Condensates of Light

810. WE-Heraeus-Seminar

12 – 16 May 2024

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 810. WE-Heraeus-Seminar:

Bose-Einstein condensation has in the last thirty years been observed in several physical systems, including cold atomic gases and exciton-polaritons, which are mixed states of matter and light in solid state systems. Other than massive particles photons usually do not exhibit Bose-Einstein condensation despite having bosonic nature, the background being that in blackbody radiation, as the textbook example for a photonic gas, the chemical potential vanishes, and at low temperature photons vanish instead of exhibiting condensation. More recently, Bose-Einstein condensations of photons has been observed in low-dimensional systems, e.g. by confining light in dye-solution filled optical microresonators, the use of plasmonic nanoparticle arrays or erbium-doped fiber cavities. Quantum fluids of light have allowed for the observation of novel quantum liquid effects, both in the regimes of near and partial thermal equilibrium.

The seminar will illuminate the different platforms and the effects observed in this rapidly evolving field. Leading experts will describe the present status of research in Bose-Einstein condensates and other quantum fluids of light, both from the theory and experimental physics side. The workshop in particular aims to highlight future perspectives, and will discuss applications of the observed new phenomena.

Scientific Organizer:

Prof. Martin Weitz	Universität Bonn, Germany E-mail: weitz@iap.uni-bonn.de
Prof. Michiel Wouters	University of Antwerpen, Belgium E-mail: Michiel.wouters@uantwerpen.be
Prof. Jan Klaers	University of Twente, The Netherlands E-mail: j.klaers@utwente.nl

Introduction

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Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday
morning

Program

Program

Sunday, 12 May 2024

17:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Monday, 13 May 2024

08:00	*BREAKFAST*	
09:00	Scientific organizers	**Welcome words**
09:10 – 10:10	Jan Klaers	**From BEC to complex condensation phenomena in two-dimensional photon gases**
10:10 – 10:55	Quentin Fontaine	**Exploring universal scaling laws in two-dimensional polariton condensates**
10:55 – 11:25	*COFFEE & TEA*	
11:25 – 12:10	Päivi Törmä	**Quantum geometric tensor in plasmonic lattices**
12:10 – 12:55	Jean-Jacques Greffet	**Photon Bose-Einstein condensation and lasing in semiconductor cavities**
13:00	*LUNCH*	

Program

Monday, 13 May 2024

15:00 – 15:20	Ivan Amelio	**Lasing in non-Hermitian flat bands: quantum geometry, coherence, and the fate of Kardar-Parisi-Zhang physics**
15:20 – 15:40	Sven Enns	**Polarization of photon Bose Einstein condensates**
15:40 – 16:15	**Poster flashes**	
16:15 – 16:35	*COFFEE & TEA*	
16:35 – 18:30	**Posters**	
18:30	*DINNER*	
20:30	**Posters (continued)**	

Program

Tuesday, 14 May 2024

08:00	*BREAKFAST*	
09:00 – 10:00	Hui Deng	**Different phases of exciton-polariton condensates**
10:00 – 10:45	Quentin Glorieux	**Hydrodynamics with fluids of light in hot atomic vapor**
10:45 – 11:15	*COFFEE & TEA*	
11:15 – 12:00	Rupert Oulton	**Photon thermalization and condensation in a quantum well open microcavity**
12:00 – 12:45	Maciej Pieczarka	**Thermalization and Bose-Einstein condensation of a photon gas in a VCSEL**
12:45	*LUNCH*	
14:00	**Excursion**	
18:30	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Wednesday, 15 May 2024

08:00	*BREAKFAST*	
09:00 – 10:00	Demetri Christodoulides	**Optical thermodynamics of nonlinear highly multimode systems**
10:00 – 10:45	Julian Schmitt	**Compressibility and equation of state in an optical quantum gas**
10:45 – 11:15	*COFFEE & TEA*	
11:15 – 12:00	Peter Littlewood	**Non-Hermitian phase transitions in polariton condensates**
12:00 – 12:45	David Snoke	**Phase correlation and flow of long-lifetime polariton condensates**
12:45	*LUNCH*	
15:00 – 15:20	Dimitrios Trypogeorgos	**Evidence for supersolidity in a polaritonic bound-in-the-continuum state**
15:20 – 15:40	Christian G. Mayer	**Time-resolved propagation measurement of exciton-polariton condensates in a kagome edge mode**
15:40 – 16:00	Paolo Comaron	**Coherent properties of a non-equilibrium polariton condensate across interaction regimes**
16:00 – 16:30	*COFFEE & TEA*	
16:30 – 17:15	Rainer Mahrt	**Progress toward integrated all-optical polariton logic**
17:15 – 18:00	Said Rodriguez	**Arcsine laws and weak ergodicity breaking of light**
18:30	*DINNER*	

Program

Thursday, 15 May 2024

08:00	*BREAKFAST*	
09:00 – 09:45	Jacek Szczytko	**Engineering spin-orbit coupling of light in weak and strong coupling regimes**
09:45 – 10:30	Mercedeh Khajavikhan	**Thermalization of modes in photonic nonlinear systems**
10:30 – 11:00	*COFFEE & TEA*	
11:00 – 11:45	Sebastian Diehl	**Universality at the onset of time crystalline order**
11:45 – 12:30	Peter Kirton	**PT symmetry breaking in open quantum systems**
12:30 – 13:00	Scientific organizers	**Conclusions**
13:00	*LUNCH*	

End of the seminar and departure /Lab visits at Bonn University

NO DINNER for participants leaving on Friday; however, a self-service breakfast will be provided on Friday morning

Posters

Posters

Aya Abouelela Johann Kroha	**Dissipative dynamics of photon Bose-Einstein condensates and fluctuations in a single-mode microcavity**
Thorsten Ackemann	**Photon thermalization and potential indications forphoton interaction in broad-area VCSELs**
Dina Atwa Khalil	**Lasing improvement by silver nanoparticles in dye-doped multilayer polymer film systems**
Christoph Bennenhei	**Organic room-temperature polariton condensate in a higher-order topological lattice**
Abraham Berman Bradley	**Low temperature optical thermodynamics for fusing incoherent pulse-trains**
Mateusz Betke	**Probing chaotic modes in nontrivial microcavity laser geometries**
Antonina Bieganowska	**Experimental determination of the phase diagram of an exciton-polariton condensate in an optical trap**
Tom Bienaimé	**Shaping pulses of light for controlling quantum systems**
Eric Boltersdorf	**Spectroscopy of heteronuclear xenon-noble gas dimers - toward Bose-Einstein condensation of vacuum-UV photons**
Tomasz Czyszanowski	**Bound states in the continuum in subwavelength periodic structures compatible with semiconductor technology**
Roos de Boer	**Continuous-wave nonlinearity and polarization rotation in a perovskite cavity**

Posters

Ludovica Dieli	**Observation of a 2D soliton gas in a quantum fluid of light**
Johannes Düreth	**Realization of higher order topological insulators in hybrid dielectric-semiconductor microcavities**
Alex Ferrier	**Positive-P simulations for open quantum spin systems**
Vashist Gangigude Ramesh	**Arcsine laws and weak ergodicity breaking in light**
Louis Garbe	**ASIP: A minimal model for incoherent bosonic transport**
Ioannis Georgakilas	**Selective organic polariton condensation in individual states of a 1D topological lattice**
Patrick Gertz	**Optical quantum gases in box and ring potentials**
Dominik Horneber	**Room temperature exciton-polariton lasing and photonic lattices with a perylene bisimide based microcavity**
Sanjay Kapoor	**Phase-only spectral shaping of photons from a quantum dot source**
Kirankumar Karkihalli Umesh Julian Schulz Frank Vewinger	**Dimensional crossover in a quantum gas of light**
Carelle Keyrouz	**Fluids of Light in disordered environments**
Roman Kramer	**Non-equilibrium dynamics of photon BEC in a chain of optical cavities in the presence of disorder**
Joshua Krauß	**Vortices in photon Bose-Einstein condensates**

Posters

David Lidzey	**Ultrafast optical control of polariton energy in an organic semiconductor microcavity**
Aurelian Loirette-Pelous	**On the validity of Kirchhoff's law in the lasing and photon Bose-Einstein condensation regimes**
Nikolas Longen	**Towards topological edge states of photons by controlled coupling of photon condensates to the environment**
Arkajyoti Maity	**Signatures and control of topological phases of interacting photons in a driven-dissipative nonlinear cavity array**
Charlie Mattschas	**Inverse solving the Schrödinger equation for precision alignment of a microcavity**
Manfred Niehus	**Bose Einstein condensates and quantum memories for future space based communication systems**
Riccardo Panico	**Exciton-polariton ring Josephson junction**
Axel Pelster	**On the theoretical description of photon gases in the dimensional crossover**
Aleksandra Piasecka	**Direct probing of the local chemical potential for photonic gas in a broad-area VCSEL**
Marius Puplauskis	**Network of phase frustrated photon Bose-Einstein condensates**
Amir Rahmani	**Exceptional points and non-Hermitian phase transition in non-linear binary systems**
Andreas Redmann	**Bose-Einstein condensation of photons in a four-site quantum ring**

Posters

Arpana Saboo	**Skyrmion lattice formation in a spin-orbit coupled spin-1 Bose-Einstein condensate**
Ross Schofield	**Continuously sustained semiconductor mediated photon BEC in an open planar-spherical microcavity**
Julian Schulz	**Dimensional crossover in a quantum gas of light**
Violetta Sharoglazova	**Unveiling hidden dynamics: Speed measurements of classically forbidden motion**
Marti Struve	**Polarized room-temperature polariton lasing in elliptical microcavities filled with fluorescent proteins**
Yijun Tang Florian Mintert	**Photon-photon correlation and breakdown of temporal coherence of photon condensate in a dye-filled microcavity**
Pietro Tassan	**Integrated ultrafast all-optical transistor**
Igor Timofeev	**Geometric and fluctuational divergences in the linear response of coherently driven microcavity polaritons and their relation to superfluidity**
Chris Toebes	**Effective low-temperature photon gas through tunnel cooling**
Michiel Yzewyn	**Kardar-Parisi-Zhang scaling in Bose-Einstein condensates of photons**

Abstracts of Talks

(in alphabetical order)

Lasing in non-Hermitian flat bands: quantum geometry, coherence, and the fate of Kardar-Parisi-Zhang physics

I. Amelio[1] **and N. Goldman**[1]

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Université Libre de Bruxelles, CP 231, Campus Plaine, B-1050 Brussels, Belgium

We show that lasing in flat band lattices can be stabilized by means of the geometrical properties of the Bloch states, in settings where the single-particle dispersion is flat in both its real and imaginary parts. We illustrate a general projection method and compute the collective excitations, which display a diffusive behavior ruled by quantum geometry through a peculiar coefficient involving gain, losses and interactions, and entailing resilience against modulational instabilities.

Then, we derive an equation of motion for the phase dynamics and identify a Kardar-Parisi-Zhang term of geometric origin. This term is shown to exactly cancel whenever the real and imaginary parts of the laser nonlinearity are proportional to each other, or when the uniform-pairing condition is satisfied.

We confirm our results through numerical studies of the π-flux diamond chain. This work highlights the key role of Bloch geometric effects in nonlinear dissipative systems and KPZ physics, with direct implications for the design of laser arrays with enhanced coherence. This talk is based on [1].

References

[1] I. Amelio and N. Goldman, arXiv:2308.08418

Optical Thermodynamics of Nonlinear Highly Multimode Systems

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Abstract: The past few years have witnessed a resurgence of interest in multimode structures, predominantly driven by the ever-increasing demand for higher information capacities. This renaissance, in turn, incited a flurry of activities in the general area of nonlinear multimode optics. The sheer complexity associated with the presence of hundreds or thousands of nonlinearly interacting modes that collectively act as a many-body system, has led to new opportunities in observing a multitude of novel optical effects that would have been otherwise impossible in single-mode settings. In this talk, a thermodynamic theory capable of describing complex, highly multimoded, nonlinear optical systems is presented. It is shown that the mode occupancies in such nonlinear multimode arrangements follow a universal behavior that always tends to maximize the system's entropy at steady-state. This thermodynamic response takes place irrespective of the type of nonlinearities involved and can be utilized to either heat or cool an optical multimode system. Aspects associated with adiabatic compressions and expansions will be discussed along with the possibility for all-optical Carnot cycles.

Exploring the coherence of a non-equilibrium exciton-polariton condensate in the interaction-dominated regime

P. Comaron[1], **E. Estrecho**[2], **M. Wurdack**[2], **M. Pieczarka**[2,3], **M. Steger**[4], **D. W. Snoke**[4], **K. West**[5], **L. N. Pfeiffer**[5], **A. G. Truscott**[6], **M. Matuszewski**[7,8], **M. Szymanska**,[1] **and E. A. Ostrovskaya**[2]

[1]*Department of Physics and Astronomy, University College London, London, UK*
[2]*ARC Centre of Excellence in Future Low-Energy Electronics Technologies and Department of Quantum Science and Technology, ANU, Canberra, Australia*
[3]*Department of Experimental Physics, Wroclaw University, Wrocław, Poland*
[4]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, USA*
[5]*Department of Electrical Engineering, Princeton University, Princeton, USA*
[6]*Department of Quantum Science and Technology, ANU, Canberra, Australia*
[7]*Institute of Physics, Polish Academy of Sciences, Warsaw, Poland*
[8]*Center for Theoretical Physics, Polish Academy of Sciences, Warsaw, Poland*

Collective phenomena in quantum many-body systems are strongly related to dimensionality, interactions and to the intrinsic equilibrium/nonequilibrium nature of the system. While coherence in a nonequilibrium systems, such as microcavity exciton-polaritons, has been previously explored [1], so far it remains unclear how depends on the interactions and how its development is affected by confinement. In this work we investigate, experimentally and theoretically, spatial coherence in a confined two-dimensional Bose gas of exciton polaritons with tunable interaction energy. We study phase correlations and steady-state properties of the gas over a wide range of interaction energy values by varying the photonic/excitonic fraction of the polaritons (interaction strength) as well as the density of polaritons. The experimental observations reveal different regimes (see Fig. 1), which agree with the beyond-mean-field modeling of the system using stochastic equations of motion. Finally, we tentatively extract a universal relationship between the power-law exponent and the "coherent fraction" of the system. Our analysis characterize the phase transition in confined driven-dissipative quantum systems, confirming that the thermalization in this systems is driven by interactions and is inhibited in the photonic regime.

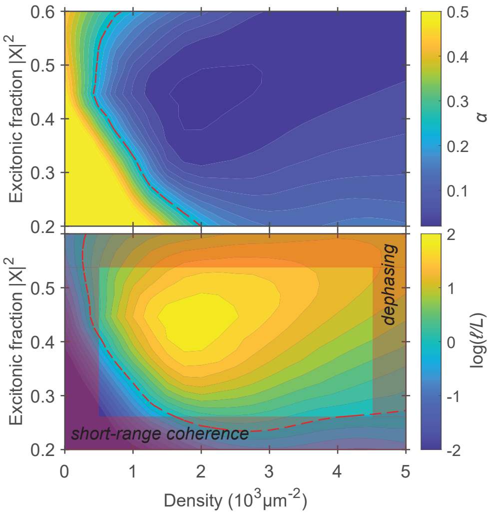

Fig. 1. Different regimes of coherence in nonequilibrium systems.

References

[1] W. Nitsche *et al.*, PRB **90**, 205430 (2014). D. Caputo *et al*, Nat. Mat. **17**, 145 (2017). Mei *et al.,* PRB **103**, 045302 (2021).

Different Phases of Exciton-Polariton Condensates

H. Deng

University of Michigan, Ann Arbor, MI, USA

Nonequilibrium systems can exhibit new types of phase transitions not found in equilibrium ones. We will introduce an interesting platform for studying such phenomena: the exciton-polaritons in semiconductor microcavities. As half-light half-matter quasi-particles, polaritons form an open, nonlinear system, where the non-equilibrium counterpart of a rich variety of many-body phases have been established, including dynamic Bose-Einstein condensate (BEC), Berezinskii-Kosterlitz-Thouless (BKT) like phase in a two-dimensional cavity, and a Bardeen Cooper Schrieffer (BCS) like polariton laser. The interplay between pumping, thermalization, decay and strong polariton interactions also give rise to phenomena unique to non-equilibrium systems, such as spontaneous limit cycle oscillations and phase separation in steady-state non-equilibrium polariton condensates. Lastly, the discovery of van der Waals semiconductors has opened opportunities to create exciton-polariton systems with novel properties and potential novel many-body phases.

Universality of time crystalline order

S. Diehl

[1]*Institute for Theoretical Physics, Cologne, Germany*

We explore the phase transitions at the onset of time-crystalline order in O(N) models driven out-of-equilibrium. The spontaneous breaking of time translation symmetry and its Goldstone mode are captured by an effective description with O(N)×SO(2) symmetry. Using the renormalization group and the $\epsilon = 4 - d$ expansion in a leading two-loop analysis, we identify a new non-equilibrium universality class. Strikingly, it controls the long-distance physics no matter how small the microscopic breaking of equilibrium conditions is. A hallmark is a universally divergent effective temperature at the transition. The relevant symmetry group is realized for magnon condensation in pumped yttrium iron garnet (YIG) films and in exciton-polariton systems with a polarization degree of freedom. We also discuss prospects of realizing Kardar-Parisi-Zhang physics via spontaneous time translation symmetry breaking.

References

[1] R. Daviet, C. P. Zelle, A. Rosch, S. Diehl *Non-equilibrium criticality at the onset of time-crystalline order in O(N) models* , arxiv:2312.13372

[2] C. P. Zelle, R. Daviet, A. Rosch, S. Diehl, *Universal phenomenology at critical exceptional points of nonequilibrium O(N) models* , arxiv:2304.09207

Polarization of Photon Bose Einstein Condensates

S. Enns[1], J. Schulz[1], K. Karkihalli Umesh[2], F. Vewinger[2], G. von Freymann[1]

[1] Department of Physics and Research Center OPTIMAS, RPTU Kaiserslautern-Landau, 67663 Kaiserslautern, Germany
[2] Institute of Applied Physics, University of Bonn, 53115 Bonn, Germany

We experimentally investigate properties of harmonically trapped photon gases and Bose-Einstein-Condensates in a dye-filled microcavity. Here we analyze the polarization of thermal and condensed light and their dependence on the pump beam's polarization. We show that, in agreement with previous theoretical work [1], there is a remarkable increase of the polarization strength above the condensation threshold. While the polarization of the condensate follows the polarization of the pump beam, the thermal light stays unpolarized. Our current experimental setup, shown in figure 1(a), allows for the creation of all possible polarization states on the Poincaré sphere for the pump beam. Also, the measurement basis can be switched from linear polarization to circular polarization by another quarter waveplate and hence the polarization of the photon gas can be evaluated properly. Utilizing a polarizing beam splitter (PBS), horizontally and vertically linear polarized or right and left circular polarized fractions of the condensate can be measured simultaneously. In contrast to previous setups, the dye solution is pumped through the cavity mirrors and the pump beam coincides with the optical axis of the resonator so that no spontaneous symmetry breaking is expected. Preliminary results are shown in figure 1(b) where the linear polarization of the pump beam is rotated by a half-wave plate and the resulting polarization strength of the condensate is calculated.

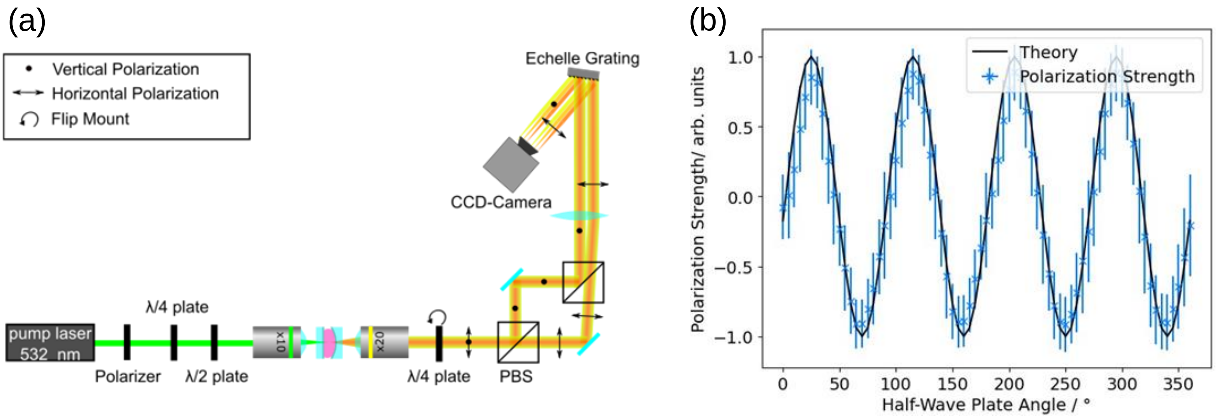

Figure 1: (a) Experimental setup for the investigation of the polarization of a photon gas and (b) Measurement result for the condensate's polarization strength with varied linear pump beam polarization

References

[1] R. I. Moodie, P. Kirton, and J. Keeling, Polarization dynamics in a photon bose-einstein condensate, Phys. Rev. A 96 (2017).

Exploring Universal Scaling Laws In Two-Dimensional Polariton Condensates

D. Pinto Dias[1], Q. Fontaine[1], F. Helluin[2], A. Lemaître[1], M. Morassi[1], L. Le Gratiet[1], I. Sagnes[1], A. Harouri[1], A. Minguzzi[2], L. Canet[2], S. Ravets[1] and J. Bloch[1]

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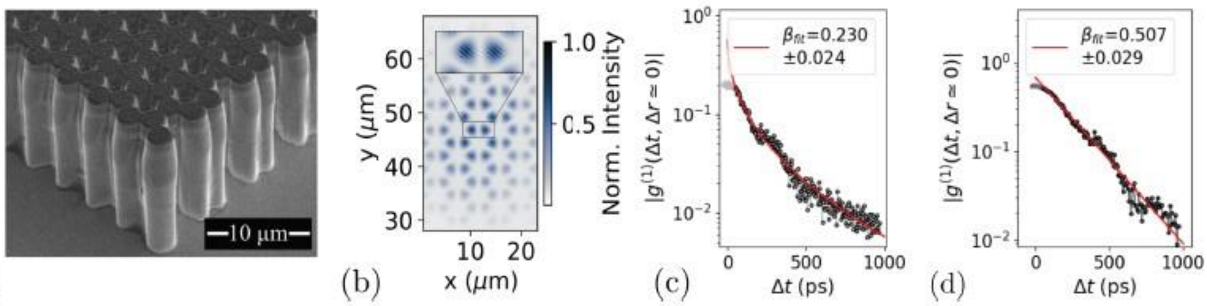
[2] LPMMC - CNRS - Univ. Grenoble Alpes, Grenoble, France

Revealing universal behaviors in different systems is a hallmark of statistical physics. In this context, the Kardar-Parisi-Zhang (KPZ) [1] equation is a paradigmatic example of universality out of equilibrium. This equation describes the critical roughening of stochastically growing interfaces in classical systems. The spatial and temporal correlation functions of the height profile exhibit scalings, with critical exponents specific to the KPZ universality class and depending only on dimensionality. While KPZ physics has been thoroughly studied in one-dimensional (1D) systems, an experimental platform is still missing for its exploration in two dimensions (2D). Interestingly, theoretical predictions show that the phase of 2D polariton condensates behaves as an interface, whose spatio-temporal evolution is described by the KPZ equation [2].

In this talk, we report optical interferometry experiments on extended 2D polariton condensates generated in lattices of coupled microcavities, see Figs (a) and (b). We retrieve the spatio-temporal decay of the first order coherence $|g^{(1)}|$. As shown in Fig (c), close to condensation threshold, the $|g^{(1)}|$ temporal decay can be nicely fitted by a stretched exponential using the characteristic KPZ growth exponent $2\beta \simeq 0.48$. At higher powers, the coherence dynamics evolves into an exponential decay, see Fig (d). We will discuss the overall measured spatio-temporal coherence behavior in the KPZ phase as well as the role of vortices in the departure from this phase at higher powers, in accordance with theoretical predictions [3, 4].



(a) (b) (c) (d)

References

[1] M. Kardar *et al*. Phys. Rev. Lett., **56**:889–892 (1986).
[2] L. He *et al*. Phys. Rev. B, **92**:155307 (2015).
[3] Q. Mei *et al*. Phys. Rev. B, **103**:045302 (2021).
[4] K. Deligiannis *et al*. Phys. Rev. Res., **4**:043207 (2022).

All-optical control of a quantum fluid of light in hot atomic vapor

Tangui Aladjidi, Quentin Glorieux

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We present an experimental platform allowing to model arbitrary 2D hamiltonians using all- optical control of fluid of light in a hot Rubidium vapor [1]. Using full-field retrieval of the quantum fluid, we can measure momenta distributions and hydrodynamical observables and use this information to probe the superfluid transition [2, 3] in a time-resolved manner. We also engineer the quantum fluid to study the dynamics of quantized vortices and scale it towards the study of turbulence [4].

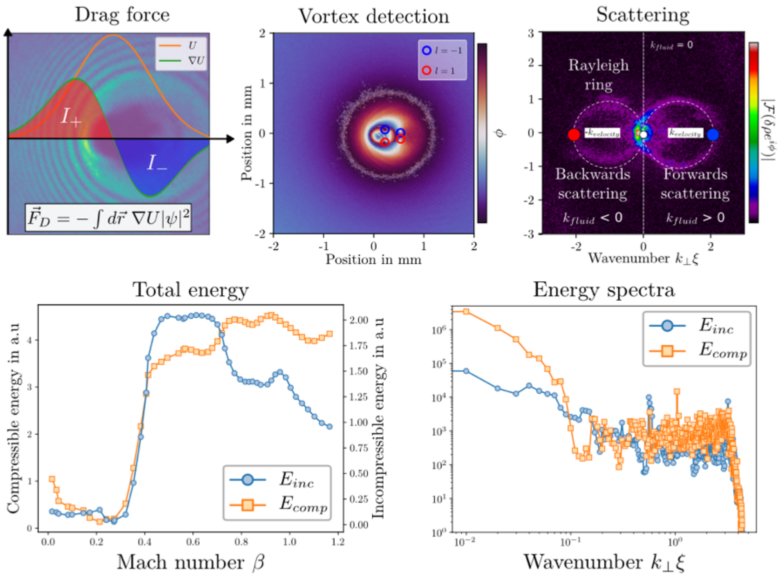

Fig. 1

References

[1] Glorieux, Q. et al. Hot atomic vapors for nonlinear and quantum optics. New Journal of Physics 25, 051201 (2023).
[2] Huynh, J. et al. Two-dimensional superflow past an obstacle of arbitrary penetrability: Exact results for the critical velocity 2023. arXiv: 2305.01293.
[3] Michel, C. et al. Superfluid motion and drag-force cancellation in a fluid of light. Nat. Comm. 9, 2108 (2018).
[4] Abobaker, M. et al. Inverse energy cascade in two-dimensional quantum turbulence in a fluid of light 2022. arXiv: 2211.08441.

Photon Bose-Einstein condensation and lasing in semiconductor cavities

Aurelian Loirette-Pelous and Jean-Jacques Greffet

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F-91127 Palaiseau, France

Photon Bose-Einstein condensation and photon thermalisation have been largely studied with molecular gain media in optical cavities. Their observation with semiconductors has remained elusive despite a large body of experimental results and a very well established theoretical framework. We use this theoretical framework as a convenient platform to revisit photon Bose-Einstein condensation in the driven dissipative regime and compare with the lasing regime [1]. We discuss the thermalisation figures of merit and the different experimental procedures to asses thermalization. We compare the definitions of lasing and condensation thresholds. Finally, we explore the fluctuations of the system and their relation to the different regimes.

References

[1] A. Loirette-Pelous, J.-J. Greffet, Laser & Photonics Rev. 2003, 2300366

Thermalization of Modes in Photonic Nonlinear Systems

M. Khajavikhan[1]

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Recently, in a series of groundbreaking works, it was shown that weakly nonlinear multimode optical systems have the capacity to undergo thermalization[1]. This phenomenon leads to a statistical redistribution of power among the corresponding supermodes– the eigenstates of the multimode configuration in the absence of nonlinearity. Notably, this power distribution adheres to the Rayleigh-Jeans law, which is the large particle limit of the Bose-Einstein distribution. In this presentation, I will discuss our experimental investigations into the thermalization phenomena in nonlinear optical multimode systems using synthetic lattices[2]. Additionally, I will describe the implications of these discoveries for implementing many-body localization, the coherent combination of incoherent beams, and the thermalization of cavity spectral modes.

References

[1] F. O. Wu, A. U. Hassan, D. N. Christodoulides, Nature Photonics 13 (11), 776-782

[2] A. L. Marques Muniz, F. O. Wu, P. S. Jung, M. Khajavikhan, D. N. Christodoulides, U. Peschel, Science **379** 1019-1023 (2023)

PT Symmetry Breaking in Open Quantum Systems

S. Kothe[1] J. Huber[2], P. Rabl[2,3] and P. Kirton[1]

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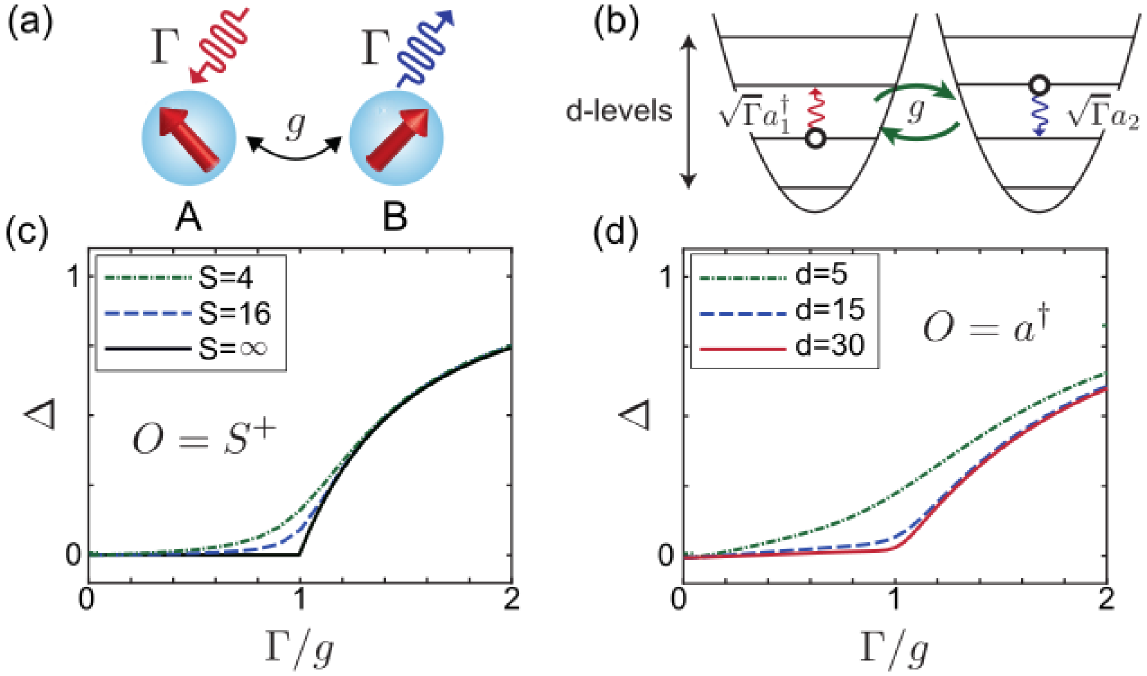
[3]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany

Parity-time symmetry breaking in coupled systems with balanced gain and loss has recently attracted considerable attention and has been demonstrated in various photonic, electrical and mechanical systems in the classical regime. In this talk I will show how these ideas can be generalised to microscopic models [1] based around master equation descriptions. The symmetries required by these equations can be realised in a variety of models which can be engineered to show novel phenomena including non-equilibrium phase transitions. Models I will describe include lattices with alternately driven and dissipative sites [2] and coupled non-linear spins [3].



References

[1] J. Huber, P. Kirton, S. Rotter, P. Rabl, SciPost Phys, **9,** 052 (2020)
[2] J. Huber, P. Kirton, P. Rabl, Phys. Rev A, **102**, 012219 (2020)
[3] S. Kothe, P. Kirton (in preparation)

From BEC to complex condensation phenomena in two-dimensional photon gases

Jan Klaers[1]

[1]*Adaptive Quantum Optics, University of Twente, PO Box 217, 7500 AE Enschede*

In contrast to Planck's black body radiation, photons can undergo Bose-Einstein condensation if the thermalization process is limited to two components of the photon k-vector. Such a scenario can be realized in effectively two-dimensional photon gases in optical microcavities, as demonstrated nearly 15 years ago[1]. The first part of my talk will introduce key physical principles, experimental techniques, and significant experimental results related to this phenomenon over recent years. In the second part of this presentation, I will cover condensation phenomena in complex potential landscapes. These potentials can be created by various means, such as nanostructuring the mirror surface[2] or altering the index of refraction of the optical medium[3]. More intricate potential landscapes, particularly those that include lattice structures, can serve as analog simulators for solid-state physics phenomena, including simulations of classical spin systems[4,5]. More broadly, these systems can reveal complex, not necessarily equilibrium-based, condensation phenomena in two-dimensional photon gases[6] and can serve as a versatile platform for conducting highly controlled quantum mechanical experiments beyond condensation phenomena.

References

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Non-Hermitian phase transitions in polariton condensates

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Non-equilibrium Bose condensation is now well established in polariton systems but the distinction between laser behavior and dilute gas behavior is not clear. We propose a novel mechanism for a nonequilibrium phase transition in a U (1)-broken phase of an electron-hole-photon system, from a Bose-Einstein condensate of polaritons to a photon laser, induced by the non-Hermitian nature of the condensate. We show that a (uniform) steady state of the condensate can always be classified into two types, loosely arising either from lower- or upper-branch polaritons. The transition between the two has analogies to the thermodynamic liquid-gas transition that has no new broken symmetry but an emergent local symmetry which appears at the critical point.[1}

This idea turns out to be generalizable to a large class of dynamical phase transitions that are controlled by mathematical singularities, known as exceptional points, both quantum and classical [2]. As a dynamical phase transition the question arises about scaling behavior and fluctuations away from mean field theory and this talk will address this on the basis of numerical simulations and scaling arguments.

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Progress toward integrated all-optical polariton logic

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While the number of transistors that make up a processor has been growing exponentially over the last five decades the clock speed stalled at a few gigahertz about 15 years ago as a result of the breakdown of Dennard scaling. All-optical logic holds the promise to allow for up to three orders of magnitude higher speed. The key challenge is to keep the power density constant while further reducing dynamic dissipation when the clock-frequency is increased.

Here, we will present ultrafast and cascadable all-optical transistors operating at room temperature in a vertical cavity structure utilizing strong exciton-photon coupling. By using a ladder-type organic semiconducting polymer in an optical microresonator, an incoming optical signal can be switched on and off within less than a picosecond. In addition, the signal can be amplified by more than a factor of 6500 within just a few micrometres device length. Furthermore, several transistors can be cascaded to realize OR and AND logic gate operation. Implementing a seeded non-ground state polariton condensation allows to configure a joint-denial truth-functional operator i.e., a universal NOR gate.
Based on these encouraging results, we will then present a way towards a scalable technology needed to fully exploit the potential of such novel all-optical transistors. Therefore, we will introduce the concept of in-plane high contrast grating (HCG) structures built by silicon photonics technology to tackle such a challenging approach. We evidence that exciton-polariton condensation with an optically active polymer as gain medium can be achieved in micrometer-sized HCG cavities at ambient conditions. By coupling two HCG resonators at close distance we demonstrate ultrafast all-optical transistor action and cascadability by utilizing seeded polariton condensation. Our experiments lay the foundations for scalable, compact all-optical integrated logic circuits that could process optical signals two orders of magnitude faster than their electrical counterparts. In addition, the possible few-photon operation of these novel device structures hold promise to bring the required switching energies down to the attojoule level.

Time-resolved Propagation Measurement Of Exciton-Polariton Condensates In a Kagome Edge Mode

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Strong coupling between photons and excitons in an optical microcavity leads to the formation of hybrid light-matter quasiparticles called exciton-polaritons. Owing to their bosonic statistics, they undergo a phase transition above a critical density to a dynamic condensate via stimulated scattering. By confining the exciton-polaritons in photonic potentials, it is possible to emulate two-dimensional lattice Hamiltonians. In this context, the etch-and-overgrowth (EnO) technique introduced by El Daïf and co-workers opens up new possibilities for the realization and control of complex and densely packed polariton lattices [1,2]. In our work, the EnO technique is used to fabricate a Kagome lattice in a III-V microcavity with GaAs quantum wells in which we observe anomalous propagation behavior of the polariton condensate along the dense-packed termination of the lattice.

The edge mode is spectrally positioned between the anti-binding S-band and the flatband. When pumping a single site, the locally generated polariton condensate propagates depending on the position of the excitation due to the symmetry breaking of the three-site unit cell. We show the existence of a unidirectional propagating mode above threshold in energy resolved real and Fourier space images. The time evolution of this process is also observed in a streak camera. The time-resolved measurements show the condensate propagation in only one direction along the lattice edge via hopping transport in the two-dimensional lattice along several single sites with a velocity of (2.31±0.19) $\mu m\ ps^{-1}$ [3]. These results suggest that unidirectional edge-state transport can emerge in a photonic platform without the necessity of an engineered topology.

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Photon Thermalization and Condensation in a Quantum Well Open Microcavity

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The thermalization of light and its ground state condensation has been extensively explored in recent years [1], with the link between laser action and Bose Einstein condensation of a thermalized photon gas in an open microcavity [2, 3] opening new ways to understand laser system. In this talk we report thermalization and condensation of light in a semiconductor quantum well weakly coupled to an open microcavity system [4]. This system consists of half a vertical external cavity surface emitting laser, constructed on GaAs with an InGaAs quantum well emitting near 925 nm, with a piezo controlled external spherical dielectric mirror positioned to achieve low cavity mode orders with well-defined transverse modes. We present evidence of cavity photon thermalization and since we have used a single quantum well with minimized absorption, α, to match the cavity loss, κ, we explore the influence of thermalization coefficient, $0.1 < \gamma = \alpha/\kappa < 10$. This level of control allows us to compare our data to recent theory on photon condensation in semiconductor systems [5]. In the condensation regime, we identify a region of ground state mode stability with good thermalization $\gamma > 1$. Meanwhile regions of poor thermalization $\gamma < 1$, and at high operation power, show multi-mode or higher order spatial mode lasing, which is consistent with the theory of dye-based condensates [6, 7]. We also assess the strength of photon-photon interactions and find a normalized interaction parameter, $\tilde{g} = 2.7 \times 10^{-3}$. Since this value increases with quantum well number, this system is promising for the possibility of observing rich interaction physics.

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Thermalization and Bose-Einstein condensation of a photon gas in a VCSEL

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Photons are historically the first particles to be considered in Bose-Einstein statistics. Surprisingly, photonic gases were among the latest to demonstrate the direct consequence of this quantum statistics - the Bose-Einstein condensation (BEC) [1]. In contrast, laser operation is usually understood in the non-equilibrium framework of optical gain over losses in a device, unlike BEC in thermodynamic equilibrium.

In this talk, I will present our observation of a BEC phase transition in a real-world device – a telecommunication laser. The sample is a broad-area (23-µm diameter aperture) oxide-confined vertical-cavity surface-emitting laser (VCSEL) designed for 980-nm optical data communication [2]. We tested several devices with different cavity mode-quantum well energy detuning $\varDelta = \varepsilon_0 - \varepsilon_{QW}$, to operate the device below the Bernard-Duraffourg lasing condition and to achieve conditions for photon gas thermalization. For the device with slightly negative detuning $\Delta \approx -5\ \mathrm{meV}$, we observed fundamental transverse-optical mode condensation, followed by a thermalized distribution of higher-order modes, in agreement with the Bose-Einstein distribution. Furthermore, we experimentally extracted the parameters of the equation of state (EOS) of the photon gas in the VCSEL. We found perfect agreement with the EOS of a textbook 2D Bose gas, confirming its thermodynamic properties. On the contrary, for a more negatively detuned device, $\Delta = -12\ \mathrm{meV}$, we observed a more standard VCSEL behavior, with multi-mode lasing at higher-order modes above the threshold current, followed by non-thermalized higher energy states.

Our results show a new perspective on understanding semiconductor VCSELs, which can be used to test the BEC physics in table-top room-temperature devices. We offer that VCSELs can operate in a thermalized regime below reaching positive gain. Moreover, our demonstration allows for observing effective photon-photon interactions mediated via semiconductor nonlinearities that lead to photon superfluidity. Finally, the thermalization mechanism and the BEC effect allow one to achieve single-mode coherent operation in a broad-area VCSEL that strongly contradict the common beliefs for these devices.

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Arcsine laws and weak ergodicity breaking of light

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We demonstrate that the time-integrated light intensity transmitted by a coherently driven resonator obeys Lévy's arcsine laws — a cornerstone of extreme value statistics [1]. We show that convergence to the arcsine distribution is algebraic, universal, and independent of non-equilibrium behavior due to non-conservative forces or non-adiabatic driving. We furthermore verify, numerically, that the arcsine laws hold in the presence of frequency noise and in Kerr-nonlinear resonators supporting non-Gaussian states. The arcsine laws imply a weak ergodicity breaking with important implications for resonant optical sensors. In particular, the sensing precision that can be attained using a finite energy budget can be greater for ensemble averaging than for time averaging of the time-integrated intensity [2]. Finally, we discuss perspectives for probing the possible breakdown of the arcsine laws in systems with memory.

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Compressibility and equation of state in an optical quantum gas

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Quantum gases of atoms, exciton-polaritons, and photons provide a test bed for many-body physics under both in- and out-of-equilibrium settings. Experimental control over dimensionality, potentials, or the coupling to reservoirs offers wide possibilities to explore phases of matter, for example, by probing susceptibilities, as the compressibility. For gases of material particles, studies of the mechanical response are well established; for optical quantum gases, they have so far remained elusive. In my talk, I will discuss experimental work demonstrating a measurement of the compressibility of a two-dimensional quantum gas of photons in a box potential inside a dye-filled microcavity, from which we obtain the equation of state for the optical medium. Finally, I will present more recent work testing the fluctuation-dissipation relation in photon Bose-Einstein condensates by independent measurements of the density response and the reservoir-induced grand canonical fluctuations.

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Phase correlation and flow of long-lifetime polariton condensates

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We are able to make polariton condensates which reach “textbook” conditions, namely, a very homogeneous system in thermal equilibrium. Interferometry measurements then allow us to extract the phase-coherent fraction (effectively the “condensate fraction”). Surprisingly, we find a very well-defined power law for the coherent fraction as a function of density, which agrees with the prediction of a simple numerical model. We also use interferometry to observe the phase gradient of the condensate in a ring trap, which shows the flow of the condensate. We see a true persistent quantized circulation, with no decay in time in a steady-state pumping geometry, after a short kick from a pulsed laser. A numerical model of the system dynamics shows how the pulsed laser generates the circulation.

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Engineering Spin-Orbit Coupling of Light in Weak and Strong Coupling Regimes

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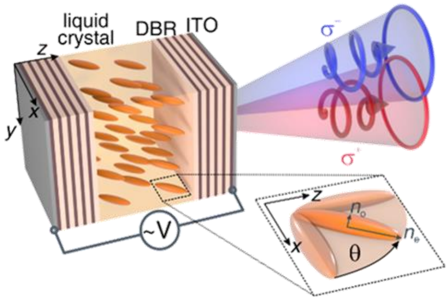
Topological photonics carries a key promise for the development of integrated optical circuits as photons, being uncharged, cannot be directly steered by an electric field. We have developed a method to electrically control the spin-orbit coupling (SOC) of light using specially designed photonic structures – birefringent microcavities. These consist of a 2-3 μm thin liquid crystal layer enclosed between two parallel distributed Bragg reflectors deposited on transparent electrodes (**Figure**).



In solid-state systems with broken inversion symmetry, SOC gives rise to the Dresselhaus and Bychkov-Rashba SOC Hamiltonians, key to spintronics, topological insulators, and superconductors. Unlike SOC in solid-state matter, which is challenging to manipulate, birefringent optical cavities offer substantial tunability of photonic modes. This has led to observing an optical analogue of the spin Hall effect and creating artificial gauge fields for parameters extending far beyond those previously considered experimentally and theoretically [1]. We discovered Rashba-Dresselhaus spin-orbit coupling in a photonic system and showed control of an artificial Zeeman splitting [2]. Additionally, we've shown how to structure light so its polarization mimics spins in a ferromagnet, forming half-skyrmions (merons) [3]. Recently we observed optical analogue of persistent spin helix, reciprocal Young's and Stern-Gerlach experiments [4] and a new type of chiral Rashba-Dresselhaus lasing [5]. Our results illustrate an effective approach of engineering artificial gauge fields and synthetic Hamiltonians with photons for the simulation of nontrivial condensed matter and quantum phenomena, promising new directions in topological photonics [6,7,8], non-Hermitian systems [6,9] and condensates of light. By embedding emitters within birefringent microcavities, we explore light-matter interactions in both weak [5] and strong coupling regimes [7,8].

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Quantum geometric tensor in plasmonic lattices

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Arrays of plasmonic nanoparticles, so-called plasmonic lattices, when combined with an emitter material (gain medium), provide a versatile platform for studies on light-matter interaction in the nanoscale, including collective coherent phenomena as well as topological photonics. We have experimentally realized a new type of condensate: a BEC of hybrids of surface plasmons and light in a nanoparticle array, with both at weak coupling and strong coupling (polariton) regime, with unique polarization and coherence properties [1-4]. In the lasing regime, we have observed bound state in continuum (BIC) modes with different topological charges [5,6]. Recently, we studied the quantum geometric tensor in these systems. We experimentally observed non-zero quantum metric and Berry curvature along the diagonals of the Brillouin zone of a square lattice of gold nanoparticles [7]. By a theoretical analysis, we show that the Berry curvature originates solely from non-Hermitian effects [8]. This is the first experimental observation of a non-Hermitian Berry curvature.

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Evidence for supersolidity in a polaritonic bound-in-the-continuum state

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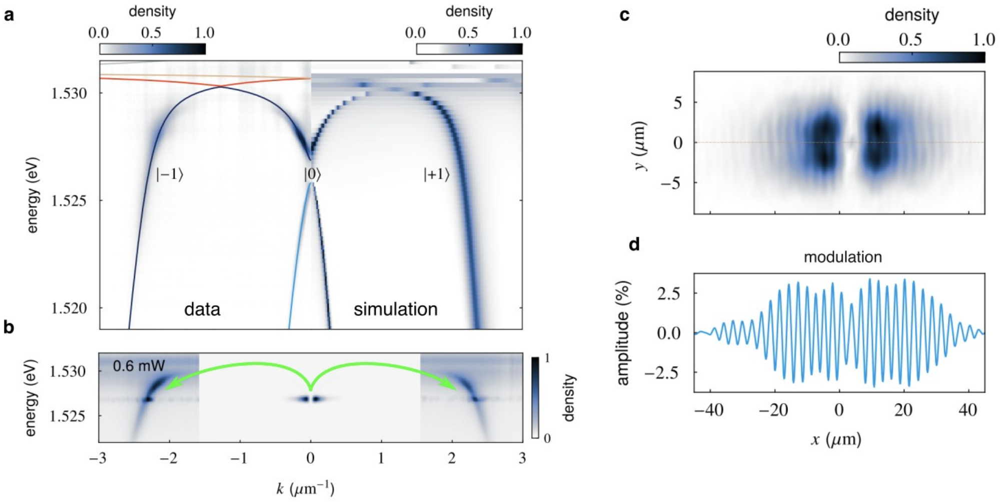

A supersolid is a counter-intuitive phase of matter where its constituent particles have a crystalline structure, yet they are free to flow without friction. This requires the particles to share a global macroscopic phase while being able to reduce their total energy by spontaneous self-organisation. This was achieved in different systems using Bose-Einstein condensates coupled to cavities, possessing spin-orbit coupling, or dipolar interactions. Here we propose and demonstrate a novel implementation of the supersolid phase made out of exciton-polaritons condensed in a topologically non-trivial bound-in-the-continuum state with exceptionally low losses [1,2]. We measure the density modulation of the polaritonic state indicating the breaking of translational symmetry with a remarkable precision of a few parts in a thousand. Direct access to the phase of the wavefunction allows us to additionally measure locally the coherence of the superfluid component. We demonstrate the potential of our synthetic photonic material to host phonon dynamics and a multimode excitation spectrum.

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Abstracts of Posters

(in alphabetical order)

Dissipative dynamics of photon Bose-Einstein condensates and fluctuations in a single-mode microcavity

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We investigate the driven-dissipative dynamics of open photon Bose-Einstein condensates in a single-mode microcavity filled with dye molecules using the Lindblad master-equation approach. In contrast to previous works[1], we perform a systematic cumulant expansion of the master equation[2]. This provides the temporal dynamics of the condensate amplitude, of the photon fluctuation and molecule excitation densities, and all other cumulants up to second order, including coupled dynamics of photon-molecule correlators. The latter turn out to be crucial. The steady state, obtained from the time evolution in the long time limit, leads to a rich phase diagram depending on the Jaynes-Cummings interaction strength and the experimentally tunable external pump power. We observe a condensation transition by tuning the pump power, followed by a decondensation transition at a larger pumping strength. A decondensation transition occurs also when the photon-molecule coupling is increased due to enhanced photon-molecule correlations which lead to a vanishing coherence of the photon system. Additionally, we observe a limit-cycle phase as well as a bi-stability region, where both the zero and non-zero condensate solutions coexist.

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Photon thermalization and potential indications for photon interaction in broad-area VCSELs

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The intriguing concept of photon condensation originally demonstrated in microcavities filled with dyes [1] has been more recently extended to semiconductor microcavities [2,3]. For a more systematic understanding of equilibrium and non-equilibrium phenomena, I am investigating electrically pumped broad-area vertical-cavity surface-emitting lasers (VCSELs) with a circular diameter of 200 μm using a microscope objective with NA 0.8 to image the spatial Fourier spectrum. Consistently an exponential decay of the strength of the photoluminescence vs modal energy is found, confirming thermalization of modes. For low injection currents, fits to the Boltzmann tail yield temperatures close to or somewhat above ambient temperature (280-340 K), which are increasing with increasing current, as one might expect. For higher injection currents, a peak structure is appearing in the photoluminescence spectra, which is however not at the lowest energy mode, and accompanied by a strong, but not complete saturation of the inferred chemical potential. This indicates a tendency towards photon condensation. The fitted temperatures drop again significantly with increasing current in this regime. The residual variation of chemical potential in the saturation regime is lower than the thermal shift of cavity-resonance and might indicate Kerr-like interactions between photons which are known to exist from earlier demonstrations of spatial solitons in these devices.

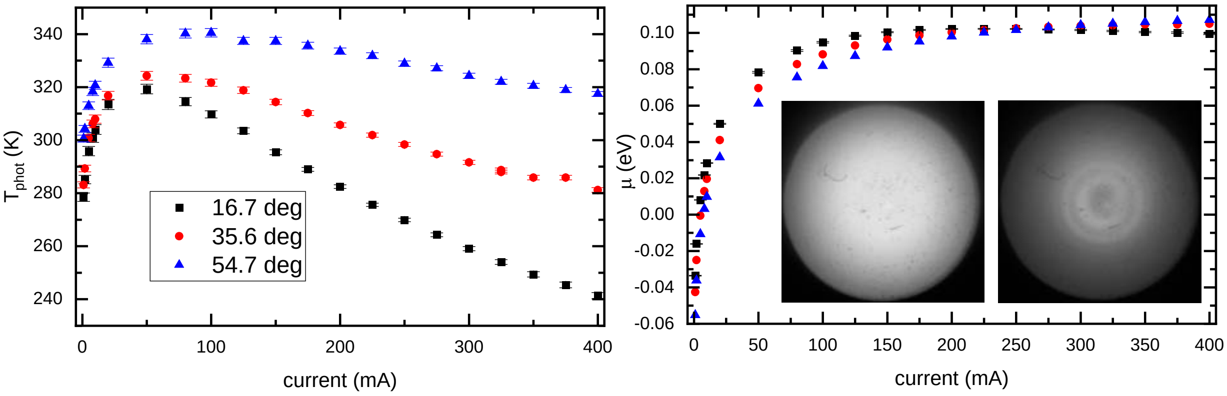

Fig. 1: Temperature (left) and chemical potential (right) of photons for three sub-mount temperatures. as extracted from a fit to the Boltzmann-tail between 0.01 and 0.02 eV from the ground state. The error bars include statistical errors but not uncertainties in calibration. The zero point of the chemical potential is arbitrary. Left (right) inset: Fourier space image at 10 (300) mA.

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Lasing improvement by silver nanoparticles in dye-doped multilayer polymer film systems.

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In this work, polyethylene glycol terephthalate (PET) film was spin-coated to create a dye-doped multilayer system. The impact of silver nanoparticles and mentioned sandwich-like film as a lasing medium were investigated. The outcomes demonstrate that the sandwich-like film has the ability to enhance photon scattering frequency and form a mirror symmetry plane. Additionally, the band-gap edge effect can effectively increase photon gain, which can then be used to achieve band-edge lasing and improve optical feedback. At the same pump energy, the lasing intensity in the sandwich-like film is almost higher than in the ordinary film system. Surface plasmon resonance of silver nanoparticles could be used as scatterers to increase the local electromagnetic field, which in turn improved the dye molecules' rate of transition. The combination of the scattering and plasmon resonance effects could increase the lasing intensity by 140% at the same pump energy. This fabrication technique is practical and simple to use, which helps to increase lasing intensity and offers a practical technical means of realizing a modulated laser.

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Organic room-temperature polariton condensate in a higher-order topological lattice

Christoph Bennenhei[1], Hangyong Shan[1], Marti Struve[1], Nils Kunte[1], Falk Eilenberger[2], Jürgen Ohmer[3], Utz Fischer[3], Stefan Schumacher[4], Xuekai Ma[4], Christian Schneider[1], and Martin Esmann[1]

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Organic molecule exciton-polaritons in photonic lattices are a versatile platform to emulate unconventional phases of matter at ambient conditions [1], including protected interface modes in topological insulators. Compared to cold atoms in optical lattices and exciton-polaritons in III-V semiconductors, which only operate at temperatures up to a few Kelvin, their main advantage are the less demanding experimental conditions at ambient temperature, which is enabled by the much larger excitons binding energy. In this work, we investigate bosonic condensation in the most prototypical higher-order topological lattice: a 2D-version of the Su-Schrieffer-Heeger (SSH) model, supporting both 0D and 1D topological modes. We study fluorescent protein-filled [2], structured microcavities defining a staggered photonic trapping potential and observe the resulting first- and higher-order topologically protected modes via spatially resolved photoluminescence spectroscopy. We account for the spatial mode patterns by tight-binding calculations and theoretically characterize the topological invariants of the lattice. Under strong optical pumping, we observe bosonic condensation into the topological modes. Via interferometric measurements, we map the spatial first-order coherence in the protected 1D modes extending over 10µm [3]. Our findings pave the way towards organic on-chip polaritonics using higher-order topology as a tool for the generation of robustly confined polaritonic lasing states.

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Low temperature optical thermodynamics for fusing incoherent pulse-trains

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The ability to merge temporal signals in a coherent fashion has been a long-standing technical challenge with paramount relevance in optical fiber communication technologies. While operating in the linear regime with narrow-linewidth sources, the problem is reduced to straightforward low-speed phase locking and polarization control. At high power, several nonlinear effects such as self-phase modulation and four-wave mixing conspire to immensely complicate the problem. Computationally expensive simulation techniques are required to accurately predict pulse dynamics within suitable error tolerances, while state-of-the-art control systems are needed to manage the many degrees of freedom of these complex systems.[1-3]

Recent work by our group has confirmed the theoretical possibility of utilizing the optical thermodynamic theory of light confined to nonlinear multimoded systems to combine optical fields which are mutually incoherent.[4] By combining the computational simplicity of working in a statistical model with the experimental capabilities of time-synthetic mesh lattices, we can quickly and efficiently model the fusion of pulse-trains which are incoherent with respect to each other.[5] By exciting pulse-trains corresponding to the fundamental and second-order modes of the mesh lattice structure, we predict a low temperature equilibrium for the four-wave mixing process which transfers most of the power into the pulse distribution associated with the fundamental mode, and artifacts of the mutual incoherence disappear. The content of our poster will outline our current progress towards experimentally realizing this phenomenon.

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Probing chaotic modes in nontrivial microcavity laser geometries

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Most commonly, top-emitting vertical-cavity surface-emitting lasers (VCSELs) have small mesas because large circular aperture devices are known to suffer from multimodal and unstable lasing, caused by current crowding effects at the edge of the aperture. Chaotic cavities have recently returned to the area of research interest, as VCSELs with chaotic cavities exhibit higher quantum efficiency, higher coherence, and higher stability [1, 2, 3].

In our contribution, we characterized individual modes of VCSELs of various geometries in both momentum and real space (near field and far field). We characterized and compared a standard circular and a broken symmetry crescent-shaped apertures and showed that breaking symmetry leads to more even lasing spatially. Moreover, using momentum space tomography, we measured the momentum distribution of the modes, which allowed us to characterize their chaotic nature in the broken-symmetry aperture. We also compare the current characteristics and output efficiencies of both devices pointing out the benefits of the chaotic aperture.

Our study shows the benefits of on non-symmetric VCSELs and provides promising prospects for their application due to their stability and homogeneity. Further research is needed to verify the stability in the multimodal emission of the chaotic cavity. We would like to study the dynamics of lasers with broken-symmetry apertures to compare them with the circular aperture characteristics.

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Experimental determination of the phase diagram of an exciton-polariton condensate in an optical trap

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Exciton polaritons, as bosons, can undergo Bose-Einstein condensation (BEC), forming a macroscopically coherent state after crossing a critical particle density. However, the spatial overlap of the high-energy excitonic reservoir and the condensate hinders reaching a coherent polariton BEC. This challenge sparked the innovative idea of optical trapping, a method that aims to separate the excitonic reservoir and the condensed polaritons [1]. By shaping the excitation laser beam into a ring, we create a circular potential trap due to repulsive interactions between polaritons and excitons. This novel approach, distinct from previous studies that used a Gaussian-shaped laser beam for sample excitation, is yet to be fully understood in terms of the condensation phase diagram of optically trapped exciton-polariton BECs.

In this comprehensive study, we experimentally investigated the polariton condensation inside an optical trap using a GaAs-based microcavity sample. The structure was nonresonantly excited with a pulsed laser shaped into a ring to obtain an effective circular potential. Our extensive power-dependent investigation of polariton condensation at various photon-exciton detunings in three different trap diameters revealed significant findings. We discovered the most favorable trap size that allows for ground state condensation in a wide range of detunings, including strongly photonic polaritons, which hasn't been observed in previous studies with homogenous excitation. Moreover, the detuning dependency on the condensation threshold power showed different trends compared to those known from the single-spot excitation phase diagram [2-3]. These results are a major advancement in our understanding of polariton condensation in optical traps and have the potential to optimize the operation of coherent polaritonic devices in the trapped geometry.

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Shaping pulses of light for controlling quantum systems

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Technological advances in optics now enable the full spatial and temporal control of pulses of light. For example, spatial structuring of their amplitude and phase can be obtained using spatial light modulators, digital micromirror devices or deformable mirros while temporal shaping can be realized with acousto-optic modulators. These techniques are currently used in wide range of applications for manipulating quantum systems.

We have developed an arbitrary waveform generator for light using a double pass acousto-optic modulator which enables on-demand amplitude and phase modulations down to light pulse duration of less than 100 ns in a compact rack-mountable setup. By measuring the amplitude and the phase with a Mach-Zehnder interferometer, it is possible to precisely obtain the desired pulse after few iterations of feedback loop correction onto the radio frequency signal that drives the acousto-optic modulator.

This technology paves the way to perform high-fidelity quantum gates on atomic qubits [1,2] or to generate novel fluids of light in propagating geometry in settings where the temporal degree of freedom is relevant [3].

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Spectroscopy of Heteronuclear Xenon-Noble Gas Dimers - Toward Bose-Einstein Condensation of Vacuum-UV Photons

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Photons confined in a dye-filled optical microcavity can exhibit Bose-Einstein condensation upon thermalization through repeated absorption and (re-)emission processes by the dye molecules. This has been experimentally demonstrated for photons in the visible spectral regime in 2010.[1] In this work, an experimental approach is investigated to realize Bose-Einstein condensation of vacuum-ultraviolet (100nm-200nm; *VUV*) photons via repeated absorption and (re-)emission cycles between two electronic state manifolds of xenon-noble gas excimer molecules in dense gaseous ensembles (pressure of up to 100bar). (Re-)emission and absorption to achieve thermalization are considered to occur between the quasi-molecular states associated with the xenon $5p^6(J = 0)$ and $5p^5 6s(J = 1)$ states, respectively. A Bose-Einstein condensate of VUV photons would serve as a coherent light source. We plan to pump the photon gas inside a high-pressure optical microcavity with light near 129nm wavelength, which can be generated by third-harmonic generation of near-ultraviolet light around 387nm.[2] The pump drives the $5p^6(J = 0) \rightarrow 5p^5 6s'(J = 1)$ transition in xenon. We report on the results of spectroscopic measurements, indicating the formation of heteronuclear noble gas excimers. Also, the fulfillment of the thermodynamic Kennard-Stepanov relation, a fundamental prerequisite for a gas to serve as a thermalization medium, has been successfully investigated.

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Bound states in the continuum in subwavelength periodic structures compatible with semiconductor technology

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Bound states in the continuum (BICs) facilitate the confinement of electromagnetic waves to subwavelength dimensions with an infinite quality (Q) factor. Optical BICs represent nonradiating electromagnetic resonant states localized in open photonic systems (above the light line), although they coexist with a continuous spectrum of unbounded states. BICs open a possibility that a single thin layer with a periodic refractive index distribution can be high Q-factor resonator enabling small mode volumes. BIC-based cavities open new possibilities in diverse applications and research fields, such as strong light-matter interactions, Bose–Einstein condensation, superfluidity, Raman scattering, and single photon sources.

However, the realization of BIC-based cavities requires configurations with up-down symmetry that in real-world designs utilize a membrane suspended in air or sandwiched between layers with matching refractive indices on both top (superstrate) and bottom (substrate). Such configurations pose difficulties in fabrication and are susceptible to collapse in the case of membrane arrangements.

Here, we employ numerical analysis and experimental demonstrations to showcase an approach that breaks vertical symmetry. By implementing periodic structures on a uniform high refractive index substrate or on judiciously designed distributed Bragg reflector (DBR) with an air superstrate, we successfully achieve BICs. Our numerical analysis, based on a three-dimensional fully vectorial optical model, reveals that configurations with broken up-down mirror symmetry enable robust light confinement within the gratings, resulting in small mode volumes and large Q-factors. These findings are verified by the experiments in which we investigate configurations realised in GaN- and GaAs-based configurations, demonstrating great freedom in the design of BIC-based cavities.

Continuous-Wave Nonlinearity and Polarization Rotation in a Perovskite Cavity

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Optical nonlinearities and birefringent media have enabled the exploration of fascinating many-body states of light and spin-orbit coupling phenomena in optics, respectively. However, to date, the combination of a strong continuous-wave nonlinearity and birefringence in condensates of light has remained elusive. Here we present experiments demonstrating strong continuous-wave nonlinearity and birefrigence in a $CsPbBr_3$ perovskite cavity. Our perovskite cavity exhibits bistability when probing a single mode, and signatures of tristability when probing nonlinearly coupled orthogonally-polarized modes. Our experiments reveal intriguing physics emerging from the interplay of polarization and nonlinearity in this system. We furthermore explore the temperature dependent optical hysteresis of our cavity, and we discover a surprising boost of the nonlinearity at a specific temperature. We suspect that the perovskite semiconductor we study undergoes a phase transition at that temperature, thereby opening up fascinating perspectives for exploring strongly correlated states of light in this system.

Observation of a 2D soliton gas in a quantum fluid of light

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In the context of nonlinear systems described by the nonlinear Schrodinger equation (NLS), the concept of soliton gas has gained attention in recent decades [1]. Theoretically described as an N-soliton solution of the NLS, and experimentally observed in 1D systems, the soliton gas still lacks a deep comprehension of the formation process. Moreover, the theoretical description relates to the analytical solutions of the 1D NLS, and cannot predict the behavior of multi-dimensional systems. The experimental investigation of soliton gases in higher dimensions is crucial for extending the 1D phenomenology to non-integrable systems. We report the observation of a two-dimensional soliton gas in a photon flow in a nonlinear optical crystal. The propagation occurs in a photorefractive crystal with saturable Kerr-type nonlinearity that can be reduced to the 2D NLS in the low-intensity limit [2]. The novelty of the work lies in the laser 2D wavefront manipulation to control the initial condition of the nonlinear propagation. This platform allows us to explore the nonlinear propagation of a 2D box, generalizing the 1D dam-break problem [3,4]. By precisely shaping both the amplitude and phase of the input wave, we investigate the transition from one-dimensional to two-dimensional extreme wave formation. The observations report the formation of shock waves regularizing the intensity discontinuities, the wave-breaking of the box in both the transverse dimensions, and the formation of localized 2D objects forming a gas. We analyzed the statistical properties of the gas. The intensity statistical distribution confirms the randomness characterizing the peaks in a soliton gas. The open questions are many and the topic needs further exploration, however, our findings broaden the understanding of soliton gas dynamics in two dimensions, demonstrating that the loss of integrability does not disrupt the fundamental soliton gas phenomenology.

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Realization Of Higher Order Topological Insulators In Hybrid Dielectric-Semiconductor Microcavities

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Since its introduction to the polariton community by El Daïf and co-workers in 2006 [1], the etch-and-overgrowth method has been a very versatile technique for the generation of photonic confinement. It is perfectly suited to manufacture large, uniform and complex potential landscapes since the confinement, as well as its coupling can be finely tuned by controlling the etch-depth [2].
Here, we improve on this method by using a dielectric top mirror consisting of SiO_2/TiO_2 layers instead of an epitaxially grown one.

In recent years, topological photonics has emerged as a powerful tool to engineer traits of optoelectronic applications [3]. We implement 0-dimensional higher order topological defects in a *breathing* Kagome lattice, as well as a 2-D Su-Schrieffer-Heeger (SSH) lattice.
Additionally, we show polariton lasing from the corner defect of the breathing Kagome lattice and the 0-D defect of the 2D-SSH lattice, as well as their coherence properties [4].

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Positive-P simulations for open quantum spin systems

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The positive-P method [1] is a numerical method by which quantum mechanical observables can be calculated from appropriate averages over stochastic trajectories in a phase space defined by bosonic coherent states. The method is both easily scalable to very large systems and exact to quantum mechanics in the limit of sufficiently large numbers of stochastic realisations but, for closed systems, self-amplification of the noise results in instabilities that limit useful results to short times. However, in recent work we demonstrated that for open quantum systems sufficiently strong dissipation can stabilise the method indefinitely [2], making it a potentially very powerful tool for simulating the many-body quantum physics of various photonic platforms in appropriately dissipative regimes. To broaden the range of physical systems accessible to this method, we now wish to extend it from purely bosonic models to those that also contain spin-1/2 degrees of freedom, such as are often applied in the context of cavity and circuit QED. We explore two ways that have been previously established in closed systems for adapting the positive-P method to spins: 1) using a Schwinger-Boson transformation to map the spins to bosons [3]; 2) defining a phase space for the spins directly using SU(2) coherent states [4]. We have implemented the positive-P method for a driven-dissipative Jaynes-Cummings model using both these approaches, and use these to characterise how the stability of the method is affected by the strength of various forms of dissipation on the spins or bosons, relative to each other and other parameters such as drive and interactions.

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Arcsine laws and weak ergodicity breaking in light

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Consider a laser-driven resonator operated as a sensor. The goal is to detect perturbations to its resonance frequency by monitoring the time-integrated transmitted or reflected intensity. Given a time budget to estimate the mean time-integrated intensity, we pose the question, what yields a better estimate: one measurement of duration τ, or m independent and identically distributed measurements of duration τ/m? For ergodic processes, both approaches are equally accurate. However, we have recently shown that the time-integrated intensity emitted by a linear resonator breaks ergodicity "weakly" [1,2]. This effect is a consequence of Lévy's arcsine laws [see Fig. 1], which are a cornerstone of extreme value statistics. In this contribution, we present the first experimental demonstration that light in a coherently-driven resonator follows the arcsine laws. We elucidate the origin of these arcsine laws and discuss their important implications for optical sensing using coherently-driven resonators.

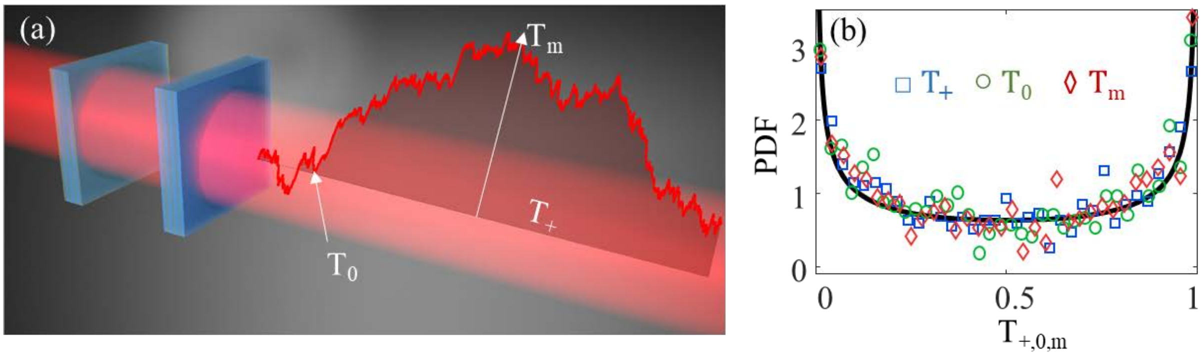

Figure 1: (a) Laser-driven single-mode optical microcavity. Shown alongside is a sample random trajectory of the time-integrated intensity transmitted through the cavity, relative to its average. Indicated on the trajectory are the time spent above the average (shaded area, T_+), time of last crossing of the average (T_0), and time of maximum deviation from average (T_m). (b) Probability distributions (PDF) of $T_{+,0,m}$ plotted with blue, green and red markers respectively. The black line corresponds to the theoretical distribution shared by $T_{+,0,m}$, as predicted by Paul Lévy's arcsine laws.

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ASIP: A minimal model for incoherent bosonic transport

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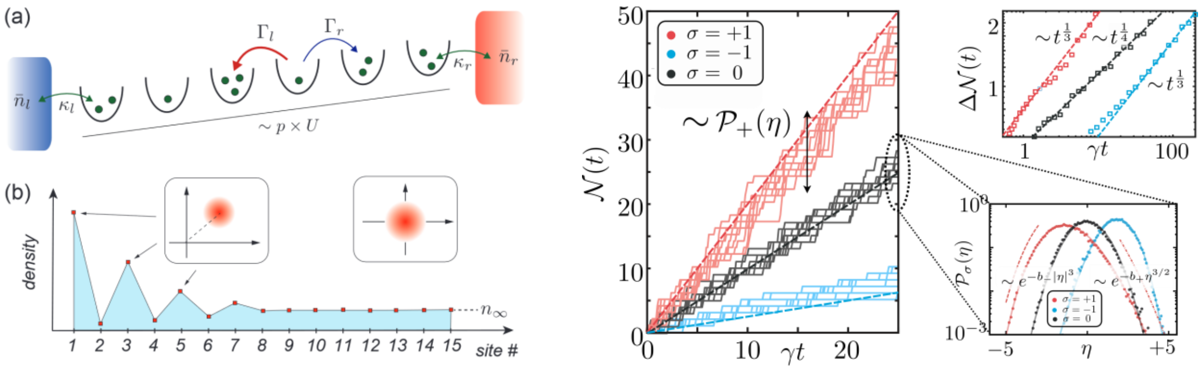
I will discuss a model describing the incoherent transport of bosonic particles through a one dimensional lattice, called **asymmetric simple inclusion process** (ASIP). Despite the absence of coherences and interactions, a signature of the Bose statistics survives: specifically, hopping to a site is **amplified** if this site is already occupied, in an effect of "stimulated transport", akin to stimulated emission. This model could be used to describe fluids of light in the strong-dephasing regime. The rich phenomenology of this model includes the formation of complex distributions alternating between thermal and condensed states; current fluctuations belonging to Kardar-Parisi-Zhang universality class; and connections to certain non-Hermitian topological models.



Left: (a) Sketch of the ASIP setup: Bosons injected from a thermal particle reservoir on the right can incoherently hop along the lattice with asymmetric rates Γl and Γr , before being emitted into a second reservoir on the left. (b) Under stationary conditions, we observe the formation of a finite boundary region with a staggered density profile; the number distribution alternates between thermal distribution and condensed states with broken U(1) symmetry. **Right:** number of jumps going through the origin versus time. Its variance shows a skewed Tracy-Window distribution, which grows in time following a t^1/3 scaling law; this indicates the current statistics belongs to the KPZ universality class.

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Selective organic polariton condensation in individual states of a 1D topological lattice

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Arrays of coupled exciton-polariton condensates have recently emerged as a promising semiconductor-based platform for analogue quantum simulations. However, the traditionally utilized monolithic cavity configurations significantly limit the possible range of tuning and control.

Here, we use a wavelength-tunable cavity with an organic active layer to demonstrate room temperature, selective condensation of polaritons in individual states of a one dimensional (1D) topological lattice. The investigated lattice is comprised of adjacent sites with alternating bond strength, a so called Su-Schrieffer–Heeger (SSH) chain.

First, we perform below threshold, angle-resolved photoluminescence measurements to populate the lattice's bandstructure. Locally exciting the center of the structure reveals a bandstructure comprised of S-like and P-like energy bands. Repeating the measurement at the edge of the structure leads to the observation of a discrete topological edge state which appears inside the first energy gap. Next, we drive the system above condensation threshold. Using the tunability of our cavity and a vibron assisted relaxation mechanism, unique to organic materials, we can selectively condense polaritons to individual states of the 1D topological lattice (Fig. 1). Using a Michelson interferometer we investigate the coherence of the condensates, which spatially extends through almost the whole structure. Finally, we showcase engineering of the energy gap and of the topological edge state localization by tuning the coupling strength within the subunits of the SSH chain.

These results showcase the potential of our highly engineerable and tunable platform for the study of topological effects and complex potential landscapes at room temperature.

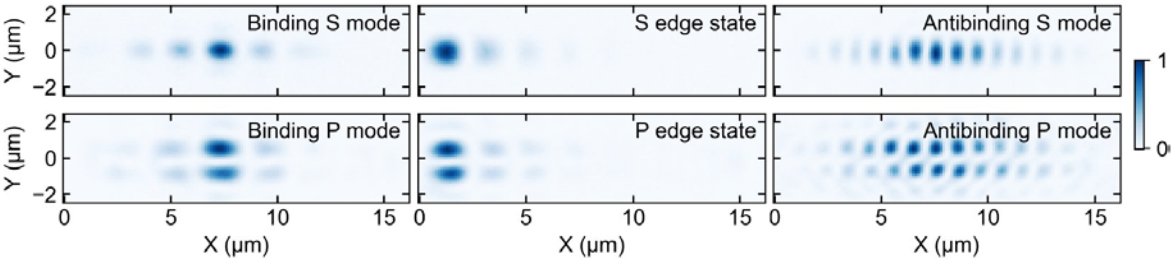

Figure 1: Real space images of polariton condensates selectively formed in six different modes of the studied lattice. The colorbar indicates the normalized emission intensity.

Optical quantum gases in box and ring potentials

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Quantum gases provide exquisite experimental control over dimensionality, shape of the energy landscape or the coupling to reservoirs, which opens the door to investigate novel states of matter both in and out of equilibrium.

Here we report on the experimental realization of a quantum gas of photons inside box and ring-shaped potentials within a dye-filled optical microcavity. The trapping potential for the particles is provided by imprinting static nanostructures on the cavity mirror surface using a laser-induced delamination of the mirror coating. In a corresponding box-shaped cavity geometry, we have realized a 2D optical quantum gas at room temperature with uniform density and measured its compressibility and equation of state. In more recent work, we have achieved the quasi-1D, periodically closed confinement of photon gases in ring potentials. Prospects of this work include studies of the Kibble-Zurek mechanism and of flux qubits.

Room Temperature Exciton-Polariton Lasing and Photonic Lattices with a Perylene Bisimide based Microcavity

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Perylene bisimides (PBIs) are organic dyes with photoluminescence quantum yields (PLQY) close to unity and excellent thermal and photo-chemical stability [1]. These features, as well as the tunability of their solid-state packing via chemical functionalization, make this material class a promising candidate for polariton lasing at room temperature. While strong light-matter interaction is well understood in conventional III-V semiconductor systems at cryogenic temperatures, the search for suitable emitter materials for robust and versatile room temperature applications is still ongoing. So far, several organic materials are found to show strong light-matter coupling and polariton lasing. Nevertheless, many of these materials lack long-term stability under ambient conditions and the tunability of their optical properties.

In this work, we fabricated optical microcavities with a neat emitter layer of a PBI monomer [2] that is shielded by voluminous bay-substituents to prevent aggregation induced PLQY-quenching. We show strong light-matter coupling with a Rabi splitting of $\hbar\Omega_R = 98\,\text{meV}$ and exciton-polariton lasing at room temperature. Furthermore, photonic confinement in zero-dimensional resonators and chains of coupled resonators is demonstrated. While the first case shows modes with dispersionless discretization in energy and atomic orbital-like shape, the coupling in a linear chain leads to the formation of a distinct band-structure. Our results pave the way for the study of non-linear bosonic systems in artificial lattices hosting a highly stable PBI as solid-state emitter. Furthermore, due to the possibility of precisely controlling the aggregation properties of the PBI, polarization dependent light-matter coupling including topological or non-Hermitian effects can be studied with PBI J-aggregate containing resonator structures.

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Phase-only spectral shaping of photons from a quantum dot source

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Semiconductor quantum dots are a promising source of single photons for hybrid quantum networks [1, 2]. Typically, the wave packet of photons emitted from a single emitter has a mono-exponentially decaying temporal profile, which is incompatible with the absorption profile of many quantum information processing units such as quantum memories [3]. The ability to modulate spectro-temporal phase of single photons is an important capability in the context of quantum information processing and distribution [3]. Here, we demonstrate spectral-shift and sideband generation of single photons emitted from a quantum dot using electro-optic phase modulation. These results are a step towards unitary pulse shaping of photons emitted from a single quantum dot.

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Dimensional crossover in a quantum gas of light

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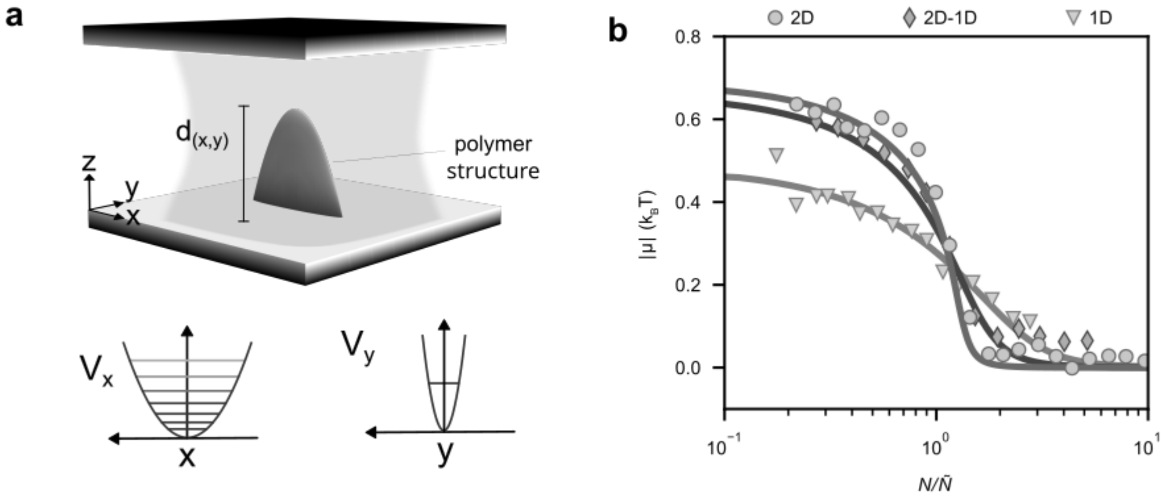
We experimentally study the properties of a harmonically trapped photon gas undergoing Bose-Einstein condensation[1] along the dimensional crossover from one to two dimensions. The photons are trapped in a dye microcavity where polymer nanostructures provide the trapping potential for the photon gas (see Figure). By varying the aspect ratio of the harmonic trap, we tune from an isotropic two-dimensional confinement to an anisotropic, highly elongated one-dimensional trapping potential[2]. Along this transition we determine the caloric properties of the photon gas and find a softening of the second-order Bose-Einstein condensation phase transition observed in two dimensions to a crossover behaviour in one dimension[3].



a The polymer structure with refractive index n_s in the cavity surrounded by dye solution with $n<n_s$ results in an attractive potential $V \propto d_{(x,y)}(n-n_s)/n$ for the trapped photon gas. **b** The change from a phase transition in 2D to a crossover in 1D is visible in the chemical potential.

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Fluids of Light in Disordered environments

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Nonlinear photonics has opened up a fascinating field known as " Quantum Fluids of Light." In this realm, photons take on unique properties, essentially acquiring an effective mass and engaging in precisely controlled effective repulsive interactions. This behavior bears a striking resemblance to how particles behave in quantum fluids, such as Helium-4 [1,2] or atomic Bose-Einstein condensates [3]. It's this intriguing parallel with such original physical systems that has ignited a surge in exploration of the field.

The growing interest in this field is fueled by the versatility and adaptability of photonic experimental platforms, giving access to features unreachable in genuine systems.
Indeed, different setups, including semiconductor microcavities [4] and propagating geometries [5], offer the means to control and manipulate the behavior of photons in the fluids of light framework.

At INPHYNI, we focus on the latter approach, using a photorefractive crystal [6-8] that allows us to manipulate the optical index in a highly flexible and reconfigurable manner [9]. In a significant recent development, our group successfully reported a direct experimental observation of the transition to superfluidity of a fluid of light past an obstacle.

Looking ahead, our research is set to explore the transition from spatial localisation to superfluidity in complex, but fully controlled environments. This transition promises to yield strong turbulence in the system and it will be investigated as well.

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Non-equilibrium dynamics of photon BEC in a chain of optical cavities in the presence of disorder

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The driven-dissipative system consisting of microcavities filled with dye molecules is of great interest due to the realization of photon Bose-Einstein condensates (BEC). The interplay of various coherent and incoherent processes involved in this system allows us to study various non-equilibrium phenomena as well as the dissipative dynamics of the photon BEC. We investigate them within the Lindblad master equation formalism and study the dynamics of coherent photons in the presence of incoherent photon fluctuations. By considering a chain of microcavities coupled via direct hopping of cavity photons, we study the expansion dynamics of both coherent and non-coherent photons, which leads to different velocities of their time evolution. Finally, in the presence of disorder, the dynamics of the photon cloud exhibit localization phenomena in this driven-dissipative system.

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Vortices in photon Bose-Einstein condensates

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Open dissipative systems of quantum fluids, especially in presence of vortices, are well studied numerically in Refs. [1-3]. Motivated by that we strive for finding a corresponding approximate analytical description of photon Bose-Einstein condensates in the presence of vortices. To this end we consider the complex Gross-Pitaevski equation of Ref. [3] and extend the variational approximation to open dissipative systems [4,5] in such a way that it is not only working for specific functions. To this end we develop a variational projection method and combine it with known methods from hydrodynamics. With this we approximately obtain a vortex solution and its corresponding velocity field, where depend on the respective open system parameters and have the same properties as obtained numerically in Ref. [2].

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Ultrafast optical control of polariton energy in an organic semiconductor microcavity

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We present a strategy [1] for the ultrafast control of polariton resonances via transient modification of an optical cavity mode. We have constructed multilayer organic semiconductor microcavities that contain two absorbers: a BODIPY-Br dye that is strongly-coupled to the cavity photon mode and a UV-absorbing conjugated polymer that is out-of-resonance. By selectively exciting the out-of-resonance polymeric absorber using ultrashort laser pulses, we modulate the cavity refractive index and generate fully-reversible blueshifts of the lower polariton branch by up to 8 meV in sub-ps timescales with no corresponding reduction in the exciton-photon coupling strength. Our work demonstrates the ability to manipulate polariton energy landscapes over ultrafast timescales.

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On the validity of Kirchhoff's law in the lasing and photon Bose-Einstein condensation regimes

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In 1860, Kirchhoff showed that the radiance emitted by a hot body is the product of its absorptivity by a universal function of temperature and frequency which he defined as blackbody radiance. With the advent of semiconductors, it has been shown that Kirchhoff's law can be extended to account for electroluminescence and photoluminescence in a cavity. Here, we investigate if Kirchhoff's law can also be used in the lasing regime. We show that both the absorptivity and Planck's function becomes negative beyond the transparency threshold. This ensures the validity of Kirchhoff's law in presence of gain. We then unveil the lasing condition by carefully analysing the resonant negative absorptivity [1]. Then, basing on a recent connection made between standard lasing and Bose-Einstein condensation of photons [2], we show that our result can be generalized to Bose-Einstein condensates of light in dye-solution-filled or semiconductor cavities. We finally show on a VCSEL example that Kirchhoff's law enables modelling with a high level of accuracy important features of the lasing or condensation regime, such as the frequency, directivity and polarization of the first lasing mode [1].

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Towards topological edge states of photons by controlled coupling of photon condensates to the environment

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Topology is an important paradigm for our understanding of phases of matter in condensed matter, cold atoms and photonic systems. Here we present a new approach to realize topological states, which result from coupling the system to an environment. In a proof-of-principle study, we first experimentally demonstrate open-system topological states using a plasmon-polariton waveguide platform. The underlying, a priori topologically trivial lattice consists of a unit cell of four lattice sites which is equipped with spatially varied losses leading to a topological band structure. By tuning the hopping and the dissipation in the waveguide system, we observe both the emergence and the breakdown of a localized topological edge state.

Moreover, we present ongoing work, in which we develop an experimental platform to study non-Hermitian topological states in lattices of photon Bose-Einstein condensates within a dye-filled optical microcavity. The coupling to the reservoir of dye molecules here allows for gain, thermalization and tunable coherence properties of the photons, opening new pathways for the exploration of topological states in open systems. Finally, the latest developments in the experimental setup are presented, showing concrete solutions to challenges in the experimental realization.

Signatures and control of topological phases of interacting photons in a driven-dissipative non-linear cavity array

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We investigate topological phases and symmetry protected edge states by probing the optical response of a Su-Schrieffer-Heeger lattice of strongly non-linear optical microcavities. The absorption spectrum and intensity correlations of the non-equilibrium steady state of the interacting photons show clear signatures of fermionized topological phases due to a correlation induced Bose-Fermi mapping. We perform a detailed analysis to investigate the onset of these phases and show how one can selectively excite edge modes, bulk modes or both via fine-tuning experimentally accessible parameters.

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Inverse solving the Schrödinger equation for precision alignment of a microcavity

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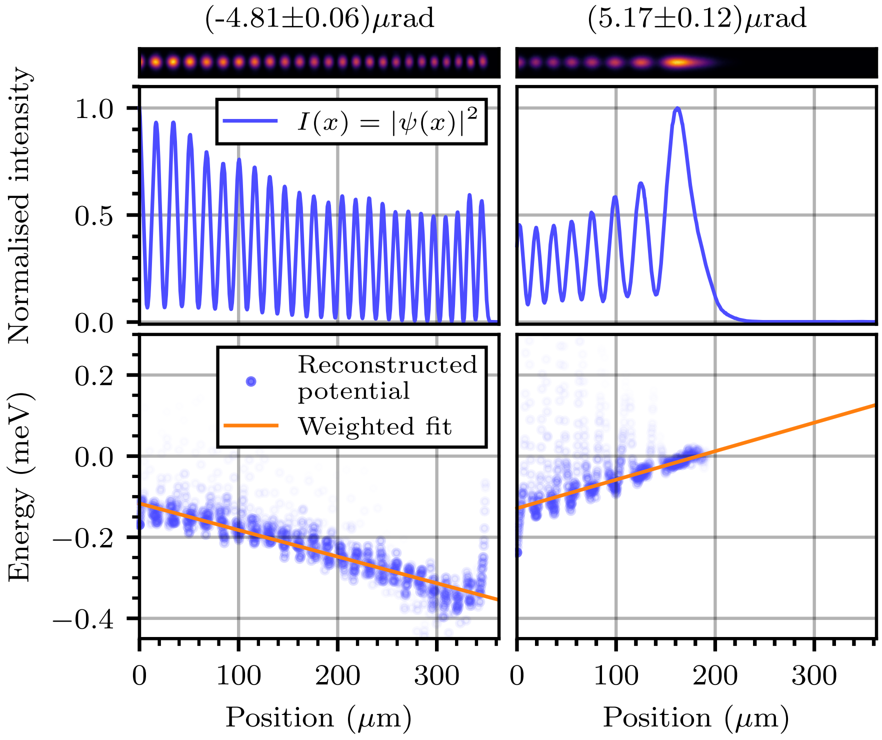
In paraxial approximation, the electromagnetic eigenmodes inside an optical microresonator can be derived from a Schrödinger-type eigenvalue problem [1]. In this framework, tilting the cavity mirrors effectively introduces a linear potential to the system. In our work, we apply solution strategies for inverse problems to precisely determine and control the relative orientation of two mirrors forming an optical microcavity. Our approach employs the inversion of the Schrödinger equation to reconstruct the effective potential landscape, and thus mirror tilts, from observed mode patterns. We investigate regularization techniques to address the ill-posed nature of inverse problems and to improve the stability of solutions.



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Bose Einstein condensates and quantum memories for future space based communication systems

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Quantum memories will have an important role in future secure quantum communication systems including space based operation. Some complex quantum systems have been demonstrated in space environment, including Bose Einstein condensates. In this contribution we review the field, discuss the state of the art and proposed missions [1,2]. And link the discussion into our ongoing and planned activities.

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Exciton-polariton ring Josephson junction

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The Josephson effect manifests in both fermionic and bosonic systems and has been extensively studied in superfluid helium[1,2] and atomic Bose-Einstein condensates[3-6]. While exciton-polaritons can aid the transition to integrated semiconductor platforms, realizing weak links in ring geometries has proven challenging. In this study we realize a Josephson junction in a polariton ring condensate, where we induce a net circulation around the ring using an optical barrier. Our experiments reveal two distinct regimes of the polariton weak link: a hydrodynamic regime with a linear relation between the phase jump at the barrier and the average current around the ring, and a Josephson regime characterized by sinusoidal behavior, where mass transport through the barrier drops to zero. The appearance of these regimes can be explained from energy considerations in a "tilted washboard" potential.

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On the theoretical description of photon gases in the dimensional crossover

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A new experimental platform for photon Bose-Einstein condensates, which has recently been built up in Kaiserslautern, is devoted to analyse the dimensional crossover in trapped photon gases from 2D to 1D [1]. As the photon-photon interaction is generically quite weak, they behave nearly as an ideal Bose gas. Moreover, since the current experiments are conducted in a microcavity, the longitudinal motion is frozen out and the photon gas represents effectively a two-dimensional trapped gas of massive bosons, where the anisotropy of the confinement allows for a dimensional crossover. A detailed investigation for such a system allows to determine its effective dimensionality from thermodynamic quantities [2]. Furthermore, we investigate how the effective photon-photon interaction [3] changes when the system dimension is reduced from 2D to 1D via an anisotropic harmonic trapping potential [4]. For increasing anisotropy we find that the thermo-optic interaction strength increases at first linearly with the trap aspect ratio and later on saturates at a certain value of the trap aspect ratio. In addition, we work out a Hamiltonian description of the effective photon-photon interaction that includes the thermal cloud and, thus, resembles a Hartree-Fock analogue theory for this kind of interaction [5]. Using an exact diagonalisation approach [6], we find that for larger trap aspect ratios the contribution of the thermal cloud can not be neglected in the analysis of experimental data.

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Direct probing of the local chemical potential for photonic gas in a broad-area VCSEL

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Thermalized photon gas trapped in an optical microcavity can undergo a Bose-Einstein condensation phase transition [1]. Chemical potential is a crucial parameter for determining the gas's thermodynamic state; for a Bose-Einstein condensate, its value should vanish at the transition point. However, recent theoretical developments [2] have predicted that a photon gas can experience nonuniform thermal bath properties in real-world devices. This underscores the importance of a detailed measurement of the local chemical potential in microcavities, which is necessary to accurately quantify semiconductor lasers as BEC of photons [3].

Broad-area electrically pumped vertical-cavity surface-emitting lasers (VCSELs) are susceptible to uneven current and temperature distribution within the laser aperture. This leads to a distribution of the chemical potential value, set by the local difference between quasi-Fermi levels for electrons and holes in the active region. Our study presents a novel approach for determining the inhomogeneous distribution of the chemical potential and the effective temperature of a thermalized photon gas in broad-area oxide-confined VCSELs. We locally probe the photon gas energy spectrum by filtering the laser's near-field emission. We extract the energy distribution by integrating the spectrum in momentum space (far field) and fit it with the Bose-Einstein distribution to obtain the local thermodynamic quantities. This method allows us to test the theoretical predictions [2] and provides unique insight into the thermalization of photon modes with different overlap with high- and low-density current regions in the device.

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Network of phase frustrated photon Bose-Einstein condensates

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A novel approach to tackling computationally challenging problems involves utilizing a physical system of coupled Bose-Einstein condensates (BEC). The problem of finding a ground state of a network of BECs can be mapped in polynomial time to any problem of the NP-Complete class. In our network, we use photonic BECs (pBECs) [1] which rapidly reach their lowest energy state, typically within a fraction of a nanosecond, after which they can be subjected to interference to extract relative phases. These phases are then interpreted as a solution to the original problem. In our setup, we employ a cavity formed by two highly reflective Bragg mirrors, a dye serving as a thermalizing agent, and a green laser acting as a photon source. Additionally, by nanostructuring [2] one of the mirrors, we achieve transverse confinement of the pBECs. We will present our latest findings on a system of negatively coupled triangular arrangement of pBECs exhibiting spin frustration.

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Exceptional points and non-Hermitian phase transition in non-linear binary systems

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A non-Hermitian Hamiltonian describes an open system that does not satisfy the condition of Hermiticity ($H \neq H^{\dagger}$). In this sense, the presence of a complex spectrum and the existence of so-called exceptional points (EPs) lead to counteractive phenomena [1]. In general, in a linear system the presence of EPs is independent of the stability of the stationary state. However, in a nonlinear system, more than one solution may be stable, which gives rise to the phenomena of bistability and multistability. In this work, we investigate a non-Hermitian binary model, accentuating the significance of nonlinearity in a non-Hermitian phase transition [2]. This model can describe a wide range of physical systems, including simple coupled oscillating modes, but also allows to describe two-component homogeneous systems. We present a general phase diagram including EP and endpoint of first-order-like phase transition (ET) (marked by stars in Fig. 1). We find that the equivalence of the endpoint to an exceptional point as found in [3] is no longer valid in the general case. Moreover, we find a regime of limit cycle solutions due to a Hopf bifurcation (C-line), which eventually disappears at an exceptional point.

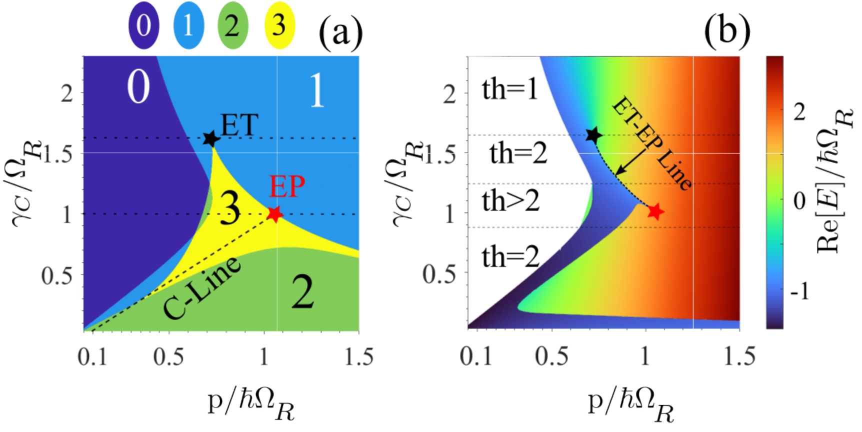

Fig. 1: In (a) the number of stationary states is marked with colors. In (b) only the lowest-energy stable state is shown

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Bose-Einstein Condensation of Photons in a Four-Site Quantum Ring

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Thermalization of radiation by contact to matter is a well-known concept, but the application of thermodynamic methods to complex quantum states of light remains a challenge. Here we observe Bose-Einstein condensation of photons in the hybridized ground state of a four-site ring-shaped potential with coherent tunnel couplings [1]. In our experiment, the periodically-closed ring lattice superimposed by a weak harmonic trap for photons is realized inside a spatially structured dye-filled microcavity. Photons thermalize to room temperature, and above a critical photon number macroscopically occupy the symmetric linear combination of the site eigenstates with zero phase winding, which constitutes the ground state of the system. The mutual phase coherence of photons at different lattice sites is verified by optical interferometry.

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Skyrmion lattice formation in a spin-orbit coupled spin-1 Bose-Einstein condensate

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We explore topological excitations in a spin-1 Bose-Einstein condensate subjected to an in-plane sinusoidally varying magnetic field and Rashba spin-orbit coupling (SOC). In the absence of SOC, the periodic magnetic field induces vortex-anti-vortex structures in the |F = 1, mF = ±1⟩ condensates at saddle-points, such that the net topological charge remains zero. The introduction of Rashba SOC breaks the system's symmetry, leading to non-conservation of overall angular momentum in the spin-1 condensate. This anisotropy results in the emergence of certain skyrmion spin textures. We provide a comparative study for various in-plane magnetic field configurations while keeping the SOC strength constant. Our numerical simulations within the mean-field framework reveal the potential to engineer diverse topological excitations controlled by the interplay between spin-orbit coupling and in-plane magnetic field in a spinor condensate.

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Continuously Sustained Semiconductor Mediated Photon BEC in a Planar-Spherical Microcavity

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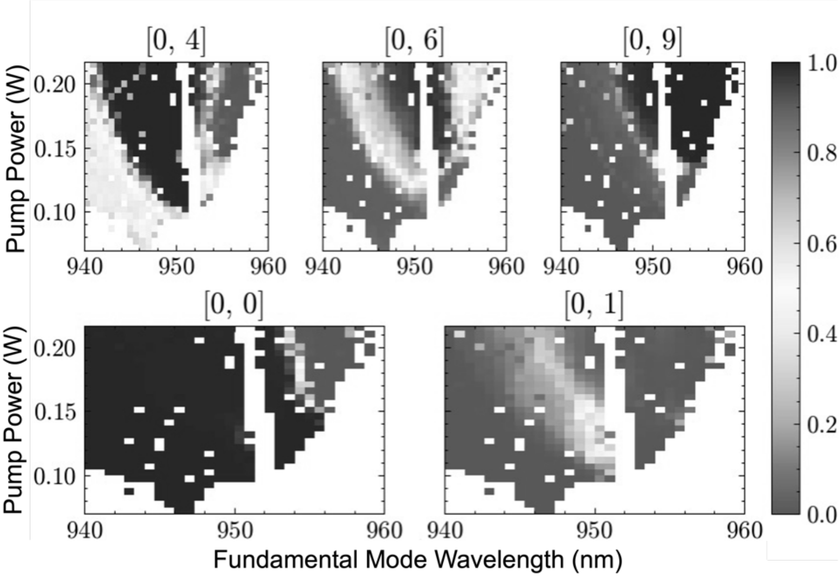
I will detail our measurements of various properties of our continuously sustainable semiconductor mediated photon Bose-Einstein condensation (BEC) in an open planar-spherical microcavity [1]. These include the phase changes of the system as we vary intensity and cavity length, and therefore condensate energy. We use images of the condensate and a convolutional neural network (CNN) trained on generated images of cavity modes to not only identify phases, but the cavity modes that constitute them. The figure shows the likelihood of given mode being occupied as a function of the cavity length and pump power. The use of images allows for phase categorisation of significantly larger systems than previously studied [2]. I will also discuss the coherence properties of the condensate and relate these to theoretical [3] and experimental studies on dye-based condensates and conventional semiconductor lasers. Finally, I will discuss future directions for our research.



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Unveiling Hidden Dynamics: Speed measurements of classically forbidden motion

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For nearly a century, quantum tunneling has been a subject of sustained scientific interest. In a prior investigation [1], we introduced an unconventional method to explore evanescent phenomena at step potentials by examining particle motion within a system of coupled waveguides. In this system, the transfer of particles between waveguides serves as a clock, facilitating the determination of particle speeds even in classically forbidden regions. We implement this idea for photons in optical microcavity, which has full experimental access to the wave function. Using a novel nanostructuring method [2], we can guide photons in diverse potential landscapes, specifically within a coupled waveguiding structure. We measure particle speeds both in classically allowed and forbidden regions. Notably, our measurements show that classically forbidden regions speed up the motion of photons. Furthermore, our observations emphasize the significance of density gradients in wave functions for the motion of particles. We hope, these outcomes will provide valuable insights into the intricate dynamics of quantum tunneling phenomena, in particular make useful contribution to the tunneling time debate. Moreover, our findings can be viewed as a test of Bohmian trajectories in quantum mechanics.

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Polarized room-temperature polariton lasing in elliptical microcavities filled with fluorescent proteins

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Excitons in organic semiconductors can couple strongly to cavity photons forming exciton polaritons at ambient conditions. In artificial photonic potentials they are an emerging platform to study polariton lasing and Bose-Einstein condensation [1,2]. In this work, we study the polarization properties of fluorescent proteins enclosed by distributed Bragg reflectors with elliptical indentations [3]. We show experimentally and numerically that the structural anisotropy of the elliptical potential and the internal TE-TM splitting of dielectric Bragg reflectors leads to a distinct polarization splitting. This splitting enforces condensation into one polaritonic mode with linear polarization. Our devices have relevant applications for the engineering and tuning of polarization in room temperature polariton lasers through additional degrees of freedom.

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Photon-photon correlation and breakdown of temporal coherence of photon condensate in a dye-filled microcavity

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The temporal coherence of an ideal Bose gas is expected to increase as the Bose-Einstein condensation is approached from below, and coherence time diverging at critical point. However, counter-example have been observed in experiment for condensates of photons formed in an externally pumped, dye-filled microcavity [1], wherein the coherence time decreases rapidly for increasing particle number above threshold. Similar breakdown is also observed in photon condensate in semiconductor cavity recently.

Theoretically, an existing theory of temporal coherence in a photon condensate [2] is able to match experiment result below threshold but fails to explain the drop of ground mode coherence above threshold. We proceed to develop a new theory based on a microscopic, multimode model of photonic condensate inside a dye-filled microcavity [3] and quantum regression theorem. This allows us to derive an equation of motion of photon-photon correlation function and extract a formula of coherence time [4]. Based on our model, breakdown of ground state temporal coherence is recovered in numerical simulation [5], we establish intermode correlations as the driving cause of the observed phenomenon.

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Integrated Ultrafast All-Optical Transistor

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The clock frequency of electronic circuits has been stagnant at a few gigahertz for almost two decades because of the breakdown of Dennard scaling, which suggests that by miniaturizing transistors, they can run faster while consuming the same power[1]. Optical-based computing offers a potential solution to this challenge[2]. However, the lack of materials with sufficiently strong nonlinear interactions necessary for achieving all-optical switches led to large device sizes and high optical energy requirements that hindered scalable architectures. Recently, microcavities utilizing polymers as photoactive material in the regime of strong light-matter interaction have enabled the development of all-optical transistors[3] capable of operating at room temperature with switching times below one picosecond[4]. Nonetheless, the realization of complex circuits was restricted due to limitations posed by non-integrated vertical cavity geometry. Here, by leveraging silicon-on-insulator technology, we realize fully integrated metamaterial-based high-index contrast grating (HCG) microcavities filled with an organic polymer (MeLPPP) as photoactive material. This platform, capable of hosting a strong-light matter interaction regime system, shows integrated on-chip exciton-polariton condensation at ambient conditions. Furthermore, by exploiting the outcoupling resonance from one (control) cavity as input for the next (transistor) cavity, through seeded polariton condensation, we demonstrate ultrafast all-optical transistor action with switching time in the order of 1ps[5]. Finally, the coupling of two resonators proves the cascadability of this technology which paves the way for the implementation of more complex logic circuits.

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Geometric and fluctuational divergences in the linear response of coherently driven microcavity polaritons and their relation to superfluidity

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We consider the possibility of superfluid behavior in a coherently driven, dissipative microcavity polariton system in gapless spectrum regimes. Previous work demonstrated the absence of such behavior for gapped spectra via a linear response analysis. The system can, however, be tuned to possess a gapless spectrum in special cases, leaving open the possibility of superfluid behavior. Here we show the absence of superfluidity in all regimes; we find a divergent linear response in the system's gapless regimes, which may be linked to phase-transition behavior. This indicates that the gapless spectrum is related to phase instability and not superfluid-enabling massless modes.

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Effective low-temperature photon gas through tunnel cooling

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It is a well-established fact that photons can thermalize in an optical microcavity through absorption and emission by an optical medium. This has led to numerous experiments studying thermalized photon gasses, among which is the Bose-Einstein condensation of photons. Here, the thermal distribution of the photons is always governed by the frequency-dependent gain and loss in this system, which in turn is given by the emission and absorption spectrum of the thermalized optical gain medium. This links the photon temperature to the temperature of the optical medium.

Studying very low-temperature systems therefore requires a cryostat to cool the optical medium, which can be experimentally challenging and expensive. A natural question to ask is whether there are other gain/loss mechanisms that can contribute to the temperature of the photon gas and thereby enable low-temperature experiments.

Taking inspiration from evaporative cooling in cold atom experiments, we aim to create an effective low-temperature photon gas by using a finite transverse trapping potential in the optical microcavity. The high energy modes of the system experience more tunneling losses than the low energy modes, thereby reducing the mean energy in the system. By fine-tuning this trapping potential, we can emulate the frequency-dependent loss equivalent to a photon gas at cryogenic temperatures. We report on our recent progress towards realizing this in an experiment.

Kardar-Parisi-Zhang scaling in Bose-Einstein condensates of photons

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Abstract

Photon Bose-Einstein-condensates could provide a novel platform for the study of out-of-equilibrium systems exhibiting Kardar-Parisi-Zhang dynamics. The KPZ equation is a nonlinear stochastic partial differential equation that was originally derived to describe the roughening of a crystal interface during its growth. Presently it is well known that many more unrelated systems; the shape of fire fronts, interfaces in bacterial colonies [1], alongside nonequilibrium polariton BEC's [2] fall into the KPZ universality class. Photon condensation is achieved in coupled optical cavities filled with dye molecules which ensure thermalization of the photons through repeated absorptions and reemissions. The unavoidable photon losses that are a consequence of the finite reflectivity of the cavity mirrors require continous laser pumping to achieve a driven-dissipative steady state. This system is described by a classical field model [3]. We use both numerical and analytical approaches to investigate KPZ scaling. In particular, the most favorable system parameters are indentified for its experimental observation in 1D and 2D setups. For 2D systems an interplay between KPZ and BKT physics is expected.

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