HL 54: 2D Materials IX – Photonic properties and devices

Time: Friday 9:30–12:45 Location: POT/0081

HL 54.1 Fri 9:30 POT/0081

Signature of interference between second and fourth order nonlinearities in atomically thin crystals — •Paul Herrmann[1], Jonas Margraf[1], Sebastian Klimmer[1], Sebastian Piehler[2], Maximilian Graml[2], Muhammad Sufyan Ramzan[3], Caterina Cocchi[3], Jan Wilhelm[2], and Giancarlo Soavi[1,4] — [1]Institute of Solid State Physics, Friedrich Schiller University Jena, Jena, Germany — [2]Institute of Theoretical Physics and Regensburg Center for Ultrafast Nanoscopy (RUN), University of Regensburg, Regensburg, Germany — [3]Institute of Condensed Matter Theory and Optics, Friedrich Schiller University Jena, Jena, Germany — [4]Abbe Center of Photonics, Friedrich Schiller University Jena, Jena, Germany

Transition metal dichalcogenides (TMDs) are a well studied class of two-dimensional materials, whose opto-electronic properties are dominated by excitons and exhibit strong light-matter interaction. The relaxed phase matching in TMD monolayers facilitates the emission of many orders of nonlinearities with approximately equal efficiency. Thus, one can in principle observe interference effects between nonlinearities of different orders N (N=2,3,4,...). Here, we observe a previously unseen modulation of the generated second harmonic upon rotation of the input fundamental polarization. By combining wavelength and power dependent measurements with macroscopic, symmetry-based calculations and microscopic density functional theory simulations, we can assign this modulation to an interference between second and fourth order terms of the nonlinear polarization.

HL 54.2 Fri 9:45 POT/0081

Measurement of optically induced broken time-reversal symmetry in atomically thin crystals — •Florentine Friedrich[1], Paul Herrmann[1], Shridhar Shanbhag[2], Sebastian Klimmer[1], Jan Wilhelm[2], and Giancarlo Soavi[1] — [1]Institute of Solid State Physics, University of Jena, Germany — [2]Institute of Theoretical Physics and Regensburg Center for Ultrafast Nanoscopy (RUN), University of Regensburg, Germany

Time-reversal symmetry (TRS) and space-inversion symmetry (SIS) are fundamental properties underlying phenomena like magnetism and non-trivial spin textures in crystals. Transition Metal Dichalcogenides (TMDs) offer a tunable platform to study the interplay of these symmetries, which can be engineered by tuning the number of layers and via all-optical bandgap modulation. We propose a powerful, all-optical approach using third harmonic (TH) Faraday rotation to probe broken TRS, regardless of the SIS [1]. By exciting mono- and bilayer TMDs with elliptically polarized light, we achieve spin-selective bandgap modulation, consequently breaking TRS. This symmetry reduction modifies the nonlinear susceptibility tensor, causing a measurable rotation of the emitted TH polarization. Our experimental results are supported by analytical theory for both mono- and bilayer TMDs and provide a unique tool to investigate spin, valley, and layer coupling in atomically thin semiconductors, thereby contributing to the understanding of the relation between crystal symmetries and the nonlinear optical response of a material.

[1] Friedrich et al., Nat. Photon., 10.1038/s41566-025-01801-2 (2025).

HL 54.3 Fri 10:00 POT/0081

Analytical Theory Of Third Harmonic Generation In Two-Dimensional Materials — •Shridhar Sanjay Shanbhag[1], Florentine Friedrich[2], Paul Herrmann[2], Sebastian Klimmer[2], Giancarlo Soavi[2], and Jan Wilhelm[1] — [1]Institute of Theoretical Physics and Regensburg Center for Ultrafast Nanoscopy (RUN), University of Regensburg, 93053 Regensburg, Germany — [2]Institute of Solid State Physics, Friedrich Schiller University Jena, 07743 Jena, Germany

Valleytronics explores the valley degree of freedom in materials like transition metal dichalcogenides (TMDs), using electrons in ±K valleys as binary states for information encoding. In valleytronics applications, efficient valley readout is crucial. We show that third harmonic generation (THG) provides an ultrafast solution to valley readout for both centrosymmetric and non-centrosymmetric materials [1].

We solved the semiconductor Bloch equations perturbatively to derive an analytical expression for the polarization state of the emitted third harmonic signal. Our analysis shows how material parameters influence the polarization and attributes polarization rotation to spin and valley dependent optical Stark and Bloch-Siegert shifts in TMDs. Our theoretical predictions closely align with experiments, providing the microscopic mechanism and thus helping advance valleytronic read-out mechanisms.

[1] Friedrich, F., Herrmann, P., Shanbhag, S.S. et al. Nat. Photon. (2025). https://doi.org/10.1038/s41566-025-01801-2

HL 54.4 Fri 10:15 POT/0081

Nonlinear optical characterization of oxidized thin layered MoS2 — •Henry Hübschmann[1], Gerhard Berth[1], Klaus Jöns[1], Katharina Burgholzer[2], and Alberta Bonanni[2] — [1]Paderborn University, Paderborn, Germany — [2]Johannes Kepler University Linz, Linz, Austria

In the field of two-dimensional structures the class of transition metal dichalcogenides (TMDs) has sparked great interest in the last decades. Semiconductor materials like molybdenum disulfide (MoS2) have found many applications in photonic and optoelectronic devices [1,2]. An important characteristic is the tunability of the band structure and therefore consequently the possibility for modification of electronic and optical properties [3]. Within this work we conduct comprehensive second order nonlinear optical analysis on thermally oxidized mechanically exfoliated MoS2. In this context a layer number dependent investigation of the nonlinear response up to seven-layer configurations of AB-stacked 2H-MoS2 is performed. Here we found fingerprints of induced structural modifications identified which manifest themselves in the strength of the nonlinear response and a resulting symmetry break of centrosymmetric media.

HL 54.5 Fri 10:30 POT/0081

quantum electrodynamics of excitons in bilayer graphene — •abraham nava mireles — the institut of photonic sciences, castelldefels, spain.

Cavity quantum electrodynamics has been a cornerstone in understanding light-matter interactions. In the so-called strong-coupling regime, these interactions cannot be described as a simple combination of their light and matter components. Instead, light and matter form new hybrid states. This project aims to push beyond into the ultrastrong coupling (USC) regime, where the interaction strength becomes comparable to the system's transition frequencies. In this regime, quantum vacuum fluctuations and elementary excitations become significant. This enables not only the control of quantum effects but also the modification of a material's ground state, even in the absence of external light. To that end, we explore the coupling between confined hyperbolic phonon polaritons (HPhPs) in hexagonal boron nitride (hBN) and excitons in bilayer graphene (BLG). The hyperbolic nature enables deep subwavelength confinement, enhancing the photonic density of states. In BLG, extended dipole transitions exhibit a nonlocal optical response, in which propagating HPhPs allow momentum-dependent transitions and access to a continuum of electronic final states. This leads to enhanced emission rates and to each exciton effectively coupling to multiple polaritonic modes, ultimately reaching a regime where the coupling strength compares to the transition frequency. This platform opens new possibilities for quantum technologies and non-perturbative light-matter engineering.

HL 54.6 Fri 10:45 POT/0081

All-TMDC nanobeam cavities with embedded $MoSe_2$ monolayers for enhanced light-matter interaction — •Aris Koulas-Simos[1], Pietro Metuh[2], Athanasios Paralikis[2], Kartik Gaur[1], Maximilian Klonz[1], Imad Limame[1], Chirag Palekar[1], Battulga Munkhbat[2], and Stephan Reitzenstein[1] — [1]Institut für Physik und Astronomie, Technische Universität Berlin, Berlin, Germany — [2]Department of Electrical and Photonics Engineering, Technical University of Denmark, Kongens Lyngby, Denmark

All-TMDC photonic structures enable enhanced light-matter interaction by combining high index contrast with atomically thin excitonic materials in a homogeneous platform [1]. Recent theoretical work [2] shows that all-TMDC nanostructures can support very large Purcell factors, highlighting their potential for nanoscale lasing. We realize WS_2 nanobeam cavities with a $MoSe_2$ monolayer embedded inside the dielectric cavity for improved field-exciton coupling compared to the conventional evanescent coupling schemes. Simulations predict a cavity mode at 766 nm with $Q \approx 4 \cdot 10^3$, a mode volume of approximately 2.6 $(\lambda/n)^3$, and a confinement factor $\Gamma \approx 0.8\%$. Cross-polarized reflectivity at room temperature reveals resonances between 725 and 760 nm with Q-factor values of 100-300, and low-temperature photoluminescence confirms coupling of the $MoSe_2$ monolayer to the cavity mode. These results establish a monolithic TMDC platform for future all-TMDC nanolasers and quantum emitters.

[1] B. Munkhbat et al., Laser Photon. Rev. 17, 2200057 (2023) [2] F. Binkowski, A. Koulas-Simos et al., arXiv:2508.05333 (2025), accepted

15 min. break or similar.

HL 54.7 Fri 11:15 POT/0081

Temperature-Dependent Moiré Polariton Formation in Bilayer MoSe2 Integrated in DBR based Microcavities — •Chirag Palekar[1], Aris Koulas-Simos[1], Imad Limame[1], Stephan Reitzenstein[1], and Bárbara Rosa[1,2] — [1]Institut für Physik und Astronomie, Technische Universität Berlin, Hardenbergstrasse 36, 10623 Berlin, Germany — [2]University of Campinas, R. Sérgio Buarque de Holanda, 777, 13085-636, Brazil

Twisted bilayer (tBL) MoSe2, which hosts moiré polaritons, when integrated into microcavities, provides a versatile platform for exploring light-matter interactions in moiré-engineered quantum materials. In the absence of the cavity, we observed the PL spectrum of the tBL exhibits multiple resonances corresponding to distinct moiré excitons. When embedded within a DBR cavity, such moiré excitons enter the strong coupling regime with the confined cavity photon mode, leading to the formation of moiré exciton-polaritons. Temperature-induced resonance tuning enables systematic control over the exciton-photon detuning, allowing modulation of the coupling strength. Remarkably, these moiré polaritons remain observable even at temperatures exceeding 150 K, underscoring the robustness of the hybridized light-matter states. Modeling the system using a coupled oscillator approach reveals a Rabi splitting as large as 11 meV. Our results demonstrate that temperature serves as an efficient external control parameter for engineering and tuning moiré exciton polaritons in twisted, atomically thin semiconductors, opening pathways toward reconfigurable polaritonic devices based on van der Waals heterostructures.

HL 54.8 Fri 11:30 POT/0081

Cavity polaritons in a hybrid van-der-Waals superconductor-semiconductor structure — •Seyma Esra Atalay, Hangyong Shan, Martin Esmann, and Christian Schneider — Carl von Ossietzky Universität Oldenburg, Germany

Monolayers of transition metal dichalcogenides (TMDs) offer new possibilities to study superconductivity. In this project, we investigate hybrid heterostructures of $NbSe_2/MoSe_2$ van der Waals layers, in the framework of cavity experiments. $NbSe_2$ and $MoSe_2$ are TMDs; superconductivity occurs in $NbSe_2$ [1], and the monolayer $MoSe_2$ is a direct band gap semiconductor that hosts excitons with high oscillator strength. By embedding the $NbSe_2/MoSe_2$ heterostructure in an open cavity [2], we achieve strong coupling between the $MoSe_2$ excitons and the cavity photons, forming exciton-polaritons, as evidenced by the pronounced Rabi gap seen in subsequent longitudinal and transversal cavity modes in where we tuned the open cavity length. This implementation of a hybrid superconductor-semiconductor monolayer polariton cavity forms the foundation of experiments to gain insight into how exciton-polariton coupling can influence the superconductive phase of $NbSe_2$ and allow us to further investigate optically tunable superconducting hybrid systems.

References [1]Xi, X., Wang, Z., Zhao, W. et al. Ising pairing in superconducting $NbSe_2$ atomic layers. Nature Phys 12, 139-143 (2016)., Journal 100, 101101 (2009) [2]J.C., Drawer et al., Nano Letters 2023 23 (18), 8683-8689

HL 54.9 Fri 11:45 POT/0081

Room temperature hybrid exciton-polaritons in a Perovskite-TMD heterostructrue — •Marti Struve[1], Hamid Pashaei Adl[1], Oliwia Janikwska[2], Sven Stephan[3], Jamie Fitzgerald[4], Paulina Plochocka[2,5], Christian Schneider[1], and Martin Esmann[1] — [1]Carl von Ossietzky Universität, Oldenburg, Germany — [2]Wrocław University of Science and Technology, Wrocław, Poland — [3]University of Applied Sciences Emden, Emden, Germany — [4]Philipps-University Marburg, Marburg, Germany — [5]Laboratoire National des Champs Magnetiques Intenses, Toulouse, France

Chemically synthesized quasi-2D halide perovskites (HaP) exhibit strong excitonic resonances with large oscillator strength, high binding energy and tunable emission, making them an interesting platform for polariton physics at room temperature. Transition metal dichalcogenide (TMD), while showing lower oscillator strength, offer access to K-valley selective rules, opening the access to polarized excitonic states. In this work, we demonstrate the formation of hybrid exciton-polaritons in a quasi-2D HaP-TMD heterostructure embedded in a planar open cavity at room temperature. Using the tunability of our open cavity we first confirm strong coupling of our materials separately. When combined the system exhibits three polaritonic branches, showing a hybridization of the polariton modes that is reproduced using a three-oscillator Hamiltonian, revealing a state where both excitonic fractions become comparable. Our results lay the foundation to imprint the accessibility of the K-valley selection rules to HaP-polaritons devices leading to additional degrees of freedom.

HL 54.10 Fri 12:00 POT/0081

Tunable Room-Temperature Polaritons Achieving the Very Strong Coupling Regime in Quasi-2D Layered Perovskites — •Hamid Pashaei Adl[1], C. Bennenhei[1], M. Struve[1], P. Peksa[2], M. Dyksik[2], M. Baranowski[2], K. W. Song[3], M. Gittinger[1], C. Lienau[1], J. K. König[4], J. M. Fitzgerald[4], N. P. Jasti[5], F. Eilenberger[6], P. Plochocka[2], E. Malic[4], O. Kyriienko[7], M. Esmann[1], and C. Schneider[1] — [1]Carl von Ossietzky Universität Oldenburg, Germany. — [2]Wroclaw University of Science and Technology, Wroclaw, Poland. — [3]Xiamen University Malaysia, Sepang, Malaysia. — [4]Philipps-Universität, Marburg, Germany. — [5]JNCASR, Bangalore, India. — [6]Max Planck School of Photonics, Jena, Germany. — [7]University of Sheffield, UK.

Layered halide perovskites are organic and inorganic 2D or quasi-2D layers, which self-assemble in solution realizations of quantum well stacks with giant exciton oscillator strengths, tunable emission spectra and very large exciton binding energies. In this contribution, we discuss widely tunable room-temperature cavity exciton polaritons at the cross-over from the strong coupling to the very strong coupling regime, in mechanically exfoliated quasi-2D Ruddlesden-Popper iodide perovskite integrated into an open microcavity. We gradually increased the cavity length and observed a pronounced anti-crossing behavior associated with successive longitudinal cavity modes. The Rabi splitting exhibited a systematic reduction with increasing cavity length; however, the scaling behavior deviated from the conventional square root dependence typically observed in the strong coupling regime.

HL 54.11 Fri 12:15 POT/0081

Optical Gain in Lasers Based on Two-Dimensional TMD Semiconductors — Tommy Schulz[1], •Daniel Erben[1], Alexander Steinhoff[2], Weng Chow[3], and Frank Jahnke[1] — [1]Institute for Theoretical Physics and Bremen Center for Computational Materials Science, University of Bremen, P.O. Box 330 440, 28334 Bremen, Germany — [2]Institute for Physics, Faculty V, Carl von Ossietzky University Oldenburg, 26129 Oldenburg, Germany — [3]Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

We present a direct comparison of the optical gain in InGaAs quantum wells (QWs) and transition-metal dichalcogenide (TMD) monolayers on SiO_2 and encapsulated in hBN. A central objective of this work is to theoretically quantify the gain and to identify its microscopic origin. As a result, we find a substantially larger magnitude of the gain in TMDs - especially in WS_2 - and comparable transparency carrier densities in both systems. The enhanced interband Coulomb interaction in TMDs provides this superior gain performance, although the valley-rich conduction band makes sustaining population inversion more challenging than in InGaAs/GaAs QWs. Encapsulating WS_2 in hBN - a common approach to improve optical quality - proves advantageous, as it reduces carrier drain into side valleys, which lowers the transparency carrier density compared with WS_2/SiO_2. Lastly, we investigate the Henry factor (α), which governs key laser properties such as linewidth behaviour. InGaAs QWs exhibit large α values near transparency, hBN-encapsulated WS_2 shows weakly negative values - an indication towards more favourable lasing performance.

HL 54.12 Fri 12:30 POT/0081

Room-temperature polariton condensate in a quasi-2D hybrid perovskite — M. Struve[1], C. Bennenhei[1], H. Pashaei Adl[1], K.W. Song[2], H. Shan[1], N. Matukhno[1], J.-C. Drawer[1], S. Stephan[1], F. Eilenberger[3], N.P. Jasti[4], D. Cahen[4], O. Kyriienko[5], C. Schneider[1], and •M. Esmann[1] — [1]Carl von Ossietzky Universität Oldenburg — [2]Xiamen University, Sepang, Malaysia

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Quasi-2D halide perovskites are chemically synthesized quantum well stacks with large exciton oscillator strength and binding energy. Although promising for polaritonics, bosonic condensation and polariton lasing have so far remained elusive in quasi-2D perovskites at ambient conditions. Here, we demonstrate room-temperature cavity exciton-polariton condensation in mechanically exfoliated crystals of $(BA)_2(MA)_2Pb_3I_{10}$ in an in-situ tunable optical microcavity [1]. We observe a polariton condensation threshold of 0.41 μJcm^{-2} per pulse and detect a strong non-linear response. Interferometric measurements confirm the spontaneous emergence of spatial coherence across the polariton condensate. Our results lay the foundation for a new class of room-temperature polariton lasers based on quasi-2D halide perovskites with great potential for hetero-integration with other van-der-Waals materials, photonic crystals and waveguides.

[1] M. Struve et al. arXiv:2408.13677 (Nat. Comms. accepted 2025)