The International Conference on Theoretical Studies and New Technologies

14th - 19th of April 2025

Varadero, Cuba

Organizers

Havana University, Havana, Cuba

Abrikosov Center for Theoretical Physics, Russia

Conference Chairman

Prof. Alexey Kavokin

Chairman of Organizing Committee

prof. Carlos Cabal Mirabal

Scientific Secretary

Dr. Stella Kavokina

Cuba used to be a favorite destination for many conferences on Condensed Matter Physics since 2007 when Havana hosted the 7th international conference on Physics of Light-Matter Coupling in Nanostructures. Before the pandemic, virtually every year the community of experimental and theoretical physicists, experts in photonics, excitonics, superconductivity, topological physics, spintronics etc was gathering in one of welcoming Cuban destinations such as Varadero, Santiago de Cuba or Trinidad. We are most happy to renew this tradition by organizing the International conference on Theoretical Sciences and New Technologies in Varadero, Cuba. We sincerely thank the University of Havana for the precious help and, especially, we are grateful to Professor Carlos Cabal Mirabal whose support ensured a smooth and efficient work of the Organizing Committee. We are very proud to host in Cuba world leaders in the physics of semiconductors such as Professors Ivchenko and Bar Joseph, the representatives of the most dynamic research-oriented universities of Europe and Asia, such as Profs. Mark Assmann, Alex Hayat, Hui Li. But besides this and perhaps first of all, the ICSNT is aimed at the integration of the new generation of theoretical and experimental physicists in the context of joint brain-storming sessions and informal discussions devoted to the most interesting and puzzling problems of the modern physics. 10 brilliant researchers from the recently created Abrikosov Center for Theoretical physics will constitute a core of the community gathering under the palms of Melia Varadero. We do hope that the relaxing atmosphere of Varadero, Cuban sun, rum and music, will play a role of fertilizer for new ideas, collaborations and international consortia. In the troubling atmosphere of 2020s such conferences might help saving the humanity and family spirit among scientists. Welcome to the ICSNT in Varadero!

Alexey Kavokin,
Conference Chairman,
Director of the ACTP

The scientific program of ICSNT-2025

14.04.2025 Monday

16^{00} – 19^{00} –Conference registration in the hotel lobby of the main building

19^{00} – 19^{30} –Welcome reception

19^{30} – 21^{00} –Free-time for a dinner at the hotel

15.04.2025 Tuesday

9.00 – 9.10 **Opening remarks to the ICSNT 2025**
Prof. A.V. Kavokin, Conference Chairman

9.10 – 10.00 – PLENARY TALK: *"Exciton fine structure in semiconductor nanostructures"*
Prof E.L. Ivchenko, Ioffe Institute, Russia

10^{00} – 10^{30} **coffee break**

Session "Polaritonics"
Chairman prof. A. Kavokin

10^{30} – 11^{10} INVITED TALK: *"Quantum Coherence of Polariton Condensates"*
Prof. Marc Aßmann, TU Dortmund, Germany

11^{10} – 11^{50} INVITED TALK: *"Ultrafast dynamics of exciton polaritons at room temperature"*
Prof. Hui Li, East China Normal University, China

Group-picture

12^{00} – 14^{30} **Lunch break**

Session "Light-matter interactions in solids"
Chairman Prof. M.E. Portnoi

14^{30} – 15^{00} *"Exciton-polaron problem in 2D"*
Prof. Vanik Shahnazaryan, MIPT University, Russia

15^{00} – 15^{30} *"Spin-Meissner Effect in Systems of Coupled Polariton Condensates"*
Dr. Andrey Kudlis, MIPT University, Russia

15^{30} – 16^{00} **coffee break**

16^{00} – 16^{30} *"All-optical temporal logic gates in localized exciton polaritons"*
Mr. Haoyuan Jia, East China Normal University, China

16^{30} – 17^{00} *"Decay of the twisted relativistic electron in a strong inhomogeneous magnetic field"*
Mr. Mikhail Epov, ITMO University, Russia

16.04.2025 Wednesday

Session "Light-matter interactions in solids" Chairman Prof. M. Aßmann

9^{10} – 10^{00} – PLENARY TALK: *"The exciton condensate interaction with the nuclei"*
Prof. Israel Bar Joseph, *Weizmann University of Science*, Israel

10^{00} – 10^{30} coffee break

10^{30} – 11^{10} INVITED TALK: *"Features and peculiarities of light-matter coupling in 2D superconducting thin films"*
Prof. Ivan Savenko, Goudong University, China.

11^{10} – 11^{50} INVITED TALK: *"Higher-order topological insulators in polariton wave lattices"*
Dr. Xuekai Ma, Paderborn University, Germany

12^{00} – 14^{30} Lunch break

Session "Photonics, plasmonics and polaritonics" Chairman Prof. I. Savenko

14^{30} – 15^{10} INVITED TALK: *"TBA"*
Prof. Zhanhai Chen, Xiamen University, China

15^{10} – 15^{50} INVITED TALK: *" Dissipative trapping of polariton condensates in various systems"*
Prof. Anton Nalitov, MIPT University, Russia

15^{50} – 16^{20} *"Widely tunable OPO in mid IR region for medical and scientific applications"*
Dr. Alexey Karapuzikov, Special technologies, Ltd, Russia

16^{20} – 17^{00} INVITED TALK: *"Integrated microring resonators for soliton generation, coherent computing, and quantum light sources"*
Dr. Dmitry Chermoshentsev, RQC, Russia

17.04.2025 Thursday

9^{30} – 16^{00} *Conference excursion. The meeting point is at the main entrance of the hotel.*

18.04.2025 Friday

Session "Light-matter interactions in solids" Chairman Prof. E. Ivchenko

9^{10} – 10^{00} – PLENARY TALK: *"Optical properties and THz applications of quasi-one-dimensional nanocarbons"*
Prof. Mikhael Portnoi, University of Exeter, UK

10^{00} – 10^{30} **coffee break**

10^{30} – 11^{10} INVITED TALK: *"Ultrafast Dynamics of Exciton-Polariton Condensates"*
Prof. Alex Hayat, Technion University, Israel.

11^{10} – 11^{50} INVITED TALK: *" Magnetophotonics for advanced control of spins"*
prof. Vladimir Belotelov, Lomonosov Moscow State University&RQC, Russia

12^{00} – 14^{30} **Lunch break**

Session "New functional materials and metasurfaces"
Chairman Prof. Israel Bar Joseph

14^{30} – 15^{00} ***"Dislocations and interdomain interlayer elastic waves in relaxed moire superlattices"***
Dr. Vladimir Enaldiev, MIPT University, Russia

15^{00} – 15^{30} *"Off-diagonal and non-Hermitian disorder in multilayer topological systems"*
Prof. Zaur Alisultanov, MIPT University, Russia

15^{30} – 16^{00} **coffee break**

16^{00} – 16^{30} *"Trion transitions in monoatomic carbon wires"*
Dr. Stella Kavokina, MIPT University& Saint-Petersburg State University, Russia

16^{30} – 17^{00} INVITED TALK: *"New trends in MRI for medical and industrial applications"*
Prof. Carlos Cabal Mirabal, Medical Biophysics Center& Havana University, Republic of Cuba

19.00-22.00 – **the conference dinner.**

19.04.2025 Saturday

Session "Light-matter interactions in solids"
Chairman Prof. Alex Hayat

9^{10} – 9^{50} INVITED TALK: *" Coherent quantum transport of microcavity exciton polaritons"*
Prof. Sanjib Ghosh, Chinese University of Hong Kong, China

9^{50} – 10^{30} **coffee break**

10^{30} – 11^{10} INVITED TALK: *"Pathways of quantum polaritonics"*
Prof. Alexey Kavokin, MIPT University & Saint-Petersburg State University, Russia

11^{10} – 11^{50} INVITED TALK: *"Polariton Lattices for Binary Neuromorphic Network Architectures"*
prof. Evgeny Sedov, MIPT University& Saint-Petersburg State University, Russia

12^{00} – 14^{30} **Lunch break**

$14^{30} – 16^{30}$ *Round table on Problems of Modern Condensed – Matter Physics*

$16^{30} – 17^{00}$ **Closing session**

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CONFERENCE PROCEEDINGS

Exciton fine structure in semiconductor nanostructures

E.L. Ivchenko

Ioffe Institute, 194021, St.-Petersburg, Russia

In the theory of semiconductors, the Coulomb-interaction operator between an electron and a hole consists of three contributions describing respectively (i) the direct Coulomb interaction responsible for the formation of a *mechanical* exciton, (ii) the short-range and (iii) long-range exchange interactions forming the so-called *Coulomb* exciton. Excitons play a dominant role in the optical properties of undoped and weakly doped low-dimensional structures. The fine structure of excitonic levels is crucial for understanding and manipulating these properties. For the exciton ground state in semiconductor nanostructures, it is determined by the exchange interaction and magnetic field induced splitting of four sublevels formed by the twofold degenerate electron and hole spin states.

We review the exciton fine structure studies performed on quantum wells, superlattices and quantum dots focusing on the anisotropic splitting of the radiative doublet in different nanostructures, namely, heavy-hole excitons that are localized at well-width fluctuations in type-I quantum wells [1], localized at a particular interface in type-II heterostructures, and confined in asymmetrical quantum dots.

Recently we have studied a special regime, where the exchange splittings, the hyperfine interaction energy and the radiative broadening are comparable in order of magnitude, and therefore the Overhauser field created by nuclear spins plays an important role [2, 3]. This regime is realized in (In,Al)As/AlAs quantum dots which are direct in the $\boldsymbol{r}$ space and indirect in the reciprocal (or $\boldsymbol{k}$) space. In the nano-objects under study, the polarization properties of the resonant photoluminescence are shown to vary with the external magnetic field in a completely different way as compared with the behavior of conventional quantum dot structures.

This work was supported by the Russian Science Foundation, grant 23-12-00142.

[1] S.V. Goupalov, E.L. Ivchenko, A.V. Kavokin, Fine structure of localized-exciton levels in quantum wells, JETP **86**, 388 (1998).

[2] D.S. Smirnov, E.L. Ivchenko, Theory of polarized photoluminescence of indirect band gap excitons in type-I quantum dots, Phys. Rev. B **108**, 195432, (2023).

[3] D.S. Smirnov, E.L. Ivchenko, Interplay between hyperfine and anisotropic exchange interactions in exciton luminescence of quantum dots, Optika i Spektroskopiya **132**, 864 (2024); arXiv:2405.15696 (2024).

Quantum Coherence of Polariton Condensates

Marc Aßmann

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Photon statistics are a powerful tool to obtain precise information about light fields, but traditional Hanbury Brown-Twiss measurements are slow. Homodyne detection is a powerful alternative approach to obtain $g^{(2)}(0)$ [1].

Here, we demonstrate that combining multichannel homodyne detection with pulsed local oscillators at 76MHz and state of the art digitizers with sampling rates around 5 Gs/s open up the possibility to measure $g^{(2)}(0)$ in less than a millisecond [2]. Simultaneously we achieve the sub-picosecond temporal resolution necessary to resolve ultrafast processes in semiconductors and tailor the mode structure of the local oscillator to utilize it as a spectroscopic tool [3] to continuously measure $g^{(2)}(0)$ and the density matrix of a light field in real-time.

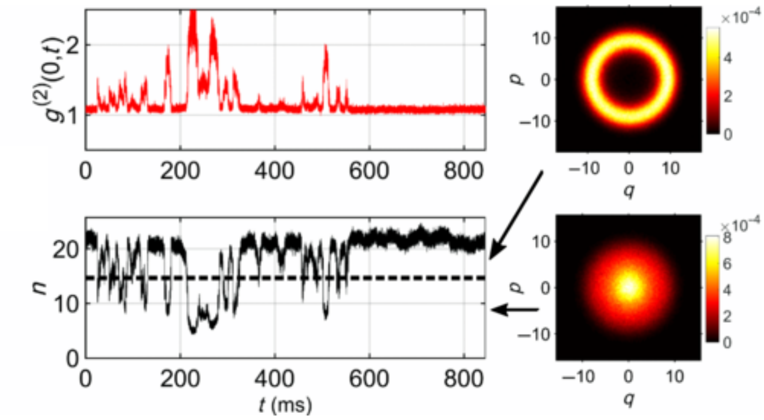

Figure 1: Real-time measurement on a polariton condensate subject to mode competition. Lower panel: The photon number shows distinct jump events indicating that the polariton system alternates between the condensed and uncondensed states as indicated by the respective Husimi Q functions on the right. Upper panel: Simultaneously, we can monitor the photon statistics of the condensate emission which show a direct correlation to the change in the state of the polariton system.

We utilize these results to observe the conditional decoherence of a polariton condensate experimentally [4] and to develop a resource-theoretical treatment [6] of the formation of coherence that relates the obtainable quantum coherence to the mixedness of a light field state.

[1] D.F. McAlister, M.G. Raymer, Phys. Rev. A 55, R1609 (1997).

[2] C. Lüders, J. Thewes, M. Aßmann, Opt. Express 26, 24854 (2018).

[3] C.Lüders et al., Opt. Mater. Express 13, 2997 (2023).

[4] C. Lüders et al., Phys. Rev. Lett. 130, 113601 (2023).

[5] C. Lüders et al., Phys. Rev. X Quantum 2, 030320 (2021).

Ultrafast dynamics of exciton polaritons at room temperature

Hui Li

East China Normal University, China

Research into ultrafast dynamics serves as a critical foundation for uncovering microscopic physical mechanisms and enabling effective control over material properties. In this context, our work focuses on the ultrafast dynamics of microcavity exciton-polariton (EP) condensates at room temperature. To this end, we have developed the femtosecond angle-resolved spectroscopic imaging (FARSI) technique, which facilitates multidimensional, time-resolved photoluminescence measurements with femtosecond precision. Using this technique, we have explored the ultrafast dynamics of macroscopic quantum states in EP condensates, uncovering key processes such as the formation, relaxation, and parametric scattering dynamics of these condensates under non-resonant excitation [1, 2]. Additionally, we have observed bosonic cascading dynamics in EP systems [3].

Building on these insights, we have proposed innovative approaches based on precise temporal control to achieve ultrafast functionalities in polariton devices. For instance, we have demonstrated femtosecond switching in room-temperature polariton condensates with an ultra-high extinction ratio by manipulating the parametric processes of the photonic component in EPs [4]. Furthermore, we have realized a complete set of polaritonic logic gates, including AND, OR, and NOT gates, through temporal manipulation of localized polariton condensates [5].

Our research not only sheds light on the novel mechanisms underlying room-temperature polariton condensation but also provides advanced methods for manipulating fundamental processes in strongly coupled light-and-matter systems. These contributions are expected to significantly benefit both fundamental studies and potential applications of polariton systems.

[1] Fei Chen, Hang Zhou, Ziyu Ye, et al., Phys. Rev. B 106, L020301 (2022).

[2] Ziyu Ye, Fei Chen, Hang Zhou, et al., Phys. Rev. B 107, L060303 (2023).

[3] Fei Chen, Hang Zhou, Hui Li*, et al., Nano Lett. 22, 2023 (2022).

[4] Fei Chen, Hui Li*, Hang Zhou, et al., Phys. Rev. Lett. 129, 057402 (2022).

[5] Hui Li*, Fei Chen, Haoyuan Jia, et al., Nat. Photon. 18, 864 (2024).

Exciton-polaron problem in 2D

V. Shahnazaryan

Abrikosov Center for Theoretical Physics, Russia

We investigate the formation of Frohlich polarons and exciton-polarons in two-dimensional (2D) polar crystalline atomic monolayers. We develop a macroscopic model relying on a Lagrangian density allowing to derive an analytic expression for dispersion of 2D longitudinal optical (LO) phonons. We apply a mean-field approximation to the problem of electron-phonon coupling, and via variational minimization derive expressions for the polaron binding energy and mass renormalization in 2D materials.

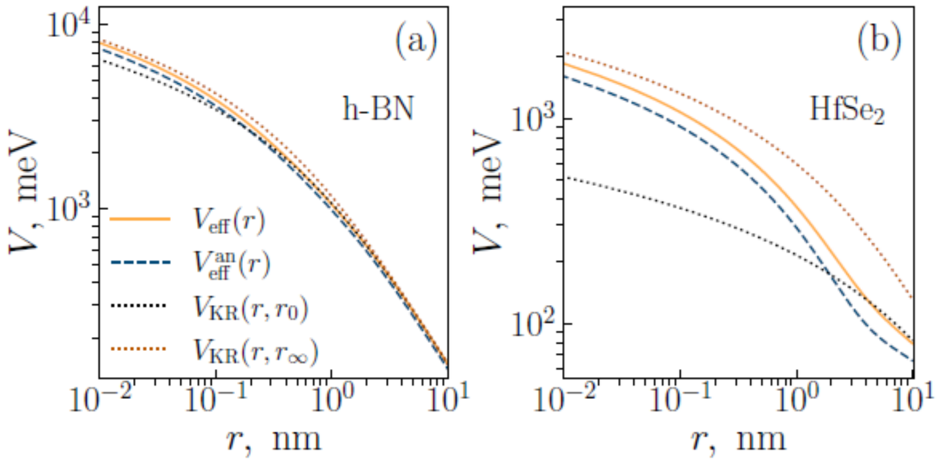

Figure 2. Effective potential of electron-hole interaction V_{eff} (solid curve), and its approximate analytical expression V^{an}_{eff} (dashed curve) for (a) h-BN, and (b) HfSe2 monolayer. The dotted curves illustrate the Keldysh-Rytova potentials $V_{KR}(r, r_\infty)$ and $V_{KR}(r, r_0)$.

Then we extend the approach to excitons interacting with LO phonons and derive a modified potential of electron-hole interaction dressed by LO phonons, shown in Fig. 1. Due to specific dispersion of LO phonons, polarons and exciton-polarons in 2D materials exhibit unique features not found in their three-dimensional counterparts. We present model calculations illustrating polaron and exciton-polaron binding energies, demonstrating the interplay between dimensionality and electron-phonon coupling.

Spin-Meissner Effect in Systems of Coupled Polariton Condensates

A. Kudlis
Abrikosov Center for Theoretical Physics, Russia
University of Iceland, Iceland

We investigate the spin-Meissner effect, also known as full paramagnetic screening, in coupled exciton-polariton condensates under the influence of an external magnetic field. In a single spinor polariton condensate, interactions between polaritons screen the Zeeman splitting below a critical field, so that the emission frequency remains independent of the magnetic field, a phenomenon referred to as spin-Meissner effect. Above this critical field, the condensate switches to full circular polarization and the magnetic field manifests as a Zeeman shift.

Extending the analysis to systems of multiple tunnel-coupled condensates, we reveal that spin-flip processes (stemming from TE-TM splitting) introduce an effective in-plane magnetic field that typically destroys the spin-Meissner regime. For instance, in a two-condensate (dyad) system, the spin-flip tunneling induces a diamagnetic-like response where the condensate frequency changes with external field. In an equilateral triangle of three condensates, various polarization textures can emerge, including half-vortex states with phase windings in one spin component only, and hidden vortex states with opposite circulation in the two spin components. Such states break the uniform screening seen in the single-condensate scenario.

By contrast, in a square geometry, certain parameter regimes allow for a cancellation of these spin-flip effects along perpendicular directions, enabling the reemergence of spin-Meissner screening below a critical magnetic field. Hence, the fate of the spin-Meissner effect is highly sensitive to the interplay of on-site polariton–polariton interactions, spin-conserving tunneling, spin-flip coupling, and lattice geometry. Our results demonstrate that specific symmetries and arrangements of coupled condensates can preserve or restore the remarkable screening of the Zeeman field, opening new perspectives for spin-based polariton devices and simulators of mesoscopic magnetic phenomena.

All-optical temporal logic gates in localized exciton polaritons

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Exciton polaritons, as bosonic quasi-particles formed by the strong coupling of excitons and photons in the semiconductor microcavities, exhibit a hybrid light-matter nature with an extremely light effective mass and strong nonlinearity. These properties enable the formation of non-equilibrium Bose-Einstein Condensation at room temperature. In recent years, leveraging the unique physical properties of these quasi-particles, numerous nonlinear device functions have been investigated, including ultra-low threshold lasing, ultrafast switches, and logic gates. Traditionally, the realization of polariton logic gates has relied on the spatial propagation of polariton fluids, which imposes high demands on microcavity fabrication and complex manipulations. In this work, we have demonstrated a full set of temporal logical gate functions, i.e. AND, OR and NOT gates, by controlling the bosonic cascading and stimulated amplification dynamics in exciton polaritons based on a collinear dual-pulse excitation scheme. Notably, the temporal NOT gate reaches a response time of ~80 fs, which holds the fastest record at present. Our work provides a novel sight for polariton manipulation. By combining the operations in the temporal domain together with in other dimensions, the information processing capability can be dramatically enhanced, opening new horizons for implementing polariton integrated circuits.

[1] H. Li, F. Chen, H. Jia, *et al.*, Nat. Photon. 18, 864 (2024).

Decay of the twisted relativistic electron in a strong inhomogeneous magnetic field

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Recent theoretical and experimental studies reveal that electrons in free space or in a constant magnetic field can carry a nonzero orbital angular momentum projection. Such quantum states are called twisted electrons. While many basic properties of twisted electrons have already been studied, several open questions remain. One of these is the stability of the vortex state. Unlike twisted photons, which are stable, twisted electrons can undergo spontaneous decay—a lowest-order QED process. It turns out that the decay rate depends heavily on the structure of the magnetic field interacting with the twisted electron. Specifically, in a z-dependent inhomogeneous magnetic field, the decay rate can be several times higher than in a homogeneous magnetic field (e.g., during transitions between Landau levels). One of the important practical consequences of this conclusion is that the decay rate increases when a free twisted electron is being focused. The sharper the focusing, the higher the decay rate becomes.

In the present study, we develop a theoretical framework based on the Foldy-Wouthuysen transformation and the Ermakov mapping operator to support the above statement. The proposed technique allows us to evaluate decay rates (and higher-order interactions of the twisted electron in an inhomogeneous magnetic field with the quantized electromagnetic field) for different configurations of the magnetic field. We analyze standard magnetic field models, such as the Glazer field and Faraday coils, as well as examine field configurations that may appear in astrophysical environments, particularly in stellar and relativistic jets.

We show that the propagation of a twisted electron in a transversely uniform but z-dependent magnetic field dramatically increases the decay rate. Additionally, we demonstrate that focusing a twisted electron results in a reduction of its lifetime.

The exciton condensate interaction with the nuclei

Israel Bar Joseph

The Weizmann Institute of Science, Israel

We study the interaction between an exciton condensate and nuclei in GaAs/AlGaAs coupled quantum wells using an oscillating (RF) magnetic field. We demonstrate that electron-nuclear spin exchange can polarize the nuclei within the quantum well where the electrons are located over a macroscopic area of ~$10^5\ \mu m^2$, and at a critical static magnetic field of B = 1.750 T, *complete* nuclear polarization in the quantum well is achieved. We find that the electron-nuclear hyperfine interaction, g, is enhanced by a factor of $\sqrt{N}$, where N is the number of excitons in the condensate. This enhancement gives rise to a collective RF mode of the condensate at $\sqrt{N}g$, which could serve as a sensitive probe for condensate coherence.

Features and peculiarities of light-matter coupling in 2D superconducting thin films

Ivan Savenko

Goudong University, China

We develop a theory of electromagnetic field-induced transport in two-dimensional (2D) superconducting thin films and monolayers at low and finite temperatures. The goal is to study the symmetries of the system and study when an external electromagnetic field's frequency and polarization can control the Cooper pairs' transport. It is known that the EM field absorption of a uniform electromagnetic field with a frequency larger than the superconducting gap is forbidden in pure superconductors. Finite absorption can occur only if electron scattering by impurities is considered. We are constructing a theory of the nonlinear photoresponse of isotropic 2D superconductors in the presence of a built-in constant supercurrent at various frequencies and temperatures and topological superconductors. This research aligns with the recent study of the superconducting diode effect. We also propose the optical photodiode, which allows for optical control of the signal propagation in the system and is magnetic field-free, as opposed to the superconducting diode, where the magnetic field is necessary.

The frequency of the control field depends on the superconducting gap. For conventional superconductors, it lies in terahertz (THz) and sub-THz regions. However, the effect we propose is general as it does not impose any substantial restrictions on the material or the frequency of the field, which can vary in quite a broad range.

Higher-order topological insulators in polariton wave lattices

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Topological insulators have been realized in various photonic systems that contain distinctive lattice structures such as honeycomb lattices, Lieb lattices, kagome lattices, and Su-Schrieffer-Heeger (SSH) chains. Here we introduce a double-wave chain in microcavity polaritons that allows the formation of topological edge states by properly configuring the structure of the potential waves, see Figure 1 below [1]. Regularly stacking multiple identical coupled waves into a 2D structure leads to multiple SSH chains in the direction perpendicular to the waves. Their combination enables the formation of higher-order topological insulators, i.e., corner states. In the nonlinear regime, more than one edge (corner) state in 1D (2D) can be stably excited under the same pump, known as multistable topological insulators. Similar higher-order topological insulators in 2D SSH lattices have been recently realized in a perovskite microcavity [2] and an organic microcavity [3] at room temperature.

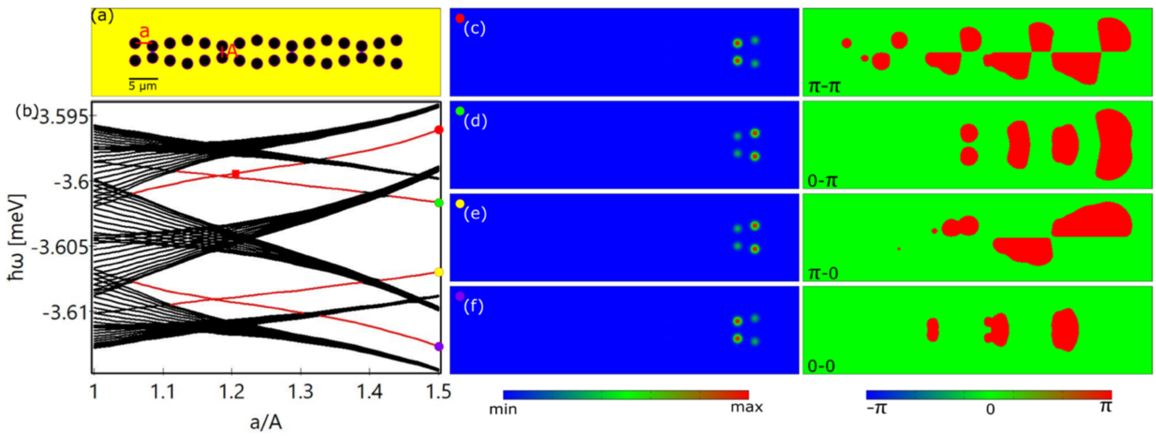

Figure 3. Edge states in double-wave chains. (a) A double-wave potential chain. (b) Spectrum of the linear eigenstates in the double-wave chain. Red lines indicate the topological edge states and black lines are the bulk states. (c–f) Amplitude (left) and phase (right) distributions of the edge states marked in (b).

[1]. T. Schneider, W. Gao, T. Zentgraf, S. Schumacher, and X. Ma, "Topological edge and corner states in coupled wave lattices in nonlinear polariton condensates", Nanophotonics **13**, 509-518 (2024).

[2]. J. Wu, S. Ghosh, Y. Gan, Y. Shi, S. Mandal, H. Sun, B. Zhang, T. C. H. Liew, R. Su, Q. Xiong, "Higher-order topological polariton corner state lasing", Science Advances **9**, eadg4322 (2023).

[3]. C. Bennenhei, H. Shan, M. Struve, N. Kunte, F. Eilenberger, J. Ohmer, U. Fischer, S. Schumacher, X. Ma, C. Schneider, M. Esmann, "Organic room-temperature polariton condensate in a higher-order topological lattice", ACS Photonics **11**, 3046-3054 (2024).

Dissipative trapping of polariton condensates in various systems

Anton Nalitov[1,2], Pavel Kozhevin[2]

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Non-resonantly generated exciton-polariton condensates present a peculiar platform for implementation of non-Hermitian trapping potentials. Such potentials emerging from spatially profiled optically inactive excitonic reservoir provide both gain and confinement and give rise to a plethora of unique dissipative phenomena. In particular, persistent quantized vortices can emerge spontaneously in out-of-equilibrium polariton condensates. This talk will overview some effects involving optically trapped polariton vortex dynamics in the vicinity of the condensation threshold, where the excitonic reservoir cannot be adiabatically eliminated, including control over vortex topological charge [1], topological states [2] and a reach diagram of nonlinear transitions [3]. We will address various setups, including optically profiled non-resonant pumping, polaritons based on photonic bound states in the continuum [4], and ion implantation, as well as various geometries, including quantum wires, dots, and rings.

[1] A. K. Bochin, A. V. Nalitov, Nonequilibrium polariton condensation in biannular optically induced traps, Optical Materials Express 13 (2), 295-303 (2023)

[2] Harrison, S. L.; Nalitov, A.; Lagoudakis, P. G.; Sigurđsson, H., Polariton vortex Chern insulator, Optical Materials Express 13(9) 2550-2562, (2023)

[3] I. Chestnov, E. Cherotchenko, A. Nalitov, Non-adiabatic polariton condensation in annular optical traps, Physical Review B **109**, 205304 (2024)

[3] M. Masharin, A. Bochin, I. Chestnov, V. Shahnazaryan, X. Ma, S. Schumacher, S. Makarov, A. Samusev, A. Nalitov, Non-Hermitian trapping of Dirac exciton-polariton condensates, in preparation

Widely tunable OPO in mid IR region for medical and scientific applications

Karapuzikov A., Boyko A., Kostyukova N.

Special technologies, Ltd., Novosibirsk, Russian Federation

The mid-infrared (IR) spectrum contains absorption lines for numerous biological objects. Consequently, sources of IR radiation find extensive applications across fields such as dermatology, ophthalmology, dentistry, as well as various other medical disciplines. Modulated mid IR laser radiation together with photo-acoustic spectroscopy is used for medical diagnostic due to high sensitivity, enhanced frequency selectivity, and fast response time.

An optical parametric oscillator (OPO) serves as a source of mid-IR radiation and requires a nonlinear crystal with specific physical properties to function. Currently, exploring new nonlinear crystals with these required characteristics is of great importance. This work summarizes our efforts to create a widely tunable coherent source in mid IR for use with photo-acoustic spectroscopy for goals of medical diagnostic of pulmonary diseases.

The most representative range is from 2.5 to 11 μm. To cover this range firstly we used fan-out MgO:PPLN for 2.5 to 4.5 μm and tweened $HgGa_2S_4$ crystals for 4.5-11 μm with 1.053 μm Q-switched pumping source.

Barium-containing ternary and quaternary chalcogenides have emerged as potential substitutes for HGS, AGS, AGSe, and ZGP crystals. In the period from 2009 to 2012, the synthesis of two promising wide bandgap ternary chalcogenide crystals, $BaGa_4S_7$ (BGS) and $BaGa_4Se_7$ (BGSe), was successfully achieved. These crystals exhibit broad mid-IR transparency ranges, spanning from 0.35 to 12 μm for BGS and from 0.47 to 18 μm for BGSe at 0% level transparency. Shortly thereafter, the quaternary barium chalcogenide compounds $BaGa_2GeS_6$ (BGGS) and $BaGa_2GeSe_6$ (BGGSe) were produced [1,2].

Wavelength tuning from 2.5 to 9 μm was obtained with sufficiently better performance. That allow us getting better sensitivity of our photo-acoustic medical gas-analyzer.

1. Badikov, V.V.; Badikov, D.V.; Laptev, V.B.; Mitin, K.V.; Shevyrdyaeva, G.S.; Shchebetova, N.I.; Petrov, V. Crystal growth and characterization of new quaternary chalcogenide nonlinear crystals for the mid-IR: $BaGa_2GeS_6$ and $BaGa_2GeSe_6$. Opt. Mater. Express 2016, 6, 2933–2938.

2. Badikov, V.V.; Badikov, D.V.; Shevyrdyaeva, G.S.; Kato, K.; Umemura, N.; Miyata, K.; Panyutin, V.L.; Petrov, V. Crystal growth and characterization of a new quaternary hexagonal nonlinear crystal for the mid-IR: $Ba_2Ga_8GeS_{16}$. J. Alloys Compd. 2022, 907, 164378.

Integrated microring resonators for soliton generation, coherent computing, and quantum light sources

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Optical properties and THz applications of quasi-one-dimensional nanocarbons

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Carbon-based nanostructures are believed to be promising candidates for terahertz (THz) applications [1]. Following our earlier work on narrow-gap carbon nanotubes and graphene nanoribbons [2], as well as graphene bipolar waveguides [3] and double quantum wells [4], we are now considering dipole optical and terahertz transitions in two other types of nanocarbons – carbynes and cyclocarbons.

The technology for synthesizing carbynes (polyyne carbon chains) has rapidly evolved over the last few years, with stable long chains deposited on substrates now a reality [5]. We have recently demonstrated and explained a strong polarization dependence of photoluminescence from highly aligned carbon chains terminated by gold clusters [6]. A prominent feature of long polyyne chains (chains with two alternating non-equal bonds) is the presence of topologically protected mid-gap edge states. For a finite-length chain, the two edge states form an even and odd combination with the energy gap proportional to the edge-state overlap due to tunneling. These split states of different parity support strong dipole transitions. We have shown [7] that for long enough carbyne chains, the energy separation between the HOMO and LUMO molecular orbitals formed by the edge states corresponds to the THz frequency range. There are several other allowed optical transitions in this system that can be used to maintain the inversion of population required for THz lasing. The frequency of THz transitions can be tuned by an external electric field [8].

Another recent achievement in nanocarbon technology is the demonstration of controlled synthesis of cyclocarbons, particularly the cyclocarbon allotropes C_{18} [9] and more recently C_{16} [10]. The properties of cyclocarbons in an external (lateral in the plane of the molecule) electric field differ drastically depending on the parity of the number of dimers in a polyyne ring. This is a direct consequence of breaking the inversion symmetry in a ring consisting of an odd number of dimers, including the famous C_{18}. Our estimates [11] show that adding just one extra carbon dimer to C_{16} is equivalent to placing this molecule in an external magnetic field of over 1000 T. For a polyyne cyclocarbon with an odd number of dimers, because of the absence of inversion symmetry, an experimentally attainable electric field should open a tunable gap between otherwise degenerate states, leading to two states with allowed dipole transitions between them in the THz range. Population inversion can be achieved again using optical pumping.

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Ultrafast Dynamics of Exciton-Polariton Condensates

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We report the first experimental observation of two-photon pumped polariton condensation, demonstrated by angle-resolved photoluminescence spectroscopy in a GaAs-based microcavity, evidenced in the quadratic input-output dependence below and above threshold. We show a temporal signature of dark exciton induced bosonic stimulation by investigating one- and two-photon pumped condensation with time-resolved photoluminescence spectroscopy, showing a clear difference in the detuning dependence of the build-up and relaxation rates of the condensate-induced blueshift under one-photon excitation compared to two-photon excitation, where a 2p-exciton-to-lower-polariton THz transition can provide another stimulation channel.

We also report the observation of the dynamic Stark effect in an exciton-polariton condensate, which could be employed for phase imprinting and shaping potential landscapes. A reversible Stark shift of femtosecond scale duration is demonstrated through pump-probe measurements of the differential reflectivity of a specially designed sample. Alongside the short-lived signature of the Stark effect, the differential reflectivity exhibits spectro-temporal oscillations predicted by coherent oscillation theory due to an interference effect in the probe-induced polarization of the system in the presence of the Stark pump. The duration of these oscillations indicates the degree of temporal coherence of the system polarization. We present a novel approach for showing the dynamic Stark shift in a condensate through analysis of the coherent oscillations in the differential reflectivity measurements.

Magnetophotonics for advanced control of spins

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Optical control of the magnetization at ultrashort time scales attracts a significant research attention. Launching and controlling magnons with laser pulses opens up new routes for applications including optomagnetic switching and all-optical spin wave emission and enables new approaches for information processing with ultralow energy dissipation. However, optical pumping of spins encounters several obstacles which partially prevent its further progress towards applications. In particular, laser beam spot is diffracted limited, which limits minimal magnetic bit size by a few hundred on nanometers. Secondly, it is not possible to write bits with in-depth resolution. As for the spin wave optical excitation, the efficiency is rather law which is not competitive with conventional microwave means.

Here, we propose to marriage the laser-induced ultrafast magnetism and nanophotonics to overcome the aforementioned obstacles and to gain new functionalities. In this talk a kind of review of recent advances in this direction achieved in our group will be presented [1-7].

The cornerstone of optomagnonics is impossibility to focus the light tighter than a diffraction limit. This limits the wavelengths of the excited spin waves in optomagnonic devices and does not allow for excitation of the fast short spin waves. Here we propose and experimentally demonstrate a novel method of the selective optical generation of the short spin waves in nanophotonic waveguide gratings. This method for optical excitation of the short spin waves with submicron wavelengths in the waveguide gratings was proposed and demonstrated experimentally [8]. It allows for the selective and tunable excitation down to ~ 100 nm spin-wave wavelengths. This opens new horizons for optomagnetic applications that are wide ranging, from logical elements to data processing devices.

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Dislocations and interdomain interlayer elastic waves in relaxed moire superlattices

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Adhesive forces acting between the layers of long-period moiré superlattices cause lattice relaxation of moire pattern into an array of domains separated by a network of dislocations [1,2]. For parallel alignment of the layers the relaxed superlattice consists of triangular domains with rhombohedral atomic structure, separated by partial dislocations [1,2]. In bilayers of transition metal dichalcogenides, the rhombohedral domains acquire a spontaneous electric dipole moment oriented perpendicular to the plane of the layers [3], and their repolarization in an electric field is determined by the motion (bending and sliding) of partial dislocations [3,4,5], characterized by an orientation-dependent energy per unit length of the partial dislocation.

In my talk, I present a realistic model [6] for partial and perfect dislocations in relaxed moiré superlattices formed at the interlayer interface of bilayer two-dimensional materials near parallel and antiparallel alignment of the layers. For a general model of interlayer adhesion energy, exact analytical expressions for the displacement field describing an individual partial dislocation is obtained, and analytical orientation-dependent relationships for the width and energy per unit length of the partial dislocation are determined. For perfect dislocations in antiparallel bilayers, a semi-analytical expression for the displacement field is derived, allowing for an analytical estimation of the dislocation width and its energy per unit length.

Additionally, it will be shown that the emergence of dislocation network gives rise to a new type of one-dimensional elastic waves in relaxed moiré superlattices, which can freely propagate along dislocation lines while remaining localized in the transverse direction within the region between domains [7]. In this case, an individual partial/full dislocation generates a series of sub-bands of interdomain elastic waves (one gapless and one or several gapped), with frequencies lying below the continuum of interlayer elastic waves in the domains. The gapless mode is characterized by imaginary frequencies in the wave vector range $q<q_c$, where the critical wave vector q_c, determined by the intersection of the dispersion relation with zero frequency, depends on the material and the orientation of the dislocation. Such dispersion indicates the instability of straight dislocations with lengths exceeding $2\pi/q_c$.

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Off-diagonal and non-Hermitian disorder in multilayer topological systems

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We have investigated the influence of off-diagonal (including non-Hermitian) disorder on the electron states of a multilayer topological insulator. Unlike the diagonal disorder, when the random variable is the on-site energy, in the off-diagonal case the random variable is the inter-sites (interlayer in our case) tunneling parameters (see, for example, [1, 2]). We have considered two types of such disorder: uniform distribution (Anderson model) and exponential distribution (Dyson model). Using two methods — expansion of the Green's function into band and localized states — we have investigated the stability of the Weyl phase and the anomalous quantum Hall effect (AQHE) phase. We have shown that the Weyl phase is stable even at large fluctuation values [3]. At the same time, the AQHE phase is preserved only at very small fluctuations. In particular, such fluctuations lead to the disappearance of the AQHE plateau. From this we concluded that uncontrolled off-diagonal disorder may be one of the causes of topological phase destruction. Finally, we investigated the off-diagonal disorder-induced Anderson localization/delocalization in a multilayer topological insulator.

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Trion transitions in monoatomic carbon wires

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Carbon is a widespread material having multiple allotropic forms. The great interest of scientific community has been especially attracted to the linear carbon forms for their unique electronic and optical properties as well as for the hard complexity of their synthesis. The recent observation of excitons and trions in sp-carbon nanowires has a fundamental importance as it presents the first experimental evidence of bright exciton states in monoatomic chains. It crowns an effort of many groups who provided the excitonic gaps calculation in one-dimensional carbon chains [1, 2] and predicted the excitonic features in carbon chains. We observe a triplet fine structure in low-temperature photoluminescence spectra that is associated with the spatially direct neutral exciton, positive and negative trion resonances [2]. The time-resolved optical response of excitons in carbon chains is found to be dependent on the bandgap of the chain and the lengths of straight parts of the chains that provides a control tool for fine tuning of the radiative properties of carbon chains for applications in carbon lasers and light-emitting diodes.

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Coherent quantum transport of microcavity exciton polaritons

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Microcavity exciton polaritons are versatile hybrid quasi-particles that combine exceptional optical properties (e.g., strong nonlinearity and ultralow-threshold lasing) with electronic characteristics (e.g., coupling with electromagnetic fields and spin-dependent responses). Here, we present that the hybrid nature of exciton polaritons induces a richer form of quantum transport than their traditional counterparts [1]. We emphasize the roles of nonlinear interactions, quantum coherence, finite lifetimes, and spin-dependent responses in quantum transport, showing how these factors interplay to induce a range of phenomena within semiconductor microcavities. Notably, we reveal that scattering of exciton polaritons due to natural disorder introduces anomalous quantum propagation, markedly different from that of particles governed by the Schrödinger or Gross-Pitaevskii equations [1]. Additionally, when spin-dependent properties are incorporated, they give rise to critical phenomena such as the non-Hermitian skin effect [2] and the optical spin-Hall effect [3]. We report our latest experimental efforts in this direction, presenting the direct observation of coherent exciton polariton [4, 5], including their spin responses, and the realization of practical devices like spin-polarizing beam splitters and spin-based NOT gates [3].

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Pathways of quantum polaritonics

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Polariton lasers [1] are semiconductor light-emitting devices based on the bosonic condensation of half-light-half-matter quasiparticles: exciton-polaritons. Due to the strong coupling of cavity photons with excitons, exciton-polaritons in microcavities have a peculiar non-parabolic dispersion. Due to the stimulated scattering to one or several quantum states, exciton-polaritons form bosonic condensates characterized by high spatial coherence and superfluid properties. Spatial-light modulators help generating traps for polariton superfluids in plane of GaAs-based microcavities, where size-quantization of many-body wavefunctions of polariton superfluids is observed. Exciting coherent superpositions of pairs of eigen states of polariton superfluids in elliptical traps we create qubits [2] characterized by very slow decoherence dynamics. The characteristic timescales are as follows: approximately every femtosecond a polariton comes in or goes out from a polariton condensate, the life-time of each individual polariton in a condensate is of the order of 10 picoseconds, the coherence time of a polariton condensate as a whole is of the order of 100 ps, the characteristic relaxation time of the spatial coherence in a trapped polariton condensates is of the order of microseconds or longer. This makes the figure of merit of qubits based on trapped polariton condensates very high, probably over 1000 or more. Quantum logic operations can be performed on these superfluid polariton qubits with use of control laser pulses. We demonstrate the Hadamard and Pauli operations on a single qubit, the entanglement of two qubits and double-qubit gate operations. The new platform for quantum computing provided by polariton lasers is highly promising due to the remarkable scalability of polariton quantum networks and their potential for room temperature operation.

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Polariton Lattices for Binary Neuromorphic Network Architectures

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The rapid growth of artificial neural networks and artificial intelligence is driven by the demand for efficient data processing and pattern recognition. However, traditional hardware implementations of these networks are constrained by computational speed and energy efficiency, limiting their applicability. These challenges have spurred interest in neuromorphic systems, which mimic the structure and functionality of the human brain to achieve greater efficiency. Among these, exciton-polariton-based networks have emerged as a promising solution, leveraging the unique properties of exciton-polaritons—quasiparticles resulting from the strong coupling of photons and excitons within semiconductor microcavities [1–3]. These systems exhibit strong optical nonlinearity and ultrafast response times on the picosecond scale, making them good candidates for high-speed, energy-efficient neuromorphic computing. Within this context, the development of binarized neural networks offers a significant breakthrough. These networks streamline operations by using binary activations or weights, enhancing speed and reducing energy demands while maintaining competitive accuracy levels.

The proposed neuromorphic network [1] is built on a lattice of exciton-polariton condensates, interconnected through nonresonant optical pumping, see figure 1**a**. Each neuron in this system is represented by a polariton dyad—a pair of polariton condensates coupled via their spatial coherence. This coherence arises from the ballistic propagation of polaritons, which ensures communication across the network. The binary nature of the network is a key feature: neurons operate in either ON or OFF states, defined by the interference patterns formed between polariton condensates in each dyad, see figure 1**c**. In the OFF (ON) state, the interference pattern exhibits a minimum (maximum) of intensity at the midpoint between the two condensates, corresponding to a reduced (enhanced) photoluminescence signal. This optical signal modifies the local potential landscape, influencing the exciton reservoir and enabling the transition between states. These states are readily distinguishable due to the sharp contrast in photoluminescence, ensuring robust signal processing. The lattice structure facilitates parallel signal processing, a significant improvement over sequential or pulse-coded binary systems. Furthermore, the modular design of the network allows for scalable configurations.

The proposed polariton network was tested on two benchmark tasks to evaluate its performance: handwritten digit recognition using the MNIST dataset [4] and voice command recognition using the Speech Commands dataset [5]. For the MNIST dataset, the network demonstrated an impressive classification accuracy of 97.5%, surpassing previously reported results for polariton-based neuromorphic systems. In the case of the Speech Commands dataset, which involves recognizing spoken digits, the network achieved a classification accuracy of 68%, outperforming traditional methods such as Hidden Markov Models with Gaussian Mixture Models (HMM-GMM). This highlights the versatility and robustness of the system in handling diverse data types, from static images to dynamic audio signals.

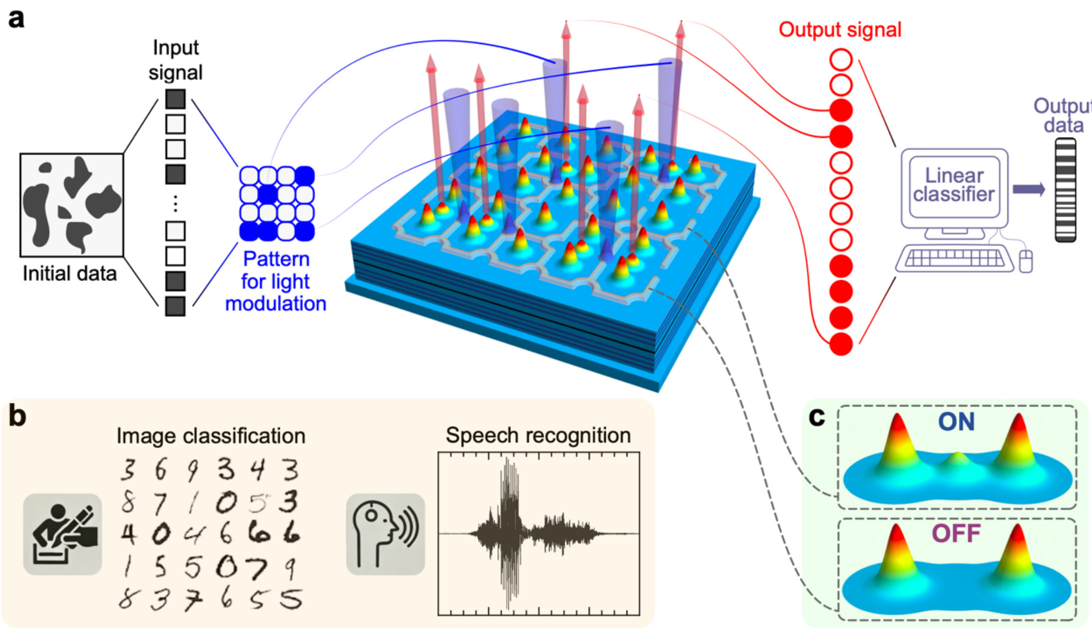

Figure 1. Working principle of the binarized polariton neuromorphic network.
(**a**) A conceptual diagram of a binarized polariton neural network. Initial data are digitized and binarized, forming the input signal. The input signal serves as a pattern for the input optical signals (blue cones). These signals then activate artificial neurons within the computational layer, generating the resultant optical output signals (red arrows). The output is processed via a linear classifier. The computational layer consists of a lattice of polariton dyads — pairs of interacting polariton condensates — that are optically excited within the plane of a semiconductor optical microcavity. The dyads are isolated from each other by potential barriers (gray) to reduce mutual influence. (**b**) Illustration of the tasks of handwritten digit recognition and spoken word recognition addressed in the study. (**c**) Illustration of polariton dyads functioning as artificial neurons, exhibiting even (OFF) and odd (ON) interference patterns.

In summary, the proposed neuromorphic network based on lattices of polariton condensates demonstrates potential for advancing hardware implementations of machine learning systems. By leveraging the unique properties of polaritons, such as their ultrafast response times, strong optical nonlinearity, and spatial coherence, the network achieves efficient parallel processing and robust binary operations. The high classification accuracies achieved on benchmark tasks, combined with the scalability and energy efficiency of the system, underscore its capability to outperform conventional neuromorphic systems. These results highlight the promise of polariton-based networks as a foundation novel computing platforms, bridging the gap between high-speed quantum-inspired computing and practical neuromorphic applications.

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