Optical Manipulation of Polariton Condensates

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Phase Locked

Trapped
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Collaboration

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**Strong Coupling Regime in Semiconductor Microcavity**

- Polaritons directly accessible by shining light on MC
- Strongly modified dispersion relations
  - reduced density of states near $k_\parallel=0$
- Small polariton mass $m_{\text{pol}} \approx 10^{-4}m_e$
- Strong non-linearities $\rightarrow \chi^3$ (exciton component)

**Strong Coupling Regime**

$$E_{\text{photon}} = \frac{\hbar c}{n_c} \sqrt{\left(\frac{2\pi}{L_c}\right)^2 + k_\parallel^2}$$

$$E_{\text{ex}}(k_\parallel) = E(0) + \frac{\hbar^2 k_\parallel^2}{2M_{\text{exciton}}}$$


FORTH Microelectronics Research Group
Univ. of Crete
High finesse GaAs microcavity

Linewidth = 90μeV
T = 6K

Experimental
Q factor ~ 16000

Modeled Q factor ~ 20000
Setup

Sample:
- High quality $5/2 \lambda$ microcavity ($Q < 16.000, \tau > 7\text{ps}$)
- $4 \times 3$ GaAs quantum wells, $9\text{ meV}$ Rabi splitting
- Cryogenics: kept at $T \approx 10\text{ K}$

Excitation:
- Single mode Ti-Sapphire laser, $\lambda = 755\text{ nm}$ (non-res.)
- Shaped by Phase modulation with spatial light modulator

Detection:
- Real & $k$-space imaging
- Energy-resolved tomography
- Interferometric phase measurement
Blueshift Potential

- Condensate
- Blueshift Potential
- Radially Accelerated Polariton Flow

- High Density of Excitons
- Repulsive Interaction "Blueshift Hill"
- Radially Accelerated Polariton Flow

Excitons $\varnothing \approx 1\mu m$

Blueshift $2\text{ meV}$

Condensate $8\mu m$
Ballistic Condensate Ejection

- Blue shift at pump: $V_{\text{max}} = g|\psi|^2$
- Polaritons expand along the ridge.

- Condensate fed by relaxing reservoir polaritons.
- Condensate remains at same energy --> fully coherent.

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Phase Locked Condensates

\[ \psi = \sqrt{\rho} \cdot e^{-i\left(\frac{E}{\hbar} + \varphi\right)} \]

\[ \theta = \frac{(E_2 - E_1)t}{\hbar} \to 0 \]

\[ \ddot{\theta} + 2\alpha\dot{\theta} = 4\tilde{g}J\frac{\alpha}{\sigma} \sin(\theta) \]

Damped Pendulum

Trapping Transition: PRL 110, 186403 (2013)
Buildup of Coherence and Phase Locking

Time resolved measurement & interferometry

Pulsed excitation, interference of one condensate with the other

Sample 10K

Pump laser

BS

Streak
N = 2: Cooperative Effect

Trapping Transition: PRL 110, 186403 (2013)

Polariton Condensates

Lower Threshold
Smaller ejection wavevector
Larger Interference fringes
N=2: 2D Quantum Oscillator

\[ \psi = \sqrt{\rho} \cdot e^{-\frac{iEt}{\hbar}} + \varphi \]


Multi-spot Excitation: N=2

Polariton Condensates
Condensate theory

- complex Ginzburg-Landau equation (cGL)

\[ i\hbar \partial_t \psi = [E(i\nabla) + g |\psi|^2 + \hbar R_R N(r, t)]\psi + i\left[\frac{\hbar}{2} R_R N(r, t) - \frac{i\hbar \eta N}{\partial_t} - \Gamma_C \right] \psi \]

- reservoir dynamics

\[ \partial_t N(x, t) = -\left[\Gamma_R + \beta R_R |\psi(x, t)|^2\right]N(x, t) + P(x) + D \nabla^2 N \]

N. Berloff

*[Nature Physics 8, 190 (2012)](http://dx.doi.org/10.1038/nphys1968)*
Simulation results

Resembles oscillating dark-solitons

How to measure?
Condensate dynamics

- Modelocking condensates

Nonlinear optics

cf: ultrafast lasers, supercontinuum generation

Visibility (%)

Self-interference every round trip time (exact match)

All the simple harmonic oscillator levels are phase coherent

Nature Physics 8, 190–194 (2012)
Tuneable oscillator

Wavepacket frequency (THz)

temporal width $\Delta t \approx t_r/n_{SHO}$

set by number of SHO states ($n_{SHO}=10$)

$$t_r = \pi L \sqrt{\frac{m^*}{2(g|\psi|^2 + \hbar R_R N)}}$$

wavepacket revival is not perfect
decays over 40ps

due to coherent wavepacket
- dispersion (SHO spacings)
- decay
- dephasing
- diffusion
Interference of Condensates

Dark Wavepacket

Bright Wavepacket

Time resolved phase locking of polariton cond. In prep.

Multi-spot Excitation: N=2

Polariton Condensates
Multiple spot excitation
Vortex lattices

- honeycomb lattice of up to 100 vortices and anti-vortices
Stretching the lattice

- Vortices formed by a linear superposition of 3 waves outflowing from each spot.
- Average distance between neighbouring vortices: \( A = \frac{4\pi}{3k\sqrt{3}} \)
- Outflow momentum dependent on power: \( k(r) = K[\omega_c - \Delta(r)] \)

G. Tosi, Nature Comm., accepted (2012)
Setup

Ti:Sapphire CW
755nm

Chopper

1st order

Diff. Order Selection

Sample

Fourier Lens

Phase Modulation

SLM

Laser Image

Display & Phase

Fourier Transform

Laser Image:
Phase Modulation +
Fourier Transformation

Sample Illumination:
4x Telescope +
50x Microscope Objective

Real & k-space
Interferometry

Dispersion Space - Energy

Spectrometer

Photoluminescence 805nm

Phase Reference Arm, magnified

Variable Density Filter

100x IR
NA=0.7

Cryostat

Variable

Fourier Lens

Ti: Sapphire CW
755nm

Chopper

1st order

Diff. Order Selection

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Cryostat
Flow Control

- Design optical potential by non-resonant laser excitation
- Blueshift gradient <-> main flow direction
- Very non-linear system: condensate shapes its own potential

$$i\hbar \partial_t \psi = \cdots + V(r)\psi + g|\psi|^2\psi$$
Phase Transition

Phase Locked
Pumps far apart

$\leftrightarrow$

Trapped
Pumps Close Together

Single Energy

Physics:
Vortex Lattice  Q. Oscillator

Condensation:
At pump  Centre

Condensation Threshold?

Trapping Transition: PRL 110, 186403 (2013)
Condensation Threshold

Below Threshold

Above Threshold
N ≥ 4: Opt. Trapped Condensates
N = 4: Optical Trapping

Trapping Transition: PRL 110, 186403 (2013)
N = 4, 6, 8, ...

Trapping Transition: PRL 110, 186403 (2013)

Polariton Condensates
Ring Condensates

Change Excitation geometry

Excitation power

Real Space

Energy

10µm

Laser

Polariton Condensates

Ring Excitation

19/22
Conclusion

• **Phase-Locking**: Cooperative Effect

• **Phase Transition**: Locked --> Trapped

• **Direct Optical Flow Control + Trapping**: SLM + Blueshift

**Future**: Explore new exciting pump geometries!
Indirect polaritons: Dipolaritons
Indirect polaritons: Dipolaritons

Dipolariton approach:
weakly-coupled double quantum wells

direct control of polariton dipole

\[ H_{PP}^{eff} = \frac{1}{2} \sum_{k,k',q} \frac{a_B^2}{A} V_{k,k',q} \hat{P}_{k+q}^+ \hat{P}_{k'-q}^+ \hat{P}_k \hat{P}_{k'} \]

dipole-dipole

- reduction of lasing threshold
- electrically-pumped polariton lasers and BECs

Dipolaritons

“tunnelling off”

direct excitons
DX

“tunnelling on”
mixed excitons
DX±IX,
static dipole moment

Dipolaritons

Combining tunnel coupling (J) and Rabi splitting (Ω)

\[
H = \begin{pmatrix}
E_C & \Omega/2 & 0 \\
\Omega/2 & E_{DX} & J/2 \\
0 & J/2 & E_{IX}
\end{pmatrix}
\]
Observation of dipolaritons

Photoluminescence of the system versus increasing bias for detuned and resonant cavity

PL is lost because electron tunnel out of the system

tunnel-split excitons, uncoupled cavity
dipolaritons, strong coupling of J and Ω

"Coupling Quantum Tunneling with Cavity Photons"
Science 336, 704 (2012)
Dipolaritons at resonance

H = \begin{pmatrix} E_C & \Omega/2 & 0 \\ \Omega/2 & E_{DX} & J/2 \\ 0 & J/2 & E_{IX} \end{pmatrix}

MP state: no DX!

\begin{align*}
|\text{MP}\rangle &= \frac{\Omega|\text{IX}\rangle - J|\text{C}\rangle}{\mathcal{S}}
\end{align*}
Barrier width dependence

Influence of the tunnelling barrier thickness (4, 7, 20 nm) on the bare tunnelling rate $J$

Excellent agreement with solution of the Schrödinger equation for tunnel coupling

ADQW simulation from solving Schrödinger equation
Summary

- Low threshold polariton lasing at 25K and RT in GaN

- Electrical and optical manipulation of polariton condensates on a chip
  polariton condensate transistor
  polariton condensate pendulum

  interactions between condensated in confining potentials

- Dipolaritons: Oriented polaritons
  new possibilities for enhancing nonlinear Interactions
  threshold reduction, control of parametric scattering
Thank you