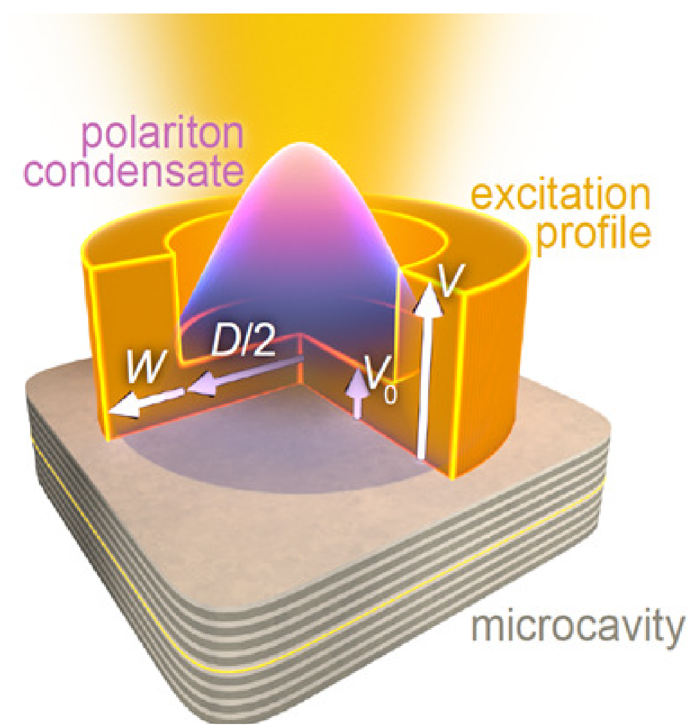
ICSCE 12

12th International Conference on Spontaneous Coherence in Excitonic Systems

10-14 June 2024

Trinity College Dublin



We are delighted to welcome you to Trinity College Dublin for the 12th International Conference on Spontaneous Coherence in Excitons. The 12th instalment of this conference continues the tradition of bringing together researchers studying quantum collective phenomena in various kinds of electronic excitations in solids and related phenomena in other physical systems. It is being held 20 years after the first ICSCE conference, in the Seven Springs, Pennsylvania, a period which has seen tremendous progress in the area of quantum condensation in solid-state systems. We hope this 12th edition will allow us to reflect on this history, while also covering hot topics in the field and looking to the next 20 years of condensate physics.

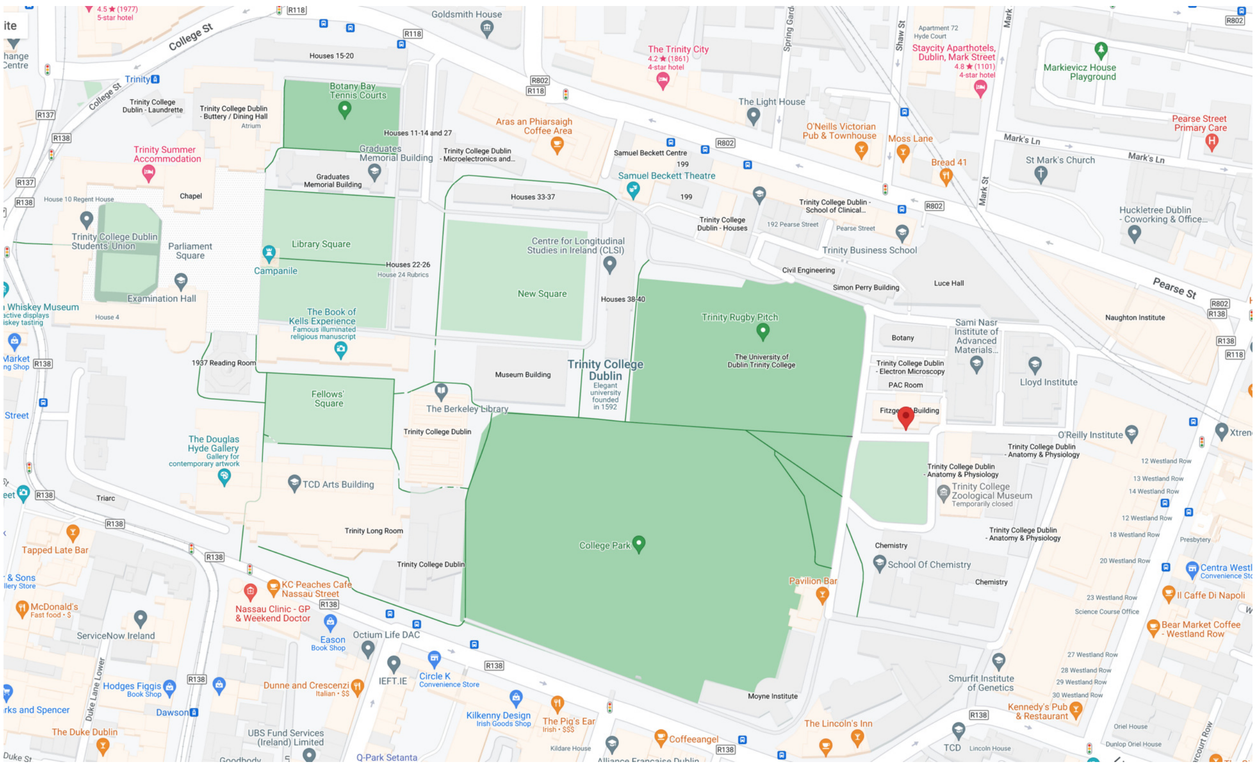
The conference topics include:

- Fundamental physics of condensates, including exciton-polariton condensates, photon condensates, and lasers.
- Nonlinear dynamics and thermodynamics of condensates, including topological effects, superfluidity, and non-equilibrium universality.
- Excitons and exciton-polaritons in new materials systems (TMDCs, Perovskites, etc).
- Condensates in metastructures and lattices.
- Organic excitons and exciton-polaritons
- Applications of condensates including optical computing.
- Exciton condensates and insulators
- Condensation and coherence in complementary systems, including atoms, lattices, and quantum simulation.

Paul Eastham, Trinity College Dublin, conference chair,
Organizing committee:
Jonathan Keeling, University of St Andrews
Francesca Marchetti, Universidad Autónoma de Madrid
Vinod Menon, The City University of New York
Barbara Pietka, University of Warsaw
Helgi Sigurdsson, University of Warsaw
David Snoke, University of Pittsburgh
Local committee:
Carlos Ortega-Taberner,
Luisa Toledo Tude,
Eoin O'Neill.

All talks are in the Physics Lecture theatre, and the breaks in the Fitzgerald library. Both are in the Fitzgerald building, which is marked in red on the map below. Lunch is in the Pavilions bar, at the end of college park, every day except Wednesday, when it will be in the Fitzgerald library. The conference dinner is on Wednesday at 7.30 pm in the Trinity City Hotel, at the top centre of the map. The conference excursion to the valley of Glendalough will leave from the college grounds after lunch on Wednesday.

Invited talks are allocated 45 minutes, and contributed talks 25 minutes, including time for questions.



Start	Mon	Tue	Wed	Thu	Fri
08:30	Coffee, pastries	Coffee, pastries	Coffee, pastries	Coffee, pastries	Coffee, pastries
09:30	Deng	Szymanska	Rapaport	Matuszewski	Richard
10:15	Rahmani	Walker	D'Alessio	Tyszka	Schmitt
10:40	Wingenbach	Sesti	Morita	Aristov	Snoke
11:05	Break	Break	Break	Break	Break
11:30	Cooper	MacDonald	Cobden	Onodera	Ravets
12:15	Marchetti	Furukawa	Lunch	Stoferle	Tude
12:40	Lunch	Lunch		Lunch	Lunch
13:15			Excursion (Glendalough)		
14:00	Zwettler	Murthy		Borjesson	Kyriienko
14:45	Bao	Seet Wei		Georgakilas	Levinsen
15:10	Bouzutschky	Sawicki		Blessan	Fontaine
15:35	Break	Break		Break	Break
15:50	G	Fabricante		Dovzhenko	Alnatah
16:15	Suarez-Forero	Trypogeorgos		Ohadi	Parish
17:00	Xu	Sigurdsson		Krizhanovskii	
			Conference dinner		

Full program and abstracts

https://www.tcd.ie/media/tcd/physics/research-groups/qlamg/pdfs/ICSCEProgram.pdf

https://tinyurl.com/3j8zdcvw

Monday

1.1	09:30	Hui Deng (Invited)	
1.2	10:15	Amir Rahmani	Exceptional points and non-Hermitian phase transition in non-linear binary systems
1.3	10:40	Jan Wingenbach	Manipulating Spectral Topology and Exceptional Points by Nonlinearity in Non-Hermitian Polariton Systems
1.4	11:30	Nigel Cooper (Invited)	Theory of Strongly Interacting Polaritons in Moiré Materials
1.5	12:15	Francesca Maria Marchetti	Optical response of doped two-dimensional semiconductors at finite temperature
1.6	14:00	Timo Zwettler (Invited)	Engineering Cavity-mediated Long-range Interactions between Atoms and Pairs
1.7	14:45	Ruiqi Bao	Topological Enhancement of Exciton-Polariton Coherence with Non-Hermitian Morphing
1.8	15:10	Alexander N. Bourzutschky	Raman phonon polariton condensation in a transversely pumped cavity
1.9	15:50	Akshaya G	Towards room-temperature polaritons in a tunable open microcavity using 2D hybrid perovskites
1.10	16:15	Daniel Suarez-Forero (Invited)	Diffusion and magnetism in moire Bose-Fermi mixtures
1.11	17:00	Huawen Xu	Quantum theory of polariton weak lasing and polarization bifurcations

Tuesday

2.1	09:30	Marzena Szymanska (Invited)	
2.2	10:15	Paul Michael Walker	Measuring Polariton Interactions at the Few Particle Level
2.3	10:40	Giacomo Sesti	Excitonic Instability in Narrow Gap Carbon Nanotubes
2.4	11:30	Allan MacDonald (Invited)	Vortex Lattice States in Strong-Magnetic-Field Charged Electron-hole Fluids
2.5	12:15	Toshiyuki Furukawa	Environmental control of recoil force derived from superfluorescence
2.6	14:00	Puneet Murthy (Invited)	Electrically defined quantum dots for excitons
2.7	14:45	Seet Wei En Nathan	Optimization of Purcell-Enhanced Microcavities with the Cylindrical Finite-Difference Time-Domain Algorithm
2.8	15:10	Krzysztof Sawicki	Occupancy-driven Zeeman suppression and inversion in trapped polariton condensates
2.9	15:50	Bianca Rae Fabricante	Narrow linewidth exciton-polariton laser
2.10	16:15	Dimitrios Trypogeorgos (Invited)	A supersolid state of exciton-polaritons in photonic crystal waveguides
2.11	17:00	Helgi Sigurdsson	Dirac exciton–polariton condensates in photonic crystal gratings

Wednesday

3.1	09:30	Ronen Rapaport (Invited)	Ultrafast electrically-reconfigurable interacting-photon circuits using waveguided dipolaritons with huge nonlinearities: from photon scattering on electrical potentials to a GHz two-photon transistor
3.2	10:15	Matteo D'Alessio	Excitons in bilayer WTe2
3.3	10:40	Yusuke Morita	Direct observation of Bose-Einstein condensate of excitons in a bulk semiconductor using mid-infrared induced absorption imaging
3.4	11:30	David Cobden (Invited)	Equilibrium excitons and superconductivity in 2D semimetal WTe2

Thursday

4.1	09:30	Michal Matuszewski (Invited)	Controlling topological light with light-matter coupling
4.2	10:15	Krzysztof Tyszka	Neural computing with exciton-polaritons in perovskite nanowires.
4.3	10:40	Denis Aristov	Directional planar antennae in polariton condensates
4.4	11:30	Tatsuhiro Onodera (Invited)	Deep physical neural networks using physics-aware training
4.5	12:15	Thilo Stoferle	Integrated, ultrafast all-optical polariton transistors
4.6	14:00	Karl Borjesson (Invited)	Strong coupling using organic molecules, targeting the idealness of polaritons and the relative size of the exciton reservoir
4.7	14:45	Ioannis Georgakilas	In-situ tunable, room-temperature polariton condensation in individual states of a 1D topological lattice
4.8	15:10	Tony Matthew Blessan	Line lasing in a two-dimensional lattice of photonic resonators
4.9	15:50	Dmitriy Dovzhenko	Electrically Controlled Interaction of Coupled Bose-Einstein condensates in a Dye-Filled Liquid-Crystal Microcavity
4.10	16:15	Hamid Ohadi (Invited)	
4.11	17:00	Dima Krizhanovskii (Invited)	Polariton effects in photonic structures based on Cu2O and transition metal dichalcogenide materials.

Friday

5.1	09:30	Maxime Richard (Invited)	Thermal and quantum-driven Bogoliubov excitationsin a driven-dissipative quantum fluid of light
5.2	10:15	Julian Schmitt	Compressibility and fluctuations of an optical quantum gas in a box
5.3	10:40	David Snoke	Can polariton ring condensate make good qubits?
5.4	11:30	Sylvain Ravets (Invited)	Synthetic polariton matter: Eigenstates tomography and metrology of interactions
5.5	12:15	Luisa Toledo Tude	Driven-dissipative condensates and the second law of thermodynamics
5.6	14:00	Oleksandr Kyriienko (Invited)	Towards nonlinear polaritonic devices with transition metal dichalcogenide bilayers
5.7	14:45	Jesper Levinsen	Trion resonance in polariton-electron scattering
5.8	15:10	Quentin Fontaine	Exploring Universal Scaling Laws In Two-Dimensional Polariton Condensates
5.9	15:50	Hassan Alnatah	Coherent fraction of an equilibrium condensate
5.10	16:15	Meera Parish (Invited)	The dark side of exciton polaritons

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. As such, the existence of nonlinear features may affect the non-Hermitian effects realized in linear cases or give rise to entirely new phenomena [2]. In this work, we investigate a non-Hermitian binary model, accentuating the significance of nonlinearity in a non-Hermitian phase transition [3]. This model can describe a wide range of physical systems, including simple coupled oscillating modes, but also allows to describe two-component homogeneous systems, in particular, it describes light and matter interaction in exciton-polariton condensation and lasing. 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 while the first-order-like phase transition line with an endpoint is present, the equivalence of the endpoint to an exceptional point as found in [4] 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.

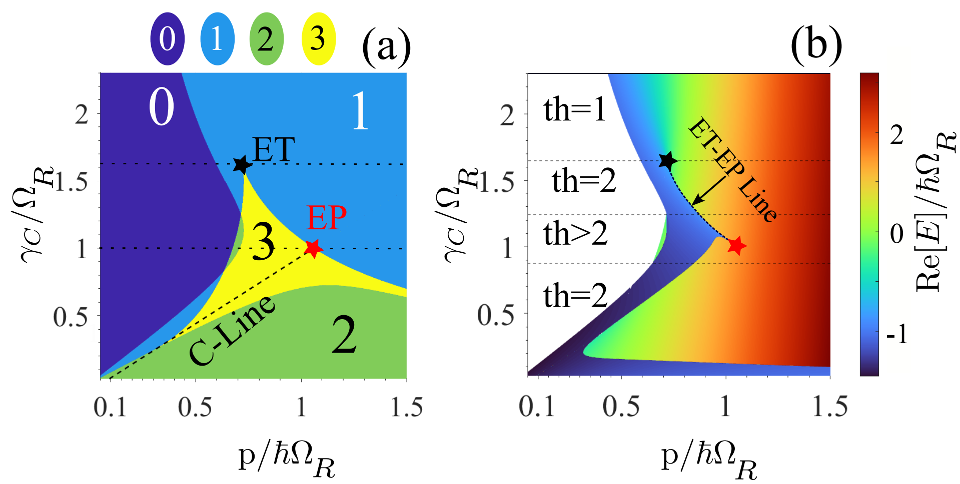

Figure 1: Phase diagrams of a binary system. In (a) the number of stationary states is marked with colors in the function of photon decay rate (γ_c) and pumping strength (p). In (b) only the lowest-energy stable state is shown. Here colors indicate the real part of the energy. In (a) and (b) the exceptional point (EP, red star) and the endpoint of the first-order-like phase transition (ET) are shown. At the C-Line two solutions coalesce and the periodic solution vanishes. Cross-sections of constant γ_c with different numbers of thresholds (th) are marked with horizontal lines.

References

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Manipulating Spectral Topology and Exceptional Points by Nonlinearity in Non-Hermitian Polariton Systems

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[b] *Institute for Photonic Quantum Systems (PhoQS), Paderborn, Germany*
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Exceptional points (EPs) are singularities in the parameter space of non-Hermitian systems at which two or more eigenvalues and their corresponding eigenvectors coalesce. EPs have attracted considerable attention in a wide range of physical systems due to their intriguing spectral topology, with potential applications in sensing driving much of the current research in this field [1]. Here we investigate spectral topology and EPs in systems with significant nonlinearity, exemplified by a nonequilibrium exciton-polariton condensate. Exciton polaritons are hybrid light-matter quasiparticles that form due to strong light-matter coupling, pairing finite lifetimes on a picosecond scale, and thus non-Hermiticity, with strong nonlinearity from polariton-polariton interactions. Under nonresonant optical excitation, spontaneous macroscopic coherence can form, known as polariton condensation [2]. With the possibility to control loss and gain and nonlinearity by optical means, this system allows for a comprehensive analysis of the interplay of nonlinearities (Kerr-type and saturable gain), with topological properties [3] and non-Hermiticity [4].

We find that the saturable gain shifts the EP in parameter space, leading to a variation in the mode coupling requirement for the observation of the EP. The repulsive polariton-polariton nonlinearity (akin to a Kerr-type nonlinearity) can induce not only an energy blueshift but also a simultaneous rotation of the Riemann surface and movement of the EP. We show that this also applies to higher-order EPs where the Riemann surfaces can show complex intersection patterns. With potential applications in mind, we further demonstrate that sensing sensitivity near the EP can be significantly enhanced by nonlinearity. In nonlinear mode control, this offers interesting insights for encircling higher-order EPs and for phase transitions at EPs. With this, our results illustrate the potential of manipulating spectral topology and related phenomena in non-Hermitian systems by nonlinearity. These results are generic enough to be applied to other non-Hermitian systems with similar nonlinearities such as in nonlinear optics and atomic systems [4].

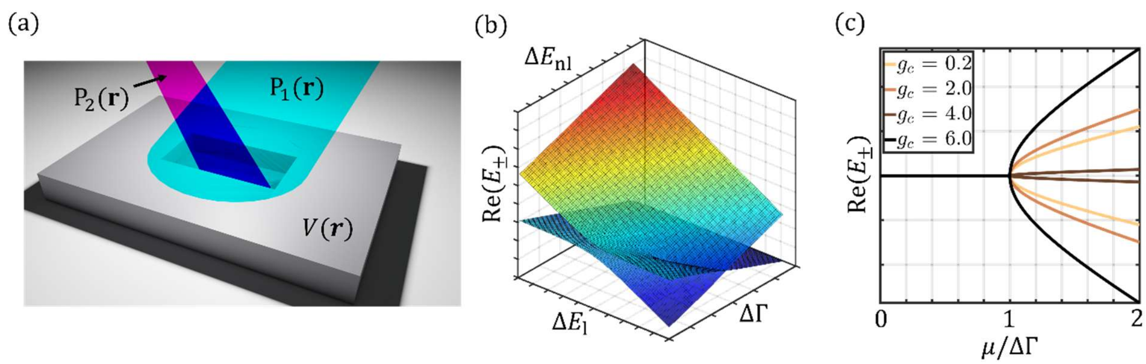

Figure 1: (a) Scheme for realization with polariton condensates in a rectangular external potential with two nonresonant pump beams. (b) Riemann surface rotation in the vicinity of an exceptional point. The Riemann surface rotation is induced by the coupled mode gain and energy in the nonlinear system, resulting in an energy correction ΔE_{nl}. (c) Nonlinearity-induced change in the eigenvalue splitting near the exceptional point depicted for different interaction strengths.

References

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4. J. Wingenbach, S. Schumacher, and X. Ma, Manipulating spectral topology and exceptional points by nonlinearity in non-Hermitian polariton Systems. *Phys. Rev. Research* **6**, 013148, (2024)

Theory of Strongly Interacting Polaritons in Moiré Materials

Arturo Camacho-Guardian (UNAM, Mexico)
Nigel Cooper (University of Cambridge, UK)

Moiré excitons promise a new platform with which to generate and manipulate hybrid quantum phases of light and matter in unprecedented regimes of interaction strength. We explore the properties in this regime, through studies of a Bose-Hubbard model of excitons coupled to cavity photons. We show that the steady states exhibit a rich phase diagram with pronounced bistabilities governed by multiphoton resonances reflecting the strong interexciton interactions. In the presence of an incoherent pumping of excitons we find that the system can realize single- and multiphoton lasers.

Optical response of doped two-dimensional semiconductors at finite temperature

F. M. Marchetti[a], A. Tiene[a], B. C. Mulkerin[b,c], J. Levinsen[b,c], and M. M. Parish[b,c]

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[b] *School of Physics and Astronomy, Monash University, Victoria 3800, AustraliaSchool of Physics and Astronomy, Monash University, Victoria 3800, Australia*

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We study the role of temperature in the optical response of doped two-dimensional semiconductors [2, 1]. By making use of a finite-temperature Fermi-polaron theory, we reveal a crossover from a quantum-degenerate regime with well-defined polaron quasiparticles to an incoherent regime at high temperature or low doping where the lowest energy "attractive" polaron quasiparticle is destroyed, becoming subsumed into a broad trion-hole continuum. We demonstrate that the crossover is accompanied by significant qualitative changes in both absorption and photoluminescence. In particular, with increasing temperature (or decreasing doping), the emission profile of the attractive branch evolves from a symmetric Lorentzian to an asymmetric peak with an exponential tail involving trions and recoil electrons at finite momentum (see Fig. 1).

In the high-temperature or low-doping regime, we obtain exact analytic expressions for the photoluminescence by using a quantum virial expansion. Our theory allows us to formally unify the two distinct theoretical pictures that have been applied to this system, where we reveal that the predictions of the conventional trion picture correspond to a high-temperature and weak-interaction limit of Fermi-polaron theory. Our results are in excellent agreement with recent experiments on doped monolayer $MoSe_2$ and they provide the foundation for modelling a range of emerging optically active materials such as van der Waals heterostructures.

We discuss the effect of temperature on the coupling to light for structures embedded into a microcavity, and we show that there can exist well-defined polariton quasiparticles even when the exciton-polaron quasiparticle has been destroyed, where the transition from weak to strong light-matter coupling can be explained in terms of the polaron linewidths and spectral weights.

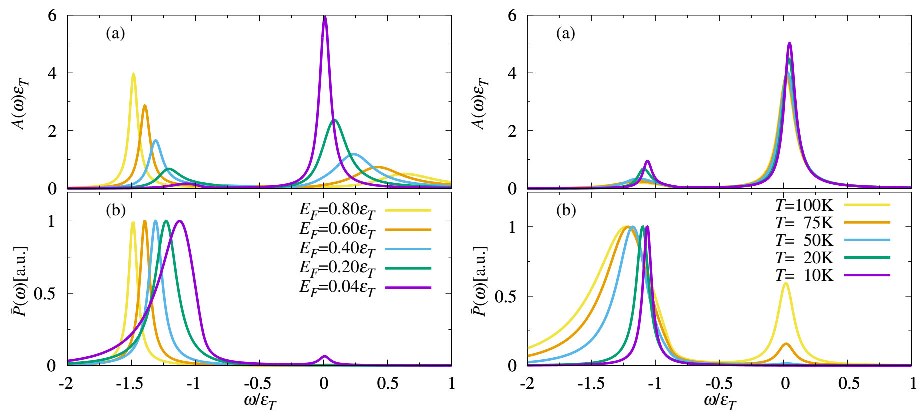

Figure 1: a) Spectral function $A(\omega)$ and (b) Lorentzian convolved photoluminescence $\bar{P}(\omega)$ for different dopings E_F and at a fixed temperature of $T = 50$ K$\simeq 0.17\varepsilon_T$ (left panels) and for different values of the temperature T and at a fixed doping $E_F = 0.1\varepsilon_T$ (right panels). Here, $\varepsilon_T \simeq 25$ meV is the trion binding energy.

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Engineering Cavity-mediated Long-range Interactions between Atoms and Pairs

Timo Zwettler,[1,2,*] Tabea Bühler,[1,2] Aurélien Fabre,[1,2] Gaia Bolognini,[1,2] Victor Helson,[1,2] Giulia del Pace,[1,2] Shun Uchino,[3] and Jean-Philippe Brantut[1,2]

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Keywords: cavity quantum material, ultracold atoms, quantum optics, strongly interacting Fermions

Cavity-coupled many-body systems constitute a new emergent field in condensed matter systems, where complex quantum materials are combined with cavity quantum electrodynamics (cQED) to substantially modify material properties by strong light-matter coupling [1–3]. We realize a prototypical cavity quantum material by combining cQED with a strongly interacting Fermi gas [4], providing an ideal, microscopically controllable platform for the study of collective light-matter coupling in strongly correlated matter [5]. The strong, short-range, two-body correlations present in the system allow for the strong coupling of ground-state pairs to excited molecular states by light via photoassociation [6]. We engineer long-range cavity-mediated interactions between atoms and pairs by transversally pumping the atom-cavity system in the vicinity of such a molecular transition. By studying self-organization as function of the molecular detuning, we uncover an atom-pair competition in the instability to density-wave order.

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Topological Enhancement of Exciton-Polariton Coherence with Non-Hermitian Morphing

Ruiqi Bao[a], Huawen Xu[a], Wouter Verstraelen[a] and T. C. H. Liew [a]

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The non-Hermitian skin effect (NHSE) has been intensely investigated over the past few years and has unveiled new topological phases, which have no counterparts in Hermitian systems [1, 2, 3, 4]. While the eigenstates' localization and non-reciprocal propagation properties have been well investigated theoretically in polaritons [5, 6], other applications of NHSE are still to be investigated.

In this work, we consider the hybridization between the NHSE in an exciton-polariton waveguide and a localized defect mode. By tuning the non-Hermiticity (the differences between decay rates for spins), because of the competition between the localization of defect and the localization of NHSE, we show that in theory the spatial distribution of ground-state of the system can be tuned. What's more, the ground state can be both spatially extended and energetically separated from other modes in the system. We calculate spatial coherence g_1 and find an enhanced spatial coherence (of typically 30 times longer) compared to regular waveguides, which is robust in the presence of disorder.

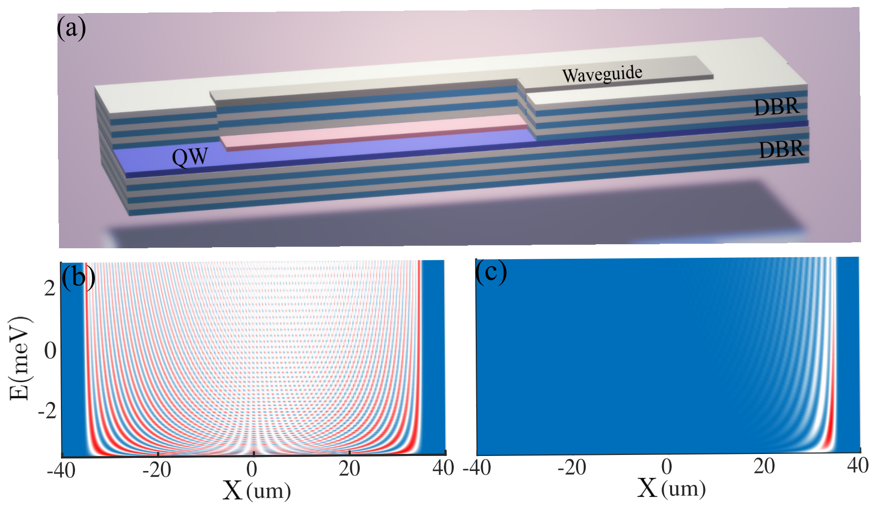

Figure 1: (a)Schematic figure of a microcavity with an etched waveguide. The microcavity is formed by two sets of distributed Bragg reflectors (DBRs) sandwiching a quantum well (QW). (b-c) Calculated eigenstates' spatial distribution in Hermitian and non-Hermitian cases, respectively.

References

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Raman phonon polariton condensation in a transversely pumped cavity

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[b] *E. L. Ginzton Laboratory, Stanford University*
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Phonons play many important roles in material properties—not least mediating superconductivity. As such, the ability to control phonon properties by hybridisation with light is an attractive prospect. However, direct coupling to phonons presents challenges, as phonon modes lie in the terahertz or infra-red range and relevant modes may not be optically active. Adapting a two-photon Raman driving scheme [1] allows one to circumvent these restrictions and exploit the same tunability that has been used for many experiments coupling cold atoms to optical cavities [2, 3]

We present a new approach to realising phonon polaritons by employing a transverse pumping Raman scheme with excitons as the intermediate excited state [4]. This approach allows hybridisation between an optical cavity mode and any Raman-active phonon mode. Moreover, this approach enables one to tune the effective phonon–photon coupling by changing the strength of the transverse pumping light. We show that such a system may realise a phonon-polariton condensate. To do this, we find the stationary states and apply Floquet theory to determine their stability, and thus identify distinct superradiant and lasing states in which the polariton modes are macroscopically populated (Figure 1). We map out the phase diagram of these states as a function of pump frequencies and strengths. Using parameters for TMDs, we show that realisation of these phases may be practicably obtainable. The ability to manipulate phonon mode frequencies and attain steady-state populations of selected phonon modes provides a new tool to engineering correlated states of electrons [5, 6].

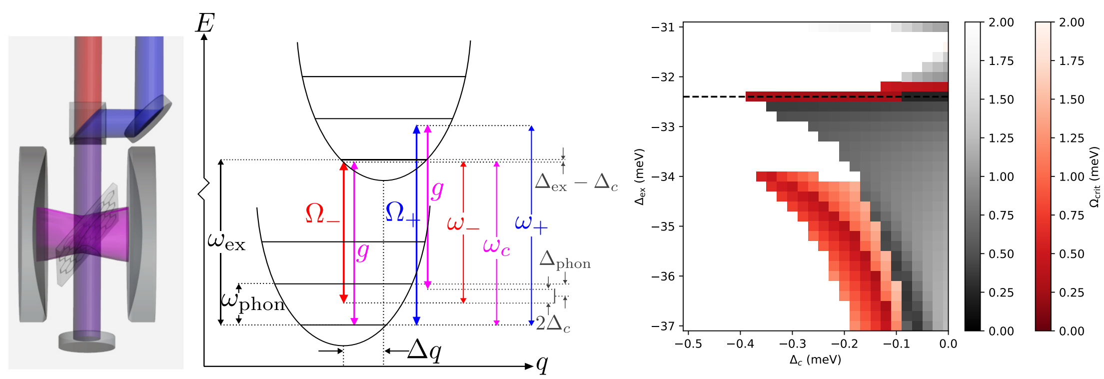

Figure 1: Left: general schematic. Center: level diagram indicating the vibronic levels, the two pumps, the cavity, and the detunings. Right: phase diagram indicating the pumping strength at which the normal phase goes unstable due to superradiance (red) or lasing (black/gray).

References

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Towards room-temperature polaritons in a tunable open microcavity using 2D hybrid perovskites

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Quantum optics is the study of interaction of individual packets of light with matter. It has seen a tremendous growth in the past few decades both theoretically and experimentally. In an optical cavity, cavity modes refer to the standing waves pattern created due to the confinement of photons. A bound electron-hole pair in a semiconductor is commonly referred to as an exciton and this can interact with photons trapped inside the cavity. When there is a strong interaction between the trapped photon and exciton, the energy levels of the entire system splits into two branches and a new quasi-particle called a polariton is formed [1]. Fine tuning the cavity parameters and exciton energies can alter the interaction strength between them, leading to the formation of polariton condensates. This strong coupling regime has emerged as an interesting area of research in quantum optics since it has variety of applications in quantum information processing and beyond [2].

When two highly reflected mirrors are placed very close to each other, they form a Fabry-Perot (FP) microcavity. To study and harness the strong coupling of a semiconductor exciton to a cavity photon, we sandwich the semiconductor between the two mirrors. Hybrid perovskites are an interesting class of 2D semiconductors that operate at room temperatures. Unlike the conventional 2D materials like transition metal dichalcogenides, perovskites can be easily synthesised in large quantities. Because of their unique multiple quantum well structure, excitons can be confined to individual layers in 2D hybrid perovskites [3]. Thus by altering different parameters of the layers, exciton dynamics can this be changed.

Previous works have demonstrated strong coupling in 2D hybrid perovskites in a FP cavity where both the reflecting mirrors are parallel [4]. At present, we are working with a tunable microcavity that has planar-concave mirrors since this allows better confinement of light [5]. The cavity is also fabricated in a way that the cavity separation can be altered. This has allowed us achieve efficient trapping of light within the microcavity. We have also synthesised perovskites with exciton energies that match with the resonant modes of the microcavity. Thus, we aim to strongly couple excitons with photons in a planar-concave microcavity and obtain condensates. The condensates will be further studied to build a photonic platform that allows quantum optics at room temperature.

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Diffusion and magnetism in moiré Bose-Fermi mixtures

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Layered 2D transition metal dichalcogenides, hosting both fermionic and bosonic correlated states, have emerged as a remarkable platform for probing many-body interactions. The study of propagation of particles in these systems offers insights into dynamics of quantum many-body systems. Bilayer moiré heterostructures can host Mott insulating states of fermions (electrons) and bosons (excitons) [1], and exploration of diffusion dynamics is particularly appealing owing to the excitonic long lifetimes (10s of ns to μs). In this work, we present a thorough investigation into the diffusion of ultra-low-density excitons within a moiré lattice, under variable electron filling (ν_e). Our findings, derived from space- and time-resolved measurements, unveil a remarkable phenomenon: a surge in diffusivity spanning over two orders of magnitude as one approaches the Mott-insulating state ($\nu_e \sim 1$). Additionally, we benchmark the presence of massive attractive-polaron in regimes with modest electron filling (0<ν_e<1), exerting a decelerating effect on diffusion compared to that of excitons in the charge-neutral region. Furthermore, magnetic field-dependent polarization measurements reveal interesting details about the nature of the system. Our study provides crucial insights into the intricate dynamics of Fermi-Bose mixtures across different densities.

Quantum theory of polariton weak lasing and polarization bifurcations

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Polariton condensates can encode information through their polarization (spin) state, which exhibits a great amount of interesting properties. While at high excitation level the linearly polarized condensates are formed, the polarization state near the condensation threshold is more complex. It was discovered [2] that a single trapped polariton condensate undergoes parity breaking bifurcation leading to random formation of two possible states of elliptically polarized condensates with opposite handedness. The polarization bifurcation near the threshold can be understood as the weak lasing effect [1]: formation of specific many-body polariton states due to the combined effect of weak polariton-polariton repulsion and a small difference in the lifetimes of single polariton states. The mean-field theory used so far to describe this phenomenon studies the polariton condensation in terms of nonlinear driven-dissipative equations, where different condensate states correspond ton fixed points or limit cycles (sometimes referred to as time crystals). This theory lacks the ability to properly address the possible coexistence of condensates near the threshold and their quantum properties, which are speculated to allow a quantum speed-up of polariton simulators. Moreover, the validity of the mean-field description of weak lasing is limited by the assumption of weak polariton-polariton interaction. An essential property of weak lasing is that the formation of a condensate is stabilized by the interaction, not by the depletion of an incoherent feeding reservoir. As a result, the condensate occupation numbers are inversely proportional to the interaction constant. The latter is controlled by the condensate confinement, so that the requirement of weak interaction is a severe limitation. In this work we discuss the properties of the trapped polariton condensate density matrix in the presence of the weak lasing effect. The system in this case obeys open-dissipative quantum dynamics described by the Lindblad master equation for the density matrix. We analyze properties of both the steady state solution and the different two-time correlators, as well as the emission spectrum from the condensate, and show how they indicate the symmetry breaking transition in the system and coexistence of condensates with different symmetries.

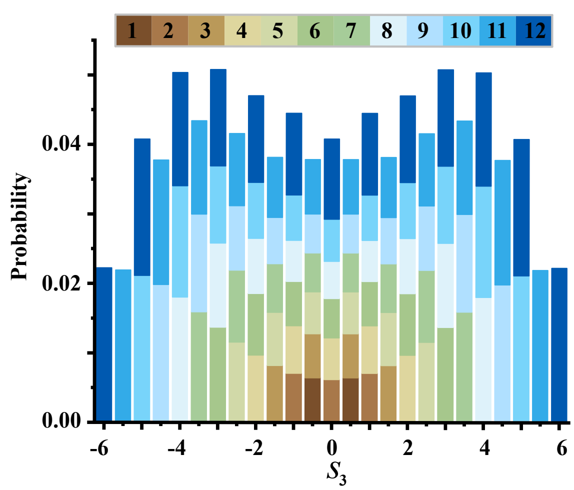

Figure 1: Probability distribution of s_3 with different contribution from states with different number of particles, where the numbers $1, 2, \ldots, 12$ (encoded by different colors) indicate the number of particles in a certain subspace of the system. The contribution from the vacuum state $|0, 0\rangle$ is excluded.

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Measuring Polariton Interactions at the Few Particle Level

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Interactions between polaritons underpin polariton condensation effects and, despite a wealth of experiments at medium and high densities, questions still remain about some details of these interactions even in the well known GaAs-based systems [1]. At the same time, there has been a recent trend towards exploring polariton interactions at ultra-low densities [2, 3, 4] where quantum effects were observed and the importance of biexciton Feshbach resonance for quantum polaritonics was recently predicted [5] and proved [6].

Here we present the latest developments in our experimental techniques which allow very low power, few-particle, all-optical switching and high sensitivity measurement of polariton interactions in the very low density regime. It is based on our previous work measuring single photon cross-phase-modulation in solid micropillar cavities [4]. Compared to that work we make a number of significant experimental steps that greatly improve the utility of the method for characterising nonlinearities. We now employ a highly flexible open-access cavity [7] which allows tuning the polariton states to measure frequency dependencies. We furthermore generate pump and probe pulses using electronically triggered high speed electro-optical modulators allowing electronic control of pulse width from $\sim$ 50 ps to 1 ns as well as repetiton rate and pump-probe delay. We use time-tagged photon counting of single photon avalanche detectors and external marker channels which allows low noise detection, separation of pump and probe by temporal shape, and high-speed polarisation dependence sweeps.

For GaAs-based cavities we have so far measured cross-phase modulations up to 21 mrad per particle for the co-circularly polarised component of the interaction constants, $\sim$ 7x higher than in solid cavities. We also find that the unexplained saturation effect present in the previous results employing continuous wave excitation is greatly reduced, allowing up to 25% modulation of the probe pulses using control pulses containing only $\sim$ 5 atto-Joules of energy. The tuneability of the open cavity system allows us to explore the frequency dependence of the saturation effect, which appears to become stronger for polariton frequencies very close the the exciton.

Going forward, the open cavity geometry can allow study of a wide range of important material systems used to implement polaritons [8]. The very high sensitivity allows resolution of nonlinear response at very low densities where complicating thermal and reservoir effects are minimised. Simple electronic control over repetition rate, pulse duration, pump-probe delay and polarisation can greatly simplify exploration of the complex processes underlying polariton interactions in semiconductors.

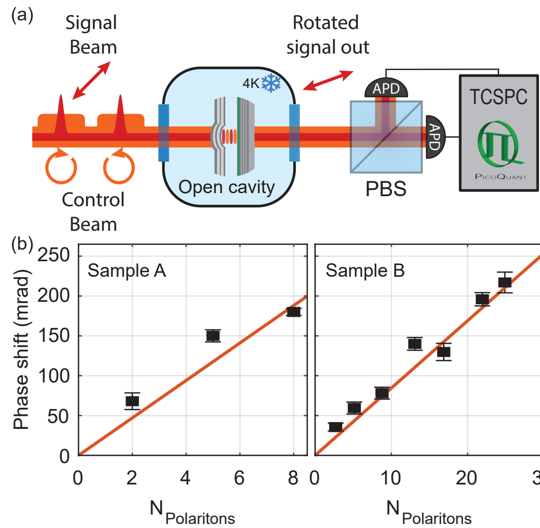

Figure 1: (a) Simplified schematic of the experimental setup. (b) Measured phase shift as a function of the excited polariton number.

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ICSCE12 Dublin 2024

Excitonic Instability in Narrow-Gap Carbon Nanotubes

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Ultraclean suspended carbon nanotubes, which are predicted to be metallic by band theory, always exhibit a many-body transport gap at low temperature [1,2]. Whereas the correlated ground state was early interpreted as a Mott insulator [1], we recently predicted that, in gapless (armchair) tubes, the gap is enforced by the permanent condensation of excitons [3]. Here we investigate thoroughly the screening of nanotubes [4], developing a model fit to samples of any size and chirality (Figure 1), which is validated by state-of-the-art first principles calculations. Our key result is that the long range of Colomb interaction, which remains largely unscreened even in the presence of Fermi points, stabilizes the excitonic insulator phase in all narrow-gap nanotubes. Furthermore, we show that the EI phase is better suited than the Mott insulator to explain available experiments [1,2], which focus on the closure of the many-body gap with the magnetic field.

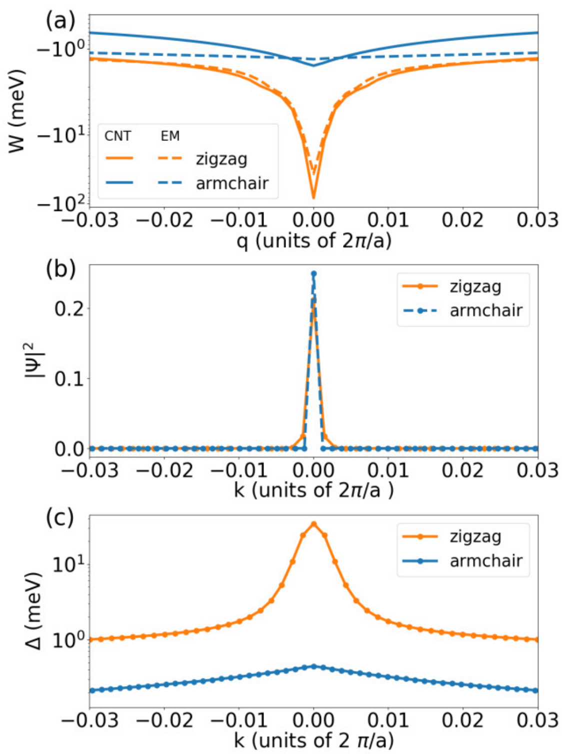

Figure 1: Plot of the screened Coulomb potential W(q) (a), the excitonic wavefunction (b), and the excitonic order-parameter (c) in the (18,0) zigzag nanotube and the (10,10) armchair nanotube. In plot (a), we compare W(q) using our model (CNT) with the standard effective-mass (EM) derivation. (a) and (c) figures are in semilogarthimic scale.

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Environmental control of recoil force derived from superfluorescence

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Light carries momentum, and it is known to exert force (optical pressure) on matter through scattering and absorption [1]. Fluorescence phenomena are also optical processes that can exert optical pressure. However, because fluorescence is generally stochastic and its direction is random, it has been believed that even if the emitters are aggregated, they would contribute little to optical pressure. In this study, we focus on superfluorescence, which is one of the synchronization fluorescence phenomena. Superfluorescence occurs when a large number of emitters are densely aggregated, causing them to correlate with each other through the exchange of emitted photons. As a result, a directional and powerful recoil force can be expected.

By employing the theory of superfluorescence regarding spatially distributed emitters [2], we formulated the optical pressure exerted by the recoil of *N* emitters interacting with light is calculated as [3]

$$F_i = -\frac{2}{\varepsilon_0}\sum_{m=1}^{N} \mathrm{Re}\left[(\nabla_r \boldsymbol{d}_i \cdot \boldsymbol{G}(r_i, r_m, \omega_i) \cdot \boldsymbol{d}_m)\langle \sigma_{10}^{i} \sigma_{01}^{m} \rangle\right],$$

where $\boldsymbol{G}(r_i, r_m, \omega_i)$ represents the Green's function of the emitted photons, r_i is the position of the i-th two-level emitter, ω_i is its resonant frequency, σ_{10}^{i} and σ_{01}^{i} represent the ladder operators, and $\boldsymbol{d}_i$ is the dipole moment. As one of the most simple example, we calculate the superfluorescence emission intensity and recoil force using the emitter arrangements as shown in Fig. 1. The emitters are arranged in sets of five, with each set positioned at the origin and points 0.5λ (where λ is the wavelength of the emitted photons) away from the origin. The force exerted on the emitters in the x-axis direction is shown in Fig. 2. It can be observed that the force is acting in the direction where the emitters are moving away from each other. It is believed that this force arises due to the correlation between distant emitters. Our formulation is valid in arbitrary system as far as we can derive the photon Green's function. We will provide a detailed report on the formulation of emission intensity and recoil force, as well as the influence of the surrounding environment using metallic nanostructures on the recoil force.

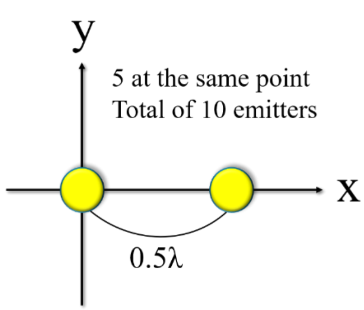

Fig. 1 Schematic picture of the most simple configuration of the emitters in vacuum.

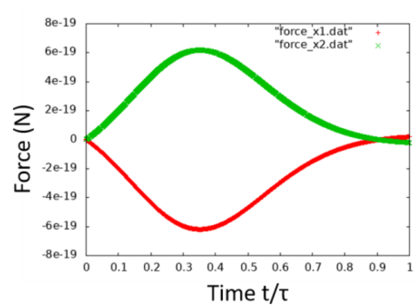

Fig. 2 Temporal variation of the recoil force on the emitters in the x-axis direction.

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Electrically defined quantum dots for excitons

Jenny Hu, Etienne Lorchat, Xueqi Chen, Kenji Watanabe, Takashi Taniguchi, Tony F. Heinz, **Puneet A. Murthy** and Thibault Chervy

An important goal in quantum photonics has been the realisation of scalable and deterministic quantum emitters in solid state devices. In this talk, I describe our recent results demonstrating electrically defined quantum dots for excitons in transition metal dichalcogenide (TMD) semiconductors[1]. We create traps for neutral excitons using nanostructured gate electrodes placed in proximity in TMD heterostructures. These gates allow us to apply strong electric fields on the TMD layer, as well as carefully define the charge density distribution. As a result, the exciton energy is varied over a nanoscopic region creating a lateral potential well. Appropriate structuring of the gates allows us to achieve diverse geometries, including 0D dots and rings. I will discuss the prospects of our technique for create large-scale arrays of independently tuned single photon sources.

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Optimization of Purcell-Enhanced Microcavities with the Cylindrical Finite-Difference Time-domain Algorithm

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The finite-difference time-domain (FDTD) algorithm has been one of the state-of-the-art computational tool for electromagnetic simulations. The direct discretisation of Maxwell' equations in the FDTD algorithm allows for the simulation of a wide range of structures and calculation of various figures of merit. A current interest in the community is to optimise the coupling of a quantum dot in purcell-enhanced microcavities. These microcavities usually comprise of circular gratings with fixed periodicities, with a quantum dot embedded in the centre (also known as a bullseye cavity). Such structures are known to exhibit purcell-enhancement with a near gaussian far field for optimal collection efficiency.

In this session, we will discuss an optimisation scheme we have done with the FDTD. An FDTD algorithm was developed in polar coordinates to optimise annular gratings as efficient single photon sources. By exploiting the azimuthal symmetry of the system, we are able to reduce a three-dimensional calculation into a two-dimensional one, allowing for efficient calculations. This allows optimisation via global optimisation methods such as the particle swarm algorithm. We will show that chirped annular gratings are superior than annular gratings of fixed periodicity due to the aperiodicity of the Bessel function. In particular, we will show that, with chirped microcavities, we can achieve Purcell Factors up to five times larger than the current state-of-the-art while maintaining comparable levels of collection efficiency.

Occupancy-driven Zeeman suppression and inversion in trapped polariton condensates

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Polariton spin is a degree of freedom that can be used to manipulate the emission properties of polariton condensates. The study addresses spin-related phenomena, which are difficult to observe due to the relatively weak Zeeman effect of exciton-polaritons in GaAs-based structures. Here, we overcome this limitation by generating optically trapped exciton-polariton condensates, which are known to possess extremely high condensate coherence time and, thus, ultra-narrow spectral linewidths (see Figure 1(a)). This makes it possible to resolve magnetically induced $\sim \mu$eV fine-energy shifts in the condensate, and identify unusual dynamical regions in its parameter space [1]. The continuous control over the polariton confinement allows exploration of two regimes of operation depending on the strength of the polariton-polariton interaction: (1) the full parametric screening of the Zeeman splitting, known as the spin-Meissner effect (see Figure 1(b)) and (2) Zeeman inversion regime, where, upon reaching the critical excitation pump power, the Zeeman splitting reverses (see Figure 1(c)). In the experiment, the transition from one range to the other occurs by adjusting the size of the optical trap, which controls the strength of the polariton-polariton and polariton-exciton reservoir interactions. Both of the above-mentioned effects have not been reported so far for optically trapped exciton-polariton condensates. We develop a mean field model based on a zero-dimensional generalized Gross-Pitaevskii equation coupled to a rate equation for the exciton reservoir, which qualitatively captures the observed effects.

Optical trapping of polariton condensate offers a powerful tool for magneto-optical studies of microcavities, which has not been explored so far. These observations bring new fundamental insights into the magnetic properties of the optically trapped exciton-polaritons. The magnetic control of the emission properties, tunability and reconfigurability, apart from their importance for the fundamental physics of polaritons, paves the way to the potential practical application of magnetically controlled polariton systems.

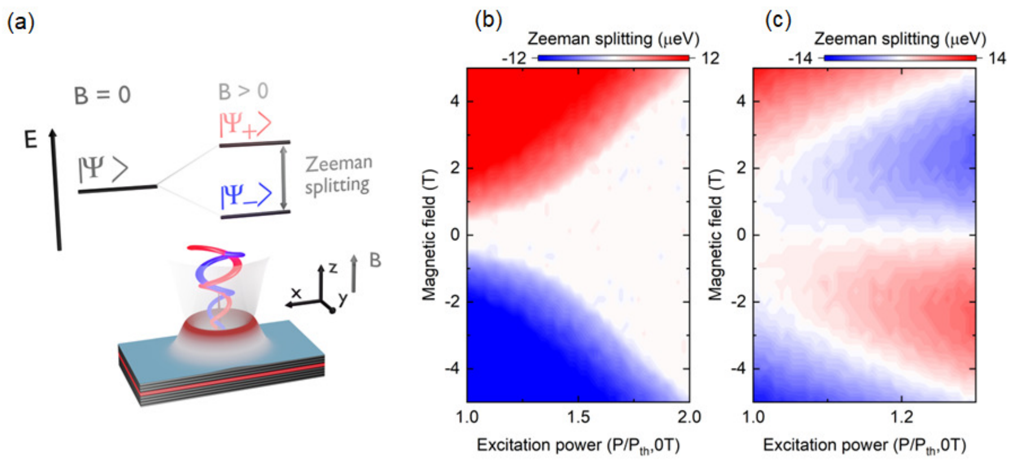

Figure 1: (a) Schematic illustration of the investigated sample. The linearly polarized, non-resonant continuous wave laser was used to create equal populations of the $|\psi_{\pm}\rangle$ polaritons. The $\sigma_{\pm}$ emission (blue and red spirals) is detected simultaneously. The magnetic field applied parallel to the sample growth axis lifts the degeneracy of the polariton spins, manifesting in a detectable energy difference between the emitted circularly polarized photons. (b) Power-induced suppression of the Zeeman splitting. The splitting vanishes at certain critical boundaries in the B-P plane (white region), becoming parametrically screened by the condensate interactions (c) Power-induced inversion of the Zeeman splitting. The splitting sign is reversed after exceeding the critical value of the excitation power.

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Narrow linewidth exciton-polariton laser

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Microcavity exciton-polaritons undergo Bose-Einstein condensation (BEC) in a wide range of temperatures across various material platforms. The decay of polaritons in the BEC results in a coherent photon emission creating a novel type of laser called a polariton laser. This type of laser features lasing without population inversion and at lower threshold levels than conventional photon lasers. However, polaritons have limited lifetimes ($\sim$ 1- 100 ps) and continuous pumping (typically optically) is necessary for the continuous-wave operation. Prior works suggest that the intensity fluctuations of the optical pump induce decoherence of the BEC [1], resulting in linewidth broadening. As a way to mitigate decoherence, optical trapping is used to minimize the overlap between the excitonic reservoir (generated by the pump) and the polariton condensate thereby achieving longer coherence times [2].

Here, we directly measure the emission linewidth and carefully study how to minimize the linewidth broadening. We report the successful realisation of an ultra-narrow linewidth exciton-polariton laser with a linewidth of $\sim$50 MHz or $\sim$ 0.21 μeV, limited by the resolution of our instrument. This corresponds to a coherence time of at least $\sim$5.3ns, 1.8X longer than previous estimates [2]. We used a reconfigurable ring-shaped excitation profile (Fig.1a) generated using a spatial light modulator. To investigate the decoherence effects stemming from the overlap of the incoherent reservoir and the condensate, we used two approaches. First, we reduce the size of the optical ring traps to increase polariton confinement and reservoir-condensate overlap. Second, we directly control the reservoir-condensate overlap by illuminating the center of the optical ring trap creating a potential offset, V_0. We tune the trap offset to carefully study the decoherence as a function of the degree of condensate-reservoir overlap. We found that a narrow linewidth is consistently achieved for a trapped polariton condensate with a high photonic content. Contrary to previous reports, we show that the reservoir does not strongly affect the emission linewidth as long as the condensate is sufficiently trapped and the pump is well above threshold. Our results will open up experimental manipulation of the macroscopic quantum state of the system owing to its long coherence time.

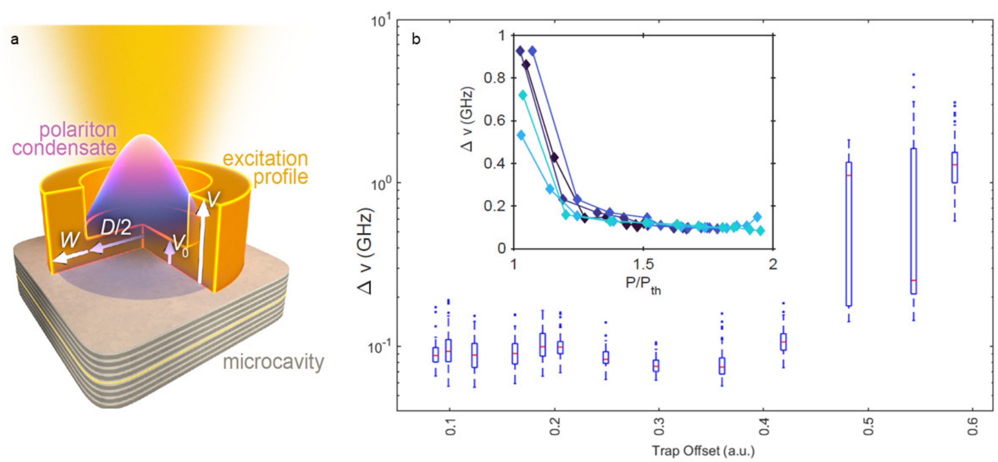

Figure 1: (a) Reconfigurable optical trap profile.(b) Spectral linewidth of the polariton condensates at various trap offsets and as a function of pump power.

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Exciton-polariton condensates in photonic crystal waveguides: from topological molecules to supersolidity

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Photonic crystal waveguides have emerged as an extremely promising platform for Bose-Einstein condensation of exciton-polaritons. They support symmetry-protected bound-in-the-continuum states (BiCs) that show large evanescent coupling strengths, vanishing linewidth, and non-trivial topology. These properties along with the tendency of BiC polaritons to preferentially condense in negative effective mass states have opened up new research opportunities, namely reprogrammable optical lattices and supersolid analogues.

Optical lattices: the saddle-dispersion of one-dimensional photonic crystal waveguides leads to a strongly anisotropic behaviour of coupled condensates, forming artificial molecules. The coupling changes from evanescent to ballistic depending on the orientation of the molecules with respect to the waveguide axis of symmetry. We have demonstrated full geometric control of the coupling strength and nature that allows to design bespoke, reconfigurable lattice models where different forms of coupling coexist. Moreover, the non-trivial phase pattern of the BiC further enriches the system and can naturally impose artifical gauge fields in these lattices.

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 measured 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 demonstrated the potential of our synthetic photonic material to host phonon dynamics and a multimode excitation spectrum.

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Dirac exciton–polariton condensates in photonic crystal gratings

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Bound states in the continuum (BICs) are confined wave-mechanical objects that offer advantageous ways to enhance light–matter interactions in compact photonic devices. In particular, their large quality factor in the strong-coupling regime has recently enabled the demonstration of Bose–Einstein condensation of BIC polaritons [1]. I will discuss recent experimental results that have demonstrated polariton condensation into a negative-mass BIC which exhibits interaction-induced state confinement [2]. This allows us to optically tailor artificial molecular complexes using polariton BIC droplets with unusual polarization topological charge structure [2]. We demonstrate the scalability of our technique by constructing artificial mono- and diatomic chains of BIC polariton condensates that display single- and double Bloch band formation. These resulst offer exciting insights into large-scale and reconfigurable polariton quantum fluids for emulation of complex many-body systems.

I will then present results on the development of the single- and many-body theory of these new effective relativistic polaritonic modes and describe their mean-field condensation dynamics facilitated by the interplay between protection from the radiative continuum and negative-mass optical trapping [3]. Our theory accounts for tunable grating parameters giving full control over the diffractive coupling properties between guided polaritons and the radiative continuum, unexplored for polariton condensates. In particular, we discover stable cyclical condensate solutions mimicking a driven-dissipative analog of the zitterbewegung effect characterized by coherent superposition of ballistic and trapped polariton waves. We clarify important distinctions between the polariton nearfield and farfield [3] explaining recent experiments [1, 2] on the emission characteristics of these long lived nonlinear Dirac polaritons.

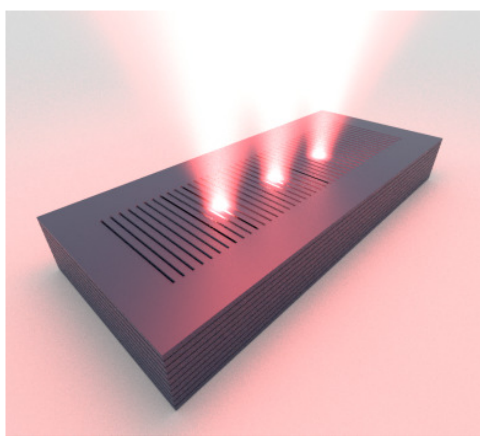

Figure 1: Subwavelength grated semiconductor waveguide supporting pumped exciton-polariton condensates

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Ultrafast electrically-reconfigurable interacting-photon circuits using waveguided dipolaritons with huge nonlinearities: from photon scattering on electrical potentials to a GHz two-photon transistor

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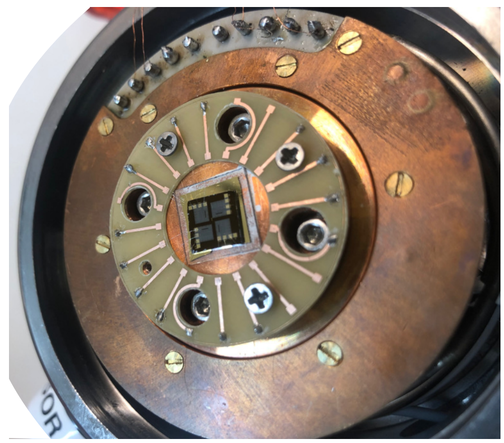
Electrically controlled photonic circuits hold promise for information technologies with greatly improved energy efficiency and quantum information processing capabilities. However, weak non-linearity and electrical response of typical photonic materials have been two critical challenges. Therefore hybrid electronic-photonic systems, such as semiconductor exciton-polaritons, have been intensely investigated for their potential to allow higher nonlinearity and electrical control, but with limited success so far, as non-polar particles do not interact sufficently with either electric fields or with other particles.



The extended range, anisotropic nature of mutual interactions between dipolar excitons however, has shown great promis to engineer strongly interacting quantum systems which are highly correlated, resulting in new manybody quantum states. Thus, the ability to hybridize dipolar excitons with confined photons should allow formation of polaritons which carry effective dipole moments, leading to "interacting dipolar photons".

We demonstrate light circuits based on photons confined in planar waveguide geometries that are hybridized with 2D-excitons that can be electrically polarized using electrical gates. This new concept leads to novel ways to control polaritons motion electrically, as well as tuning the position and strengths of their mutual interaction, that can reach surprisingly huge values.

Here, a new class of planar waveguide devices are shown, that elucidate the exciting physics that can be explored and the pormising quantum-photonic applications that can be developed with such on-chip dipolariton circuits.

First, we demonstrate that surprisingly, “dipolar light” can very effectively undergo coherent scattering from local electrical potentials, in a manner consistent with quantum scattering theory of ultra-light dipolar particles. Remarkebly, the scattered light exhibit phase shifts that can be precisely controlled with voltage, a result promising for constructing single photon phase gates.

Then, we utilize sectioned electrical gating of the waveguides to construct ellectrically reconfigurable potential landscapes for flying dipolaritons. With this architecture, we demostrate an ultrafast electrical mirror for photons with a GHz switching time, and then an electrically-controlled photon transistor based on enhanced dipolar interactions between slow polaritons. The polariton transistor displays blockade and anti-blockade by compressing a dilute dipolar-polariton pulse exhibiting very strong dipolar interactions. These surprisingly large nonlinearities are well explained using a simple density-dependent polarization field that very effectively screens the external electric field. Remarkably, we show that ellectrically induced-dipoles can have an order of magnitude enhancement of the nonlinearities over fixed dipoles, a result that should have significant future implications.

Finally, we demonstrate photon correlation measurements from a transistor with resonantly injected dipolaritons, displaying both anti-bunching and bunching, reconfigured and tuned simply by changing the gate voltage, showing that such electrically controlled planar geometry of waveguided dipolaritons is a very promising platform for complex interacting light circuitry for quantum-photonics applications.

Biography

Ronen Rapaport is a Professor of Physics at the Racah Institute of Physics at the Hebrew University of Jerusalem, Israel (HUJI). Ronen has received his PhD in Physics from the Technion, Israel in 2001, where he studied the physics of exciton polaritons. Ronen then became a principle investigator (MTS) at the Optical Physics department, Bell Laboratories, where he conducted research in various fields related to quantum nano-structures of semiconductors until 2007. Ronen is heading the Nanophotonics of Quantum Structures Lab (NPQSL) at HUJI, with research efforts ranging from many-body quantum physics of excitons and polaritons in low dimensional quantum structures, to light-matter coupling of quantum emitters and nano-optical devices.

Excitons in bilayer WTe_2

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Bilayer WTe_2 is a remarkable two-dimensional metal, since it exhibits a macroscopic out-of-plane electric dipole in spite of the presence of charge carriers that screen the electrostatic forces between ions [1]. At low temperature the system develops a narrow transport gap, like its monolayer counterpart where the appearance of the gap has been attributed to condensation of excitons [2]. The similarities between transport measurements in mono and bilayer structures suggest that similar excitonic physics is at play in the bilayer. Moreover, contrary to other known bilayer excitonic insulators, in which electrons and holes are spatially separated, in WTe_2 interlayer tunneling is significant. This might impact the observable features of the putative exciton condensate, giving rise to a coherent contribution to the electric dipole, due to the interband electric polarization of excitons.
In this work we investigate bilayer WTe_2 both from first principles and with a model built upon the symmetries of the system, focusing on the characterisation of excitons by means of the Bethe-Salpeter equation. The ultimate goal is to assess the instability against exciton condensation, as well as to predict its possible experimental fingerprint.

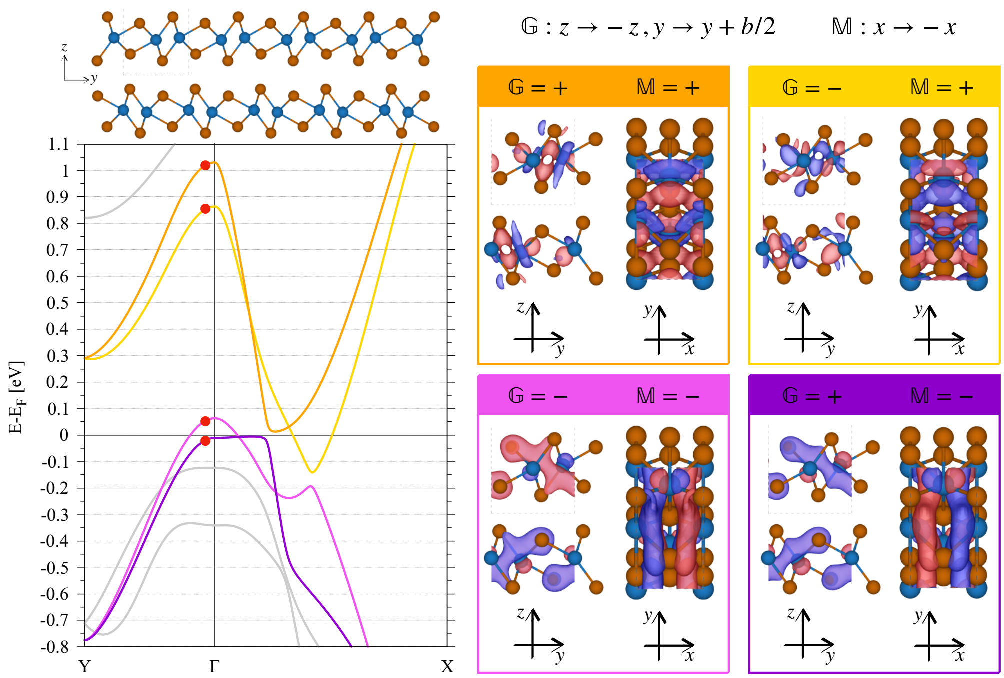

Figure 1: Side view of bilayer WTe_2 (1T' phase) and its band structure computed ad the DFT-PBE level. The four insets on the right show the real part of Kohn-Sham wavefunctions at the k-points marked by the red dots for the four bands with corresponding colour. The side and top views in each inset allow to determine the sign of the states with respect to the glide symmetry ($\mathbb{G}$) and the mirror symmetry ($\mathbb{M}$) of the crystal structure.

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Direct observation of Bose-Einstein condensate of excitons in a bulk semiconductor using mid-infrared induced absorption imaging

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The 1*s* paraexcitons in cuprous oxide (Cu_2O) have attracted interest as one of the most promising candidates for exciton Bose-Einstein condensates (BEC) in a bulk semiconductor. The 1*s* paraexcitons in Cu_2O, which are decoupled from the radiation field, are purely matter-like quasi-particles. The weakness of the coupling between paraexcitons and the radiation field brings about a long paraexciton lifetime of over several hundred nanoseconds. This long lifetime is beneficial for preparing cold paraexcitons via exciton–phonon interactions. A great deal of effort has been made on studies of paraexciton BEC at liquid helium temperatures around 2 K since the 1990s [1]. However, the two-body inelastic collisions between paraexcitons prevent paraexcitons from reaching thermal equilibrium at a high BEC transition density of 10^{17} cm^{-3}. In previous research [2], the target exciton temperature was set for reduced critical densities to mitigate two-body inelastic collisions. Since the paraexciton diffusion at sub-1 K hinders an efficient accumulation of paraexcitons, a method for effective collection of 1*s* paraexcitons in a strain-induced trap potential was used. Accumulation of trapped paraexcitons exceeding the BEC critical number at an exciton temperature of 800 mK led to the observation of a phenomenon called “relaxation explosion”, suggesting the BEC transition of paraexcitons. However, two-body inelastic collisions induce the large instability of the condensate at a BEC transition density of 10^{16} cm^{-3}.

The formation of a stable condensate requires a reduced BEC transition density of 10^{15} cm^{-3} to avoid two-body inelastic collisions. To fulfil this requirement, we succeeded in the formation of trapped paraexcitons at a temperature of sub-100 mK using a dilution refrigerator [3]. For the quantitative detection of BEC of dark paraexcitons, we developed mid-infrared induced absorption imaging associated with the 1*s*–2*p* transition of paraexcitons at dilution temperatures. We carefully designed our setup that allows for introducing the mid-infrared probe light into the dilution refrigerator with a minimal amount of excess heat. The achievement of absorption imaging at dilution temperatures enabled us to extract the spatial density distribution of trapped paraexcitons and to observe the paraexciton condensate as a locally condensed signal in a trap potential [4]. Unconventionally, the maximum condensate fraction that we observed is 0.016, which is two orders of magnitude smaller than that expected for an ideal Bose gas. To further investigate this new type of BEC, we performed absorption imaging at higher excitation powers than reported in [4], varying the delay between a pump light and a probe light. We intend to present these results along with the details of [4]. Based on these results, we will discuss the time evolution of the spatial profile of the paraexciton cloud.

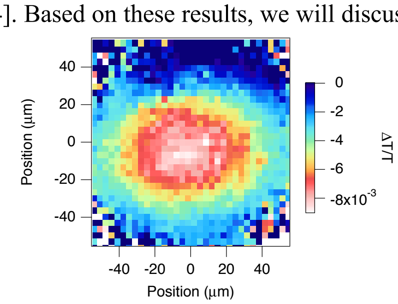

Figure 1: Typical absorption image of paraexcitons at an excitation power of 72 mW. The pulsed probe light was introduced into the crystal after the fall of the quasi-cw excitation light.

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Equilibrium excitons and superconductivity in 2D semimetal WTe_2

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In a two-dimensional semimetallic material that contains separate small electron and hole pockets, electron-hole correlations will be strong and excitons might even exist spontaneously in equilibrium. WTe_2 appears to be such a semimetal, and both monolayer and bilayer WTe_2 do indeed show unusual insulating electrical characteristics and a thermodynamic gap that opens at the charge-neutral point on cooling. Suggestions that the charge-neutral state is an excitonic insulator, formed by exciton condensation, are confounded by the absence of any charge density wave, though the possibilities of spin-density waves and biexciton condensation remain. I will describe our ongoing attempts to investigate this intriguing electronic state and its relationship with the topological boundary modes, ferroelectricity and superconductivity all seen in the same material. Some interesting possibilities are that scattering in the boundary modes could be sensitive to the electron-hole correlations; the ferroelectric order parameter could be a probe of coherence; and the superconductivity could be mediated by excitons.

Controlling topological light with light-matter coupling

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Coupling between light and matter can be treated as a tool for controlling dynamical systems at ultrashort timescales. It opens the way to creating new states and quasiparticles, existing both in the classical and quantum regimes. The variety of forms in which light-matter interactions manifests in nature brings the possibility to create topological states of light, which are candidates for enabling efficient quantum information processing.

In this talk I will describe our theoretical research on topological protection in one-dimensional chains going beyond the well-known Su–Schrieffer–Heeger (SSH) model. We demonstrate that engineering topological states of light in systems characterized by Rashba-Dresselhaus spin-orbit coupling [4] can lead to topological protection even in the case of non-staggered chains. I will review the research on non-Hermitian topological states in exciton-polariton lattices and describe the emerging bulk-boundary correspondence [2]. Importantly, in both cases we show the existence of topological states which have no analog in the standard SSH model.

In the second part of my talk I will describe recent theoretical and experimental results on vortex turbulence and Onsager clustering in dissipative quantum fluids of light [3, 1]. The detailed investigation reveals the physical mechanism behind the formation of a negative-temperature state as well as the conditions required for the formation of vortex clusters in the presence of particle loss.

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Neural computing with exciton-polaritons in perovskite nanowires.

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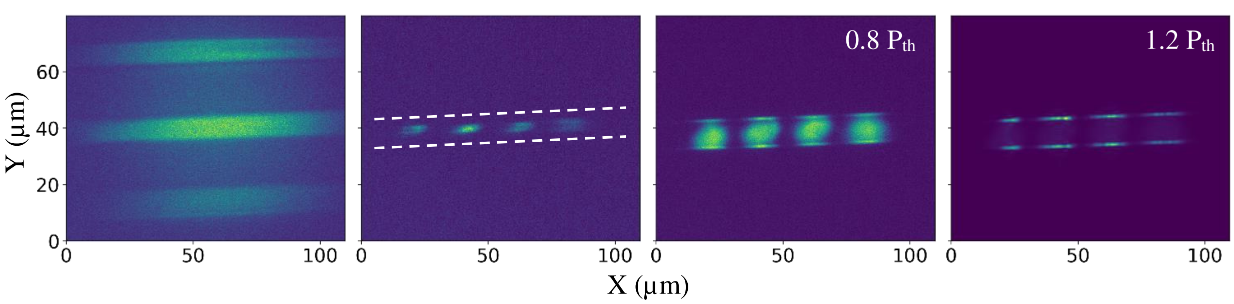
Research on optical neural networks (ONN) gained popularity as they potentially offer a significant advantage in processing speed and energy efficiency, making them crucial for handling complex computations and large datasets in real-time applications. Implementation of ONN requires linear operations to be performed on a signal carrier which is sent between the nonlinear network nodes. Although linear operations are easily accessible in the optical domain most nonlinear effects arise under the high excitation powers of pumping laser. This sparked interest in the development of nonlinear nodes based on effects appearing in microcavities with exciton-polaritons which promise energy-efficient nonlinear transformation due to strong light-matter coupling and exciton-polariton ability to condense following Bose-Einstein statistics.[1] Although networks based on such structures have been demonstrated, one significant limitation in the scaling of such a solution is the low-temperature operation, which is required to observe non-linear effects in classical structures based on III-V and II-VI semiconductors. Recently a lot of effort went into the investigation of perovskite-based microcavities towards room temperature exciton-polaritons. In this context, we developed a versatile method for creating perovskite waveguides capable of hosting exciton-polaritons at room temperature.[2] These structures support the formation of spatially extended condensates of coherent exciton-polaritons. We demonstrated polariton lasing occurring at the edges of microwires, with substantial blueshifts observed under high excitation power. The high mutual coherence between different lasing signals at edges, as evidenced in far-field photoluminescence and angle-resolved spectroscopy, indicates the formation of a coherent polariton condensate. We use these effects to generate condensation sites that may work as separate or coupled nonlinear nodes of ONN (as shown in Fig.1). The waveguides are composed of $CsPbBr_3$ monocrystals in a process allowing the formation of various 2d structures which accounts for the high versatility of such platform in the context of implementing different ONN architectures including reservoir computing, feed forwards networks and spiking neural networks. Our findings delineate a path for developing a scalable, versatile, and energy-efficient platform for the realization of various neuromorphic computing paradigms in the optical domain.

Figure 1: Separate uncoupled non-linear nodes created by pulsed and non-resonant excitation of perovskite wire with 4 beams of a ps-pulsed laser. From left: sample image, 4 beam spots, wire emission below the condensation threshold, edge-emission above condensation threshold. Images are normalized in intensity.



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Directional planar antennae in polariton condensates

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Exciton-polaritons are bosonic quasiparticles formed in strong coupling regime between photonic and excitonic components in semiconductor microcavity [5]. Light effective mass and high nonlinear interaction of polaritons permit nonequilibrium Bose-Einstein condensation at elevated temperatures [3] and ballistic outflow from localized pumping spots [9]. Creating propagating polariton waves away from the pump spots and their control is an important step towards building reprogrammable all-optical circuitry and logic [4]. Polariton guiding using resonant ejection is one method to create polariton flow in desired direction [2, 10] and can be done without relying on fabrication techniques, making sample irreversibly applied for each specific case. However, resonant pumping demands careful calibration of the excitation beam angle and energy which is not very feasible for practical devices [6]. Nonresonant control over the flow of condensate polaritons is another all-optical way of polariton guiding, which utilizes repulsive nature of exciton-polariton interaction [7]. Recently the design of reconfigurable planar microlenses realized only by structured nonresonant excitation beams was proposed [8]. Such a scheme is conceptually similar to the propagation of optical waves in a medium, where use of lenses is an established method of light guiding, promising a possibility to create far separated and intense polariton flow with small pumping area. Here we present the experimental realization of such an all-optical planar microlens with the use of spatial light modulators to structure a nonresonant excitation beam into a planoconcave lens-shape. The effect of pump power, which regulate interplay between gain and blueshift of polariton mode, as well as the geometry of lens-shaped pump were studied and the strategy to optimize focusing of condensate outside of reservoir is proposed [1]. Our work underpins the feasibility to guide nonlinear light in the cavity plane using nonresonant excitation schemes, offering perspectives on future optically reprogrammable on-chip polariton circuitry.

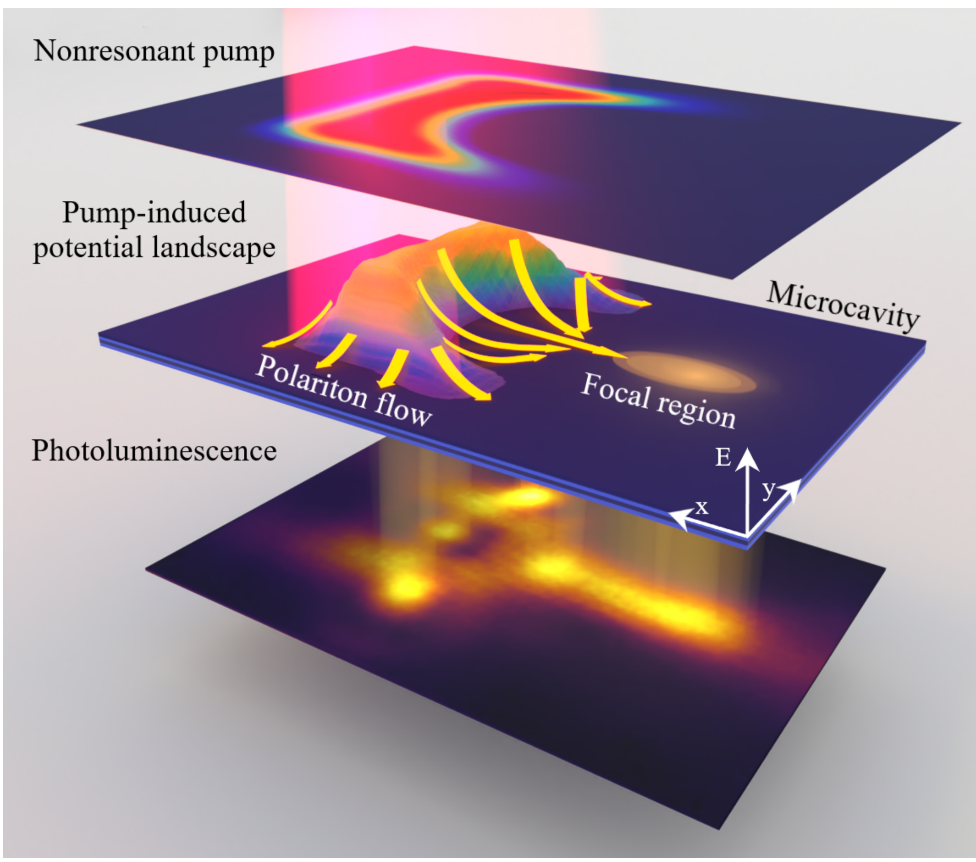

Figure 1: Schematic of nonresonant lensing effect.

ICSCE12 Dublin 2024

Deep physical neural networks using physics-aware training

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Deep neural networks have become ubiquitous in today's data-driven world, but their energy requirements increasingly limit their scalability and broader use. In this work [1], we propose the construction of deep physical neural networks that are made from layers of controllable physical systems, which can learn hierarchical representations of input data analogous to deep neural networks. To train these physical neural networks, we introduce a hybrid in situ-in silico algorithm, *physics-aware training*. This training method has favourable scaling properties as it uses backpropagation, the de-facto training method for deep neural networks. To demonstrate the universality of our approach, we train diverse physical neural networks based on optics, mechanics, and electronics to experimentally perform audio and image classification tasks. Our approach broadens the possibility of using novel physical systems for deep learning and potentially enables them to perform machine learning faster and more energy-efficiently than conventional electronic processors.

Towards the end of the talk, I will also highlight our recent work [2] on applying this framework towards a programmable integrated photonic platform with a large number (~10,000) of parameters. We constructed a *2D-programmable waveguide*, where the refractive-index distribution $n(x, z)$ of a slab waveguide is arbitrarily programmable in real-time. Using physics-aware training, we train the complex multimode wave propagation in the chip directly to perform machine learning.

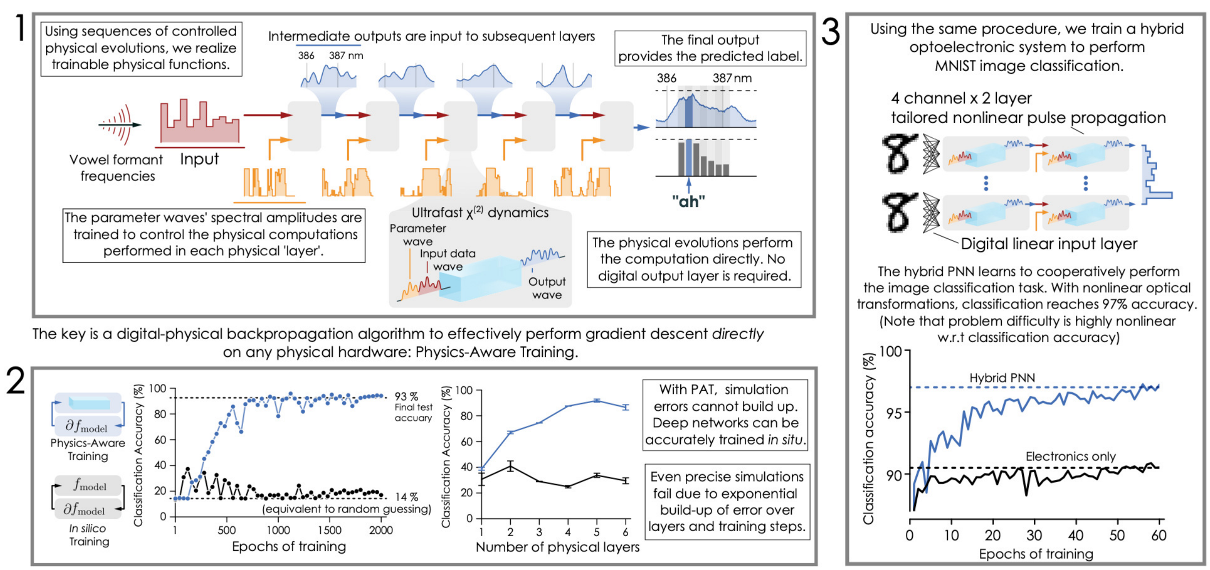

Figure 1: Training deep physical neural networks (PNNs) based on nonlinear optics with physics-aware training (PAT). Figure adapted from Ref. [1]. All results shown are experimental.

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Integrated, ultrafast all-optical polariton transistors

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**contributed equally*

Integrated all-optical logic could drive a new paradigm for computing architectures. Based on strong light-matter coupling all-optical transistors exhibiting ultrafast switching and room-temperature operation have recently been demonstrated using polaritons in vertical cavities [1,2]. Here, we leverage silicon photonics processing technology for realizing high index contrast grating microcavities with an organic polymer as photoactive material (Fig. 1a) to demonstrate polariton condensation and strong light-matter interaction integrated on a chip. In this configuration, the cavity modes are in the plane of the chip, and the light can be guided between separate cavities. Thereby we can overcome the scalability roadblock that existed with vertical cavities, which have been the work horse of polariton physics for decades.

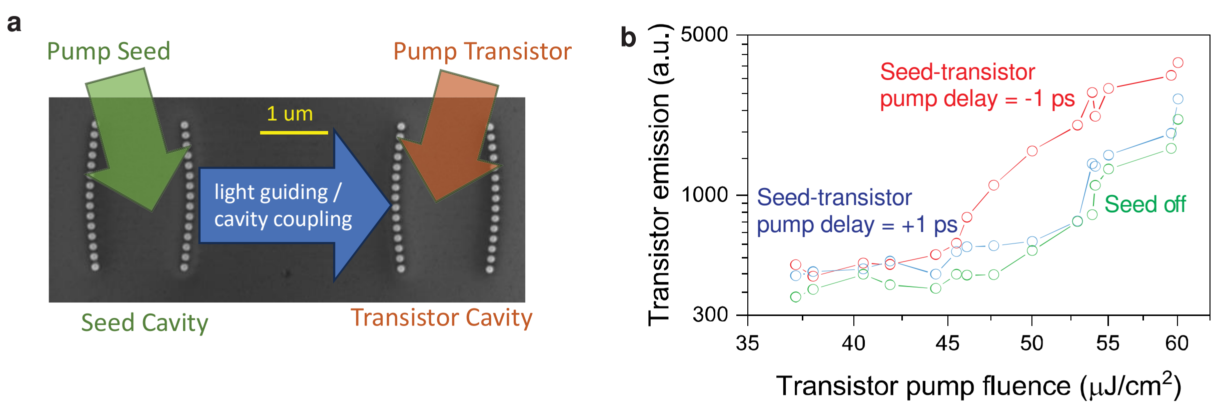

Figure 1: Coupled high contrast grating cavities with polariton condensates. a, Scanning electron microscopy image and illustration of the excitation and coupling of the "seed" and the "transistor" cavities. b, Output of the transistor cavity for "right" (-1 ps) and "wrong" (+1 ps) timing between seed and transistor pump pulse and when the seed is off. When the polariton condensate in the seed cavity is pumped first, its output effectively seeds the condensate in the transistor cavity and thereby lowers the condensation threshold of the transistor cavity.

We observe all-optical transistor action and prove the cascadability of the device concept by realizing two identical, coupled microcavities where in one cavity ("seed") a spontaneous polariton condensate is created as input to the other cavity ("transistor") (Fig. 1b) where it then can induce the polariton condensation process. We investigate the ultrafast polariton condensation dynamics on sub-picosecond timescale and extract the key transistor metrics like signal amplification (up to factor 60) and on/off extinction ratio (up to 9:1).
Our results open the door for integrated, ultrafast all-optical transistors with scalability allowing more complex optical logic circuits.

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Strong coupling using organic molecules, targeting the idealness of polaritons and the relative size of the exciton reservoir

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Strong light-matter coupling generates hybrid states that inherit properties of both light and matter, effectively allowing the modification of the molecular potential energy landscape. This phenomenon opens a plethora of options for manipulating the properties of molecules, with a broad range of applications in physics, chemistry, and materials science. In this presentation, I will start with introducing the fundamentals of strong light-mater coupling.[1, 2] How an optical cavity can be used to increase the electromagnetic field experienced by a molecule to the point where new hybrid light-matter states, called polaritons, emerge. I will go through our work on modelling polariton relaxation, using rate equations, where the polariton branch is discretized into a finite number of states.[3] Ideally, when N number of molecules collectively couple with an optical mode, 2 polaritonic and N-1 dark states (the exciton reservoir) are formed. However, the value of N has not been directly experimentally measured. I will go through a method where the relative number of N can be attained, enabling the possibility to obtain the dependency of the polariton relaxation on N.[4] The absorbance spectrum of organic molecules is typically energetically broad. For organic molecules, the width of the absorbance spectrum is often quite similar to the Rabi splitting, and such systems can not be classified as ideal. To link theory with experiments, it is therefore necessary to either introduce non-idealness in the theory or make molecules with more narrow absorbance bands. I will show our attempts of making organic molecules that can be processed into neat films with narrow absorption bands and still be able to enter the ultra-strong coupling regime. Towards the end of my talk, I will go through our trials to apply polaritons in different photophysical context, with the first one discussed being organic solar cells.[5-9]

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In-situ tunable, room-temperature polariton condensation in individual states of a 1D topological lattice

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Microcavity exciton-polaritons are bosonic, light-matter quasiparticles resulting from strong coupling between a cavity's resonance mode and the excitonic transition of an active material placed inside the cavity. Due to their bosonic nature, at sufficient densities, polaritons can undergo Bose Einstein condensation, making them a promising platform for a semiconductor based analog quantum simulator.

In this work, 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 weak and strong bonds, a so called Su-Schrieffer–Heeger (SSH) chain, which was originally used to model polyacetylene.

First, to probe the topological signatures of the studied structure, we measured the angle-resolved photoluminescence by locally exciting the structure with a 400 nm continuous-wave laser. By exciting the center of the structure we observe a well resolved bandstructure with clearly formed S-like and P-like energy bands. Repeating the measurement at the edge of the structure leads to the observation of a slightly different bandstructure. Inside the first energy gap a discrete energy state has appeared, indicating the formation of a topological edge state in the studied lattice's bandstructure. Furthermore, we studied the system above polariton condensation threshold, using a frequency-doubled, amplified Ti:sapphire laser at 400 nm, with a 1 kHz repetition rate and approximately 150 fs pulse duration. Using the tunability of our cavity and a vibron assisted relaxation mechanism [1], unique to organic materials, we are able to selectively condense polaritons to individual states of the 1D topological lattice (Fig. 1). Using a Michelson interferometer we investigated the coherence of the condensates, which exhibited long range spatial coherence spanning through almost the whole structure. Finally, we measured and compared three structures with different ratio between the weak and the strong bond. We showcased engineering of the energy gap and of the topological edge state localization by tuning the coupling of the weak bond.

These results display the high level of tunability and engineerability of our platform and showcase its potential for the study of topological effects and the simulation of complex Hamiltonians at room temperature.

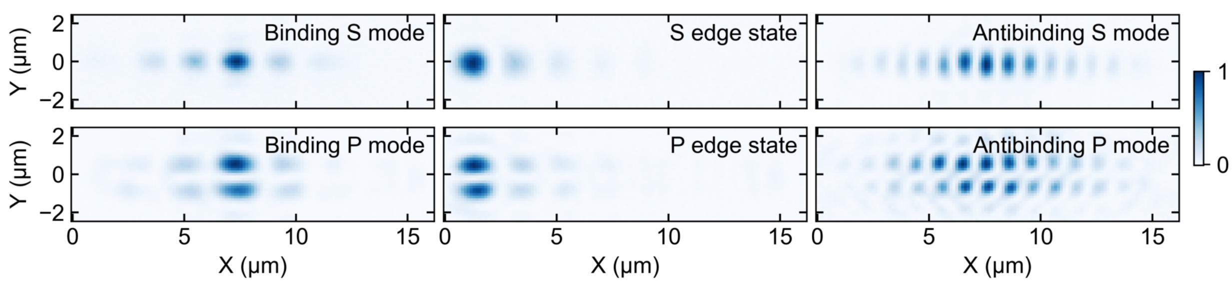

Figure 1: Experimental, real space images of polariton condensates, selectively formed in six different modes of the studied lattice. The three upper images indicate modes that originate from the S-like band and are comprised of two bulk modes (Binding S and Antibinding S) and the topological edge state. The three images at the bottom part of the figure are the equivalents of the previous modes, but this time they originate from the P-like band, which can be seen by the symmetry of the lobes (notch in the center). The colorbar indicates the normalized emission intensity.

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Line lasing in a two-dimensional lattice of photonic resonators

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The engineering of specialty lasing systems with unconventional mode structures is one of the modern challenges in the development of integrated coherent sources. The goals are to engineer miniaturised configurations, with high efficiency, and enhanced functionalities. Some examples of successful configurations include Bound States in the Continuum [1], lasing modes with Orbital Angular Momentum [2], the use of Dirac-based band structures [3] and topological lasers [4]. In this work, we address the challenge of engineering and implementing a two-dimensional lattice of coupled photonic micropillars with one-dimensional lasing line modes. Such a configuration opens the possibility of implementing densely packed independent lasing modes in a two dimensional matrix.

To engineer line lasing modes in a two-dimensional lattice, we introduce a novel lattice configuration, named the orbital Lieb SP lattice. It is based on a square Lieb lattice that combines micropillars of two different diameters to design orbital bands with a hybrid S and P mode nature. Each micropillar is composed of two dielectric Bragg mirrors confining a λ cavity with an InGaAs quantum well. Figure 1(a) displays a schematic of the lattice: B sites with large diameter occupy the corners of a square lattice, while A and C sites, with small diameter, are positioned at the midpoints of the edges of the square structure. The diameter difference leads to different energy confinement resulting in SP mode interactions: p_x, p_y orbitals of B sites couple to s orbitals of C and A sites as depicted in Fig. 1(b). This coupling allows for an exotic band dispersion in which each band is dispersive along one direction and flat along the perpendicular one, as shown in Fig. 1(c). Consequently, the eigenmodes are line modes confined in one direction and propagating in the other direction. Here, we experimentally demonstrate the selective lasing into these line modes (Fig. 1(d)). By exciting the lattice with an elongated Gaussian spot along either vertical or horizontal orientations we show lasing along any desired line of the lattice. Figure 1(e) shows the case of lasing in two crossing line modes. Surprisingly, the two modes phase lock producing an exotic mode laser in the form of a cross.

Our results open interesting perspectives in the use of orbital lattices to engineer unconventional lasing configurations and raise questions about the mechanisms behind the mode-locking of orthogonal lasing modes.

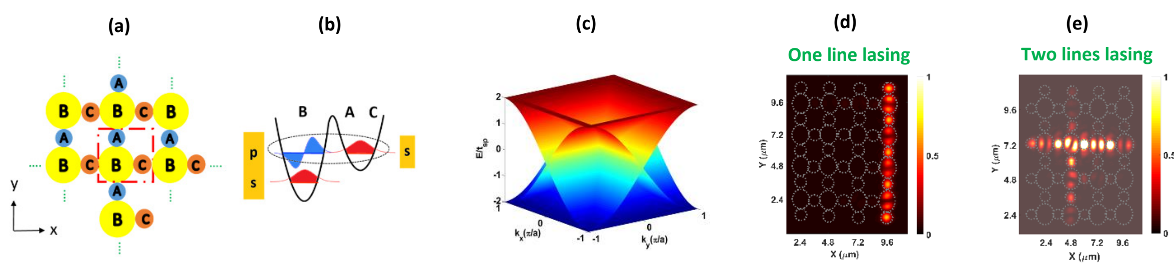

Figure 1: (a-b) Lieb sp lattice geometry and schematics of sp mode interaction, c) Dispersive-flat band dispersion, d) Line mode lasing along vertical direction, e) Two lines lasing - vertical and horizontal direction for a 4×4 lattice.

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Electrically Controlled Interaction of Coupled Bose-Einstein condensates in a Dye-Filled Liquid-Crystal Microcavity

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Non-equilibrium Bose-Einstein condensates (BEC) in photonic systems are promising for exploring and engineering phases of matter under extreme conditions and can be used to perform analogue simulations at both cryogenic and room temperatures [1, 3]. In order to establish a robust and scaleable platform for computing based on non-equilibrium photonic condensates problems of tuneability and reconfigurability should be addressed. Here we demonstrate electrical control over interaction between coupled BECs in an organic dye-filled liquid crystal (LC) microcavity at room temperature. We bring optical reconfigurability by controllable driving of each condensate with a focused non-resonant optical excitation. Similar to the well known behaviour of polaritonic BEC in GaAs systems at cryogenic temperatures we observe power dependent in-plane momentum of the coherent emission above the threshold. We utilise it to form a coupled state in a dyad (see Figure 1) or even a small lattice of condensates with the coupling strength depending on the distance between the pumping spots and pumping power. Additionally, high birefringence of the LC provides wide range tuneability of the dispersions for the microcavity optical modes with different polarisation and allows further control over coupling efficiency by changing the in-plane component of the emission. In particular, significant detuning of one of the linearly dispersion modes allows for the realization of the Rashba-Dresselhaus spin-orbit coupling regime when emission from each pumping spot with opposite spins is additionally split in both real and Fourier space bringing the spin degree of freedom to the system. Moreover, we show that by changing the relative polarisation of the pumping spots we can bring the system to the regime of next-nearest-neighbour interaction, demonstrated previously in inorganic systems by means of distance-periodic pseudospin screening [2].

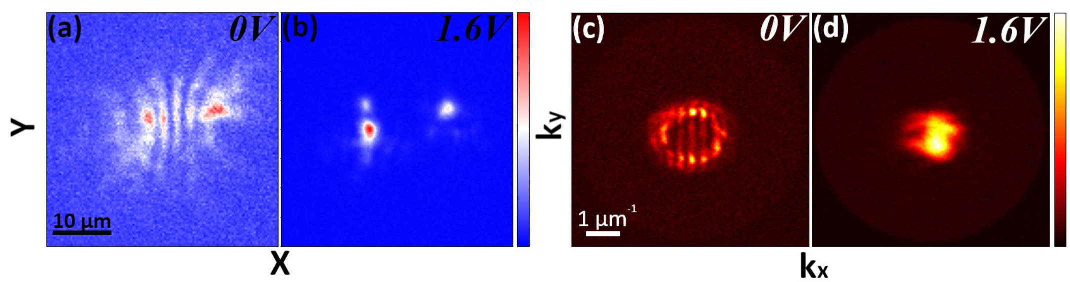

Figure 1: Emission properties of two non-resonantly pumped spots: measured (a,b) real-space and (c,d) momentum-space photoluminescence (a,c) without and (b,d) with external voltage applied.

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Polariton effects in photonic structures based on Cu_2O and transition metal dichalcogenide materials.

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Polaritonic structures, where hybridisation between light and matter leads to giant Kerr-like optical nonlinearities, are very promising for various classical and quantum applications and optical circuitry[1], where active control of light by light is required. In my talk I will focus on systems based on Cu_2O and transition metal dichalcogenide materials.

In Cu_2O crystals Rydberg excitons, excited states with high principal numbers and large Borh radii, may enable strong Kerr-like optical nonlinearities due to Rydberg blockade. Rydberg exciton-polaritons were observed recently[2]. We investigated Kerr-like nonlinearity of Rydberg exciton-polaritons for states up to n = 7 under resonant excitation using picosecond laser pulses[3]. The polariton non-linearity coefficient scales with principal quantum number as $n^{4.4}$, which is in agreement with the Rydberg blockade theory. The time-resolved pump-probe experiments revealed complex dynamics due to interplay between the Rydberg exciton-exciton interactions, interactions with long-lived 1s exciton reservoir and plasma arising from Auger recombination. Our experiment is the first laying stone towards utilising extended Rydberg states for giant optical nonlinearities and I will discuss further perspectives with such systems.

In the second part of my talk I will discuss polaritonic systems based on transition metal dichalcogenides (TMDC). Strong coupling has been observed with excitons in TMDC monolayers in microcavities, waveguides[4] and topological photonic crystals[5]. The polariton nonlinearity comparable to that in III-V structures has been demonstrated. Moreover, the bulk TMDC materials possess large in-plane refractive indices and refractive index anisotropy potentially giving an advantage over other commonly used dielectric materials (Si, GaP etc) for design of novel integrated photonic devices and circuits[6]. We fabricated spin Hall topologically trivial and non-trivial photonic lattices in 100-150 nm thick WS_2 films and observed chiral propagating modes at the interface between them. Integration of such TMDC based metasurfaces with atomically thin TMDC films ($MoSe_2$, WSe_2 and others) and other semiconductor/dielectric materials paves the way towards development of novel hybrid photonic and polaritonic devices.

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Thermal and quantum-driven Bogoliubov excitations in a driven-dissipative quantum fluid of light

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Under coherent laser drive, one can generate a macroscopic steady-state population of exciton-polariton which is nowadays well-known to behave as a genuine quantum fluid [1], albeit one which is uniquely not isolated, nor at thermal equilibrium (excluding rare exceptions). The theory predicts that its elementary excitations are well described by Bogoliubov theory, in striking analogy with weakly interacting ultracold atom condensates. While this prediction has been supported by numerous indirect experimental observations such as the emergence of a superfluid state above a critical density [2], a direct experimental demonstration has proven hard to obtain.

Recently, we measured the spectral function of the elementary excitations that are created on top of a coherently driven polariton condensate as a result of the system's intrinsic fluctuations. This observable provides a direct measurement of the excitations dispersion relation (that agrees with a recent pump-probe experiment [3]), as well as (u,v), the parameters at the heart of the Bogoliubov transformation. We found these observations to be in quantitative agreements with textbook Bogoliubov theory [4].

But the most striking observation that we report in [4] is the fact that we do observe a sizeable steady-state population of elementary excitations on top of the condensate, without probing the system at all, meaning that the condensate is coupled to an intrinsic source of fluctuations. In an isolated equilibrium system like ultra cold atoms, in absence of probe, thermally-excited Bogoliubov excitations are expected due to the system finite temperature. The case of driven-dissipative quantum fluids of light is fundamentally different as they are not at thermal equilibrium, and their open character means that they are coupled to their external environment. The latter indeed determines the generation of elementary excitations on top of the condensate via two different contributions: (i) by coupling to the extra-cavity photon vacuum, and (ii) by coupling to the thermal vibrations of the solid-state lattice that these quantum fluids live in. Previous theoretical works have focused on (i) and found that it does results in a steady-state stream of Bogoliubov excitations, and that the extra-cavity photons that they relax into are pair-correlated and entangled [6]. (ii) had never been considered so far in this context.

By quantitative comparison between our measured spectral function of the excitations, and a Bogoliubov theory that we developed to include fluctuations sources (i) and (ii) [4], we find that the Bogoliubov excitations that we observe are dominantly due to (ii). This is an unprecedented thermodynamical situation the context of Bogoliubov physics in which a driven-dissipative condensate is weakly coupled (i.e. as compared to the loss rate) to a thermal reservoir. We show for instance that even at vanishing lattice temperature (ii) still generates elementary excitations due to the quantum vacuum of the lattice vibrations. We also show that (ii), in spite of its thermal nature, can also generate strongly-correlated photons pairs.

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Compressibility and fluctuations of an optical quantum gas in a box

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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 [1]. Upon entering the quantum degenerate regime, the density response to an external force sharply increases, hinting at a highly compressible Bose gas. In other recent work, we have demonstrated a test of the fluctuation-dissipation relation in a photon Bose-Einstein condensate coupled to a particle reservoir. By independent measurements of the second-order correlations and the reactive response of the condensate population to a varied dye-cavity detuning, we verify for the first time a universal, temperature-dependent relation between the particle number fluctuations and the corresponding susceptibility in a Bose-Einstein condensate [2].

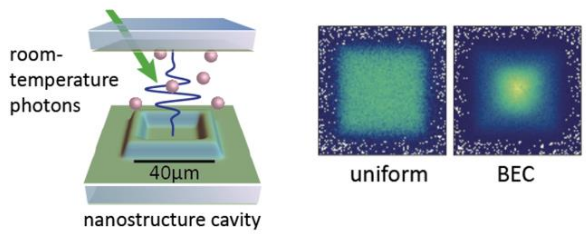

Figure 1: Dye-filled nanostructured optical microcavity confining a thermalized optical quantum gas with uniform surface density. Above a critical photon number of Bose-Einstein condensation into the ground state of the box trap is observed.

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Can polariton ring condensate make good qubits?

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We have generated polariton condensates with quantized circulation in a ring trap, with the direction of circulation deterministically controllable by a short pulse. The circulation is truly persistent current, in that the decay of the circulation seen in time-resolved experiments is measured as zero, in steady state for hundreds of times longer than the polariton lifetime, with no evidence of any instability. A numerical model of the Gross-Pitaevskii equation with quantum fluctuations shows how the dynamics of the system leads to this stable circulation.

This and related polariton systems are highly analogous to a superconductor circulating in a ring, and have been proposed as platforms for qubits. However, there are also important differences from superconducting qubits. I will discuss what would be needed to make good qubits using circulating polaritons.

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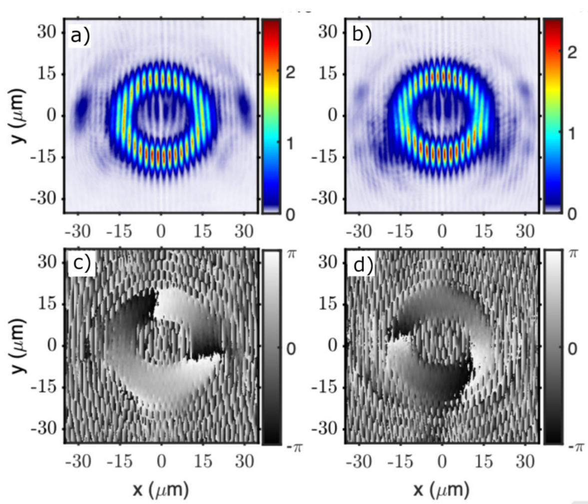

Figure 1: a) and b) Measured interference patterns for left- and right-circulating polariton condensate. c) and d) The extracted phase maps from (a) and (b), respectively.

Synthetic polariton matter: Eigenstates tomography and metrology of interactions

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Exciton polaritons are half-photonic and half-electronic excitations that allow exploring many fascinating phenomena such as driven-dissipative Bose-Einstein condensation, polariton superfluidity, nonlinear parametric effects… [1] Moreover, when trapped into lattices, exciton-polariton lattices form a platform of choice for exploring synthetic polariton matter. Indeed, polariton lattices are being used to study non-Hermitian physics, topological physics, non-linear physics, and hold great promise for future investigations related to strongly correlated and quantum physics [1]. On the way towards enhancing the functionalities of such synthetic polariton materials, new tools need to be developed. In particular, how can one measure the eigenstates of the lattice and get direct to access the lattice topology? Also, what is the precise value of polariton-polariton interaction at the few polariton level? In this talk, I will provide answers to these questions by describing two recent experiments. In the first experiment, we developed an interferometric method to measure the eigenstate structure and the Berry curvature in polariton lattices. I will illustrate the measurement method using the example of the staggered honeycomb lattice. In the second experiment, we developed a three-colour spectroscopy technique to measure polariton-polariton interactions. Importantly, this method is independent of the polariton number calibration, and reservoir contributions cancel out at low power, thus providing a precise measurement of two-body polariton-polariton interactions.

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Driven-dissipative condensates and the second law of thermodynamics

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Polariton condensates occur away from thermal equilibrium, in an open system where heat and particles are continually exchanged with reservoirs. These phenomena have been extensively analyzed in terms of kinetic equations [1]. Based on the collection of knowledge about polariton kinetics provided by these simulations and by experimental works, we constructed a few-level model that captures the main processes involved in the buildup of a ground-state population of polaritons. This allows condensation to be understood as the output of a heat engine and exposes the thermodynamic constraints on its occurrence. The model, illustrated in fig. 1, consists of a three-level system interacting with a field and connected to a hot and a cold thermal reservoir, that represents a non-resonant pump and the lattice phonons. This subsystem can drive a condensate, through polariton-polariton scattering, which produces work in the form of coherent light emission from the microcavity. We obtain a phase diagram as a function of the temperatures of the two baths and analyze this phase transition.

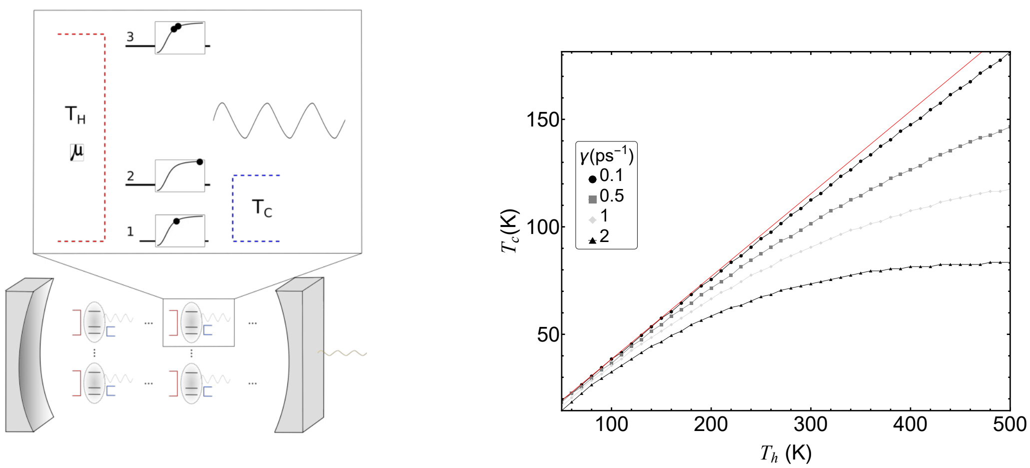

Figure 1: On the left a diagram shows the gain and loss of the microcavity as it interacts with many three-level system. Each of these systems is treated as an independent heat engine, with arrows indicating the preferable transitions. On the right, we display the phase diagram of polariton condensation as a function of the temperatures of the hot and cold reservoir for different photonic decay rates.

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Towards nonlinear polaritonic devices with transition metal dichalcogenide bilayers

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The development of nonlinear optical devices requires a platform where light-matter interaction effectively leads to hybridisation between light and matter. This can be achieved with exciton polaritons, where strong coupling between the modes introduces an effective nonlinear response for photons. To utilise this response for designing fast all-optical devices, one requires studying different sources nonlinearity and their manifestation in dynamical effects.

We have studied the two sources of nonlinear response for polaritons arising in monolayers of transition metal dichalcogenides (TMDCs). One is the Coulomb repulsion and related effects of dipole-dipole interaction as well as Rydberg blockade. The second source, being inherent to the strong coupling regime, is the Pauli blockade coming from non-bosonicity of excitons. This leads to the nonlinear phase space filling (NPSF), also referred as a nonlinear optical saturation. Recently, we have seen nonlinear saturation to be the dominant nonlinear effect in 2D materials [1], cuprous oxide [2], homobilayers of MoS_2 [3], and moiré heterobilayers of TMDCs [4, 5]. However, the theoretical description of nonlinear phase space filling to date remains limited to specific type excitons, homogeneous samples, and did not include dynamical operation required for developing nonlinear polaritonic devices.

In the talk, I will show how nonlinear phase space filling can be described at a microscopic level and in the non-perturbative regime. Using examples from bilayer TMDC systems, I will introduce saturation for hybridized excitons in homobilayers of MoS_2, and show that the asymmetry in tunnelling can provide a distinct nonlinear contribution to the optical response observed in the reflectivity measurement [3]. I will then continue to describe theoretically strongly-coupled two-dimensional (2D) polaritonic lattices, motivated by recent experiments in moiré heterobilayers of TMDCs [4]. Studying the effects of non-bosonicity, cooperative light-matter coupling, and Coulomb blockade, I will show several regimes for observing the nonlinear Rabi quench due to the phase space filling, corresponding to planar, fractured, and ultralocalized NPSF [5]. In the case of planar saturation we note that the Rabi frequency decreases exponentially as a function of exciton density. For the fractured case, where excitons form a lattice with lattice sites exceeding exciton size, we observe step-like saturation, where the slope of NPSF changes with density (observed experimentally in [4]).

Finally, I will describe a novel approach to dynamical effects underpinned by nonlinear saturation, leading to features of optical response that cannot be explained via other nonlinear contributions. This will be supported by experimental results for systems based on bilayers of TMDC that show a promise as nonlinear optical switches for all-optical logics.

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Trion resonance in polariton-electron scattering

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Strong interactions between charges and light-matter coupled quasiparticles offer an intriguing prospect with applications from optoelectronics to light-induced superconductivity. Here, we investigate how the interactions between electrons and exciton-polaritons in a two-dimensional semiconductor microcavity can be resonantly enhanced due to a strong coupling to a trion, i.e., an electron-exciton bound state. We develop a microscopic theory that uses a strongly screened interaction between charges to enable the summation of all possible diagrams in the polariton-electron scattering process, and we find that the polariton-electron interaction strength can be strongly varied and enhanced in the vicinity of the resonance. We furthermore derive an analytic approximation of the interaction strength based on universal low-energy scattering theory. This is found to match extremely well with our full calculation, indicating that the trion resonance is near universal, depending more on the strength of the light-matter coupling relative to the trion binding energy rather than on the details of the electronic interactions. Thus, we expect the trion resonance in polariton-electron scattering to appear in a broad range of microcavity systems with few semiconductor layers, such as doped monolayer $MoSe_2$ where such resonances have recently been observed experimentally [2]. Our work is published in [1].

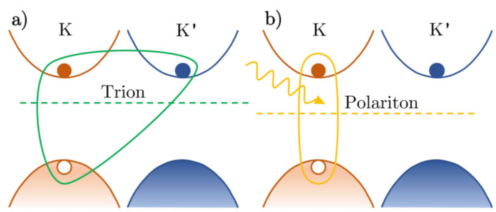

Figure 1: Schematic illustration of the trion resonance in intervalley polariton-electron scattering, using the band structure of $MoSe_2$ as an example. Panel **a** shows the charges involved in the negatively charged trion (encircled by the green line), with the trion energy drawn in dashed green. In panel **b**, the exciton polariton formed by the photon and electron-hole pair in the K valley is encircled in yellow. The corresponding energy (dashed yellow) is tunable, allowing one to achieve a resonance condition with the trion.

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Exploring Universal Scaling Laws In Two-Dimensional Polariton Condensates

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Universality is a powerful concept allowing to reveal the same macroscopic behaviors in seemingly unrelated systems. 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 polariton condensates behaves as an interface, whose spatiotemporal evolution is described by the KPZ equation [2, 3]. Since the phase is a compact variable, the physics is enriched by the possible emergence of vortices. Recent experiments have demonstrated that the coherence of 1D polariton condensates show spatiotemporal decay characteristic of the KPZ universality class.

In this talk, we report optical interferometry experiments on extended 2D polariton condensates generated in lattices of coupled microcavities, see Figs. 1a and 1b. We analyse the spatiotemporal decay of the first order coherence $|g^{(1)}|$. As shown in Fig. 1c, 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. 1d. We will discuss the overall measured spatiotemporal 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 [4, 5].

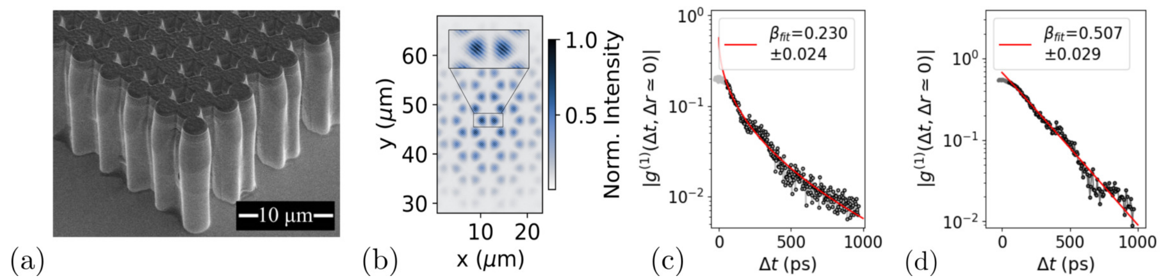

Figure 1: (a) Scanning electron microscope image of the polariton lattice. (b) Experimental interferometry pattern of the condensate. (c-d) Measured values of $|g^{(1)}|$ and its fit (red) at powers p_1 (c) and $p_2 > p_1$ (d).

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Coherent fraction of an equilibrium condensate

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We report recent progress on the measurement of the coherent fraction of a two-dimensional Bose gas in thermal equilibrium. We have created a homogeneous exciton-polariton gas in equilibrium, realizing the textbook paradigm of a uniform Bose Gas in two-dimensions. Under these conditions, we have measured the coherent fraction of this Bose gas from very low density up to density well above the condensation threshold. These measurements reveal a consistent power law of $n_c/n_{\rm tot} \propto n_{\rm tot}^{3.2}$ for the coherent fraction over nearly three orders of magnitude of density variation. The same power law is seen in numerical simulations solving the two-dimensional Gross-Pitaevskii equation for the equilibrium coherence; these simulations also show that the power law corresponds to the coherence length in the system growing as $n_{\rm tot}^{1.6}$. This power law has not been predicted by prior analytical theories.

Figure 1 shows the experimental polariton occupation of a homogeneous polariton gas, which is well described by a Bose-Einstein distribution for all densities indicating that the polaritons are in true thermodynamic equilibrium. The coherent fraction was measured by interfering the light emitted by the polariton gas $\vec{E}\,(k_x, k_y, t_0)$ with its mirror symmetric image $\vec{E}\,(-k_x, k_y, t_0)$ using Michelson interferometry. The integral of the fringe visibility over the total set of momentum states gives a direct measurement of the coherent fraction of this polariton gas. The increase of the coherent fraction fits the power law $n_{\rm tot}^{3.2\pm0.1}$ over a range of density of nearly three orders of its magnitude, as the density increases through the critical value. The agreement with the Gross-Pitaevskii numerical simulations for a homogeneous gas in equilibrium shows that the results of our experiments are truly universal, realizing the textbook paradigm of a uniform Bose Gas in two-dimensions in thermal equilibrium.
This work has been supported by the National Science Foundation through Grant DMR-2004570.

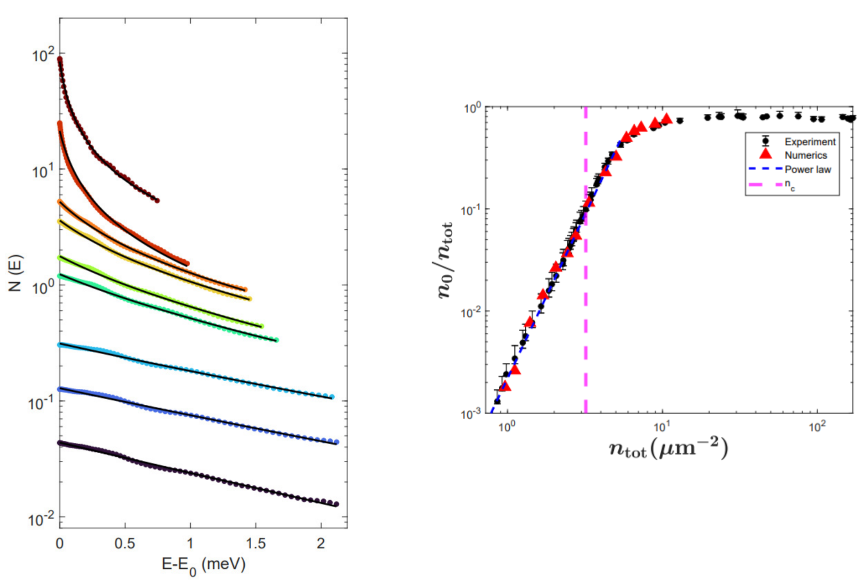

Figure 1: **Left panel** occupation of the lower polariton as a function of energy. The solid lines are best fits to the equilibrium Bose-Einstein distribution. **Right panel** black circles: experimentally measured coherent fraction as a function of the total polariton density, Red triangles: coherent fraction defined the same way, for the numerical simulations using Gross-Pitaevskii equation. Blue line: $n^{3.2}$ power law. The vertical dashed line denotes the critical density, which is defined as the total density of polaritons at the threshold power $P/P_{\rm th} = 1$.