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# Optical induced vortices and persistent currents in polariton condensates

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**Abstract.** Observation of quantized vortices in non-equilibrium polariton condensates, suggesting parallels with conventional superfluids, have been reported either by spontaneous formation and pinning in the presence of disorder [1, 2] or by imprinting it onto the signal or idler of an optical parametric oscillator (OPO) [2]. Here we report the first observation of a polariton condensate receiving a quantized angular momentum by means of a short optical pulse and maintaining its rotation for a time much longer than the pulse duration, the polariton and coherence lifetimes. This observation shows a peculiar character of polariton condensates and reveals analogies with supercurrents in superconductors or persistent flow in condensates [3].

## 1. Introduction

Since the first experimental observation of strong coupling in microcavities [4], polaritons have displayed lots of interesting phenomena. As they are bosonic particles with mass up to  $10^5$  times lighter than the electron mass, they can achieve a macroscopically coherent state at liquid-He and higher temperatures. The connection between long range spatial coherence and superfluidity is well established for Bose-Einstein condensates at thermal equilibrium, but there are doubts whether superfluidity can be displayed by out-of-equilibrium systems [5]. One example of these systems are the microcavity polaritons, which can attain a macroscopically coherent state by means of two different processes.

When pumped non-resonantly, with pump energies much higher than the polariton energies, the created high-energy excitons spontaneously generate polaritons after relaxation processes. These polaritons can reach a Bose-Einstein condensed state at standard cryogenic temperatures [6], showing a massive occupation of the ground state, an increase of temporal coherence, and the build-up of long-range spatial coherence and linear polarization. Under these conditions, polaritons show characteristics that point out on the direction of superfluidity, like spontaneous appearance of vortices [1] and Bogoliubov-like excitations [7].

A second way to obtain a polaritonic macroscopically coherent state is to create an optical parametric oscillator (OPO) pumping resonantly at the inflexion point of the lower polariton branch (LPB) [8]. After scattering processes, a large number of polaritons go to a low-energy, single state that displays collective dynamics consistent with superfluidity, as linear dispersion

accompanied by diffusionless motion, flow without resistance when crossing an obstacle and suppression of Rayleigh scattering [9], as well as the controlled creation of vortices and the subsequent observation of anti-vortices [2]

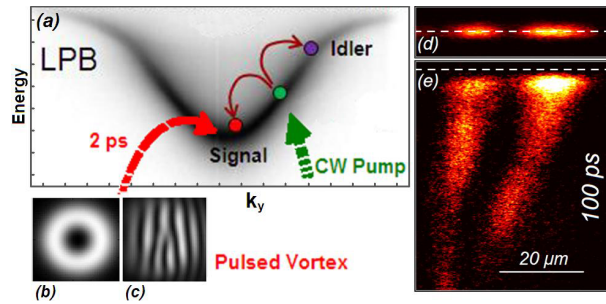
However, superfluidity in non-equilibrium systems should be understood as multiple metastable flow patterns [5], and therefore the superfluidity of microcavity polaritons can be tested by the observation of persistence of quantized vortices. In this paper, we report the observation of a metastable persistent superflow carrying quantum of angular momentum, staying much longer than both the duration of the excitation ultrafast imprinted pulse and the polariton lifetime [10].

## 2. Experiments

In our experiment, the sample is an AlGaAs microcavity with a Rabi splitting  $\Omega_R = 4.4\text{meV}$ , maintained at 10 K. With a CW Ti-Al<sub>2</sub>O<sub>3</sub> laser, we pump the sample resonantly at the inflection point of the LPB (Fig. 1a). At a given time we stimulate the signal with a pulsed vortex beam (Fig. 1b) resonant with the signal at  $k = 0$ , lasting for 2 ps.

Using a streak camera, we can follow the evolution in time of the vortex generated by the pulsed probe. To eliminate the contribution of the steady state, we subtract the emission of the OPO in absence of the probe pulse. Fig. 1d shows a cross section of the pulsed probe while the consequent spatial – and temporal – resolved emission of the polaritons is shown in Fig. 1e.

In order to demonstrate the vortex angular momentum, we detect the phase pattern generated by interfering the signal with an expanded spatial region far from the vortex core (where the phase is approximately constant) in a Michelson interferometer. A fork-like dislocation (Fig. 1c) with a difference of  $m$  arms corresponds to phase winding by  $2\pi m$  around the vortex core.

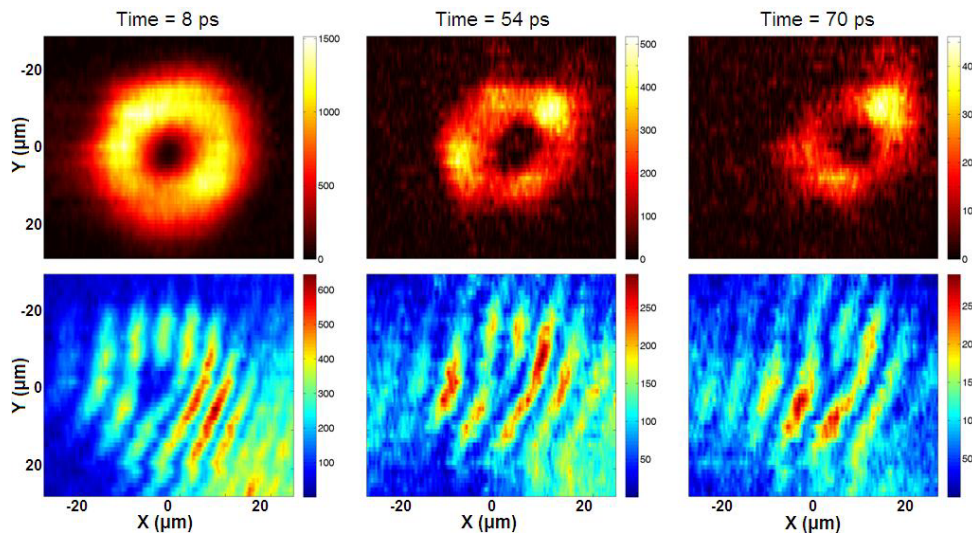


**Figure 1.** Experimental conditions to create a vortex in a polariton system. With a CW Ti-Al<sub>2</sub>O<sub>3</sub> laser we pump the inflection point of the LPB generating a signal population at  $k = 0$  by parametric scattering (a). With a pulsed probe in a donut shape (b) lasting for 2 ps (d) we stimulate the generation of an extra signal population maintained by the CW polariton reservoir. The vortex state of the probe is characterized by a fork-like dislocation when we interfere the probe with a constant-phase beam (c). Using a streak camera we study the evolution in time of the extra polariton population by removing the OPO background (e).

### 2.1. Results

The arrival of the probe stimulates the creation of an extra population that reaches its maximum density in about 5 ps and has a lifetime of 25 ps (Fig. 3). The donut shape of the probe is inherited by the polaritons and is observed up to 70 ps after the arrival of the pulse (Fig. 2 - upper panels). Making the light emitted by the polaritons interfere with its expanded plane wave in a Michelson interferometer, we observe a single fork-like dislocation on the interference

fringes at the vortex core, indicating that the vortex is single-quantized (Fig. 2 - lower panels). To measure the amount of rotation of the polaritons, i. e., the fraction of polaritons that are in the single quantized vortex state, we have calculated the visibility of the extra fringe related to the vortex, as showed in Fig. 3a. We have found that the visibility is maintained at  $\sim 94\%$  from the time of the appearance of the vortex until the last signal can be detected [11].



**Figure 2.** Time evolution of a polariton signal after the arrival of a 2 ps pulsed vortex laser probe. The real space images (upper panels) show that the triggered polaritons donut shape that is preserved until at least 70 ps. The interference profiles (lower panels), obtained by interfering in a Michelson interferometer the vortex with its expanded part, show a single fork-like dislocation at the vortex core with a high contrast at the three different times, revealing that the triggered rotating current persists for at least 70 ps.

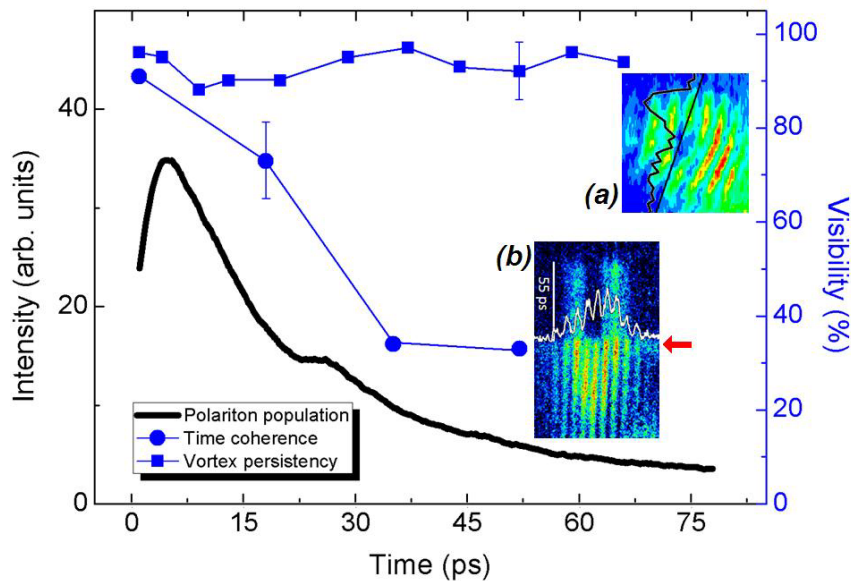
To study the time coherence of the vortex, we have delayed the expanded part of the vortex by moving one arm of the Michelson interferometer. In this situation we visualize in the streak camera, up to the arrival of the delayed and expanded signal (marked by an arrow in Fig. 3b), the cross section of the vortex followed by the sudden appearance of a fork-like dislocation interference pattern. The time coherence can be measured by calculating the visibility of the fringes at the time the two arms start to interfere (Fig. 3b) The visibility, as expected, reads 91% at  $t = 0$  and decays to 30% within 40 ps.

### 3. Conclusions

We have been able to inject ultrafast pulsed vortices with quantized angular momentum in a polariton condensate in the parametric regime and observed that polaritons maintain its permanent flow for a time much longer than the driving field, the vortex lifetime and the coherence time. This constitutes a new instance showing that polaritons in the OPO regime, although being an out-of-equilibrium system, also display superfluid properties as those found in cold atoms and liquid helium.

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**Figure 3.** Time evolution of the vortex population density (solid line), rotation persistency (squares) and time coherence (circles). The polariton population decays within a lifetime of  $\sim 25$  ps and during this time the current rotation remains constant with a visibility of  $\sim 94\%$ , while the time coherence, measured by delaying one of the two arms of the Michelson interferometer, goes down from 91% to 30% within 40 ps. To obtain the visibility of the vortex, we measure the intensity of the maximum and minimum of the fork dislocation at each time (a).

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