Manipulating Polariton Condensates on a Chip

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Acknowledgements

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Spectroscopy

IESL-FORTH
Growth & Device Fabrication

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- New generation of semiconductor lasers operating in the so called strong light-matter coupling regime

- Electrical and optical manipulation of polariton condensates on a chip
  - polariton condensate transistor
  - interactions between independent condensates
  - electrical control of polariton condensate
The concept of the semiconductor laser diode proposed by Basov in 1959
N. G. Basov, B. M. Vul and M. Popov
Soviet JETP, 37(1959)

First GaAs laser diode demonstrated by Robert N. Hall in 1962.

Pulsed operation at liquid nitrogen temperatures (77 K)

In 1970, Zhores Alferov, Izuo Hayashi and Morton Panish independently developed CW laser diodes at room temperature

The laser disc player, introduced in 1978, was the first successful consumer product to include a laser, but the compact disc player was the first laser-equipped device to become truly common in consumers' homes, beginning in 1982.
Fundamental Optical Processes Involved in Operation of Semiconductor Lasers

Absorption

\[ E_2 \rightarrow E_1 \]

\[ \text{hv} \]

Spontaneous emission

\[ E_2 \rightarrow E_1 \]

\[ \text{hv} \]

Stimulated Emission

\[ E_2 \rightarrow E_1 \]

\[ \text{hv} \]

\[ \text{hv} \]

conduction band

valence band

\[ \text{creation of electron hole pair as a result of the absorption of the photon h}_v \]

\[ a. \]

\[ b. \]
To achieve non-equilibrium conditions, an indirect method of populating the excited state must be used.

When population inversion ($N_2 > N_1$) between level 1 and 2 is achieved, optical amplification at the frequency $\omega_{21}$ can be obtained. Because at least half the population of atoms must be excited from the ground state to obtain a population inversion, the laser medium must be very strongly pumped. This makes three-level lasers rather inefficient.
Strong Coupling Regime

Strong Coupling Regime ($\Omega \gg \gamma$):

emitted photon will be reabsorbed before it leaves the cavity

⇒ Spontaneous Emission is a reversible process

$\gamma$: loss channel

$\Omega$: coupling strength between optical transition of the material and the resonance photon mode
Monolithic Semiconductor Microcavity

- Combine electronic and photonic confinement in the same structure

- QWs placed at the E-field maxima
Strong Coupling Regime in Semiconductor Microcavity

- Strongly modified dispersion relations
  new properties

- small polariton mass $m_{pol} \approx 10^{-4}m_e$

- strong non-linearities $\Rightarrow \chi^3$ (exciton component)

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

\[ E_{\text{exciton}}(k_{||}) = E(0) + \frac{\hbar^2 k_{||}^2}{2M_{\text{exciton}}} \]


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Bose-Condensation and Concept of Polariton Lasing

Imamoglu et al., PRA 53, 4250 (1996)

Bosonic character of cavity polaritons could be used to create an exciton-polariton condensate that would emit coherent laser-like light.

Polaritons accumulate in the lowest energy state by bosonic final state stimulation.

The coherence of the condensate builds up from an incoherent equilibrium reservoir and the BEC phase transition takes place.

The condensate emits spontaneously coherent light without necessity for population inversion.
New Physics & Applications

- Strong-coupling provides a new insight into a number of very interesting fundamental physical processes and applications

Polaritons are Bosons

- Bose condensation
- stimulated scattering

Polariton vs Photon Laser

- ultralow threshold polariton lasers
- all optical switches and amplifiers
Polaritonics

From a device perspective:
- Near speed of light lateral transport
- Light effective mass
- Condensate regime readily available on a chip even at RT

New directions: electrically driven polariton devices
Polariton based Devices
“Polaritonics”
Room temperature Polariton LED

Emission collected normal to the device

- Clear anticrossing observed
- Direct emission from exciton polariton states
- Rabi splitting of 4.4meV at 219 K

Transport driven device

Collapse of Strong Coupling Regime at High Densities

- Injection density at 22mA $\sim 10^{10}$ pol/cm$^2$

![Diagram showing normalized EL intensity vs energy for different currents](image)

- Relaxation bottleneck
- Relaxation on lower branch governed by polariton-polariton interactions (dipole-dipole)

- Dotted line at $T=235K$
High finesse GaAs microcavity

Linewidth = 90μeV
T = 6K

Experimental
Q factor ~ 16000

Modeled Q factor ~ 20000
Non-resonant optical excitation

- Rabi splitting of 9.2 meV at 50K
- Reflectivity dips relatively small
GaAs Polariton Laser 25K

- Nonresonant optical pumping above stopband

- Very low threshold at 25K ~ 6.5mW strong coupling

Polariton Condensate Transistor Switch
**Polariton Condensate Transistor Switch**

**Motivation:** Although photonic circuits have been proposed, a viable optical analogue to an electronic transistor has yet to be identified as switching and operating powers of these devices are typically high.

**Common perception:** In the future, charged carriers have to be replaced by information carriers that do not suffer from scattering, capacitance and resistivity effects.

**Approach:** Polaritons being hybrid photonic and electronic states offer a natural bridge between these two systems.

- **Excitonic** component allows them to interact strongly giving rise to the nonlinear functionality enjoyed by electrons.
- **Photonic** component restricts their dephasing allowing them to carry information with minimal data loss and high speed.

Macroscopic quantum properties of polariton condensates make them ideal candidates for use in quantum information devices and all optical circuits.

Gao et al., PRB 85, 235102 (2012)  
Generating Polariton Condensate Flow

- Polariton condensate forming at the ridge end

- Local pump induced blueshift and lateral confinement forces polariton flow along the ridge

Only top DBR is etched
Ballistic Condensate Ejection

- blue shift at pump $V_{max} = g |\psi|^2$
- polaritons expand along the ridge

Fourier plane

Polariton Condensate Built-up

• Ballistic transport of polaritons
• Polaritons flow and relax in the direction of negative detuning
• Condensate forming at the ridge end

• spatially separated and angle resolved emission

Increasing source intensity

Distance (µm) | Angle (deg) | Energy (eV) |
---|---|---|
-20 | -20 | 1.542 |
0  | 0  | 1.540 |
20 | 20 | 1.538 |
40 | 40 | 1.538 |
60 | 60 | 1.538 |

CCD slit

Objective

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Polariton Condensate Transistor Switch

- Polariton propagation is controlled using a second weaker beam that gates the polariton flux by modifying the energy landscape.
Gating Polariton Condensate Flow

- Gate beam power 20 times weaker than source
- Second condensate appears between source and gate at higher gate powers
- At higher powers gate re-pumps the condensate at the ridge end
Gating Polariton Condensate Flow

Theoretical modeling by Tim Liew

- gating efficiency up to 90% is demonstrated
Electrical and optical control of polariton condensates
Electrical control of polariton dispersions

- Application of electric field to the QW tunes the exciton energy through QCSE
- Reduction in exciton oscillator strength & Rabi splitting have to be considered
Electrical control of polariton dispersions

- Clear tuning of the lower polariton branch energy
- Schottky diode allows local spatial field to be applied
Control of polariton dispersions in nonlinear regime

- Electric tuning of the lasing energy observed
Interactions Between Condensates

- Can we make two independent condensates interact on a chip?
- What happens if we launch two condensates against each other

Spontaneous formation and optical manipulation of extended polariton condensates

E. Wertz¹, L. Ferrier¹, D. D. Solnyshkov², R. Johne², D. Sanvitto³, A. Lemaitre³, I. Sagnes¹, R. Grousson⁴, A. V. Kavokin⁴, P. Senellart¹, G. Malpuech² and J. Bloch⁴*
Buildup of Coherence and Phase Locking

Time resolved measurement & interferometry

Pulsed excitation, interference of one with the other

Sample 10K
Pump laser
Streak
Polariton condensates in a parabolic optical trap

- equal spaced energies SHO wavefunctions
- harmonic potential - quantum pendulum

G. Tosi et al. Nature Physics 8, 190 (2012)
Oscillations observed under pulsed excitation regime

2 spots separated by 25 microns

Streak camera measurement

Increasing pump power
Summary

- Low threshold polariton lasing at 25K

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

  polariton condensate pendulum

Interactions between condensates in confining potentials
PostDoc positions at FORTH-IESL

3 Postdoctoral Research Fellow Positions on Polaritonic Devices

The aim is to develop novel class of electrically injected polariton devices.
Positions:
(1) Electrically injected polariton lasers
(2) Polaritonic circuits and transistors
(3) Design, growth and fabrication of microcavity structures

Living allowance under an employment contract: 21,600 €/year.
Highly motivated and qualified candidates with solid academic background and experimental experience are encouraged to apply.

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Implemented under the "ARISTEIA" Action co-funded by the (ESF) and National Resources.

“APOLLO” Aristeia grant
Thank you