Dynamics of resonantly excited exciton-polariton fluids in GaAs microcavities in the absence of an exciton reservoir

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Abstract. We address dynamics of a low polariton (LP) system excited resonantly in a wide range of wave vectors by converging 2.5-ps-long Gaussian pulses. The spatial coherence in an LP system excited by incoherent light is found to form very slowly in the absence of an exciton reservoir, the coherence length at the delay time of 250 ps and T=2 K being less than 2.5 µm. The LP fluid excited by coherent linearly polarized pulses does not lose the inherited high spatial coherence and polarization and demonstrates dynamic compression to a condensate state at the LP branch bottom. In the LP fluid excited by elliptically polarized pulses the components with opposite circular polarizations are compressed almost independently of each other.

1. Introduction
Exciton polaritons in semiconductor microcavities (MCs) are half-light-half-matter boson quasiparticles forming due to coupling of the optical and matter modes in the strong light-matter coupling regime [1]. Owing to the small effective mass, about 10⁴ times smaller than the electron mass, polaritons demonstrate quantum coherent properties at relatively low densities. [2] Until recently, most studies of lower polariton (LP) systems were carried under nonresonant excitation of an exciton reservoir in quantum wells in the active MC layer. Condensation of LPs in GaAs and CdTe-based planar MCs was observed up to several tens of Kelvin [3-5] and up to room temperatures in GaN and ZnO-based MCs [6, 7]. An array of spectacular phenomena characteristic of Bose-Einstein condensates was discovered in these systems such as quantized vortices [8], quenching of Zeeman splitting [9], the Josephson effect [10], and others. This enables us to treat them as dynamic Bose-Einstein condensates exhibiting multiple specific features associated not only with finite lifetime, but also with its interaction with the exciton reservoir that ensures a flow of particles into the decaying condensate. In particular, the interaction of LPs with the exciton reservoir leads to a strong decrease in the coherence lengths in non-resonantly excited condensates. Therefore, it is most interesting to study the dynamics of a LP system resonantly excited in a wide range of wave vectors without excitation of an exciton reservoir.

Recent studies of freely evolving resonantly excited LP condensates at the LP branch bottom showed that they retain long-range spatial coherence during tens of picoseconds [11, 12]. Moreover, the LP coherence is not disturbed in a freely decaying condensate excited in laterally strained MCs at
the upper sublevel even when it switches to the polarization beat mode (or “internal Josephson oscillations”) because of its polarization instability. [13] Thus, it can be concluded that any incoherent LP scattering at low temperature is very weak and, therefore, dynamics of resonantly excited polariton systems is completely determined by the interparticle interaction.

In this work, we investigated dynamics of LP systems excited resonantly in a spot with a diameter of ~100 μm in a wide range of wave vectors using short coherent and incoherent converging Gaussian laser beam pulses. The initial spatial (r) and momentum (k) distributions of LPs were controlled by those in the exciting pulse since the tunneling of photons through the Bragg mirrors with transformation into LPs is attended with spin and in-plane wave vector conservation. [14, 15] The initial states of the LP-systems excited by incoherent and coherent light are qualitatively different: in the first case they are spatially incoherent, and in the other case they inherit the coherence of the laser beam. We have found that the spatial coherence in the LP system excited by incoherent light is formed very slowly whereas the LP fluid excited resonantly by coherent linearly polarized convergent 2.5-ps-long Gaussian pulses retains inherited high spatial coherence and polarization and demonstrates dynamic compression to a condensate state at the LP branch bottom. In the case of excitation by elliptically polarized pulses the components with opposite circular polarizations are compressed in the fluid almost independently of each other.

The paper is structured as follows. The sample and the experimental techniques are described in Sec. 2. Section 3.1 presents the results of the studies of time evolution of spatial and momentum distributions of LPs and long-range spatial coherence in a freely decaying linearly polarized LP fluid, the dynamics of spatial distribution in the fluid excited by elliptically polarized light is presented in Sec. 3.1. Finally, the conclusion is given in Sec. 4.

2. Experimental details.

The structure under investigation was a 2λ GaAs/AlAs MC grown by molecular beam epitaxy on a GaAs substrate. It contained four sets of four 10-nm-thick In_{0.05}Ga_{0.95}As quantum wells separated by 10-nm-thick GaAs barriers. 25 and 29 AlAs and GaAs pairs in the top and bottom Bragg mirrors ensured the high quality factor of the MC resulting in the LP decay rate γ≈30 μeV. The Rabi splitting was 7.5 meV.

LPs were excited resonantly by a mode-locked Ti:sapphire laser generating a periodic (80 MHz) train of 2.5-ps-long pulses with a large aperture and spectral width. The lateral size of the Gaussian beam focused at the cavity plane is very small, Δr/s=5.5/Δk, i.e. ~1.6 μm at Δk=3.4 μm⁻¹. Thereby we displaced the MC with respect to the focal plane, which enabled to study the joint evolution of a very large number of wave harmonics and the transient self-organization effects in the decaying large-size LP system. The diameter of the excited spot, d≈40 μm, was achieved by putting the sample at a distance of z=110 μm in front of the focus.

Linearly polarized laser pulses generated a linearly polarized LP system at E_{LP}(k=0)+0.2 meV, or 3 meV below the exciton energy, E_X, which was sufficient to avoid excitation of the exciton reservoir. The experiments were performed at T=2 K. The LP emission was registered in transmission geometry from the back side of the sample to avoid any contribution from the scattered laser beam. The LP emission was detected using a streak camera with 2-ps time resolution.

The first-order long-range spatial correlation function g^(1) was determined from the measurements of the interference of light emitted from different sample points. [12]

3. Experimental results and discussion.

3.1 The dynamics of linearly polarized LP fluid.

Figure 1 shows measured time dependencies of spatial and angle distribution of LP emission from the MC at resonance excitation with linearly polarized 2.5-ps-long convergent Gaussian laser beam pulses at E_{LP}(k=0)+0.2 meV, T=2K, and P=0.1 mJ/pulse. The excited LP fluid inherits laser beam polarization and retains it during decay. Figure 1 shows that the spatial dynamics of the LP fluid resembles that of
the exciting convergent Gaussian beam: the fluid diameter first decreases and then increases. At the same time, the minimum full width at half maximum (FWHM) of the LP density, $\Delta x$, ($\approx 8 \mu m$) is much larger than that in the exciting Gaussian beam ($\approx 1.6 \mu m$).

Another feature absent in the Gaussian beam is the appearance, at large $t$, of a pronounced dip at $x=0$. At $T=2$ K the LPs with large $k$ can relax to the band bottom with phonon emission. This LP scattering is incoherent. To estimate its contribution to the fluid dynamics we studied time dependencies of interferograms of direct and mirror images of spatial distribution of LP emission. Figure 3 displays interferograms that were recorded at $P=0.1$ nJ/pulse for several delay times with a small fringe period of 2.5 $\mu m$ in order to have several periods in the waist region. Figure 3 shows that the visibility of the interference fringes in the interferograms remains nearly unchanged in the decaying LP system during a long time. Therefore, we conclude that the decaying LP system retains the coherence inherited from the exciting pulse, i.e. the incoherent scattering of LPs is negligible and the dynamics of the LP fluid is controlled by the interparticle interaction and LP decay as well as in the LP condensates excited directly at the LP band bottom.

The measurements of the spatial dynamics of the LP system resonantly excited by an incoherent convergent Gaussian beam showed that in this case the excited LP system does not shrink. Figure 4
displaying interferograms recorded at T=2 K and P=0.9 nJ/pulse for several delay times shows that the visibility of the interference fringes in the interferograms increases very slowly in the decaying LP, the coherent length being less than 2.5 μm even at t=260 ps. Hence, we conclude that the LP condensation time in the absence of the exciton reservoir is very long.

The reason for the observed monotonic compression of LP fluid excited by a converging coherent Gaussian beam in the MC located in front of its focus is the direction of the LP k vectors to the spot center inherited from the exciting light. The flow of the peripheral LPs to the center counteracts the expansion inherent in the LP system with a repulsive interaction. On the other hand, the repulsive interaction of LPs in the fluid inhibits the motion of peripheral LPs with large k toward the center and leads to a narrowing of the LP distribution in the momentum space. This is clearly seen in the measured time dependence of in-plane wave vector distribution of LPs, shown in Fig.1.

Stabilization of the LP fluid diameter dp at t =11-14 ps suggests a depletion of the flow of peripheral LPs to the center. Figure 1 shows that at this moment the FWHMs of the LP distributions are minimal in both the coordinate and momentum spaces, 6.8 μm and 0.8 μm⁻¹, respectively. Their product, ΔkΔx ≈ 5.5, exactly matches the product for a coherent emitter. Measurements of I(x) and I(k) at different P showed that an increase in Δx with increasing P is accompanied by a decrease in Δk and the product ΔkΔx is constant. Thus, dynamic compression of LP fluid leads to formation of self-shaped condensates of limited size at the LP branch bottom.

Further dynamics of self-shaped LP condensate is controlled by interparticle interactions. One could expect that the repulsive interaction would lead to its gradual spatial expansion with narrowing of its distribution in the k space. However, Fig. 1 shows a qualitatively different dynamics: the condensate breaks up with appearance of dips in the centers of LP distributions in both k and r spaces. This behavior is a direct consequence of the energy conservation in the free LP fluid. Indeed, the expansion of the fluid results in a decrease of its density, n~1/Δx², and interaction energy, Eint~α²Δx² ~I/Δx² where α is the LP interaction constant. The decrease in Eint is compensated by the corresponding increase in the LP kinetic energy, which leads to appearance of high-energy LPs flying apart with high velocities and, finally, to a two-lobe pattern in real and momentum spaces. Since the excited coherent LP fluid retains the inherited linear polarization, we used the scalar Gross-Pitaevskii equation to describe its dynamics. The calculated time dependencies of I(x) and I(k) are shown in Fig. 2. They were calculated for parameters hωp, γ, z , and ω0 used in the experiment. The only adjustable parameter P. The comparison of Figs.1 and 2 shows that the calculated time dependencies reproduce very well the dynamic compression of the LP fluid and formation of the self-shaped coherent condensate state at the LP branch bottom with ΔkΔx ~ 5.5, which corresponds to emission of a fully coherent state with the spatially uniform phase. They also reproduce further breaking up of the condensate with formation of a two-lobe pattern in both k and r spaces.

3.2 The dynamics of elliptically polarized LP fluid.

Figure 5 shows the spatial distributions of two, σ′ and σ, circularly polarized components of the emission of the LP fluid excited with 2.5-ps-long elliptically polarized convergent laser pulses at various delay times after the exciting pulse. The excitation is at hωp = ELP+0.5 meV, the degree of circular polarization of the exciting beam is ρp=(Ip−Ip)/(Ip+Ip) =0.85, P = 0.1 nJ/pulse, ωp=1.3 μm z = −110 μm. Figure 5 shows that the LP fluid inherits laser polarization but, unlike a fluid excited by linearly polarized light, it does not retain the inherited spatially uniform polarization. In particular, the minor σ′ polarized component shrinks much more than the prevailing σ one, its FWHM in the waist range, Δx ~ 5.5±0.5 μm is almost twice less than Δx ≈ 15±0.5 μm. As a result, ρ decreases strongly in the center of the fluid, from −0.85 at t=10 ps to −0.25 at t=12 ps. The decrease in ρ at x=0 is followed by its increase above 0.85 at |x|>11 μm.

To find out the cause of the violation of the spatial uniformity of the LP fluid polarization excited resonantly by an elliptically polarized convergent coherent Gaussian beam, we calculated the
The calculated spatial distributions of $\sigma^-$ and $\sigma^+$-polarized LP emission components are shown in Fig. 6. In the calculations we used the ratio of the coupling constants of LPs with opposite ($\alpha_2$) and identical ($\alpha_1$) spin projections in GaAs MCs, $\alpha_2/\alpha_1 = -0.05$. [16, 17] The other parameters, namely, the LP lifetime, the duration, aperture, and degree of polarization of the exciting beam, and the size of the exciting spot on the MC, were the same as those in the experiment. The only adjustable parameter was the excitation density that was changed to reproduce the value $\Delta x^+ \approx 15 \mu m$ measured in the experiment.

The comparison of the calculated and measured dynamics of the spatial LP distribution in the fluid shows that simulation reproduces the main features of the dynamics of its $\sigma^-$ and $\sigma^+$ components. In particular, simulation predicts the value $\rho_2(x=0)=0.2$ and the ratio $\Delta x^+ / \Delta x^- = 3.2$, which are very close to the experimental values of 0.25 and 2.7, respectively. A much stronger compression of the minor $\sigma^-$ component shows that the two circularly polarized components in the fluid are nearly independent. The simulations have shown that the very weak coupling of the components with opposite circular polarizations is well explained by the smallness of the ratio of the coupling constants of LPs with opposite and identical spin projections.

4. Conclusion.
The dynamics of the LP system with a lateral size of several tens of microns excited resonantly in a wide range of wave vectors with 2.5-ps-long convergent Gaussian beam pulses when the active region of the cavity is in front of the waist has been investigated in high-$Q$ GaAs-based MCs. It has been found that in the absence of an exciton reservoir, the LP fluid excited by coherent laser pulses retains inherited high spatial coherence for tens of picoseconds, which suggests that the incoherent polariton-phonon scattering is negligible in spite of a wide LP energy distribution. As a result, the time evolution of the spatial and momentum distributions of the fluid LPs is mainly controlled by the interparticle interactions and well described by the Gross-Pitaevskii equation. In particular, we have shown that an interplay of ballistic self-focusing of LPs involved by LP excitation with convergent Gaussian beam pulses and defocusing caused by the repulsive interaction between polaritons results in
formation of a dynamically compressed coherent LP condensate state at the LP band bottom with spatially uniform phase. This state persists for several picoseconds until the LP-LP repulsion causes its expansion in both spatial and momentum spaces.

Dynamic compression of an elliptically polarized LP system is found to occur without preserving its initial polarization: the dynamics of the weakly interacting components with $\sigma^+$- and $\sigma^-$-polarizations is practically independent of the interaction between them.

It was also established that in the absence of an exciton reservoir the spatial coherence in the LP system resonantly excited by incoherent light forms very slowly, the coherence length at $T=2$ K being less than 2.5 $\mu$m at the delay time of 250 ps.

**Acknowledgement** We are grateful to M. M. Glazov for fruitful discussions and P. Savvidis for the high-Q MC. The work was supported by the Russian Science Foundation (Russian Federation) (Grant No. 14-12-01372).

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