Report: First realisation of a polariton interferometer

Chris Sturm
Universität Leipzig
Institut für Experimentelle Physik II
Linnéstr.5
04103 Leipzig

1 Purpose of the visit

Exciton-plaritons are bosonic quasi-particles which can undergo a Bose-Einstein condensation [1]. Due to their composite nature, half excitonic and half photonic, exciton-polaritons have fascinating properties which make them rich of physical effects, such as superfluidity [2], formation of half [3] and integer solitons [4] and vortices [5]. Furthermore, exciton-polaritons are also interesting for spin-based optoelectronic devices [6]. Due the conservation of the spin momentum, the polarisation of the emitted light is directly connected to the spin polarisation of the related particle. Furthermore, the polarisation of the excited polaritons can be controlled by the polarisation of the excitation laser [6].

Recently, high quality GaAs-based microcavity samples were developed at the Laboratoire de Photonique et de Nanostructures (LPN) which enables a polariton condensate to propagate frictionless in the 100µm-range [7, 8] and makes such microcavities interesting for polariton circuits. A fundamental building block for such circuits is an interferometer. I. A. Shelykh *et al.* proposed recently a design for a Berry-phase interferomter [9]. However the drawback of this design is, that it has a very low injection and extraction efficiency. The aim of this project was to overcome this drawback and to realise a polariton interferometer using an improved design.

2 Main results and description of the work

To overcome the drawback of the low injection and extraction efficiency of the proposed design two different approaches were used: structures based on multi-mode interferences and structures where the separation is realised by a bent wire which splits up into two arms.

The multi-mode interference structures (MMI) based on the concept of wave guiding [10] and the fact that an electrical field at the entrance of the structure is self-produced at a certain distance. Between the entrance and the self-produced image a multiple of the initial electrical field distribution can be found which can be used for the out-coupling and therewith for the separation of the polariton condensate. The position where the doubled image can be found depends on the width of the MMI as well as on the position

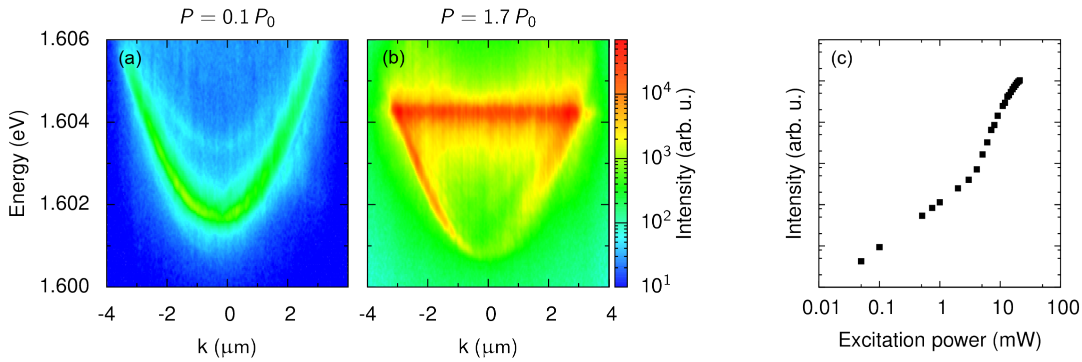

Fig. 1: Exciton-polariton dispersion below (a) and above (b) the threshold for polariton condensation. (c) Emission intensity as a function of the exciton power.

of the entrance [10]. Therefore, for the investigation of the applicability of the MMI for the separation of a polariton condensate, different MMIs with different widths and positions of the entrance were designed.

The second type of structures based on the idea to replace the sharp edges at the interface, which are present in the originally proposed designed and prevent the injection of the polaritons into the interferometer, by a smooth separation of the wire which has a "Y" like shape. This smooth bend of the wire should reduce the reflection of the polaritons at the interface and should enable to separate the flowing condensate into the two arms of the interferometer. For the investigation of the separation and reunification of the condensate, two different types of structures were prepared: a "half" interferometer structure, where the both arms of the interferometer are connected by a ring (Fig. 2a) and the "full" interferometer structure where the same mechanism of a bending wire for the separation of the condensate was used for the reunification (Fig. 4a).

The developed designs were transferred by electron-beam lithography onto a planar GaAs-based microcavity grown by molecular beam epitaxy. The detailed design of the planar microcavity can be found in the article of E. Wertz *et al.* [11]. After the transfer of the design, reactive ion etching was applied in order to obtain the desired structures. The polariton dispersion above and below the threshold is shown in Fig. 1 as well as the integrated emission intensity as a function of the excitation power. For the latter one a strong non-linear behaviour is observable which confirms the formation of a polariton condensate.

In the paper of the I. A. Shelykh *et al.* [9] the modulation of transmission and therewith the dephasing of the condensate between the two arms was achieved by applying a magnetic field. This is for the structures used in this work not applicable since high magnetic fields are needed because the excitonic g-factor is close to zero. Therefore, the idea was to control the dephasing optically by using a second laser. This laser will enhance locally the exciton-polariton concentration and therewith the interaction with the reservoir.

In the following, the main results obtained for the interferometer based on the bent wire will be presented. The work of the MMI is still under progress and a flow of the polariton condensate was already observed there.

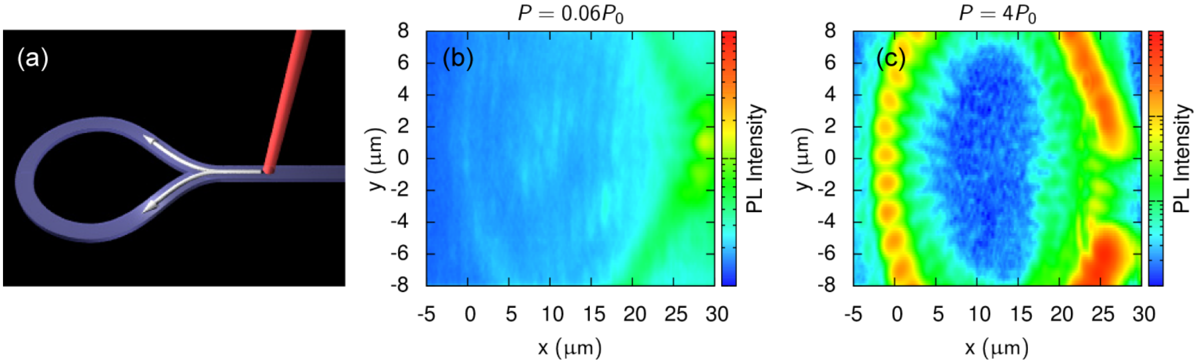

Fig. 2: Schematic of the structure where the red line represents the excitation laser whereas the white arrows indicate the flow of the polaritons. The real space image of the ring part of the structure below (b) and above (c) the threshold.

Half interferometer structure

The splitting and the coherence of the divided condensate was investigated by using a "half" interferometer structure. By exciting the structure in the wire part, propagating polaritons are created and injected into the interferometer arms. The real space images below and above the condensation threshold are shown in Fig. 2. For low excitation powers, only exciton-polariton emission around the excitation spot is observable and the emission from the ring is very weak. At the threshold, an exciton-polariton condensate is formed. However, due to its low density at the threshold, the intensity within the ring remains very weak. Furthermore, the splitting of the wire acts like a perturbation of the system and so incoming polaritons are reflected and trapped which reduces the injection efficiency of the condensed polaritons into the ring. At larger powers a sufficiently high polariton concentration is injected into the ring to observe interference fringes caused by the interference of anti- and clockwise propagating polaritons. The measured interference pattern is well reproduced by a simple model which takes into account the superposition of two oppositely propagating waves (Fig. 3). Furthermore at these high excitation powers several exciton-polariton condensates appear at the excitation spot. However, within the ring, the number of states is highly reduced and the wave vector of these states in the ring is similar, so that the observed intensity can be described by taking into account only one condensate with an averaged in-plane wave vector ($k_{\|}$).

As mentioned above, the phase of the condensate was manipulated optically by an additional excitation at one arm of the interferometer. For this purpose, the excitation laser was split into two beams and the second beam was focussed to this arm with a spot diameter twice that of the main excitation beam and a much lower excitation power (P_2). For selected excitation powers P_2 the measured intensity pattern in the ring is shown in Fig. 3a. The change of $k_{\|}$ induced by the second excitation spot leads to a phase difference between the anti- and clockwise propagating condensate which depends on P_2. This leads to a spatial shift of the fringes and a maximum phase difference of up to 2.5π was achieved (Fig. 3b). Beside the phase shift of the condensate, the enhanced concentration of the polaritons in the reservoir creates a barrier which reduces the transmission. The "barrier effect" also increases with increasing P_2 and

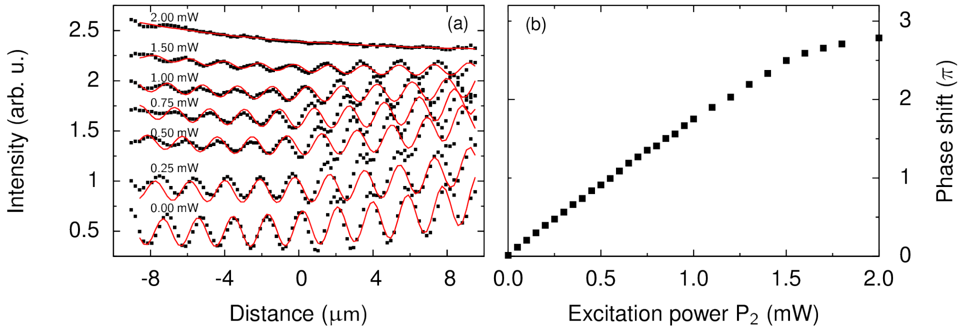

Fig. 3: (a) Intensity pattern in the ring part of the half interferometer structure for different excitation powers P_2. The excitation power for the creation of the condensate was kept constant to be $P_1 = 16\,\text{mW}$. The symbols denotes the intensity obtained from the experiment whereas the red solid represents the calculated interference pattern as explained in the text. (b) The extracted phase difference between the anti- and clockwise propagating condensate as a function of P_2.

therefore the visibility of the fringes in the ring decreases with increasing P_2 (Fig. 3a). Nevertheless, these experiments represent the first demonstration for an optical control of the dephasing of a polariton condensate.

Full interferometer structure

In the following, the first results obtained at the full interferometer structure will be described. In these experiments the excitation configuration was chosen to be the same as for the "half" structure, i.e. the main excitation spot was focussed on the input wire and the second one on one arm of the interferometer. A real space image of this structure is shown in Fig. 4b and the emission from the polariton condensate is clearly observable in the interferometer arms as well as in the output wire which demonstrates the applicability of the chosen design.

The transmitted fraction of the condensate through the reunification area (in the following called transmission (T)) is determined by the ratio of the integrated photoluminescence (PL) intensity taken from the output wire (I_{out}) and the sum of the PL intensity from top and bottom arm ($I_{i,t}$ respective $I_{i,b}$) close to the reunification area, i.e. $T = I_{\text{out}}/(I_{i,t} + I_{i,b})$. The integrated intensities as well as the transmission are shown in Fig. 4c and 4d as a function of P_2. In contrast to the integrated intensity within the interferometer arms, for the intensity of the output wire as well as for the transmission, an oscillation with increasing P_2 is observable which is due to the phase difference between the condensate propagating in the top and bottom arm induced by P_2. This leads to either constructive or destructive interference in the output wire. The fact, that the intensity does not fully vanish, as expected for destructive interference, can be attributed on the one hand to non-idealities of the structure. The concentration of the propagating condensate is for both arms different which leads to a constant background intensity and the contrast in the oscillation is reduced. On the other hand different condensate states are injected into the interferometer arms which gains a slightly different phase shift and therefore the condition for destructive or constructive interference is not fulfilled at the

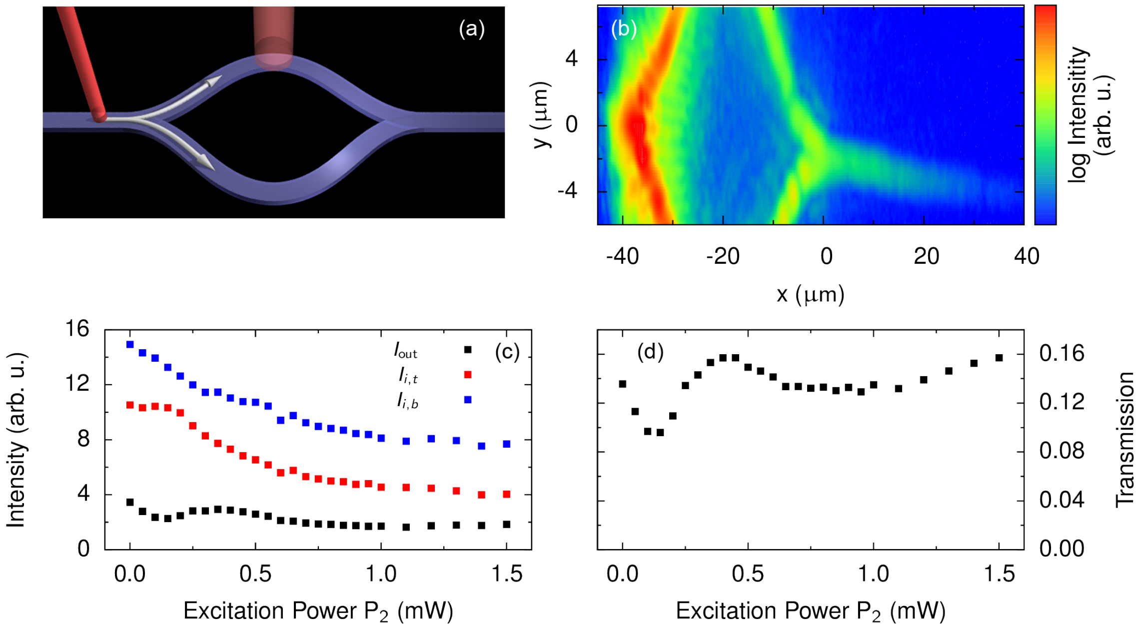

Fig. 4: (a) Schematic of the interferometer and the experiment. (b) Real space image of the PL emission of the interferometer in a false colour scale. The region of the excitation is blocked in order to avoid a saturation of the used CCD camera. (c) The integrated intensity in the output of the interferometer (out) and in the top ($I_{i,t}$) and bottom ($I_{i,b}$) arm close to the unification point as a function of the excitation power P_2. (d) The transmission $T = I_{\text{out}}/(I_{i,t} + I_{i,b})$ as a function of P_2.

same power P_2 for all these states. It should be mentioned, that the transmission is underestimated since the intensities $I_{i,t}$ and $I_{i,b}$, which are used for the calculation of T, are composed by the intensity of the incoming and reflected polaritons.

Summary

To summarise, during my stay at the Laboratoire de Photonique et de Nanostructures (LPN) a design for a polariton interferometer was developed which allows to split and combine a propagating polariton condensate. The observation of interference fringes in the ring part of the "half" interferometer structure as well as the high condensate transmission into the output wire of the full interferometer structure demonstrates the successful applicability of the developed design. Furthermore, it was possible to control optically the dephasing of the condensate and to achieve a phase shift up to 2.5π. Therewith it was possible to control the transmission behaviour of the interferometer. This represents an important step towards the realisation of polariton circuits, observation of non-linear effects like the formation of the Berry-phase and opens a new possibility for the investigation of the physics of polaritonic quantum fluids. The presented results will be published in an article which will be submitted to Physical Review Letters.

3 Acknowledgement

I would like to thank the whole GOSS group at the LPN for the friendly and warm atmosphere during the stay. Especially I want to thank my direct co-workers there, J. Bloch, A. Amo, D. Tanese, M. Abbarchi, and V. G. Sala which introduced me to a new type of material system and kindly supported me during my investigations of condensed polaritons. The presented experiment would not possible without the structuring of the sample which was done by I. Sagnes, whom I want to warmly thank. G. Malpuech and D. Solnyshkov in LASMEA I would like to thank for the theoretical discussions which were very helpful for the understanding of the physical processes in these structures. Furthermore, I want to thank B. Dagens from IEF for the discussion during the design of the interferometer structure. Last but not least I would like to thank the European Science Foundation (ESF) within the framework 'Common perspectives for cold atoms, semiconductor polaritons and nanoscience' for the financial support which gave me the opportunity to work at the LPN and to broaden my horizon in this new but related field. These experiences and the learned physics are very helpful for the understanding and investigation of the polariton condensates in ZnO structures which are recently observed at the Universität Leipzig.

References

[1] J. Kasprzak *et al. Nature* **443**, 409 (2006).

[2] A. Amo *et al. Nature Phys.* **5**, 805 (2009).

[3] H. Flayac *et al. Phys. Rev. B* **83**, 193305 (2011).

[4] A. Amo *et al. Science 332*, 1167 (2011).

[5] D. Sanvitto *et al. Nature Phot.* **5**, 610 (2011).

[6] T.C.H. Liew*et al. Physica E* **43**, 1543 (2011).

[7] E. Wertz *et al. Nat. Phys.* **6**, 860 (2010).

[8] D. Tanese *et al. Phys. Rev. Lett.* **108**, 036405 (2012).

[9] I. A. Shelykh *et al. Phys. Rev. Lett.* **102**, 046407 (2009).

[10] L. B. Soldano and E.C.M. Pennings *Journal of Lightwave Technology.* **13**, 615 (1995).

[11] E. Wertz *et al. Appl. Phys. Lett.* **95**, 051108 (2009).