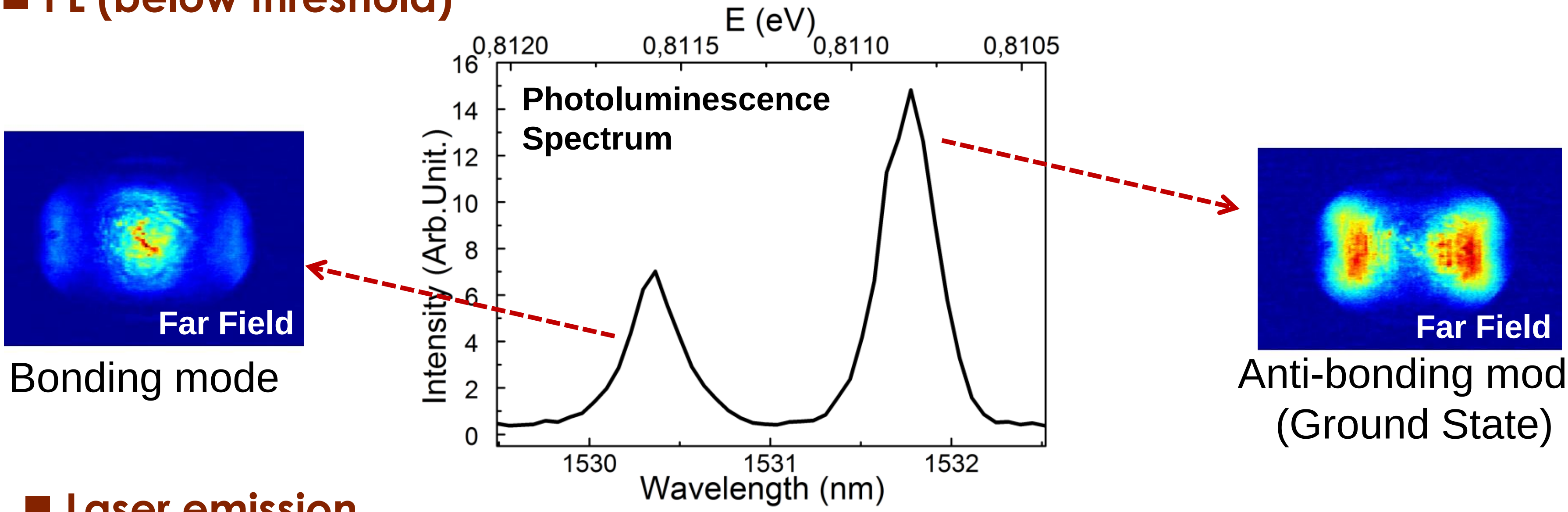


- λ_{pump} = 808 nm
- w = 1.5 µm
- PZT position control (accuracy = 1 nm)

- Quasi-CW measurements
- 30ns-triangular pulses
- Rep. rate 50-200 kHz
- 500 MHz-bandwidth detection

PhC Molecule characterization

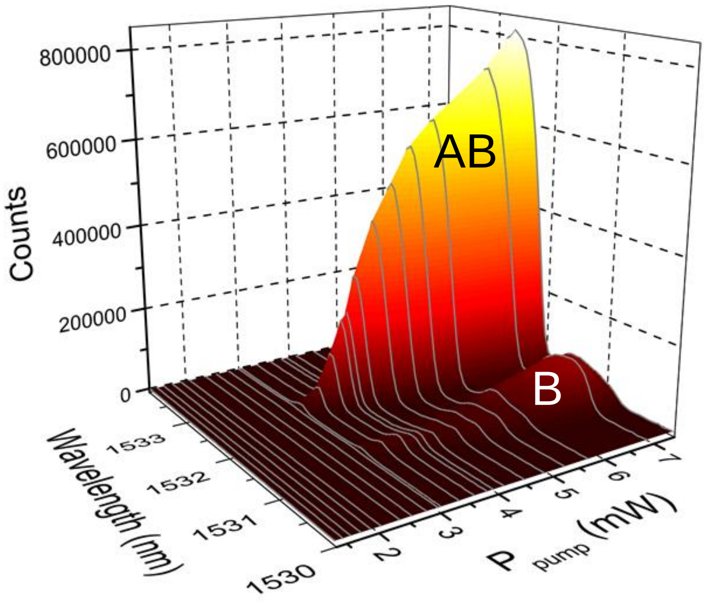
- **PL (below threshold)**



Bonding mode

Anti-bonding mode
(Ground State)

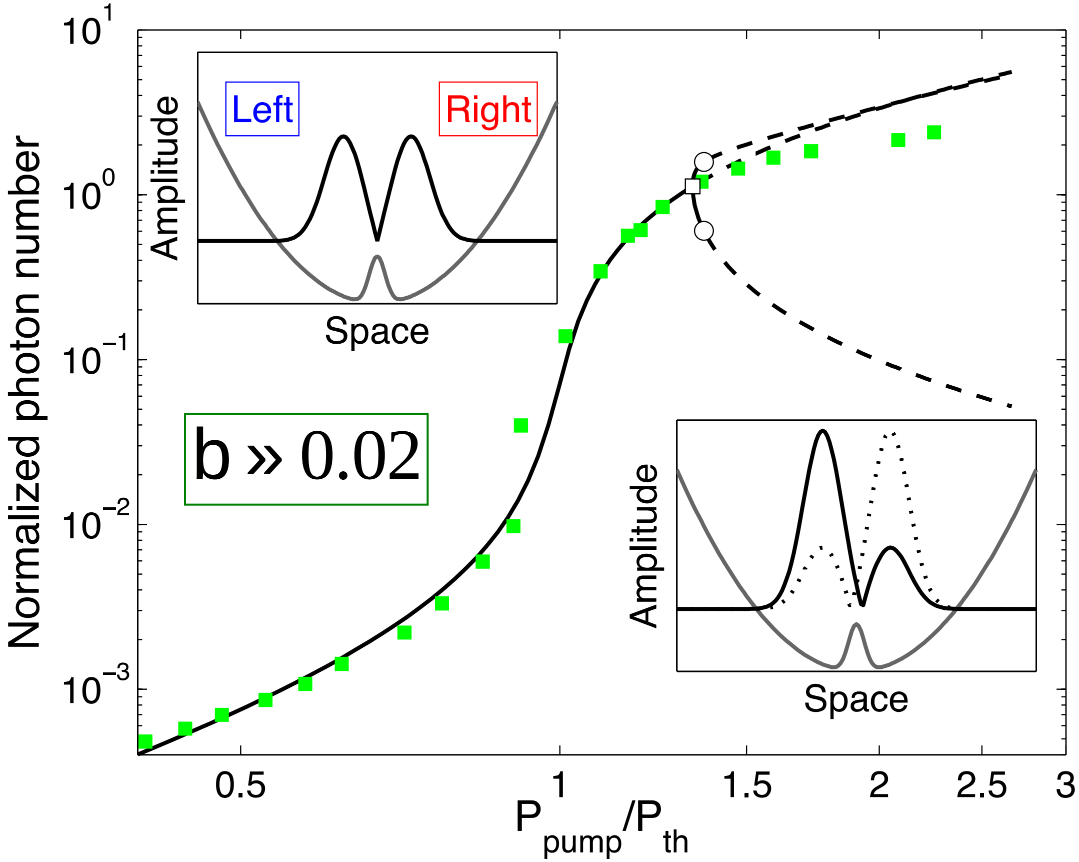
- **Laser emission**



Anti-bonding (AB) mode
lasing (lower optical losses)

Coupled nanolaser emission

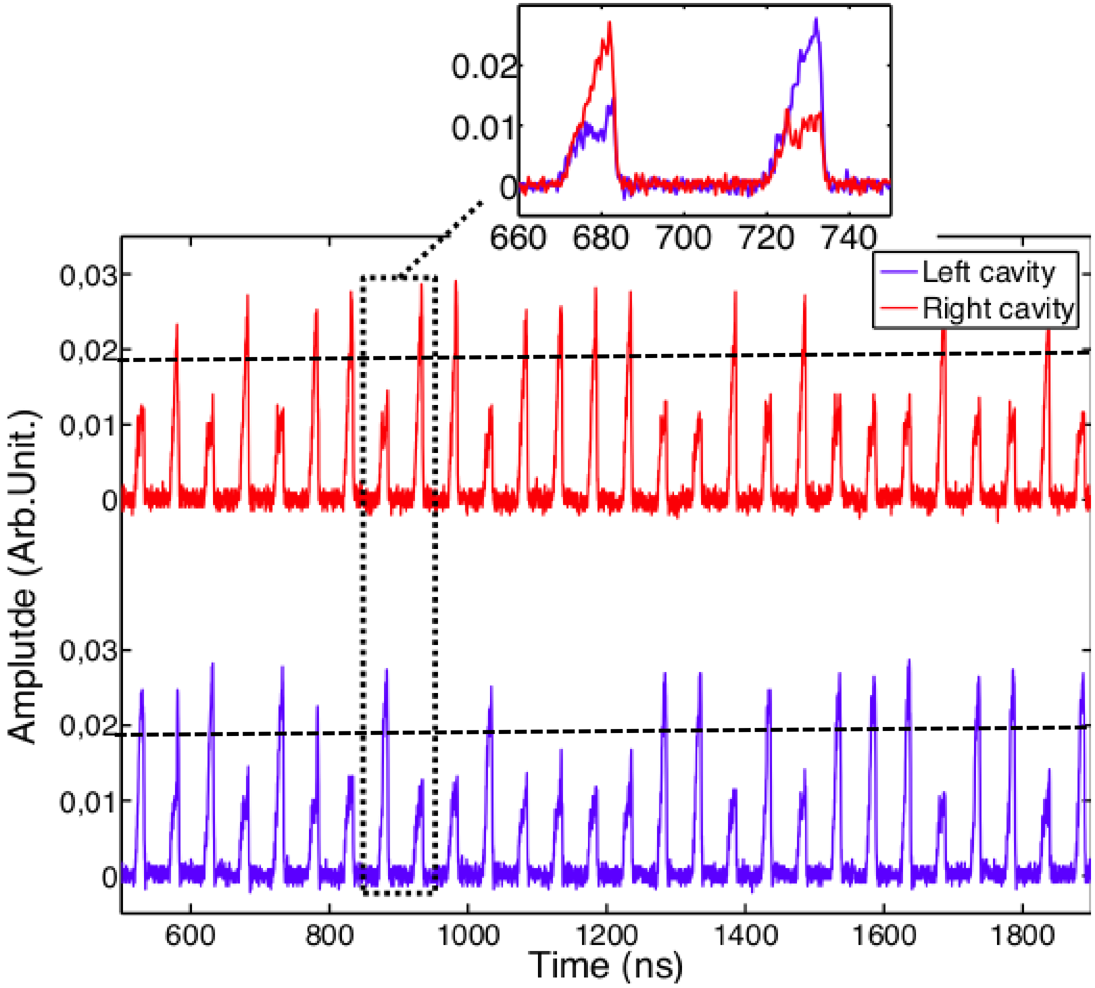
Comparison rate equation model/measurements of laser curves



- Spectral maxima of the AB mode (green squares)
- Numerical solution of coupled lasers rate equations (black line)
- Prediction of two co-existing steady state branches above $P_p = 1.33\ P_{th}$
- Pitchfork bifurcation (black hollow square) and Hopf bifurcations (black hollow circles)

Time domain measurements (I)

Lasers output time sequence



- ☐ Lasers emission time sequence measured independently
- ☐ Alternation of “high blue-low red” and “high red-low blue” events
- ☐ Discrimination of events through a peak detection with fixed threshold (black dashed line)

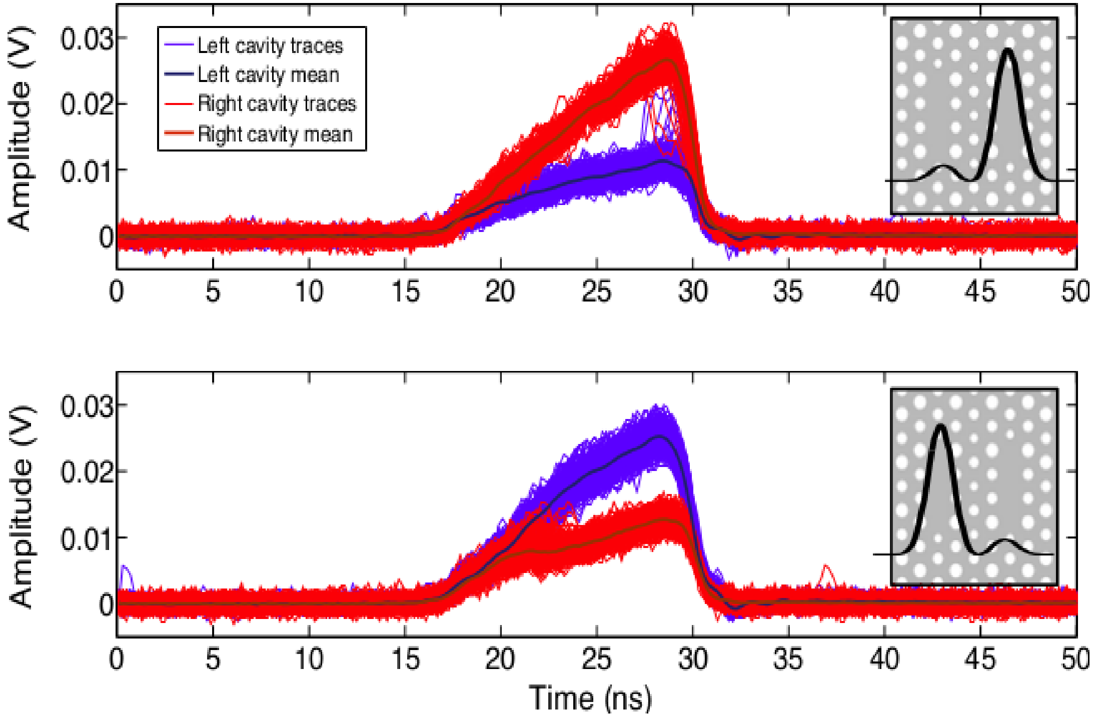
Time domain measurements (II)

■ Averaged time traces

- ☐ Averaged traces over 100s consecutive pulses
- ☐ Two identified states:

  Left-low / Right–high « L0R1 »

  Left-high / Right-low « L1R0 »

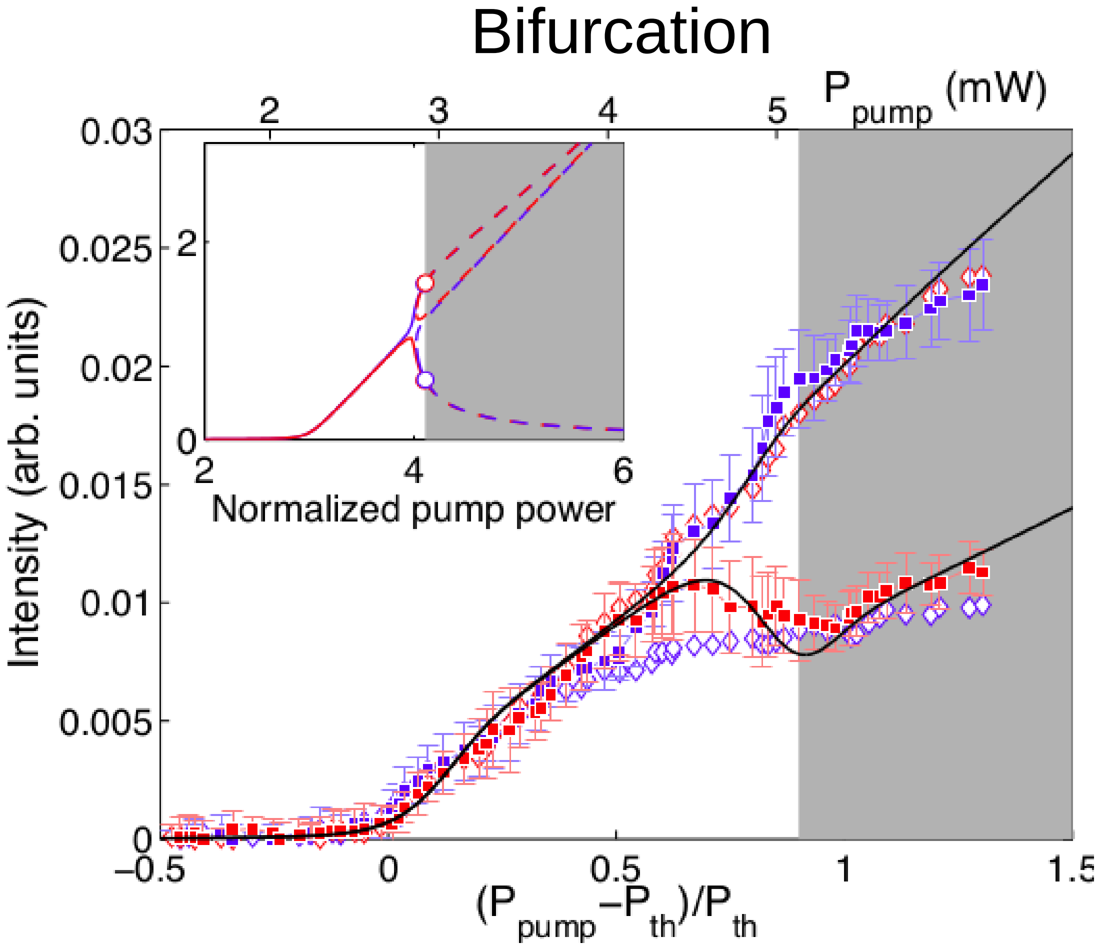


✓ **Two identified alternating states L0R1 and L1R0**

Time domain measurements (III)

Comparison model/measurements

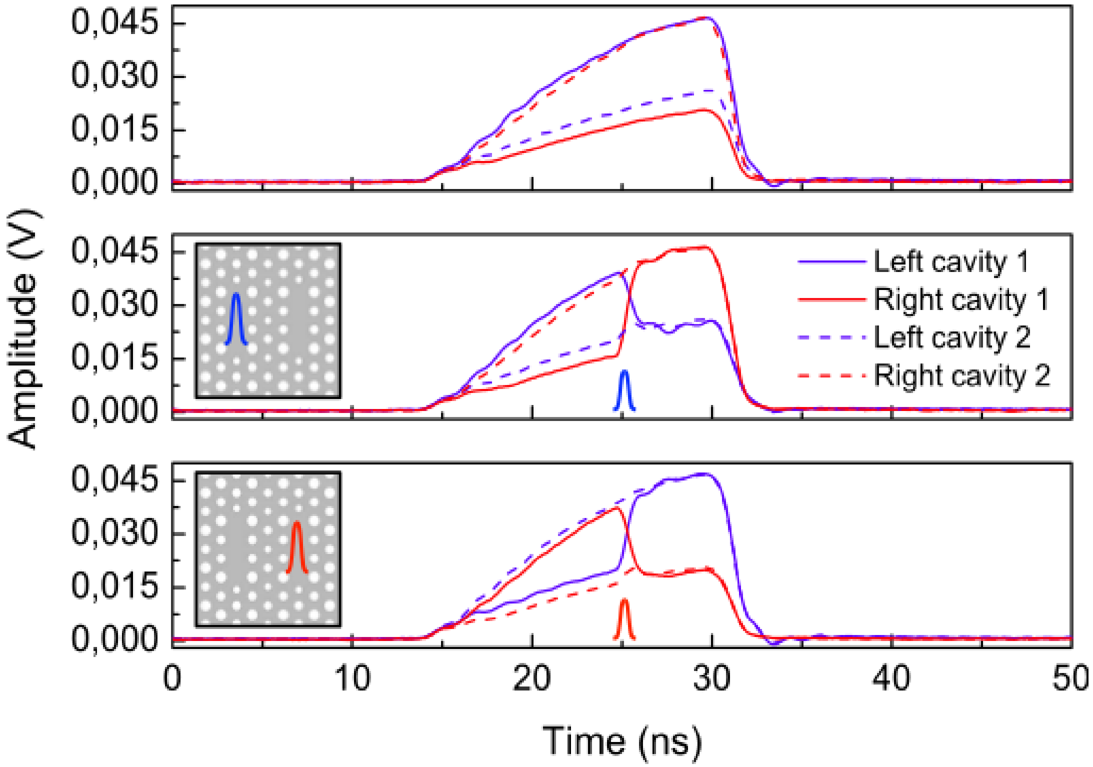
- Averaged traces vs instantaneous pump power (blue and red squares)
- Numerical integration of coupled lasers rate equations (black line)
- Fast oscillations (Jospehson oscillations) averaged by photodetectors (grey area)



P. Hamel et al, Nature Photon. 2015

Coexistence of mirror images (I)

■ Coexistence of **broken parity** states



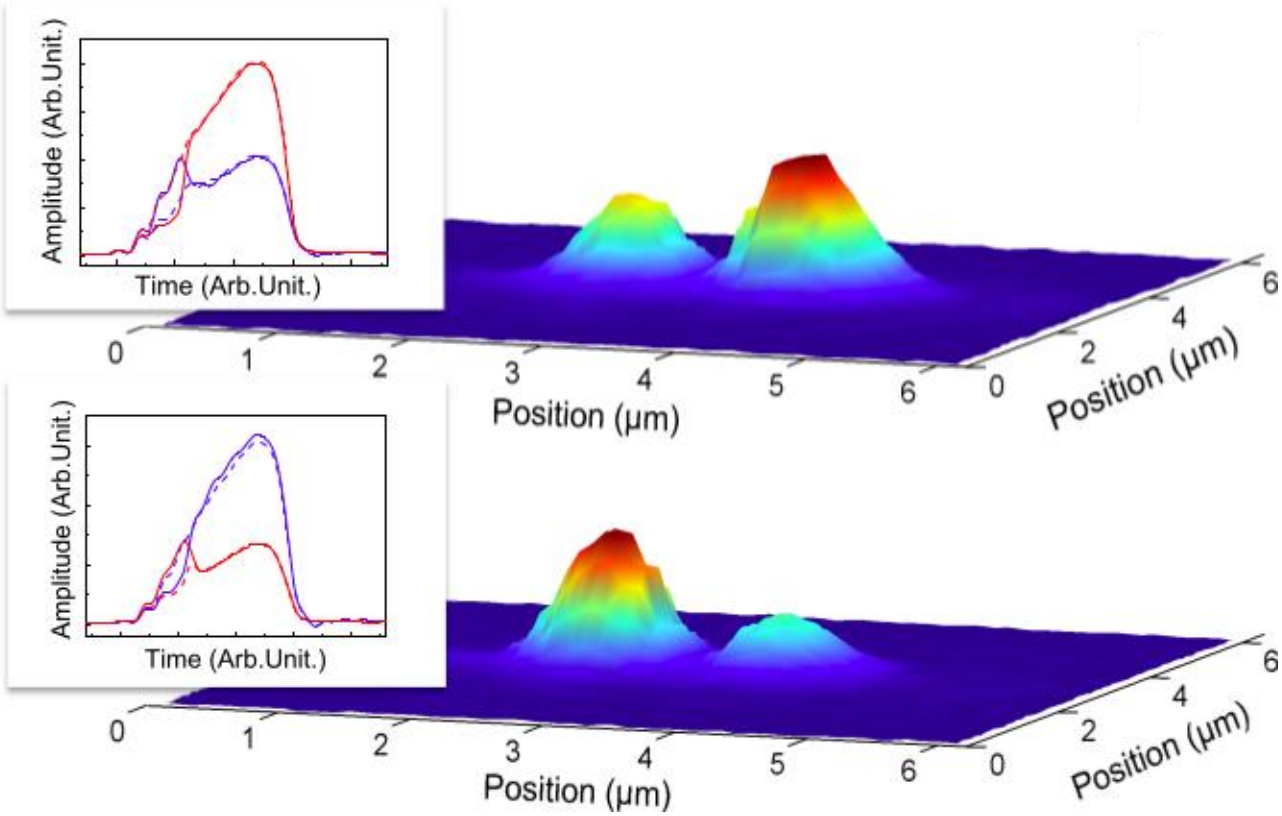
- ❑ Switch induced by a perturbation pulse
- ❑ Short perturbation (100 ps duration) applied on one cavity
- ❑ Only one state flipped by the perturbation

✓ **Coexistence demonstrated via switching**

P. Hamel et al, Nature Photon. 2015

Coexistence of mirror images (II)

- **Intensity profile on a slow 2D camera**



✓ **Early perturbation locks broken parity states→ stabilization**

P. Hamel et al, Nature Photon. 2015

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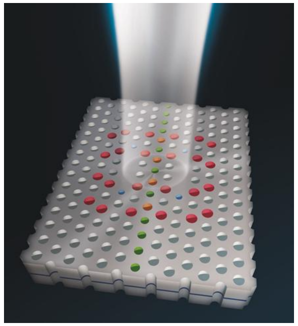
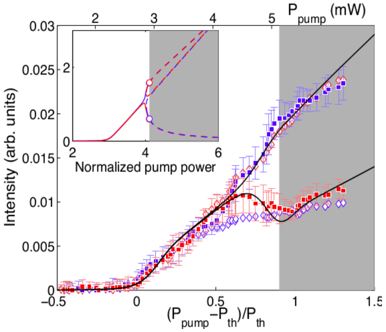
Summary & Conclusions

Spontaneous mirror-symmetry breaking demonstrated in two coupled nanolasers



- In the smallest photonic system ever found (V~0.2 µm^3)
  ~ **100 photons** at SSB threshold
- Compact system with **strong nonlinearity** and **controllable coupling**



- **Pitchfork bifurcation** through time domain measurements
- **Control of broken parity states** via short pulse switching

Prospects

- **Integrated nanophotonic flip-flop memories**
- **Larger molecules** (e.g. 3-cavities with different coupling configurations) and **networks**
- Photon number can be lowered from 100 to ~ 10→**Quantum correlations close to SSB**

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- P. Hamel (post-doc)

- M. Marconi (post-doc)

- A. Levenson

INSTITUT D'OPTIQUE

- C. Sauvan
- P. Lalanne

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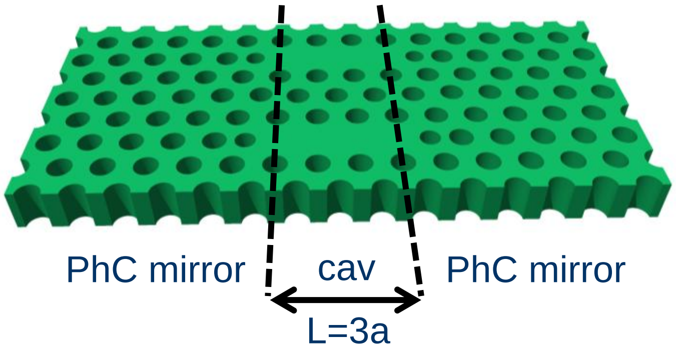
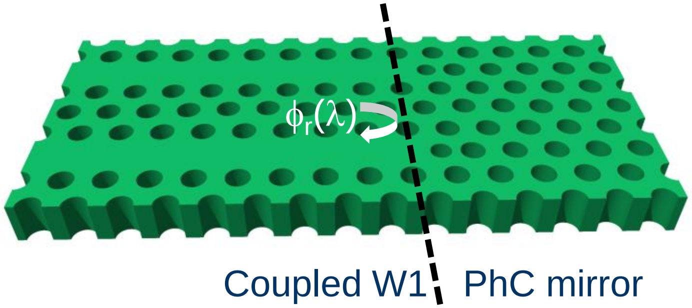
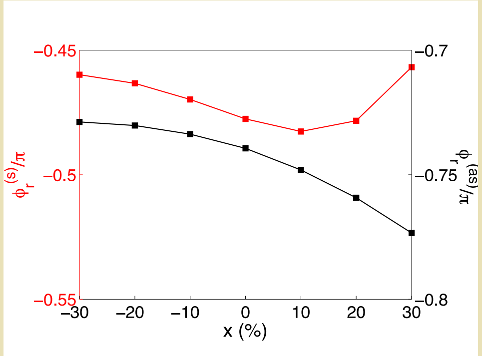
- ANR “Calin”
- ANR “OptiRoc”

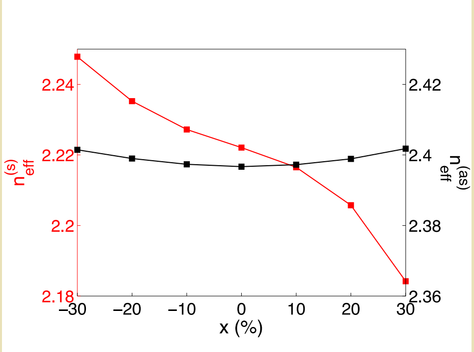
… Thank you!!





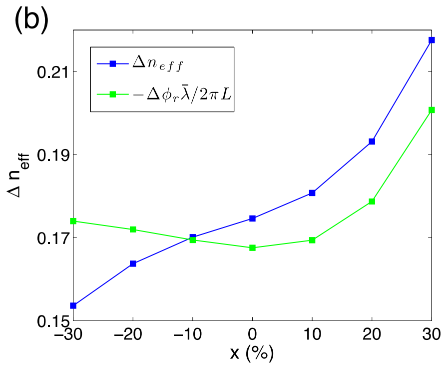
Bloch modes in coupled W1:



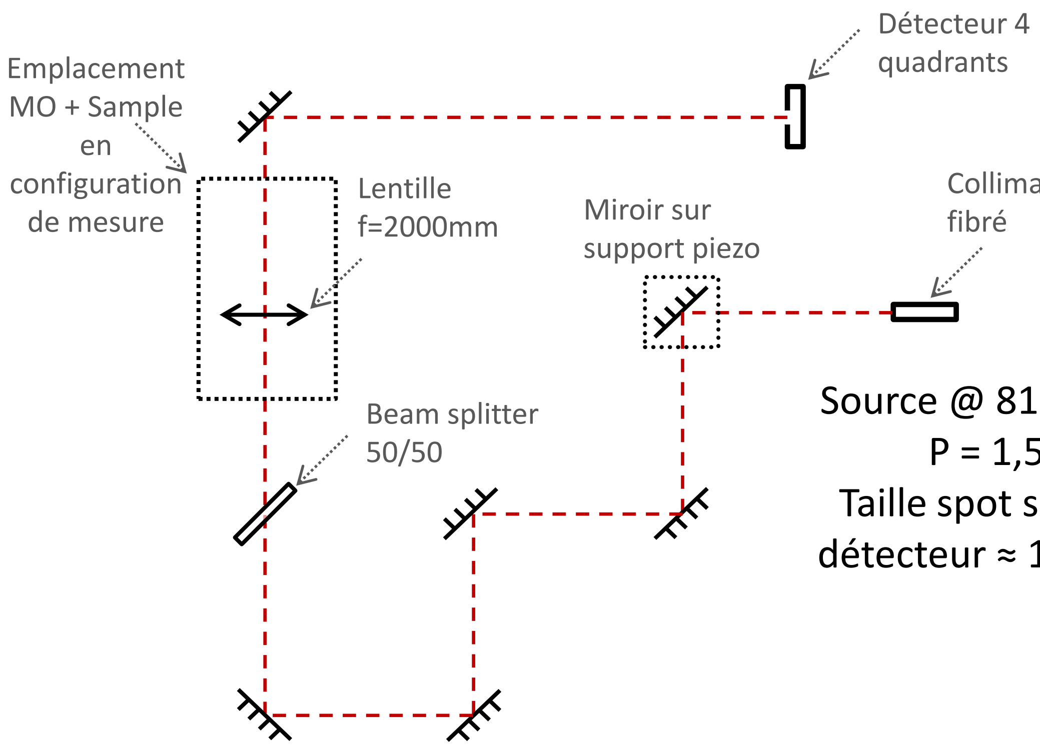


Phase matching:

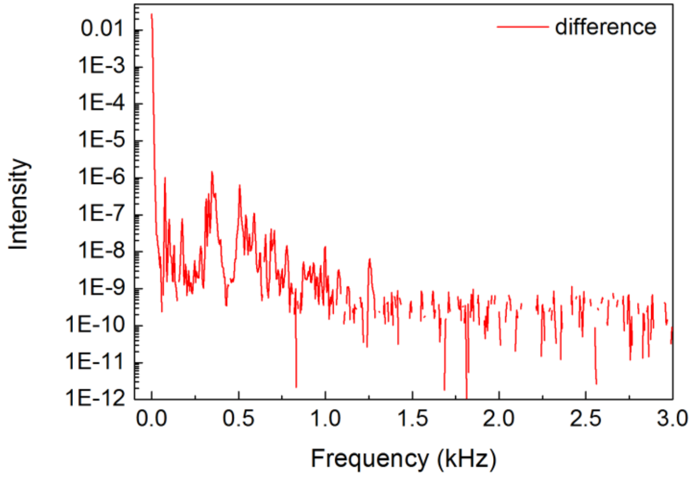
$$\Delta\lambda = \left(p - \frac{\phi_r}{\pi}\right)^{-1}\left(2L\Delta n_{eff} + \frac{\Delta\phi_r}{\pi}\lambda\right)$$



Mesure du jitter angulaire



Source @ 810nm
P = 1,5mW
Taille spot sur le détecteur ≈ 1mm



	Calibration	0 à 100 Hz	100 Hz à 150 kHz
Aire	4,62e-4	8,37e-5	3,57e-8
Déplacement	8 µm	3,4µm	70nm
Angle		1,7µrad	35nrad
Déplacement au plan focal*		3,1nm	64pm**

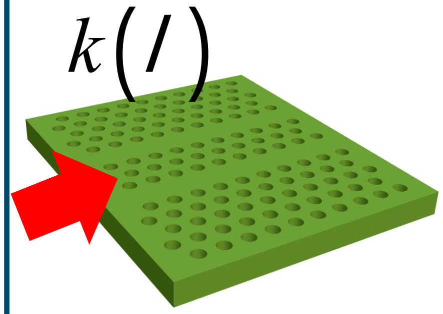
*Focale du MO = 1,8 mm

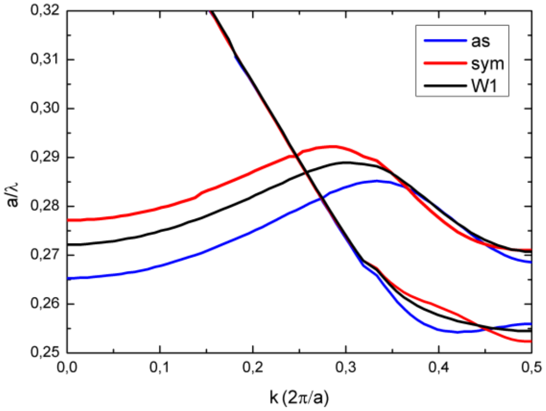
** To be compared with:
1) spatial shot noise:
$w_p/2 \sqrt{N_p} \sim 30$ pm
(N_p the number of pump photons during 30 ns)

2) Tolerance to spatial shift (evaluated numerically)= 500 pm

Our scheme: adjacent L3 cavities

Mode splitting in two evanescently coupled W1 waveguides:





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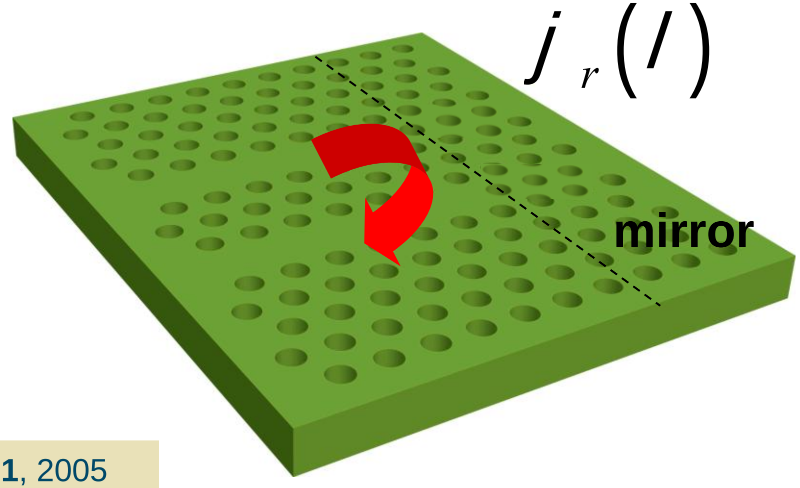
Reflectivity phase on PhC mirror:



Sauvan *et al.*, PRB **71**, 2005

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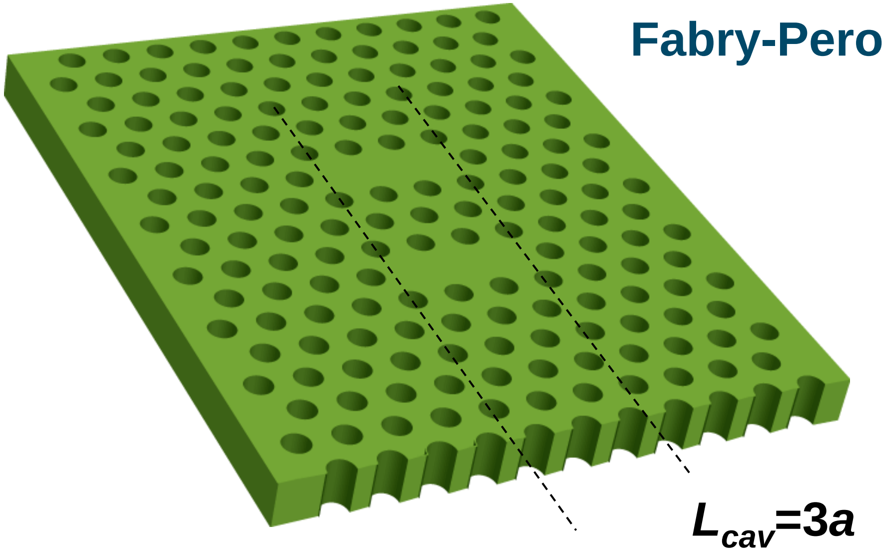
Fabry-Perot model: phase matching condition

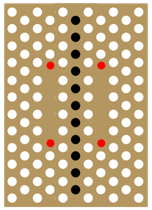


$$k^s\left(\lambda_0^s\right)L_{cav}+\varphi_r^s\left(\lambda_0^s\right)=p\pi$$

$$k^a\left(\lambda_0^a\right)L_{cav}+\varphi_r^a\left(\lambda_0^a\right)=p\pi$$

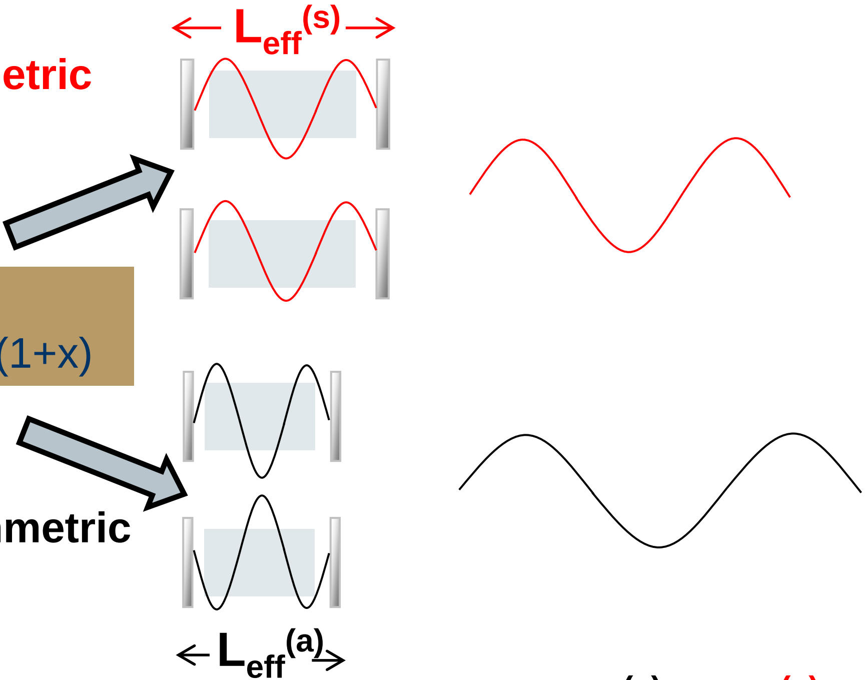
$$\lambda_0^s \neq \lambda_0^a$$

Phase matching in coupled L3 cavities with barrier engineering



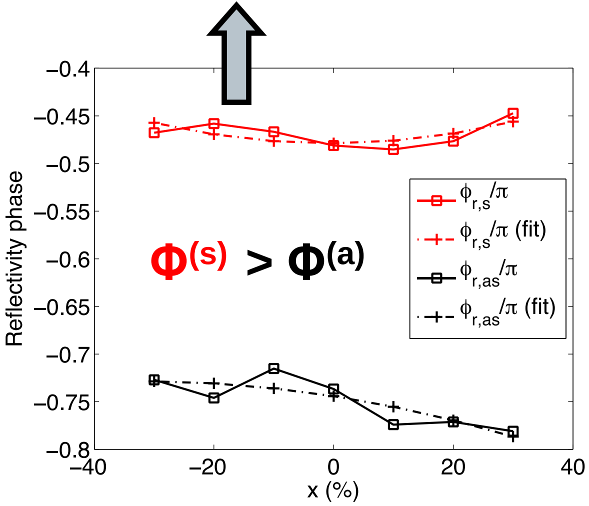
Symmetric

Tuning
the barrier: $r_3 = r_0(1+x)$

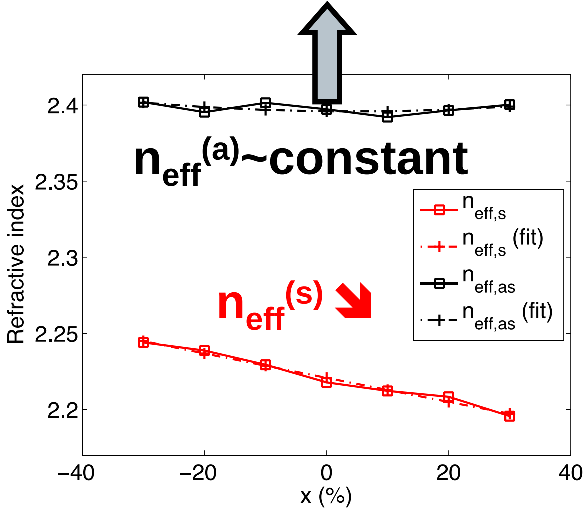


Anti-symmetric

$L_{eff}^{(s)} > L_{eff}^{(a)}$



$n_{eff}^{(a)} > n_{eff}^{(s)}$



Phase matching condition (*):

$$\Delta n + \frac{\Delta\varphi\,\bar{\lambda}}{2\pi L} = \left(p - \frac{\bar{\varphi}}{\pi}\right)\frac{\Delta\lambda}{2L}$$

Mode crossing:

$$\Delta\lambda = 0 \Leftrightarrow \Delta n + \frac{\Delta\varphi\,\bar{\lambda}}{2\pi L} = 0$$

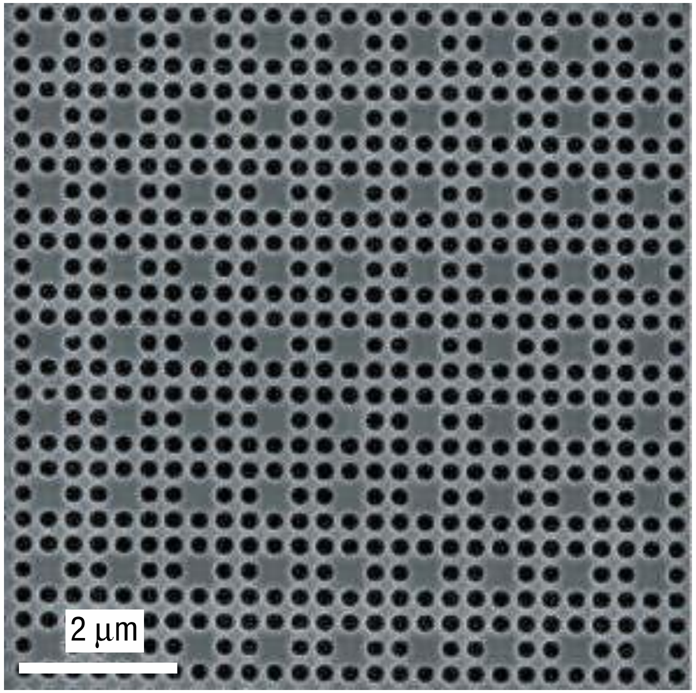
This occurs for x~-10%:

mode crossing (degeneracy)

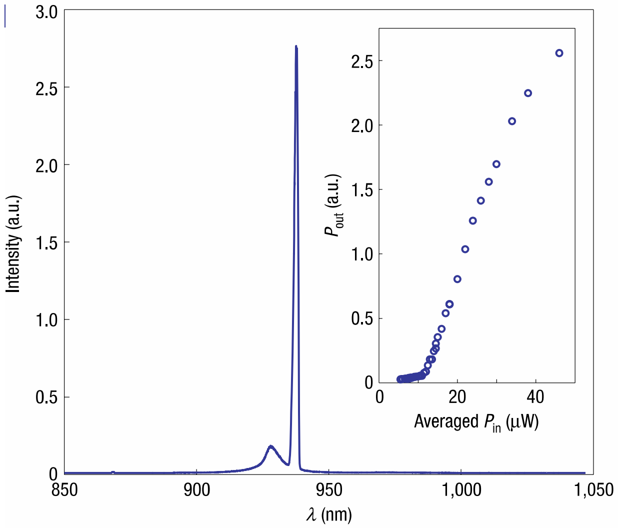
$(*)\ \Delta f \equiv f_a - f_s;\ \bar{f} \equiv (f_a + f_s)/2$

What is beyond phase locking?

Coupled-cavity photonic crystal lasers: phase locking



H. Altug et al, Nature Phys (2006)
H. Altug et al, Opt Express (2005)
G. Vecchi et al, Opt Express (2007)



…Now: Can spatial symmetry (parity) be spontaneously broken?

- For integrated optics: memories, logic gates
- Quantum correlated photon sources

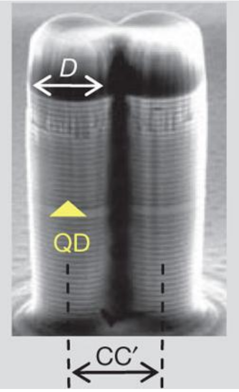
✓ Small photon number (low power)
✓ Integrated, scalable, small foot-print

Photonic Molecules: Context

See eg, S. Boriskina, “Photonic molecules and spectral engineering,” in *Photonic Microresonator Research and Applications*, Springer US, 2010.

Quantum information

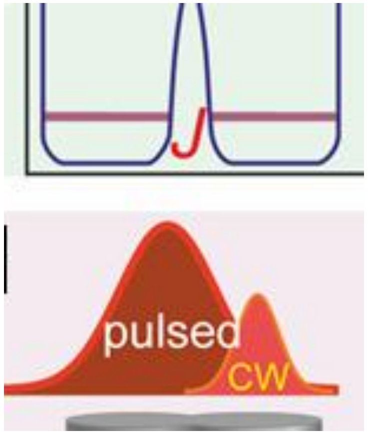
Efficient extraction of photon pairs

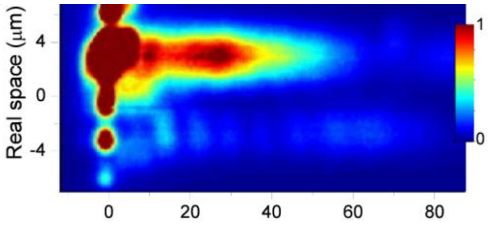


Dousse *et al*,
Nature **466**, 2010

Polariton condensates

Self-trapping in micropillars

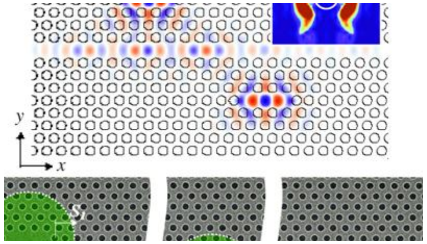


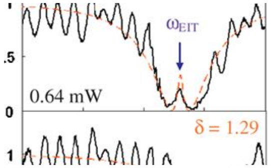


Abbarchi et al., Nat. Phys. **9**, 2013

Photonic Crystals

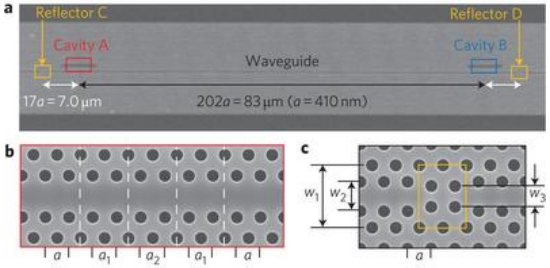
Optical EIT





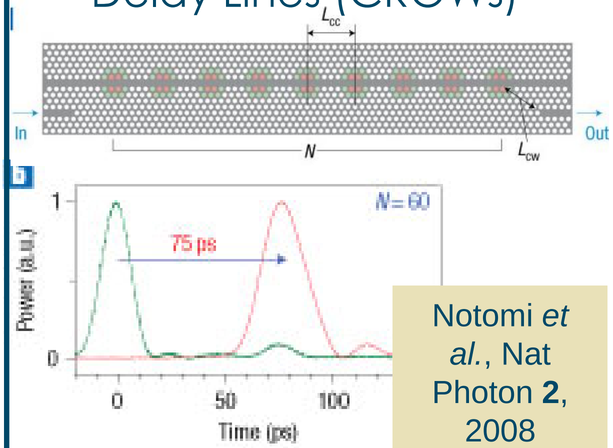
Yang *et al*,
PRL **102**, 2009

Strong Coupling from distant cavities



Sato *et al.*, Nat Photon **6**, 2012
(Noda’s group)

Delay Lines (CROWs)

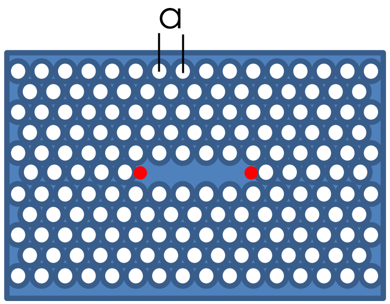


Notomi *et al.*, Nat Photon **2**, 2008

Light coupling to free space

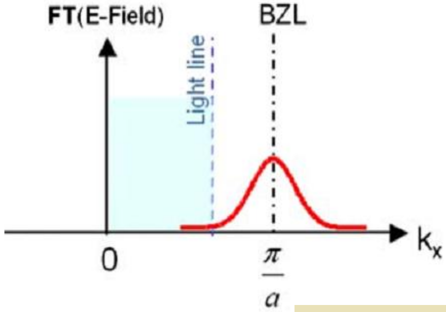
- **Band-folding technique to improve beaming quality:**

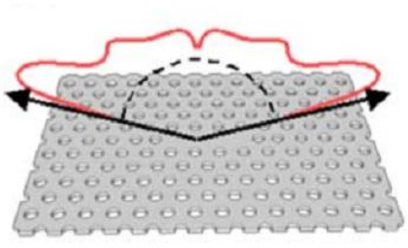
Unfolded cavity



Shift & shrink of end holes

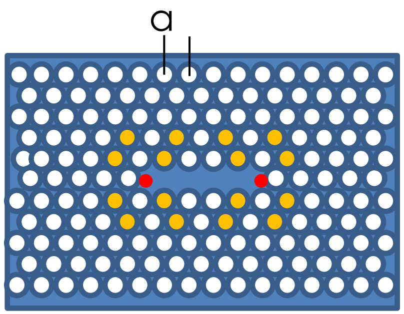
Y.Akahane et al., Nature **425**, 944–947(2003).





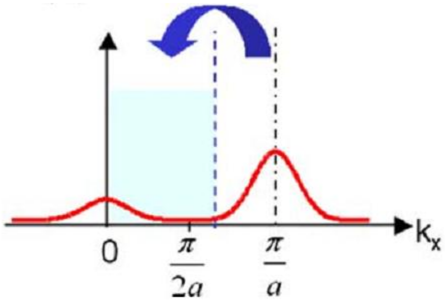
N-V.-Q.Tran et al., PRB 79, 041101R (2009)

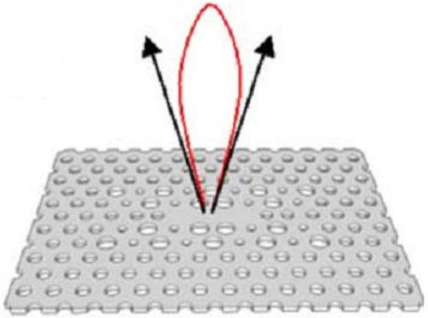
Folded cavity



Periodic modulation of radius around the cavity

N-V.-Q.Tran et al., PRB 79, 041101R (2009)

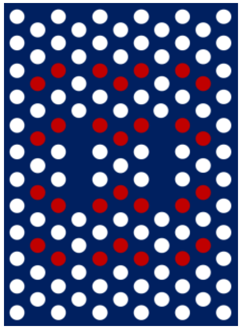




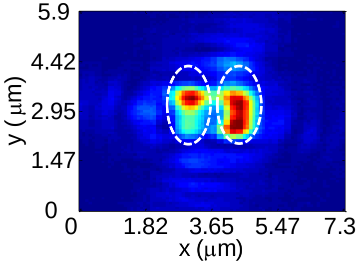
S.L.Portalupi et al., Optics Express Vol.**18**, No 15, 16068 (2010)

PhC nanocavity engineering (I): beaming and Q-factor

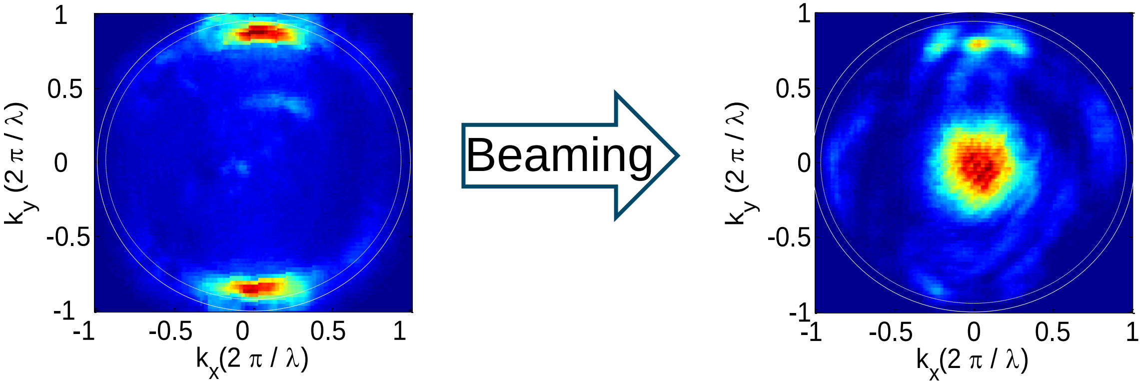
■ Beaming technique applied to PhC Molecules



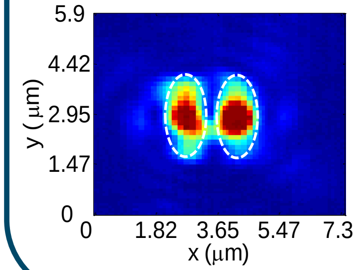
Intensity profile



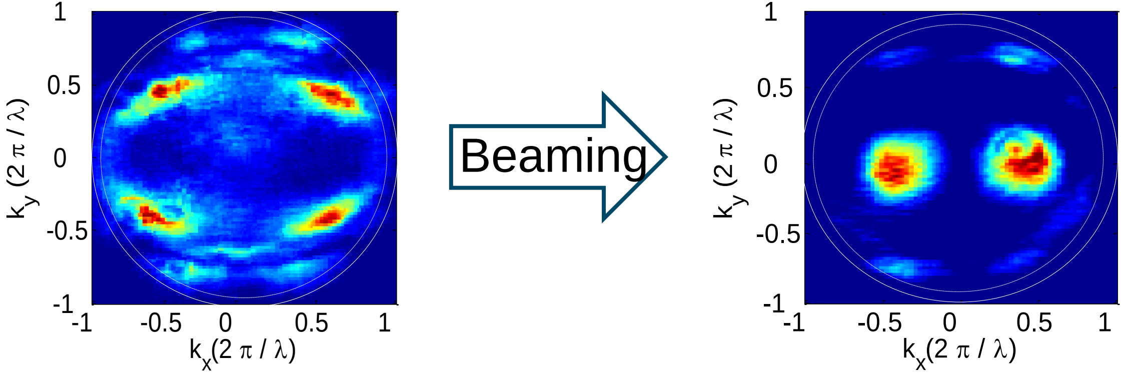
Bonding mode emission diagram



Intensity profile



Anti-bonding emission diagram



Haddadi et al, APL 2012