Russian-German-French

Laser Symposium

2018

KAZAN · RUSSIA

4th Russian-German-French Laser Symposium

PROGRAM & ABSTRACTS

April 23–27, 2018
Kazan, Russia

Scope

This Russian-German-French Laser Symposium is the fourth symposium in this series, which was conceived as a driving force for furthering collaborative efforts between the countries. One of the major targets of these symposia is bringing together scientists working in various fields of Laser Physics in Germany, France, and Russia from universities, research institutes and the industry to discuss latest updates in the field and to find possible collaborations. Traditionally, many young scientists, postdoctoral researchers and students, are invited to and participate in these symposia.

The symposium program will host a few plenary talks, sessions of oral presentations (invited and contributed talks) and poster sessions. The number of attendees will include 10 invited participants from each side. Selection of national participants is responsibility of the Russian, French, and German co-chairs, correspondingly. The working language of the Symposium is English.

Symposium Topics

- Quantum and Atom Optics
- Cold Atoms Physics
- High Precision Optical Measurements
- Nanophotonics and Nanoplasmonics
- Quantum Sensors
- Physics of Quantum Information
- Optical Physical Beyond Limits
- Optical Imaging
- Other related topics

Organizers

Kazan Quantum Center at Kazan National Research Technical University
Zavoisky Physical-Technical Institute, Kazan Scientific Center of Russian Academy of Sciences
Institute of Laser Physics, SB of Russian Academy of Sciences
Institute of Spectroscopy, Russian Academy of Sciences

Sponsors

This Symposium has been supported by the Government of Russian Federation (Project No. 14.Z50.31.0040, Feb. 17, 2017)

Symposium co-chairs

Sergei Bagayev, RAS, Institute of Laser Physics, Novosibirsk, Russia
Elisabeth Giacobino, CNRS, Université Pierre et Marie Curie, France
Gerd Leuchs, MPL, Universität Erlangen-Nürnberg, Germany

Scientific Program Committee

Laurent Larger, University of Franche-Comte
Victor Zadkov, Institute of Spectroscopy, Russian Academy of Sciences
Alexey Taichenachev, Institute of Laser Physics, Russian Academy of Sciences
Aleksey Zheltikov, Moscow State University

Local Organizing Committee / Contacts

Albert Kh. Gilmutdinov, Kazan Quantum Center at Kazan National Research Technical University, chair
Sergey A. Moiseev, Kazan Quantum Center at Kazan National Research Technical University, s.a.moiseev@kazanqc.org
Alexey A. Kalachev, Zavoisky Physical-Technical Institute, Kazan Scientific Center of Russian Academy of Sciences, a.a.kalachev@mail.ru

Location

The symposium will take place at Kazan National Research Technical University named after A. N.Tupolev – KAI at the following address: Kazan, Chetayeva str., 18a

PROGRAM

24 April 2018 (Tuesday)

Time	Event / Title of the talk	Page
08:30–09:00	**Registration**	
	Session I Chair: Sergey Bagayev, Novosibirsk, Russia	
09:00–09:45	"Rabi oscillations of x-ray radiation between two nuclear ensembles", [PLENARY] **Adriana Pálffy**, Max-Planck-Institut für Kernphysik, Heidelberg, Germany	10
	Session II Chair: Gerd Leuchs, Erlangen, Germany	
09:45–10:15	"Fiber-optic quantum thermometry", [INVITED] **A. M. Zheltikov** (1, 2), I. Fedotov (1, 2), (1) Lomonosov Moscow State University, Moscow, Russia; (2) Kazan National Research Technical University named after A. N. Tupolev, Kazan, Russia	11
10:15–10:45	"Transporting neutral atoms in optical lattices at the quantum speed limit", [INVITED] Manolo R. Lam (1), Natalie Thau (1), Thorsten Groh (1), Carsten Robens (1), Wolfgang Alt (1), Dieter Meschede (1), Antonio Negretti (2), Tommaso Calarco (3), **Andrea Alberti** (1); (1) Institut für Angewandte Physik, Bonn, Germany; (2) Zentrum für Optische Quantentechnologien, Hamburg, Germany, (3) University of Ulm and Center for Integrated Quantum Science and Technology (IQST), Germany	12
10:45–11:00	"Atomic clocks based on coherent population trapping resonances in alkali atom vapors", [ORAL] **S. M. Ignatovich**, M. N. Skvortsov, Institute of Laser Physics SB RAS, Novosibirsk, Russia	13
11:00–11:30	**Coffee**	
	Session III Chair: Victor Zadkov, Troitsk, Moscow, Russia	
11:30–12:00	"Many-body interactions of cold Rydberg atoms and quantum information", [INVITED] **I. I. Ryabtsev** (1, 2), I. I. Beterov (1, 2), D. B. Tretyakov (1, 2), E. A. Yakshina (1, 2), V. M. Entin (1, 2), P. Cheinet (3), P. Pillet (3); (1) Rzhanov Institute of Semiconductor Physics SB RAS, Novosibirsk, Russia, (2) Novosibirsk State University, Novosibirsk, Russia, (3) Laboratoire Aime Cotton, CNRS, University Paris-Sud, ENS Paris-Saclay, Orsay, France	14
12:00–12:30	"Photon echo quantum memory in optical and microwave resonators", [INVITED] **S. A. Moiseev** (1, 3), K. I. Gerasimov (1, 3), R. R. Latypov (2), M. M. Minnegaliev (1), E. S. Moiseev (1, 2), N. S. Perminov (1, 3), K. V. Petrovnin (2), V. Urmancheev (1), O. N. Sherstyukov (2), (1) Kazan National Research Technical University named after A. N. Tupolev, (2) Kazan Federal University, (3) Zavoisky Physical-Technical Institute, Federal Research Center "Kazan Scientific Center of RAS", Kazan, Russia	15
12:30–12:45	"Developing narrowband heralded single-photon sources based on spontaneous parametric down-conversion", [ORAL] D. A. Turaikhanov, D. O. Akatiev, **I. Z. Latypov**, A. V. Shkalikov, A. A. Kalachev, Zavoisky Physical-Technical Institute, Federal Research Center "Kazan Scientific Center of RAS", Russia	16
13:30–14:30	**Lunch**	

Time	Event / Title of the talk	Page
14:30–16:30	Lab tour to the labs at KAI and Kazan Quantum Center	
16:30–17:00	**Coffee**	
	Session IV Chair: Adriana Palffy, Heidelberg, Germany	
17:00–17:30	"Electron acceleration/filamentation", [INVITED] I. Tsymbalov (1,2), S. Shulyapov (1), I. Mordvincev (1, 3), K. Ivanov (1, 3), D. Gorlova (1, 2), G. Gospodinov (1), V. Prokudin (1), R. Volkov (1), A. Brantov (3), V. Bychenkov (3), V. Nedorezov (2), **A. Savel'ev** (1); (1) Faculty of Physics & International Laser Centre, Lomonosov Moscow State University, Moscow, Russia; (2) Institute for Nuclear Research RAS, Moscow Russia; Lebedev Physical Institute RAS, Moscow, Russia	17
17:30–18:00	"Shaping the spectra of short x-ray pulses by mechanical means", [INVITED] **Jörg Evers**, Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany	18
18:00–18:30	"Laser spectroscopy at storage rings and accelerator facilities", [INVITED] **Thomas Walther** for the Laser Cooling and Radris Collaborations, Institute of Applied Physics, Technical University Darmstadt, Darmstadt, Germany	19
18:30–19:00	"Measuring the temperature and heating rate of a single ion by high resolution imaging", [INVITED] **Bharath Srivathsan** (1), Martin Fischer (1, 2), Lucas Alber (1, 2), Markus Weber (1), Markus Sondermann (1, 2), and Gerd Leuchs (1, 2, 3); (1) Max Planck Institute for the Science of Light, Erlangen, Germany; (2) Friedrich-Alexander-Universität Erlangen-Nurnberg, Department of Physics, Erlangen, Germany; (3) Department of Physics, University of Ottawa, Ottawa, Ontario, Canada	20
19:00–22:00	**Welcome reception**	

25 April 2018 (Wednesday)

Time	Event / Title of the talk	Page
	Session V Chair: Laurent Laurent, Franche-Comté, Besançon, France	
09:00–09:45	"Planar plasmonic optics and its applications", [PLENARY] V. I. Balykin, **P. N. Melentiev**, Institute of Spectroscopy, Troitsk, Moscow, Russia	21
	Session VI Chair: Jörg Evers, Heidelberg, Germany	
09:45–10:15	"Dressed atom picture for quantum plasmonics", [INVITED] **G. Colas des Francs**, ICB, CNRS/Université Bourgogne Franche Comté, Dijon, France	22
10:15–10:45	"Quantum and Nonlinear Optics with Single Nanostructures" [INVITED] **V. N. Zadkov** (1), V. I. Balykin (1), P. N. Melentiev (1), Yu. V. Vladimirova (2), and Feng Song (3), (1) Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow, Russia; (2) International Laser Center and Faculty of Physics, Lomonosov Moscow State University, Moscow, Russia; (3) Photonics Center, College of Physical Sciences, Nankai University, Tianjin, P. R. China	23
10:45–11:00	"Coupling nano-particles and light field by strong focusing with a deep parabolic mirror", [ORAL] **V. Salakhutdinov**, M. Sondermann, L. Carbone, E. Giacobino, A. Bramati, G. Leuchs, Max Planck Institute for the Science of Light, Erlangen, Germany	24
11:00–11:30	**Coffee**	

Time	Event / Title of the talk	Page
	Session VII Chair: Andrey Naumov, Troitsk, Moscow, Russia	
11:30–12:00	"Laser-deposited topological nanoclusters – quantum size effects in electrophysics and optics of thin films", [INVITED] A. V. Kavokin (1), **S. M. Arakelian** (2), A. O. Kucherik (2), S. V. Kutrovskaya (2), A. V. Osipov (2), A. V. Istratov (2); (1) University of Southampton, England; (2) Vladimir State University, Vladimir, Russia	25
12:00–12:30	"New hybrid crystalline metal-carbon flakes with unusual optical properties", [INVITED] **A. A. Manshina** (1), Yu. Petrov (2), P. Banzer (3, 4), G. Leuchs (3, 4); (1) Institute of Chemistry, St. Petersburg State University, St. Petersburg, Russia; (2) Faculty of Physics, St. Petersburg State University, St. Petersburg, Russia; (3) Max Planck Institute for the Science of Light, Erlangen, Germany; (4) Department of Physics, University Erlangen-Nürnberg, Erlangen, Germany	26
12:30–13:00	"Coherent spin dynamics of erbium doped crystals at sub-Kelvin temperatures", [INVITED] **Pavel Bushev**, Experimentalphysik, Universität des Saarlandes, Saarbrücken, Germany	27
13:30–14:30	**Lunch**	
14:30–16:30	Bus transfer and lab tour to the Zavoisky Physical-Technical Institute	
16:30–17:00	**Coffee**	
	Session VIII Chair: Sergei Arakelian, Vladimir, Russia	
17:00–17:30	"Probing of local fields in solids by fluorescence nanoscopy with single probe molecules" [INVITED] **A. V. Naumov** (1, 2), A. A. Gorshelev (1), M. G. Gladush (1, 2), J. Köhler (3, 4, 5), and L. Kador (3); (1) Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow, Russia; (2) Moscow State Pedagogical University, Moscow, Russia; (3) University of Bayreuth, Institute of Physics, Bayreuth, Germany; (4) University of Bayreuth, Soft-Matter Spectroscopy, Bayreuth, Germany; (5) Bavarian Polymer Institute, Bayreuth, Germany	28
17:30–17:45	"Fluorescence intermittency of single core/shell quantum dots depending on laser excitation intensity", [ORAL] **I. Yu. Eremchev**, I. S. Osad'ko, A. V. Naumov, Institute of Spectroscopy, Troitsk, Moscow, Russia	29
17:45–18:00	"Double-pulse non-resonant laser control of coherent molecular motions in condensed media", [ORAL] **A. V. Leontyev**, V. S. Lobkov, V. G. Nikiforov, A. G. Shmelev, D. K. Zharkov; Zavoisky Physical-Technical Institute; Federal Research Center "Kazan Scientific Center of RAS", Kazan, Russia	30
18:00–18:30	"Bragg scattering from a fractured Bose-Einstein condensate", [INVITED] V. M. Porozova (1), **L. V. Gerasimov** (2), D. V. Kupriyanov (1); (1) Department of Theoretical Physics, Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia; (2) Department of Physics, M. V. Lomonosov Moscow State University, Moscow, Russia	31
18:30–19:00	"Laser additive technologies: modern achievements and further perspectives", [INVITED] A. Kh. Gilmutdinov, K. Yu. Nagulin, A. I. Gorunov, I. V. Tzivilsky, Kazan National Research Technical University named after A. N. Tupolev, Kazan, Russia	32
19:00–20:00	**Poster Session**	

26 April 2018 (Thursday)

Time	Event / Title of the talk	Page
	Session IX Chair: Alexey Kalachev, Kazan, Russia	
09:00–09:45	"Photonic delay dynamics emulating spatio-temporal networks: From chimera states to photonic artificial intelligence", [PLENARY] **L. Larger** (1), M. Jacquot (1), Y. Maistrenko (1, 2), Y. K. Chembo (1, 3), and D. Brunner (1); (1) FEMTO-ST Institute, CNRS & Université Bourgogne Franche-Comté, Besançon, France; (2) Institute of Mathematics, Center for Medical and Biotechnical Research, NAS of Ukraine, Kyiv, Ukraine; (3) GeorgiaTech-CNRS, Mirror UMI location, Atlanta GA, USA	44
	Session X Chair: Sergei Moiseev, Kazan, Russia	
09:45–10:15	"Synthetic nonabelian gauge fields in integrated photonic waveguides", [INVITED] Lucas Teuber, Mark Kremer, Alexander Szameit, and **Stefan Scheel**; University of Rostock, Institute of Physics, Rostock, Germany	45
10:15–10:45	"High dimensional frequency bin entanglement applications", [INVITED] **J.-M. Merolla** (1), B. Galmez (1), Y. Chembo (2, 1); (1) FEMTO-ST institute, CNRS & Université Bourgogne Franche-Comté, Besançon cedex, France; (2) GeorgiaTech-CNRS Joint International Laboratory, Atlanta Mirror Site School of Electrical and Computer Engineering, Atlanta, USA	46
10:45–11:00	"Various applications for ultracold ions: quantum logic, optical and radio frequency clocks", [ORAL] **I. Semerikov** (1, 2), I. Zalivako (1, 2), A. Borisenko (1, 2), V. Sorokin (1, 2), K. Khabarova (1, 2), N. Kolachevsky (1, 2); (1) P. N. Lebedev Physical Institute, Moscow, Russia; (2) Russian Quantum Center, Skolkovo, Moscow, Russia	47
11:00–11:30	**Coffee**	
	Session XI Chair: Igor Ryabtsev, Novosibirsk, Russia	
11:30–12:00	"Recent advances in high-precision optical clocks based on ultracold atoms and ions," [INVITED] S. N. Bagayev, **A. V. Taichenachev**, Institute of Laser Physics SB RAS, Novosibirsk, Russia	48
12:00–12:30	"Novel applications of homodyne detection in satellite quantum communications and coherent beam combining", [INVITED] **C. R. Müller** (1, 2), K. Seshadreesan (1, 2), F. Sedlmeir (1, 2), S. Chatterjee (1, 2, 5), C. Marquardt (1, 2), G. Leuchs (1, 2, 3, 4); (1) Max Planck Institute for the Science of Light, Erlangen, Germany; (2) Department of Physics, University of Erlangen-Nuremberg, Erlangen, Germany; (3) Institute for Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia; (4) Max Planck University of Ottawa, Centre for Extreme and Quantum Photonics, Ottawa, Ontario, Canada; (5) SAOT, Erlangen Graduate School in Advanced Optical Technologies, Erlangen, Germany	49
12:30–13:00	"Efficient dissipation-enabled excitation transfer for quantum information processing", [INVITED] **Gernot Alber**, Institute of Applied Physics, Technical University of Darmstadt, Germany	50
13:30–14:30	**Lunch**	

Time	Event / Title of the talk	Page
	Session XII Chair: Andrea Alberti, Bonn, Germany	
14:30–15:00	"Towards triplet generation using engineered optical fibers", [INVITED] **N. Joly**, J. Hammer, A. Cavanna, X. Jiang, M. Chekhova, Max Planck Institute for the Science of Light, Erlangen, Germany	51
15:00–15:30	"What is quantum?", [INVITED] **Gerd Leuchs**, Max Planck Institute for the Science of Light, Erlangen, Germany	52
15:30–16:00	"Hybrid atomic-photonics: New paradigm for integrated quantum optics", [INVITED] **Hadiseh Alaeian**, 5. Physikalisches Institut, Universität Stuttgart, Stuttgart, Germany	53
16:30–17:00	**Coffee**	
	Session XIII Chair: Christian Müller, Erlangen, Germany	
17:00–17:30	"Towards off-resonant Raman quantum memory in an isotopically pure rare-earth-ion doped crystals", [INVITED] R. A. Akhmedzhanov (1, 2), L. A. Gushchin (1, 2), S. L. Korableva (3), N. A. Nizov (1), V. A. Nizov (1), D. A. Sobgayda (1, 2), I. V. Zelensky (1, 2), **A. A. Kalachev** (2); (1) Institute of Applied Physics of the Russian Academy of Science, Nizhny Novgorod, Russia; (2) Zavoisky Physical-Technical Institute, Federal Research Center "Kazan Scientific Center of RAS", Kazan, Russia, (3) Kazan Federal University, Russia	54
17:30–17:45	"Magic wavelength for 1.14 mkm clock transition in Thulium", [ORAL] **E. Kalganova** (1, 2), A. Golovizin (1, 2), D. Tregubov (1, 2), D. Shevnin (1), V. Bushmakin (1), D. Sukachev (1, 2, 3), K. Khabarova (1, 2), V. Sorokin (1, 2), N. Kolachevsky (1, 2); (1) P. N. Lebedev Physical Institute, Moscow, Russia; (2) Russian Quantum Center, Skolkovo, Moscow, Russia; (3) Harvard University, Dept. of Physics, Cambridge, Massachusetts, USA	55
17:45–18:00	"A new technique for ghost imaging: ghost photoanisotropic objects imaging", [ORAL] A. S. Chirkin, **S. A. Magnitskiy**, P. P. Gostev, M. V. Lomonosov Moscow State University, Moscow, Russia	56
18:00–18:15	"Squeezed vacuum from a whispering gallery mode resonator", [ORAL] A. Otterpohl (1, 2), **F. Sedlmeir** (1, 2), G. Schunk (1, 2), T. Dirmeier (1, 2), G. Shafiee (1, 2), U. Vogl (1, 2), D. Strekalov (1, 2), T. Gehring (3), H. G. L. Schwefel (4), U. L. Andersen (3), G. Leuchs (1, 2), and Ch. Marquardt (1, 2); (1) Max Planck Institute for the Science of Light, Erlangen, Germany; (2) Department of Physics, University of Erlangen-Nuremberg, Erlangen, Germany; (3) Department of Physics, Technical University of Denmark, Lyngby, Denmark; (4) The Dodd-Walls Centre for Photonic and Quantum Technologies, Department of Physics, University of Otago, Dunedin, New Zealand	57
18:15–18:30	"Spatially distributed genuine multipartite entanglement enables EPR steering of Bose-Einstein condensates", [ORAL] **P. Kunkel**, M. Prüfer, H. Strobel, D. Linnemann, A. Frölian, T. Gasenzer, M. Gärttner, M. K. Oberthaler, Kirchhoff-Institut für Physik, Heidelberg, Germany	58
18:30–18:45	"Wide-tunable OPO laser on new nonlinear structures", [ORAL] **D. B. Kolker**, Institute of Laser Physics SB RAS, Novosibirsk, Russia	59
18:45–19:00	"High-resolution spectroscopy of cold Mg atoms", [ORAL] **A. N. Goncharov**, Institute of Laser Physics SB RAS, Novosibirsk, Russia	60
19:00–19:15	**Closing remarks**	

ABSTRACTS

Rabi oscillations of x-ray radiation between two nuclear ensembles

Adriana Pálffy
Max-Planck-Institut für Kernphysik, Heidelberg, Germany
email: palffy@mpi-hd.mpg.de

The realization of the strong coupling regime between a single cavity mode and an electromagnetic resonance is one of the centerpieces of quantum optics. In this regime, the reversible exchange of a photon between the two components of the system leads to so-called Rabi oscillations [1]. Strong coupling is used in the optical and infrared regimes to produce non-classical states of light, enhance optical nonlinearities, and control quantum states for computing purposes.

Here, we report from the theory side on the first observation of Rabi oscillations of an x-ray photon between two resonant ^{57}Fe-layers embedded in two coupled cavities [2]. The theoretical predictions for the observed oscillation are based on an effective Hamiltonian for the system, in which the two layers couple strongly. A sinusoidal beating in the system's temporal evolution as signature of the Rabi oscillations, as well as the splitting of the nuclear resonances in the reflected light spectrum have been confirmed by experiment. These observations significantly advance the development of the new field of x-ray quantum optics [3].

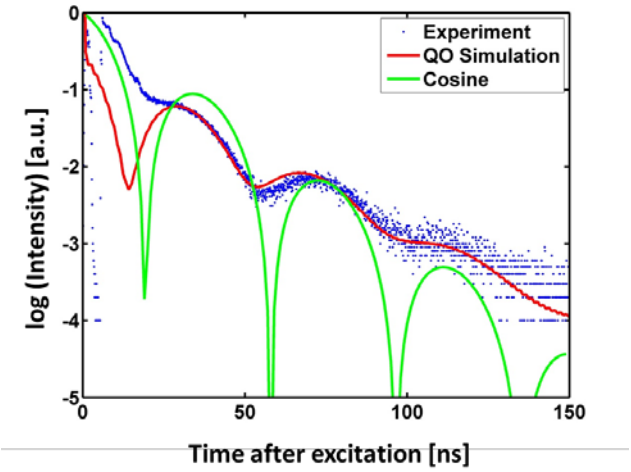


Figure 1: Temporal response of the sample with two resonant ^{57}Fe-layers, displaying clearly visible Rabi oscillations [2]. The theoretical curves are a Fourier transform of the energy-resolved reflectivity, and an exponentially damped cosine whose period is the Rabi frequency, respectively.

References:

[1] M. Brune *et al.*, Phys. Rev. Lett. 76, 1800 (1996).
[2] J. Haber *et al.*, Nature Photonics 11, 720 (2017).
[3] B. W. Adams *et al.*, J. Mod. Opt. **60**, 2 (2013)

Fiber-optic quantum thermometry

I.V. Fedotov,[1,2,3] A.A. Lanin,[1,2,3] Y.G. Ermakova,[4,5] E.E. Serebryannikov,[1,2,3] S. Blakley,[6] D.A. Sidorov-Biryukov,[1,2,3] D.S. Bilan,[4,5] I.V. Kelmanson,[4] A.B. Fedotov,[1,2,3] S.Ya.Kilin,[7] K. Sakoda,[8] P. Hemmer,[6,9] A.A. Talipov[3], I.Z. Latypov,[3,9] A.G. Shmelev, [3,9] M.A.Smirnov[3], K.V. Petrovnin,[3] V.V.Belousov,[4,5] S.A. Moiseev[3,9] and A.M. Zheltikov[1,2,3,6,11]

[1] Physics Department, International Laser Center, M.V. Lomonosov Moscow State Univ., Moscow 119992, Russia
[2] Russian Quantum Center, ul. Novaya 100, Skolkovo, Moscow Region, 143025 Russia
[3] Kazan Quantum Center, Kazan National Research Technical Univ. n.a. A.N.Tupolev-KAI, 10 K. Marx, Kazan 420111, Russia
[4] Shemyakin and Ovchinnikov Institute of Bioorganic Chemistry, Russian Academy of Sciences, Moscow 117997, Russia
[5] Pirogov Russian National Research Medical University, Moscow 117997, Russia.
[6] Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA
[7] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
[8] National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan
[9] Kazan E.K. Zavoisky Physical-Technical Institute of the Russian Academy of Sciences, 10/7 Sibirsky Tract, Kazan 420029, Russia
[10] Princeton University, Princeton, NJ, 08544-5263 USA
[11] Kurchatov Institute National Research Center, pl. akad. Kurchatova 1, Moscow 123182, Russia

Integration of nitrogen–vacancy diamond photonics with advanced fiber-optic technologies provides a versatile fiber-optic platform for quantum temperature sensing, offering unique solutions for biophotonics and neuroscience.

Transporting neutral atoms in optical lattices at the quantum speed limit

Manolo R. Lam[1], Natalie Thau[1], Thorsten Groh[1], Carsten Robens[1], Wolfgang Alt[1], Dieter Meschede[1], Antonio Negretti[2], Tommaso Calarco[3], Andrea Alberti[1]

alberti@iap.uni-bonn.de

[1] *Institut für Angewandte Physik, Wegelerstr. 8, 53115 Bonn, Germany*
[2] *Zentrum für Optische Quantentechnologien, Luruper Chaussee 149, 22761 Hamburg, Germany*
[3] *University of Ulm and Center for Integrated Quantum Science and Technology (IQST), Germany*

State-dependent transport of neutral atoms in optical lattices is essential for quantum information processing schemes based on controlled cold collisions, where distant atoms are brought into contact to acquire conditional phase shifts. State-dependent transport operations also play a fundamental role to realize discrete-time quantum walks. Implementing fast, robust transport operations allows us to outrun decoherence, thereby boosting the number of operations realizable within the coherence time.

I will report on experiments demonstrating fast, optimal-control-based state-dependent transport of neutral atoms: Atoms in two possible internal states are transported, depending on their internal state, by an integer number of lattice sites without creating additional motional excitations at the end of the transport operation. For this purpose, we use polarization-synthesized optical lattices [1, 2]—a novel implementation of state-dependent periodic potentials— which allow us to modulate rapidly in time both position and depth of each individual lattice potential for both spin-up and spin-down internal states. During transport, several motional excitations are created in our (anharmonic) optical potentials and, yet, these excitations are fully refocused to the motional ground state once the atom has reached the arrival point.

The time-energy uncertainty relation, however, sets a fundamental limit on how fast atoms can be transported from one lattice site to the adjacent one. By using optimal control theory, we experimentally demonstrate we can operate high-fidelity spin-dependent transport of atoms at the quantum speed limit. This application allows us to mimic atom tunnelling on the time scale of 10 μs, which is orders of magnitude shorter than the typical time necessary for true tunnelling through the optical-lattice potential.

[1] C. Robens, J. Zopes, W. Alt, S. Brakhane, D. Meschede, and A. Alberti, "Low-Entropy States of Neutral Atoms in Polarization-Synthesized Optical Lattices," Phys. Rev. Lett. **118**, 065302 (2017).

[2] C. Robens, S. Brakhane, W. Alt, D. Meschede, J. Zopes, and A. Alberti, "Fast, High-Precision Optical Polarization Synthesizer for Ultracold-Atom Experiments," Phys. Rev. Applied **9**, 034016 (2018).

Atomic clocks based on coherent population trapping resonances in alkali atom vapors

S.M. Ignatovich [1], M.N. Skvortsov [1], V.I. Vishnyakov [1],
N.L. Kvashnin [1], V.A. Vasiliev [1] , S.N. Atutov [1,2],
D.V. Brazhnikov [1,3], V.I. Yudin [1,3,4] , A.V. Taichenachev [1,3] and S.N. Bagayev [1,3]

[1] *Institute of Laser Physics SB RAS, Novosibirsk, Russia*
[2] *Institute of Automation and Electrometry SB RAS, Novosibirsk, Russia*
[3] *Novosibirsk State University, Novosibirsk, Russia*
[4] *Novosibirsk State Technical University, Novosibirsk, Russia*

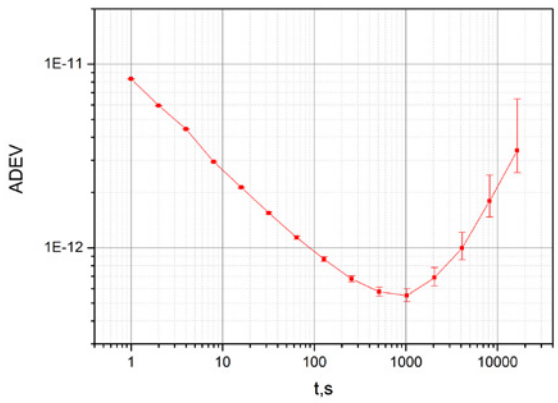
The most promising technology for building of miniature radiofrequencies clocks for mobile applications involves approach based on the coherent populations trapping (CPT) phenomenon. Due to full optical scheme of clock and modern light sources CPT can combine such features as small sizes, low power consumption, high frequency stability. Here we present the recent progress of development a CPT atomic clocks based on VCSEL laser stabilized for Cs resonances. We achieve short term instability 8×10^{-12} at 1 s and long term $5{,}5\times10^{-13}$ at 1000 s, with sizes physical package <50 mm^3, and power consumption <1 W.

The setup was based on self-made glass spherical Cs cell with 5mm diameter and 100 Torr neon buffer gas inside. Cell was assembled between Helmholts coils that applied a longitudinal magnetic field on the order of 10 μT to lift the Zeeman energy levels' degeneracy and to separate the "clock" resonance. The cell was surrounded by a magnetic shield from permalloy metal.

For observing of resonance we apply VCSEL laser with wavelength 894 nm corresponding D1 absorption line of Cs. Bichromatic scheme of pump of cesium energy levels was done with microwave modulation of laser current at the frequency 4,5 GHz. For better resonance contrast optical scheme with circular polarization was used. For that a quarter-wave plate was mounted in front of the Cs cell.

We analyzed width and contrast of resonance in dependence from optical power. Best signal noise ratio was observed with power of optical pump equal 10 uW, where width of resonance was 2,6 kHz and contrast ~1%. The absorption contrast is defined as the ratio of the change in light absorption due to the CPT resonance to the absorption off CPT resonance. Also was measured main shifts of CPT resonance: intensity shift, shift from cell temperature, magnetic field shift.

Observed instability in optimal regime is shown at Pic.1



Pic. 1. Allan deviation of CPT clock at Cs D_1 line.

Many-body interactions of cold Rydberg atoms and quantum information

I.I.Ryabtsev[1,2], I.I.Beterov[1,2], D.B.Tretyakov[1,2], E.A.Yakshina[1,2], V.M.Entin[1,2], P.Cheinet[3], P.Pillet[3]

[1]*Rzhanov Institute of Semiconductor Physics SB RAS, 630090 Novosibirsk, Russia*
[2]*Novosibirsk State University, 630090 Novosibirsk, Russia*
[3]*Laboratoire Aime Cotton, CNRS, Univ. Paris-Sud, ENS Paris-Saclay, 91405 Orsay, France*

Strong long-range interactions between highly excited Rydberg atoms form the basis for quantum information processing with neutral trapped atoms [1]. Entangled states can be generated using a temporary excitation of ground-state atoms to a strongly interacting Rydberg state. In this report we will present our related experimental results on long-range many-body interactions between cold Rb Rydberg atoms in a magneto-optical trap, as well as our theoretical results on quantum information processing with Rydberg atoms.

In the experiments with cold Rb atoms we have observed for the first time a resonant dipole-dipole interaction (Stark-tuned Förster resonance) between two cold Rb Rydberg atoms confined to a small laser excitation volume [2]. We also observed radio-frequency-assisted Förster resonances in a few cold Rb Rydberg atoms which cannot be tuned by dc electric field [3,4]. They imply an efficient transition from van der Waals to resonant dipole-dipole interaction due to Floquet sidebands of Rydberg levels appearing in the rf-field. This method can be applied to enhance the interactions of almost arbitrary Rydberg atoms with large principal quantum numbers. Some exotic quantum simulations demand to control the interactions of simultaneously three atoms. Three-body Förster resonances at long-range interactions of Rydberg atoms were first predicted and observed in Cs Rydberg atoms [5]. In these resonances, one of the atoms carries away an energy excess preventing the two-body resonance, leading thus to a Borromean type of Förster energy transfer. We have recently observed the three-body Förster resonances for a few Rb Rydberg atoms [6]. As the observed three-body resonances appear at the different dc electric field with respect to the two-body resonance, they represents an effective three-body operator, which can be used to directly control the three-body interactions in quantum simulations and three-qubit quantum gates with Rydberg atoms.

We also proposed theoretically a novel scheme of deterministic single-atom excitation in mesoscopic ensembles based on the adiabatic passage and Rydberg blockade [7], developed schemes of quantum gates with mesoscopic ensembles containing random number of atoms [8-10], tomography of quantum gates based on Rydberg atoms [11] and schemes of quantum gates based on the adiabatic passage of the Stark-tuned Forster resonances [12,13].

This work was supported by the RFBR Grants No. 16-02-00383 and 17-02-00987, the Russian Science Foundation Grants No. 16-12-00028 (for laser excitation of Rydberg states) and 18-12-00313 (for theoretical analysis), the Siberian Branch of RAS, the Novosibirsk State University, the public Grant CYRAQS from Labex PALM (ANR-10-LABX-0039) and the EU H2020 FET Proactive project RySQ (Grant No. 640378).

[1] I.I.Ryabtsev et al., Physics − Uspekhi **59**, 196 (2016).
[2] I.I.Ryabtsev et al., Phys. Rev. Lett., **104**, 073003 (2010).
[3] D.B.Tretyakov et al., Phys. Rev. A **90**, 041403(R) (2014).
[4] E.A.Yakshina et al., Phys. Rev. A **94**, 043417 (2016).
[5] R.Faoro et al., Nature Comm. **6**, 8173 (2015).
[6] D.B.Tretyakov et al., Phys. Rev. Lett. **119**, 173402 (2017).
[7] I.I.Beterov et al., Phys. Rev. A **84**, 023413 (2011).
[8] I.I.Beterov et al., Phys. Rev. A **88**, 010303(R) (2013).
[9] I.I.Beterov et al., Laser Physics **24**, 074013 (2014).
[10] I.I.Beterov et al., Quantum Electronics **47** (5) 455 (2017)
[11] I.I.Beterov et al., J. Phys. B **49**, 114007 (2016)
[12] I.I.Beterov et al., Phys. Rev. A **94**, 062307 (2016).
[13] I.I.Beterov et al., Phys. Rev. A **97**, 032701 (2018).

Photon echo quantum memory in optical and microwave resonators

S.A.Moiseev [1)] K.I.Gerasimov [1)], R.R.Latypov[2)], M.M.Minnegaliev [1)], E.S.Moiseev [2)], N.S.Perminov[3)], K.V.Petrovnin [2)], R.V.Urmancheev[1)], O.N.Sherstukov[2)]

[1)] Kazan Quantum Center, Kazan National Research Technical University n.a. A.N.Tupolev-KAI, 10 K. Marx, Kazan,420111, Russia.

[2)] Kazan Federal University, 18 Kremlyovskaya Str., Kazan, 420008, Russia.

[3)] Zavoisky Physical-Technical Institute, Federal Research Center "Kazan Scientific Center of RAS"

e-mail: s.a.moiseev@kazanqc.org

The photon echo approach provides a quite rich possibilities for experimental implementation of quantum storage of multi-qubit light fields. Herein, the promising technological facilities are opened for the impedance matched resonator schemes of the photon echo quantum memory. In this report, we discuss such schemes in optical and microwave spectral ranges and we show that multi-resonator schemes can be especially effective for the storage of broadband light fields in free space and QED cavity schemes. Our first experiments have been performed at room temperature for the storage of weak microwave pulses in two multi-resonator schemes with largest quantum efficiency of 0.165. Our analysis shows that the quantum efficiency of such scheme can be considerably increased by using high-quality superconducting resonators. Moreover, we have found that the efficiency can reach 0.999 if negative effects of spectral dispersion will be highly suppressed by using optimal spectral parameters of the resonators (its frequencies and coupling constants with common waveguide resonator). The studied schemes are finally discussed for the multi-qubit quantum memory of superconducting quantum computer.

Developing narrowband heralded single-photon sources based on spontaneous parametric down-conversion

D.A. Turaikhanov, D.O. Akatiev, I.Z. Latypov, A.V. Shkalikov, A.A. Kalachev
Zavoisky Physical-Technical Institute,
Federal Research Center "Kazan Scientific Center of RAS", Kazan, Russia
e-mail: bibidey@mail.ru

Sources of narrow-band single- and two-photon states are important elements of devices designed for optical quantum computing and quantum communications [1]. In particular, single-photon wave packets with a spectral width ranging from several MHz to several GHz can efficiently interact with atoms and atomic ensembles and, therefore, form a basis for implementing various quantum data processing protocols using quantum memory [2].

In this presentation, we discuss our recent experimental results devoted to implementing narrowband heralded single-photon sources based on spontaneous parametric down-conversion (SPDC). In particular, backward-wave SPDC regime in a nonlinear periodically poled KTP waveguide was observed [3] demonstrating narrowing of the emission spectrum in the backward-wave SPDC regime in comparison with the usual SPDC regime by about an order of magnitude. In addition, we report on the realization of a tunable single-photon source compatible with quantum memories based on isotopically pure crystals doped with Nd^{3+} ions, which is based on the cavity-assisted SPDC in a PPLN crystal [4]. Finally, experiments on developing narrowband heralded sources of single-photon states with a controllable orbital angular momentum are discussed.

[1] M.D. Eisaman, et al. // Rev. Sci. Instrum., 82, 071101 (2011)
[2] N. Sangouard, et al. // Rev. Mod. Phys., 83, 33 (2011)
[3] I.Z. Latypov, et al. // Quantum Electronics 47, 827 (2017)
[4] D. Akatiev, et al. // EPJ Web of Conferences // 161, 02026 (2017)

Electron acceleration, gamma emission & nuclear reactions using dense relativistic laser plasma

I.Tsymbalov[1,2], S.Shulyapov[1], I.Mordvincev[1,3], K.Ivanov[1,3], D.Gorlova[1,2], G.Gospodinov[1], V.Prokudin[1], R.Volkov[1], A.Brantov[3], V.Bychenkov[3], V.Nedorezov[2], A.Savel'ev[1]

[1]*Faculty of Physics & International Laser Centre, Lomonosov Moscow State University, Moscow, Russia*

[2]*Institute for Nuclear Research RAS, Moscow Russia*

[3]*Lebedev Physical Institute RAS, Moscow, Russia*

abst@physics.msu.ru

Experimental & numerical studies of interaction of femtosecond laser radiation with intensity up to $5x10^{18}$ W/cm^2 with dense plasma, conducted recently using terawatt femtosecond laser facility at MSU, are presented. Main stress was on the control of plasma parameters (luminosity in X-ray and gamma ranges, generation of bunches of relativistic electrons and fast multicharged ions) and their optimization by choosing interaction regime and preplasma parameters. The latter is unavoidable due to action of prepulses with different intensity and duration always pertaining in the temporal structure of a powerful femtosecond pulse. That is why we are paying a lot attention to the contrast of the laser pulse at nano- and picosecond scales.

The preplasma extent was controlled by changing time delay between the pulses and energy density of the nanosecond pulse. Experimental techniques included hard x-ray and gamma-ray measurements, direct detection of accelerated electrons, as well as angularly resolved second and three halves harmonic spectra measurements. We also used plasma shadowgraphy and interferometry to access plasma parameters before and at the instant of the femtosecond pulse action.

We studied two specific set of parameters then electron heating is very efficient and gamma quanta as high as 7-10 MeV appeared at intensity of 2000 PW/cm2. A substantial increase both in gamma yield and "temperature" were obtained by the proper adjustment of the time delay between the two pulses (0-5 ns), while gamma yield dropped to almost zero values if the nanosecond pulse came 10-20 ns in advance of the femtosecond one. Comprehensive optical diagnostics (shadowgraphy, interferometry, angular resolved self-emission measurements) data allowed us to estimate the electron density profile. The latter profile was used for making numerical Particle-in-cell simulations which describe the gamma yield enhancement well. We also illustrate how the observed drop in gamma yield within a certain range of delays was due to ionization defocusing of the femtosecond beam in an expanding longscale ($L/\lambda>1$) preplasma.

For clarification of the electron acceleration mechanisms numerical simulations were done using fully relativistic 3D3V PIC code for laser-plasma interaction and electron acceleration. Parameters of nanosecond and femtosecond laser pulses coincided with the experimental ones.

We also considered photo induced near threshold nuclear reactions induced by corpuscular emission of laser produced plasma as a diagnostic tool for high energy particles and photons. While for a single particle detection plenty of methods were developed in nuclear physics, laser produced plasma demands new approaches as it emits huge amount of particle in a time much less than the temporal response of standard nuclear techniques.

"Low" threshold gamma-D and gamma-Be photonuclear reactions were studied experimentally. We also consider gamma-gamma reactions (long-lived isomer production) for plasma diagnostics. We present numerical simulations using GEANT 4.0 package supporting our estimates and experimental data.

It is worth mention that our research is relevant to laser-plasma interaction at higher intensities, since the pulse contrast is naturally limited by ASE, prepulses, or parametric luminescence, etc. Our findings may pave the way to further optimization of high energy particle sources based on extremely intense laser plasma interaction.

Nuclear measurements were supported by RSF grant# 16-12-10039, long scale laser- plasma interaction study is supported by RFBR (grants#16-02-00263, 16-02-00213, 18-32-00416, 18-32-00868. Computer simulations were done using Lomonosov supercomputer of Moscow State University

Shaping the spectra of short x-ray pulses by mechanical means

Jörg Evers

Max Planck Institute for Nuclear Physics, Heidelberg, Germany
email: joerg.evers@mpi-hd.mpg.de

Ideas from quantum optics based on coherence and interference play an important role in studying, controlling, and utilizing quantum dynamics. Recent improvements in existing and upcoming x-ray light sources prompt the question, whether such techniques could also be applied in the hard x-ray regime [1]. This would not only be essential for fully exploiting the potential of these machines, but could also pave the way for new applications. In turn, x-ray quantum optics could also evolve into a promising platform for the study of light-matter interactions.

One particular branch is the interaction of x-rays with large ensembles of Mössbauer nuclei. These nuclei feature resonances with exceptionally narrow linewidth, and form the basis for a broad range of applications in the natural sciences.

However, the spectra of short x-ray pulses delivered by state-of-the-art sources are orders of magnitude broader in energy than the narrow resonances. Thus, only a tiny fraction of the photons interact resonantly with the sample, while the vast majority of photons form an off-resonant background. In this talk, I will show how the precisely controlled mechanical motion of a resonant target can be used to shape the spectrum of a given x-ray pulse, such that the number of resonant photons in the pulse is significantly increased [2]. This increased intensity results in shorter measurement times, and enables measurements with presently too low signal rates.

Next, I will show how mechanical motions of a suitable target allow for the generation of tunable phase-coherent x-ray double-pulse sequences, and demonstrate that these double-pulses can be used to coherently control excitons in large ensembles of atomic nuclei in a pump-probe setting. In a proof-of-principle experiment, we find clear signatures of basic light-matter interactions such as stimulated emission and absorption between the nuclei and the x-rays [3].

[1] B. W. Adams, C. Buth, S. M. Cavaletto, J. Evers, Z. Harman, C. H. Keitel, A. Pálffy, A. Picon, R. Röhlsberger, Y. Rostovtsev, K. Tamasaku, *X-Ray Quantum Optics,* J. Mod. Opt. 60, 2 (2013)

[2] K. P. Heeg, A. Kaldun, C. Strohm, P. Reiser, C. Ott, R. Subramanian, D. Lentrodt, J. Haber, H.-C. Wille, S. Goerttler, R. Rüffer, C. H. Keitel, R. Röhlsberger, T. Pfeifer, J. Evers, *Spectral narrowing of x-ray pulses for precision spectroscopy with nuclear resonances,* Science 357, 375 (2017)

[3] K. P. Heeg et al., in preparation

Laser Spectroscopy at Storage Rings and Accelerator Facilities

Thomas Walther for the Laser Cooling and Radris Collaborations
TU Darmstadt, Institute for Applied Physics, 64289 Darmstadt

In this contribution we report on recent progress of our laser spectroscopic experiments at GSI/FAIR.

The first experiment is related to laser cooling of highly relativistic ion beams. The goal is to produce beams with a narrow momentum distribution for high luminosity collision experiments and high precision laser spectroscopy. Laser cooling shows several advantages over other cooling techniques such as electron cooling. Specifically, for high ion energies electron cooling becomes significantly more difficult and challenging. This is of particular relevance as the construction of FAIR is on its way. We will discuss the similarities and differences to Doppler cooling for cold atom physics and analyse first cooling results. Finally, we will detail the laser systems we have specifically developed for this experiment. They are fiber amplifier based cw and pulsed laser systems frequency converted into the UV spectral range. Since the latter are to be used in a technique referred to as white light cooling, the pulsed systems are designed to be flexible in terms of repetition rate, pulse duration and spectral width. Finally, an overview over the planned cooling facilities at FAIR is given.

During the second part of the talk, we will report on our laser spectroscopic investigations of transfermium elements. Laser spectroscopy is a versatile tool to unveil fundamental atomic properties of an element and information on the atomic nucleus. The heaviest elements are of particular interest as their electron shell is strongly influenced by electron-electron correlations and relativity changing the electron configuration and consequently the chemical behavior. The elements beyond fermium (Z>100) are accessible in fusion evaporation reactions at minute quantities and at high energies, hampering so far their optical spectroscopy. Only recently, we were able to identify optical transitions in nobelium (Z=102) in an experiment employing the so-called **RA**diation **D**etected **R**esonance **I**onization **S**pectroscopy (RADRIS) technique. With this technique a first identification and characterization of a strong $^{1}S_0 \rightarrow {}^{1}P_1$ ground state transition in nobelium was possible. The resonances for the isotopes $^{252\text{-}254}$No were measured as well as the hyperfine splitting in ^{253}No. In combination with atomic calculations, we determined the evolution of the deformation of the nobelium isotopes in the vicinity of the deformed shell closure at neutron number N=152 and extracted the magnetic moment and the spectroscopic quadrupole moment of ^{253}No. We will discuss the technique, present some of our spectroscopic results and will discuss the next steps, i.e. the extension of the RADRIS method to more exotic nobelium isotopes and to the next heavier element lawrencium (Z=103) as well as developments for higher resolution spectroscopy.

Measuring the temperature and heating rate of a single ion by high resolution imaging

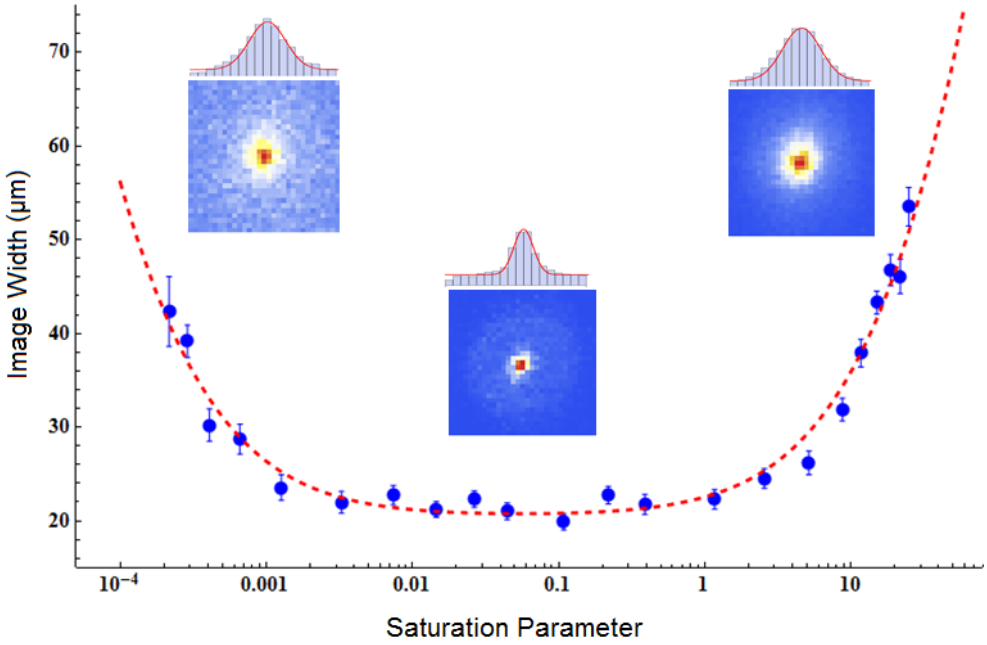
Bharath Srivathsan[1], Martin Fischer[1,2], Lucas Alber[1,2], Markus Weber[1], Markus Sondermann[1,2], and Gerd Leuchs[1,2,3]

[1]Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, DE.
[2]Friedrich-Alexander-Universitat Erlangen-Nurnberg, Department of Physics, Staudtstr. 7/B2, 91058 Erlangen, DE.
[3]Department of Physics, University of Ottawa, 25 Templeton Street, Ottawa, Ontario K1N 6N5, CA

Free space approach to interaction between light and a single atom relies on tightly focusing the light onto the atom [1]. In such experiments the temperature of the atom gets particularly important when the focal intensity distribution is comparable in width to the spatial wavefunction spread of the trapped atom [2]. In order to quantify the best achievable coupling, it becomes necessary to measure the absolute temperature of the atom. On the other hand, in experiments with trapped ions, another important thermometric figure of merit, in addition to absolute temperature is its heating rate. Over the years, several experiments to measure heating rates have been performed to better understand the origins of anomalous heating [3].

Here, we present a technique based on high resolution imaging to measure the absolute temperature, and the heating rate of a single ion trapped at the focus of a deep parabolic mirror. We collect the fluorescence light scattered by the ion during laser cooling, and image it onto an electron-multiplying charge-coupled device (EMCCD) camera. The image recorded on the camera is a convolution of the point-spread function (PSF) of the imaging system, and the spatial probability distribution of the ion. Accounting for the width of the PSF and the magnification of the imaging system, we determine the spatial extant of the ion, from which we infer the mean phonon occupation number in the trap.

Further, we perform similar measurements by varying the power or the detuning of the cooling laser. We determine the heating rate by a fit to a well-known theoretical model for laser cooling in a harmonic trap [4]. In other established schemes [5] for measuring the heating rate, the ion is initially heated up to temperatures a few orders of magnitude above the Doppler limit. In contrast, we measure the heating rate with the ion always maintained in a state of thermal equilibrium, at temperatures close to the Doppler limit.



[1] M. Sondermann, et.al. Applied Physics B, 89 (4), 489-492 (2007)
[2] M. Fischer, et.al. Applied Physics B 123, 48 (2017).
[3] M. Brownnutt, et.al. Rev. Mod. Phys. 87, 1419 (2015).
[4] S. Stenholm Rev. Mod. Phys. 58, 699 (1986).
[5] J. H. Wesenberg, et.al. Phys. Rev. A 76,053416 (2007).

Planar plasmon optics and its applications

V.I. Balykin, P.N. Melentiev
Institute of Spectroscopy, Troitsk, Moscow, Russia

The key advantage of plasmonics is in pushing our control of light down to the nanoscale. It is possible to envision lithographically fabricated plasmonic devices for future quantum information processing or cryptography at the nanoscale in two dimensions. Here we demonstrate the development of the basic elements of planar plasmonic optics: plasmonic optics media, focusing and reflecting plasmonic elements, plasmonic interferometer, plasmonic autocorrelator and planar plasmonic quantum generator.

Dressed atom picture for quantum plasmonics

G. Colas des Francs
ICB, CNRS/Univ. Bourgogne Franche Comté, Dijon, France

E-mail address: gerard.colas-des-francs@u-bourgogne.fr

Optical microcavities can store light for a long time allowing efficient light-matter interaction with important applications in quantum technologies, lowthreshold laser, supercontinuum laser or indistinguishable single photon source. Light-matter interaction is generally quantified thanks to the Purcell factor Q/V where Q and V refers to the quality factor and mode volume of the cavity, respectively. Cavity quantum electrodynamics (cQED) relies on the extremely high quality factor but at the price of diffraction limited sizes. That is why strong efforts have be done since a decade to transpose cQED concepts to nanophotonics and plasmonics [1]. Particular attention has been devoted to the strong coupling regime [2-6] since it offers the possibility of a control dynamics of the light emission, as e.g. photon blockade or coherent control.

One particular difficulty in extending Purcell factor to plasmonics originates from plasmon leakages so that no simple definition of the mode volume appears although their near-field subwavelength confinement. In this work, we first discuss the definition of the plasmonic Purcell factor based on classical considerations (dipolar emission in plasmon) for both propagating (SPP) and localized (LSP) surface plasmon polaritons [7]. We specifically investigate the role the leakages in the emitter-plasmon coupling process and some alternative definition for characterizing their subwavelength confinement.

We then consider quantum approach and derive an effective hamiltonian [6,7], defined in the Jaynes Cummings model, which allows us to describe the metallic nanoparticle-emitter interaction in full analogy with cQED formalism. This fully transposes cQED concepts to nanophotonics although relying on a different strategy to enhance light-matter interaction, namely confining the mode volume instead of increasing the duration of interaction. We notably show that the coupled plasmon emitter system behaves like an emitter in a multimodal lossy cavity. We explicitely discuss the mode hybridization in the dressed atom picture [8]. We also characterize the emission spectra in both the near-field and far-field zones.

Our theoretical model can be applied to study the multiple-emitters problem. In this case, the presence of each emitter induces a set of plasmonic modes. According to the orientation of the dipole moments of the emitters and their positions relative to the nano-particle, this set of modes will overlap in a constructive or destructive way leading to efficient/blockade population transferts or superradiance/subradiance effects.

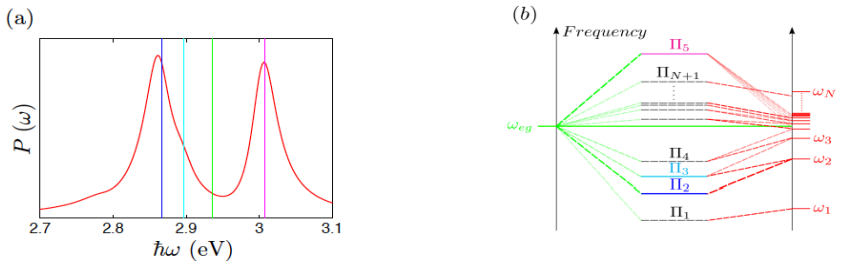


Fig. 1. Spectrum calculated for an emitter located at 2 nm from the surface of a silver nanoparticle. The vertical lines indicate the hybrid modes resulting from the strong coupling. b) Energy diagram of the plasmon dressed atomic states.

[1] M.Tame *et al*, *Quantum plasmonics*, Nature Physics 9, 329 (2013).
[2] Belessa *et al, Strong Coupling between Surface Plasmons and Excitons in an Organic Semiconductor*, Phys. Rev. Lett. **93**, 0364041 (2004)
[3] P. Lodahl *et al*, *Interfacing single photons and single quantum dots with photonic nanostructures*, Rev. Mod. Phys. **87**, 347, 2015.
[4] C. van Vlack and P. Hughes, *Spontaneous emission spectra and quantum light-matter interactions from a strongly coupled quantum dot metal-nanoparticle system,* Physical Review B 85, 075303 (2012).
[5] A. Delga *et al*, *Quantum Emitters Near a Metal Nanoparticle: Strong Coupling and Quenching,* Phys. Rev. Lett.**112**, 253601 (2014).
[6] G. Zengin *et al*, *Realizing Strong Light-Matter Interactions between Single-Nanoparticle Plasmons and Molecular Excitons at Ambient Conditions,* Phys. Rev. Lett. **114**, 157401 (2015).
[7] G. Colas des Francs *et al*, *Plasmonic Purcell factor and coupling efficiency to surface plasmons. Implications for addressing and controlling optical nanosources,* J. Opt. **18**, 094005 (2016)
[8] B. Rousseaux *et al, Adiabatic passage mediated by plasmons: A route towards a decoherence-free quantum plasmonic platform,* Phys. Rev. B **93**, 045422 (2016).
[9] D. Dzsotjan *et al, Mode-selective quantization and multimodal effective models for spherically layered systems,* Phys. Rev. A **94**, 023818 (2016).
[10] H. Varguet *et al, Dressed states of a quantum emitter strongly coupled to a metal nanoparticle,* Opt. Lett. **41**, 4480 (2016).

Quantum and Nonlinear Optics with Single Plasmonic Nanostructure

V. N. Zadkov[†], V. I. Balykin[†], P. N. Melentiev[†], Yu. V. Vladimirova[*], and Feng Song[‡]

[†]*Institute of Spectroscopy, Russian Academy of Sciences, Fizicheskaya Str. 5, Troitsk, Moscow 108840, Russia*
[*]*International Laser Center and Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia*
[‡]*Photonics Center, College of Physical Sciences, Nankai University, Tianjin 300071, P.R.China*

Nonclassical behavior of light reveals already at the single-atom-level in resonance fluorescence both as the sub-Poissonian behavior of the photon-number statistics and as the phenomenon of antibunching of scattered photons. Over few last decades, such a single-atom level of experiments for studying nonclassical light from single quantum emitters was also achieved in emerging field of nanophotonics [1], which demonstrates reliable sources of nonclassical light from single quantum emitters, including those embedded in different nanostructures. In this talk, we will explore both quantum and nonlinear optics effects that appear during interaction of a single quantum emitter with a plasmonic nanostructure (a metal nanoparticle, MNP) in an external electromagnetic field.

In the first part of our talk we will discuss effects of Quantum Optics and will first give an overview of the mechanisms of modification of the local field and radiative and nonradiative decay rates of a two-level quantum emitter located in close proximity to a plasmonic nanoparticle. Simple analytical expressions are given for both the local field enhancement, the modified total decay rate of the atom near the metal nanosphere and the frequency shift of the atomic transition. Then, we will analyze in more detail the polarization distribution at the nanoscale around the nanoparticle and show that this distribution has a complex structure, which drastically depends on the polarization of the incident laser field and on the parameters of the plasmon resonance of the nanoparticle. After that, we will describe the photon-number statistics in resonance fluorescence of a two-level quantum emitter near a metal nanosphere, driven by a laser field with finite bandwidth, as a function of atom's location around the nanoparticle, the intensity of the incident laser field, its bandwidth, detuning from the atomic resonance, and polarization . Finally, we will analyze the antibunching effect of photons from the resonance fluorescence in the system "metal nanosphere and a two-level atom" driving by the incident laser field [2].

In the second part of our talk we will discuss nonlinear optical effects of a single plasmonic nanostructure and be focused specifically on the giant optical nonlinearities of such structures. Due to a strong light absorption by metals, it is believed that plasmonic nanostructures cannot be used for generating intensive radiation harmonics in the UV spectral range, which is not correct as we proved experimentally. We present here our experimental results of investigation of the nonlinear optical interaction of laser radiation with a single gold nanostructure in the Split-Hole Resonator (SHR) geometry [3] under the-state-of-the-art experimentally realized conditions. Several multipole plasmon resonances can simultaneously be excited in the SHR nanostructure.Then, a strong nonlinear optical interaction at the frequencies of these resonances that will lead to (i) the second-harmonic generation, (ii) the third harmonic generation (THG), and (iii) light generation at the mixed frequencies. The THG nearfield amplitude reaches in experiment 0.6% of the fundamental frequency field amplitude, which enables creation of UV radiation sources with a record high intensity. The UV THG may then find many important applications including biomedical ones (such as cancer therapy).

Acknowledgements: The authors acknowledge financial support from the Russian Foundation for Basic Research (grants Nos. 16-02-00816, 18-52-53040).

References

1. S. V. Gaponenko, *Introduction to Nanophotonics* (Cambridge Univ. Press, New York, 2010).
2. Y. V. Vladimirova, V. V. Klimov, V. M. Pastukhov, and V. N. Zadkov, Phys. Rev. A **85**, 053408 (2012); E. D. Chubchev, Yu. V. Vladimirova, V. N. Zadkov, Optics Express **22**, 20432 (2014); *ibid*, Laser Phys. Lett. **12**, 015302 (2015); V. M. Pastukhov, Yu. V. Vladimirova, V. N. Zadkov, Phys. Rev. A **90**, 063831 (2014); *ibid*, submitted for publication (2017); Yu. V. Vladimirova, E. D. Chubchev, V. N. Zadkov, Laser Physics **27**, 025901 (2017); Yu. V. Vladimirova, V. N. Zadkov, European Phys. J. Web of Conf. **132**, 01003 (2017).
3. P. N. Melentiev, A E. Afanasiev, A. A. Kuzin, A. S. Baturin and V. I. Balykin, Optics Express **21**, 13896 (2013); P. N. Melentiev, A. E. Afanasiev, A. V. Tausenev, A. V. Konyaschenko, V. V. Klimov, V. I. Balykin, Laser Phys. Lett. **11**, 105301 (2014); P. N. Melentiev, A. E. Afanasiev, A. A. Kuzin, V. M. Gusev, O. N. Kompanets, R. O. Esenaliev, V. I. Balykin, Nano Lett., **16**, 1138 (2016).

Coupling nano-particles and light field by strong focusing with a deep parabolic mirror

V. Salakhutdinov*, M. Sondermann, L. Carbone, E. Giacobino, A. Bramati, G. Leuchs
Max Planck Institute for the Science of Light, Staudtstraße 2, 91058 Erlangen, Germany

We demonstrate the optical trapping of nano-emitters (CdSe/CdS 'dot-in-rod') in the focus of a deep parabolic mirror. In many cases, the fluorescence light emitted by the trapped particles exhibits $g2(0) < 0.5$, suggesting the trapping of a source of single photons [1]. However, we will argue that despite this observation more than one nano-particle is contained in the trap.

We also present an approach how to determine the orientation of nano-particles inside the trapping potential by analysing their intensity distribution pattern. Furthermore, we discuss the restrictions for trapped nano-particles to be aligned by the electric field of the dipole trap at room-temperature.

[1] V.Salakhutdinov et al., Optica, vol. 3, 11 (2017).

Laser-deposited topological nanoclusters – quantum size effects in electrophysics and optics of thin films

Alexey V. Kavokin[1)], Sergey M. Arakelian[2)], Alexey O. Kucherik[2)], Stella V. Kutrovskaya[2)], Anton V. Osipov[2)], Aleksandr V. Istratov[2)]

1)University of Southampton, England
2)Vladimir State University, Vladimir 600000, Russia
e-mail: arak@vlsu.ru

1. The physical properties of nanocluster systems are very sensitive to the form, size and distance between their composing elements. The fact is very well known for any material in general, but to change these parameters and to carry out the stable conditions for ordinary solid state object we need both to put the object under extremal high pressure ($\gtrsim 10^6$ atm) and to work in low (liquid He) temperature range ($\lesssim$30K).

In contrast, the nanocluster structures can be easily modified in necessary direction and by controllable way in the femtonanophotonics experiments. The variation of the enumerated above topology parameters can result in new type of correlation states for charged particles. Moreover, the electronic energetic bands of the materials can vary dramatically in the case resulting in new physical behavior of the system, in particular, in optical response.

In superconductor problem the question usually is how to fabricate the coupling states (around the forbidden band) at high (usually nitrogen) temperature ($\gtrsim$140 K) for charge particles being responsible for electroconductivity. Some alternative mechanisms of electron coupling for nanocluster system (not via standard phonon coupling) may be realized in principle.

2. We studied in both theory and experiment the laser-induced nanocluster structures of different types (in topology and element composition) taking into account the correlations in nanoparticle ensemble by quantum states. The problem of high temperature superconductivity due to topological surface structures with correlated states (resulting in coupled states on new dimensional principles) are under our consideration.

3. We applied several laser procedures to obtain the nanostructures and thin films with controllable topology. Namely in addition to the direct laser modification of solid surfaces, we used, first, the laser ablation of targets in liquid to obtain colloidal systems and, second, to deposit the nanoparticles from the colloid on a solid surface for formation of nanostructures in necessary way by two technique: the laser radiation action and the droplets falling from the nozzle.

4. In electrophysics experiment, we have seen competition between increase conductivity while opening new channels in a spatially inhomogeneous charged structure and increase the resistance by increasing of the areas between the conductive grains. Such electrical transport properties (due to quantum correlated states resulting in tunnel and hopping electroconductivity) may be presented as a special type of topological electrophysical surface structures (both localized and delocalized coupled states for charge carriers). Dramatic enhancement of electroconductivity (in several orders) has been observed in our experiments due to variation of topological peculiarities of a nanocluster thin film system.

As to optical properties for bimetallic (Au+Ag) films we demonstrated that it is possible to control both the plasmon resonance behavior and propagating plasmon waves due to inhomogeneous structure (being a random manifestation of special schemes for travelling waves). Absence of narrow plasmon resonance is namely due to inhomogeneous nanostructures.

In addition, we observed the formation of the artificial meso-atom nanostructures when positive nucleus being the Si-atom are covered by negative charged Au-atoms. Such objects may be presented as a shell-like dot structure, and the modelling of the unusual structures and properties has been carried out by us for different conditions.

5. Obtained results give us an opportunity to establish the basis of new physical principles to create the functional elements for optoelectronics and photonics in hybrid set-up (optics + electrophysics) by the different topology controllable nanoclusters with dramatic increase of both electroconductivity and optical response vs spatial structure of nanoclusters in thin films at room temperature.

1. Alexey V. Kavokin, Stella V. Kutrovskaya, et. al. The crossover between tunnel and hopping conductivity in granulated films of noble metals. Superlattices and Microstructures V. 111, Nov. 2017, P. 335-339.
2. Stella V. Kutrovskaya, Sergei M. Arakelian, et. al. The Synthesis of Hybrid Gold- Silicon Nano Particles in a Liquid. Scientific Reports 7: 10284 (6 pp.), Aug 2017.

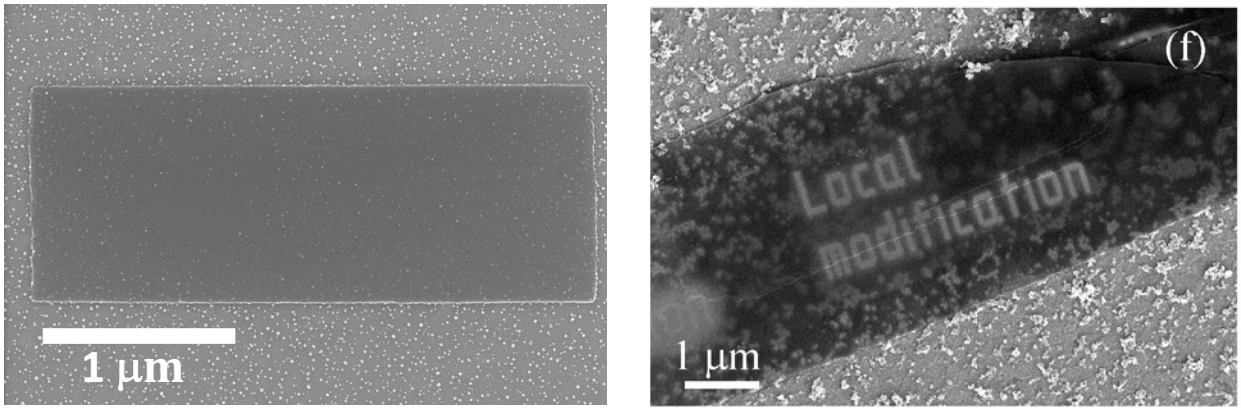
New hybrid crystalline metal-carbon flakes with unusual optical properties

Alina Manshina[1], Yuriy Petrov[2], Peter Banzer[3,4], Gerd Leuchs[3,4]

[1] *Institute of Chemistry, St. Petersburg State University, Universitetskii pr. 26, St. Petersburg, 198504, Russia*
[2] *Faculty of Physics, St. Petersburg State University, Ulianovskaya St. 1, St. Petersburg, 198504, Russia*
[3] Max-Planck Institute for the Science of Light, Staudtstr. 2, Erlangen, D-91058, Germany
[4] Department of Physics, University Erlangen-Nürnberg, Staudtstr. 7/B2, Erlangen, D-91058, Germany

The hybrid nanomaterials possess a wide spectrum of important properties that may be gained by controllably varying such parameters as their composition, structure and morphology. In addition, combining different components in the same structure and their mutual influence enables obtaining materials that exhibit not only additive properties of the components but also new ones caused by synergetic effects.

Here we present the hybrid nanomaterial never realized before – the combination of crystalline 2D carbon and incorporated bimetal Au-Ag nanoclusters. Our experiments on laser-induced synthesis demonstrate the possibility of the direct creation of 2D hybrid metal/carbon flakes in just one step. The deposited flakes were found to be atomically smooth, regularly shaped flat structures of 1-2 μm x 4-7 μm with thickness of 10 – 100 nm which consist of bimetal Au-Ag nanoclusters c.a. 3 nm in diameter distributed in crystalline carbonaceous matrix (Figure 1a). The carbonaceous matrix itself was found to be a novel carbon allotrope – hydrogenated carbon with pure sp^2 hybridization and monoclinic crystal cell.



a b

a) SEM image of the single hybrid flake, b) local modification of a nano flake with focused helium-ion beam.

We found that the hybrid flakes can be cut or/and modified by means of irradiation with a focused helium ion beam (FIB) – Fig. 1b. Thus, complex planar elements with high special resolution can be created with FIB.

The synergetic combination of crystalline carbonaceous 2D matrix with plasmonic Au-Ag nanoclusters results in unique optical properties. Examples are high birefringence of 0.102 observed under normal incidence of the light and surface-enhanced Raman effect that is promising for the detection of complex bio-toxic substances.

Acknowledgements

This research has been partially supported by the Russian Foundation of Basic Research (RFBR 17-03-01284).

Coherent spin dynamics of erbium doped crystals at sub-Kelvin temperatures

Pavel Bushev

Experimentalphysik, Universität des Saarlandes, D-66123 Saarbrücken, Germany

Rare-earth (RE) doped solids represent today one of the widely exploited materials for the modern laser and telecommunication industry. Yet, recently, they have raised a strong interest in the field of quantum information storage, signal processing and communication. The RE ions possessing a half-integer spin are also known as Kramers ions. The exclusive feature of some Kramers ions, such as Nd^{3+}, Yb^{3+}, and Er^{3+}, is the presence of optical transitions within the standard telecommunication bands, which is very attractive for quantum repeater applications. There, RE-doped crystals can be used as quantum memory elements for a long-lived storage of entangled photons.

One of the main challenge associated with using crystals doped with Kramers ions in memory applications is their quite strong unquenched electronic magnetic moment, which in the case of Er^{3+} reaches nearly 8 μB. At weak magnetic fields and conventional temperatures of T > 1.5 K, large electronic spins mediate a rapid spin– lattice relaxation process which limits the spin coherence time. Another contribution to the decoherence is caused by magnetic dipolar interactions with another electronic spins. Therefore, in order to attain long coherence time, high magnetic field up to 7 T and low temperatures of 1.5 K are used to polarize an electronic spin bath. By following this prescription the longest optical coherence time of 4.4 ms among solid-state systems has been demonstrated for 0.001% Er^{3+}:Y_2SiO_5 (Er:YSO). Also, in the very recent experiments Rančić et al demonstrated optically addressable hyperfine states of ^{167}Er:YSO with coherence time of 1.3 s.

Contrary to that, we propose to follow another strategy. The detrimental role of spin–lattice and spin–spin relaxation processes on quantum coherence can be reduced by deep freezing of RE-doped crystals down to ultra-low temperatures, i.e. T << 1K, at much weaker fields. I report on investigation of spin decoherence properties of Er doped YSO and YLF crystals at such extreme conditions. Also, I will briefly report on confocal microscopy of SiV center in diamond and implementation of optical control of its spin states also at ultra-low temperatures.

References:

N. Kukharchyk et al., New J. Phys. 20, 023044 (2018)
N. Kukharchyk et al., Opt. Lett. 43, 935 (2018)
J. Becker et al., Phys. Rev. Lett. 120, 053603 (2018)

PROBING OF LOCAL FIELDS IN SOLIDS BY FLUORESCENCE NANOSCOPY WITH SINGLE PROBE MOLECULES

A.V. Naumov[1,2], A.A. Gorshelev[1], M.G. Gladush[1,2],
J. Köhler[3,4,5], and L. Kador[3]

[1] Institute for Spectroscopy, Russian Academy of Sciences, 108840 Troitsk, Moscow, Russia
[2] Moscow State Pedagogical University, 108840 Moscow, Russia
[3] University of Bayreuth, Institute of Physics, D-95440 Bayreuth, Germany
[4] University of Bayreuth, Soft-Matter Spectroscopy, D-95440 Bayreuth, Germany
[5] Bavarian Polymer Institute, D-95440 Bayreuth, Germany

We introduce a novel experimental approach for mapping effective local values of dielectric characteristics of solid films and the analysis of related local-field enhancement effects. The technique is based on the imaging and spectroscopy of single chromophore molecules at cryogenic temperatures. Since the fluorescence lifetime T_1 of a dye molecule imbedded in a transparent matrix depends on the properties of the encapsulating medium it has long been a challenge to obtain information about inhomogeneities in the host material by simply measuring T_1 times of individual molecules distributed over some volume. The factors that change the lifetime in the matrix are connected to existence of the local density of the photon states and the local response of the medium to incident light. Both factors are conventionally attributed to local effective values of the dielectric function describing the surroundings of each chromophore light emitter. Thus, knowing the T_1 distribution reveals the distribution of effective susceptibilities or refractive indices as well as the pattern of the local fields. In our experiment spatial mapping of the local values is accomplished by localizing the corresponding chromophores with nanometer accuracy. We demonstrate this approach for a polycrystalline film doped with terrylene molecules. We also report a significant progress in the theory of luminescence enhancement due to the local field effects.

This work was partially the Russian Foundation for Basic Research – Grant RFBR № 17-02-00652.

Fluorescence intermittency of single core/shell quantum dots depending on laser excitation intensity

I.Yu. Eremchev, I.S. Osad'ko, A.V. Naumov

Institute of Spectroscopy RAS, Troitsk, Moscow, Russia

Here the results of experimental and theoretical studies of single core/shell quantum dots fluorescence are presented [1, 2].

Intensity dependence of average times for on- and off- states for a single quantum dot were measured and analyzed in the framework of modified charging model. In addition to charging model (Effros and Rosen) with distribution of charge traps (outside the core) it utilizes idea about core/shell interface localized states, which works as doorways for transition to off-states. These states allow to explain power-law distribution of on-states time intervals. It was supposed that power-law (truncated power-law) distribution of on- and off- time intervals are result of sum of large but finite number of processes (exponential) with different characteristic times. It allows us to overcome the problem of the average from the power-law distributed value and to obtain equations for average times for on- and off- states. We did it in assumption of Auger and tunneling nature of transitions between on- and off- states and achieved corresponding equations for intensity dependence.

In performed experiment we found inverse quadratic power dependence for average time of on-states and practically absence for off-states. Our results confirm that transitions from "on-states" to "off-states" in single CdSe/ZnS nanocrystal (in our experiment) are originated from Auger ionization, whereas transition from "off-" (trapped states) to on-state are result of tunneling neutralization. In our experiment we had a deal with fluorescence tracks that looked like random telegraphic signal (RTS).

The work was supported by Russian Science Foundation 14-12-01415.

[1] Eremchev I.Yu., Osad'ko I.S., Naumov A.V., J. Phys. Chem. C (2016), 120 (38), 22004
[2] I.S. Osad'ko, I.Y. Eremchev, A.V. Naumov, J. Phys. Chem. C (2015), 119, 22646

Double-pulse non-resonant laser control of coherent molecular motions in condensed media

A.V. Leontyev, V.S. Lobkov, V.G. Nikiforov, A.G. Shmelev, D.K. Zharkov
Zavoisky Physical-Technical Institute,
Federal Research Center "Kazan Scientific Center of RAS", Kazan, Russia
e-mail: mailscrew@gmail.com

The technique of double-pulse laser control of the induced anisotropy of medium associated with coherent molecular motions is proposed. In fact, pump pulses with linear orthogonal polarizations, controllable intensities, and timings make it possible to manipulate various molecular responses. For example, we have shown that the technique with the optically heterodyne-detected optical Kerr effect (OHD-OKE) registration can be successfully used as a selective spectroscopy of low-frequency molecular responses in liquid. A detailed analysis of third-order optical responses indicates strongly that the double-pulse excitation is a useful spectroscopic technique allowing to obtain precise information on molecular dynamics in liquids.

Bragg scattering from a fractured Bose-Einstein condensate

V.M. Porozova,[1] L.V. Gerasimov,[2] D.V. Kupriyanov[1]

[1]*Department of Theoretical Physics, Peter the Great St.Petersburg Polytechnic University*
Polytechnicheskaya 29, 195251 St-Petersburg, Russia

[2]*Department of Physics, M.V. Lomonosov Moscow State University*
Leninskiye Gory 1-2, 119991, Moscow, Russia

Elastic light scattering from a macroscopic atomic sample existing in the Bose-Einstein condensate (BEC) phase reveals a unique physical configuration of interacting light and matter waves. For a sample of sufficient length the optical excitation transports as a specific polariton wave and the propagation Green's function obeys the scattering equation which we present. The complicated polariton dynamics could be tracked in the outgoing channel of the scattered photon as we show via numerical solution of the scattering equation for one-dimensional geometry. The results are analyzed and compared with predictions of the conventional macroscopic Maxwell theory for light scattering from a non-degenerate atomic sample of the same density and size.

We observe a significant difference with predictions of the Maxwell theory once the BEC is fractured into a number of the interfering matter wave fragments, which crucially modifies its density distribution. We show that in this case the scattering evolves towards conditions of Bragg diffraction, which strongly affects the process and can coherently redirect the propagating polariton wave in the backward or other directions associated with the condensate fragmentation.

LASER ADDITIVE TECHNOLOGIES: THE MODERN ACHIEVEMENTS AND FURTHER POSSIBILITIES

A. Gilmutdinov, K. Nagulin, A. Gorunov, I. Tzivilsky

Kazan National Research Technical University, K. Marx str. 10, 420111, Kazan, Russia

E-mail: Knagulin@mail.ru

Modern additive manufacturing uses two common kinds of technology of synthesis using metals and functionally graded materials: selective laser melting (SLM) and laser cladding or so-called direct metal deposition (DMD). SLM is based on the layering of the powder material with a subsequent selective laser sintering of powder particles. DMD is based on the delivery of the powder particles by gas flow with its subsequent melting by a laser beam on the surface of the grown products. None of these technologies do not fully correspond to the requirements of modern industrial production in terms of: accuracy, simplicity, speed of manufacturing and final cost of the produced objects.

The SLM technology provides an acceptable accuracy, but significantly loses in speed, simplicity and cost of manufacturing. Increase in the size of an object to be produced causes exponential growth of cost and time of its manufacturing by this method.

The DMD technology is relatively simpler (than SLM), has a less product size limitation and provides a high speed of manufacturing, but does not reach the required level of accuracy. This is mostly described by a fact that a precise manufacturing of a desired surface was not a historically initial goal of such a technology. DMD has been commonly used for creation of coatings and repair of worn areas of objects.

However, the recent scientific results make a possibility to argue that the potential opportunities of DMD technology are not fully exhausted. It is possible to design novel type of the laser cladding head and technological modes for precision laser powder cladding, which will provide the required values of accuracy, productivity and profitability of additive manufacturing using powder materials, including functionally graded materials. An analysis of the recent-year publications shows that the research centers leading in a field of additive technologies are actively finding solutions for the actual problem. Development of a high-precision method of additive manufacturing will provide a leap ahead in the development of modern industrial production. The latest trends in laser technologies for additive manufacturing are presented, as well as a history of their developments.

The work was performed with the support of the Ministry of Education and Science of the Russian Federation, decree N220, state contract No.14.Z50.31.0023 and state contract No. 9.3236.2017/4.6.

Ultrafast relaxation processes in nanocomposites with colloidal semiconductor quantum dots as revealed by incoherent photon echo

Artem Arzhanov, Kamil Karimullin, Andrei Naumov
Institute for Spectroscopy RAS, 5 Fizicheskaya Str., 108840, Moscow, Troitsk, Russia
Moscow State Pedagogical University, 29 Malaya Pirogovskaya Str., 119435 Moscow, Russia
e-mail: arzhanov.artyom@gmail.com

Study of photo-physical properties of semiconductor quantum dots is of a great interest in modern physics and materials science. One can introduce quantum dots in a transparent solid matrix, to fix them in space and to protect them from the aggressive effects of the environment. The resulting material – nanocomposite, is not described by a simple combination of properties of nanoparticles and a solid matrix, but there is a complex set of these properties with entirely new unique characteristics. To use quantum dots doped materials in quantum optics a detailed study of the dynamical processes, namely, the optical dephasing is necessary. Such studies can be performed by means of time-domain spectroscopy, namely, the photon echo. In this paper, we describe incoherent photon echo (IPE) studies of a thin film of colloidal quantum dots in a wide range of cryogenic temperatures.

We used double-coated colloidal 3 – 7 nm CdSe/CdS/ZnS quantum dots (QD-light, Russia), dissolved in high concentration in toluene to prepare the samples. Special arrangement and procedure of spreading quantum dots on a glass substrate have been developed to prepare the samples [1]. Additional measurements were performed by means of luminescence microspectroscopy to clarify their optical quality and spectral properties [2]. Measurements were performed by home-build photon echo spectrometer (see, e.g. [3]). PE signals were detected using a Cooke SensiCam HighSpeed CCD-camera. The sample was placed into a helium cryostat (RTI, Russia). The typical 2-pulse IPE (2IPE) decay curve consists of sharp intensive peak in the region of zero delays and tail. In order to find the optical dephasing time T_2 we fit this tail with the standard expression $I_{2IPE} = I_0 + C\exp(-4\tau / T_2)$, where I_0, C and T_2 are fitting parameters. The procedure was repeated at different temperatures from 4.5 K and up to 50 K, thus the temperature dependence of the inverse optical dephasing time was found.

We obtain ultrafast (with characteristic times about picoseconds) optical dephasing in a studied temperature range. Possible reasons for such fast processes can be related to the inhomogeneity of the structure of the quantum dots themselves, to the features of the internal dynamics of the emitting core, and also to the surface states on the shells. In addition, the dispersion in size and the strongly inhomogeneous local environment can lead to ultrafast relaxation in the ensemble of quantum dots.

The work is partially supported by the Russian Science Foundation (#14-12-01415 – manufacturing of a thin films of quantum dots) and the Russian Foundation for Basic Research (# 18-02-01121 – photon echo spectroscopy). K.K. and A.A. acknowledge the grant of the President of the Russian Federation (#MK-342.2017.2 – new luminescent materials based on quantum dots).

References

1. K.R. Karimullin, et al., J. Phys. Conf. Ser. **859** (2017) 012010.
2. K.R. Karimullin, A.I. Arzhanov, A.V. Naumov, Bull. RAS Phys. **81** (2017) 1396.
3. M.V. Knyazev, K.R. Karimullin, A.V. Naumov, Phys. Stat. Sol. RRL **11** (2017) 1600414.

A comparison of seeded and unseeded photon triplet generation

Cameron Okoth[1], Andrea Cavanna[1], Nicolas Y. Joly[2,1], and Masha V. Chekhova[1,2,3]

[1] *Max Planck Institute for the Science of Light, StaudtStraße 2, 91058 Erlangen, Germany*
[2] *University of Erlangen-Nürnberg, Staudtstrasse 7/B2, 91058 Erlangen, Germany*
[3] *Department of Physics, M. V. Lomonosov Moscow State University, Leninskie Gory, 119991 Moscow, Russia*

Non-linear optical phenomena have always played an incredibly important role in the development of quantum optics, which in turn has fueled research into the ever expanding field of quantum informatics. Parametric down conversion (PDC) is perhaps the most well established technique to generate non-classical light and has been used to demonstrate fundamentally quantum effects such as the violation of Bell's inequalities and sub-Poissonian statistics. Despite PDC being recognised as a fundamental quantum experiment, the two photon state generated via PDC seems to display far less exotic quantum features compared the complex entangled states or multi-dimensional GHZ states generated via PDC's high order counterparts. However, to date high-order parametric down conversion processes beyond second-order PDC have still not been observed.

The most natural place to begin the search for high order effects is with third order parametric down conversion (TOPDC), as the strength of non-linear effects generally diminishes with higher order terms. To this end we calculate the rate of three photon emission from TOPDC in bulk media. We compare the expressions for the two photon emission rate associated with PDC and three photon emission rate generated by TOPDC. By introducing a parameter called the effective vacuum field we find a compact way of relating the rate of PDC emission to that of TOPDC emission and discuss the consequences of the relationship.

By making estimates based on the experimental parameters, we infer that the rate of direct TOPDC emission from bulk materials is unlikely to be observed by current detectors. Although there are several proposals to improve TOPDC emission, for example, generation in waveguides, we chose to focus our attention on improving the efficiency of the TOPDC process by utilizing a coherent seed. Comparing the expected rate of seeded TOPDC to that of PDC, we show that both processes are analogous and the generated state is the same. The two processes only differ in terms of their respective rates of emission. Discussing the consequences of seeding TOPDC, we anticipate that seeding higher order processes leads to the same result of 'reducing' the high order process to the next lower order process.

In addition, we show preliminary experimental results on the observation of photons generated via seeded TOPDC in calcite.

Single molecule spectroscopy of Mg tetra-azoporphyrins in polymer matrix at low tempretatures

A.O. Savostianov[1], I. Yu. Eremchev[1,2], A.A. Gorshelev[1], A.V. Naumov[1,2,3], A.S. Starukhin[4]

[1] *Institute of Spectroscopy RAS Troitsk, Moscow 108840, Russia*
[2] *Moscow Institute of Physics and Technology, Dolgoprudny, Moscow region 14170053, Russia*
[3] *Moscow Pedagogical State University, Moscow 119991, Russia*
[4] *B.I. Stepanov Institute of Physics, NAS, Belarus, Minsk 220072 , Belarus*
e-mail: savostianov.a@isan.troitsk.ru

Here we report the results of our measurements of the low-temperature fluorescence excitation spectra of single Mg-tetraazoporphyrins embedded into the polyisobutylene matrix. Electronic zero-phonone lines (ZPL) and spectral trails in the wide range (up to 4000 GHz) at 6K were detected. Spectral diffusion (time-dependent shifts of ZPLs) in the anomalous wide spectral range up to 950 GHz has been found.

Single-molecule spectroscopy (SMS) is a quite novel but well-established experimental technique. Today SMS of impurity center embedded into a solid-state host matrix is a powerful tool for investigations of chromophores intermolecular dynamic and interactions with surroundings, exploring of local dynamics of solids with different degree of disorder. The SMS method is especially powerful at cryogenic temperatures where narrow zero-phonon lines (ZPL) which correspond to pure electronic transitions in chromophores are available. [1,2]

Among the huge variety of potentially promising chromophores tetrapyrrolic compounds – porphryrins and its metal complexes (e.g. [3]). These compounds are omnipresent in nature and play important role in biological systems such as a chlorophyll, hem – non-protein part of hemoglobin, enzymes: cytochrome, catalase, peroxidase, vitamin B12 and many others. Consequently they are of particular interest for studying the processes of photosynthesis and energy conversion in biological objects; when developing new products for phototherapy and terraphenics; as the basis of new catalytic systems. Moreover, these luminophores are promising materials for developments of effective sources of non-classic light for quantum computing.

Although a sufficient number of metalloporhyrins has a large value of quantum yield, there is actually only one experiment where ZPLs of single porphyrins were detected [4].

In our research, detection of ZPLs of single Mg tetraazoporphyrins (Mg-TAP) molecules embedded to amorphous polyisobutylene host at cryogenic temperatures (6K) was first implemented. Repeated detection of fluorescence excitation spectra of single luminophores was carried out in the wide spectral range (up to 4000 GHz) using continuous-wave tunable dye laser (Coherent CR-599) with the effective linewidth of 10 GHz. Spectral diffusion with wide distribution of values of spectral shifts (from 10 up to 950 GHz in several shifts) has been observed and analysed. The presence of spectral shifts significantly exceeding in their characteristic values observed earlier [5], may indicate the existence of intramolecutar conformational changes.

This work was done with the support of the Program of the Russian Academy of Sciences (“Actual problems of photonics”). Part of the work (A.A.S.) was done with the support of Horizon 2020 program (grant 645628).

References:

1. M. Orrit, W.E. Moerner, High Resolution Single-Molecule Spectroscopy in Condensed Matter, in Physics and Chemistry at Low Temperatures / Ed. By L. Khriachtchev, 2011, Pan Stanford Publishing: Singapore. p. 381-417.
2. A.V. Naumov, Physics-Uspekhi, 56, 605 (2013).
3. Y.G. Gorbunova, A. Martynov, P. Stuzhin, O.I. Koifman, Macroheterocycles, 10, 400 (2017).
4. A. Starukhin, A. Shulga, J. Sepiol, R. Kolos, V. Knyukshto, A. Renn, U.P. Wild, Chem. Phys., 285, 121 (2002).
5. A.V. Naumov, Y.G. Vainer, M. Bauer, S. Zilker, L. Kador, Phys. Rev. B, 63, 212302 (2001).

Correlated photon pair generation via spontaneous four-wave mixing in optical nanofibers

Shukhin A.A.[1], Kalachev A.A.[1], Keloth J.[2], Hakuta K.[2]

[1]*E.K. Zavoisky Kazan physical-technical institute, Kazan, Russia*
[2]*Center for photonic innovations, University of electro-communications, Tokyo, Japan*

Abstract

In this work, we investigate nondegenerate spontaneous four-wave mixing (SFWM) in tapered optical fibers (also called micro/nano-fibers (MNF)) for correlated photon-pair generation. To make nanofibers for photon generation at telecommunication band we theoretically study the spectral features of the SFWM in MNF with an irregular profile, which naturally occurs while fiber tapering. We made an array of 11 MNFs with similar profiles and experimentally demonstrate the source of correlated photon pairs. Because of using MNF as a nonlinear medium, the source can be compatible with the existing fiber networks due to the ideal mode matching.

Quantum theory of laser cooling on forbidden transitions

O.N. Prudnikov, R.Ya. Ilenkov, A.V. Taichenachev, V.I. Yudin
Institute of Laser Physics SB RAS, Novosibirsk, Russia
Novosibirsk State University, Novosibirsk, Russia

Abstract: We study laser cooling of atoms with narrow-line optical transition, i.e. in regimes when quantum nature of laser-light interactions results significant effect on atom kinetics. We demonstrate the minimum of laser cooing temperature is reached for the light field detuning close to -3 recoil frequency, i.e. is much differ from standard Doppler cooling theory is used for semiclassical description of laser cooling. We define a set of dimensionless parameters that describe the steady state solution of cold atom distribution in laser light and cooling time. The results can be used for analysis an optimal conditions of laser cooling of atoms with narrow lines *Ca, Sr* and *Mg* are of interest for optical time standards.

Nowadays deep laser cooled of neutral atoms are routinely used for broad range of modern quantum physics researches including metrology, atom optics, and quantum degeneracy studies. There are well-known techniques for laser cooling below the Doppler limit, like sub-Doppler polarization gradient cooling [1-3], velocity selective coherent population trapping [4-6] or Raman cooling [7,8] are restricted to atoms with degenerated over angular momentum energy levels or hyperfine structure. However, for atoms with single ground state like ^{24}Mg, ^{40}Ca, ^{88}Sr, ^{174}Yb are of interest for developing optical time standard these techniques cannot be applied.

For atoms with nondegenerate ground state over the angular momentum, the basic theory based on semiclassical approach predicts the limit of laser cooling temperature with the minimum is proportional to natural linewidth γ of exited state $k_B T_D \approx \hbar\gamma/2$, is so called the Doppler limit.

One of the way of reaching deeper cooling temperature for these atoms is to use a narrow optical transition (clock transition) with smaller natural linewidth γ. For these atoms we may expect the lower temperature, however the basic semiclassical theory becomes no more valid due to violation of the main requirement that is called semiclassical limit $\omega_R << \gamma$ (with $\omega_R = \hbar k^2/2M$ is recoil frequency describes the energy obtained by atom at rest due to spontaneous emission or absorption of the light field photon with momentum $\hbar k$).

In our analysis we try to build a quantum theory of laser cooling for the case far beyond the semiclasical limit, i.e. for the case of $\omega_R/\gamma \geq 1$. This allows us to clarify the laser cooling mechanisms with narrow-line optical transitions and estimate the light field parameters for minimum cooling temperature and cooling time. Considering this task, we also try to answer the principal question on possibility of direct laser cooling of atoms with applying the field resonant to narrow-line optical transition, or it just a matter of appropriate laser field parameters.

References:

1. J. Dalibard and C. Cohen-Tannoudji, J. Opt. Soc. Am. B **6**, 2023 (1989).
2. Y. Castin and J. Dalibard Europhys. Lett., **14,** 761-766 (1991)
3. O.N. Prudnikov, A.V. Taichenachev, A.M. Tumaikin, V.I. Yudin JETP Letters **70**, 443 (1999)
4. A. Aspect, E. Arimondo, R. Kaiser, N. Vansteenkiste, and C. Cohen-Tannoudji, PRL **61,** 826 (1988)
5. A. Aspect, E. Arimondo, R. Kaiser, N. Vansteenkiste, and C. Cohen-Tannoudji, JOSA B **6,** 2112 (1989)
6. O.N. Prudnikov, E. Arimondo, JOSA B **20,** 909-14 (2003)
7. M. Kasevich and S. Chu, Phys. Rev. Lett. **69,** 1741 (1992).
8. J. Reichel, F. Bardou, M. Ben Dahan, E. Peik, S. Rand, C. Salomon, and C. Cohen-Tannoudji, PRL **75,** 4575 (1995).

Addressable optical quantum memory in Tm^{3+} : $Y_3Al_5O_{12}$ crystal

Minnegaliev M.M., Gerasimov K.I., Urmancheev R.V. and Moiseev S.A.

Kazan Quantum Center, Kazan National Research Technical University n.a. A.N.Tupolev – KAI, K. Marx str. 10, 420111, Kazan, Russia

Abstract. We experimentally demonstrate selective retrieval of weak input light pulses in revival of silenced echo scheme (ROSE) of optical memory. The addressing became possible due to the observed linear Stark effect on $^3H_6 - {}^3H_4$ optical transition of Tm^{3+} ions in $Y_3Al_5O_{12}$ crystal. In contrary to the well-known lack of linear Stark effect in D_2 symmetry of Tm^{3+} ions in this crystal, the observed data are in good agreement with the a suggestion that local inhomogeneous electric fields break symmetry at Tm^{3+} ion sites and make it possible linear Stark shifts in a presence of external electrical fields. It is worth noting that realized scheme allows selective retrieval with high accuracy and can be used in the effective quantum memories.

RAPID ANALYSIS OF AFTERPULSING COUNTS USING RANGED AMPLITUDES

Smirnov M.A.,[1] Perminov N.S.,[1] Nigmatullin R.R.[2] and Moiseev S.A.[1]

[1] Kazan Quantum Center, Kazan National Research Technical University named after A. N. Tupolev, K. Marx str., 10, Kazan, 420011, Russia
[2] Department of Radio-electronics and Information-Measuring Technique, Kazan National Research Technical University named after A. N. Tupolev, K. Marx str., 10, Kazan, 420011, Russia

Abstract: Single-photon detectors based on avalanche photodiodes (SPAD) are key elements of quantum communication systems. The afterpulsing effect limits detection rate of SPAD and requires an optimal hold-off time. We propose a novel approach for statistical analysis of afterpulsing counts. The approach can be applied for rapid characterization of SPAD devices by using a small number of the dark counts.

SUPEREFFICIENT CASCADED QUANTUM MEMORY

N.S.Perminov[1,2], S.A.Moiseev[1,2]

[1] Kazan Quantum Center, Kazan National Research Technical University n.a. A.N.Tupolev-KAI, K. Marx 10, Kazan 420111, Russia
[2] Kazan E.K. Zavoisky Physical-Technical Institute of the Kazan Scientific Center of the Russian Academy of Sciences, Sibirsky tract, 10/7, Kazan, 420029, Russia
samoi@yandex.ru

Abstract. Based on the scheme of multiresonator quantum memory [Phys. Rev. A, 95, 012338, 2017], we are developing a long-lived broadband superefficient multiresonator quantum memory in which a common resonator is connected with an external waveguide and with a system of high-quality miniresonators containing long-lived resonant electron spin ensembles. The scheme with 4 miniresonators has been numerically analyzed and it was shown that it could be used for storage of a broadband signal field to the electron spin ensembles with quantum efficiency 99.99%.

Towards efficient broadband photon echo quantum memory for quantum communication

N.M.Arslanov and S.A.Moiseev
Kazan Quantum Center, Kazan National Research Technical University n.a. A.N.Tupolev-KAI, K. Marx 10, Kazan 420111, Russia
samoi@yandex.ru

Abstract. Significant progress in the creation of local fiber-optic quantum communications led to great interest in the development of global quantum communications, as well as distributed quantum computing. For successful solution of these problems, need use the multi-qubit quantum memory (QM). Herein, AFC-protocol has shown visible advantages in practical realization of broadband quantum storage. which seems to be attractive for using in quantum repeater.
The practical usage of the quantum memory devices requires a quite large quantum efficiency 90% of light storage. Unfortunately the highest quantum efficiencies of AFC protocol 35% have been obtained in 2009 in free space scheme of QM. The search for and implementation of ways to improve quantum efficiency becomes an important problem of using AFC for solving many practical problem. Therefore, further improvement of the AFC protocol makes it necessary to find real ways to increase quantum efficiency to the required level.

Below we present a modified AFC-protocol based on the spectrally-dispersion approach providing optimal parameters for highly efficiency broadband quantum storage. We investigated the optimal spectral design of periodic structure of narrow lines (AFC-structure) within the inhomogeneously broadened atomic transition which are created for the implementation of broadband AFC photon echo quantum memory. The influence of the spectral design on the suppression of negative dispersion effects in the AFC-echo retrieval was studied for different spectroscopic parameters of atomic media. The maps of the assigned spectral quantum efficiency have been constructed for the created AFC-structures characterized by different spectral design, finesse and optical depth. By using this approach we also demonstrate a possibility of efficient multiplexing of the light field storage in such AFC-protocol.

Based on the performed analysis, we discuss the possible ways for experimental implementation of highly efficient broadband AFC-protocol on inorganic crystals doped by the rear-earth ions which seems especially promising of using in optical quantum repeaters.

DISPERSION-SHIFTED PHOTONIC CRYSTAL FIBER AS A SOURCE OF CORRELATED PHOTON PAIRS

Smirnov M.A.,[1] Petrovnin K.V.,[1] Latypov I.Z.,[1] Talipov A.A.,[1] Fedotov I.V.,[1,2,3,4] Shmelev A.G.[1] Zheltikov A.M.[1,2,3,4,5] and Moiseev S.A.[1]

[1] Kazan Quantum Center, Kazan National Research Technical University named after A. N. Tupolev, K. Marx str., 11, Kazan, 420011, Russia

[2] M.V. Lomonosov Moscow State University, Vorobevy Gory, Moscow, 119991, Russia

[3] Texas A&M University, College Station, Texas, USA

[4] International Center for Quantum Optics and Quantum Technologies (the Russian Quantum Center), ul. Novaya 100, Skolkovo, Moscow Region, 143025, Russia

[5] National Research Centre 'Kurchatov Institute', pl. akad. Kurchatova 1, Moscow, 123182, Russia

Abstract: Photonic crystal fiber is a promising medium for the generation of correlated photon pairs. Correlated photon pairs can be generated in a fiber based on the four-wave mixing process. We generated correlated photon pairs in a dispersion-shifted photonic crystal fiber in the normal region at 845 nm and 1274 nm. This fiber can be used as a source of photon pairs in quantum communications.

Dual-chirped optical parametric amplification of IR femtosecond pulses up to multi-terawatt power

S.A. Frolov, V.I. Trunov

Institute of Laser Physics SB RAS, Novosibirsk, Russia

Photonic delay dynamics emulating spatio-temporal networks: From chimera states to photonic artificial intelligence

L. Larger[1], M. Jacquot[1], Y. Maistrenko[1,2], Y.K. Chembo[1,3], and D. Brunner[1]
1: FEMTO-ST Institute, CNRS & Univ. Bourgogne Franche-Comté, Besançon, France
2: Institute of Mathematics, Center for Medical and Biotechnical Research, NAS of Ukraine, Kyiv, Ukraine
3: GeorgiaTech-CNRS, Mirror UMI location, Atlanta GA, USA

Delay dynamics are well known for their infinite dimensional phase space. An analogy with space-time dynamics was proposed 20 years ago from a theoretical perspective. In this talk, we will develop such an analogy from two particular point of views recently explored through experimental investigations in photonic, with optoelectronic nonlinear delay oscillators.

Emerging and self-sustained spatio-temporal patterns, known as chimera states in network of oscillators, will be first reported and analyzed in such purely temporal, but high-dimensional enough, dynamics. The conditions for their occurrence will be described and analyzed with respect to the characteristic operating parameters of the delay dynamics, and a highly multi-stable organization of the parameter space will be reported.

Second, a novel application of delay dynamics in photonic will be reported, consisting in a brain-inspired information processing system. Again, space-time properties will be emphasized, showing how a delay dynamics can efficiently emulate a complex ensemble which acts as a network of neurons capable to process information. An experimental speech recognition test will be reported with unprecedented processing speed, up to 1 million words/second classification rate, moreover with very low word error rate.

[1] T. Erneux and P. Glorieux, "Laser dynamics", *Cambridge University Press* (2010).
[2] L. Larger and J.M. Dudley, *Nature*, News & Views, vol.465(7294), pp.41-42 (2010).
[3] D. Abrams and S. Strogatz, "Chimera States for Coupled Oscillators", *Physical Review Letters*, vol. 93(17), 174102 (2004).
[4] H. Jaeger, H. Haas, "Harnessing nonlinearity: predicting chaotic systems and saving energy in wireless communication", *Science*, vol.304, pp. 78-80 (2004).
[5] L. Larger, B. Penkovsky, Y. Maistrenko, "Laser chimeras as a paradigm for multistable patterns in complex systems", *Nature Communications*, 6:7752 (2015).
[6] L. Larger, A. Baylòn-Fuentes, R. Martinenghi, V.S. Udaltsov, Y.K. Chembo and M. Jacquot, "High-Speed Photonic Reservoir Computing Using a Time-Delay-Based Architecture: Million Words per Second Classification", *Physical Review X*, vol.7, 011015 (2017).

Synthetic nonabelian gauge fields in integrated photonic waveguides

Lucas Teuber, Mark Kremer, Alexander Szameit, and Stefan Scheel
University of Rostock, Institute of Physics, Albert-Einstein-Str. 23, 18059 Rostock, Germany

Geometric phases are an intriguing aspect of quantum mechanics which manifest themselves in a path-dependence of the Hilbert space evolution of a quantum system, the most prominent examples of which are the Aharonov-Bohm effect as well as conical intersections of potential energy surfaces. Frequently, these phases appear just as (commuting) real numbers. In more general situations, however, they are matrix-valued quantities that give rise to nonabelian holonomies that depend on two or more consecutive paths and their mutual ordering.

Nonabelian geometric phases are known to occur in quantum systems with degenerate energy levels [1], and can be implemented in atomic systems using STIRAP-type processes between dark states, i.e. states with zero energy eigenvalue [2]. Dark states arise naturally in systems with degenerate energy levels that are all coupled to one common state, e.g. in a Lambda-type or tripod configuration [3].
Here we will show how to implement a nonabelian geometric phase using a STIRAP-type process in an integrated photonic waveguide structure, utilizing the formal equivalence between the electromagnetic wave equation in paraxial approximation and the time-dependent two-dimensional Schroedinger equation. The structure consists of a number of waveguides placed around a central waveguide and whose couplings can be tuned by adjusting their mutual separation. As a structure with three waveguides surrounding a central waveguide possesses two dark states, a nonabelian geometric phase associated with a U(2) group transformation can be implemented. We will show how to design and implement a gauge-invariant Wilson loop as a four-sequence plaquette in an abstract parameter space [4] and discuss the measurement procedure for evaluating the Wilson loop.

[1] F.Wilczek and A.Zee, Phys. Rev. Lett. 52, 2111 (1984).
[2] J.Dalibard, F.Gerbier, G.Juzeliunas, and P.Ohberg, Rev. Mod. Phys. 83, 1523 (2011).
[3] R.G.Unanyan, B.W.Shore, and K.Bergmann, Phys. Rev. A 59, 2910 (1999).
[4] L.Teuber, M.Kremer, A.Szameit, and S.Scheel, in preparation.

High dimensional frequency bin entanglement applications

J.-M. Merolla†, B. Galmez†, Y. Chembo‡†*
† FEMTO-ST institute [UMR 6174], CNRS & Univ. Bourgogne Franche-Comté
15B avenue des Montboucons, 25030 Besançon cedex, France
‡ GeorgiaTech-CNRS Joint International Laboratory [UMI 2958], Atlanta Mirror Site
School of Electrical and Computer Engineering, 777 Atlantic Dr NW, Atlanta GA 30332, USA.
* Corresponding author: Jean-Marc Merolla, jeanmarc.merolla@univ-fcomte.fr

The use of high-dimensional entangled states is a key enabler for high-capacity quantum communications and key distribution, quantum computation, information processing. For the success of these quantum photonic applications, **high visibility quantum interference and high integration is essential**. Among the different degrees of freedom of photons, time-energy entangled photon pairs at telecommunication wavelengths allow the implementation of high visibility experiments and are especially well suited for integration with the current fiber optic infrastructure. Many experiments exploits the concept of **time bins**, in which the photons are detected at discrete times, because the time-bin entangled states are robust with respect to decoherence over large distances. Since 2010 our group has introduced the concept of frequency bin entanglement and, for the first time, we have demonstrated Bell inequality violations using high frequency electro-optic phase modulation. Several groups have proposed different potential applications using the same phase modulation techniques. These new approaches encourage to further work on frequency bin entanglement, which is a promising candidate to consolidate information processing solutions based on quantum photonics technology. Indeed the frequency domain is attractive, because **(i)** the frequency domain is naturally of high dimensionality, and **(ii)** building blocks such as frequency entangled source, modulators and filters involved in the manipulation methods can be integrated on chip. This is why the frequency degree of freedom in quantum photonic undoubtedly offers a promising platform for scalable and robust quantum information processing.

In this contribution, we will report on different frequency bin entanglement architectures we have implemented using standard Telecom optoelectronic devices such as electro-optic phase modulators and filters. Proof of concept experiments will be presented demonstrating high reliability and high potentiality of the approach.

[Ali16] O. Alibart *et al.*, Journal of Optics 18, 104001 (2016).
[Bar08] J T Barreiro, T C Wei, & P G Kwiat, P. G, Nature Physics, 4, 282-286 (2008).
[Cap10] J. Capmany and C. R. Fernandez-Pousa, J. Opt. Soc. Am., B 27, A119 (2010).
[Dyn09] F. Dynes *et al.*, Opt. Express Vol. 17, 11440-11449 (2009)
[Dad11] A C Dada, J Leach, G S Buller, M J Padgett, & E Andersson, Nature Physics 7, 677-680 (2011).
[Ima2017] P.Imany *et al.*, arXiv:1709.05274v2 , 18 Sep 2017.
[Kre14] M Krenn, *et al.* Proceedings of National Academy of Sciences 111, 6243-6247 (2014).
[Kue17] M. Kues *et al.*, Nature, 546, p.622 (2017).
[Luk17] J. M. Lukens and P.Lougovski ,Optica, vol.4(1) (2017).
[Oli10] L. Olislager *et al.*, Phys. Rev. A, 82(1), 013804 (2010).
[Oli12] L. Olislager *et al.*, New J. of Phys. 14, 043015 (2012).
[Oli14] L. Olislager *et al.*, Phys.Rev. A, 89(5) 052323 (2014).
[Rog2016] S. Rogers, D. Mulkey, X. Lu, W. C. Jiang and Q. Lin, ACS Photonics, 3(10), pp. 1754-1761 (2016).

Various applications for ultracold ions: quantum logic, optical and radio frequency clocks

I. Semerikov[1,2], I. Zalivako[1,2], A. Borisenko[1,2], V. Sorokin[1,2], K. Khabarova[1,2], N. Kolachevsky[1,2]

[1]P.N. Lebedev Physical Institute, Leninsky prospekt 53, 119991 Moscow, Russia
[2]Russian Quantum Center, 100 Novaya St., Skolkovo, Moscow 143025, Russia
e-mail: ilia179@mail.ru

Utracold ions can be used in a number of different applications. For example, ion based quantum logic algorithms have showed the best fidelity and ion qubits demonstrate the best relative coherence time [1] which makes ions perspective base for quantum computing. On the other hand, Yb^+ ion clock has reached an outstanding $3x10^{-18}$ relative uncertainty [2]. In combining with long storage times, reliable trapping and one beam cooling it makes ions good candidates for transportable optical clocks.

Our group has started projects in both promising branches mentioned above. We work on development of quantum logic algorithms based on $^{25}Mg^+$ qubits trapped in a linear Paul ion trap. We have demonstrated many particle linear crystals as well as single $^{24}Mg^+$ ions (fig 1). Doppler cooling at $^2S_{1/2}\rightarrow{}^2P_{3/2}$ transition allows reaching crystallization but to cool ions further to the ground motional state sideband cooling is necessary. The sideband cooling on stimulated Raman transition requires additional 285 nm laser, which also can be used for selective photoionization of neutral Mg. We plan to assemble such homemade laser system in the nearest future.

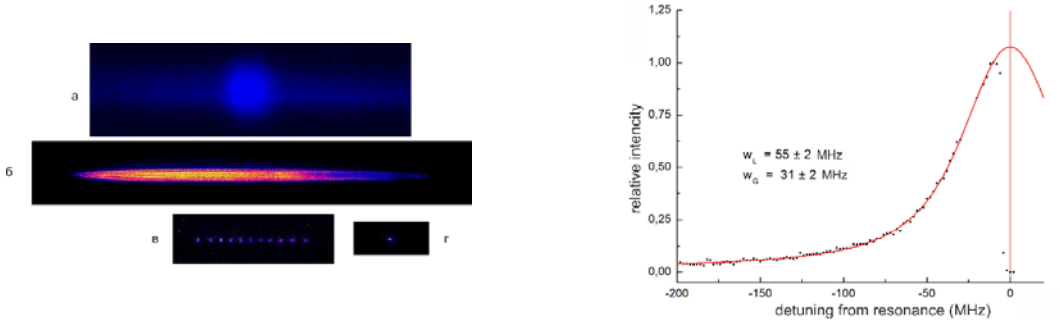


Fig 1. a) Mg^+ cloud, big crystall,ion chain, single ion. b) Cooling $^2S_{1/2}\rightarrow{}^2P_{3/2}$ transition profile in $^{25}Mg^+$

The second project is aimed for compact and transportable optical ion clock based on quadrupole $^2S_{1/2}\rightarrow{}^2D_{3/2}$ transition in $^{171}Yb^+$ ion. Yb^+ ion is very promising since all the transitions used are now available by means of direct diode lasers. We work on new design for cooling, repumping and clock laser systems in order to reach required robustness and stability together with compactness and simplicity. The goal relative instability of the clock is $5x10^{-16}$ at 24 hours averaging time.

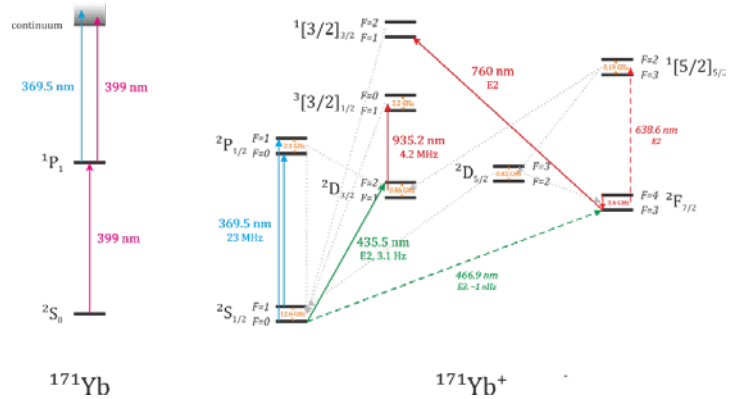


Fig 2. $^{171}Yb^+$ and ^{171}Yb partial energy level structure.

Quantum logic project is supported by RSF (grant number 16-12-00096) and optical clock work is supported by Russian Ministry of education, (project ID number: RFMEFI61017X0010)

[1] Debnath S. et al. Demonstration of a small programmable quantum computer with atomic qubits //Nature. – 2016. – T. 536. – №. 7614. – C. 63.

[2] Huntemann N. et al. Single-ion atomic clock with 3× 10− 18 systematic uncertainty //Physical review letters. – 2016. – T. 116. – №. 6. – C. 063001.

Recent advances in high-precision optical clocks based on ultracold atoms and ions

Sergey Bagayev[1,2] and Alexey Taichenachev [1,2]
[1] Institute of Laser Physics, Novosibirsk, Russia
[2] Novosibirsk State University, Novosibirk, Russia
e-mail: bagayev@laser.nsc.ru, taichenachev@laser.nsc.ru

***Abstract*— New methods and approaches in precision laser spectroscopy of forbidden transitions in ultracold atoms and ions are discussed with an emphasis on contributions of Institute of Laser Physics SB RAS.**

Keywords —optical clocks, forbidden transitions, Ramsey method, ultracold atoms and ions, optical lattice, Paul trap

I. INTRODUCTION

Presently, laser spectroscopy and fundamental metrology are among the most important and actively developed directions in modern physics. Frequency and time are the most precisely measured physical quantities, which, apart from practical applications (in navigation and information systems), play critical roles in tests of fundamental physical theories (such as QED, QCD, unification theories, and cosmology) [1,2]. Now, laser metrology is confronting the challenging task of creating an optical clock with fractional inaccuracy and instability at the level of 10^{-17} to 10^{-18}. Indeed, considerable progress has already been achieved along this path for both ion-trap- [3,4] and atomic-lattice-based [5,6] clocks.

Work in this direction has stimulated the development of novel spectroscopic methods such as spectroscopy using quantum logic [7], magnetically induced spectroscopy [8], hyper-Ramsey spectroscopy [9], spectroscopy of "synthetic" frequency [10] and others [11]. Part of these methods was developed in order to excite and detect strongly forbidden optical transitions. The other part fights with frequency shifts of various origins. In the present talk we will review both parts with a special emphasis on methods developed and studied in Institute of Laser Physics SB RAS, Novosibirsk. The history and present status of experimental works devoted to the optical frequency standards will be discussed.

Acknowledgment

The work was supported by the Russian Scientific Foundation (projects No. 16-12- 00052 and No. 16-12-00054).

References

[1] S.N. Bagayev et al., Appl. Phys. B 70, 375 (2000).
[2] S.A. Diddams et al., Science 306, 1318 (2004).
[3] T. Rosenband et al., Science 319, 1808 (2008); C.W. Chou et al., Phys. Rev. Lett. 104, 070802 (2010).
[4] N. Huntemann et al., Phys. Rev. Lett. 116, 063001 (2016).
[5] T. Akatsuka,M. Takamoto, and H. Katori, Nature Physics 4, 954 (2008).
[6] N. Hinkley et al., Science 341, 1215 (2013); B.J. Bloom et al., Nature 506, 71 (2014).
[7] P.O. Schmidt et al., Science 309, 749 (2005).
[8] A.V. Taichenachev et al., Phys. Rev. Lett. 96, 083001 (2006); Z. Barber et al., Phys. Rev. Lett. 96, 083002 (2006).
[9] V.I. Yudin et al., Phys. Rev. A 82, 011804(R) (2010); N. Huntemann et al., Phys. Rev. Lett. 109, 213002 (2012); T. Zanon-Willette et al., Phys. Rev. A 96, 023408 (2017)
[10] V.I. Yudin et al., Phys. Rev. Lett. 107, 030801 (2011); V.I. Yudin et al., Phys. Rev. A 94, 052505 (2016).
[11] V.I. Yudin et al., Phys. Rev. Lett. 113, 233003 (2014).

Novel Applications of Homodyne Detection in Satellite Quantum Communications and Coherent Beam Combining

Christian R. Müller[1,2], Kaushik Seshadreesan[1,2], Florian Sedlmeir[1,2], Sourav Chatterjee[1,2,5], Christoph Marquardt[1,2], and Gerd Leuchs[1,2,3,4]

[1]Max Planck Institute for the Science of Light, Staudtstraße 2, 91058 Erlangen, Germany
[2]Department of Physics, University of Erlangen-Nuremberg, Staudtstraße 7/B2, 91058 Erlangen, Germany
[3]Institute for Applied Physics, Russian Academy of Sciences, 603950 Nizhny Novgorod, Russia
[4]Max Planck–University of Ottawa Centre for Extreme and Quantum Photonics, 25 Templeton Street, Ottawa, Ontario K1N 6N5, Canada
[5]SAOT, Erlangen Graduate School in Advanced Optical Technologies, Paul-Gordan-Strasse 6, 91052 Erlangen, Germany
christian.mueller-hirschkorn @mpl.mpg.de

Homodyne detection is the essential measurement scheme in coherent communications and also a key component in many continuous-variable quantum optics experiments. In a homodyne detector, the signal state is interfered with a bright coherent auxiliary beam, the local oscillator LO, on a symmetric beam splitter and the emerging states are detected by two photo diodes. After appropriate amplification and filtering of the difference of the resulting photo currents, the signal is proportional to a quadrature variable of the signal state.
We report on two applications of homodyne detection in the quantum information processing group at MPL – quantum optical signal exchange between an Optical Ground station and an optical satellite, and the quantum-limited coherent combination of optical beams.

Optical satellite links offer an exciting testbed for probing the laws of physics at the interface between quantum mechanics and general relativity. We could recently show that atmospheric noise in satellite links could be overcome [1] and that challenges arise merely due to the significant attenuation dominated by diffraction losses. Here, we motivate the feasibility of quantum squeezing detection in Ground-to-Satellite links using optical homodyne detection technology already in orbit. The detection process is complicated by the fact that the homodyne detectors aboard of optical communication satellites often provide an efficient resolution of only one bit. We show that despite this extreme constraint quantum squeezing can still be detected efficiently.

Coherent beam combining refers to the process of merging independent input beams with locked relative phases. This technique allows to extend the power scaling of fibre amplifier systems beyond the current limitations caused by thermal mode instabilities [2, 3], but can also be considered for quantum-limited coherent input beams. The noise profile of the combined beam depends crucially on the relative optical phases in the combining step. The phase lock can be based on the detection of single photons or on variants of homodyne detection. In either case, the precision is fundamentally limited by quantum uncertainty. We report the first quantum mechanical noise limit calculations for coherent beam combining, and we compare our results to the performance of a quantum-limited amplifier [4].

[1] K. Günthner et al., "Quantum-limited measurements of optical signals from a geostationary satellite", Optica **4** (6), 611-616 (2017).
[2] T. Eidam et al., "Experimental observations of the threshold-like onset of mode instabilities in high power fiber amplifiers", Opt. Express **19** (14), 13218-13224 (2011)
[3] C. Gaida et al., "Coherent combination of two Tm-doped fiber amplifiers", Opt. Lett. **40**(10) 2301-2304 (2015)
[4] C. M. Caves, "Quantum limits on noise in linear amplifiers", Phys. Rev. D **26**, 1817-1839 (1982)

Efficient dissipation-enabled excitation transfer for quantum information processing

Gernot Alber, Nils Trautmann

Institut für Angewandte Physik, Technische Universität Darmstadt, D-64289 Darmstadt

It is a major problem of quantum information processing to develop highly efficient excitation transfer mechanisms from a single photon with a rather arbitrary pulse shape to a single quantum emitter in a way that challenging complications arising from conditional tailoring of laser pulses and from imperfections affecting postselective photon detection processes can be circumvented. In this contribution we discuss a family of such mechanisms whose basic ideas have been discussed recently [1]. Contrary to previous approaches based on coherent quantum processes our mechanisms are enabled by an appropriate balancing of relevant dissipative processes, such as spontaneous photon emission and cavity decay. This way single-photon wave packets of rather arbitrary pulse shapes can trigger highly efficient excitation transfer to material quantum emitters so that for photon wave packets with sufficiently small bandwidths the high efficiency of such an excitation transfer becomes even independent of the photon wave packet's shape.

Our proposed excitation transfer schemes are based on single-photon-induced optical pumping processes which turn dominant dissipative processes, such as spontaneous photon emission by an emitter or cavity decay, into valuable tools for quantum information processing and quantum communication. They work for arbitrarily shaped single-photon wave packets with sufficiently small bandwidths provided a matching condition is satisfied which balances the dissipative rates involved. In particular, they do not require additional laser pulses or quantum feedback and do not rely on high finesse optical resonators. They can be used to enhance significantly the coupling of a single photon to a single quantum emitter implanted in a one-dimensional waveguide or even in a free space scenario, for example. Thus these schemes offer promising features for realizations of scalable quantum communication networks as they relax restrictive requirements on the synchronization of the nodes of a network (detailed knowledge on arrival times and on pulse shapes of the photons is not required) and as their efficiencies are not limited by efficiencies of single-photon detectors. They can be applied to a variety of different scenarios including fibre- and cavity-based architectures as well as architectures without any optical resonators. In particular, they can serve as basic building blocks for various protocols relevant for quantum information processing. As examples setups for a deterministic single-atom single-photon quantum memory and for a deterministic frequency converter are discussed.

[1] N. Trautmann and G. Alber, Phys. Rev. A 93, 053807 (2016).

Towards triplet generation using engineered optical fibers

N. Joly, J. Hammer, A. Cavanna, X. Jiang, M. Chekhova
Max Planck Institute for the Science of Light, Staudtstraße 2, 91058 Erlangen, Germany

Optical fiber is an attractive means for efficient third-order nonlinear optics such as the observation of soliton, four-wave mixing and third harmonic generation (THG). Recently the interest for THG in optical fiber has experienced an important revival due to some features it has in common with the third-order spontaneous down conversion (TOSPDC). By contrast with THG, where three low-energy photons at $_p$ are converted into one photon at $3\ _p$, TOSPDC allows the creation of three distinct low-energy photons from one single photon. When the generated photons are all identical, the TOSPCD and THG can be seen as the exact reverse processes from each other. Unfortunately, chromatic dispersion prevents intra-modal phase matching in waveguide, and this yields poor integral overlap and limited conversion efficiency. For that reason, the observation of TOSPDC remains a challenging task, which has not yet been accomplished. It is therefore important to find suitable strategies to carefully design an appropriate dispersion landscape to fulfill phase-matching between low-order spatial modes in order to maximize the conversion process. Here we present several promising experiments using gas-filled hollow-core photonic crystal fiber [1,2] and pressure-tunable dispersion of sub-micron scale tapered fibers (Fig.1).

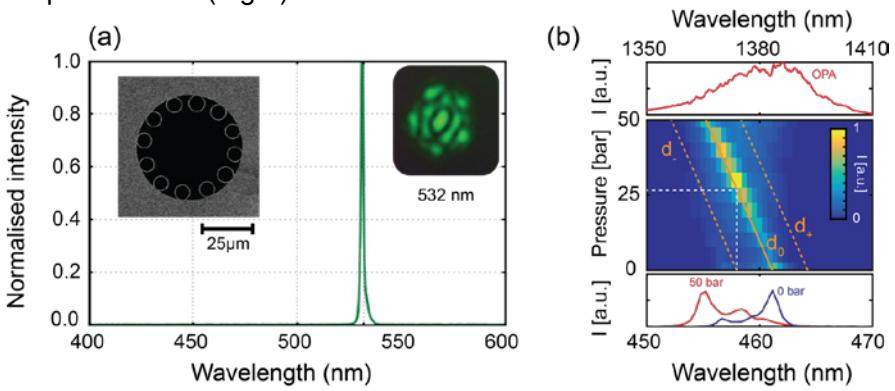


Fig. 1: (a) Third harmonic generation in a Xe-filled hollow-core PCF. The Insets show an SEM of the fibre and the mode at the generated wavelength. (b) Pressure tuning third harmonic in a tapered fibre embedded in an Ar-filled gas-cell.

In both cases the gas-pressure reveals a powerful handle to fine-tune the generation of third harmonic. We also show a newly designed microstructured fiber (Fig.2), which allows phase matching between single-lobbed spatial modes [3].

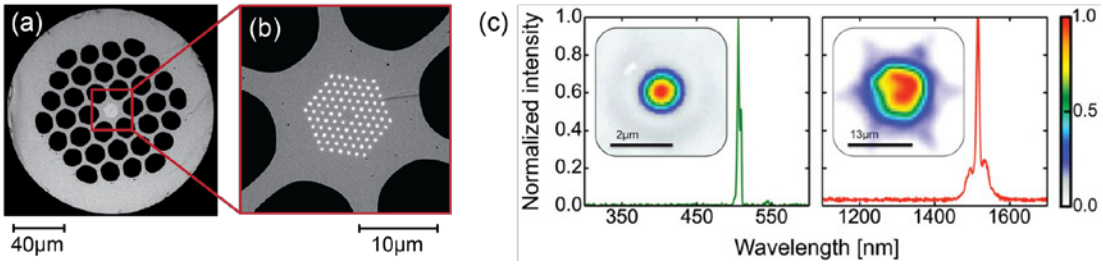


Fig. 2: (a,b) micrograph of the hybrid PCF made of SF6 and LLF1 glass. (c) Experimental spectrum of the generated third-harmonic. The insets show the mode at the pump and the third-harmonic wavelengths.

[1] J. Nold *et al.*, "Pressure-controlled phase matching to third harmonic in Ar-filled hollow-core photonic crystal fiber," Opt. Lett. **35**, 2922 (2010)
[2] A. Cavanna *et al.*, "Photonic crystal fiber designs for third-harmonic and photon triplet generation," OSA Non linear Optics topial meeting, Hawai, paper NTh2A.7 (2017)
[3] A. Cavanna *et al.*, "Hybrid photonic-crystal fiber for single-mode phase matched generation of third harmonic and photon triplets," Optica **3**, 952 (2016)

What is quantum?

Gerd Leuchs,
Max-Planck-Institute for the Science of Light, Erlangen, Germany

Sometimes the boundary between quantum and classical systems seems diffuse. The discussion in the talk will attempt to make the distinction clear.

Hybrid Atomic-Photonics: New Paradigm for Integrated Quantum Optics

Hadiseh Alaeian

5. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

Atoms with narrow-line resonances play a major role in high precision measurements like magnetometry and atomic clocks. Due to their long inherent coherence time, atoms can serve as quantum memories as well. Moreover, as they possess well-defined electronic levels, coherent interactions with the photon fields can be used to manipulate their quantum states very precisely. Besides, the capability of the optical excitation and read out, increase the spatial resolution of the atomic sensors. Within the last couple of decades interfacing atoms with engineered confined light fields has been a proper playground for investigating various quantum-electrodynamical effects. So far different strategies have been utilized successfully to integrate atoms with a confined light field, for example in high-finesse optical cavities, hollow core fibers, and tapered nanofibers.

While cold atom setups provide ideal conditions and controllability to explore different coupling regimes, the large setups required to cool and trap the atoms have hindered their scalability for any realistic quantum networks. Thermal vapors, on the other hand, allow for less precision and control, but their low technical complexity and suitable compatibility with miniaturization and integration make them a promising candidate for realizing scalable networks.

In this talk, I review our recent results on integrated thermal vapors with engineered light fields. Since the velocity of the atoms in a thermal vapor limits their coherence times a larger coupling rate is required to control the atoms efficiently. To achieve a larger Rabi frequency while still having reasonable laser power we have used Nano-photonic devices with tightly-focused electromagnetic fields and small mode-volumes. In particular, we have investigated the interaction between atomic transitions in the thermal vapor of rubidium (Rb) and optical modes of Si_3N_4 waveguides, ring resonators, and Mach-Zehnder interferometers. Moreover, I will briefly introduce the Monte-Carlo simulation method that has been developed in our group to model the interaction of the atoms with the device by properly incorporating the surface effects via Casimir-Polder potentials. In addition to the tailored atom-light manipulations, strong atom-atom interactions in particular between Rydberg atoms can be used to realize quantum devices and strong nonlinearities. Utilizing these features, we demonstrate a completely new single-photon source that benefits from four-wave mixing and Rydberg blockade to generate single photons in an on-demand time window. Besides, I will present some of our most recent results on two-photon spectroscopy and its potential and promise for compatibility with the well-established silicon photonics technology. The talk will be concluded with some of our ideas and perspectives for using this platform for cavity QED studies and devising new schemes for investigating atom-atom interactions in a low-dimensional light field.

Towards off-resonant Raman quantum memory in an isotopically pure rare-earth-ion doped crystals

R.A. Akhmedzhanov[1,2], L.A. Gushchin[1,2], S.L. Korableva[3], N.A. Nizov[1], V.A. Nizov[1], D.A. Sobgayda[1,2], I.V. Zelensky[1,2], A.A. Kalachev[2]
[1]Institute of Applied Physics of the Russian Academy of Science, Nizhny Novgorod, Russia
[2]Zavoisky Physical-Technical Institute,
Federal Research Center "Kazan Scientific Center of RAS", Kazan, Russia
[3]Kazan Federal University, Kazan, Russia
e-mail: a.a.kalachev@mail.ru

In recent years, much effort has been directed towards the implementation of optical quantum memories, which form a platform for developing scalable all-optical quantum computers and quantum repeaters. The most promising approaches to the problem involve interaction of light with atomic ensembles. Among them, isotopically pure rare-earth-ion-doped solids are of particular interest. They can demonstrate very small inhomogeneous broadening of optical transitions, reaching tens of MHz [1, 2], which proves to be smaller than the hyperfine splitting of the energy levels of impurity ions. As a result, these crystals are promising candidates for implementing memory protocols based on off-resonant Raman interaction [3–5].

In this presentation, theoretical and experimental results obtained recently on the way to realization of such quantum memories are discussed. In particular, isotopically pure crystals $Y^7LiF_4:^{143}Nd^{3+}$ demonstrating inhomogeneous broadening of optical absorption lines about 34 MHz were grown and studied. Free-space [6] and cavity-assisted [7] optical quantum memory protocols based on atomic frequency comb was demonstrated in such crystals. 15-fold enhancement in quantum memory efficiency was achieved for the cavity case. Promising Λ-structures for implementing off-resonant Raman interaction were determined and signal-to-noise ratio was estimated for the case of single-photon absorption and emission [8]. Finally, electromagnetically induced transparency has been observed in a symmetrical Λ-like system formed by two hyperfine sublevels of the ground state corresponding to a zero first order Zeeman (ZEFOZ) transition [9].

[1] C.W. Thiel, T. Böttger, R.L. Cone // J. Lumin. 131, 353 (2011)
[2] N. Kukharchyk, et al. // Optics Letters, 43, 935 (2018)
[3] X. Zhang, A. Kalachev, O. Kocharovskaya // Phys. Rev. A 87, 013811 (2013).
[4] A. Kalachev, O. Kocharovskaya // Phys. Rev. A 88, 033846 (2013).
[5] X. Zhang, A. Kalachev, O. Kocharovskaya // Phys. Rev. A 90, 052322 (2014).
[6] R.A. Akhmedzhanov, et al. // Laser Physics Letters 13, 015202 (2016)
[7] R.A. Akhmedzhanov, et al. // Laser Physics Letters 13, 115203 (2016)
[8] A. D. Berezhnoi, A.A. Kalachev // Quantum Electronics 47, 790 (2017)
[9] R.A. Akhmedzhanov, et al. // arXiv: 1711.05720

Magic wavelength for 1.14 um clock transition in Thulium

E. Kalganova[1,2], A. Golovizin[1,2], D. Tregubov[1,2], D. Shevnin[1], V. Bushmakin[1], D. Sukachev[1,2,3], K. Khabarova[1,2], V. Sorokin[1,2], N. Kolachevsky[1,2]

[1] P.N. Lebedev Physical Institute, Leninsky prospekt 53, 119991 Moscow, Russia

[2] Russian Quantum Center, 100 Novaya St., Skolkovo, Moscow 143025, Russia

[3] Harvard University, Department of Physics, Oxford St. 17, Cambridge, 02138 Massachusetts, USA

e-mail: kalganova.elena@gmail.com

Our group works on development of thulium-based optical lattice clock. The clock utilises magnetic-dipole transition $4f^{13}(^2F^o)6s^2$ (J = 7/2, F = 4) → $4f^{13}(^2F^o)6s^2$ (J = 5/2, F = 3) at λ = 1.14 um with natural linewidth of γ= 1.2 Hz. Here we report on the experimental study of the properties of clock transition.

An optical lattice magic wavelength (MWL) for thulium clock transition has been predicted to be near 807 nm [1]. We use a tunable Ti:Sa laser to form the 1D optical lattice for an experimental search of MWL. To increase the dipole trap depth range for precise MWL determination we have built power enhancement cavity with finesse $F \approx 10$. We interrogate ($F = 4$, $m_F = 0$)→($F = 3$, $m_F = 0$) clock transition to avoid line broadening caused by linear Zeeman effect and shift due to dipole-dipole interaction. The ($F = 4$, $m_F = 0$) state is prepared using optical pumping by linearly polarized light which is slightly detuned from (F=4)→(F=4) transition at 530.7 nm. Since the transition ($F = 4$ $m_F = 0$) → ($F = 4$ $m_F = 0$) is forbidden, the population accumulates at $m_F = 0$ sub-level.

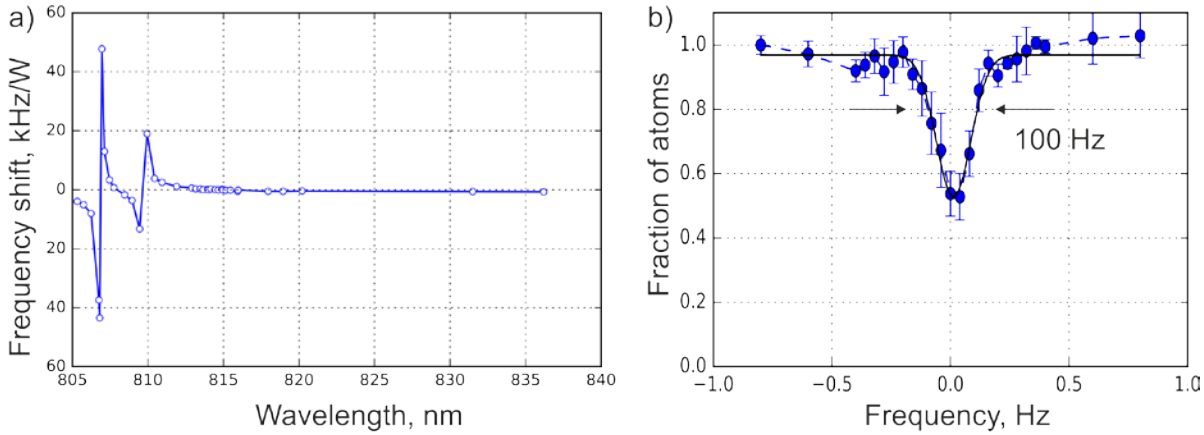


Fig. 1 a) Clock transition frequency shift per 1W optical lattice power vs. lattice wavelength. b) Clock transition spectral line recorded at lattice wavelength 814.4 nm.

We have measured the dependence of the clock transition frequency shift on lattice wavelength in the range 805-837 nm (Fig. 1a) and experimentally determined positions of two magic wavelengths at 808 nm and 814.5 nm. The clock transition linewidth near MWL narrows up to Fourier limit of 100 Hz for 10 ms probe clock pulse (Fig. 1b). Two features at 807 nm and 809.5 nm correspond to transitions from the upper clock level. It is seen that clock transition frequency shift levels off to very small value for lattice wavelengths larger than 820 nm. That confirms our theoretical prediction of small (<2 a.u.) differential static polarizability of the clock levels which corresponds to 20 mHz frequency shift at 300 K that is comparable to Al+ ion clock [2]. The total estimated frequency uncertainty of thulium-based optical clock is 5×10^{-18} in fractional units [1].

[1] D. Sukachev et al. "Inner-shell magnetic dipole transition in Tm atoms: A candidate for optical lattice clocks.", *Phys. Rev. A* **94(2),** 022512 (2016)

[2] A. D. Ludlow et al., "Optical atomic clocks", *Rev. Mod. Phys.* **87**, 637 (2015)

A new technique for ghost imaging: ghost photoanisotropic objects imaging

A.S. Chirkin, S.A. Magnitskiy, P.P. Gostev

M.V. Lomonosov Moscow State University, Moscow 119992, Russia

The method of ghost imaging (GI) in optics was proposed and implemented for the first time in the mid-90s of the last century. The first experiment was based on correlated quantum states. It was later discovered that ghost images can be observed with thermal spatially incoherent light. The field of application of GI concepts is constantly expanding. The time variant is implemented, i.e. recovery of information in time signals .There is a proposal to transfer the GI method to the terahertz spectral region. Ghost images in the x-ray range were observed. Recently GI concept was implemented for electron beams and for pairs of cold helium atoms. However, all known GI schemes refer to isotropic objects, i.e. to objects that do not change the polarization state of the test radiation. Therefore, the polarization state of the radiation illuminating the object did not play a role. At the same time, in many cases, valuable information about the properties of an object is contained in the polarization state of the field scattered by the object or transmitted through it. The purpose of this contribution is to show that the GI principle can be transferred to objects with a polarization-sensitive structure (e.g., anisotropic objects or biological tissue).

Squeezed vacuum from a whispering gallery mode resonator

Alexander Otterpohl[1,2], Florian Sedlmeir[1,2], Gerhard Schunk[1,2], Thomas Dirmeier[1,2], Golnoush Shafiee[1,2], Ulrich Vogl[1,2], Dmitry Strekalov[1,2], Tobias Gehring[3], Harald G. L. Schwefel[4], Ulrik L. Andersen[3], Gerd Leuchs[1,2], and Christoph Marquardt[1,2]

[1]Max Planck Institute for the Science of Light, Staudtstraße 2, 91058 Erlangen, Germany
[2]Department of Physics, University of Erlangen-Nuremberg, Staudtstraße 7/B2, 91058 Erlangen, Germany
[3]Department of Physics, Technical University of Denmark, Fysikvej, 2800 Kgs. Lyngby, Denmark
[4]The Dodd-Walls Centre for photonic and Quantum Technologies, Department of Physics, University of Otago, 730 Cumberland Street, 9016 Dunedin, New Zealand
florian.sedlmeir@mpl.mpg.de

Strong nonlinear interactions require large optical fields. One of the most successful platforms to efficiently excite nonlinear effects with continuous wave pump fields are optical resonators where long confinement times and small mode volumes can be achieved. A particularly powerful platform for nonlinear interactions is a whispering gallery mode (WGM) resonator since it combines several beneficial properties: high Q-factors, a rich mode structure over a wide frequency range, small mode volume within the dielectric host material and a tuneable coupling rate.

We are working with millimeter sized optical WGM resonators made from single crystalline lithium niobate. In those high-Q ($\sim 10^7$ - 10^8) devices, we achieve ultra-efficient parametric down conversion (PDC) with oscillation thresholds in the microwatt pump regime [1]. Below oscillation threshold, photon pairs (signal and idler) are generated, which can be used to prepare heralded single photon states. We demonstrated that WGM resonators are a particularly versatile single photon source: due to the evanescent coupling mechanism, the bandwidth of the single photons is tuneable and strong geometric dispersion allows to tune their wavelength over hundreds of nanometers [2]. In addition, truly single mode operation without additional filtering can be achieved by exploiting the complex phase-matching conditions in a WGM resonator [3].

When the OPO is tuned to the degenerate point, signal and idler photons are no longer distinguishable since they have identical wavelength and polarization. In this mode of operation, the vacuum squeezed light is generated. We demonstrate for the first time a WGM based OPO tuned to the degenerate point, where we are able to measure vacuum squeezing close to the oscillation threshold of a few microwatt. Currently, the observed squeezing (~1.5dB) is limited by our capability to overcouple the resonator. This, however, is only a technical limitation and can be overcome by engineering the coupling and reducing the resonator size. Reasonable squeezing values at sub-milliwatt level pump powers can be expected.

[1] J. U. Fürst, D. V. Strekalov, D. Elser, A. Aiello, U. L. Andersen, Ch. Marquardt, and G. Leuchs, "Low-Threshold Optical Parametric Oscillations in a Whispering Gallery Mode Resonator" Phys. Rev. Lett. **105**, 263904 (2010).

[2] M. Förtsch, J. U. Fürst, C. Wittmann, D. V. Strekalov, A. Aiello, M. V. Chekhova, C. Silberhorn, G. Leuchs, and Ch. Marquardt, "A Versatile Source of Single Photons for Quantum Information Processing" Nat. Commun. **4**, 1818 (2013)

[3] M. Förtsch, G. Schunk, J. U. Fürst, D V. Strekalov, T. Gerrits, M. J. Stevens, F. Sedlmeir, H. G. L. Schwefel, S. W. Nam, G. Leuchs, and Ch. Marquardt, "Highly efficient generation of single-mode photon pairs using a crystalline whispering gallery mode resonator" Phys. Rev. A **91**, 023812 (2015)

Spatially distributed genuine multipartite entanglement enables EPR steering of Bose-Einstein condensates

P. Kunkel[1], **M. Prüfer**[1], **H. Strobel**[1], **D. Linnemann**[1], **A. Frölian**[1], **T. Gasenzer**[1], **M. Gärttner**[1], **and M. K. Oberthaler**[1]

[1] *Kirchhoff-Institut für Physik, Universität Heidelberg, 69120 Heidelberg, Germany*

e-mail: *philipp.kunkel@kip.uni-heidelberg.de*

Heisenberg's uncertainty relation poses a fundamental limit on the simultaneous knowledge of two noncommuting observables. Yet, quantum mechanics allows for nonlocal correlations between two systems such that a measurement in one system allows for prediction of the outcome in the other one with a precision beating the local uncertainty limit which is known as Einstein-Podolsky-Rosen (EPR) steering [2]. These nonclocal correlations are one of the key resources for quantum technologies. Here, we experimentally show that entanglement, which is produced in a Bose-Einstein condensate (BEC) by local contact interactions in a single spatial mode, can be spatially distributed to yield nonlocal correlations which we verify by demonstrating EPR steering (see Fig. 1). Our experiment illustrates that entanglement of indistinguishable particles can be mapped to individually addressable subsystems, which has been proposed recently [3, 4]. This kind of entanglement is therefore as useful, in the sense of the LOCC (local operation and classical communication) paradigm, as entanglement between distinguishable particles.

We start our experiment with a BEC consisting of $N \approx 11,000$ ^{87}Rb atoms held in a crossed optical dipole trap. The atoms are prepared in the magnetic substate $m_\mathrm{F} = 0$ of the $F = 1$ hyperfine manifold. We use spin mixing to coherently populate the states $m_\mathrm{F} = \pm 1$ with atom pairs which is equivalent to spin nematic squeezing [5]. Since the atoms of the BEC are in principle indistinguishable, the correlations are shared among all atoms in the atomic cloud. By switching off the longitudinal confinement, the BEC expands in the remaining wave-guide potential and the entanglement is distributed in space. After expansion, we read out the relevant spin observable by applying a resonant rf-pulse followed by state selective absorption imaging. The high optical resolution of our imaging system enables the definition of distinct systems by partitioning the absorption signal. We measure two noncommuting spin observables and find in each partition that the fluctuations well exceed the local uncertainty constraint. Yet, we show that the measurement outcome in one subsystem of the atomic cloud can be used to infer the result in the remaining part better than allowed by the fundamental local uncertainty, which verifies that these parts are EPR entangled.

By partitioning the absorption signal into three parts of equal length we demonstrate that each part is steered by the remaining ones. This confirms three-way steering. To further elucidate the multipartite character of the generated entanglement, we construct a witness which connects the inference value of bipartite EPR steering to genuine multipartite entanglement. With this witness we reveal up to genuine five-partite entanglement.

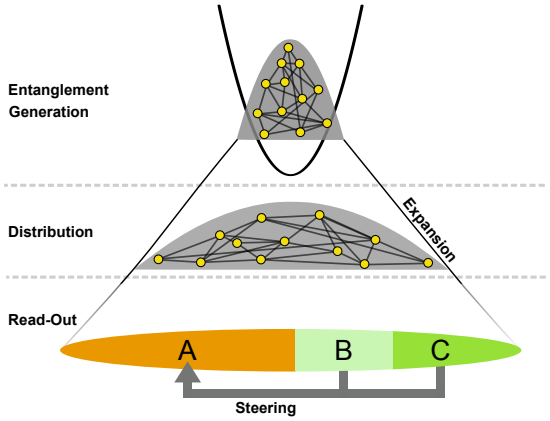


Figure 1: Experimental scheme to distribute entanglement in space [1].

[1] P. Kunkel et al., arXiv:1708.02407 [cond-mat.quant-gas] (2017).

[2] M. D. Reid et al., Rev. Mod. Phys. **81**, 1727-1751 (2009).

[3] P. Hyllus, L. Pezzé, A. Smerzi, and G. Tóth, Phys. Rev. A **86**, 012337 (2012).

[4] N. Killoran, M. Cramer, and M. Plenio, Phys. Rev. Lett. **112**, 150501 (2014).

[5] C. D. Hamley, C. S. Gerving, T. M. Hoang, E. M. Bookjans, and M. S. Chapman, Nat. Phys. **11**, 167-172 (2015)

Widely tunable OPO at MID-IR spectral region based on new nonlinear crystals

Dmitry Kolker[1,2,3], A.Boyko[1,2], N.Kostyukova[1,2]

[1]Research Laboratory of Quantum Optics Technology, Novosibirsk State University, 1 Pirogova St., 630090Novosibirsk, Russia

[2]Institute of Laser Physics SB RAS, Akad.Lavrentyeva Ave. 13/3, 630090 Novosibirsk, Russia

[3]Novosibirsk State Technical University, K. MarksaAve. 20, 630072 Novosibirsk, Russia

We are reporting about progress in development of MID-IR sources based on $LiGaSe_2$(LGSe), $BaGa_4Se_7$(BGSe)and fan-out PPLN OPO pumped by Nd:YAG and Nd:YLF laser at 1 μm.LGSe is related to orthorhombic lithium ternary chalcogenides with the chemical formula $LiBC_2$, where B=In or Ga and C=S or Se. The first time LGSe was reported at [1]. LGSe and $LiGaS_2$ (LGS) have the same symmetry (point group ***mm2***, space group $Pna2_1$), their bandgaps at room temperature are 3.13 and 3.62 eV, respectively [1, 2]. Some observations on the relation between the stoichiometry of LGSe and LGS and their color were also described in [3]. The LGSe transparency allowed covering a spectral range above 4 μm. Also LGSe are promising nonlinear crystal for conversion of laser radiation to the mid-IR spectral range and can be pumped by ~1 μm laser without two-photon absorption. Recently two new promising ternary chalcogenide compounds have been successfully synthesized in large size using the Bridgman-Stockbarger technique: $BaGa_4S_7$ (BGS) [4-6] and BGSe [6-8].BGSe nanosecond optical parametric oscillator pumped at 1 μm[9, 10]. Damage threshold measurements yielded values as high as 2.04 J/cm^2 at 100 Hz pulse repetition rate, one of the largest among existing MIR $\chi^{(2)}$nonlinear materials.

Fan-out quasi-phase-matched nonlinear-optical structures are attractive for laser frequency down-conversion from near-IR to mid-IR region in optical parametric oscillator (OPO), or wise version for up-conversion by second-harmonic generation (SHG). We are reporting about multispectral OPO based on PPLN fun-out structure pumped by nanosecond Nd:YAG laser. For the generation of wide spectral range from 2.7 to 4.2 μm the full aperture (3×20 mm^2) of structure (Λ=27.5-32.5 μm) was used. In this paper, a LGSe OPO pumped by a nanosecond Nd:YAG laser is presented. The OPO spectral tuning range from 4.8 up to 9.9 μm was demonstrated[11] here by angle tilting of the LGSe element in the OPO cavity. Mid-infrared idler wave tuning from 2.6 μm to 10.4 μm is demonstrated [9]with an angle-tuned type-I (*o-ee*) BGSe*y*-cut sample, highlighting the superior performance of this novel large bandgapchalcogenide nonlinear crystal to generate tunable coherent radiation over its full MIR transparency range (0.47 – 18 μm).

References

[1] A. Eifler, V. Riede, J. Brückner, S. Weise, V. Krämer, G. Lippold, W. Schmitz, K. Bente, W. Grill: 2000, *Jpn. J. Appl. Phys*. **39**, Suppl. 39-1, 279

[2] K. Kuriyama, T. Nozaki: 1981, J. Appl. Phys. 52, 6441

[3] J. Brückner, "I-III-VI-Verbindungshalbleiter mit Lithium als Gruppe I-Element: Kristallzüchtung und Charakterisierung", Dissertation, Albert-Ludwigs-Universität, Freiburg i.Br. (1997)

[4] Schunemann P G, Pomeranz L A and Magarrell D J 2015 First OPO based on orientation-patterned gallium phosphide (OP-GaP) 2015 *CLEO 2015 Digest, paper* SW3O.1 (Optical Society of America, 2015).

[5] Lin X, Zhang G and Ye N 2009 Growth and Characterization of $BaGa_4S_7$: A new crystal for mid-IR nonlinear Optics*Crystal Growth & Design***9** 1186-89

[6] Guo Y, Zhou Y, Lin X, Chen W and Ye N 2014 Growth and characterizations of $BaGa_4S_7$ crystal*Opt. Materials***36** 2007-2011

[7] Badikov V, Badikov D, Shevyrdyaeva G, Tyazhev A, Marchev G, Panyutin V, Noack F, Petrov V and Kwasniewski A 2011 $BaGa_4S_7$: wide-bandgap phase-matchable nonlinear crystal for the mid-infrared*Opt. Mat. Express***1** 316-20

[8] Badikov V, Badikov D, Shevyrdyaeva G, Tyazhev A, Marchev G, Panyutin V, Petrov V and Kwasniewski A 2011 Phase-matching properties of $BaGa_4S_7$ and $BaGa_4Se_7$: Wide-bandgap nonlinear crystals for the mid-infrared*Phys. Status Solidi RRL***5** 31-33

[9] D.B. Kolker et al J. Phys. Commun. 2 035039 (2018)

[10] Nadezhda Y. Kostyukova, Andrey A. Boyko, Valeriy Badikov, Dmitrii Badikov, Galina Shevyrdyaeva, Vladimir Panyutin, Georgi M. Marchev, Dmitry B. Kolker, and Valentin Petrov "Widely tunable in the mid-IR $BaGa_4Se_7$ optical parametric oscillator pumped at 1064 nm" Opt. Lett. 41(15) 3667-3670 (2016).

[11] V.Vedenyapin, A Boyko, D Kolker, L Isaenko, S Lobanov, N Kostyukova, A Yelisseyev, J-J Zondy and V Petrov, "$LiGaSe_2$ optical parametric oscillator pumped by a *Q*-switched Nd:YAG laser", Laser Physics Letters 13(11).

High-resolution spectroscopy of cold Mg atoms

A.N. Goncharov[1,2,3], A.E. Bonert[1], M.A. Tropnikov[1], V.I. Baraylia[1], S.A. Kuznetsov[1]

[1]Institute of Laser Physics SB RAS, pr. Lavrent'eva 13/3, 630090 Novosibirsk, Russia
[2]Novosibirsk State University, st. Pirogova 2, 630090 Novosibirsk, Russia
[3]Novosibirsk State Technical University, pr. Karla Marksa 20, 630092 Novosibirsk, Russia

This paper presents the results of experimental studies aimed at the development of an optical frequency standard based on ultra-cold magnesium atoms with relative frequency uncertainty and long- term stability at the level of $\Delta\nu/\nu$ 10^{-17} -10^{-18}. The cloud of cooled Mg atoms localized in the magneto-optical trap (MOT) was interrogated with time separated laser pulses resonant to $^1S_0$-$^3P_1$ transition [1]. Narrow Ramsey-Borde fringes with the width of 390 Hz (HWHM) were detected. We stabilized the frequency of our clock laser system at 457 nm to narrow fringes. The results of stabilization were studied with femtosecond comb based on Ti:Sa laser. Long-term stability of $\sigma(\tau) \sim 5\ 10^{-15}$ at averaging time $\tau = 10^3$ was obtained [2,3].

We also present our theoretical an experimental efforts [4,5] to deep laser cooling of Mg atoms to a temperature of about 10-50 μK for further their localization in an «optical lattice».

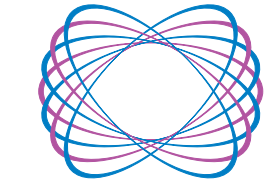
The work was supported by the Russian Science Foundation (project no. 16-12-00054).

[1] A. N. Goncharov *et al.*, Quantum Electron. 44, 521 (2014).
[2] A.N.Goncharov *et al*. Journal of Physics: Conf. Series 793, 012008 (2017).
[3] A.N.Goncharov *et al*, Frequency stabilization of laser radiation on the narrow resonances of cold magnesium atoms, Quantum Electron. 48, #5 (2018) (to be published).
[4] O.N. Prudnikov *et al*, Quantum Electron., **46**, 661 (2016).
[5] O.N. Prudnikov *et al* Journal of Physics: Conference Series. 793, 012021 (2017).

Ответственный редактор: С. М. Ахмин, технический редактор О. Б. Яндуганова.
Издательство КФТИ ОСП ФИЦ КазНЦ РАН, 420029, Казань, Сибирский тракт, 10/7, лицензия № 0325 от 07.12.2000.

Отпечатано с оригиналов заказчика

АЦП “Линк” · Казань, ул. Карла Маркса 51, телефон +7 (843) 251-55-61



ФИЗТЕХПРЕСС