First and second order coherence of exciton-polariton condensates

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Abstract: We investigate the first and second order coherence of exciton-polariton condensates both in coordinate and momentum space. The measured correlations provide insights into the phase and intensity fluctuations induced by polariton interactions.

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Bose-Einstein condensation (BEC) is commonly characterized by the condensation in momentum space as well as the existence of a long-range order. The nature of coherence in such a macroscopic quantum system is sensitive to the interaction among the constituent bosons. Therefore, characterizing various aspects of coherence of the condensates can provide insights into the role of many-body interaction in BECs. We show the first and second order coherence properties of exciton-polariton condensates and discuss the phase and intensity fluctuations extracted from these measured correlations.

Exciton-polaritons in planar semiconductor microcavities are composite bosons in the low density limit and have been a candidate for BEC due to their light effective mass and insensitivity to local disorders. In the strong coupling regime, the reversible energy exchange between the microcavity photons and QW excitons leads to the anti-crossing of eigenstates, known as the upper and lower exciton-polaritons (UPs and LPs). Unlike exciton-polaritons in bulk semiconductors, cavity exciton-polaritons involve no transport and are fully characterized by the in-plane wavenumber, enabling a direct measurement of the exciton-polariton dispersion and momentum distribution of particles through angularly resolved spectroscopy (Fig. 1a). This peculiar characteristic of exciton-polaritons allows us to determine the first and second order coherence both in coordinate and momentum space, using Young's double-slit interference experiment and Hanbury Brown-Twiss (HBT) type measurements, respectively.

The exciton-polaritons have been demonstrated to condense in momentum space and exhibit spontaneous buildup of macroscopic spatial and temporal coherence [1-4]. Under an elliptical excitation spot with an axial-to-radial aspect ratio of 2:1, the exciton-polariton momentum distribution evolves from isotropic into an anisotropic distribution with a reversed axial-to-radial aspect ratio (Fig. 1b and 1c). Furthermore, the product of the spreads of the LP distribution in momentum and coordinate spaces is only ~2 to 4 times the Heisenberg uncertainty limit. The anisotropic and narrow momentum distribution above a threshold pumping rate is supportive of a long-range spatial coherence across the condensate. Using Young's double-slit interference experiment, we measured a spatial coherence length of the condensate up to ~20 μm, limited by the pumping spot size as shown in Fig. 1d (see also Supplementary Information of [4]). We further perform interference measurements in momentum space to characterize the correlations of LPs as a function of in-plane wavenumber (not shown). These first order correlations reflect the phase fluctuation in coordinate and momentum space.

The second order coherence function [$g^2(\tau=0)$, where τ is the time delay] of a polariton condensate was first reported in [1]. Using the setup shown in Fig. 2a, we improve the overall time resolution of the HBT setup to ~60 ps (in contrast to ~500ps) and investigate $g^2(0)$ with more accurate control of the filtering in both coordinate and momentum space. In Fig. 2b, we show the measured $g^2(0)$ for LP emission centered near in-plane wavenumber k=0 (full collection angle $\delta\theta$~0.5°) as a function of the pumping rate for emissions collected from (I) the whole pumping spot and (II) a 6 μm diameter area (by placing a pinhole in the first conjugate near-field image plane), both under a pumping spot of ~60x120 μm^2. Below the condensate threshold, the measured $g^2(0)$ is close to 1 due to finite time response of the photon correlation system (~60ps). In case (I), $g^2(0)$ rises sharply to more than 1.8 above the threshold and decrease gradually to ~1.5. In case (II), $g^2(0)$ increases monotonically to ~1.6. We further determine the decay of $g^2(0)$ with increasing Δk in momentum space (Fig. 2c & 2d). The distinct different of $g^2(0)$ for these two cases in momentum space suggest the intensity fluctuations of the condensates are not necessarily identical to the phase fluctuations. When the collection angle is increase to accommodate the whole condensate ($\delta\theta$~8°), $g^2(0)$ recovered to ~1. These phase and intensity fluctuations are likely caused by the interaction among polaritons.

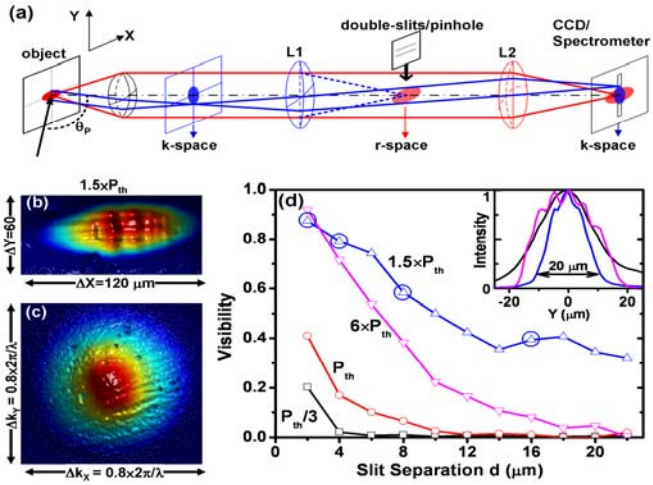

Figure 1: **(a)** Schematic of the micro-photoluminescence setup composed of an objective and two identical relay lenses (L1: removable and L2) for imaging and spectroscopy in coordinate and momentum space. The Fourier (back focal) plane of the sample located in the object plane, with coordinate X and Y, is imaged onto to a CCD camera directly or through an imaging spectrometer. This arrangement allows determination of the LP distribution in momentum space (far-field) as well as the LP dispersion relation. For imaging and spectroscopy in coordinate space (near-field), the repositionable lens L1 is removed. **(b) & (c)** False-color near-field and far-field images of an exciton-polariton condensate. The pumping rate is 1.5 P_{th}, where $P_{th} \approx 30$mW is the condensate threshold pumping power. An anisotropic distribution with a reversed axial-to-radial aspect ratio in coordinate space develops above threshold. **(d)** Young's interference experiment is conducted in a symmetrical arrangement with slits positioned at an equal distance from the optical axis as shown in (a). The visibility of the interference patterns as a function of the slit separation for various pumping rates. At just above the threshold, the visibility remains finite until the slits separation reaches the dimension of the condensate (solid blue line in the inset). The coherence length decreases with increasing pumping rate despite of the increase in the dimension of the condensate (magenta triangles and lines).

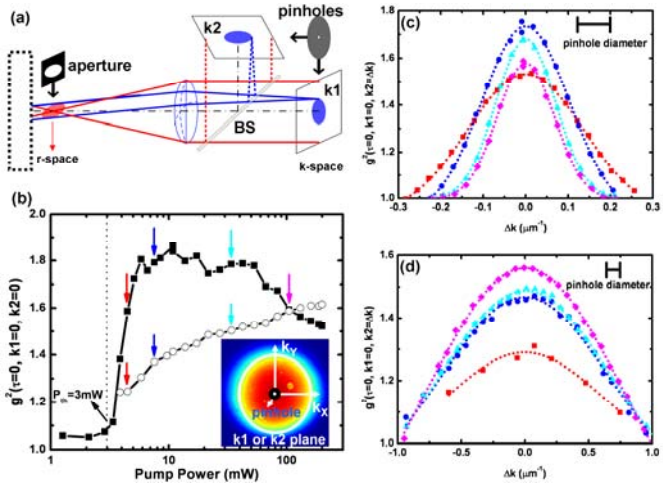

Figure 2: **(a)** Schematic of the HBT measurement setup. The part similar to that shown in Fig. 1(a) is symbolized by the dashed box. LP emission at two points near k1 and k2 can be selected by pinholes positioned in momentum space after the beam-splitter (BS). The pinholes selectively filter LP emission within $\delta\theta=0.5^\circ$ (corresponding to $\delta k=0.07$ μm^{-1}) as shown in the inset in (b). The filtered emission is then redirected to the microchannel plate photomultiplier and photon correlation system (overall time resolution ~40ps). **(b)** $g^2(\tau=0)$ measured for two points near the center of the far-field emission (in-plane wavenumber k1=k2=0) as a function of pump power with a near-field filter with an aperture of 6 μm diameter (open circles) and without the aperture (solid squares). **(c)** $g^2(\tau=0)$ measured for two points at k1=0 and k2=0+Δk. $g^2(\tau=0)$ drops quickly to 1 for $|\Delta k|>0.2\mu m^{-1}$ when the LP emissions from the whole pumping spot pass the aperture. The corresponding pump powers are indicated by arrows in (b). **(d)** $g^2(\tau=0)$ for k1=0 and k2=0+Δk with near-field filtering by an aperture of 6 μm diameter. Note the difference of axis scales between (c) and (d). Experiments are conducted using a ~2ps Ti:Sapphire laser pumping at an incident angle of ~60° as described in [4].

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