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Report on the doctoral thesis of

of **Mr. Mateusz Król** entitled

"Spin effects of cavity photons and exciton-polaritons in planar optical resonators"

Optical semiconductor devices are of enormous importance for an energy-efficient and interconnected society in the 21st century. University research covers a wide range from basic research to application orientation. While commercial devices of today predominantly rely on well-understood group III-V semiconductor, Mr. Król studies a range of novel emitter materials and cavity designs, with a dominant focus on polarization phenomena in planar microcavities in the so-called strong coupling regime. These materials include, liquid crystal microcavities, transition metal dichalcogenides and 2D perovskite materials. An essential role is played here by the so-called strong light-matter interaction, in which optical modes and matter excitations hybridize in semiconductors to form novel light-matter states: the exciton polaritons. These quasiparticles have a number of fascinating properties that make them a research object of high interest. Mr. Król theoretically studied, designed, and investigated a number of different microcavity settings and I will summarize the thesis in brief.

The thesis begins with a concise introduction into basic concepts of microresonators, strong light-matter coupling as well as basic concepts of topology and winding numbers. The work is refreshing in that it avoids lengthy textbook style introductions, but rather introduces important concepts and the state-of-the-art along the way. This helped significantly and is making it a particularly interesting read.

The thesis continues in chapter 2 with an introduction on a relatively new cavity type, featuring optically anisotropic media, such as the birefringent nematic liquid crystal materials used here.

Chapter 3 to 6 contain the main scientific results, starting with results on spin photon textures in liquid crystal microcavities, revealing a plethora of polarization dependent phenomena. The realization of skyrmion/merons is discussed including potential for logical operations. Subsequently, the (N,N) and (N+2,N) regime are realized and flanked by simulated spectra employing the Berreman method. A case in identified, in which the incident light wavelength can be inverted from +2 (the regular TE/TM case) to -2, allowing for exotic second order antimeron polarization textures. In the context of future perspective (or current limitations of the experimental platform), real-space polarization textures of meron-antimeron lattices are discussed.

The tunability of the liquid crystal is subsequently employed to study the emergence of exceptional points and their annihilation in chapter 4. After a short introduction into non-Hermitian physics, Mr. Król systematically studies exceptional points emerging from diabolic points in the (N,N) as well as (N+2,N) regime. In the latter, the strength of non-Hermiticity can be adjusted, leading ultimately to a controlled emergence and annihilation of exceptional points.

Chapter 5 deals with the introduction of individual $WSe_2$ monolayers, as well as bi-, tri-, ... layer structures in planar optical microcavities. Here, the interesting polarization properties stem from the fact that spin-valley locking naturally occurs, linking momentum and polarization properties. Strong coupling is realized in planar microcavities as well as open-cavities, where one mirror can be position controlled using a piezo actuator. This setting allows for the systematic investigation of the coupling strength as a function of the cavity width as well as the strong-coupling of multilayers with up to four and six monolayer thickness. Finally, the degree of circular polarization is studied in detail as a function of detuning, coupling strength and emitted photon energy. Interestingly, it is found that maximum valley polarization of the polaritons can be found close to the trion resonance of the TMDC monolayer.

The final chapter 6 goes back to using liquid crystal microcavities for the realization and control of non-vanishing Berry curvatures, using the 2D perovskite PEPI. Detailed basic analysis of the emitter material as well as theoretical studies of the strong coupling with inactive and active perovskite layers are performed. These findings can subsequently be experimentally confirmed and strong coupling in a liquid crystal microcavity with a 2D perovskite is shown. Subsequently, the tunable cavity is employed to realize non-trivial band structures in the Rashba-Dresselhaus spin-orbit coupling regime in photoluminescence as well as with transmission measurements, which are quite impressive. An interesting feature of the platform is shown in that the liquid crystal cavity allows for a voltage control of the position of the Berry curvature poles in momentum space.

Overall, the thesis by Mr. Król evolves around a very interesting and timely subject. The range of experiments and utilized materials is impressive and the research results are of high quality. The graphic representation and schematic drawings are outstanding, enormously helping the reader to understand the challenging geometrical settings. The works are published in high-level scientific journals including Science and Optica. Overall, Mr. Król highlights six papers, where he is the first author of four and second author of two papers. Also, a large amount of additional contributions to high-level publications (including a first author paper in Phys. Rev. Lett.) are mentioned. The manuscript is well written throughout, clear and concise.

In summary, Mr. Król's work has decisively extended the understanding of the implementation of novel polarization phenomena in optical microcavities and contributed to this field of research in a very meaningful way. It is evident that he has demonstrated extraordinary technological and experimental skill in this work. Further, the manuscript displays a comprehensive understanding of physics as well as excellent analytical skills

Taking everything into consideration, I recommend the acceptance of Mr. Król's dissertation to the faculty and explicitly propose it for a distinction.

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