Sustained propagation and control of topological excitations in polariton superfluid

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Abstract

We present a simple method to compensate for losses in a polariton superfluid. Based on a weak support field, it allows for the extended propagation of a resonantly driven polariton superfluid with minimal energetic cost. Moreover, this setup is based on optical bistability and leads to the significant release of the phase constraint imposed by resonant driving. This release, together with macroscopic polariton propagation, offers a unique opportunity to study the hydrodynamics of the topological excitations of polariton superfluids such as quantized vortices and dark solitons. We numerically study how the coherent field supporting the superfluid flow interacts with the vortices and how it can be used to control them. Interestingly, we show that standard hydrodynamics does not apply for this driven–dissipative fluid and new types of behaviour are identified.

1. Introduction

The control and manipulation of quantum states is a challenging goal in modern physics. Among recent developments, the discovery of quantum states, such as Bose–Einstein condensates and superfluids, in solid-state quasi-particles like exciton polaritons opens up new perspectives [1, 2] in the study of the fundamental properties of quantum fluids on a semiconductor chip. In a semiconductor microcavity with embedded quantum wells that have an excitonic transition resonating with the cavity mode, the strong coupling regime can be easily reached [3], giving rise to a system of eigenmodes which is an indistinguishable mix of excitons and cavity photons, called microcavity polaritons. The unique balance between the dissipative nature of these quasi-particles and their nonlinear dynamics leads to the generation of a polariton superfluid [4].

A simple way to observe exciton polaritons is to quasi-resonantly drive the system with a laser field. For homogenous excitation or a large enough excitation spot, slightly blue-detuned with respect to the polariton energy, optical bistable behaviour is observed [5]. The associated hysteresis cycle (see figure 2) delimits two different regimes: (i) a linear regime for a weak driving field ($I < I_c$) and (ii) a highly nonlinear regime for a strong driving field ($I > I_c$), in which the system exhibits superfluid behaviour. In this regime, several specific quantum fluid properties have been predicted and observed recently in polaritonic systems, e.g. frictionless propagation [2], a vortex pair and soliton generation [6–9], heralding a new way of studying the quantum hydrodynamics of superfluids.

In this article we study the intermediate case between the linear and nonlinear regime ($I_c < I < I_c$): the bistable regime. As we will show, the bistable regime exhibits rich dynamical features, allowing for the compensation of dissipation inherent to these fluids, and thus for extended propagation of the superfluid flow at low energetic cost. Moreover, as shown in [8], the resonant driving field tends to lock the phase of the generated superfluid, inhibiting the formation of topological excitations such as vortices or solitons. Therefore, an engineered driving profile is required to observe such fundamental excitations [6, 7, 9]. Because of the
inhomogeneous density profile of the fluid resulting from the engineered driving profile, this approach makes thorough hydrodynamics studies difficult. In this work we show how with two driving fields—one to create the superfluid and one to support it—we can avoid the locking effect of the phase, which allows the generation and propagation of vortices in a homogeneous superfluid. A combination of the macroscopic enhancement of the propagation, together with the absence of the phase locking effect, allows the hydrodynamics of the vortex-pair dynamics in superfluids to be analysed in detail. Interestingly, we show that fine-tuning the properties of the topological excitations can be achieved by controlling the intensity of the support field. This flexibility allows the specific hydrodynamic behaviour of these driven dissipative systems to be emphasized, which is at odds with standard equilibrium hydrodynamics.

2. Macroscopic enhancement of superfluid propagation

To explore the bistable regime we consider two driving fields with the same frequency $\omega_p$, in-plane wave-vector $k_0$, and circular polarization. One driving field of high intensity ($I_2 > I_1$) is localized and used to create a polariton superfluid. The second driving field, which is homogeneous in time and space (an infinitely extended constant field), acts as a support field and is of weak intensity ($I_1 < I_2$). Time evolution in these conditions is described by a generalized Gross–Pitaevskii equation (1):

$$i\partial_t \begin{pmatrix} \psi_c(x, t) \\ \psi(x, t) \end{pmatrix} = \hbar \begin{pmatrix} \frac{F_c + F_t(x)}{0} \\ 0 \end{pmatrix} e^{-ik_0x - \omega_p t}$$

$$+ \hbar \begin{pmatrix} \omega_c(k) + V(x) - i\frac{\gamma_c}{2} \\ \Omega_g \omega_k^0 + g|\psi(x, t)|^2 - i\frac{\gamma_c}{2} \end{pmatrix} \times \begin{pmatrix} \psi_c(x, t) \\ \psi(x, t) \end{pmatrix}$$

where $\psi_c(x, t)$ represents the cavity (exciton) field, $\omega_c(k)$ is the energy dispersion of the cavity modes, and $\hbar \omega_k^0$ is the exciton energy assuming no dispersion (infinite mass). $\gamma_c$ is the decay rate of the cavity (exciton) modes, and $g$ is the exciton-exciton interaction; $V(x)$ is the photonic potential. The first term of equation (1) refers to the driving field. $F_c(x)$ represents the driving amplitude profile of the field necessary to create a polariton superfluid and $F_t$ is the profile of the support driving ($I_2 = |F_t|^2$).

We illustrate the proposed method in figure 1, presenting the steady state photonic density of a polariton superfluid on a logarithmic scale, flowing from left to right (black curves) in a defect-free planar microcavity ($V = 0$) for a total driving profile $F_c(x) + F_t$ represented by red dashed curves. In the upper panel, only the driving $F_c(x)$, localized on the left, acts on the system (i.e. $F_t = 0$), creating a polariton superfluid whose density falls exponentially outside the driven region due to the finite polariton lifetime. In this case, taking into account the current state of the art in microcavity fabrication, which allows a polariton lifetime of around 50 ps (in the literature, only one article [10] has reported a longer polariton lifetime, going up to 100 ps for a very specific sample), the achievable propagation distances are limited to about 30 $\mu$m. In strong contrast, the lower panel of
maximum extension of the support. We anticipate that propagation distances of fluid is supported along its propagation. This suppression of superfluid decay occurs even for a weak support flow \( |F_r(0)|^2 = I_r(0) \gg I_r = 0 \), shown in green. In figure 1, there are nearly two orders of magnitude between the intensity required to create the superfluid \( I_r(0) \) and the intensity necessary to support its propagation \( I_r \). The modulations observed nearby the region where the superfluid is injected are due to the sharp profile of \( F_r(x) \). The oscillations observed are dispersive shock waves [11, 12]. Without support, due to the strong decay experienced by the fluid, these oscillations are barely visible, whereas with support, the shock waves are clearly visible—even though they are rapidly attenuated.

In realistic experiments, the propagation distances are limited mainly by the available power, which fixes the maximum extension of the support. We anticipate that propagation distances of 100 \( \mu \)m will be easily obtained with standard setups; longer distances of up to 200 \( \mu \)m or more will require specific arrangements (powerful lasers, mode shaping) but are still within reach. More importantly, this strong enhancement of the propagation distance is obtained regardless of either the microcavity characteristics or the intrinsic polariton lifetime, relaxing the stringent fabrication requirements, which are still very hard to fulfil despite the recent technological improvements.

This macroscopic enhancement of superfluid propagation is a direct consequence of the optical bistability. Bistability is typical for quasi-resonantly driven nonlinear Kerr media [13]. Many rich phenomena are related to this effect such as a large variety of solitonic solutions [14]. It is characterized by two distinct critical driving intensities, \( I_c \) and \( I_r \), \( (I_c < I_r) \) between which the system is bistable and can either be in the linear regime or in a nonlinear/superfluid regime. This behaviour is clearly visible in figure 2, where we plot the polariton density as a function of the support intensity. The density was obtained by performing simulations similar to the one reported in figure 3, but omitting the potential barrier (\( V = 0 \)). The density was obtained through spatial averaging far enough from the region where the polariton superfluid is injected. Here the red curve only corresponds to the support whereas the blue curve corresponds to the support and pump. If we trigger the superfluid regime with a local pump field, the superfluid is maintained even with weak support intensity. The combination of pump and support fields has been previously explored in nonlinear optical systems in the context of bright soliton written-erasure protocol [15], considering ‘light bullet’ propagation [16] or optical circuits [17], also mixed with the spin degree of freedom [18] (not considered here). In contrast, here we will use this scheme to explore the hydrodynamic properties of the upper branch of the optical bistability.

**3. Sustained superfluid propagation and hydrodynamics**

In order to probe the superfluidity and to reveal its characteristics, we place a large localized potential photonic barrier in the stream of the fluid just below the pump region (\( V = 0 \)). A similar scheme without support has been used to identify the different hydrodynamical regimes of a polariton superfluid [8]. Having just the pump above the potential barrier allows the total release of the phase locking due to resonant driving. Depending on
the flow speed and speed of sound \( c_s = \sqrt{m g n / \hbar} \), where \( m \) is the effective mass of the polariton and \( n \) is the polariton density), different hydrodynamical regimes can be observed, associated with the appearance, or lack, of topological excitations \([6, 7]\). Here we focus on the turbulent regime where pairs of vortices nucleate at the edge of the defect and follow the superfluid stream. In figure 3 panel O, we show a snapshot of the polariton density when no support is present (similar setup as in \([8]\)). The pump with a peak intensity, corresponding to the black dot labeled P in figure 2, is localized in the upper part where the figure colourscale is saturated; below it, we can distinguish the photonic defect. The other panels in figure 3 correspond to sustained propagation using a support field that is continuous and homogeneous in space and whose intensity increases from panels A to F, as noted above each panel (the labels refer to figure 2). In figure 4 we show the phase profile of the fluid corresponding to the density profile shown in figure 3. Firstly, we see—as described in figure 1—that the presence of the support allows the superfluid to be propagated over more than 100 \( \mu m \) with a constant density. This is in strong contrast with the results shown in panel O and observed in \([6–9]\), where the density strongly decreased along the propagation, modifying the fluid properties significantly. Thanks to the infinitely extended constant support field we obtain a large and homogeneous superfluid.

Moreover, the support provides other original effects, especially regarding its interaction with the generated vortex pairs. In panels A to F we clearly see a vortex stream starting from the potential barrier and following the flow, whose characteristic changes as the support field increases. Vortices and antivortices (with opposite

**Figure 3.** The normalized density profile (snapshot) of the polariton superfluid propagating through a photonic defect for different support intensities (increasing from left to right). The pump intensity localized above the photonic defect is fixed and corresponds to the black dot P in figure 2. The label of each panel refers to a point in figure 2, and the intensity of the support driving is indicated at the bottom of each panel in arbitrary units. The red dots and blue circles indicate the vortices and antivortices, respectively. The other parameters are identical to those in figure 1.

**Figure 4.** The phase profile (snapshot) of the polariton superfluid corresponding to the different panels of figure 3 for increasing the support intensity from left to right.
are marked, respectively, with red stars and blue circles and correspond to a small density point (visible in figure 3) and to a phase singularity (visible in figure 4). As reported in the upper panel of figure 5, the vortex density in the stream reduces as the support increases, until the vortices no longer propagate. This happens even if we are still within the bistable region (see panel E with \( I_1 < I < I_2 \)). The vortex density scales inversely with the intensity of the support field. In the supplementary material, a video presents the dynamical evolution of the polariton density over 0.5 ns. They show that for strong support, the emission of vortices still takes place, but instead of generating vortex pairs that propagate along the flow, they are forced to recombine near the potential barrier. This effect leads to a vortex stream with a constant density far from the potential barrier not directly connected to the emission rate. The origin of this effect is not yet clearly understood, but is attributed to the dual nature of the fluid, partly excitonic and partly photonic, which is strongly modified in the shadow of a purely photonic defect. Moreover, as is clearly visible in the video (see footnote 4), the vortex speed \( v_p \) decreases when the support increases, as reported in the lower panel of figure 5. Their speed is reduced by \( \sim 50\% \) to increase the support by a factor of 10. For a support intensity close to the lower limit of the bistability \( I_1 \), the vortices flow at almost the same speed as the superfluid. Interestingly, the vortex speed scales with the inverse of the amplitude of the driving field and not with its intensity, highlighting the coherent nature of this effect. Instead of pushing the vortices according to the momentum direction imposed by the support field, the support field slows them down; it acts as a friction force on the vortex pairs. Thus, by controlling the amplitude supporting the propagation of the polariton superfluid, we can control the properties of the vortex streams.

In the present case, the propagation speed of the vortex cannot be understood considering individual vortex interaction with the support field. The propagating entities are vortex pairs, characterized by a separation distance \( d \) which reduces as the support intensity increases. The propagation of vortex pairs in irrotational liquids is a well-understood phenomenon \cite{20}. In conventional fluids, the relative speed of vortex–antivortex pairs with respect to the fluid speed evolves as

\[
|v_f - v_p| = \frac{\kappa}{2\pi d}
\]

where \( \kappa \) is the vortex circulation. In superfluids, the circulation around the vortex core is quantized as \( \kappa = 2\pi \hbar / m \) \cite{21}. Consequently, the product of the pair separation \( d \) and the vortex speed \( v_p \) should be equal to a constant \( \hbar / m \). We report this value in figure 6 (red dashed line), which is independent of the support intensity,

\[3 \text{ Number of vortices per micrometre along the propagation direction.}
\[4 \text{ See supplemental material video, available online at stacks.iop.org/njp/19/095004/mmedia.} \]
together with the product \(|v_f - v_p|d\) gathered from the simulations (black error bars). Figure 6 clearly shows that both results coincide for a strong support intensity. Nevertheless, for a weak support intensity (from \(I_s\) to \(I_s/\lambda_c \approx 0.15\)) the deviation is significant. The increasing uncertainty observed in figure 6 is a direct consequence of the small number of vortices propagating for a strong support. This out-of-equilibrium superfluid exhibits interesting hydrodynamic properties which deviate significantly from standard conservative fluids. This is attributed to the driven-dissipative nature of the fluid and raises the question about how far the standard hydrodynamics stand from fluids of light. The resonant driving provided by the support present here is small enough to allow the formation of topological excitations, but still modify the properties of the fluid beyond standard hydrodynamics. This highlights the need for careful analysis and further studies in order to properly compare the driven-dissipative superfluid to that of the equilibrium.

Notice that the fluid velocity, linked to the driving field (support and pump) in-plane wave vectors \(k_p\), is the same in panels A and E of figures 3 and 4, whereas the density increases by less than 10%. The intensity of the pump field is kept constant and corresponds to \(I_s(0)/\lambda_c > 2\). For each panel the vortex propagates in a superfluid such as \(v_f < c_s\). However, wavefronts of the Cherenkov type are present near the potential barrier (figure 3). They appear because the density profile close to the pump is not monotonic (see lower panel in figure 1), leading to a local supersonic regime characterized by Cherenkov wavefronts. Upon passing the potential barrier, the density stabilizes to be in a superfluid regime, and accordingly the Cherenkov wavefront fades away [8, 19].

When the intensity of the support is high enough, the phase of the fluid is locked to the support phase. This phase locking effect can be used to manipulate the propagation path of the vortex pairs. In figure 7 we represent the polaritonic density averaged in time. Upon averaging over time, the vortex stream appears as a low-density fluid such as \(\nu_f^d\) to that of the equilibrium. The resonant driving provided by the support present here is small enough to allow the formation of topological excitations, but still modify the properties of the fluid beyond standard hydrodynamics. This highlights the need for careful analysis and further studies in order to properly compare the driven-dissipative superfluid to that of the equilibrium.

Notice that the localized control barely changes the local density, inducing no significant local energy blue shift. The phase profile, upon averaging in time, presents very small modulations, making them unmeasurable in principle. This is due, on the one hand, to the number of vortices that are too small to significantly have an impact on the phase on average, and on the other hand to the stream that has always been formed by vortex–antivortex pairs, cancelling each other’s contribution to the time-averaged phase profile. With this localized field, we lock the phase of the superfluid, locally inhibiting the formation of phase modulations and therefore forcing the vortex stream to modify its trajectory.

To conclude, we numerically study the interaction between a support driving field and the propagation of a polariton superfluid in detail. We demonstrate how the propagation of such a superfluid can be macroscopically extended for low power use. Using this method we report that the release of the phase locking effect induced by the resonant support is such that the formation of topological excitations as vortices is possible. We show that by modulating the support, the properties of a vortex stream can be significantly manipulated. Through a thorough analysis of the properties of the propagating vortices we also demonstrate that sustained out-of-equilibrium
superfluid hydrodynamics does not coincide with standard conservative hydrodynamics. Based on this unique feature, we illustrate how the vortex path can be controlled. This work paves the way to the study of the hydrodynamics of polariton superfluids within an experimentally feasible setup, which was not achievable before. Moreover, it sheds light on the phase locking mechanism characteristic of resonant driving and uses the same mechanism to achieve fine control of the topological excitations taking place within these fluids.

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Figure 7. The time-integrated normalized density profile of a polariton superfluid with support driving ($I/I_0 = 0.14$) in the presence of an extra localized driving highlighted by the red dashed lines and star. The extra driving in the left and middle panels is an asymmetric Gaussian beam with a width of $\sigma = 2\, \mu m$ along the direction normal to the dashed line and an infinite width in the normal direction. The red star in the right panel indicates the position of a symmetric Gaussian beam with a width of $\sigma = 2\, \mu m$. The time integration is taken over 0.5 ns; the parameters correspond to figure 1.
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