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Report on the doctoral thesis of

of **Mr. Marcin Muszyński** entitled

"Self-Organizing Photonic Potentials of Different Dimensions in Liquid Crystal Microcavities with Spin-Orbit and Light-Matter Couplings"

Thanks to their exceptional optical qualities and tunability, liquid crystals (LC) have been employed in a wide range of technological applications. Most notably, liquid crystal displays (LCD) became immensely popular across many electronic devices during the 1990s and continue to be a widely understood and readily accessible display technology today. The same principles behind LCDs are also integral to modern spatial light modulators. Beyond displays, LCs play key roles in smart windows, Optical filters, including ultra-narrow Fabry–Pérot microcavity filters, and sensing applications, such as temperature indicators, humidity and chemical sensors. Moreover, liquid-crystal spatial light modulators (SLMs) have become fundamental tools in contemporary optics and photonics. These devices - especially LC-on-Silicon types - offer precise, high-resolution control over light's phase, amplitude, and polarization, enabling applications in holography, beam steering, optical computing, augmented and virtual reality, adaptive optics, and quantum optical systems.

In his thesis, Marcin Muszyński explores planar liquid-crystal optical microcavities - a distinctive architecture where a highly birefringent liquid-crystalline medium fills an optical resonator. Such a design enables dynamic manipulation of the confined light's energy and polarization. The research pursues two primary objectives: (i) probing nonlinear optical effects across both the weak and strong light–matter coupling regimes, and (ii) realizing spatially structured photonic potentials involving aspects of different dimensionalities.

After a short overview of the structure and motivation of the thesis, chapter 2 introduces the most crucial concepts relevant for this thesis in a precise and thorough way. Liquid crystals and liquid crystal optical microcavities are discussed with a precise focus on polarization dependent aspects and Rashba–Dresselhaus spin–orbit coupling. Furthermore, important aspects of light-matter interactions and photonic confinement are introduced.

Chapter 3 describes in detail the experimental as well as theoretical methods. This includes the sample fabrication as well as a quite compact introduction to the spectroscopic setups, optimized for the investigation of liquid-crystal optical microcavities. After a short introduction to relevant modelling approaches, the Mr. Muszyński uses the opportunity to give a detailed and clean account of the various author contributions typical and natural for this type of thesis.

Chapter 4-8 contains the main results of this thesis, followed by a summary appendix and a very thorough list of references.

Chapter 4 describes a continuously tunable P580-doped LCMC laser operating in the weak light–matter coupling regime, with ~200 meV (50 nm) tunability in the visible range. This enables lasing in the Rashba–Dresselhaus regime, producing two orthogonally circularly polarized beams whose interference yields Persistent Spin-Helix lasing. The spatial S_3 Stokes profile is used to assess orbital–polarization inseparability. The study also examines PSH dependence on detuning (ΔHV) and sample–objective distance, clarifying discrepancies in prior period measurements. These results form the basis for extending the system to the strong coupling regime, discussed in the next chapter. The author provides a much-appreciated discussion on the choice of emitter materials for this thesis and discusses drawbacks and limitations regarding heating, irreversible defect formation and photobleaching in an open and constructive way. Main results have been published in [M. Muszyński et al., *Phys. Rev. Appl.* **17**, 014041 (2022)]. The tuning range and flexibility of this laser design in quite impressive and potential combinations of LCMC with conventional vertical cavity surface emitting lasers are discussed.

Chapter 5 can be considered a highlight of this thesis, generally full of many interesting results. This chapter reports on a liquid crystal optical microcavity with the organic emitter material MeLPPP in the strong light–matter coupling regime. The presence of strong coupling is made plausible by effective mass changes in the lower polariton branch and a voltage-dependent anti-crossing. It is indeed difficult to cleanly observe an anti-crossing in the angular resolved measurements for organic microcavities. However, while some signs of strong coupling are present, the voltage-dependent anti-crossing is not fully convincing. In the introduction to strong coupling on page 36 the author makes the important distinction between photon lasing polariton lasing and a polariton BEC, including a clarification of the sometimes ambiguous term of "polariton condensate". In this context reference [82] is referred to repeatedly. Unfortunately, while the data is highly interesting the authors does not fully follow his clean introduction. While indeed, long-range phase coherence is essential for a BEC, this is also true for polariton lasing or photon lasers [cf. Ref. 80]. Thermalization and Bose distribution above threshold are unfortunately not provided. While it is entirely possible that the author observes a polariton BEC, addition work would be needed for an unequivocal demonstration. The author continues to use artificial Zeeman splitting (i.e. detuning Δ_HV) to selectively get polariton emission from H- or V-polarized modes, depending on the excitation or the applied voltage. This behavior effectively realizes a polariton switch that enables control over both the condensate's polarization and its energy. In the RDSOC regime, the condensate occupies both the negative-mass state at k = 0 and two degenerate dispersion minima, forming polarization stripes whose positions vary shot-to-shot, indicating spontaneous translational symmetry breaking. The persistence of stripes despite structural disorder, along with vortex detection points to superfluidity in a stripe phase. The polarization resolved tomography measurements and theory presented in Fig. 5.11 h) and i) are in good qualitative agreement hinting at a supersolid phase at room temperature. The data is currently under peer-review and a preprint is available [M. Muszyński et al., arXiv:2407.02406 (2024)].

In Chapter 6 Mr. Muszyński introduced a self-organized periodic photonic potential created from ULH-LCMC doped with a laser dye. By adjusting growth parameters, the potential landscape can be engineered into various configurations, it maintains macroscopic alignment and offers a fast and simple fabrication route to photonic potential landscapes. The birefringent liquid crystal's periodicity produces two distinct band structures, each with photonic band gaps for orthogonal linear polarizations. An advantage of ULH-LCMC is the dynamic tunability of its band structure through an external electric field allowing for reversible band evolution for both polarizations, including higher-order gap formation. The results are explained using a microscopic LC molecular orientation model. The central results are published here [M. Muszyński et al., *Laser & Photonics Reviews* **18**, 2400794 (2024)].

Towards the end of the chapter, the author discusses preliminary ideas regarding topologically non-trivial domain boundary defects. While indeed an exponential localization of the defect mode is necessary, it would be important to motivate in detail why e.g. a non-zero Zak number is expected.

Chapter 7 presents a dye-doped optical microcavity with liquid crystal torons in the weak light–matter coupling regime. Single torons act as zero-dimensional photonic traps with unique state ladders, exhibiting donut-shaped ground-state polarization and distinct first excited states. Toron size, tuned via sample position or applied voltage, influences the energy spectrum in a non-intuitive way—both lowest states can decrease in energy with reduced size, and very small torons show state inversion due to a topological ground-state transition from an orbital-angular-momentum (OAM) state to an s-symmetric state. Interferometric measurements confirm OAM in the ground state, with opposite signs for opposite circular polarizations, identifying it as an optical analogue of a Landau level arising from a synthetic magnetic field generated by position-dependent birefringence. Additionally, self-organized 2D toron lattices exhibit photonic band structures reflecting both lattice symmetry and individual toron polarization features. A publication of these results is currently in preparation [M. Muszyński, et al. Ground state orbital angular momentum lasing from liquid crystal torons.].

The final experimental chapter 8 is dedicated to the explorative investigation of angle-resolved optical and polarization behavior of a monocrystalline, polymer-stabilized, dye-doped Blue Phase I (BPI) crystal with [001] orientation. The intrinsic chirality of the BPI crystal creates photonic bandgaps that are highly selective for circular polarization: one handedness is blocked and amplified at the band edge, while the opposite is transmitted unimpeded. The author experimentally mapped these polarization-specific stopbands using angle- and energy-resolved tomography—i.e., Kossel pattern analysis—and confirmed the observations with simulations. This is done in a very detailed and thorough fashion.

Finally, the BPI is embedded in a microcavity. Due to the small lattice constant, the three-dimensional photonic potential had minimal influence on photonic modes. Instead, a simple cholesteric liquid crystal cavity model accurately described the observed linear-mode splitting, which enabled a double-threshold dual lasing regime presented in Fig. 8.16.

The thesis is a comprehensive work on fundamental investigations of a novel platform that integrates cavity photons, spin-orbit coupling induced by the high birefringence of liquid crystals, strong light-matter interactions through suitably embedded light emitters, and various engineered photonic potentials. This system can be considered a very welcome and important addition to the field of photonic simulators, emulating quantum materials and exploring new potentials for future optoelectronic devices. In addition, all the phenomena discussed in this thesis occur at room temperature and can be dynamically tuned with an external electric field, making this platform not only a versatile tool for fundamental studies with controllable parameters but also underline the potential for future photonic applications. The thesis is well written with only a few typos. The figures and graphic displays are mostly very good. Occasionally, important information in the figures (e.g. color bars or varied parameter) must be searched in the figure captions or the main text. Overall, this is a very comprehensive thesis. Results are published in good journals, are well received by the international community and are helping to mature a novel and exciting optoelectronic platform.

After taking everything into consideration, I recommend the acceptance of Mr. Muszyński to the faculty and propose it for a distinction.

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Minor corrections:

Page 9: Exprimental -> Experimental

Page 12: telecom band -> telecom C-band

Page 32: Eqn. (18): E_LPB,UPB should be E_UPB,LPB

Page 33: Detuning should be defined at energies at k_||=0.

Page 39: While there are plenty of of photonic topological insulators, Refs. [110–112] deal with polaritonic Tis.

Page 48: Kindly inform the reader what the scales in Fig. 3.5 are.

Page 69: Please check reference to chapters 3-5.

Page 72: "This approach has already been demonstrated in experiments considering the formation of BEC in RDSOC valleys [9,20]" Ref. [20] uses polariton laser in the title and polariton condensate in the text.

Page 78: Rabi splitting \Omega misses an \hbar.

Page 87: Fig. 5.13 f) the fit is pink, not red.

Page 108: latice -> lattice