technische universität
dortmund

Fakultät Physik
Experimentelle Physik 2

Technische Universität Dortmund - Experimentelle Physik 2 - D-44221 Dortmund – Germany

Prof. Dr. Marc Aßmann

Otto-Hahn-Straße 4a
D-44227 Dortmund
Telefon +49 231 755 8818
E-mail marc.assmann@tu-dortmund.de

Dienstgebäude/Raum:
CP/CP-01-191

Magdalena Robak
Politechnika Wrocławska
Wydział Podstawowych Problemów Techniki
Wybrzeże Wyspiańskiego 27
A1 p. 234
50-370 Wrocław
Poland

Dortmund, 31. Oktober 2024

Report – PhD Thesis – Biegańska

Report on the PhD thesis submitted by Dąbrówka Biegańska with the title:

„Novel properties of exciton polaritons“

Reviewer statement

My name is Marc Aßmann and I am a full professor for semiconductor physics at TU Dortmund University. My main research direction involves spectroscopy on nontrivial solid-state systems, especially Rydberg excitons and polariton condensates. I do not know Dąbrówka Biegańska personally, but I am familiar with her scientific work through her publications. Therefore, I am able and willing to provide an unbiased review of her PhD thesis.

Structure and composition of the thesis

This thesis consists of 212 pages and a preface of additional 20 pages. It is divided into 6 main parts – some of them are subdivided into additional chapters - a preface and an appendix section. The research is put into context properly. The relevant literature has been cited adequately and the author shows deep understanding of it. The structure of the thesis is coherent and a logical flow from chapter to chapter can be identified easily as outlined below.

General content of the thesis

The thesis begins with a short preface section that provides an overview over the following parts that constitute the thesis

.

Part 1 forms the introductory section of the thesis and is further divided into 4 chapters. The first chapter describes the basic concept of exciton polaritons along with some key properties, such as pseudospin properties and non-Hermitian effects. This part also describes the more general and technical aspects of polaritons. Among them are a concise summary of the diverse material platforms used to realize exciton-polaritons, ranging from traditional III-V materials to TMDs. This part also contains brief overview of possible applications of exciton-polariton systems for polariton lasing, all-optical gates, qubit analogues and even neuromorphic computing. Although some of the applications are based on degenerate polariton systems, this chapter focuses on the linear regime of low-density exciton-polaritons.

In chapter 2, the properties of degenerate polariton systems, so called polariton condensates, are discussed. A brief general review of Bose-Einstein condensation is given and special emphasis is placed on the peculiarities of condensation in open quantum systems, especially with respect to the two-dimensional nature of the BEC in microcavity polaritons. A short discussion of the effect of polariton-polariton interactions is added, containing also some discussion of the excitation spectrum of the condensed mode.
Chapter 3 provides a very brief outlook on the remaining thesis. Chapter 4 introduces the experimental methods used throughout the thesis. These include micro-PL measurements in real and momentum space, a discussion of the optical setup and a summary of the software used for data analysis.

Part 2 of the thesis is the first section containing actual experimental results obtained by Dąbrówka Biegańska. She performed the experiment and analyzed the experimental data. The section focuses on studies of the excitation spectrum of an optically trapped polariton BEC when considering the anisotropy arising from the momentum dependent TE-TM splitting which acts as an effective magnetic field. It is found that this anisotropy translates to an anisotropy of the excitation spectrum and the polarization-resolved excitation spectra become highly nontrivial. The results render it possible to provide an accurate estimate for the two spin-dependent polariton-polariton interaction constants. Also, the full spin textures for the collective excitations in momentum space are identified.

Part 3 focuses on the topological properties of the non-Hermitian polariton system. Here, Dąbrówka Biegańska mainly contributed to data analysis. Here, polaritons in a halide perovskite structure at room temperature are studied. Here, it was found that in the parameter space of the non-Hermitian system, individual points occur, where the eigenvectors and the eigenvalues of the complex energies coalesce – so called exceptional points. Due to the polariton pseudospin, a pair of exceptional points forms, which gives rise to a topological invariant that behaves akin to half-vortices, which means that it is not of integer nature. The key finding here is the identification of this spectral

winding in an inherently non-linear system, which opens up interesting perspectives on the interplay between nonlinear systems and topology in non-Hermitian systems.

Part 4 presents a study AlGaAs/AlAs quantum wells, where the material composition is tailored to give rise to relatively large effective masses for the electrons and accordingly also large exciton binding energies. Dąbrówka Biegańska performed the experiments and analyzed the experimental data. It is found that close to the Gamma-X crossover not only the expected direct excitons form, but also spatially and momentum-indirect excitons form, where the electrons are confined in the barrier and the holes are confined in the quantum well. In contrast to the hole dispersion, the electron dispersion is anisotropic and thus also indirect excitons with different effective masses may form, depending on the nature of the electron levels involved. The experiments were performed on a quantum well, where one of the distributed Bragg reflectors has been removed and mainly consisted of low-temperature time-resolved and time-integrated photoluminescence measurements. The key finding here is a thorough study of the properties of the indirect excitons arising, which is difficult as indirect excitons are necessarily difficult to study with optical means. Especially the detailed study on the influence of localization on the photoluminescence properties is highly interesting.

Part 5 is a continuation of the studies described in part 4 and focus on the same type of quantum wells placed in a full microcavity, so that the strong coupling regime is reached. Here, Dąbrówka Biegańska designed the experiment, performed it and analyzed the experimental data. It is found that as the coherent coupling between the indirect excitons and the photonic mode is rather weak, the presence of two different indirect exciton modes results in a rather uncommon shape of the dispersions in momentum space. The photonic mode and the first indirect exciton mode actually attract rather than repel. This anomalous dispersion can be reproduced by means of a model incorporating 3 coupled oscillator modes, where one of them is highly dissipative. The shape of the dispersion momentum state may become an inverted parabola or a double-peaked one.

Part 6 finally provides a summary of the results obtained in this thesis and places them within the context of the field. Finally, there is an appendix providing additional details.

Overall academic merit of the thesis

When considering the present thesis with respect to the state of the art in the field, it is clear that the scientific value of the results presented here is without any doubt substantial. As parts of the thesis have been published in high quality journals such as Science Advances and the Physical Review Letters, the merits of the results presented here are also recognized by the scientific community. The present thesis provides a significant advance in the field of research combining nonlinear and non-Hermitian physics that

contributes to our understanding of the excitation spectrum of degenerate polariton gases and its properties in artificial gauge fields. These findings will in turn be extremely helpful to the polariton community as it allows for precise tailoring of these gauge fields to obtain exact control over the properties of polariton systems. These results may find applications in all-optical functional elements and polariton based optical circuits and logic gates. Along similar lines, also the precise individual determination of the spin-anisotropic polariton-polariton interaction constants that was realized within this thesis is a huge achievement. These two constants are of fundamental importance in understanding the nontrivial spin textures that arise in spatially extended polariton systems and are notoriously hard to identify as usually only their relative magnitude can be obtained in experiments. The experimental technique introduced here to identify both constants will be of significant value to the community. Finally, it should be noted that the experiments performed within the frame of this thesis show a high degree of complexity and the data analysis methods go way beyond what is commonly expected from a PhD student, Therefore, without any doubt, Dąbrówka Biegańska clearly demonstrated that she has the relevant expertise and theoretical knowledge to independently conduct scientific work in the domain of optical spectroscopy and semiconductor physics.

Originality of the work and original contribution to the field

As outlined already in the section on the content of the thesis, the studies performed were all collaborative in nature, but the contributions by Dąbrówka Biegańska can be singled out and identified clearly. In most cases, sample design and growth and numerical simulations were performed by her collaboration partners, while she performed the experiments and performed the data analysis. These are very substantial contributions as there is usually a substantial optimization cycle, in which the details of the next run of experiments must be adapted based on the results of the data analysis performed before. Especially when considering the challenges tackled within this thesis, that corresponds to a highly original solution to the scientific problems raised as Dąbrówka Biegańska did not just apply known experimental techniques to some system, but partially had to develop the necessary experimental techniques and data analysis methods herself, which is a relevant and original achievement of significant value to the polariton community.

Recommendation

Considering the contributions to the field made by Dąbrówka Biegańska which I outlined above, I strongly suggest that the PhD degree should be awarded to her. When taking her substantial achievements and the high impact of her publications in journals such as Science Advances into account, it is clear that her measurements that made it possible to assess a non-integer topological invariant in a non-Hermitian system for the first time and the consecutive data analysis are exceptional.

Therefore, I also recommend that she should be awarded with the highest distinction.

Major questions and suggestions:

- Considering the strong emphasis placed on non-Hermitian physics and complex eigenenergies in general in this thesis, it is a bit surprising that in section 2.3. on the excitations of a condensate and the Bogoliubov dispersion only real energies are considered and, e.g., the diffusive Goldstone mode is not taken into account. Is there a special reason for that?
- In the discussion of the anomalous dispersion realized via dissipative coupling, there seems to be a large discrepancy between the measured linewidth of the X_Z exciton and the linewidth assumed in the model. As the measured linewidth is already the inhomogeneously broadened one, it seems unlikely that the additional factor of 2, by which the model assumption is larger than the measured one actually reflects the physical linewidth. Is it clear where this difference originates from?
- Along similar lines, in the three-coupled oscillator model the coupling of the highly dissipative X_Z exciton mode to the other exciton mode and to the photonic mode is extremely strong and is assumed to be on the order of 10.6 and 17 meV, respectively. What is the physical mechanism of this coupling?

Minor questions and suggestions:

- On page x in the preface, 7^{th} line from the end of the page, “gaugue” should read “gauge”.
- The heading of section 2.1.1 should read “BEC of weakly interacting particles”
- On the middle of page 39 there is a “the” too much in the phrase “in the the excitation modes”.
- On page 59, the first sentence “there have been” should read “there has been”.
- On page 121, “milielectronovolts” should read “millielectronvolts”.
- On page 145, it is not clear what is meant by “the excitation existence”.
- On page 179, “throughout my hole Doctoral studies” should read “throughout my whole Doctoral studies”.

The questions outlined above are not critical in any sense and the present thesis clearly is an excellent one. If any further questions should arise, please do not hesitate to contact me.

Best regards

Prof. Dr. Marc Aßmann