Light-Matter Interfaces for Quantum Enhanced Technologies

Hotel Sol Marina Palace, Nessebar, Bulgaria, September 9 – 12, 2019

LIMQUET SCHOOL

BOOK OF ABSTRACTS

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Svetoslav Ivanov and Nikolay Vitanov

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Programme

Monday, September 9

Morning Session

09:00-10:00 **Gérard Colas des Francs**, *cQED-like description for quantum plasmonics*

10:00-11:00 **Dominique Sugny**, *Optimal control with applications in quantum technologies*

11:00-11:30 **Coffee break**

Noon Session

11:30-13:00 **Gheorghe Sorin Paraoanu**, *Introduction to quantum information processing with superconducting qubits*

Evening Session

17:00-17:20 **Muhammad Ahmed**, *Towards glass integrated platform dedicated to quantum optics*

17:20-17:40 **Juan Rafael Alvarez Velasquez**, *Cavity-based photon-generation schemes using STIRAP re-preparation*

17:40-18:00 **Al-Mahmoud**, *Broadband Polarization Rotator*

18:00-18:20 **Akshay Balgarkashi**, *Double Photonic Structure with Quantum Dot in Nanowire*

18:20-18:40 **Hayk Gevorgyan**, *Ultrahigh-Fidelity Composite Rotation Gates*

18:40-19:00 **Mark IJspeert**, *Single-atom trapping with optical tweezers for deterministic cavity loading*

Tuesday, September 10

Morning Session

09:00-10:00 **Boris Naydenov**, *Quantum control of spins using Nitrogen Vacancy centres in diamond*

10:00-11:00 **Andon Rangelov**, *Classical physics analogues of quantum systems*

11:00-11:30 **Coffee break**

Noon Session

11:30-13:00 **Simon Pigeon**, *Polariton fluid of light*

Evening Session

17:00-17:40 **Bruce Shore**, *Tips on talks – how to present a seminar*

17:40-18:20 **Bruce Shore**, *Tips on writing – how to write a technical paper*

18:20-19:00 **Business Meeting**

Wednesday, September 11

Morning Session

09:00-10:00 **Patrick Cheinet**, *Rydberg atoms and their interactions I*

10:00-11:00 **Patrick Cheinet**, *Rydberg atoms and their interactions II*

11:00-11:30 **Coffee break**

Noon Session

11:30-13:00 **Matthias Wollenhaupt**, *Ultrafast coherent control of electron wave packets*

Evening Session

17:00-17:20 **Kirthanaa Indumathi**, *Frequency-bin Entanglement: The engineering process*

17:20-17:40 **Ana Mićević**, *Universal electro-optic modulator*

17:40-18:00 **Mackrine Nahra**, *Single photon source in nanodiamonds for integrated quantum photonics*

18:00-18:20 **Corentin Pignot**, *Strong coupling of a single ion to a cavity*

18:20-18:40 **Mateja Pršlja**, *Microscopy/spectroscopy with single photon detection and high timing resolution*

18:40-19:00 **Astghik Saharyan**, *Microscopic and phenomenological models of driven systems in structured reservoirs*

19:00-19:20 **Xiao Yu**, *Photonic circuits for quantum optics*

Thursday, September 12

Morning Session

09:00-10:00 **Arno Rauschenbeutel**, *Chiral Quantum Optics I*

10:00-11:00 **Arno Rauschenbeutel**, *Chiral Quantum Optics II*

11:00-11:30 **Coffee break**

Noon Session

11:30-12:15 **Boyan Torosov**, *Coherent control via composite pulses*

12:15-13:00 **Genko Genov**, *Introduction to Dynamical Decoupling for Quantum Technologies*

List of Abstracts

TOWARDS GLASS INTEGRATED PLATFORM DEDICATED TO QUANTUM OPTICS

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In the last few years, the excitation of light sources has been successfully implemented using several integrated optical devices within a few nanometers. For example, the excitation of nano-emitters has been realised by surface plasmon polaritons (SPPs) in nano-antennas optical cavities with nanocrystals, nanowires and metallic waveguides. The used materials (silicon and noble metals) for the excitation process are characterized by high losses in the visible spectral range. Our target is how to enhance the light confinement in design integrated device using low-loss materials. Consequently, the coupling between nanostructures and waveguide will increase. Our choice has converged towards ion exchanged optical waveguides (IEW). However, the excitation of the nanostructures with this kind of waveguides is not well-spread because it has low light confinement due to the low index contrast between the core and cladding. In our work one proposal is reported to enhance the field confinement in IEW. Firstly, dielectric thin film of high index material (TiO2, SiC, ZnO, etc.) deposited above IEW is used to increase the light confinement inside the waveguide [11]. The hybrid modes with higher effective indices occur because of the propagation of the guided mode through the structure. Furthermore, two waveguides coupled will appear, due to excited modes of the TiO2 layer resulting from the evanescent wave of the guiding mode in IEW that will enhance the light confinement inside the IEW. The nanosource will be placed on the top of the structure and will be excited by an incident light. Simulation results were obtained using the 3-D finite differential time domain (3-D FDTD) method. Our proposed design will enhance light guidance through the IEW due to the presence of an SiC slab. In this work, the role of the dielectric slab is studied at different thicknesses, lengths, materials and widths to get the optimum dimensions of the slab and study their impacts on enhancing the light confinement and the measured transmission. We demonstrated that the proposed structures allow increasing the measured transmission to 68%. We will also present our recent work on coupling our waveguides with electrically excited plasmon sources.

CAVITY-BASED PHOTON-GENERATION SCHEMES USING STIRAP RE-PREPARATION

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The strong coupling of an atom to a cavity offers unparalleled control over the generation of single photons with tunable properties. Such atom-cavity systems, based on vacuum stimulated Raman processes (V-STIRAP) can provide a priori deterministic photon sources with arbitrary control of the photon amplitude and phase envelope in space, being able to produce photons which are orders of magnitude longer than single photon detector resolutions. Attempts at producing polarized single photons with these schemes have driven magnetic sub-levels of atoms in an alternating order. However, due to nonlinear Zeeman effects, these schemes show low efficiencies when attempting to produce more than two photons sequentially. In this report, a method

to re-prepare the initial magnetic state of a 87Rb atom using two overlapping STIRAP beams is proposed.

BROADBAND POLARIZATION ROTATOR

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We propose a new scheme of a tunable Polarization rotator with arbitrary angle of rotation for a wide range of wavelength. It is composed by a sequence of three wave plates, two of which serve as half wave plates and one serves as a full wave plate with respect to the central wavelength. All the wave plates are intentionally rotated at specific angles with respect to their fast-polarization axes in order that the device is broadband by using the composite pulses analogies, from the quantum mechanics. This rotator is robust against the initial polarization direction as well.

DOUBLE PHOTONIC STRUCTURE WITH QUANTUM DOT IN NANOWIRE

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The goal of this project is to achieve quantum dots in nanowires, possibly in the telecom domain. In this presentation, we will report on progress in the growth of InAs segments on GaAs nanowire arrays on Si substrate by the self-catalyzed method. In order to define pristine InAs segments, we consume the Ga droplet on top of GaAs NWs and replace it with an indium droplet or directly deposit InAs segments. EDX results indicate that InAs accumulates preferentially on the facets close to nanowire tip. By following different growth strategies, we aim to maximize accumulation of InAs at the nanowire top facet. Such InAs segments grown on GaAs nanowires are confined using a GaAs shell capping layer. The optical properties of these segments are investigated using cathodoluminescence spectroscopy.

RYDBERG ATOMS AND THEIR INTERACTIONS

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CQED-LIKE DESCRIPTION FOR QUANTUM PLASMONICS

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INTRODUCTION TO DYNAMICAL DECOUPLING FOR QUANTUM TECHNOLOGIES

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Developments in quantum technologies are increasingly important nowadays for various applications in computation, sensing, and communication of data. However, protection of quantum systems from the environment remains a challenge. In this talk, I will present an overview of the technique of dynamical decoupling (DD), which uses pulses or continuous fields to alter the time evolution of a system and suppress the effect of unwanted noise while retaining sensitivity to particular interactions and signals [1].

First, I will discuss pulsed DD, which has been applied extensively for compensation of environmental noise. Important requirements are high pulse powers to limit dephasing during a pulse and high repetition rate, so refocusing is much faster than the correlation time of the environment. A second approach is continuous DD, where the system is driven with a protecting dressing field for the entire duration of the experiment, and has also been demonstrated to compensate for noise sources in various media, e.g., in color centers in diamond and trapped ions. Finally, I will also discuss a mixed scheme where continuous and pulsed DD are combined to use of the advantages of both pulsed and continuous DD [2].

[1] D. Suter and G. A. Alvarez, Rev. Mod. Phys. 88, 041001 (2016); C. L. Degen, F. Reinhard, and P. Cappellaro, Rev. Mod. Phys. 89, 035002 (2017).

[2] G. T. Genov, N. Aharon, F. Jelezko, and A. Retzker, Quantum Sci. Technol. 4 035010 (2019).

ULTRAHIGH-FIDELITY COMPOSITE ROTATION GATES

H. Gevorgyan

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Quantum rotation gates are key elements in various fields of high-precision technologies, such as quantum information, nuclear magnetic resonance, electron spin resonance, atomic clocks, atomic interferometry, retarders and rotators in polarization optics, etc. In quantum information processing (QIP), rotation gates are the subject of the so-called circuit optimization problem. Here we propose to construct quantum rotation gates by using composite pulses, i.e. so-called composite rotation gates (CRGs). Composite pulse sequences are an efficient, robust and flexible technique for coherent control of quantum systems. They have the remarkable capability to efficiently eliminate systematic errors in one, two or even more experimental parameters. There are two main cost parameters of implementation – the overall gate error and the overall gate run-time. Our objective is to derive CRGs with the highest possible accuracy, bandwidth and the shortest execution time for a certain number of constituent pulses.

We focus at the high-fidelity Hadamard gate, for which we obtain different types of composite pulses, which maintain the fidelity above the 99.99% quantum computing benchmark. Separate and simultaneous compensation of different systematic errors is studied numerically. The results significantly expand the possible experimental variants beyond the well-known pulses that are analytically found in the so-called nuclear magnetic resonance quantum computing (NMR QC).

SINGLE-ATOM TRAPPING WITH OPTICAL TWEEZERS FOR DETERMINISTIC CAVITY LOADING

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Efficient single-atom single-photon interfaces are essential to many applications in quantum information processing. The potential of such hybrid systems for the delivery of single photons and distributed entanglement has been demonstrated using 87Rb atoms stochastically loaded into a high-

finesse optical cavity to achieve strong coupling [1]. Whilst this source constitutes an excellent testbed, probabilistic loading limits the scalability of its design. In addition, the ballistic transit of atoms across the cavity mode gives rise to time-dependent coupling strengths. In this work we present techniques for the cooling, trapping and imaging of single atoms [2]. We demonstrate dipole trapping of individual, laser-cooled 87Rb atoms captured from a magneto-optic trap on time scales exceeding 40 s. We analyse the effect of trap depth and optical molasses density on the lifetime and average occupation of the dipole trap. Such a deterministic means of holding a single atom in place is an important step towards the deterministic cavity loading scheme required for a scalable atom-photon quantum interface.

[1] T. D. Barrett et. al., Quantum Science and Technology 4(2), 025008, (2019).

[2] N. Holland et. al., Journal of Modern Optics 65(18), 21332141, (2018).

FREQUENCY-BIN ENTANGLEMENT: THE ENGINEERING PROCESS

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Our group has been designing and performing proof of concept experiments majorly focused on frequency-bin entanglement since 2010. Entanglement manipulation in the frequency domain is a relatively new concept and has recently gained attention for its robustness and scalability. Entanglement manipulation in the frequency domain is an attractive candidate to replace other conventional manipulation systems because (i) the frequency domain naturally offers high dimensionality, and (ii) building blocks such as frequency entangled source, modulators and filters involved in the manipulation method 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.

This talk covers the basics of frequency-bin entanglement and provides the experimental results and insights into implementing novel manipulation techniques to make the system more efficient, stable and robust.

UNIVERSAL ELECTRO-OPTIC MODULATOR

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Precise control over all properties of light is essential not only for experimental studies of light-matter interaction, but also for successful integration of technologies in quantum systems. Electro-optic modulators (EOMs) are standard components in laboratories since they offer a fast and versatile tool for manipulation of various light properties, making them ideal for amplitude, phase, frequency and position tuning of lasers. However, with the current commercially available technologies, it is necessary to use different electro-optic devices to address different properties of light, which increases the complexity of the optical systems. Here I present the first step towards the creation of a universal EOM that provides different types of modulation at once in a single device. I present the basic working principle of a device that combines phase and amplitude modulation, as well as the experimental tools necessary for its characterization.

SINGLE PHOTON SOURCE IN NANODIAMONDS FOR INTEGRATED QUANTUM PHOTONICS

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The negatively charged silicon-vacancy (SiV-) centers in diamonds have emerged as a very promising candidate for quantum emitters due to their narrow emission line.[1] Modifying the emission properties and enhancing the interaction strength of (SiV-) coupled to a novel nanophotonic platform, based on the so called ion exchange waveguides, is a challenge for integrated quantum photonics.

This work aims to study and compare physical properties of nanodiamonds NDs and optical properties of SiV- centers in NDs prepared under the same HPHT conditions [2] but with different conditions. We present the effect of growth temperature, and treatment methods on the morphology, crystallinity of nanodiamonds and on the optical properties of SiVin nanodiamonds.

[1] Sternschulte H., et al. Physical Review B, 50.19 (1994).

[2] V. Davydov, et al. JETP Letter 99, pp. 673–678 (2014).

QUANTUM CONTROL OF SPINS USING NITROGEN VACANCY CENTRES IN DIAMOND

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Colour centres in diamond and especially the nitrogen-vacancy centres (NVs), show remarkable physical properties making them good candidates for quantum bits, single photon sources and precise magnetic field sensors with a nanometre spatial resolution. These defects can be measured at the single cite level even at room temperature, allowing to perform a variety of fundamental experiments. In this talk the physics of NV centres with a focus on their spin properties will be reviewed and various applications will be discussed. It will be shown how a single NV centre can be used for imaging magnetic fields with a nanoscale resolution, thus revealing interesting magnetic phenomena. Then the realisation of nanoscale Nuclear Magnetic Resonance (NMR) will be demonstrated, where a single nuclear spin sensitivity is reached. Furthermore, NV centres can be used not only for the detection of nuclear spins, but also for their control, allowing to implement Dynamic Nuclear Polarisation (DNP) for improving NMR signals by few orders of magnitude. Finally, a solid state quantum simulator based on a 2D layer of nuclear spins in the vicinity of a single NV will be presented.

INTRODUCTION TO QUANTUM INFORMATION PROCESSING WITH SUPERCONDUCTING QUBITS

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POLARITON FLUID OF LIGHT

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STRONG COUPLING OF A SINGLE ION TO A CAVITY

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The strong coupling regime between an ion and a cavity is of vital importance for many quantum information scheme. During this talk, I will present how we are reaching strong coupling in our setup with the use of cavity cooling for cooling the ion instead of regular Doppler cooling.

MICROSCOPY/SPECTROSCOPY WITH SINGLE PHOTON DETECTION AND HIGH TIMING RESOLUTION

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Microscopes are one of the devices, that are highly needed in various scientific areas, e.g. biology, medicine, material science, chemistry etc. Today exist plenty of microscopic techniques with high plane, vertical or time resolution, that are capable of measuring different properties of the sample. To make a satisfying research we would need to use more than one technique, but that requires few microscopes and mowing the sample between them. One of solutions is to combine more techniques into one device, where they could work simultaneously and create informations with high spatial, vertical and time resolution at the same time. I will first present some of the microscopic techniques, the way to unite them and the difficulties of that task. Then I will briefly introduce devices developed by our company qutools, that could be used in a new modulated microscope. I will state few examples of a wanted device, there advantages, disadvantages and how they could be upgraded.

CLASSICAL PHYSICS ANALOGUES OF QUANTUM SYSTEMS

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Analogy is a basic concept for understanding nature, since it analyses and connects different phenomena linked by common properties or similar behavior. Specifically, the analogies between classical physical theories and quantum phenomena reveal the fact that similar mathematical formalisms apply to phenomena that cannot be related in all aspects and are a priori conceptually different. The role of mathematics is crucial, because the essence of the analogy resides in the fact that completely different systems can be modeled by similar mathematical equations.

In particular, analogies between wave optics and quantum mechanics have been highlighted since the early days of quantum mechanics: wave effects like interference and diffraction were borrowed from optics and applied to demonstrate the wavy nature of quantum particles, as electrons, neutrons and atoms. After the full development of quantum theory and the rise of coherent light sources, the exchange of concepts in the opposite direction started to occur.

In this talk I am going to show several formal analogy between the Schrödinger equation of quantum system of two and three states and classical systems.

CHIRAL QUANTUM OPTICS

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MICROSCOPIC AND PHENOMENOLOGICAL MODELS OF DRIVEN SYSTEMS IN STRUCTURED RESERVOIRS

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We study the paradigmatic model of a qubit interacting with a structured environment and driven by an external field by means of a microscopic and a phenomenological model. The validity of the so-called fixed-dissipator (FD) assumption, where the dissipation is taken as the one of the undriven qubit is discussed. In the limit of a flat spectrum, the FD model and the microscopic one remarkably practically coincide. For a structured reservoir, we show in the secular limit that steady states can be different from those determined from the FD model, opening the possibility for exploiting reservoir engineering. We explore it as a function of the control field parameters, of the characteristics of the spectral density and of the environment temperature. The observed widening of the family of target states by reservoir engineering suggests new possibilities in quantum control protocols.

TIPS ON TALKS – HOW TO PRESENT A SEMINAR

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TIPS ON WRITING – HOW TO WRITE A TECHNICAL PAPER

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OPTIMAL CONTROL WITH APPLICATIONS IN QUANTUM TECHNOLOGIES

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COHERENT CONTROL VIA COMPOSITE PULSES

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The technique of composite pulses has the unique advantage of combining ultrahigh accuracy similar to resonant techniques with robustness to parameter imperfections similar to adiabatic passage techniques. It is a method which has been primarily developed in nuclear magnetic resonance several decades ago. In the recent years, however, an increasing interest has been devoted to study the composite pulses, especially in the context of coherent control, quantum optics and quantum information. In this tutorial we introduce the theoretical approach behind the derivation of composite

sequences and review many applications in different physical systems.

ULTRAFAST COHERENT CONTROL OF ELECTRON WAVE PACKETS

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PHOTONIC CIRCUITS FOR QUANTUM OPTICS

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Enhancing the light-matter interaction at single-atom/photon level is required for quantum technologies. The coupling strength depends on the quality factor Q and effective volume V of the involved mode by the ratio Q/V. High and efficient light matter interaction can be achieved in cavity-based systems. In this project, we aim at transposing quantum optics techniques to nanophotonics using hybrid plasmonic-photonic nanostructures taking benefit of sub-wavelength dimensions. Surface plasmon polaritons (modes sustained by metallic nanostructures) present low mode volumes and can interface light and matter at the nanoscale. We propose to use innovative photonic structures with quantum emitters, coupled to 1D and 2D photonic and/or plasmonics waveguides.

In the talk, I will report the fabrication progress and share some results about the quantum dots deposition and Yagi-Uda antenna-planar waveguide coupling. The plan and primary design for the first secondement will also be mentioned.

LIMQUET Programme

Time	Mon, Sep 9	Tue, Sep 10	Wed, Sep 11	Thu, Sep 12
09:00-10:00	Colas des Francs	Naydenov	Cheinet	Rauschenbeutel
10:00-11:00	Sugny	Rangelov	Cheinet	Rauschenbeutel
11:00-11:30	coffee	coffee	coffee	coffee
11:30-13:00	Paraoanu	Pigeon	Wollenhaupt	Torosov/Genov
	Lunch	Lunch	Lunch	Lunch
17:00-17:20	Ahmed	Shore	Indumathi	
17:20-17:40	Alvarez Velasquez		Mićević	
17:40-18:00	Al-Mahmoud	Shore	Nahra	
18:00-18:20	Balgarkashi		Pignot	
18:20-18:40	Gevorgyan	Business	Pršlja	
18:40-19:00	IJspeert	Meeting	Saharyan	
19:00-19:20			Yu	
20:30			**school dinner**	