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Original article

Oscillating vorticity in single ring exciton polariton condensates

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ABSTRACT We study annular flows of exciton polaritons in exciton polariton condensates emerging in cylindrical optical micropillar cavities under the spatially localised non-resonant laser pumping. Annular flows indicate nonzero vorticity of the polariton condensate associated with the appearance of polariton vortices around the center of the micropillar. We report an experimental observation of single ring shaped condensates in the regime of vorticity oscillating in time. We reproduce the vorticity oscillations numerically and reveal possible control parameters for manipulating by the oscillation period.

KEYWORDS polariton, exciton-polariton condensate, persistent current, micropillar, vortex

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1. Introduction

Light interacting with matter can considerably change its properties. An essential condition for this is the energy exchange of light radiation and matter excitations, which occurs near their energy resonance. Such exchange can be provided in specially designed structures of microcavities [1]. A microcavity represents a semiconductor or dielectric layer of width of a light wavelength sandwiched between two distributed Bragg reflectors. The central layer contains one or several quantum wells (QWs) embedded in the antinodes of the cavity electric field. Mircocavity photons strongly couple to excitons in QWs and form exciton polaritons, new eigenmodes of the microcavity system.

Polaritons inherit bosonic nature from both their constituents and can form a macroscopic coherent state of the Bose-Einstein condensate [2] characterized by a single wave function $\Psi(\mathbf{r})$. Due to the localization of polaritons in the microcavity growth direction, polariton problems are typically two-dimensional, $\mathbf{r} = (x, y)$. Due to the limited quality factor of microcavities, polaritons possess a finite lifetime. The consequence of this is the fact that the polariton condensates are dissipative. Nevertheless, the condensates can exist in microcavities for infinitely long time without losing coherence in the presence of external pumping by laser radiation. Another peculiarity of the polariton condensates, which stems in part from their dissipative nature, is that, as a rule, they are characterized by internal currents (flows) of polaritons [3–5].

In this regard, when describing polariton condensates, one should speak about achieving not stationary states, but steady states. The last definition is more capacious. It describes a system whose parameters do not change in time, while allowing the movement of polaritons in the cavity plane. The polariton current density determined as $\mathbf{J}(\mathbf{r}) = \mathrm{Im}[\Psi^*(\mathbf{r})\nabla\Psi(\mathbf{r})]$ is helpful for characterising polariton currents. By writing the wave function as $\Psi(\mathbf{r}) = \sqrt{\rho(\mathbf{r})}\exp[i\varphi(\mathbf{r})]$, where $\rho(\mathbf{r})$ and $\varphi(\mathbf{r})$ are the density and phase of the polariton condensate, we can reduce the expression to the form $\mathbf{J}(\mathbf{r}) = \rho(\mathbf{r})\nabla\varphi(\mathbf{r})$.

Internal flows are inherent in some topological objects in quantum fluids, including vortices that represent the movement of the fluid along a closed circuit [3, 6]. Since polariton systems are non-conservative, internal polariton currents can be justified by the inhomogeneity of gain and losses within the polariton condensate area, provided that the overall gain-loss balance is maintained. This is especially relevant when spatially localized pumping and microcavity structures with a complex in-plane profile are used for obtaining polariton condensates. Among such structures are, e. g., mesas [7], planar polariton waveguides [8, 9], micropillars [10–12].

A series of our papers is devoted to azimuthal currents of polaritons in polariton condensates excited in cylindrical micropillars by the spatially localised non-resonant optical pump [10–15]. The currents in such condensates are persistent and quantum, characteristic of the corresponding vortex eigenstates of the effective trap for polaritons and quantitatively characterized by the azimuthal quantum number of the vortex topological charge m. At the same time, the currents take place in the spatially inhomogeneous non-conservative system in the presence of external pumping. Herewith the polariton localization area is responsible for the spatial distribution of the polariton current density $\mathbf{J}(\mathbf{r})$ in the microcavity plane. The localization area is generally determined by the geometry of the effective trap, in particular, by the shape of the pillar, as well as by the shape and size of the pump spot [16–19]. The latter acts as a control parameter for polariton currents in our consideration.

For characterizing azimuthal polariton currents, it is convenient to introduce the reduced orbital angular momentum (OAM) of the polariton condensate $\ell = N^{-1}\displaystyle\int [xJ_y(\mathbf{r}) - yJ_x(\mathbf{r})]d\mathbf{r}$ and its winding number $m = (2\pi)^{-1}\displaystyle\int_S d\varphi$, where $N = \displaystyle\int |\Psi(\mathbf{r})|^2 d\mathbf{r}$ is the population of the polariton condensate, S is the closed pass within the condensate around its center of mass [14]. A non-zero value ℓ indicates the presence of azimuthal currents of polaritons in the condensate, while a non-zero value of m indicates vorticity of the condensate. As one has shown in [12], the presence of the former does not necessarily require the presence of the latter. Vorticity implies that the condensate supports closed azimuthal persistent currents of polaritons and is characterized by the integer nonzero winding number m which ensures the phase change by a multiple of 2π for one turn around the pillar, $\phi|_{\theta=2\pi} - \phi|_{\theta=0} = 2\pi m$, θ is the azimuthal angle. In this regime, one can speak about the polariton vortices.

In our papers [10–15], we have reported observation of polariton condensates in the form of concentric rings. We have shown that by changing the size of the micropillar, on can excite polariton current states in the form of single and concentric rings [10, 13, 15]. However, in our studies we dealt with polariton condensates in the steady state regime. As one has mentioned above, in this regime, despite the internal currents, the parameters of the condensate remain unchanged in time, including the population N, OAM ℓ and the winding number m of the condensate, as well as its density and phase distribution.

In the experiment described in our recent paper [14], we have observed for the first time the regime of oscillating vorticity in a double concentric ring condensate excited in cylindrical micropillar. In this regime, the parameters N, ℓ and m of the condensate exhibit oscillations in time with a constant period. We have identified convincing traces of the oscillations in an interference experiment with time averaging of measurements. When considering the manuscript by the reviewers, the following issue arose, which later on repeatedly raised in discussions of the results of the work. Double concentric ring condensates, although of fundamental interest, are rather specific objects of study. At the same time, single ring condensates are more basic, and their application prospects are more obvious [20–22]. In addition, they require lower pump powers, they are better protected from mixing with other both radial and azimuthal modes. However, vorticity oscillations have not yet been observed in such condensates. In this article, we eliminate this omission. We demonstrate the regime of vorticity oscillations in single ring polariton condensates excited by the non-resonant laser pump in a cylindrical micropillar cavity. We investigate the properties of the polariton condensate using interferometry measurements. We support our observations with numerical simulations based on the solution of the generalized Gross-Pitaevskii equation. We estimate the period of vorticity oscillations and show that it can be controlled by changing the shape of the effective trap for polaritons, in particular, the ellipticity of the pump spot.

2. Experimental observation of single ring polariton condensates in the regime of oscillating vorticity

In the experiment, we excited single ring polariton condensates in a cylindrical micropillar of diameter of 25 μm. The micropillar was etched from a GaAs microcavity of width of $5\lambda/2$ containing a set of embedded quantum wells. The quality factor of the microcavity was measured as about $1.6 \cdot 10^4$. The sample was kept in the helium-flow cryostat at $T = 4$ K. The excitation of the condensate was performed by a continuous wave laser beam focused close to the center of the micropillar in the regime of non-resonant pumping (with energy about 110 meV above the bottom of the lower dispersion branch of polaritons). Two types of measurements were performed in the experiment. First, we detected

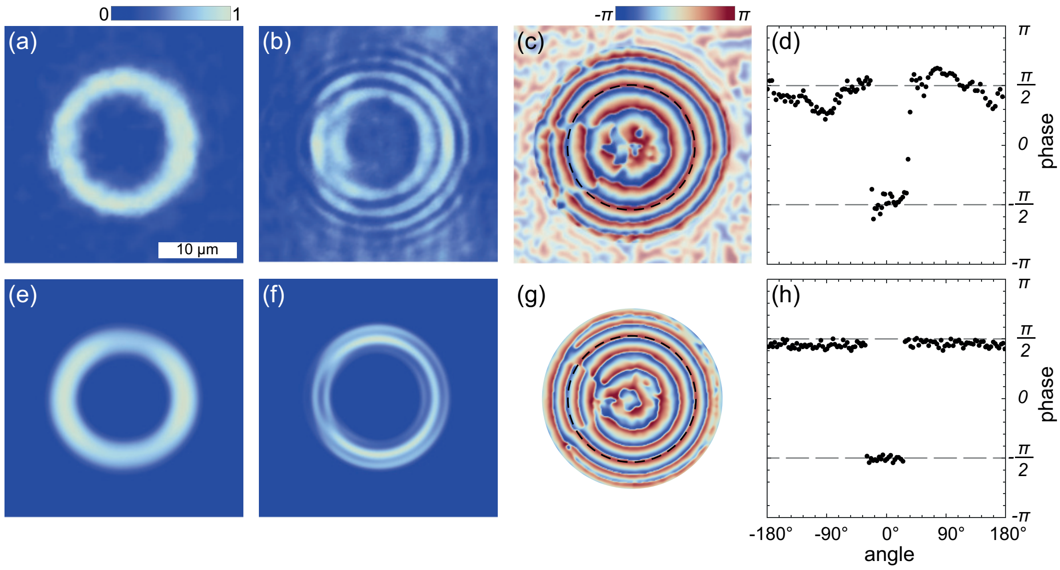

FIG. 1. Observation (top panels) and simulation (bottom panels) of the single ring polariton condensate with oscillating vorticity. (a) Image of the time-averaged PL distribution of the condensate indicating the condensate density distribution in the micropillar, (b) image of interference of PL of the condensate with the reference spherical wave, (c) distribution of the phase of the condensate relative to the phase of the reference wave extracted from panel (b), and (d) the phase variation around the condensate ridge indicated by a black dashed circle in panel (c). Panels (e–h) have the same meaning as (a–d), respectively, but for the simulated data. Dashed lines in (d) and (h) are guides for the eye indicating constant phases $\pm\pi/2$.

photoluminescence (PL) of the polariton condensate to reveal distribution of density of polaritons in the micropillar plane. Second, we detected interference of PL of the condensate with the coherent spherical reference wave using the Mach-Zehnder interferometer. See details of the sample and measurements in Refs. [10, 14].

The results of measurements are shown in Fig. 1(a–d). Photoluminescence of the polariton condensate shown in Fig. 1(a) confirms that under the excitation conditions described above the condensate possesses a single ring shape. The possibility of taking such a shape for the condensate was ensured by the ring shape of the effective potential trap. The latter was composed of two component. The outer wall of the trap was formed by the edge of the cylindrical micropillar. The inner wall was formed by the repulsive reservoir of incoherent excitons emerging within the pump spot under the non-resonant optical excitation. While the stationary potential from the pillar keeps unchanged during the experiment, the shape and height of the optically induced potential is subject to control by controlling the shape of the pump spot and the pump power.

For running azimuthal currents, in our experiments we slightly shifted the pump beam from the center of the pillar [10, 11]. A submicrometer shift is sufficient for this. When the system is chiral, it acquires a preferred direction of the polariton current. Nevertheless, the shift of the pump spot alone is not able to break equivalence between clockwise and counterclockwise directions. In our papers [10–14], we have shown that chirality can be acquired by the polariton system when the shift coexists with another symmetry breaking inclusion, e. g., deformation of the pump beam, defects in the stationary potential landscape. In this case, polariton currents emerge in the condensate manifested as spiral fringes in the images of interference of PL of the condensate and the spherical reference wave. In the absence of polariton currents, spirals degenerate to concentric rings (like Newton's rings in the textbook optical experiment).

The interferometry image obtained in our experiment is shown in Fig. 1(b). One can see that the interference fringes represent concentric rings, each having two breaks at some points. This considerably differs the image from those in the cases of azimuthal polariton currents and in the absence of currents in the single ring condensate. Figs. 1(c,d) show the extracted from 1(b) distribution of the phase of the condensate relative to the phase of the reference wave, and the azimuthal variation of the phase along the ridge of the condensate (indicated by a black dashed circle in the panel (c)), respectively. One can see that the phase between the fringe breaks remains constant, while at the points of the breaks it undergoes jumps by $\pm\pi$.

The interference fringe breaks indicating the phase jumps are known for polariton condensates with fractional OAM [11, 12]. However, for such states the phase jump coexists with a dip in the density distribution, thus the fractional OAM condensates possesses a half-moon shape. This is inconsistent with the azimuthally homogeneous density distribution in our experiment, illustrated in Fig. 1(a). To explain this observation, following [14], we assume that in the experiment we observe not a steady state single ring polariton condensate, but the condensate, whose vorticity oscillates

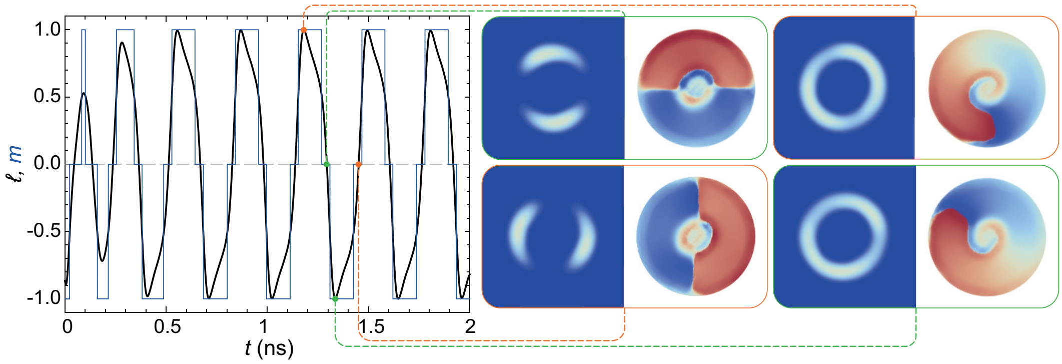

FIG. 2. Simulated evolution of OAM $\ell(t)$ (black curve) and the winding number $m(t)$ (blue curve) of the single ring polariton condensate in the regime of oscillating vorticity. Right panels show spatial distribution of the density and phase of the condensate at time moments indicated by color circles in the left panel.

in time. Thus, the panels 1(a) and 1(b) show averaged in time density distribution and interferomentry image of the single ring condensate in the oscillating regime. To confirm the validity of our assumption, we support our observations with the numerical experiment, described in the next section.

3. Numerical simulation of single ring polariton condensates in the regime of oscillating vorticity

To simulate behavior of the polariton condensate in the micropillar, we use the generalized Gross–Pitaevskii equation for the polariton wave function $\Psi(t,\mathbf{r})$ [14, 23, 24]:

$$i\hbar\partial_t\Psi(t,\mathbf{r}) = \left[-\frac{\hbar^2}{2M}\nabla^2 + V(r) + \alpha|\Psi(t,\mathbf{r})|^2 + \alpha_{\mathrm{R}} n_{\mathrm{R}}(t,\mathbf{r})\right]\Psi(t,\mathbf{r}) + \frac{i\hbar}{2}\left[\frac{\hbar\Lambda_0}{M}n_{\mathrm{R}}(t,\mathbf{r})\nabla^2 + Rn_{\mathrm{R}}(t,\mathbf{r}) - \gamma\right]\Psi(t,\mathbf{r}), \quad (1)$$

where M is the effective mass of polaritons in the microcavity plane, $V(r)$ is the stationary potential of the micropillar taken in the complex form $V(r) = V_{\mathrm{R}}(r) + iV_{\mathrm{I}}(r)$. The real part is taken as $V_{\mathrm{R}}(r) = V_0\left\{\tanh[a(r-d/2)] + 1\right\}/2$, where V_0 and d are the height of the potential and the diameter of the pillar, a is the fitting parameter. The imaginary part responsible for damping due to etching of the pillar [9, 14, 25] can be obtained from the real part by replacing $\eta \to \eta'$, $\eta = V_0, a, d$. α and α_{R} are the polariton-polariton interaction constant and the interaction constant of polaritons with optically excited excitons in the reservoir, respectively, $n_{\mathrm{R}}(t,\mathbf{r})$ is the density of the exciton reservoir. The imaginary term in Eq. (1) is responsible for relaxation processes in the polariton condensate. The term proportional to Λ_0 is responsible for the energy relaxation of polaritons [14, 23, 24] with Λ_0 being the relaxation constant. R is the stimulated scattering rate from the exciton reservoir to the condensate, γ is the decay rate of polaritons.

The exciton reservoir density obeys to the following rate equation:

$$\partial_t n_{\mathrm{R}}(t,\mathbf{r}) = P(\mathbf{r}) - \left(\gamma_{\mathrm{R}} + R|\Psi(t,\mathbf{r})|^2\right) n_{\mathrm{R}}(t,\mathbf{r}), \quad (2)$$

where $P(\mathbf{r})$ is the pump power taken in the Gaussian form:

$$P(\mathbf{r}) \propto \exp\left[-\frac{x^2 + (y/s)^2}{2w^2}\right]. \quad (3)$$

In (3), w is the width of the beam, s is responsible for the ellipticity of the pump spot. We use s as the control parameter in our consideration. γ_{R} is the decay rate of excitons in the reservoir.

We use the following values of the parameters for simulations. The effective mass of polaritons is $M = 3\cdot 10^{-5} m_{\mathrm{e}}$, where m_{e} is the free electron mass, the polariton and exciton decay rates are $\gamma = 0.025$ ps^{-1} and $\gamma_{\mathrm{R}} = 0.02$ ps^{-1}, respectively, the stimulated scattering rate is $\hbar R = 0.1\,\mathrm{meV}\,\mu\mathrm{m}^2$, the interaction coefficients are $\alpha = \alpha_{\mathrm{R}}/2 = 3\,\mu\mathrm{eV}\,\mu\mathrm{m}^2$, the energy relaxation constant is $\Lambda_0 = 0.0063\,\mu\mathrm{m}^2$, the pump width is $w = 2.9\,\mu\mathrm{m}$. The parameters of the stationary potential: $V_0 = -3V_0' = 3\,\mathrm{meV}$, $a = a' = 4\,\mu\mathrm{m}^{-1}$, $d = 25\,\mu\mathrm{m}$ and $d' = 25.7\,\mu\mathrm{m}$.

The results of simulations of the single ring polariton condensate in the regime of oscillating vorticity are illustrated in Fig. 2. In order to achieve the oscillations, we have undertaken the following. We have introduces a weak ellipticity in the pump spot, taking $s = 0.86$. We have also taken the initial conditions as random distribution of the polariton density accompanied by a seed in the form of a vortex with $m = -1$ in the phase component. One can see that the resulting polariton state exhibits oscillations of OAM $\ell(t)$ and the winding number $m(t)$ between -1 and $+1$ with the period estimated as about 300 ps. As a possible drivers of the vorticity oscillations, we distinguish the interplay between

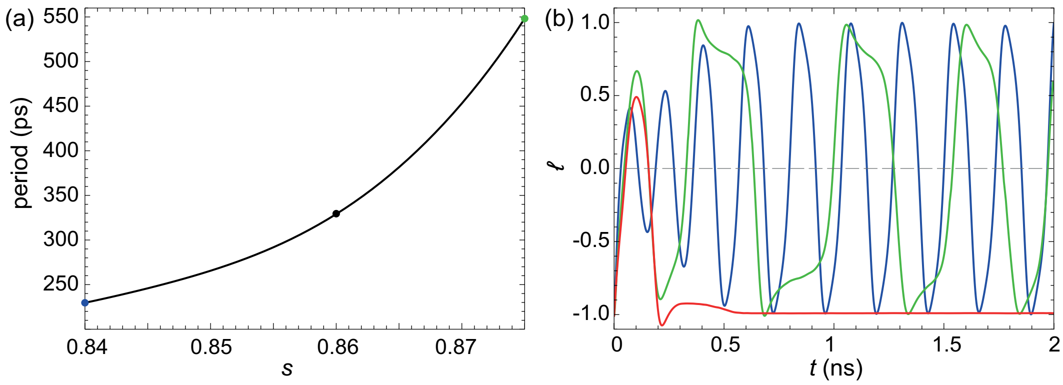

FIG. 3. (a) Simulated dependence of the period of oscillations of the vorticity of the single ring polariton condensate on the ellipticity of the pump spot s for the parameters indicated in the text. (b) Evolution of OAM of the condensates at different ellipticities: $s = 0.84$ (blue), $s = 0.875$ (green) and $s = 0.88$ (red).

interactions of polaritons in the system and the dissipative coupling of the interacting condensate modes, which leads to the creation of the limit cycle state [26–28]

The right panels in Fig. 2 show the intermediate states through which the condensate passes during oscillations. Among them are the states characterized by azimuthally homogeneous density distribution and azimuthal polariton currents in the clockwise or counterclockwise directions as well as the states with the dumbbell-like density distribution and a kink in the distribution of the phase.

The averaged polariton density distribution and the interferometry image reconstructed from the numerical data accompanied by the phase distribution are shown in Figs. 2(e–h) in comparison with the experimental data, cf. Figs 2(a–d). One can see that all peculiarities of the observations are very well qualitatively reproduced by the numerical simulations.

The period of the vorticity oscillations depends on many factors among which is the landscape of the effective trapping potential. In our simulations, the parameter of the system that contributed to the appearance of the oscillations is the ellipticity of the pump spot s. For the used parameters of the system and of the pump, in Fig. 3(a) we show the dependence of the period of oscillations on the ellipticity s. One can see that the period increases with s nearly quadratically. In Fig. 3(b), we show several examples of evolution of OAM $\ell(t)$ in time at different s. One should note that the range of the considered values of s from 0.84 to 0.875 was not chosen arbitrarily. The upper boundary of the range is limited by the computational resources, namely for $s > 0.875$ the period of oscillations, if they are still present, exceeds the considered time range. For s below the lower boundary, the oscillations do not occur. The reason for this may be, e. g., the loss of stability of the oscillating solution or its insufficient pumping to compensate for the losses [13].

4. Conclusion

In this manuscript, we have demonstrated both experimentally and theoretically oscillations of vorticity of the single ring exciton polariton condensate excited in the cylindrical micropillar by the nonresonant laser pump. For observing traces of the oscillations, we used interferometry measurements for detecting averaged in time interference of PL of the condensate with the reference spherical wave. In the numerical experiments, we have shown that ellipticity of the pump spot can act as an effective control tool for manipulating by the period of oscillations. The results of our study are promising for application in the developing new devices for classical and quantum computing with use of polariton flux bits and qubits [22, 29].

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