Observation of BKT Transition in BEC of Exciton-Polaritons in a Semiconductor Microcavity

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Abstract: The first-order spatial correlation function of a Bose-Einstein condensate of exciton-polaritons in a semiconductor microcavity is measured. It behaves as the Berezinskii-Kosterlitz-Thouless theory predicts and decays with a power-law.
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1. Introduction

Exciton-polaritons are quasi-particles which can be described as a superposition of cavity photons with quantum well excitons [1]. At low temperatures, polariton lasing, which can be explained by Bose-Einstein-condensation (BEC), has been observed [2,3]. Typical characteristics of the light emitted by a polariton condensate are the built-up of spontaneous coherence, line-width narrowing, and a non-linear increase of the emitted intensity as a function of pump power [4].

A Michelson interferometer can be used to measure the first-order spatial coherence function $g^{(1)}(x, -x)$ since it is proportional to the fringe visibility [5]. The theory [6,7] predicts that the correlation function of a BEC follows a power-law of the form $g^{(1)}(x, -x) = (x / \lambda_p)^{-a_p}$ with $a_p \leq 1/4$, which can be considered as a signature of the Berezinskii-Kosterlitz-Thouless (BKT) transition.

2. Sample and experimental setup

The used semiconductor sample consists out of a $\lambda/2$ AlAs cavity which is surrounded by AlAs/AlGaAs Bragg reflectors on both sides. Four GaAs quantum wells have been grown into the central antinode of the standing photon wave in the cavity. The Rabi-splitting between the upper and lower polariton at zero detuning is $2g \simeq 9.6$ meV and the quality factor of the cavity (as measured in the far red detuned regime) is $Q_{\text{cavity}} \simeq 3000$. A helium flow cryostat is used to keep the temperature at 5 K.

The sample is non-resonantly pumped with a perpendicular incident continuous-wave laser beam. We use a Gaussian spatial pump profile (which can only efficiently create a BEC in the lowest mode with which it maximizes the overlap), since other spatial profiles excite several quantized modes [8] which might create undesired artifacts and the measured overall visibility might decay faster than the actual coherence for each individual mode, since any interference between modes at different energies averages out during the integration time of the camera.

The light emitted by decaying exciton-polaritons reaches a Michelson interferometer with variable path-length difference [7] as depicted in figure 1 a. The light which travels through the first arm of the interferometer is reflected by a mirror and directed towards the camera, whereas the light in the other arm is reflected by a reflection prism which flips the image along the y-axis before directing it to the camera. Therefore at the camera the light which is emitted at point (x, y) of the sample interferes with the light from point $(-x, y)$. The wave-fronts from the two arms reach the camera at a slightly different angle which gives rise to interference-fringes. Scattered light from the pump laser is filtered out before reaching the camera.

A piezo is used for changing the path-length difference by slightly moving the prism and the interferogram is recorded for many different path-length differences. The measured intensity of each of the pixels (corresponding to position $(\pm x, y)$ on the sample) as a function of the path-length change L follows a sine law of the form $I(L) = B + A \times \sin(2\pi (L - L_0) / \lambda_{\text{sin fit}})$ as shown in figure 1 b. The first order correlation function is identical to the visibility and can therefore be calculated as $g^{(1)}(x, -x) = A / B$ from the fit parameters A and B. The same sine fit also gives the phase $\varphi = 2\pi L_0 / \lambda_{\text{sin fit}}$ which can be used to confirm that the fit was able to extract reliable data (figure 1 d).[7]

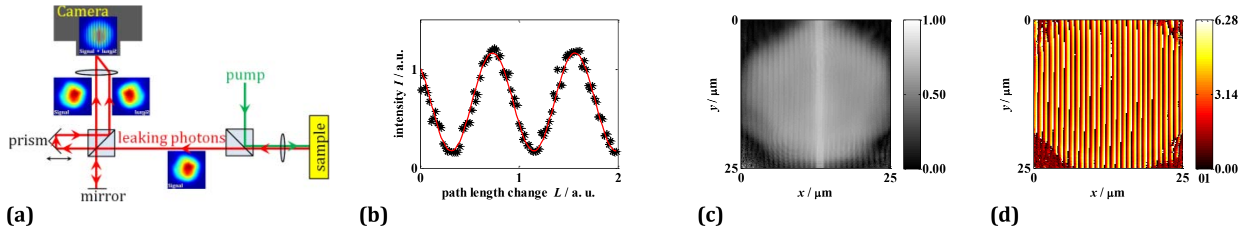

Figure 1: Experimental Michelson interference setup to measure the fringe visibility (a). The intensity of each pixel behaves like a sine function if plotted as a function of the path length change L or prism position (b). By performing the sine fit for each pixel (b), we get the two-dimensional plots for visibility (c) and phase (d). The region where the phase plot (d) shows fringes is also the region where the visibility data (c) is reliable, whereas data at other regions is essentially just noise.

3. Theoretical predictions

The theory predicts that the correlation function of a BEC follows a power-law of the form $g^{(1)}(x, -x) = (x / \lambda_p)^{-a_p}$ with $a_p = 1 / (n_s \lambda_T^2)$ where n_s is the superfluid density, λ_T is the thermal wavelength and λ_p has the dimension of a length. This implied that above condensation threshold, increasing the pump-power, which also increases the superfluid density n_s, is expected to decrease the exponent a_p. Comparing the entropy and energy corresponding to the creation of a free vortex in the condensate shows that for $n_s < 4 / \lambda_T^2$, the BKT transition occurs, where free vortices, which destroy the spatial coherence, are created. Therefore the BKT mechanism predicts that the exponent a_p reaches ¼ at threshold and smaller values at higher pump powers. [6,7,9]

4. Results of measurement

Close to zero detuning, we observed that $g^{(1)}$ follows a power-law (figure 2 a&b). A power dependent measurement shows that the exponent a_p^{measured} decreases with increasing pump power (figure 2 c), as predicted by the theory. Far above the threshold power, we observed $a_p^{\text{measured}} \lesssim 0.1$ which means that the condensate shows strong correlation over long distances.

For comparison, we also calculated $a_p^{\text{calculated}} = 1 / (n_s \lambda_T^2)$ for which we assumed that the total density n_{total}, which can be estimated from the exciton-polariton lifetime and the rate at which photons leave the sample, is twice the superfluid density n_s. As figure 2 c shows, $a_p^{\text{calculated}}$ approximately matches a_p^{measured}.

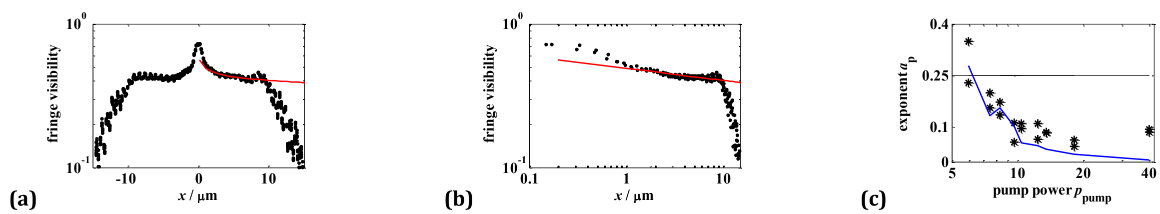

Figure 2: Measured visibility with fitted power law shown in lin-log-plot (a) and in a log-log-plot where the power law becomes a straight line (b). In this specific example the fit gives $a_p \simeq 0.08$. Increasing the pump power above the condensation threshold of $\simeq$ 5 mW decreases the fitted exponents a_p^{measured} (black stars) and the calculated exponent $a_p^{\text{calculated}}$ (blue line) as shown in (c).

5. Conclusion

We used a Michelson interference setup to measure the first order spatial correlation function $g^{(1)}(x, -x)$ of the light emitted from an exciton-polariton condensate in a micro-cavity. We observed a decay of $g^{(1)}$ with a power-law whose exponent decreases with increasing exciton-polariton density, as predicted by the theory.

6. References

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