Experimentelle Physik 2

Seminar Festkörperphysik (CMP Seminar)

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Nonlinear hybrid light-matter states in semiconductor photonic structures

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Quantum platforms that use photons as qubits hold great promise for quantum optical applications, including computing, communication, optical neural networks, and imaging. A key challenge in these applications is the realization of scalable systems that enable strong single-photon interactions. Hybrid light-matter states, formed by 2D exciton-polaritons in photonic structures with embedded quantum wells or 2D materials, present a promising solution by enabling strong photon-photon interactions and ensuring scalability. This advancement paves the way towards development of quantum logic gates, photon number detectors and sorters, and deterministic generation of complex entangled photonic states, both in discrete and continuous variables. The strong polariton nonlinearity also results in many-body phenomena ranging from superfluid-like behaviour of light, Bose-Einstein condensation to ultra-low power bright and dark soliton physics.

In my talk I will review these phenomena in GaAs-based polariton microcavites and waveguides [1-3]. I will present recent results on utilising the strong polariton nonlinearity to control the phase of one photon by another in a zero-dimensional microresonator [4]: phase shifts up to 150 mRad per single photon (polariton) are observed. This result paves the way towards development of scalable quantum nonlinear photonic devices and programmable quantum circuits [5]. Finally, I will discuss enhanced polariton nonlinearities and perspectives in other semiconductor materials such as monolayers of transition metal dechalcogenides [6,7] and Cu_2O [8,9].

[1] "Observation of bright polariton solitons in a semiconductor microcavity" M. Sich, D. N. Krizhanovskii et al., **Nature Photonics** volume 6, pages 50–55 (2012)

[2] "Ultra-low-power hybrid light–matter solitons", P. M. Walker, L. Tinkler, D. V. Skryabin et al., and D. N. Krizhanovskii, **Nature Comm**. 6, 8317 (Oct 2015)

[3] "Spatiotemporal continuum generation in polariton waveguides" P. M. Walker et al., D. N. Krizhanovskii **Light: Science & Applications** 8 (1), 6 (2019)

[4] "Few-photon all-optical phase rotation in a quantum-well micropillar cavity" Tintu Kuriakose, Paul M. Walker, Toby Dowling, Oleksandr Kyriienko et al, & Dmitry N. Krizhanovskii **Nature Photonics** volume 16, pages 566–569 (2022)

[5] Nielsen, K. H., Wang, Y., Deacon, E., Sund, P. I., Liu, Z., Scholz, S., ... & Lodahl, P. (2024). "Programmable Nonlinear Quantum Photonic Circuits". **arXiv preprint arXiv:2405.17941**.

[6] "Exciton–polaritons in van der Waals heterostructures embedded in tunable microcavities", S. Dufferwiel et al., K. S. Novoselov, J. M. Smith, M. S. Skolnick, D. N. Krizhanovskii, A. I. Tartakovskii, **Nature Comm**. 6, 8579 (Oct 2015)

[7] "Highly nonlinear trion-polaritons in a monolayer semiconductor" R. P. A. Emmanuele, M. Sich et al, & D. N. Krizhanovskii **Nature Communications,** volume 11, Article number: 3589 (2020)

[8] "Rydberg exciton–polaritons in a Cu_2O microcavity" Konstantinos Orfanakis, Sai Kiran Rajendran, Valentin Walther, Thomas Volz, Thomas Pohl & Hamid Ohadi **Nature Materials** volume 21, pages767–772 (2022)

[9] "Nonlinear Rydberg exciton-polaritons in Cu_2O microcavities" Maxim Makhonin, Anthonin Delphan, Kok Wee Song, Paul Walker, Tommi Isoniemi, Peter Claronino, Konstantinos Orfanakis, Sai Kiran Rajendran, Hamid Ohadi, Julian Heckötter, Marc Assmann, Manfred Bayer, Alexander Tartakovskii, Maurice Skolnick, Oleksandr Kyriienko, Dmitry Krizhanovskii. **Light Sci Appl**. 13(1):47. (2024) doi: 10.1038/s41377-024-01382-9.