Quantum fluids of light

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General motivations
Why cavity polaritons?

How do we perform experiments?
Band structure?

Why non-linearities?

Where do we go??

Quantum fluids of light?
Many body physics: fascinating macroscopic physics

Superfluidity

Fractional Quantum Hall effect

Graphene

Topological insulators
Quantum fluids of light as an analogous system

\[ i\hbar \frac{\partial \psi}{\partial t} = H\psi \]

Same Hamiltonian \( \Rightarrow \) Same physical properties

Why use synthetic quantum material?

- System « easier » to probe, manipulate
- Create new geometries, new properties \( \Rightarrow \) Applications
- Realize experiments impossible to predict because of complexity of numerical simulations (many body physics): **quantum simulations**

Original idea: [R. Feynman., Int. J. Theor. Phys. 21, 467 (1982)]

Nature 14 November 2012
Quantum fluids of light as an analogous system

- Photons have no mass!
- Photons have no charge!
- Photons do not interact (or so weakly)!
- Photons are bosons (not fermions like electrons!)
Quantum fluids of light as an analogous system

- Photons have no mass! Effective mass in a cavity
- Photons have no charge!! Artificial gauge field
- Photons do not interact (or so weakly)! Yes when coupled to electronic excitations
- Photons are bosons (not fermions like electrons!)

Nobody is perfect!

Bose-Hubbard

\[ \hat{H} = -J \sum_{\langle m,n \rangle} \hat{a}_m^\dagger \hat{a}_n + \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1) \]
Driven-dissipative photonic Bose-Hubbard model

Out of equilibrium quantum physics

Ciuti & Carusotto, Rev. Mod. Phys. 85, 299 (2013)
Emulation with light

Chiral edge states


Quasicrystal

P. Vignolo et al., New J. Phys. 16 (2014) 043013

Synthetic Landau levels

N. Shine et al., Nature 354, 671 (2016)

Non reciprocal lasing


Topological edge states Si

M. Hafezi, Nat. Phot. 7, 1001 (2013)

A. Crespi, Nature Photonics 7, 322 (2013)

Semiconductor microcavities: cavity polaritons
Bose-Einstein condensation of exciton polaritons


T = 10 K


Polariton density

CdTe

T = 5 K

Benoid Deveaud

Le Si Dang
Polariton superfluidity

Cristiano Ciuti and I. Carusotto PRL 242, 2224 (2005)
Emulating Dirac Physics

Pillar diameter = 3 µm
Interpillar distance a = 2.4 µm

Graphene energy bands

Castro Neto et al., Rev. Mod. Phys. 81 (2009)

Dirac cones

Jaqmin et al., PRL 112, 116402 (2014)
See also Yamamot (Stanford), Krizhanovskii (Sheffield)
Propagation of light in a non-linear medium

\[ i \frac{\partial \mathcal{E}}{\partial z} = -\frac{1}{2k_0} \nabla_\perp^2 \mathcal{E} + U \mathcal{E} + \gamma |\mathcal{E}|^2 \mathcal{E} \]

- kinetic energy
- external potential
- non-linear interaction
Propagation of light in a non-linear medium

- **Photorefractive crystal**
- **Thermo-optic liquid (methanol)**
- **Atomic vapor**

M. Bellec, C. Michel (INPHYNI)
C. Michel et al. Nature Com 2018

D. Faccio Edinburgh
Q. Glorieux, A. Bramati (LKB)
PRL 120, 055301 (2018)
Outline

Lecture 1: Introduction to cavity polaritons

Lecture 2: Polariton non-linearities: Superfluidity, BEC
December 10th

Lecture 3: Polariton lattices
December 12th

Lecture 4: Quantum fluids of light in propagating geometry
December 17th
Quentin Glorieux, LKB
Lecture 1: Introduction to cavity polaritons
Microcavity polaritons

Excitonic polaritons: Mixed light-matter particles

Photons confined in an optical cavity
- Very light \((m=0 \text{ in vacuum})\)
- Very fast
- No interactions

Excitons confined in a quantum well
- Very heavy
- Very slow
- Interactions
Photon confinement

Distributed Bragg reflector

\[ \lambda_B \]

\[ \lambda_B/4 \]

Very high reflectivities

\[ \text{Reflectivity} \]

\[ \lambda (\mu m) \]

\[ n_1n_2n_1n_2n_1 \]
Photon confinement

**Distributed Bragg reflector**

\[ \lambda_B \]

\[ \lambda_B/4 \]

**Fabry-Perot resonator (microcavity)**

\[ n_1 n_2 n_1 n_2 n_1 \]

Very high reflectivities

- \[ \lambda_B \]
- \[ \lambda_c \]

Optical mode

Normal incidence
Microcavity polaritons

GaAs/AlGaAs based structures

5 K

Top DBR

 Bottom DBR

Optical cavity

Bragg mirror GaAs/AlAs

Cavity

Bragg mirror GaAs/AlAs

TEM, G. Patriarche, LPN

\[ E_c = \frac{\hbar \omega}{n} \sqrt{k_x^2 + k_y^2 + \left( \frac{\pi n}{L_c} \right)^2} \]

\[ E_c (k) = E_c (k = 0) + \frac{\hbar^2 k^2}{2 M_{phot}} \]

with \( M_{phot} = \frac{p^2 \pi^2 \hbar^2}{L_c^2 n^2} \)
Microcavity polaritons

GaAs/AlGaAs based structures

5 K

Top DBR
Quantum Wells

Bottom DBR

Excitonic resonance

Quantum well exciton

AlGaAs   GaAs   AlGaAs

Exciton

PLE sig. (arb. units)

Energy (eV)

1.62  1.63  1.64  1.65  1.66  1.67  1.68

12 K Cal

e_{1hh1}^{n=1}

Energy (eV)

E_d

n=1
Microcavity polaritons

GaAs/AlGaAs based structures

5 K

Top DBR
Quantum Wells
Bottom DBR

Quantum well exciton

\[ E_x(k) = E_x(k = 0) + \frac{\hbar^2 k^2}{2M_x} \]

with \( M_x = m_e + m_h \)

Typically \( \frac{M_x}{M_{phot}} = 10^4 \)
Microcavity polaritons

GaAs/AlGaAs based structures

5 K

Top DBR
Quantum Wells

Bottom DBR

Microcavity polaritons: mixed exciton-photon states

Cavity

AlGaAs
GaAs
AlGaAs

Emission energy (eV)

k_{in-plane} (\mu m^{-1})

Angle $\theta$ (°)

Upper polariton

Photon

Exciton

Lower polariton

~ 5meV

Claude Weisbuch
PRL 69, 3314 (1992)
Microcavity polaritons

\[ H_{k//} = \begin{pmatrix} E_X(k_{//}) & g \\ g & E_C(k_{//}) \end{pmatrix} \]

\[
E_1 = \frac{E_X(k_{//}) + E_C(k_{//})}{2} - \frac{\Delta(k_{//})}{2}
\]

\[
E_2 = \frac{E_X(k_{//}) + E_C(k_{//})}{2} + \frac{\Delta(k_{//})}{2}
\]

\[
\Delta(k_{//}) = \sqrt{(E_C(k_{//}) - E_X(k_{//}))^2 + 4g^2}
\]

with

Rabi splitting 2g
Microcavity polaritons

\[ |\text{polariton}\rangle = \alpha |\text{photon}\rangle + \beta |\text{exciton}\rangle \]

Exciton photon detuning:
\[ \delta = Ec(k = 0) - Ex(k = 0) \]

s-shaped dispersion: inflexion point
Probing polariton states: Angle resolved experiments

Selective excitation and probe of polariton states

$k_\parallel = \frac{\omega}{c} \sin(\theta)$
How to generate microcavity polaritons?

Resonant excitation

- Control of:
  - Energy
  - $k_{\parallel}$
  - Phase

Non resonant excitation

- Population of many low energy modes
- Creation of an excitonic reservoir
- Possibility to enter a stimulated regime: lasing, Bose E
Measurement of Cavity-Polariton Dispersion Curve from Angle-Resolved Photoluminescence Experiments

R. Houdré,1 C. Weisbuch,1,2 R. P. Stanley,1 U. Oesterle,1 P. Pellandini,1 and M. Illegems1

1Institut de Micro- et Optoélectronique, Ecole Polytechnique Fédérale de Lausanne, CH 1015, Lausanne, Switzerland
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(Received 11 March 1994)

**FIG. 2.** Series of photoluminescence spectra at \( T = 77 \text{ K} \), for an emission angle from \(-12^\circ\) to \(41^\circ\). The Fabry-Pérot at normal incidence is resonant with the quantum well exciton.

**FIG. 3.** Cavity-polariton dispersion curves, deduced from angle-resolved photoluminescence measurements, for different resonance conditions. (a) Resonance at \( \theta = 0^\circ \) (case of Fig. 2). (b) Resonance at \( \theta = 29^\circ \), and (c) \( \theta = 35^\circ \). The continuous lines are theoretical calculations and the dashed lines are the unoccupied exciton and cavity dispersion curves. The intercetion energy (1) and exact resonance position are determined from the minimum splitting between both photoluminescence lines. An external emission angle grid is drawn on (a).

Phys. Rev. Lett. 73, 2043 (1994)
Probing polariton states: Angle resolved experiments

Sample

Fourrier plane

Spectrometer slit

Energy

-30 -20 -10 0 10 20 30
Angle (°)

Energy (meV)

-30 -20 -10 0 10 20 30
Angle (°)

Energy (meV)

-30 -20 -10 0 10 20 30
Angle (°)

1470 1475 1480 1485 1490 1495
Energy (meV)

Centre de Nanosciences et de Nanotechnologies
Typical experimental scheme

Far field imaging: k space

Real space imaging

Energy

Density

Interference with a reference beam

Coherence map

Emission statistics

Phase dislocations

- vortices

- solitons

Far field imaging: k space

Real space imaging

Energy

Density

Interference with a reference beam

Coherence map

Emission statistics

Phase dislocations

- vortices

- solitons
Cavity polaritons: an exciton-photon mixed state

\[ |\text{polariton} > = \alpha |\text{photon} > + \beta |\text{exciton} > \]

- **\( \alpha^2 \) photon part**
- **\( \beta^2 \) exciton part**

**Properties**
- Photonic component \( \text{low mass} \ (10^{-5} m_e) \)
**Microcavity polaritons**

\[ |\text{polariton}\> = \alpha |\text{photon}\> + \beta |\text{exciton}\> \]

*Exciton photon detuning:*
\[ \delta = E_c(k = 0) - E_x(k = 0) \]

s-shaped dispersion: inflexion point

Effective mass:
\[ \frac{1}{M_{pol}} = \frac{1}{\hbar^2} \frac{\partial^2 E}{\partial k^2} \]

At \( k = 0 \):
\[ \frac{1}{M_{pol}} = \frac{\alpha^2}{M_{phot}} + \frac{\beta^2}{M_{exc}} \]

Beyond inflexion point: negative effective mass

\[ \delta > 0 \]

\[ \delta = 0 \]

\[ \delta < 0 \]
Probing polariton states: Real space propagation

Resonant pulsed excitation

In-plane propagation of excitonic cavity polaritons

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FIG. 2. Propagation in real space of the secondary emission source as observed on the streak camera for several detunings. The diaphragm is close to the reflection and $\theta_r = 7.8^\circ$. 

Group velocity
Probing polariton states: Real space propagation

\[ v_g(k) = \frac{1}{\hbar} \frac{\partial E}{\partial k} \quad v_g(k) = \alpha^2 v_{\text{phot}}(k) + \beta^2 \chi(k) \]

FIG. 3. Group velocity of the resonantly excited lower branch polaritons as a function of the detuning for different incident angles $\theta_i$. The points are the measured values for $\theta_i = 7.8^\circ$ (■), $\theta_i = 6.2^\circ$ (♦), and $\theta_i = 4.3^\circ$ (▲). The solid, dashed, and dotted lines...
Cavity polaritons: an exciton-photon mixed state

\[ |\text{polariton} \rangle = \alpha |\text{photon} \rangle + \beta |\text{exciton} \rangle \]

- **\( \alpha^2 \) photon part**
- **\( \beta^2 \) exciton part**

**Properties**
- Photonic component \( \rightarrow \) low mass (10\(^{-5}\) \( m_e \))
- Short lifetime (1-100 ps) \( \rightarrow \) dissipative system
Polaritons have a finite (short) lifetime: 1-100 ps
Cavity polaritons: an exciton-photon mixed state

\[ |\text{polariton}\rangle = \alpha |\text{photon}\rangle + \beta |\text{exciton}\rangle \]

- \( \alpha^2 \) photon part
- \( \beta^2 \) exciton part

Properties:
- Photonic component \( \rightarrow \) low mass \( (10^{-5} m_e) \)
- Short lifetime (1-100 ps) \( \rightarrow \) dissipative system
- Pseudo spin
Polariton spin

Spin: electron: ± 1/2
heavy hole: ± 3/2

Photon have an angular momentum: ± 1

Exciton: \( J_z = \pm 1 \)
\( J_z = \pm 2 \)

Only \( J=1 \) excitons are coupled to light

Polaritons have two spin projections:
\[
\begin{align*}
\sigma^+ \\
\sigma^-
\end{align*}
\]

\( j_z = \pm 1 \)
\( j_z = \pm 1 \)

One-to-one relationship between pseudospin state and polarisation degree
Polariton spin: Intrinsic magnetic field

Cavity modes linearly polarized: TE-TM splitting

Energy (eV)

\[ k_{\parallel} (\mu m^{-1}) \]

TM pola.

TE pola.

Effective magnetic field

\[ H_{\text{eff}} = \frac{\hbar}{\mu_B g} \Omega_k \]

\[ \Omega_x = \frac{\Omega}{k^2} (k_x^2 - k_y^2), \quad \Omega_y = 2 \frac{\Omega}{k^2} k_x k_y, \quad \Omega = \frac{\Delta_{\text{LT}}}{\hbar} \]

boundary conditions for the electromagnetic field at the interface of the different dielectric layers

Kavokin et al. PRL 95, 136601 (2005)
Optical spin Hall effect

\[ \frac{\partial \mathbf{S}}{\partial t} = \mathbf{S} \wedge \tilde{\Omega}(\theta) + \frac{\mathbf{S}_0}{\tau_1} - \frac{\mathbf{S}}{\tau} \]

Kavokin et al. PRL 95, 136601 (2005)
Optical spin Hall effect

$\tau_{\text{pol}} = 10\text{ps}$

Kavokin et al. PRL 95, 136601 (2005)
Cavity polaritons: an exciton-photon mixed state

\[ |\text{polariton}\rangle = \alpha |\text{photon}\rangle + \beta |\text{exciton}\rangle \]

- **\( \alpha^2 \) photon part**
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**Properties**
- Photonic component \( \rightarrow \) low mass \( (10^{-5} \, m_e) \)
- Short lifetime (1-100 ps) \( \rightarrow \) dissipative system
- Pseudo spin
- Sensitivity to magnetic field
Magneto-luminescence

Quantum well

Cavity

$\Delta E_{Zeeman} \approx 1.7 \text{ meV}$

$B = 7T$

$\Delta E_{Zeeman} \approx 1.2 \text{ meV}$
Cavity polaritons: an exciton-photon mixed state

\[ |\text{polariton} > = \alpha |\text{photon} > + \beta |\text{exciton} > \]

- Properties
  - Photonic component: low mass \((10^{-5} m_e)\)
  - Short lifetime (1-100 ps): dissipative system
  - Pseudo spin
  - Sensitivity to magnetic field
  - Polariton Interaction: Highly non linear system (Kerr like)
  - Polariton lattices
Polariton lattices

Gold deposition on top mirror

Surface acoustic waves


Stanford

Cerda-Méndez *et al.*, PRB **86**, 100301(R) (2012)

Berlin
During-growth photonic trap

Deveaud’s group at EPFL

Würzburg

Coupled mesas

El Daïf et al., APL 88, 061105 (2006)
Idrissi Kaitouni et al., PRB 74, 155311 (2006)
Cerna et al., PRB 80, 121309 (2009)
Hybrid cavities

Fiber-closed cavity

Imamoglu, Reichel,

**Figure 1:**
- **(a)** Schematic representation of the fiber-closed cavity setup.
- **(b)** Energy spectra and piezo voltage graph.

**References:**
- Besga et al., Light: S&A 3, e135 (2014)
- See also T. Fink et al., Nature Physics 14, 365 (2018)
Polariton in 1D cavities

Electron beam lithography + ion dry etching

Polariton lateral confinement

Quantization of $k_x$: $k_x = n\pi/w$

$n=1,2,3,...$

$E_n(k_y) = E_0 + \frac{\hbar^2}{2m} \left( \frac{n^2\pi^2}{w^2} + k_y^2 \right)$
1D periodic potential: free particle approach

\[ E\psi(x) = -\frac{\hbar^2}{2m} \frac{\partial^2 \psi(x)}{\partial x^2} + V(x)\psi(x) \]

\[ V(x) = \frac{\hbar^2}{2m} \frac{n^2 \pi^2}{w(x)^2} \]

D. Tanese et al., Nature Com. 4, 1749 (2013)
Aubry André (Harper) quasi-periodic potential

On-site potential incommensurate with the lattice period

\[ a = 2 \, \mu m \]

V. Goblot et al., Arxiv1911.07809

Polariton lattices: Tight binding approach

Polariton lattices: Tight binding approach
Engineering of a 1D flatband: “comb” lattice

Pillar diameter = 3 µm
Interpillar distance = 2.4 µm

Far field emission

F. Baboux et al. PRL116, 066402 (2016)

Emission of flat band in real space
Strong light-matter coupling in two-dimensional atomic crystals

Xiaoze Liu¹², Tal Galfsky¹², Zheng Sun¹², Fengnian Xia³, Erh-chen Lin⁴, Yi-Hsien Lee⁴, Stéphane Kéna-Cohen⁵ and Vinod M. Menon¹²*
Ground-State Chemical Reactivity under Vibrational Coupling to the Vacuum Electromagnetic Field


**Figure 1.** a) The light–matter strong coupling between the Si–C stretching vibrational mode and a cavity mode that results in the Rabi splitting. b) The silane deprotection reaction of 1-phenyl-2-trimethylsilylacetylene used in the present study.

**Figure 4.** The reaction rate ([PTA]=2.53 M, $h\Omega_{\text{in}}=98 \text{ cm}^{-1}$) as a function of temperature (Eyring equation plot) for reactions inside the ON resonance cavity (red squares) and outside the cavity (blue squares).
Summary

- Hybrid exciton-photon quasi-particles
- Tunable properties: effective mass, group velocity
- Lateral confinement: engineering of band structure
- Spin dependent interactions
- Optical access to all physical properties