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Lattices of quantized vortices in polariton superfluids

Réseaux de tourbillons quantifiés dans les superfluides de polaritons

Thomas Boulier, Emiliano Cancellieri, Nicolas D. Sangouard, Romain Hivet, Quentin Glorieux, Élisabeth Giacobino, Alberto Bramati *

Laboratoire Kastler Brossel, UPMC – Sorbonne Universités, CNRS, ENS-PSL, Research University, Collège de France, 4, place Jussieu, case 74, 75005 Paris, France

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ABSTRACT

In this review, we will focus on the description of the recent studies conducted in the quest for the observation of lattices of quantized vortices in resonantly injected polariton superfluids. In particular, we will show how the implementation of optical traps for polaritons allows for the realization of vortex–antivortex lattices in confined geometries and how the development of a flexible method to inject a controlled orbital angular momentum (OAM) in such systems results in the observation of patterns of same-sign vortices.

RÉSUMÉ

Dans cet article de synthèse, nous nous concentrerons sur la description d'études récentes menées dans le but d'observer des réseaux de tourbillons quantifiés dans des superfluides de polaritons injectés de manière résonante. En particulier, nous montrerons comment l'implémentation de pièges optiques pour les polaritons permet la réalisation de réseaux tourbillon–anti-tourbillon dans des géométries confinées et comment le développement d'une méthode flexible pour injecter un moment angulaire orbital contrôlé (OAM) dans de tels systèmes permet l'observation de motifs de tourbillons de mêmes signes.

1. Introduction

In semiconductor microcavities [1,2], polaritons, the half-light, half-matter particles arising from strong coupling between excitons and photons behave like weakly interacting composite bosons. Due to their excitonic part, they exhibit non-linear interactions, while their photonic part allows creating and detecting them optically. In this sense, the polariton system is part of a wider family of systems where an effective photon–photon interaction can be engineered, resulting in a hydrodynamical-like behavior. Such systems are labeled as quantum fluids of light [3].

* Corresponding author.
E-mail address: alberto.bramati@lkb.upmc.fr (A. Bramati).

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A coherent polariton gas of large density can be obtained by resonant laser excitation [4], which allows probing any specific state of the polariton dispersion. Density, phase, temporal and spatial coherence, but also motion, can be directly accessed by well-developed optical techniques. Any type of in-plane potential landscape can be designed by lateral patterning of microcavities, mesa fabrication [5], or by using optical potentials induced by exciton–exciton interactions, as recently demonstrated in references [6,7].

All these ingredients make polariton systems a unique platform to study quantum fluid effects in a semiconductor chip and to evidence properties very difficult to access in other systems. This has been clearly demonstrated by the numerous results obtained since the first observation of polariton BEC [8]. Superfluidity and Čerenkov regime of polaritons have been demonstrated in 2009 [4] with an original experimental scheme based on the interaction between a dense mono-kinetic flow of polaritons and a defect. This allowed confirming the superfluid nature of a polariton flow and to observe, for the first time, the formation of oblique-dark and bright-dissipative solitons [9–11].

For what concerns the observation of vortices, several works have focused on this subject but, so far, only few of them focus on arrays of vortex–antivortex pairs and of vortices of the same sign. Among the others, of particular relevance is the work of Keeling and Berloff, theoretically studying [12] the formation of a rotating polariton BEC, pumped out of resonance trapped in a harmonic potential. From the experimental point of view, the nucleation of vortices has been addressed in non-resonant configurations, as well as in resonant configurations and in optical parametric oscillator (OPO) schemes. For what concerns out-of-resonant schemes, vortex formation in disordered landscapes has been achieved [13] and hydrodynamical nucleation of vortex pairs have been observed by colliding a flux of polaritons on a structural defect of a planar cavity [14]. Regarding resonantly pumped systems, vortex formation has been observed, similarly to the out-of-resonant case, by colliding a moving fluid of polaritons with a structural defect of a planar cavity [9,15]. In these cases, however, a metallic mask has been used to block the laser pump in the region behind the defect, in order to allow the phase of the scattered polaritons to evolve freely. Finally, vortices have also been observed in the optical parametric oscillator (OPO) scheme [16,17].

We will show in the following that the new possibilities offered by confining polaritons in optically generated potential traps allow creating interaction-shaped vortex–antivortex lattices [18,19]; moreover, we will illustrate a new flexible method based on the use of a spatial light modulator (SLM) for the direct phase imprint in a polariton fluid; this allows the creation of a rotating polariton fluid in an annular geometry, leading to the formation of a chain of same-sign vortices [20]. These results constitute a significant step forward in our understanding of the quantum fluids of light and open the way to the study of Abrikosov-like physics in these systems.

1.1. Sample

The planar microcavity used in the present work was built by using the molecular beam epitaxy technique at the "École polytechnique fédérale de Lausanne" (EPFL), Switzerland, by Romuald Houdré [21,22]. The sample is made of three $In_{0,04}Ga_{0,96}As$ quantum wells placed at the antinodes of the cavity electromagnetic field.

The cavity is GaAs-based with a typical length $2\lambda/n_c$ for $\lambda = 835$ nm (the excitonic resonance), where $n_c = 3.54$ is the cavity GaAs substrate optical index. The Bragg mirrors forming the cavity are made of 21 (front mirror) and 24 (back mirror) GaAs–AlAs pairs. The measured polariton linewidth is less than 85 μeV (limited by the spectrometer resolution), and the polariton lifetime is estimated at about 15 ps from time resolved measurements. The back mirror lies on a GaAs substrate polished to allow working in transmission mode. During epitaxial growth, a very small angle of the order of 10^{-4} degrees was implemented between the Bragg mirrors to continuously change the cavity thickness. This angle allows for a very fine control of the photon–exciton detuning. The change in the cavity thickness modifies linearly the energy of the cavity photon with the position on the sample while the exciton energy remains constant. Exciton–photon detuning from +8 meV to −4 meV can be achieved, with an energy gradient of about 710 $\mu eV\,mm^{-1}$. The Rabi splitting for our sample is measured to be 5.1 meV.

1.2. Injection methods

There are two main methods to inject polaritons in a microcavity. One is the so-called "out-of-resonance" pumping and consists in injecting in the cavity high-energy photons with a laser. Depending on the efficiency of the relaxation phenomena, polaritons can thermalize and form a quasi-Bose–Einstein condensate [8]. With this injection method, a large exciton population is created in addition to the polariton population. The second technique to create a fluid of polaritons is "resonant injection" (or "quasi-resonant"), which we will use in the following. It consists in injecting laser photons directly at an energy and in-plane wavevector resonant with the lower polariton branch. In this way, the energy and the wavevector of the resulting polariton population are fully controlled. Using a continuous laser, we can create large polariton populations whose properties (momentum, energy, density, phase, spin) are inherited from the pump. This controlled injection allows the study of propagation-related phenomena [4,23,24], and quantum hydrodynamic experiments are achievable under this pumping scheme. Note that this is unlike the out-of-resonance setup, where the coherence and the in-plane wavevector of the pump are lost during the relaxation process. In the quasi-resonant scheme, one can induce a small energy difference between the laser and the polariton energy. With this quasi-resonant pumping, the nonlinearities play an important role and induce a bistable behavior accompanied by many interesting phenomena [3,4].