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Polariton condensates put in motion

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Abstract
We present several examples of the interesting phenomenology shown by a moving polariton condensate in semiconductor microcavities. The superfluid behavior is probed by colliding the polariton condensate against physical obstacles in the form of natural defects of the sample, demonstrating a clear suppression of scattering when the speed of the flow lies below the critical velocity. At higher velocities Čerenkov-like shock waves around the defect and disruption of the condensate are also observed.

1. Introduction

1.1. Bose–Einstein condensates

Bose–Einstein condensates (BECs) have the very interesting property of displaying superfluid behavior when moving below the Landau critical velocity. This behavior consists of a motion without friction, as a flow without viscosity. Under these conditions a small obstacle is not able to excite the superfluid, leaving unaltered the condensate trajectory. In the case of atomic condensates the origin of this effect is attributed to the linearization at small momenta of the excitation spectrum [1], which suppresses small excitations in the BEC [2, 3]. However, above the critical velocity there are possible states available for the BEC to be excited, which results in the loss of its superfluid character. In this regime the supersonic condensate will behave as a normal fluid showing typical Čerenkov patterns when colliding against an object [4]. These effects are amongst the most striking features of this quantum state which has very interesting phenomenologies and behaviors, still far from being completely understood [5, 6].

1.2. Microcavity polaritons

Polaritons are quasiparticles composed of a mixture of photons and excitons, which result from the strong coupling between the electromagnetic field enhanced by a cavity of micrometer dimensions and the dipole present in a semiconductor quantum well (QW) [7]. These quasiparticles have a peculiar dispersion which is shown in figure 1(a) together with the bare excitonic and photonic dispersions. The lower branch polaritons (LPB) have several interesting properties that are of great advantage in the formation and observation of condensed polariton states. The density of states of these quasiparticles is extremely low thanks to the very small mass given by the photonic component ($\sim 10^{-5}$–$10^{-4} m_e$). Due to their excitonic character they manifest a Coulomb repulsion which leads to strong nonlinearities, sometimes used in resonant excitation to obtain signal and idler states as in an optical parametric oscillator (OPO). The recent achievement of Bose–Einstein condensation using polaritons in microcavities [8–10] has opened the way to the study of this peculiar state of matter in a semiconductor chip. Physical phenomena associated with supercurrents, superfluidity or quantized vortices are some of the most interesting significant effects which may have strong technological impact.

2. Experiment

The sample used in our experiment was a $\lambda/2$-thick AlAs microcavity, surrounded by two, very highly reflective, Bragg mirrors with 15 pairs of $Al_{0.1}Ga_{0.9}As$/AlAs layers on the top and 25 on the bottom. The active layer was a 20 nm thick GaAs QW, which was placed at the antinode of the electromagnetic field. The sample was wedged along the x direction to allow for

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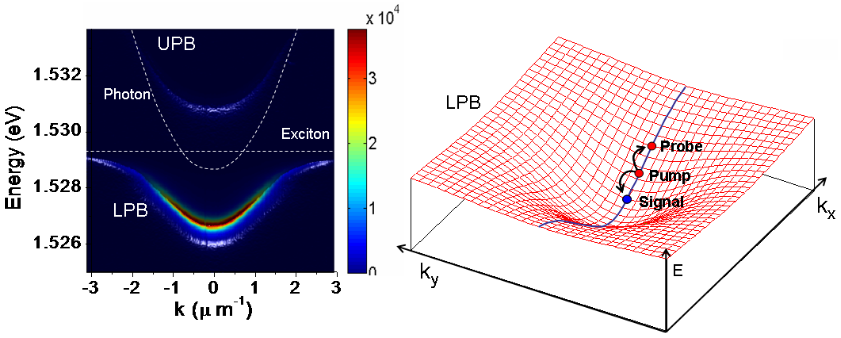

Figure 1. (a) Experimental dispersion of the UPB and LPB slightly negatively detuned. (b) Schematic diagram of the LPB along the k_x and k_y axes.

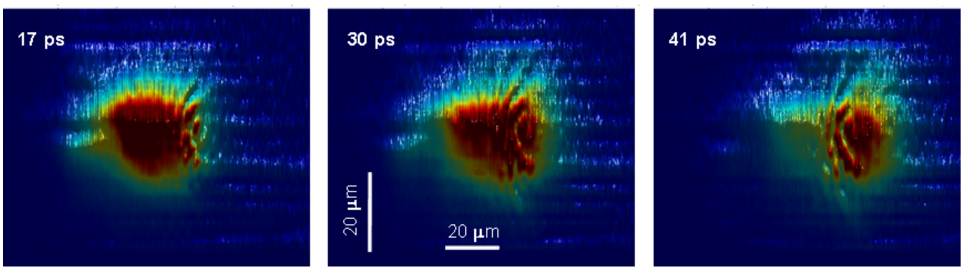

Figure 2. Snapshot of the polariton condensate moving across the pump spot and crossing an object in the middle of its trajectory.

the variation of the cavity-exciton detuning. At zero detuning the exciton–photon coupling gives a Rabi splitting of 4.4 meV. The experiments were performed at a cryogenic temperature of 10 K and using a very high numerical aperture lens (0.6) so that the sample could be accessed by angles as large as 25°. A CW Ti-sapphire laser, with a spot size of $\sim$100 μm, was used on resonance with the inflection point of the LPB at 10° (corresponding to $k_\mathrm{p} = 1.5\ \mu$m) to generate the OPO signal and idler states by stimulated final state occupation. In the standard configuration [11, 12], the signal is generated spontaneously after the threshold to initiate the parametric scattering is reached. Consequently a signal at $k_\mathrm{s} = 0$ is generated, maintaining the phase matching conditions for the in-plane momentum of the pump (k_p), idler (k_i) and signal (k_s): $k_\mathrm{s} = 2k_\mathrm{p} - k_\mathrm{i}$ and energy $2E_\mathrm{p} = E_\mathrm{s} + E_\mathrm{i}$ are satisfied. However, in the case of the present experiment we trigger the OPO (TOPO) with a pulse probe of 2 ps duration tuned at energy E_i and momentum k_i, so that the signal of such a process would be generated with a k_s of finite momentum close to the bottom of the LPB. The experiment is aimed at producing a polariton condensate, with a finite velocity, which is able to travel across the pump spot for times longer than the cavity lifetime. This is possible thanks to a slowing down of the dynamics of the signal decay time approaching the threshold for the parametric process [13].

Figure 1(b) shows, schematically, the position of the probe, pump and the resulting TOPO signal on the LPB dispersion. As can be seen, the signal is generated at a final k-vector which gives rise to a moving polariton condensate across the pump spot with velocities v_g given by the local dispersion: $v_\mathrm{g} = \frac{1}{\hbar}\frac{\partial E}{\partial k}$.

This fluid of polaritons, after the probe has triggered the OPO, moves with velocities between 0.7 and 1.5 μm ps^{-1}, depending on the excitation conditions and simply self-sustained by the parametric scattering of pump polaritons. It is observed through a streak camera for time and space/momentum resolved images at the energies around the signal state emission.

3. Results and discussions

Figure 2 shows a sequence of three temporal snapshots of the polariton condensate moving across the pump spot from left to right. In the center of the trajectory a natural defect, formed during the sample growth, of small dimensions (compared to the signal spatial extension) is positioned in such a way that the signal is forced to cross it before reaching the edge of the CW pump spot. The defect is clearly visible in the middle of the image due to a strong modulation of the signal density in the form of waves across the defect. These waves are typical of objects traveling at velocities above the speed of sound and also observed for expanding atomic BEC clouds [4] and resonantly pumped polaritons [14]. However, for polaritons the very strong nonlinearities do not allow direct access to the excitation spectrum of the condensate, which can only be observed by the indirect effect of an obstacle on the flow pattern. In the case shown here, the appearance of the shock waves is due to the pump induced modulation of the signal intensity, the latter being formed by the parametric scattering of two pump polaritons into signal and idler states. However, the polariton condensate at the signal state, shown in the figure, is observed to cross the defect without losses, displaying neither

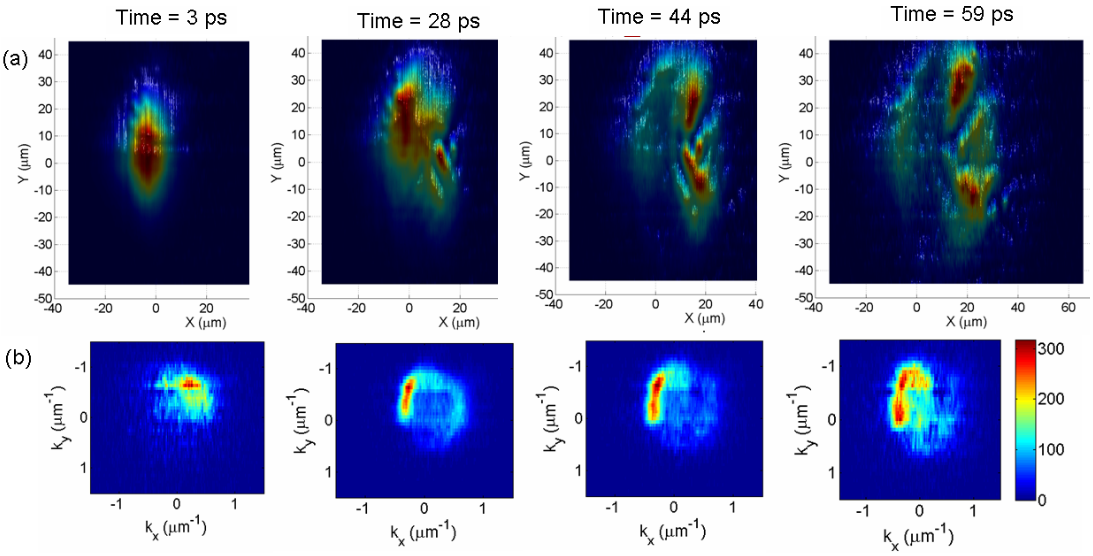

Figure 3. Polariton of the signal state showing Čerenkov dispersion against an obstacle. (a) Real and (b) momentum space images of four temporal snapshots.

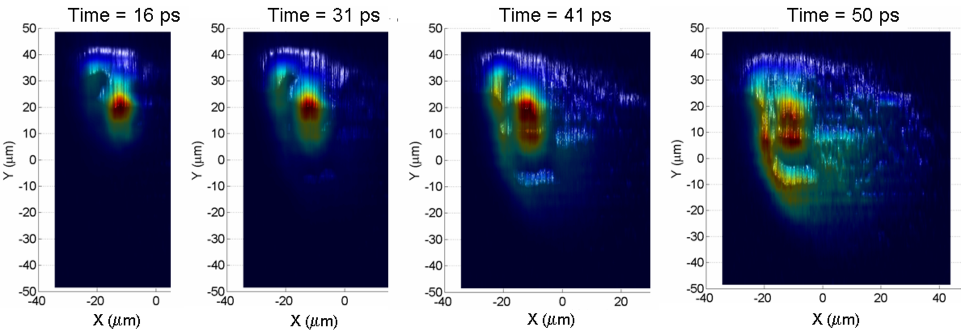

Figure 4. Images of polaritons scattering against a big defect for which the superfluid regime is lost.

scattering nor dissipation. Images in momentum space [5] (not shown here) confirm that the condensate conserves its own momentum, showing a single sharp k-vector at k_s both before and after the collision.

To further prove that the signal is not simply dragged by the pump, we show in figure 3(a) the same signal polariton, this time traveling against a similar defect in the structure at velocities above the speed of sound. In this case the collision event is dramatically changed. The signal splits into two main patterns with several fringes alongside preferential trajectories, in a similar manner to the pump state observed reflected into the signal of the previous figure, the only difference being that the Čerenkov patterns are shown dynamically in time and not under constant flow conditions. As can be deduced from the Fourier plane images of figure 3(b), the momentum of the condensate before and after the collision is now not conserved and typical Rayleigh scattering around the LPB elastic ring is observed.

Finally, as a counter-example, we can see in figure 4 a case in which the polariton signal coherence is completely lost. In these snapshots a defect of considerable dimensions is placed a few microns away from the point at which the signal is generated. The condensate is now broken due to the severe collision of the polariton condensate with the obstacle. This results in the change of the flow behavior from a superfluid to a classical dissipative fluid: the signal polaritons scatter all around and fill the whole space occupied by the CW pump before decaying as soon as the edge of the pump spot is reached.

4. Conclusions

In summary, we have shown several examples of the collision of a polariton droplet against natural defects, arising from the microcavity growth, which doubtlessly demonstrate the superfluid behavior and the variety of different phenomena that a polariton condensate put in motion can manifest.

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