Formation of a collective bosonic polaron in the exciton polariton condensate

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Abstract. Creation of bosonic condensates of exciton polaritons in microcavity structures requires an external pumping. The routine pumping scheme implies the excitation of higher energy states, which then relax into the ground state feeding the condensate. The excess of an energy is dropped to the crystal lattice. Thus the heat released in this process is an essential constituent of any polariton experiment. The recent research proposes that such a heat can assist the localization of the polariton condensate. This proposal were experimentally confirmed in the regime of a pulsed excitation. Here we investigate the formation of the localized polariton state under continuous wave excitation and study the dynamical regimes leading to the formation of the localized state.

1. Introduction

Exciton polaritons formed in microcavity structures are mostly attractive for their ability to condense in a single quantum state [1,2]. The condensates of exciton polaritons possess a number of fascinating properties allowing them to serve as a multi-purpose tool for exploring fundamental quantum many-body and nonequilibrium phenomena. Because of the strong dissipation polariton condensates requires external pump to compensate the losses. The pump excites the high-energy states which then relax into the condensate being stimulated by the bosonic nature of polariton quasiparticles. The energy relaxation is assisted by the emission of acoustic phonons which transfer the energy excess to the crystal lattice. Thus heating of the sample is an inalienable companion of any experiment with the incoherent excitation of polariton condensate. Although the threshold of polariton lasing is relatively low in the state of the art samples and the intensity of the incoherent pumping is also small, the heating is still rather prominent [3].

The heat usually involves substantial troubles in any solid-state system operating upon quantum principles. Phonons serve as a source of dephasing and provides the additional energy relaxation channel [4]. However there were several documented manifestations of the wholesome back action of the heat released under optical excitation of semiconductor structures [5,6]. The most prominent one [5] demonstrates the effect of the self-induced localization of a polariton wave packet excited with a short coherent optical pulse. Instead of the ballistic spreading of the polariton cloud which is anticipated in
the presence of the polariton repulsion, a sudden collapse of a polariton superfluid into a tight spot was observed. Among the other possible explanations of this surprising behavior, the hypothesis of the formation of a bosonic polaron state was advanced. It implies that the presence of polaritons leads to the local increase of the temperature, which involves renormalization of the semiconductor band gap resulting in lowering of the exciton energy and thus favoring the polariton localization. This mechanism allows to localize the polariton wave packet and to stabilize it on a picosecond time scale. Here we propose the mechanism, which admits the formation of the steady state of the polariton condensate in the presence of a continuous wave optical pump. The following section describes the principles of the localization in details.

2. The polaron mechanism of localization in exciton polariton condensates

The main principles of the proposed mechanism of the heat-assisted localization of polariton condensates are schematically illustrated in figure 1. It implies that the exciton polaritons are typically created by the tightly focused laser beam. Since the pump is spatially localized, it generates a finite size cloud of the condensate. For the sake of simplicity we assume the ideal microcavity system, which is devoid of disorder or intentionally prepared potential landscape. Thus, the condensate density maximum inevitably locates at the position of the maximal gain, see figure 1b.

![Figure 1](image)

Figure 1. The sketch of the heat-assisted localization mechanism of the polariton condensate. (a) The shape of the external laser pump which creates the condensate. (b) The shape of the condensate formed beneath the pump shown on the panel (a). (c) The temperature profile arising due to the phonon-assisted stimulated transitions of excitons from the incoherent excited states to the single ground state. (d) The potential trap, which shape follows the temperature profile shown on the panel (c).

The replenishment of the condensate population is provided by stimulated transitions from the uncondensed phase – the reservoir of incoherent excitons. The rate of these transitions, which is proportional to the product of the condensate and the reservoir densities due to the stimulated nature of the scattering events, is maximal at the center of the pump spot. Since the relaxation of hot excitons
from the incoherent reservoir to the condensate ground state is assisted by the emission of acoustic phonons, the temperature of the structure locally increases at the position of the condensate maxima, see figure 1c. As is well known, heating of the semiconductor crystal leads to the decrease of the band gap, which involves the lowering of the exciton energy and therefore the polariton energy as well. The local trap providing the localization potentials for polaritons appears, see figure 1d.

The described localization mechanism resembles the formation of the polaron state. Actually, by the modification of the crystal structure the condensate couples to the lattice. Such a coupling modifies the structure of the condensate leading to its localization. The main distinction from a single electron problem well known in the solid-state physics [7] is that the condensate contains up to thousands identical particles and all of them contributes the localization. That is why we address this state as collective bosonic polaron state. In the next section we study how the described mechanism affects the properties of the polariton condensate.

3. The formation of the collective bosonic polaron state

3.1. The system under consideration

We consider the condensate of exciton polaritons excited by the non-resonant continuous wave pump. We limit ourselves with the one-dimensional system which is realized, for instance, in the case of trapping of a condensate in a microwire [8]. We model this system the mean field approach by the complex Ginzburg-Landau equation for the condensate the order parameter (the wave function) $\Psi$ coupled to the rate equation for the incoherent exciton density $n$:

$$\frac{i\hbar}{\partial t} \frac{\partial \Psi}{\partial t} = \left( -\frac{\hbar^2}{2m_p} \Delta + \alpha_c |\Psi|^2 + \alpha_r n_r - V_T + \frac{i\hbar}{2} \left( R n_r - \Gamma_r \right) \right) \Psi, \quad (1a)$$

$$\frac{\partial n}{\partial t} = -\left( \Gamma_r + R |\Psi|^2 \right) n_r + P. \quad (1b)$$

Here $\Delta = \partial^2 / \partial x^2$ is the Laplace operator, $m_p$ is the polariton effective mass, $\alpha_c$ is a strength of the polariton-polariton repulsion, $\alpha_r$ describes the repulsion between condensate polaritons and the excitons from the reservoir, $\Gamma_c$ is the condensate decay rates while $\Gamma_r$ denotes the reservoir decay, $P$ is the pump rate, $R$ defines the rate of transitions from the reservoir to the condensate.

The term $V_T$ accounts for the potential trap arising due to the local variation of the lattice temperature. We assume that the shape of this trap is proportional to the rate of stimulated scattering from the reservoir, which is defined as $R n |\Psi|^2$ from the equation (1a). Note that here we ignore the dynamics of the temperature taking into account that the diffusive heat transport is slow on the picosecond time scale typical for the condensate dynamics. In the steady state regime the relaxation of the temperature should be balanced by the heating source. Thus we assume that the local variation of the temperature $\Delta T$ is proportional to the phonon emission rate, $\Delta T = \beta R n |\Psi|^2$ with a proportionality coefficient $\beta$.

Considering the temperature dependence of the energy band gap of GaAs, which is the most popular material of the microcavity structures, we approximate the heat-induced potential as

$$V_T \approx -2\alpha_o T_o \Delta T - \alpha_o \Delta T^2, \quad (2)$$

where $\alpha_o = 2.65 \cdot 10^{-3}$ meV K$^{-2}$. This assumption is valid for the case of an exciton-like lower polariton branch and in the low temperature limit when $T_o$ and $\Delta T$ do not exceed few tens of Kelvin.

3.2. The sink-type steady state of the condensate

Next, we model the condensate formation in the presence of the non-resonant inhomogeneous pump. For simulations we take the initial condensate distribution as a small amplitude white noise. The initial occupation of the reservoir corresponds to the trivial ($\Psi = 0$) solution of equations (1), i.e. $n = P / \gamma_R$. The pump shape is taken in the super-Gaussian form.
where $w$ is the pump width and $m$ is a smoothness parameter (in particular for the calculations we take $m = 30$). We expect that for the wide pumping ($w$ about hundred micrometers) the solution should resemble the condensate obtained in the spatially homogeneous system, at least far away from the pump edges.

Figure 2. The condensate formed spontaneously from the initial white noise under the super-Gaussian pump (3) in the absence of thermally induced energy red shift, $\beta = 0$ (left column) and in the presence of it with $\beta = 0.2$ K ps $\mu$m$^2$ (right column). Panels (a) and (b) show the time dynamics of the condensate density $|\Psi|^2$ while (c) and (d) demonstrates the steady-state polariton density and exciton reservoir $n_t$ distributions established after 1000 ps of evolution. The dashed curves in (c) and (d) indicate the pump shape. Panels (e) and (f) demonstrates the profiles of the polariton current density $j$ (red curves, right axes) and the divergence of the current (blue curves, left axes). The parameters are $\Gamma_p = 0.33$ ps$^{-1}$, $\Gamma_r = 1.5\Gamma_p$, $R = 0.03$ ps$^{-1}$ $\mu$m$^2$, $\alpha_c = 0.006$ meV $\mu$m$^2$, $\alpha_i = 2\alpha_c$, $P_0 = 3P_{pb}$, where $P_{pb} = \Gamma_c \Gamma_i / R$. The pump width is $w = 180 \mu$m.
The results of numerical simulations are presented in the figure 2. When heating is absent (left column), i.e. $\beta=0$, the condensate density follows the shape of the pump, see panel (c). Some differences appear in the vicinity of the pump edges only where the condensate flows out of the pump spot because of the polariton repulsion. At that, the modulus of the polariton flux, which is determined as $j = \frac{\hbar}{m} \text{Im} \left( \Psi^*, \frac{\partial \Psi}{\partial x} \right)$, gradually increases as the distance from the center grows (panel (e)). If the pump is wide, the condensate stays almost at rest ($j \approx 0$) in the central region resembling the homogeneous ground state.

Accounting for the thermally induced trapping potential $V_T$ allows for the new solution to appear (right column in figure 2). At the initial stage the quasi-homogeneous solution with the weak polariton current outflowing from the center forms. But this state is then destroyed spontaneously and the two contrapropagating currents arise at the pump edges and flow towards the centre, see panel (b). These currents interfere forming a stable bright soliton-like pattern with oscillating tails located on the homogeneous background, figure 2d.

To get inside into the origin of the structure of this solution we make the Madelung transformation for the equation (2a), $\Psi = \psi(r) \exp[i\phi(r)]$, and obtain

$$\frac{\partial j}{\partial x} = (Rn_c - \Gamma_s)\psi^2,$$

$$-\frac{\hbar^2}{2m_\psi} \Delta \psi + (\alpha_\psi \psi^2 + \alpha_\psi n_c - V_i - \mu)\psi + j^2 \psi^4 = 0,$$

The divergence of the current, which is a local measure of the gain according to equation (4a), dramatically falls down to negative values at the position of the condensate density maximum, see figure 1f. Thus, this peak connects two domains of the incoming currents and serves as a sink.

Formation of the observed solution should be attributed to the self-focusing effect originating from the heating of the lattice. The effective attraction provided by the heat results in the shrinkage of the condensate profile which becomes a little tighter than the pumping spot. Thus the reservoir density $n_c = P/\left(\Gamma_s + R|\Psi|^2\right)$ acquires pronounced peaks near the pump boundaries – cf. red curves on the panels (c) and (d) of figure 2. According to equation (4a) these peaks correspond to the local gain and serve as sources, $\partial j/\partial x > 0$, see figure 2f. The sources produce polariton fluxes which flow on the homogeneous background towards each other and give rise to the density peak.

On the contrary, in the heating-free case two sinks, i.e. the regions where $\partial j/\partial x < 0$, locate near the pump boundaries. These sinks drag off the polariton flows from the center of the pump. Thus the polariton flux gradually increases from the center of the pump to the periphery and falls steeply at the position of the sinks – see figure 2e.

3.3. The polaron formation dynamics

The complex Ginzburg-Landau equation admits solution in the form of sink provided that the background is stable [9]. Unfortunately, the driven-dissipative model (1) predicts that the polariton condensate is prone to lose its dynamical stability under definite parameters [10]. The lost of stability of the background is the main cause preventing formation of the sink-type solution.

Different manifestations of the unstable dynamics in the system with the super-gaussian pump are shown in figure 3. The pump width $w$ and the smoothness parameter $m$ are the same as in figure 2. Under the weak pump amplitude $P_0 = 1.5P^\text{th}$ close to the threshold the turbulent dynamical state is formed, see figure 3a. The modulational instability of this type is attributed to the presence of the exciton reservoir [10]. It typically develops at the relatively low pump densities and disappear as the pump increases. Note that at the initial stage the state close to the homogeneous ground state ($k = 0$) is formed but than it destabilizes and the states with low momenta are excited.
Figure 3. Formation of the condensate under different values of pumping amplitude: (a) $P_0 = 1.5P_{th}$; (b) $P_0 = 2.1P_{th}$; (c) $P_0 = 5P_{th}$. For all panels $\beta = 0.2$ K ps $\mu m^2$. Other parameters are the same as in figure 2.

Formation of the stable sink-type steady-state at the intermediate value of the pump power $P_0 = 3P_{th}$ is demonstrated in figure 3b. Note that under this particular conditions the ground state formed initially is still dynamically unstable. However the state with nonzero wave vector can be stable under the same parameters. As a result even if the ground state is destroyed by the instability, the stable sink can still be formed provided that the incoming currents are stable. In this case the laminar fluxes appear near the pump boundaries and spread towards the center switching the system dynamics from the turbulent to the laminar regime.

With the further increase of the pump power the instability restores. For instance, the figure 3c shows the regime of instability involving excitation of the high-momenta states realizing under the strong pump $P_0 = 5P_{th}$. Thus the stable polaron solution can be observed under intermediate values of the pump power.

4. Conclusion
The effect of self-localization of exciton-polariton condensate due to the heating of the crystal lattice caused by the relaxation of reservoir excitons into the single quantum state is analysed. If the heating efficiency exceeds the critical level, the effective nonlinear trapping potential is formed. Because of its driving-dissipative nature the polariton condensates supports the persistent currents owing towards the centre of the trap where the condensate acquires the soliton-like density peak. The various dynamical regimes of the condensate in the presence of heat-induced attractive interaction is described.

5. Acknowledgment
This work was supported by the RFBR Grants No. 16-32-60102, 17-52-10006 and partially by the President of Russian Federation for state support of young Russian scientists, Grant MK-2988.2017.2. The support from the Ministry of Education and Science of the Russian Federation, project no. 16.1123.2017/4.6, is also acknowledged.

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