Optical Nanofibre Applications: From Quantum to Biotechnologies (ONNA 2025)

829. WE-Heraeus-Seminar

16 – 21 March 2025

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 829. WE-Heraeus-Seminar:

Optical nanofibers, also known as nanoscale optical waveguides or nanowires, represent a fascinating class of optical structures with diameters typically on the order of hundreds of nanometers to a few micrometers. These ultrathin fibers, usually made of dielectric or semiconductor materials, exhibit remarkable optical properties that make them versatile platforms for fundamental research and various applications. Whispering-gallery-mode (WGM) resonators are conceptually and technologically closely linked to optical nanofibers because of their shared principle of strong light confinement through total internal reflection, which leads to the formation of evanescent fields that extend beyond the surface of the structure. For this reason, nanofibers and WGM resonators also share many fields of application, ranging from photonics, to quantum optics, to sensing and metrology, to nonlinear optics and frequency conversion, to opto-mechanics.

The last two decades have seen a steady increase in interest and in the size and cohesiveness of the community surrounding optical nanofibers and WGM resonators. This can be attributed to advances in fabrication techniques, a growing understanding of light-matter interactions, the diverse range of applications, and emerging technologies and challenges. At the same time, other nanophotonic platforms and their use in research and applications are also developing rapidly, often inspired by pioneering work with nanofibers and whispering gallery mode resonators. This seminar will bring together experts in (quantum) nanophotonics research and applications to assess the current state of this rapidly evolving interdisciplinary field and to discuss future developments. It will provide a high-profile venue to meet and discuss with the leaders in the field, as well as to promote its relevance and potential to the next generation of researchers.

Scientific Organizers:

Prof. Arno Rauschenbeutel	Humboldt-Universität zu Berlin, Germany E-mail: arno.rauschenbeutel@hu-berlin.de
Prof. Síle Nic Chormaic	OIST Graduate University, Japan E-mail: sile.nicchormaic@oist.jp

Introduction

Administrative Organization:

Dr. Stefan Jorda
Elisabeth Nowotka

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Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday
morning

Program

Program

Sunday, 16 March 2025

17:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Monday, 17 March 2025

08:00	*BREAKFAST*	
08:45 – 09:00	Scientific organizers	**Opening Comments**
09:00 – 09:45	Frank Vollmer	**A single-molecule technology for decoding protein biophysics**
09:45 – 10:30	Nikita Toropov	**Spherical microresonators: From thermo-optoplasmonic single-molecule sensing to cavity quantum electrodynamics effects**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Stephan Goetzinger	**Efficient generation and manipulation of single photons with a single molecule**
11:45 – 12:30	Witlef Wieczorek	**Microcavity optomechanics with suspended photonic crystal reflectors**
12:30	*LUNCH*	

Program

Monday, 17 March 2025

14:00 – 14:20	Antonio Balena	**Fabrication and characterization of deterministic metal nanostructures on tapered optical nanofibers by blurred electron beam-induced deposition**
14:20 – 14:40	Maarten Hoogerland	**States of light generated by cold atoms and mediated by optical nanofibres**
14:40 – 15:00	Minsu Jang	**Fabrication and characterization of large millimeter-scale microbubble cavities with high Q-factor**
15:00 – 15:20	Rusi Lu	**Small-molecule ice micro/nano fibers**
15:20 – 15:30	**Conference photo**	
15:30 – 16:00	*COFFEE and TEA BREAK*	
16:00 – 16:45	Constanze Bach	**Emergence of second-order coherence in superfluorescence**
16:45 – 17:30	Robert Loew	**Hot vapor spectroscopy with integrated photonic waveguides**
17:30 – 17:45	Stefan Jorda	**About the WE-Heraeus-Foundation**
17:45 – 18:30	**Discussion**	
18:30	*DINNER*	
19:30 – 20:30	**Poster Flash talks I**	
Open end	**Poster I**	

Program

Tuesday, 18 March 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Pascal Del'Haye	**Integrated photonics with low temperature SiN and visualization of microresonator modes**
09:45 – 10:30	Hong Tang	**High Purcell photonic resonators for light-atom coupling**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Alper Kiraz	**Advancing biological imaging: From light sheet microscopy to deep learning-enhanced solutions**
11:45 – 12:30	Lan Yang	**Whispering-gallery microresonators sensors: Fundamentals and applications**
12:30	*LUNCH*	
14:00 – 14:30	Mark Sadgrove	**Electron beam methods for optical nanofibers**
14:30 – 15:00	Sylvie Lebrun	**Study of self-heated tapered silica microfibers by laser**
15:00 – 15:30	Abraham Qavi	**Controlling light to reimagine clinical diagnostics**
15:30 – 16:00	*COFFEE and TEA BREAK*	

Program

Tuesday, 18 March 2025

16:00 – 16:45	Aswathy Raj	**Rydberg atom interactions at the interface of an optical nanofiber**
16:45 – 17:30	Sebastian Hofferberth	**Rydberg quantum optics meet nanofibers**
17:30 – 18:30	**Discussion**	
18:30	*DINNER*	
19:30 – 20:30	**Poster Flash Talks II**	
Open end	**Posters II**	

Program

Wednesday, 19 March 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Beatriz Olmos Sanchez	**Modified dipole-dipole interactions in the presence of a nanophotonic waveguide**
09:45 – 10:30	Alexander Poddubny	**Non-hermitian skin effect in waveguide quantum electrodynamics**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Tal Carmon	**Optical resonators of many phases of matter**
11:45 – 12:30	Yulia Semenova	**Recent advances in sensing with optical fibre microresonators**
12:30	*LUNCH*	
14:00 – 18:30	**Excursion**	
18:30	*DINNER*	
19:30 – 20:15	Kerry Vahala	**The new integrated high-Q landscape**
Open end	**Discussion**	

Program

Thursday, 20 March 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Thomas Pohl	**Non-equilibrium phases of dipole-coupled quantum emitters**
09:45 – 10:30	Lucia Hackermueller	**Bayesian sensing and photon storage using atoms in a fibre void**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Hadiseh Alaeian	**Rydberg photonics**
11:45 – 12:30	Jean-Charles Beugnot	**Nanofiber platform to manipulate photons and phonons**
12:30 – 14:00	*LUNCH*	
14:00 – 14:30	Ahreum Lee	**Atomic arrays with tunable spacing coupled to an optical nanofiber**
14:30 – 15:00	Alban Urvoy	**Optical routing with arrays of cold atoms around a nanofiber**
15:00 – 15:30	Saijun Wu	**Toward optical spin-wave control at a ferromagnetic 2D-MOT optical naofiber interface**
15:30 – 16:00	*COFFEE and TEA BREAK*	

Program

Thursday, 20 March 2025

16:00 – 16:45	Silvia Soria	**Microbubble Resonators based Photoacoustic Detection and Characterization of Flowing Contrast Agents in Real Matrixes.**
16:45 – 17:30	Alejandro Gonzalez-Tudela	**Generating and controlling propagating quantum states of light with waveguide QED**
17:30 – 18:00	**Poster Prize Award**	
18:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Friday, 21 March 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Takao Aoki	**Nanofiber cavity quantum electrodynamics systems for distributed quantum computing**
09:45 – 10:30	Chen-Lung Hung	**Collective emission from a dense atomic ensemble coupled to a nanophotonic resonator**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Hanna Le Jeannic	**Photon-photon interactions using single solid-state emitters and waveguides**
11:45 – 12:30	Anders Sørensen	**Quantum computation based on photon-emitters in waveguide**
12:30 – 12:45	Scientific organizers	**Closing remarks**
12:45	*LUNCH*	

End of the seminar

Departure

NO DINNER for participants leaving on Saturday; however, a self-service breakfast will be provided on Saturday morning

Posters

Posters

Samuel Begumya	**Quantum sensing with NV centres in nanodiamonds coupled to optical nanofibres**
Lucien Belzane	**Towards efficient coupling of single nanodiamonds to an optical fiber for single photon emission**
Pablo Bianucci	**Cavity optomechanics in an infinite cylinder**
Xiaoyu Cheng	**Enhancing Atom-Photon Interaction with Integrated Nano-photonic Resonators**
Victor Rueskov Christiansen	**Jaynes-Cummings interaction with a traveling light pulse**
Knut Domke	**Rydberg superatoms coupled with super-extended evanescent field nanofiber at the single-photon level**
Michelangelo Dondi	**Rb-filled hollow-core fibres a novel approach to atomic sensing**
Idriss Douss	**Coupling slow-mode nanophotonics and cold atoms : a versatile Waveguide QED platform**
Xinxin Hu	**Entanglement and coherence in the resonance fluorescence of a two-level quantum emitter**
Krishna Jadeja	**Rydberg interactions with an optical nanofiber**
Kritika Jain	**Efficient long-range entanglement generation using a composite nanofiber waveguide**
Yuan Jiang	**Dynamical beats of short pulses in waveguide QED**
Damandeep Kaur	**Toward a low-cost SERS probe by ion-exchanged processed optical fibers**
Anna Kortel	**Interaction of charged ONF with Rydberg atoms**

Posters

Tangi Legrand	**Rydberg interactions in ultracold Ytterbium**
Ramgopal Madugani	**Whispering gallery mode optimisation by precision microbubble cavity fabrication**
Aseel Mahmood	**Tunable terahertz frequency generation using spherical whispering gallery mode micro-resonators**
Ludwig Müller	**Rydberg superatoms coupled with super-extended evanescent field nanofiber at the single-photon level**
Silpadas Nedoolil	**Towards a room-temperature visible light single photon source by using rare earth ion-doped fibre taper**
Lucas Pache	**Towards the observation of collective radiance phenomena in a one-dimensional array of waveguide-coupled atoms with sub-lambda/2 spacing**
Pramitha Praveen Kamath	**Microparticle manipulation in the evanescent field of an optical nanofibre**
Felipe Quinteros Moro	**Exact solution for two excited atoms in a delay-induced non-markovian multiphoton system.**
Philipp Schneeweiss	**Measuring deviations from a perfectly circular cross-section of an optical nanofiber at the Ångström scale**
Zohreh Shahrabifarahani	**Towards "enhanced directional coupling in ONF-MOT system"**
Stéphane Trebaol	**Near-ultraviolet high-Q whispering-gallery-modes microresonators for laser frequency stabilization**
Xitao Tu	**Ultrasensitive micro/nanofiber sensors and actuators**
Marina Țurcan	**The quantum cooperative description of photons in Raman emission**

Posters

Xueyi Wang	**Ultra-thin silicon nitride micro wheel-resonator for enhanced light-atom interaction**
Shuhei Yoshida	**Impact-parameter selective Rydberg-Rydberg collision by optical tweezers**

Abstracts of Talks

(in alphabetical order)

Rydberg Photonics with Thin-Film Cuprous Oxide

Hadiseh Alaeian
Elmore Family School of Electrical and Computer Engineering, Purdue University, West Lafayette 47906, USA.
Department of Physics and Astronomy, Purdue University, West Lafayette 47906, USA.

Cuprous oxide (Cu_2O) has gained attention as a solid-state material with the potential for hosting excitonic Rydberg states. These states are defined by high principal quantum numbers (n), leading to significantly larger wavefunctions. As a result, Cu_2O exhibits strong dipole-dipole ($\propto n^4$) and van der Waals ($\propto n^{11}$) interactions, making it an attractive platform for solid-state quantum technologies. Thin-film Cu_2O samples are of particular interest as they can be meticulously fabricated to reduce defects, allowing for the observation of extreme single-photon nonlinearities via the Rydberg blockade.

In this presentation, I share our recent findings on the spectroscopic absorption and photoluminescence of Rydberg excitons in synthetic Cu_2O thin films. Our results show a series of yellow excitons extending up to a principal quantum number of $n = 7$. I discuss our progress in the bottom-up assembly of 2D arrays of Rydberg excitons, which could make a platform for simulating lattice models. Furthermore, I present promising results from coupling Rydberg excitons with silicon nitride photonic circuitry, marking a significant advancement in Rydberg photonics. Finally, I will cover our theoretical results on open quantum system phase transitions that can be explored using strongly interacting Rydberg polaritons. These discoveries pave the way for the development of scalable and integrated on-chip quantum devices based on Rydberg states in Cu_2O.

Nanofiber Cavity Quantum Electrodynamics Systems for Distributed Quantum Computing

Takao Aoki
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Distributed quantum computing, where many quantum processing units containing small to moderate number of qubits are connected to form a large-scale quantum network, is a promising approach to realize a quantum system with a large number of qubits required for fault-tolerant universal quantum computing.

Cavity quantum electrodynamics (QED) systems can be utilized to construct a distributed quantum computer, provided that multiple atoms can be strongly coupled to the cavity in an individually addressable manner, and that these units can be interconnected with minimal losses. We have been developing nanofiber-based cavity QED systems with these characteristics. (Fig. 1).

In this talk, we will present our experimental research on a nanofiber cavity QED system with a trapped single atom in the strong coupling regime[1], demonstration of the setting of coupled-cavities QED, where two nanofiber cavity QED systems are coherently connected in an all-fiber fashion[2,3], development of high-finesse nanofiber cavities for achieving high cooperativity in nanofiber cavity QED[4-6], and the recent progress toward distributed quantum computing with nanofiber cavity QED systems.

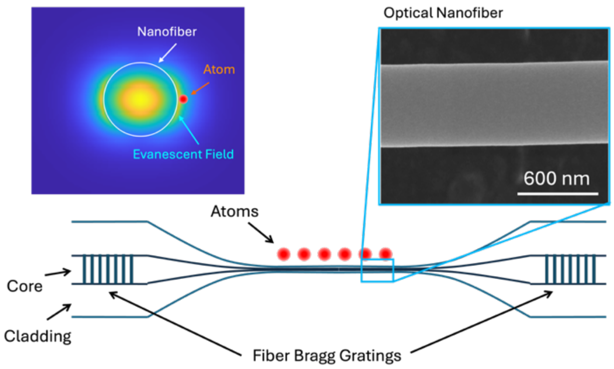


Fig. 1. Nanofiber cavity QED system with trapped atoms.

References

[1] S. Kato and T. Aoki, Phys. Rev. Lett. 115, 093603 (2015).
[2] S. Kato et al., Nature Communications 10, 1038 (2019).
[3] D. White et al., Phys. Rev. Lett. 122, 253603 (2019).
[4] S. K. Ruddell et al., Opt. Lett. 45, 4875 (2020).
[5] S. Kato and T. Aoki, Opt. Lett. 47, 5000 (2022).
[6] S. Horikawa et al., Rev. Sci. Instrum. 95, 073103 (2024).

Emergence of second-order coherence in superfluorescence

Constanze Bach, **Felix Tebbenjohanns, Christian Liedl, Philipp Schneeweiss, Arno Rauschenbeutel**

Department of Physics, Humboldt-Universität zu Berlin, 10099 Berlin, Germany

Recently, superradiant bursts of light have been, for the first time, experimentally observed for a cascaded quantum system [1]. This was realized using an ensemble of waveguide-coupled effective two-level atoms that exhibit chiral, i.e., propagation direction-dependent coupling to the waveguide mode. Here, we experimentally investigate the second-order quantum coherence function $g^{(2)}(t_1, t_2)$ of a superradiant burst in a cascaded quantum system [2]. We observe that second-order coherence emerges in the course of the decay of the atomic ensemble. This is a clear feature of the underlying collective dynamics that is also at the origin of the superradiant burst itself. We furthermore study the dynamics of the second-order coherence function of the emission in dependence on the initial average dipole moment of the ensemble. Interestingly, for ensembles below and above full inversion, $g^{(2)}(t, t) \approx 1$ for all times, indicating that the light is coherently scattered, even during the early dynamics of $t = 0$. In addition to these observations, we find an anti-correlation of photon detection events, i.e., $g^{(2)}(t_1, t_2) < 1$, in certain parameter regions in which $t_1 \neq t_2$, indicating that light emerges from the ensemble in bunches. Our findings contribute to understanding the fundamentals of light-matter interaction and reveal that, despite the fundamentally different coupling Hamiltonian, superradiance in cascaded and symmetrically coupled systems feature a strikingly large number of similarities.

References

[1] Liedl, C, et al. PRX **14**, 011020 (2024)

[2] Bach, C, et al. arXiv 2407.12549 (2024)

Fabrication and characterization of deterministic metal nanostructures on tapered optical nanofibers by blurred electron beam-induced deposition

A. Balena[1,2], M. D'Amato[1], M. F. Kashif[2], C. Ding[1], L. Belzane[1], H. Le Jeannic[1], M. De Vittorio[2,3], F. Pisanello[2], A. Bramati[1]

[1] *Laboratoire Kastler Brossel, Sorbonne University, CNRS, ENS-PSL University, Collège de France, Paris, France*
[2] *Istituto Italiano di Tecnologia, Center for Biomolecular Nanotechnologies, Arnesano, Italy*
[3] *Department of Health Technology, Drug Delivery and Sensing Section (IDUN), Technical University of Denmark (DTU), Kongens Lyngby, Denmark*

This study introduces a novel method for fabricating metallic nanostructures with controlled geometry and composition deterministically positioned onto tapered optical nanofibers (ONFs) using Electron Beam Induced Deposition (EBID). ONFs, single-mode optical fibers with intense evanescent fields at sub-wavelength diameters, offer unique opportunities for plasmonic enhancement. However, the ONF's fragility has posed significant fabrication challenges, as conventional high-energy deposition techniques often damage the delicate fiber structure. To address this issue, we developed a "blurred" EBID (BEBID) technique, exploiting deliberate beam defocusing to reduce local pressure, minimizing vibration, and thus preventing fiber damage during deposition. Using this technique, we show the possibility to tune the material's permittivity acting on the fabrication parameters, to tune the Platinum (Pt) percentage of the Pt/C composite material deposited. Moreover, we show how a nondestructive plasma oxygen post-treatment can enhance the Pt percentage inside the deposited structures. The BEBID-fabricated Platinum (Pt) nanostructures were optically characterized, performing scattering spectra and polarization measurements that are in good agreement with Finite-Difference Time-Domain (FDTD) simulations, verifying the effectiveness of this gentle fabrication approach. Numerical simulations predict that ordered arrays of Pt nanopillars on TNFs could improve overlap between the scattered field and the guided fiber modes, enhancing light-matter interactions. This BEBID technique opens new avenues for fabricating complex nanostructures on TNFs, which are expected to advance applications in various fields, such as surface-enhanced Raman scattering (SERS)[1] with nanoantennas and quantum photonics with single-photon emitters[2].

References

[1] L-H. Chen et al., J. Lightwave Technol. **37**, 11, (2019)
[2] M. Sugawara et al., Phys. Rev. Research **4**, 043146 (2022)

Nanofiber platform to manipulate photons and phonons

Jean-Charles Beugnot

FEMTO-ST Institute, CNRS, Université de Franche-Comté, Besancon, France

Brillouin scattering has found extensive applications in advanced photonics functions, including microwave photonics, signal processing, sensing, and lasing. More recently, it has been employed in micro- and nano-photonic waveguides [1]. Tapered optical fibers, due to their small transverse dimensions, exhibit a range of optical and mechanical properties that render them highly attractive for both fundamental physics research and technological applications. In contrast to standard telecom fibers, where Brillouin scattering is characterized by a single Lorentzian resonance centered at 10.86 GHz (@ 1550 nm), tapered silica fibers exhibit multiple Brillouin resonances at various frequencies ranging from 5 GHz to 10 GHz, originating from surface, shear, and compression elastic waves (see Figure 1a) [3]. For a large evanescent optical field surrounding the nanofiber, we observe an efficient Brillouin scattering in gas [4]. We show drastic Brillouin scattering enhancement by increasing the gas pressure with a maximum Brillouin gain which is 79 times larger than in a SMF (fig 1.b) [4].

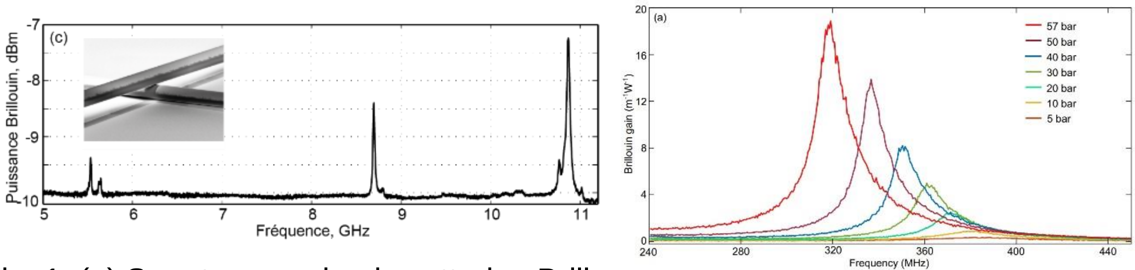


Fig. 1: (a) Spontaneous backscattering Brillouin spectrum in tapered silica optical fiber [2]. (b) Brillouin gain spectra along the 10cm nanofiber gas cell filled with CO_2 at different pressures [3].

References

[1] Benjamin J. Eggleton, Michael J. Steel and Christopher G. Poulton "Brillouin Scattering, " Elsevier, (2022).

[2] J.-C. Beugnot, S. Lebrun, G. Pauliat, H. Maillotte, V. Laude, and T. Sylvestre, Nature Communications 5, 5242 (2014).

[3] F. Yang, F. Gyger, A. Godet, J. Chrétien, L. Zhang, M.Pang, J-C. Beugnot, L. Thévenaz, Nature Communication, 13 (1), p. 1-8 (2022).

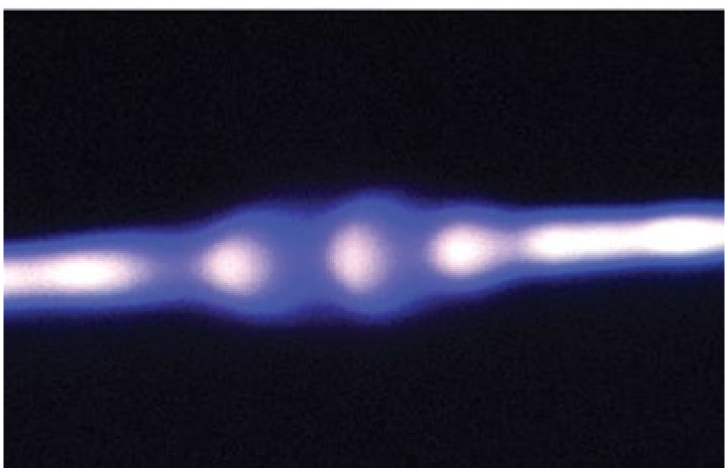
[4] A. Godet, A. Ndao, T. Sylvestre, V. Pecheur, S. Lebrun, G. Pauliat, J.-C. Beugnot, and K. Phan Huy, Optica 4, 1232 (2017).

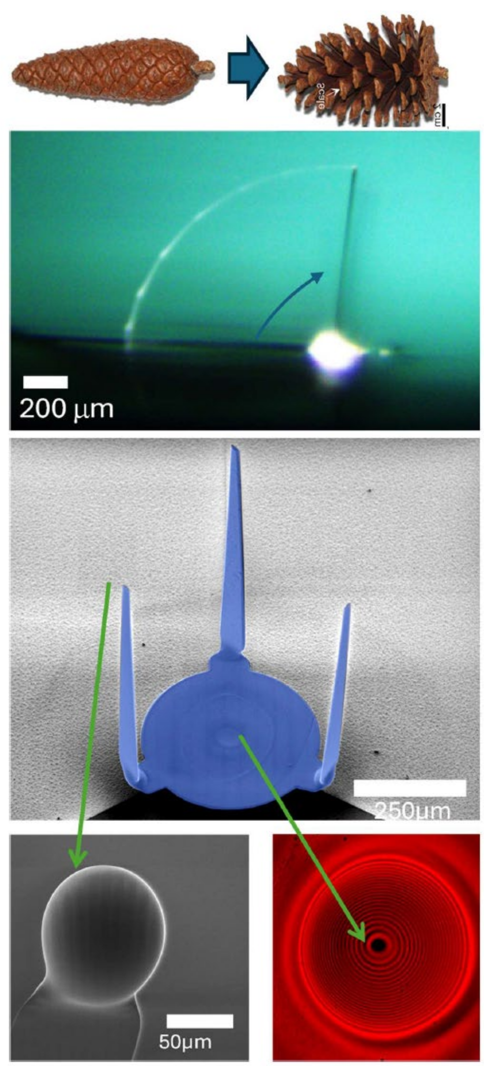
[5] . M. Zerbib, M. Romanet, T. Sylvestre, C. Wolff, B. Stiller, J-C. Beugnot, and K. P. Huy, APL Photonics, (2024).

Optical Resonators of Many Phases of Matter

Tal Carmon, School of Computer and Electrical Engineering, Tel Aviv University, Israel

Plasma, an ionized gas, permits electrical control of optical gain, loss, and refractive index, raising the question of why it has not been utilized in optical microcavities. Similarly, liquid walls in resonators and fibers enable light interaction with capillary waves; yet, microfluidic devices typically rely on solid boundaries that prohibit such water waves. Here, we present optical microcavities filled with plasma, enabling electrically controlled optical properties, including absorption-induced transmission, electro-switching, and refractive indices below one. For liquids, we introduce fibers and resonators made strictly of water, permitting interactions between light and water waves. Furthermore, using emulsifiers, we demonstrate the softest optical resonator operating near the limit where Brownian fluctuations break our device. Furthermore, Borrowing hygroscopic principles used in nature for seed-release, we harness surface tension using lasers to melt on-chip SiO2 sheets, generating snap-motion foldings with nano-resolution alignment, at 19,600 m/s^2 acceleration. Our extremely rapid on-chip folding method might impact 3D-integrated electro-opto-mechanical circuits by allowing 3D nano-alignment capabilities, structural freedom, as well as ultrahigh optomechanical Qs, and size-to-weight ratios.





Efficient generation and manipulation of single photons with a single molecule

Stephan Götzinger

Max Planck Institute for the Science of Light, Erlangen, Germany
University of Erlangen–Nuremberg, Erlangen, Germany

Novel concepts aiming at efficient processing of information require a strong and controlled coupling of single photons with single atomic quantum systems. In this talk, I will first give an introduction to the efficient generation of single photons using planar dielectric antennas. These antennas allow us to collect the emission from an arbitrarily oriented single quantum emitter with >99% efficiency. By using a planar metallo-dielectric antenna applied to an organic molecule, we demonstrate the most regular stream of single photons reported to date. The measured intensity fluctuations were well below the shot-noise limit and amounted to 2.2 dB squeezing.

In the second part of the talk, I will discuss our efforts toward the realization of quantum networks and present experiments where photons and single solid-state emitters strongly interact. A single molecule can amplify a weak laser beam and generate nonlinear effects like three-photon amplification and four-wave mixing. To achieve an even stronger interaction, we have coupled a single molecule to a tunable Fabry-Perot microcavity. The system is operated in the strong coupling regime of cavity quantum electrodynamics, where a strong Purcell factor effectively turns the molecule into a two-level quantum system. We observe 99% extinction of a laser beam, which means that our molecule in the cavity acts almost as a perfect scatterer of photons.

Generating and controlling propagating quantum states of light with waveguide QED

A. González-Tudela[1]

[1]*Instituto de Física Fundamental, C/Serrano 113bis, CP28006, Madrid*

Generating and controlling propagating quantum states of light are a key resource for future photonic quantum technologies. In this talk, I will review several works on how to generate quantum states of light exploiting super/subradiant effects in waveguide QED systems [1,2,3,4]. Then, I will also show how to engineer controlled photonic phases between propagating photons using only two-level systems coupled to topological multi-mode waveguides [4]

References

[1] AGT *et al*, Phys. Rev. Lett. **115**, **163603** (2015)
[2] AGT *et al*, Phys. Rev. Lett. **118,** 213601 (2017)
[3] V. Paulisch *et al*. Phys. Rev. A **99 (4)**, 043807 (2019)
[4] M. Perarnau-Llobet *et al*. Quantum Science and Technology **5**, 025003 (2020)
[5] T. Levy-Yeyati *et al*, arXiv: 2407.06283

Bayesian sensing and photon storage using atoms in a fibre void

L. Hackermueller[1]

[1]School of Physics and Astronomy, University of Nottingham, NG7 2RD, Nottingham, UK

I will report on recent results in a new type of microscopic atom-photon interface [1] applying Bayesian methods. Bayesian methods promise enhanced device performance and accelerated data collection. We demonstrate an adaptive Bayesian measurement strategy for atom number estimation utilising a symmetry-informed loss function. Compared to a standard un-optimised strategy, our method yields a five-fold precision enhancement in the atom number estimate. Equivalently, it enables to achieve a target precision with a third of the data points. These results will boost readout in quantum computing, communication, metrology, and the wider quantum technology sector.

In our system, Cs atoms are first cooled in a magneto-optical trap, transferred to an optical dipole trap and positioned inside a transverse, 30 μm diameter through-hole in an optical waveguide, created via laser micromachining [2]. We use this system to demonstrate fibre-coupled electro-magnetically induced transparency and compact photon storage and sensing.

For portable quantum technologies additive manufacturing or 3D-printing offers unique advantages. We have demonstrated a full magneto-optical trapping setup based on 3D-printing techniques including a 3D-printed ultra-high vacuum chamber. Freedom of design enables remarkably compact and resilient systems and allows weight reduction of more than 70% [3]. We have extended this method to transparent elements and will report on the world's first 3D-printed vapour cells [4].

References

[1] M. Overton et al., "Five-fold precision enhancement in a cold-atom experiment via adaptive symmetry-informed Bayesian strategies" arXiv: 2410.10615 (2024).

[2] E. da Ros et al., "Cold atoms in micromachined waveguides: a new platform for atom-photon interaction ", Phys. Rev. Res. 2, 033098 (2020)

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[4] F. Wang et al., "Performance-optimized components for quantum technologies via additive manufacturing", Quantum Sci. Technol. 10, 015019 (2025)

Rydberg superatoms meet nanofibers

S. Hofferberth[1]

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We realize effective two-level emitters by exploiting the Rydberg blockade effect of atomic ensembles. By confining N~10.000 atoms to a single blockaded volume, the ensemble only supports a single excitation creating a so-called Rydberg superatom. Due to the collective nature of the excitation, the superatom effectively represents a single emitter coupling strongly to single photons. The directional emission of the superatom into the inital probe mode realizes a waveguide-like system in free-space without any actual light-guiding elements. I will show how we use one or more such superatoms to study waveguide QED of strongly coupled emitter and realize as one application a number-resolving photon-absorber.

In free space the scaling of the Rydberg superatom system is limited by diffraction of the probe beam. To overcome this limitation, we are currently developing a new experiment combining optical nanofibers with tweezer-trapped atomic ensembles. Our goal is to realize a system of 10-50 effective emitters strongly coupled to a single fiber mode. I will discuss our planned setup using ultrathin (d<100nm) fibers combined with ultracold Yb atoms and present our current status towards Rydberg superatoms near a nanofiber.

States of light generated by cold atoms and mediated by optical nanofibres

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The controlled generation of photons and photon number states a valuable resource for quantum information protocols. Additionally, the interaction of these photons with far-away quantum systems is key to establishing entanglement among long-distance quantum systems.

In this presentation, we discuss progress towards the generation of well-defined, multi-photon, non-classical states of light in a fibre resonator. To that end, we trap neutral caesium atoms on the waist of an optical nanofibre using a two-colour trap. We create a fibre resonator by manufacturing Fibre-Bragg Gratings (FBGs) on either side of the nanofibre part of the fibre. We aim to create the non-classical states of light in this resonator.

In preliminary experiments, we form a magneto-optical trap (MOT) of caesium atoms around the waist of an optical nanofibre (diameter 400 nm). One end of the nanofibre terminates in a single-photon detector module (SPCM) and the other end is connected to a length of standard optical fibre and terminated with an FBG. An auxiliary laser excites the atoms, causing them to emit into the nanofibre. The emitted photons travel to the FBG and back to interact with the atoms again. This is more accurately described as two distant collections of atomic ensembles.

In the figure, we show the absorption of a probe laser by the trapped atoms on the nanofibre (left) and the ratio of the rates of fluorescence photons travelling directly towards the detector and those having travelled to the distant (32 m one-way travel distance) as a function of the excitation laser frequency. We compare our experimental results with the results of calculations based on a transfer-matrix approach [1].

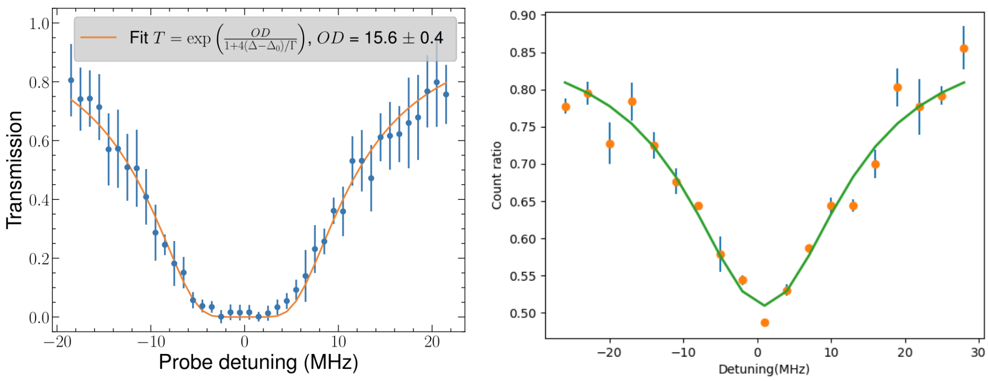

Figure 1: Transmission of atoms trapped by the two colour trap (left) and the ratio of direct and indirect photon count rates in the preliminary experiments (right)

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Collective emission from a dense atomic ensemble coupled to a nanophotonic resonator

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Control and manipulation of the collective excited states of multiple quantum emitters that are coupled to nanophotonic waveguides or resonators could open new avenues in engineering light-matter interfaces. Densely packed quantum emitters that are collectively coupled via multiple photonic modes could exhibit dissimilar emission dynamics into these modes depending on the emitter configuration and how they are excited. One significant example is “selective radiance” in a sub-wavelength spaced atom array [1], where a collective excitation couples to a phase-matched photonic mode with collective enhancement (superradiance) while being suppressed in coupling to all other radiative modes due to phase-mismatch (subradiance). In this talk, I will report experimental realization of many-atom trapping on a nanophotonic microring resonator [2,3]. I will discuss our experimental and theoretical studies on the collective emission of a dense atomic ensemble interacting via a resonant whispering-gallery mode (WGM) of the microring and the free space radiative modes. Our results show that these trapped atoms, once driven by the WGM into a steady state or a time-Dicke state, can superradiantly couple to the resonator while showing signatures of subradiant or superradiant emission to free space. I will discuss how these effects impact a collective light-matter interface and the potential of our platform to realize selective radiance using an ordered atom array.

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Advancing Biological Imaging: From Light Sheet Microscopy to Deep Learning-Enhanced Solutions

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The advent of deep learning has revolutionized digital optical microscopy. Traditional image processing techniques, such as thresholding and watershed transformations, have largely been replaced by deep learning approaches that leverage problem-specific deep neural network models. Beyond data analysis, deep learning has also proven to be a powerful tool for enhancing the overall performance of optical microscopes. For instance, deep learning-based methods can improve the signal-to-noise ratio, achieve super-resolution imaging beyond the diffraction limit, and even generate virtually stained images from unstained samples.

In this talk, I will provide an overview of our recent research projects in biological imaging. Our work spans several imaging technologies, including the development of a light sheet fluorescence microscope for imaging cleared tissues, a structured illumination microscope utilizing image scanning microscopy for super-resolution imaging, and fiber bundle-based fluorescence imaging systems. I will highlight our recent advancements in deep learning-based solutions, including:

- Enhancing the contrast and resolution of fiber bundle-based microscopy,
- Automating cell counting and viability analysis,
- Analyzing brain vasculature,
- Classifying white blood cells in peripheral blood smear images.

Additionally, I will discuss our latest project on the in vivo study of ciliary motion in nasal airways using laser speckle imaging.

Photon-photon interactions using single solid-state emitters and waveguides

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Abstract:
Interactions between photons and light are at the core of many advances in quantum optics, enabling both fundamental explorations and technological breakthroughs. This talk will explore how nanophotonic platforms, and in particular nanophotonic waveguides, in the context of waveguide-QED, can be used not only to efficiently collect single-photon emissions but also to help engineer photon-photon interactions.

We will focus on solid-state quantum emitters, such as quantum dots and color centers, and their integration with photonic waveguides to enhance light-matter interactions. Starting with single-photon emission properties, we will examine the behavior of quantum emitters from colloidal perovskite nanocrystals [1], which operate at room temperature, to color centers in diamond. Special emphasis will be placed on coupling these emitters with nanophotonic waveguides, including optical nanofibers, to enable efficient light collection and tailored interactions.

Moving beyond single-photon sources, we will highlight the potential of quantum emitters embedded in photonic waveguides, such as self-assembled InGaAs quantum dots in GaAs photonic crystal structures. These systems demonstrate highly indistinguishable and bright single photons while also achieving strong light-matter coupling. This coupling facilitates "giant nonlinearities" [2], enabling phenomena like single-photon-level induced phase shifts [3] and photon-photon interactions [3]. We will discuss the fundamental and general physics at work when a few (one, two) photons interact with any two-level emitter in a waveguide. And show that this can lead to the production of time-frequency entangled states. Finally, we will discuss the broader applications of this platform, not only for quantum information processing but also for deepening our understanding of light-matter interactions within these seemingly simple yet profoundly rich systems.

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Study of self-heated tapered silica microfibers in air by laser

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The control of laser self-induced temperature of micro and nanofibers is one of the key towards stable operation range for the applications using these devices. However there is still very little research into this issue and very few systematic studies in the literature In addition, most studies are carried out under vacuum [1] or in a controlled atmosphere [2]. In this work we propose an experimental method that enables to measure the temperature increase of silica optical microfibers under laser injection in air. This method presents several advantages: it is very simple to implement and enable to make spatially distributed measurements not only along the microfiber part but also along both tapers. The influence of several parameters are tested (waist diameter, length, laser wavelength). For example, a significant temperature of 50°C (resp. 65°C) was measured for a continuous wave power of 200 mW inside a microfiber having a diameter of 4 µm (resp. 3 µm) and a length of 10 mm at a wavelength of 1.48 µm. The experimental data are in good qualitative agreement with the simulation program we implemented. These studies will enable to predict the temperature increase for other geometrical and laser parameters.

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Atomic arrays with tunable spacing coupled to an optical nanofiber

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Quantum optics and quantum information technologies greatly benefit from systems of emitters coupled to a waveguide which enables long-range interactions. One of the leading platforms in waveguide quantum electrodynamics is neutral atoms coupled to an optical nanofiber, offering excellent scalability and compatibility with existing neutral atom technologies. Creating an ordered atomic array interfaced with an optical nanofiber, however, has faced challenges, particularly in achieving sufficient tunability and scalability simultaneously. Optical dipole traps using guided red-detuned beams can form atomic arrays with many sites, but tuning lattice constant commensurate with the resonant wavelength is non-trivial. Alternatively, interfacing optical tweezers with nanofibers provides significant tunability but struggles with scalability. In our work, we demonstrate creation of an optical accordion lattice, with thousands of sites and tunable lattice constants ranging from 0.8 to 2.0 times the resonant wavelength [1]. This approach employs a stack of binary phase transmission gratings that are 4f-imaged onto the nanofiber. The quality of the optical lattice directly depends on the precision of e-beam lithography, which has resolution well below optical wavelengths. We discuss our ongoing experiment toward realization of an ordered array of Rb85 atoms trapped within these accordion lattice sites and coupled to the nanofiber mode.

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Hot vapor spectroscopy with integrated photonic waveguides

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The spectroscopy of hot atomic vapors, especially of rubidium and cesium, is a hot topic since the early studies of Bunsen and Kirchhoff more than 150 years ago. Today the precision spectroscopy of alkali gases, and some molecular gases, ranges from fundamental research to real world applications. Especially the possibility to integrate light sources, optics, electronics in a miniaturized way has been driving the field forward during the last decade. One way to integrate atomic spectroscopy with versatile optical components are photonic waveguides made of various materials, such as silicon, silicon nitride or KDP, lithographically structured with industry standard processes. This state of the art technology allows for high quality photonic structures such as waveguides, splitters, resonators, interferometers, which can now be combined with the linear and non-linear optical properties of atomic gases.

In this talk we will present, how to realize various types of integrated spectroscopy cells with a focus on applications in quantum optics, especially nonlinear effects down to the single photon level. 1) A two-photon scheme is used to optically alter the refractive index to implement a low power pure optical switching scheme. 2) The light induced dipole-dipole interaction can be exploited to render line-shifts when arranging the atomic gas inside a slot-waveguide to an effective one-dimensional system, and 3) The excitation of Rydberg atoms in close vicinity of a waveguide will allow in future to make use of the strong van-der-Waals interaction between two Rydberg atoms.

Small-Molecule Ice Micro/Nano Fibers

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The waveguiding properties of a micro/nano fiber (MNF) are primarily determined by its material composition. Conventional MNFs are made from materials such as glass and polymer that are solids at room temperature. To expand the waveguiding capability of the MNF, here, under low temperature, we demonstrate MNFs made from small-molecule ice that are typically liquids or gases at room temperature.

Firstly, using an electric field-enhanced growth method, we successfully fabricated single-crystal water ice MNFs with diameters ranging from 10 μm to less than 800 nm. These ice MNFs can guide visible light with a measured loss around 0.2 dB/cm, and are promising for ultra-low-loss optical waveguiding at ultraviolet spectrum. Under cryotemperature, these MNFs can be reversibly bent with a maximum strain of 10.9%, which approaches the theoretical elastic limit of water ice. As water ice is one of the most abundant and important crystalline solids on Earth’s surface and plays an essential role across a diverse range of topics in chemical physics, life science, geophysics, astronomy, and other disciplines, these water ice MNFs are attractive to a variety of fields.

Secondly, by drawing supercooled organic small-molecule droplets at low temperature, we obtained ice MNFs made from a variety of organic small molecules including ethanol and toluene. These organic ice MNFs are amorphous in structure, and have lengths up to 5 cm and diameters down to 200 nm. They can guide visible light with loss down to 0.025 dB/cm that approaches the material absorption limit, and offer high optical nonlinearity for low-threshold supercontinuum generation. Also, these MNFs have excellent mechanical flexibilities with allowed elastic strain up to 3.3%.

As a new type of MNFs, small-molecule ice MNFs may offer new opportunities from optical waveguiding and optical sensing, to ice physics and ice mechanics at the micro- or nanoscale.

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Modified dipole-dipole interactions in the presence of a nanophotonic waveguide

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When an emitter ensemble interacts with the electromagnetic field, dipole-dipole interactions are induced between the emitters. The magnitude and shape of these interactions are fully determined by the specific form of the electromagnetic field modes. If the emitters are placed in the vicinity of a nanophotonic waveguide, such as a cylindrical nanofiber, the complex functional form of these modes makes the analytical evaluation of the dipole-dipole interaction cumbersome and numerically costly. In this work, we provide a full detailed description of how to successfully calculate these interactions, outlining a method that can be easily extended to other environments and boundary conditions. Such exact evaluation is of importance as, due to the collective character of the interactions and dissipation in this kind of system, any small modification of the interactions may lead to dramatic changes in experimental observables, particularly as the number of emitters increases. We illustrate this by calculating the transmission signal of the light guided by a cylindrical nanofiber in the presence of a nearby chain of emitters.

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Non-Hermitian Skin Effect in Waveguide Quantum Electrodynamics

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Non-Hermitian skin effect (NHSE) has now become the paradigmatic example of the topologically nontrivial impact of loss or gain in optical and condensed matter systems. Here, I will present our latest theoretical results on an analog of NHSE in the platform of waveguide quantum electrodynamics — the area of quantum optics studying interaction with propagating photons with atoms in a waveguide [1].

I will focus on the Non-Hermitian Skin effect for the bound states of interacting photons propagating in a waveguide and chirally coupled to an array of atoms [2]. I will demonstrate the concentration of bound modes at the edge of the array that can be interpreted as a non-Hermitian skin effect. The mechanism behind this effect is rather unusual: contrary to the usual local loss or gain, the spectrum for the bound states in the infinite structure is lossless. Still, the non-Hermiticity for bound pairs is driven by their dissociation into scattering states in the finite structure, as shown in the Figure.

The coexistence of the continuum with the quasiparticle dispersion branch is a generic feature for the energy spectra of various many-body systems, for example, with plasmonic or magnonic excitations. Thus, we believe that our results could apply beyond one-dimensional systems and beyond setups with atom-photon coupling.

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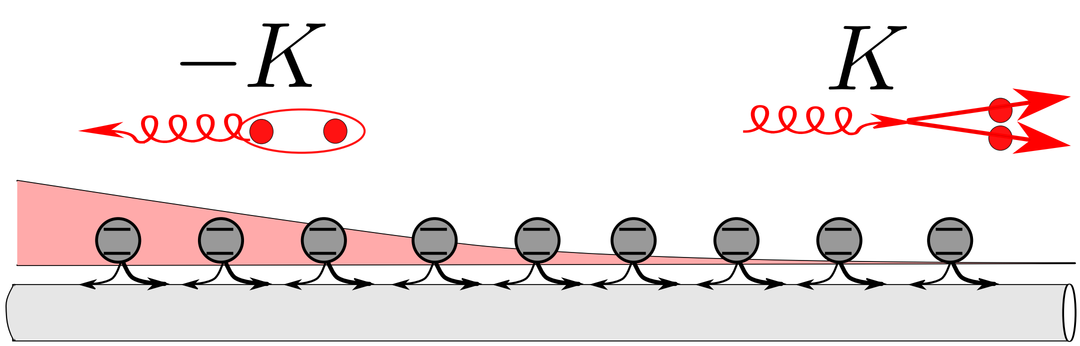

Non-equilibrium phases of dipole-coupled quantum emitters

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Coupling light to dense assemblies of quantum emitters gives rise to a range of interesting collective and cooperative phenomena. In this talk we will explore the role of static dipole-dipole interactions for the cooperative optical response of ordered ensembles of emitters and study their non-equilibrium phase diagram under strong optical driving. In particular, we will discuss interaction effects on superradiance and show that dipolar interactions between multi-level systems can lead to non-stationary long-time behaviour without a classical counterpart, i.e. time crystalline phases that are driven purely by quantum fluctuations.
We will consider realisations in two-dimensional atomic lattices as well as one-dimensional chains coupled to an optical fiber, and discuss effects of particle motion in such systems.

Controlling Light to Reimagine Clinical Diagnostics

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Current analytical paradigms within the clinical landscape include techniques such as polymerase chain reaction, lateral flow assays, and enzyme-linked immunosorbent assays (ELISAs). Despite their widespread use, these techniques face several challenges, not limited to poor analytical sensitivity, limited multiplexing capabilities, and/or a lack of quantitative information. There exist critical needs within the diagnostic space for new techniques that not only address these critical gaps, but also are scalable, inexpensive, and generalizable.

Herein, we highlight the use of WGM sensors to address the aforementioned gaps. Whispering gallery mode sensors take advantages of fabrication techniques from industry, enabling reproducible fabrication with refined, high precision techniques. The improved analytical sensitivity of WGM devices also allows for improved analytical and clinical sensitivity, in addition to new detection modalities. To highlight their clinical use, we leverage microring resonators via a commercial chip-based photonic resonator platform for the rapid and multiplexed detection of filoviral biomarkers. Compared to gold-standard techniques, WGM sensors show superior clinical and analytical sensitivity, thereby enabling a more rapid and actionable diagnosis of infection.

We also highlight our ongoing efforts towards microbubble and microdroplet photonic resonators – integrated optofluidic devices that offer high Q-factor with the ease of fluidic handling. Finally, we touch on diagnostic characteristics important for the implementation of photonic devices into clinical settings.

Rydberg atom interactions at the interface of an optical nanofiber

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Rydberg atoms are highly excited atoms that have strong dipole-dipole interactions and large radiative lifetimes, which makes them useful for quantum technology applications. Interfacing Rydberg atoms with optical nanofibers (ONF) offers strong atom-light interactions and a useful platform to explore surface-atom interactions. Our system consists of an ONF overlapped with a cloud of laser-cooled Rubidium-87 atoms confined in a magneto-optical trap (MOT). Rydberg excitation is achieved via a two-photon process, where the first photon is from the cooling beams, and the second photon is guided through the ONF [1]. When atoms undergo Rydberg excitation they are lost from the MOT, resulting in a reduction of fluorescence, giving us an indirect measurement of the excitation rate. We achieve Rydberg state excitation for principal quantum numbers from n = 24 to 68, and observe that nD states seem to be easier to excite than nS states for ONF-based Rydberg experiments [2]. To further explore the Rydberg blockade mechanism and the effect of surface-atom interactions, an evanescent field-mediated, two-color optical dipole trap is implemented. Using machine learning, we optimize the dipole trap and increase the number of trapped atoms. We aim to utilize this linear chain of trapped atoms to demonstrate the two-photon evanescent field Rydberg excitation and further explore the properties of Rydberg excitation at the interface of an ONF. This platform can be further exploited to study the effects of high-intensity trapping beams on Rydberg excitation and to explore ionization effects in the system. Moreover, a linear chain of trapped Rydberg atoms could be useful for studies of quantum many-body physics and has potential applications in quantum simulations.

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Electron beam methods for optical nanofibers

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Often in nanophotonics experiments, a device with nanometer scale features is utilized using an optical setup with resolution no better than half of one micron. Furthermore, in setups where a nanoscale optical emitter is coupled to a nanoscale device, it is typically challenging to deterministically place the emitter at the desired location, let alone scan the position in order to optimized design.

A solution to this problem has existed for some time – the method of electron beam induced luminescence – which allows optical excitation of nanostructures at the same time as they are observed in an scanning electron microscope (SEM) [1]. However, this method has until now required a special SEM, and because induced luminescence was collected in the far field, has no special advantage experiments using nanowaveguides, where coupling to the waveguide rather than free-space is the primary goal.

Here I will briefly introduce our results using a standard scanning electron microscope with electron induced luminescence collected via an optical nanofiber. A simple fiber feedthrough allows access to the signal, which, for a bare fiber, has a broad spectrum, with discrete features from various defects in silica. The method allows the study of the photonic density of states for the nanofiber itself [2] but also, crucially, any nanostructures coupled to it. Aside from making electron beam spectroscopy available for any SEM which has a spare vacuum port, our method provides a convenient platform for nanofiber photonics as we will show.

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Recent advances in sensing with optical fibre microresonators

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Fibre-based optical microresonators provide unique benefits, including high Q factors, ease of integration into existing fibre optic systems, and robustness, making them a compelling choice for various sensing applications. They can be customized by altering the fibre structure or diameter or by introducing different materials and variations in the refractive index. This enables tuning of their optical properties, such as resonance wavelengths and free spectral ranges, which to date has been challenging to achieve with monolithic optical microresonators. This work explores new approaches to tuning fibre-based microresonators and their applications in the sensing of microfluidic flows, micro displacement, and 2D micro force measurement.

Quantum computation based on photon-emitters in waveguide

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A single photon emitter with an internal qubit degree of freedom in a waveguide constitutes an almost idea source of spin-photon entanglement. For suitable waveguide and emitter configurations, this photon emission process can be extended to create multi-photon entangled states. Performing Bell-state measurements (also known as fusions) on some of the photons can merge the entangled states into even larger entangled structures. The structures can be scaled to fully fault tolerant quantum computation.

I will discuss recent theoretical and experimental work performed in Copenhagen on how to perform fusion based quantum computation by exploiting quantum emitters in waveguides. Experimentally we use quantum dots in photonics crystal waveguides to emit multi-photon entangled state [1] and have performed elementary fusion operations [2]. At the same time, we are theoretically optimising the architectures for how to convert these resources into fully fault tolerant quantum computers [3].

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Microbubble Resonators based Photoacoustic Detection and Characterization of Flowing Contrast Agents in Real Matrixes.

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Whispering Gallery mode microbubble resonator (MBR) are used as optical transducers to detect the photoacoustic (PA) signal generated by plasmonic nanoparticles. We have simulated a flow cytometry experiment by letting the nanoparticles run through the MBR during measurements and we estimate PA intensity by a Fourier analysis of the read-out signal. This method exploits the peaks associated with the MBR mechanical eigenmodes, allowing the PA response of the nanoparticles to be decoupled from the noise associated with the particle flow whilst also increasing the signal-to-noise ratio. The photostability curve of a known contrast agent is correctly reconstructed, validating the proposed analysis and proving quantitative PA detection.
Absorbance spectra of suspensions of plasmonic nanoparticles were also accurately reconstructed through the photothermal conversion that they mediate in a microbubble resonator. This thermal detection produces spectra that are insensitive towards light scattering in the sample, as proved experimentally by comparing the spectra of acqueos gold nanorods suspensions in the presence or absence of milk powder. In addition, the microbubble system allows for the interrogation of small samples (below 40 nl) while using a low-intensity beam (around 20 µW) for their excitation. The experiment were run to demonstrate the feasible implementation of the MBR system in a flow cytometry application (e.g., the detection of venous thrombi or circulating tumor cells), particularly regarding wearable appliances. Indeed, these devices could also benefit from other MBR features, such as the extreme compactness, the direct implementation in a microfluidic circuit, and the absence of impedance-matching material.

High Purcell Photonic Resonators for Light-Atom Coupling

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Hybrid atomic vapor-photonic integrated circuits, which allow atom vapors to strongly interact with photonic waveguide, offer a promising platform for compact and efficient quantum information processing. Here we present an overview of the visible photonics platforms that are currently being developed at Yale for supporting light-vapor coupling, including AlN, LN and SiN waveguide and resonators. We will then focus on a specific device based on a suspended silicon nitride microwheel resonator, which provides large evanescent optical field for enhanced coupling with atoms. This resonator could achieve a high Purcell factor of 97.5 at 780 nm.

Spherical Microresonators: from Thermo-Optoplasmonic Single-Molecule Sensing to Cavity Quantum Electrodynamics Effects

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We present recent advancements in the study of active and passive optical microresonators. Here, active microresonators are defined as spherical microresonators doped with ytterbium ions as emitting materials, while passive microresonators are undoped counterparts. Both types support whispering-gallery modes (WGMs), renowned for their exceptionally high Q-factors, which enable single-molecule sensitivity. The performance of these sensors is further enhanced by coupling them with plasmonic nanoparticles, which localise probing fields into nanoscale areas, enabling optoplasmonic sensing.

In this study, we analyse the passive WGM cavity response to single molecules under test, focusing on changes in resonant wavelengths and spectral linewidths. Typically, wavelength shifts are red, with no change in the full width at half maximum (FWHM), indicating a reactive sensing mechanism. However, we demonstrated that at varying light intensities, the resonant wavelengths exhibit both red and blue shifts [1]. Notably, blue shifts are accompanied by an increase in FWHM, attributed to the thermo-optoplasmonic mechanism: molecules under test absorb probing light and dissipate it as heat, forming localised heated regions in the analysed solution, that induce negative wavelength shifts.

Exploring higher light intensities revealed the influence of optoplasmonic sensors on the reaction of molecules under test, exerting forces in the femtoNewton range [2]. We demonstrated that enzyme molecules immobilised on the sensor exhibited enzymatic activity, which was reduced under higher probing light intensity. This is due to increased mechanical work performed by the enzymes to react with substrate molecules.

Finally, we present active WGM microresonators doped with ytterbium ions. Ytterbium's simple atomic structure, featuring two Stark-split principal manifolds ($^2F_{5/2}$ and $^2F_{7/2}$), often results in spectrally unresolved emission bands under normal conditions. At low temperatures, this energy structure can be spectrally resolved. In our work, ytterbium-doped microspheres, supporting WGM, at room temperatures demonstrated enhanced emission intensity with reduced FWHM. That is attributed to the Purcell enhancement, where emission is coupled to cavity modes, modifying the emission rates and help identifying Stark-split sub-levels .

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Optical routing with arrays of cold atoms around a nanofiber

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In recent years, coupling atoms to nanophotonic structures has become a promising approach to realize nonlinear quantum optical protocols, offering better scalability and figures of merit than free-space approaches, as well as new paradigms for atom-photon interactions. In particular, the use of nanophotonic waveguides has emerged as powerful tool for such implementations, due to the strong atom-photon coupling in single pass configuration arising from the tight transverse confinement of the propagating light. I will present our recent progress in this emerging neutral-atom waveguide-WED field of research with two experiments: an optical router with a nanofiber, and if time permits, towards strong coupling with slow-mode nanophotonic waveguides.

Using an atomic array trapped around a nanofiber in a Bragg configuration [1], we implemented a mirror consisting of a few thousand atoms that can be switched from a transparent to a reflective state using an additional laser field in Electromagnetically Induced Transparency configuration. This implementation of a reflective photon router works at record-low fW power levels. We further pushed the performance by adding a third laser field coupled to the metastable state, which can control the reflectance of our atomic Bragg mirror with as low as a few tens of photons, putting the few-photon nonlinearity regime within reach.

A powerful additional degree of freedom of nanophotonic waveguides is the possibility to engineer the dispersion relation by periodically structuring the waveguide. Close to the photonic band gap, slow modes arise whose coupling to nearby atoms is enhanced, realistically to reach strong coupling. We have designed waveguides that can support a slow-mode resonant with an atomic transition, as well as dipole trapping in the vicinity of the waveguide [2]. Loading atoms near the waveguide is a strong challenge and I will describe how novel structures and optical techniques can be used.

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The New Integrated High-Q Landscape

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The advent of ultra-low-loss (ULL) silicon nitride waveguides [1,2] has revolutionized the field of high-Q microresonators. With quality factors approaching 1 billion, ULL microresonators are now fabricated in CMOS-compatible foundries, offering enhanced feature-size control and high-yield microfabrication for sophisticated resonator systems. This presentation will explore recent advancements in devices and systems leveraging ULL microresonator technology, including pulse-pair mode-locking [3], continuous dispersion control [4], and the synthesis of record-low phase-noise microwave signals through optical frequency division [4,5]. Additionally, the discovery of the photo-galvanic effect in silicon nitride [6-9] has enabled access to second-order nonlinearities within this platform—a capability traditionally limited to non-centrosymmetric dielectric systems. The application of this effect to integrated, ultra-high-coherence visible light generation [10] will also be discussed.

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A Single-Molecule Technology for Decoding Protein Biophysics

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This talk introduces a cutting-edge single-molecule technology based on optical whispering gallery modes—micro-interferometers that transduce signals from individual molecules with extraordinary sensitivity. By focusing on the physics of single-molecule processes, this technology provides unprecedented insights into how proteins and enzymes function dynamically in health and disease. Following the 2024 Nobel Prize in Chemistry's recognition of advancements in protein design and structure prediction, the spotlight now shifts to real-time decoding and control of single-molecule processes. Photonic sensors, integrated with AI and molecular dynamics simulations, enable the direct measurement of protein conformational states, aggregation dynamics, and reaction pathways of single enzymes. These advances reveal critical processes such as neurotransmitter-membrane interactions, prion-like protein aggregation in Alzheimer's disease, and rate-limiting steps in enzymatic reactions. Additionally, my laboratory explores the potential for new control of biological reactions using optical nanoreactors, which leverage optical forces, temperature, and microfluidics to manipulate biosynthesis with the ultimate goal of demonstrating *de novo* DNA synthesis. We combine single-molecule technology with single-photon detection to investigate ultra-weak photon emissions in nature, uncovering their role in fundamental biological processes. Furthermore, when applied to reactions catalysed by plasmonic particles, the photonic sensor can reveal the dynamics of catalysis within nanoenvironments of single- or few-atom catalysts. Importantly, there are multiple opportunities to further improve sensitivity, time resolution, and also non-invasive sensing at ultra-low photon counts through the integration of plasmonics and quantum optical techniques. Finally, the talk will highlight how this approach illuminates quantum biological phenomena.

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Microcavity optomechanics with suspended photonic crystal reflectors

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Mechanical resonators offer new opportunities for quantum technologies, in particular, for quantum sensing, quantum transduction, or for fundamental experiments. Precise read-out and control of mechanical motion is required for these purposes and can be achieved by coupling the mechanical displacement to light in optomechanical devices [1]. I will present our recent work towards reaching new parameter regimes in the interaction between light and mechanical motion. We have developed a fully integrated optomechanical microcavity [2] using suspended photonic crystal reflectors [3], which shows interesting novel optomechanical effects [4] and may allow realizing photonic bound states in the continuum [5], [6]. This system could be capable of reaching the strong or ultra strong single photon coupling regimes, which would offer new ways to generate nonclassical optomechanical states [7], [8].

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Toward optical spin-wave control at a ferromagnetic 2D-MOT optical naofiber interface

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I would like to present our ongoing efforts to explore a novel optical-nanofiber (ONF) quantum optical interface. First, we propose and demonstrate a ferromagnetic trapping structure [1], which features an electronically tunable ultra-straight zero-field line aligned with the ONF. This design enables quasi-continuous, field-free operation of the 2D-MOT-ONF platform without the need to switch off the magnetic field gradient. Next, leveraging shaped sub-nanosecond pulses [2] and composite picosecond pulses [3], we drive an auxiliary D1 transition to impart a geometric phase to the near-field D2 optical spin-wave excitation. These spin-wave excitations are pre-generated either by a nanosecond D2 probe pulse or directly by the MOT beams. Transient spectroscopy measurements largely align with numerical simulations of the interaction between the atomic ensemble and ONF-guided photons in the near field, though a few unexpected phenomena remain unexplained. Finally, with the field uniformity and strong confinement provided by the ferromagnetic structure, I will discuss the prospects of developing an ONF interface with enhanced interaction length for photon storage, as well as new quantum optical scenarios involving interactions between co-guided atoms [4] and photons.

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Whispering-Gallery Microresonators Sensors: Fundamentals and Applications

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Optical sensors are at the forefront of advancements in biomedical research, clinical diagnostics, and environmental monitoring. Among the diverse sensing technologies, whispering-gallery-mode (WGM) resonators have gained prominence for their unique ability to enhance interactions between light and biological targets, presenting new opportunities for ultra-sensitive and label-free detection of small objects, such as nanoparticles, molecules, and cells, in biomedical research. This seminar will explain how nanomaterial interactions with a high-Q WGM resonator can alter photon trajectories and lifetimes, offering precise and quantifiable measurements. Groundbreaking applications, such as the detection and sizing of nanoparticles—including single virions—using ultra-sensitive, self-referencing microresonators and microlasers, will be explored [1]. Furthermore, the seminar will highlight how optical gains in microlasers can push detection limits beyond conventional passive resonators. Innovative sensing strategies, including barcode technology leveraging collective responses of multiple resonances to enhance sensitivity and dynamic range of sensing measurement [2], label-free detection via photoacoustic spectroscopy, and AI-enhanced target classification [3], will be discussed for their transformative potential in biomedical sensing. The versatility of WGM sensors will be demonstrated through a probe-type configuration capable of scanning surfaces to collect resonance-enhanced Raman signals [4]. In particular, a WGM microprobe that enhances the sensitivity of commercial Surface-Enhanced Raman Spectroscopy (SERS) test papers will be presented, demonstrating its potential for highly sensitive, label-free molecular detection. The presentation will conclude with the introduction of a handheld sensing platform, a compact evolution of traditional setups, promising to expand the accessibility and applicability of WGM sensor technology.

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Abstracts of Posters

(in alphabetical order)

Quantum sensing with NV centres in nanodiamonds coupled to optical nanofibres

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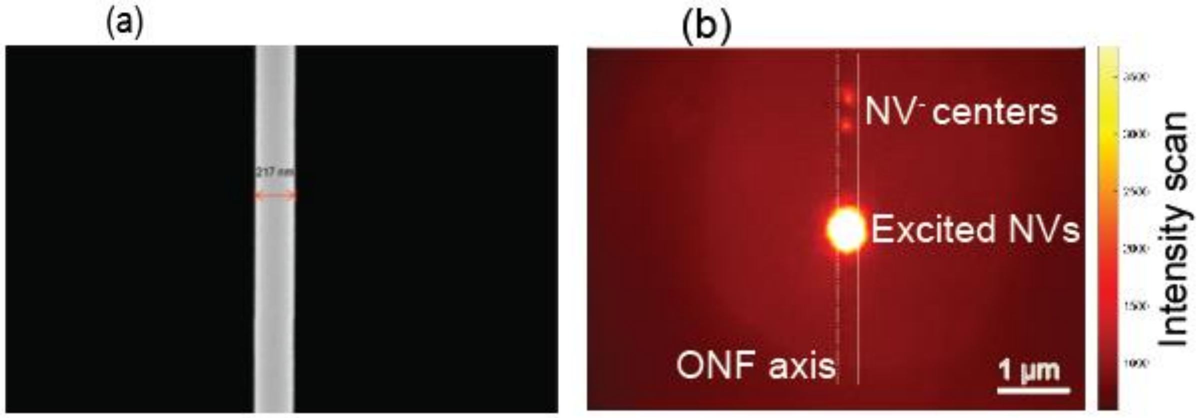
Nitrogen-vacancy (NV) colour centres in diamond have excellent optical properties, stable fluorescence emission at room temperature, and a long electron spin coherence time. In the quantum sensing field, NV centres perform excellently in nanoscale detection of electromagnetic fields and temperature sensing with high sensitivity. Optical fibre sensing technology has been developed rapidly in recent years with a wide range of applications. Optical fibre systems can be effectively combined with NV centres because of their easy integration and operation, thereby enhancing the collection efficiency of emitted fluorescence which improves signal strength during measurements [1]. This work investigates techniques for optimizing the coupling efficiency between NV centres in nanodiamonds and optical nanofibres [2]. This hybrid quantum sensor system can be applied to magnetic field, biological, and other physical measurements. We also explore potential applications for this platform in both quantum and biological sensing.



(a) SEM image showing optical nanofibre (ONF) with a diameter of 217 nm (b) Microscope image of the ONF after deposition of nanodiamonds with NV centres (excited by a 532 nm laser).

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Towards Efficient coupling of single nanodiamonds to an optical fiber for single photon emission

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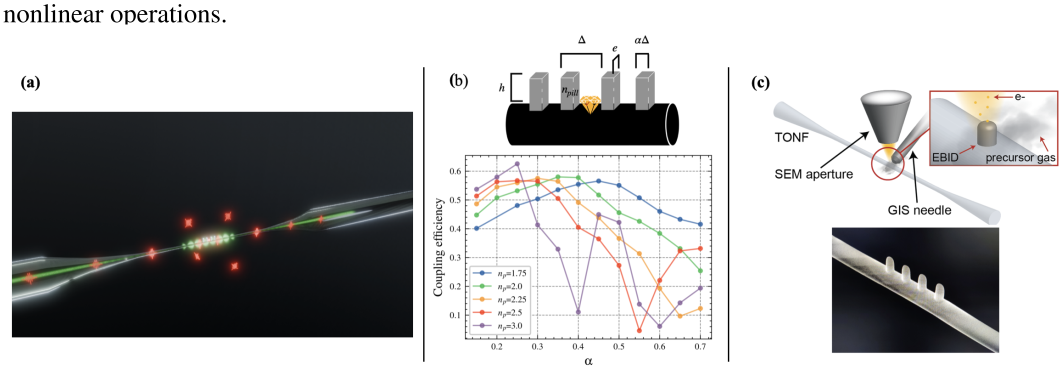
The development of integrated quantum technologies relies on efficient single-photon sources and deterministic quantum operations. Solid-state quantum emitters coupled to nanophotonic structures present a promising solution. This work investigates color centers in nanodiamonds, particularly Germanium Vacancy (GeV) [1], Silicon Vacancy (SiV), and Magnesium Vacancy (MgV) centers, a novel, understudied emitter [2], at both room and cryogenic temperatures. These nanodiamonds are chosen for their stability and superior coherence properties at cryogenic conditions, outperforming other colloidal quantum emitters. To access their emission, we have successfully deposited GeV nanodiamonds on tapered optical nanofibers by gently contacting a diluted droplet to the nanofiber [3], demonstrating coupling to the confined evanescent field of the nanofiber mode. Building on this achievement, we aim to study the system at cryogenic temperatures, enabling detailed optical characterization of the nanodiamonds and cooling of the integrated nanofiber-nanodiamond system. Current collection efficiencies are limited to 30% [4], and improving light-matter coupling efficiency remains a key goal for high-performance single-photon sources and more advanced applications such as efficient photon-photon interaction using w-QED [5], a future prospect. To achieve this, we are investigating the deterministic fabrication of dielectric and plasmonic nanostructures on the nanofiber surface using an "electron beam induced deposition" (EBID) technique recently developed in our group. By optimizing the composition, geometry, and placement of these nanostructures a simple pattern of pillars around the emitter should increase coupling efficiency up to 60% while maintaining high transmission in the nanofiber. Additionally, we are currently developing a "pick-and-place" technique with an Atomic Force Microscope (AFM) for precise and deterministic emitter positioning onto the nanofiber [6]. This work advances integrated photonic devices for single-photon sources and will address key challenges in photonic quantum computing such as the ability to perform nonlinear operations.



(a) Nanofiber single photon source (conceptual illustrations). (b) Coupling efficiency enhancement simulations. (c) Nanopillars fabrication on a nanofiber with an EBID technique.

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Cavity Optomechanics in an Infinite Cylinder

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Cavity optomechanics, the study of the interaction of confined optical modes with mechanical vibrations, has been the focus of significant research efforts[1]. Whispering gallery mode (WGM) resonators, where the ultra-high Q factors and moderately small mode volumes lead to strong optomechanical effects[2], have been a particularly fruitful platform for research in optomechanical interactions.

Surface nanoscale axial photonics (SNAP) optical resonators are a kind of WGM resonator where the optical confinement is provided by a minuscule variation in the effective radius of a glass cylinder[3]. We have fabricated SNAP resonators with a flame-based method, using commercially available optical fibers as the starting material.

The mechanical modes of an infinite solid cylinder can be solved using a semi-analytical method[4]. We have numerically solved this model to find the vibration frequencies of axial longitudinal modes.

When the modes in SNAP resonators are excited with a power higher than the optomechanical oscillation threshold, the interplay between the light radiation pressure and the mechanical vibrations lead to parametric optomechanical oscillations which can be detected in the signal transmitted through the resonator.[2].

We have measured the mechanical frequency of optomechanically-induced oscillations in 7 different SNAP resonators with different fabrication parameters, and found a single mechanical frequency that matches well that expected from the modelling. This is experimental evidence of the optical excitation of axial longitudinal mechanical waves in SNAP resonators made from optical fibers.

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ONNA, 2025

Enhancing atom-photon interaction with integrated nanophotonic resonators

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We study hybrid devices consisting of thermal atomic vapor and nanophotonic structures for manipulating the interaction between atoms and photons.

We exploit cooperative effects to develop a compact, on-demand and highly efficient single-photon-source using the Rydberg blockade effect. In order to excite Rb atoms to the Rydberg states efficiently, the corresponding light field is locally enhanced by ultralow-loss micro-ring resonators. Due to the large spatial extent of Rydberg atoms, we carefully design the ring resonators to realize sufficient interactions between Rydberg atoms and the evanescent field from the resonator. In order to create individual photons deterministically, we use the Four-Wave-Mixing (FWM) process in the Rydberg blockade regime inside a thermal vapor cell to develop a single-photon-source at room temperature.

To realize this goal, it is necessary to study Rydberg excitation in photonic integrated vapor cells. We excite and detect Rydberg excited Rb atoms with tapered, freestanding waveguides. Tapered narrow waveguides push out evanescent field that enables the excitation of Rydberg atoms. A specially designed, electric circuit patterned vapour cell and a transimpedance amplifier enables electric read out of single Rydberg excitation.

Jaynes-Cummings interaction with a traveling light pulse

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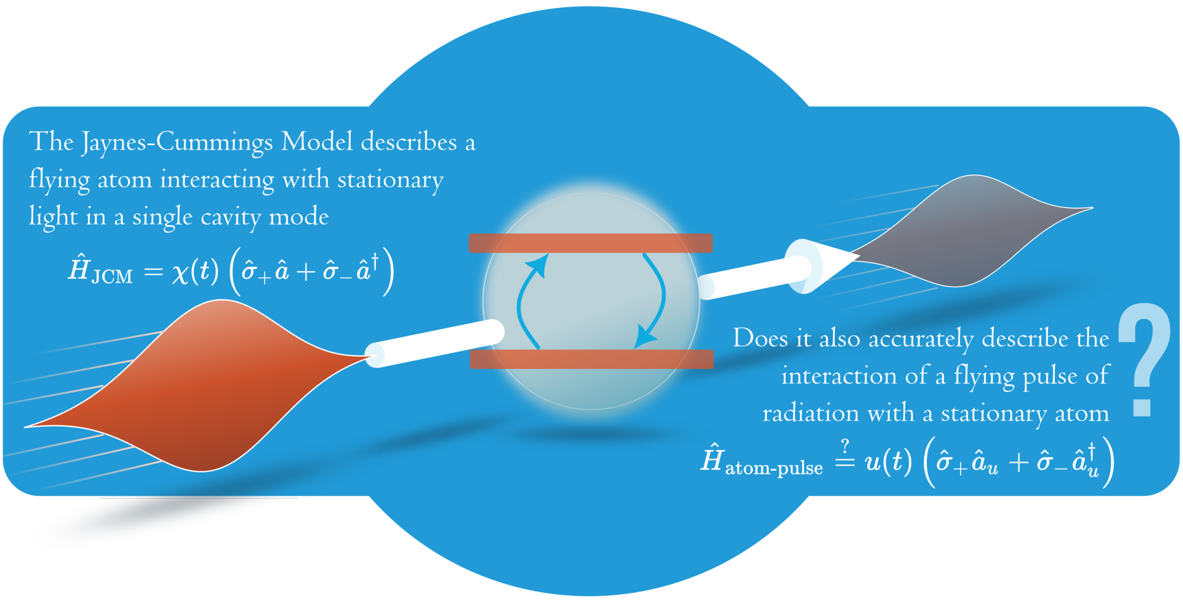
We have developed a theory that effectively describes the interaction of temporal modes of bosonic radiation with other quantum systems by having a virtual (i.e. not real) cavity leak a quantum pulse in the desired pulse shape. The desired temporal mode shape is defined by the time-dependent decay rate for the virtual cavity, while the bosonic content of the pulse is the same as the content of the virtual cavity. Similarly, the output multi-mode radiation of a quantum system can be picked up by defining a basis of temporal modes and having virtual cavities pick up the quantum content of these modes.

The Jaynes-Cummings model provides a simple and accurate description of the interaction between a two-level quantum emitter and a single mode of quantum radiation. Due to the multimode continuum of eigenmodes in free space and in waveguides, the Jaynes-Cummings model should not be expected to properly describe the interaction between an emitter and a traveling pulse of quantum radiation. We show that our cascaded quantum system approach that accurately describes the interaction of a quantum system with an incident quantum pulse of radiation, lead to a master equation with different Jaynes-Cummings-like Hamiltonians and damping terms when applied to the two-level system.



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Rydberg superatoms coupled with super-extended evanescent field nanofiber at the single-photon level

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Both Rydberg superatoms driven by free-space photonic modes and single emitters coupled to photonic waveguides have paved the way for strong coherent light-matter coupling at the few-photon level. By combining advantages of both ideas, we aim to achieve homogeneous coupling of multiple Rydberg superatoms coupled to a field confined by a nanofiber. Fibers with diameters of a few hundred nanometers are successfully used to trap and couple arrays of single atoms by their evanescent field. Recent advances allow the fibers to be tapered to even smaller diameters, allowing more than 99% of the energy to be guided outside the fiber with effective field diameters of & 13 λ [1], bringing them up to typical Rydberg blockade radius sizes.
On this poster, we will we will present the current status of planning and building our new Nanofiber experiment such as the vacuum chamber and first tests of the nanofibers. We select Ytterbium due to its advantage of having the two-photon Rydberg excitation transitions close together with 399nm and 395nm, which simplifies the fiber design and is expected to have low thermal dephasing effects.

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Rb-FILLED HOLLOW-CORE FIBRES
A NOVEL APPROACH TO ATOMIC SENSING

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Cold neutral atoms offer a promising platform for next-generation quantum technologies. In particular, laser-cooled alkali atoms exhibit exceptional sensitivity, enabling applications in precision magnetometry. However, while laboratory-based atomic sensors demonstrate remarkable stability and accuracy, they are often bulky, fragile, and prohibitively expensive for widespread deployment.

Our research explores an alternative approach by integrating a Rb atomic cloud within the hollow core of a Photonic Crystal Fiber (PCF), aiming to develop a robust and scalable sensing platform. This fiber-integrated system provides several advantages over conventional setups: it enhances portability, improves mechanical stability, and facilitates industrial scalability.

To achieve efficient optical addressing of Rb atoms at 780 nm, we leverage standard telecom components operating at 1560 nm. We employ Second-Harmonic Generation (SHG) via a Periodically-Poled Lithium Niobate (PPLN) crystal, using an all-fiber laser system where two semiconductor lasers (for cooling and repumping) are combined, amplified in an Erbium-Doped Fiber Amplifier (EDFA), and frequency-doubled.

Our current efforts focus on creating and characterizing an ultracold Rb atomic cloud using a Magneto-Optical Trap (MOT). The next challenge lies in efficiently loading these atoms into the fiber while maintaining ultracold temperatures. Ultimately, we aim to demonstrate a proof-of-concept quantum sensor capable of detecting magnetic fields, paving the way for compact, field-deployable magnetometers and other quantum devices.

Coupling slow-mode nanophotonics and cold atoms : a versatile Waveguide QED platform

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Interfacing cold neutral atoms and photons guided in nanoscale waveguides has raised a large interest over the recent years. Those novel light-matter interfaces are a promising route to achieve strong atom-photon coupling in single pass with applications in quantum non-linear optics, quantum computing, or quantum simulation. Nanoscale waveguides enable tight transverse confinement of propagating light over long ranges, facilitating arrays of atoms trapped in the evanescent field of guided modes. Furthermore, this strong transverse confinement significantly enhances individual atom-photon coupling in single-pass configurations. Remarkable advances have been obtained with optical nanofibers and many different collective phenomena have been explored [1]. Nevertheless, the β factor that quantifies the atom-photon interaction remains relatively low, usually just below 1%.

To overcome the limitations of nanofibers, photonic crystal waveguides (PCWs) present promising properties and more tunable parameters. Especially, their precise dispersion engineering enables low group velocities near a band edge, potentially enhancing interaction by several orders of magnitude [2]. In our group, we have been developing such a platform, aiming to couple the slow-mode of a Photonic crystal waveguide with individually trapped cold Rubidium atoms [3].

Despite the promises of this new waveguide-QED paradigm, interfacing cold atoms with nanophotonic devices raises many technical challenges from the design and nanofabrication of the waveguide to its integration in a cold-atom set-up. Particular considerations have to be made when designing this kind of hybrid platform such that a high β can be ensured while taking into account the robustness to inherent nanofabrication imperfections [3]. In addition, ensuring optical transport of cold atoms close to dielectric surfaces such as the waveguide's edge is a daunting task, as direct atom-surface interactions would alter the waveguide's dispersion properties [4]. Moreover any light used for optical transport of the atoms would get reflected by the surface, compromising the efficiency of trap loading. Our approach to tackle this challenge is to use a specific optical tweezer made of the sum of Laguerre-Gauss (LG) modes, as proposed in [5], and which would allow for tighter traps and reduce reflections on the waveguide surface. Building on this theoretical proposal, we report our progress in implementing high-purity LG superposition tweezers in the micron regime and characterizing these traps.

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Entanglement and coherence in the resonance fluorescence of a two-level quantum emitter

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The resonance fluorescence of a single two-level emitter is a fundamental phenomenon in quantum optics and is a key resource for photonic quantum technologies. It is well-known that the scattered field consists of a stream of photons that shows anti-bunched statistics. However, as we recently experimentally showed [1], this behaviour can be viewed as a quantum interference effect between two distinct wo-photon components of the scattered light, commonly referred to as coherent and incoherent, which interfere perfectly destructively interfere. Furthermore, it turns out that the incoherently scattered component consists of energy-time entangled photon pairs. Here, the properties of these two-photon components are the subject of further. In particular, we study their interference behaviour in order to analyse the coherence and indistinguishability of photons emitted at different times. Our results demonstrate a high degree of coherence between the emitted photon pairs, which opens up new pathways for the realization of sources of entangled photon pairs based on resonance fluorescence from a single two-level emitter.

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Rydberg atoms are a much-considered platform for quantum computing, due to the Rydberg blockade effect. Incorporating an optical nanofibre (ONF) into a Rydberg atom experiment brings several advantages. Longer interaction ranges for electric fields result in more atom-light interactions, and due to the effect of evanescent light fields, the power required for Rydberg excitation is reduced. Rubidium-87 atoms within a magneto-optical trap (MOT) are excited to Rydberg states using a two-photon process. As atoms are excited to Rydberg states, they are lost from the MOT. This results in a decrease in the MOT fluorescence, which is related to the Rydberg excitation rate. States with principal quantum number in the range of n=24 to n=68 have been achieved. We have now implemented a two-colour dipole trap via the ONF with the goal of exciting Rydberg states from an array of trapped atoms. This will allow the effect of the ONF on the properties of Rydberg atoms to be studied, as well as Rydberg-Rydberg interactions.

Efficient Long-Range Entanglement Generation Using a Composite Nanofiber Waveguide

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Optical nanofibers (ONFs) have become a promising platform for quantum information processing, particularly in neutral atom quantum computing, due to their ability to trap and probe atoms while facilitating long-range entanglement. While single ONFs are limited in efficiency and complex systems like slot or alligator waveguides add unnecessary intricacy, our composite waveguide, comprising two parallel ONFs, offers a simpler and more effective solution. This dual-fiber configuration enhances atom-waveguide coupling, improving photon collection and reducing photon loss. Using dyadic Green's function methods, we show that the two-ONF system boosts coupling efficiency by over 60% compared to single ONFs and delivers a nearly tenfold increase in Purcell factors for surface-bound emitters. Additionally, it significantly reduces Lamb shifts at selective trapping sites, critical for quantum metrology and atom trapping. A key breakthrough is the generation of long-range entanglement between two quantum emitters with minimal laser driving power. At a low driving strength of $\Omega = 0.45\Gamma$, entanglement persists indefinitely in the two-ONF system, while it vanishes over time in single-ONF setups. These results, combined with the simplicity of all-fiber systems and their compatibility with existing telecommunications technologies, demonstrate the practical potential of composite nanofiber systems to advance quantum technologies through enhanced light-matter interactions and novel functionalities specific to slot waveguides.

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Fabrication and Characterization of Large Millimeter-Scale Microbubble Cavities with High Q-Factor

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Whispering Gallery Mode (WGM) sensors are highly sensitive platforms that enhance light-matter interactions, enabling applications such as single-molecule detection and sensing of pressure, ultrasound, and temperature. Among various cavity structures, microbubble-based cavities are particularly attractive in biomedical applications due to their ability to directly integrate microfluidics. However, conventional methods for fabricating microbubbles face challenges in achieving uniform heat transfer, limiting cavity diameters to below 100 μm. Larger cavities are advantageous for specific applications, as they can facilitate greater volume throughput. Furthermore, for seamless integration with microfluidic systems, it is crucial that cavities are easily compatible with fluidic components to facilitate practical applications. In this study, we present an innovative system capable of fabricating millimeter-scale microbubble cavities uniformly. Utilizing precisely aligned CO_2 lasers and automated tube rotation, we achieved uniform and reproducible fabrication of large cavities. Notably, the proposed fabrication method does not require pre-tapered structures or complex pre-processing steps, simplifying the process. Moreover, the cavities are easily compatible with off-the-shelf fluidic components, enhancing their potential for future microfluidic-based applications. We systematically examined the effects of critical parameters—laser intensity, internal pressure, and rotation speed—on cavity size and symmetry to identify optimal fabrication conditions. The fabricated millimeter-scale cavities exhibit outstanding optical performance, achieving Q-factors exceeding 10^7. We also provide experimental insights into the Q-factor variation with cavity size. Additionally, we highlight unique phenomena arising from the thin-walled microbubble structure and millimeter-scale diameters. These findings expand the design possibilities for WGM sensors and offer a pathway toward developing next-generation high-performance biosensors and physical sensors.

Dynamical beats of short pulses in waveguide QED

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We experimentally and theoretically study the evolution of a weak light pulse confined in a waveguide crossing an ordered array of atoms [1]. In particular, we focus on the limit of single-photon resonant pulses with a temporal width shorter than the atomic lifetime, a relevant regime for quantum information protocols in waveguide QED [2]. We observe a sharp division in the resulting temporal behavior: at short times, while the pulse is still in the medium, there is a buildup of a macroscopic polarization (exciting atoms into a superposition). After that, the transmitted pulse is determined by the radiative decay of the macroscopic polarization (or collective atomic radiation) [3-5]. We propose a theoretical effective model based on macroscopic electrodynamics, which can be microscopically derived from a multiple-scattering input-output theory. The results deepen our understanding of single-photon pulse propagation, crucial for many waveguide-QED-based quantum information protocols.

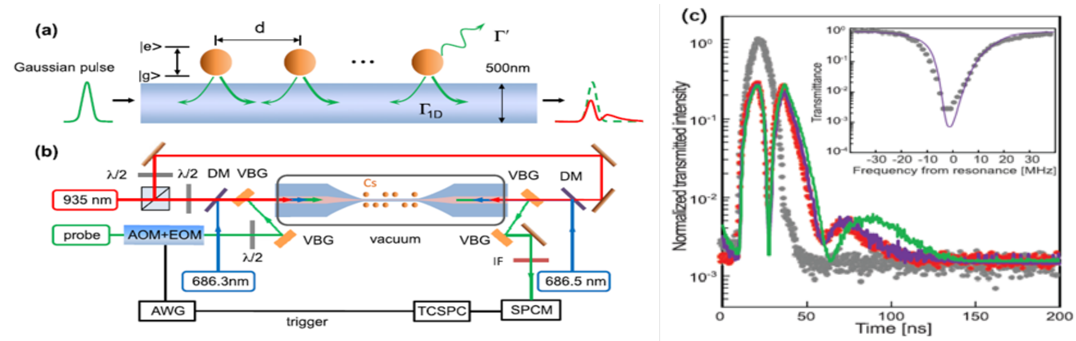

FIG. 1. (a) The atomic array in the nanofiber-trapped. (b) Schematic of the experiment. (c) Time dependence of the transmitted intensity for a 10 ns FWHM pulse propagating in a medium of OD = 11.6.

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Toward a low-cost SERS probe by ion-exchanged processed optical fibers

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Ion-exchange process has attracted continue and growing attention as suitable technique in many application fields, from Integrated Optics to glass strengthening up to the enhancement of light source and photovoltaic cell performances [1]. In addition, this method is used in Plasmonic due to the possibility to induce the formation of metal nanoparticles (i.e.: silver nanoparticles, Ag NPs) in the glass matrix by an ad hoc thermal post-process [2]. In the present work, the use of this low-cost procedure for the realisation of a fibre optic probe for SERS applications is reported. As a first step, the ability of ion – exchanged soda-lime glass microrods to work as active SERS substrates is demonstrated [3]. Therefore, from this result, one can move on to the next step: a piece of a multimode optical fibre, loaded at its end with a thin layer of the same soda-lime glass, is potentially able to work - in backscattering - as a SERS probe when Ag NPs are exposed on the same layer by a suitable ion-exchange process. These results pave the way towards the development of low-cost fibre optic SERS probe, alternative to those realised by sophisticated and expensive lithographic processes [4], for sensing/biosensing applications.

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Interaction of charged ONF with Rydberg atoms

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Rydberg atoms are a very promising candidate for quantum technologies. We have realised Rydberg excitation of cold ^{87}Rb atoms using the evanescent light field of an optical nanofibre (ONF) for principal quantum numbers n = 24 up to n = 68. To further explore the Rydberg blockade mechanism and the effect of surface-atom interactions, we have realised a two-colour fibre-based optical dipole trap mediated via the evanescent fields. Currently, we are working towards using this linear chain of atoms to explore Rydberg excitation from the dipole trap and further study the properties of Rydberg excitation at the interface of an ONF. In the case of a steady state MOT with the trapping laser beams through the ONF, we identified the problem of the Rydberg excitation spectrum deformation and broadening. Our aim is to investigate the influence of the different combinations of laser beams going through optical nanofibre on the Rydberg excitation spectra.

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Rydberg interactions in ultracold Ytterbium

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Mapping the strong interactions between Rydberg excitations in ultra-cold atomic ensembles onto photons opens the door to achieving high optical nonlinearities at the single-photon level. While previous demonstrations of this concept have relied exclusively on alkali atoms, two-valence-electron species like ytterbium offer unique advantages, such as narrow-linewidth laser cooling and, for Yb-174, potentially longer coherence times of polaritons compared to earlier Rubidium-based experiments.

In this poster, we present our new ytterbium apparatus including Yb-specific challenges as light-induced atomic repulsion and two-photon ionization processes, and discuss our progress towards photon-photon interactions by Rydberg polaritons. We also report the spectroscopic characterization of ultra long-range Yb Rydberg molecules that arise as bound states in the low energy scattering of a highly excited Rydberg electron and a ground state atom.

Our experimental setup featuring a dual-chamber compact design and a two-color MOT allows the creation of dipole trapped atomic ensembles at high density and low temperature, with 5 x 10^6 atoms and T < 10 µK within 2 s. Further evaporative cooling down to condensation is possible. Additionally, a field ionization system with ion detection via a Micro-Channel Plate enables high-precision spectroscopy.

Whispering Gallery Mode Optimisation by Precision Microbubble Cavity Fabrication

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Whispering gallery mode (WGM) microbubble cavities, with their hollow structure, are highly advantageous for sensing applications [1–4], as they can hold fluids and particle solutions internally. This enables sensing and trapping with minimal disruption from the surrounding environment. Additionally, the unique geometry of microbubbles provides an opportunity for studying optical spin-orbit coupling [5]. However, their bottle-like shape results in a dense spectrum of WGMs that share the same radial and azimuthal mode numbers but differ in polar mode numbers. This dense WGM spectrum poses a challenge for applications such as sensing, requiring a single, isolated mode, hence precise engineering of the modes within these devices is essential to overcome this limitation.

Microcavity lasers designed using transformation optics [6] highlight the usefulness of precise device engineering. In this study, we investigate precision fabrication techniques to achieve selective WGM isolation and optimisation [7], both spectrally and spatially. Additionally, we aim to engineer microbubbles for particle sensing and trapping at localised intensity hotspots, as well as for applications in directional light emission.

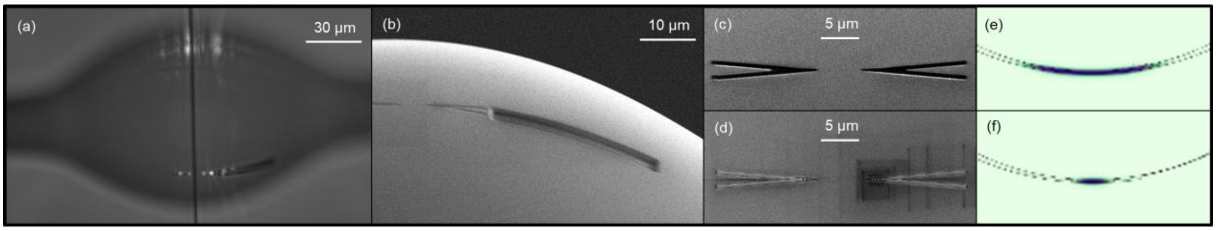

Fig. 1. (a) IR image of a microbubble coupled to a fibre taper. (b) A rectangular (or circular) milling of a microbubble with a wall thickness of 0.8 μm for mode filtering. Finer refractive index control with (c) a micro-scale and (d) framed nano-scale patterns. COMSOL simulations of the fundamental mode field cross-section (e) before and (f) after surface engineering.

In this work, we investigate focussed ion beam (FIB) processing of microbubble cavities that are fabricated using a focussed CO_2 laser on tapered glass capillaries internally pressurised with N_2 gas [4]. Initially, we milled large rectangular or circular features off-equator on the microbubbles, as illustrated in Fig. 1(a, b). This process resulted in significant filtering of higher-order modes when coupling light from a tunable 1550 nm laser into the cavity via a fibre taper. Additionally, we milled around the equator to modify the wall thickness by inscribing micro-lines as shown in Fig. 1(c) and framed nano-lines and circles with dimensions under 500 nm as shown in Fig. 1(d). The framed nano-inscribing facilitated spatial mode confinement, supported by COMSOL simulations and experimental mode field observations presented in Fig. 1(e, f). Despite these surface modifications, the devices retained selected WGMs with Q-factors as high as 10^5. Further refinement of this milling technique could enable precise WGM isolation, aid in the realisation of spin-orbit interactions, and directional light emission.

In conclusion, we have demonstrated WGM spectral and spatial control using FIB milling on a microbubble cavity wall. Further refinement of this technique may enable us to control specific WGMs and may provide a means for realising the spin-orbit interaction of light. The pressure-tuning ability of these devices may aid us in the near- and far-field observation of such an interaction. Furthermore, it is possible to interface the resonators with micro or nanoparticles (by filling them with liquid particle solution) to study spin-orbit-induced dynamics.

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Tunable Terahertz Frequency Generation Using Spherical Whispering Gallery Mode Micro-Resonators

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This study investigates the generation of terahertz (THz) frequencies using spherical Whispering Gallery Mode (WGM) resonators and studies their possibility as optical filters. By leveraging the high-quality factor and mode confinement characteristics of WGM resonators, we demonstrate the ability to generate and control THz frequencies via precise adjustments in the resonator's geometric properties, specifically the sphere radius. Numerical simulations indicate that the resonator size significantly affects the generated THz frequencies and their tunability.
To enhance functionality further, we propose future work involving the coating of spherical resonators with advanced materials, enabling additional control over frequency characteristics. The integration of coatings allows for the manipulation of refractive index contrast and the potential for active tuning, broadening the application scope of these resonators. The proposed technique incorporates geometrical and material design strategies to achieve high-performance tunable optical filtering.
This work may deliver a footpath to novel THz optical filters suitable for applications in spectroscopy, telecommunications, and sensing. The results pave the way for cost-effective, compact, and highly adaptable solutions in advanced photonics systems.

Keywords: THz Generation; WHMR; Spherical Resonators, Optical Filters, Tunable Photonics.

Contribution submission to the conference Bonn 2025

Rydberg superatoms coupled with super-extended evanescent field nanofiber at the single-photon level — •Ludwig Müller[1], •Knut Domke[1], Tangi Legrand[1], Thomas Hoinkes[2], Xin Wang[1], Eduardo Uruñuela[1], Wolfgang Alt[1], and Sebastian Hofferberth[1] — [1]Institute of Applied Physics, University of Bonn, Germany — [2]Department of Physics, Humboldt University of Berlin, Germany

Both Rydberg superatoms driven by free-space photonic modes and single emitters coupled to photonic waveguides have paved the way for strong coherent light-matter coupling at the few-photon level. By combining advantages of both ideas, we aim to achieve homogeneous coupling of multiple Rydberg superatoms coupled to a field confined by a nanofiber. Fibers with diameters of a few hundred nanometers are successfully used to trap and couple arrays of single atoms by their evanescent field. Recent advances allow the fibers to be tapered to even smaller diameters, allowing more than 99 % of the energy to be guided outside the fiber with effective field diameters of $\gtrsim 13\,\lambda$ [1], bringing them up to typical Rydberg blockade radius sizes.

On this poster, we will we will present the current status of planning and building our new Nanofiber experiment such as the vacuum chamber and first tests of the nanofibers. We select Ytterbium due to its advantage of having the two-photon Rydberg excitation transitions close together with 399 nm and 395 nm, which simplifies the fiber design and is expected to have low thermal dephasing effects.

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Part:	**Q**
Type:	**Poster**
Topic:	**2.3 Ultrakalte Plasmen und Rydbergsysteme; 2.3 Ultracold Plasmas and Rydberg Systems**
Keywords:	**Waveguide QED; Ultracold Ytterbium; Rydberg superatoms; Nanofiber**
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Towards a room temperature visible light single photon source by using rare earth ion-doped fibre taper

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Room temperature visible light single photon sources would be beneficial for the development of quantum technologies. Here the work is concentrated on designing and fabrication of a room-temperature visible light single photon source by using rare-earth ion doped fibre tapers which are made thin enough to isolate single ions and to reach the single photon emission regime [1]. For achieving highly efficient and high-brightness visible photon sources by direct pumping, it is necessary to do a detailed characterization study on various ion-doped matrices which is made possible by recent development of GaN blue lasers.

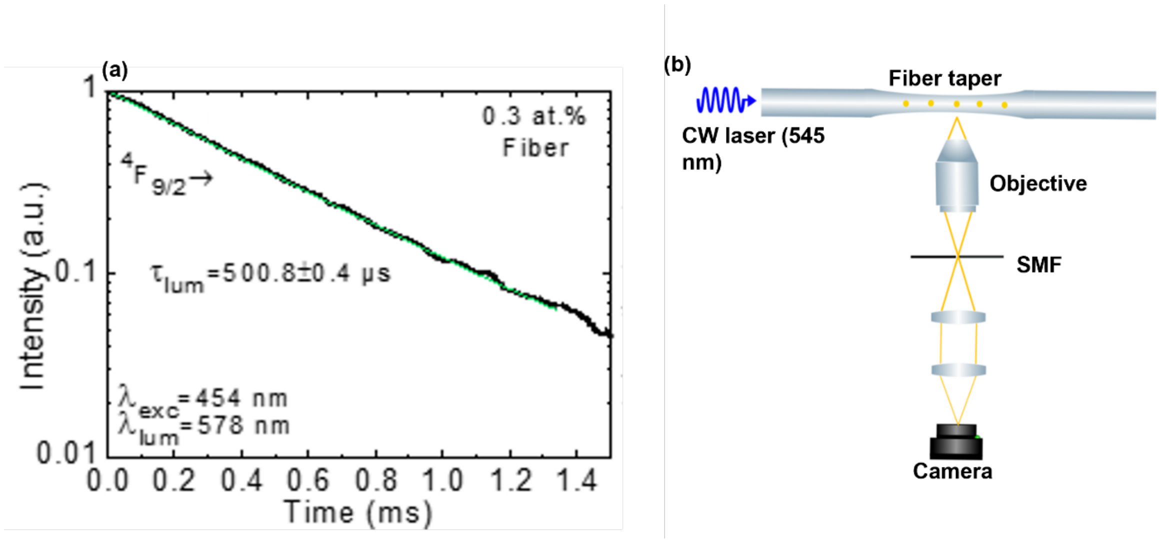

Fig. 1. a) Luminescence decay curves for Dy3+ ions in a commercial single-clad aluminosilicate glass fibre (Exail, France). b) Schematic of imaging setup of fibre taper.

The short luminescence lifetime (500 µs) of dysprosium ion in silica fibre (Fig. 1 (a)) is compatible with the development of single photon sources [2]. Aforementioned schematic (Fig. 1 (b)) of imaging set up is used for imaging the quantum emission from the isolated ions inside the tapered fibre. Single photon emission will be validated by intensity autocorrelation measurements. Such photon sources could then be used to demonstrate quantum applications like quantum random number generation and quantum communication as future aspects.

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Towards the observation of collective radiance phenomena in a one-dimensional array of waveguide-coupled atoms with sub-$\lambda/2$ spacing

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Recently, it has been shown theoretically that the fidelity of photon storage and retrieval in quantum memories scales exponentially better with the number of emitters if one harnesses the collective response of closely spaced atoms ordered in an array [1]. The improved scaling relies on the effect of selective radiance, that is, destructive interference that suppresses scattering into undesired modes. This occurs when the period of an array of emitters is less than half of the atomic resonant wavelength of the probe laser ($d < \lambda/2$). In order to realize this situation, we trap and optically interface laser-cooled cesium atoms using a two-color nanofiber-based dipole trap [2]. It is composed of a blue-detuned partial standing wave and two red-detuned running wave light fields, which counter-propagate in the fiber to compensate the inhomgenous broadening due to the vector light shift [3]. The resulting trapping potential consists of two 1D-arrays of trapping sites on the opposite sides of the nanofiber, where the axial period is $d \simeq 0.35\lambda$. Radially, the minima of the trapping potential are located at a distance of 300nm from the fibers surface. We characterize the trap by measuring the trap frequencies, the total number of stored atoms, the fraction of sites filled with a single atom in the collisional blockade regime, and the lifetime of the atoms.

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Microparticle manipulation in the evanescent field of an optical nanofibre

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ABSTRACT

The evanescent field generated by an optical nanofibre (ONF) provides a unique platform for manipulating and studying microscale objects like metallo-dielectric Janus particles (JPs) [1]. This work looks at the dynamics of these particles when placed in the evanescent field of an ONF and the effects on the particle motion with a change in polarization. To address the current limitations in the manipulation of such anisotropic particles, we are manipulating JPs, - specifically, silica microspheres half-coated with gold, —using optical forces generated in the evanescent field of the ONF. The evanescent field effectively locks the JPs to the ONF, restricting radial motion while allowing propulsion along the direction of the fiber-guided light. We have seen that JPs exhibit faster propulsion compared to similar dielectric particles due to the interaction between the metallic component of the JP and the evanescent field, resulting in stronger optical forces. The work is extended to analyse the effects on such particles under different polarizations of light. In conclusion, the study highlights precise control of metallo-dielectric composite particles, portraying the evanescent field of an ONF as a promising tool to overcome limitations in conventional particle manipulation methods.

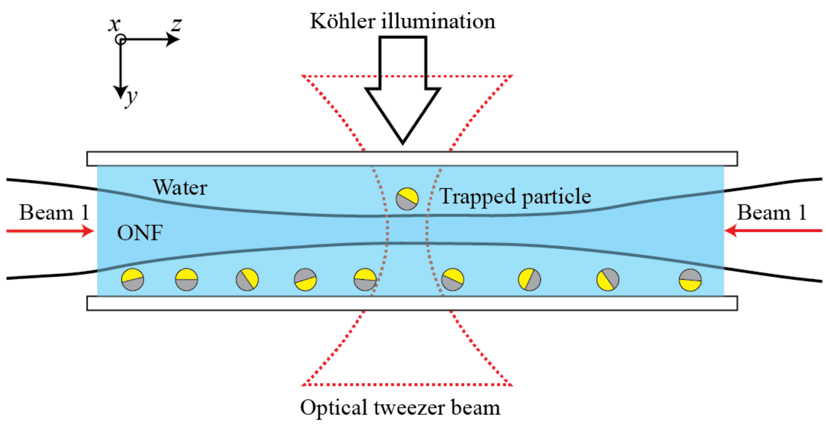

Fig. 1. Schematic of the experimental setup; the particles are trapped using an optical tweezers which is switched off once the JP is trapped in the evanescent field; Beam 1 and Beam 2 cancel the scattering forces acting on the particle, allowing it to be influenced only by the gradient force

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Exact solution for two excited atoms in a delay-induced non-markovian multiphoton system.

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We investigate the non-Markovian dynamics of two fully excited two-level atoms coupled to a one-dimensional waveguide with time delays and multiphoton occupancy of the waveguide. Our study reveals how delayed photon exchange can synchronize atomic states, leading to the formation of an entangled dark state and a two-photon bound state in the continuum [1,2]. This behavior includes the subfluorescence phenomenon, a counterpart to superfluorescence [3], where emission is suppressed rather than enhanced. These delay-induced effects highlight a spontaneous mechanism for generating and stabilizing entanglement between distant quantum emitters, offering promising applications for quantum networks and long-distance quantum communication systems

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Measuring deviations from a perfectly circular cross-section of an optical nanofiber at the Ångström scale

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Tapered optical fibers (TOFs) with sub-wavelength-diameter waists, known as optical nanofibers, are powerful tools for interfacing quantum emitters and nanophotonics. This demands stable polarization of the fiber-guided light field. However, the linear birefringence resulting from Ångström-scale deviations in the nanofiber's ideally circular cross-section can lead to significant polarization changes within millimeters of light propagation.

Here, we experimentally investigate such deviations using two in-situ approaches. First, we measure the resonance frequencies of hundreds of flexural modes of the nanofiber, which can be thought of as a doubly clamped beam in this context. Assuming an elliptical cross-section with semi-axes a and b, the differing second moments of area for vibrations along these axes result in a splitting of the resonance frequencies. By analyzing the measured resonance pairs, we estimate $|a-b| \approx 3$ Ångström for a nanofiber with a nominal diameter of 500 nm. An analytical model links this elliptical cross-section to the linear birefringence of the nanofiber. Second, we monitor the polarization of the guided light field along the nanofiber [1]. By analyzing the scattered light as a function of the axial position, we confirm the birefringence inferred from the flexural mode frequencies.

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Towards enhanced directional coupling in an optical nanofibre-cold atom system

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We aim to study two-photon absorption in cold ^{87}Rb atoms near an optical nanofiber nanofibre (ONF), focusing on the $5S_{1/2}$ to $6S_{1/2}$ transition. This investigation will enable us to explore the directional coupling of photons emitted during atomic de-excitation into the ONF (Fig. 1). Initial results indicate that introducing a seed laser at a wavelength of 795 nm, corresponding to the $5S_{1/2}$ to $5\mathrm{P}_{1/2}$ transition, significantly influences the coupling direction of the emitted photons at wavelength 79498 nm. At near-zero or very low seed laser power (on the order of a few pW), most of the light generated photons couples backward relative to the seed laser's propagation direction. However, as the seed laser power increases, the coupling direction reverses, resulting in forward coupling.

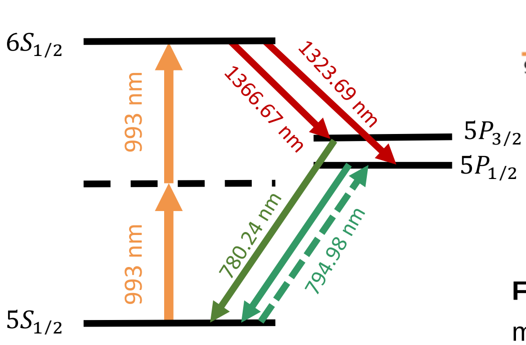

Fig. 1: The atomic energy levels for ^{87}Rb involved in the experiment. The dashed line represents the seed laser used in the experiment

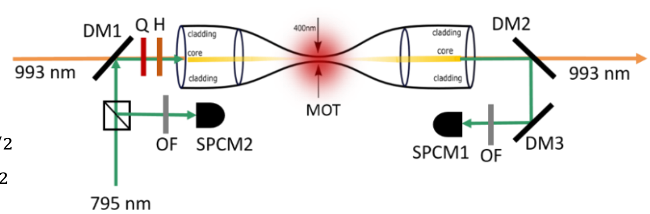

Fig. 2: Schematic of the experimental setup. DM: dichroic mirror, Q: Quarter wave-plate, H: Half wave-plate (wave plates are used for polarization adjustment), SPCM: single-photon counting module, OF: Optical filter at 795 nm.

Further investigations into changing other parameters, such as polarization of the excitation and seed laser beams, and different powers for the excitation beam will enable us to better understand the observed behaviour.

Near-ultraviolet high-Q whispering-gallery-modes microresonators for laser frequency stabilization

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Whispering gallery mode (WGM) microresonators have been extensively studied since decades for their unique properties like large Q-factor, long photon lifetime storage and small optical volume. Despite the huge interest for those compact microresonators, they have been mainly studied in the near infrared region [1]. Since few years, the need of short wavelength compact coherent sources like single-frequency lasers and optical frequency combs, as tools for high precision spectroscopy, pushes the research community to investigate the potential of WGM resonators at short wavelengths.
We report the full characterization of fused silica (Heraeus F300) WGM microspheres in the near ultraviolet at 420 nm [2]. An intrinsic microsphere Q-factor in excess to 10^8 limited by surface roughness (Fig. 1 a)) is reported. In the near infrared region, water deposition on the microsphere surface degrades the Q-factor over time toward the 10^7-10^8 range. Thanks to the water transparency window around 420 nm, no degradation is observed, which allow stable operation of WGM based photonic devices at short wavelengths.

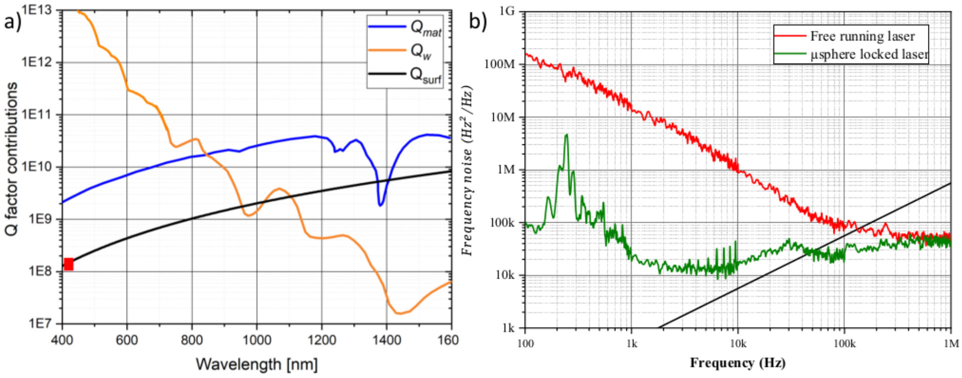

Fig. 1. a) Q-factor contributions to the intrinsic Q-factor. Red square correspond to the measured intrinsic Q-factor. Q_{mat}, Q_w, Q_{surf}, refer to the material, water layer and surface roughness Q-factor respectively. b) Frequency noise measurement of the free running and µsphere locked laser. The beta-line is plotted in black color.

The microsphere is then used as a frequency reference for the stabilization of a commercial external cavity diode laser (ECDL) emitting at 420 nm in a Pound-Drever-Hall servolocking setup. Frequency noise of the free running and locked laser are presented on Fig. 1 b). Once the ECDL is locked on a resonance of the high-Q WGM microsphere, the FN is reduced up to 30 dB between 100 Hz and 400 kHz, which corresponds to an integrated linewidth narrowed down from 887 to 91 kHz. Further reduction could be obtain by adjusting the gap to reach the critical coupling regime where minimum frequency noise is expected.

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Ultrasensitive Micro/Nanofiber Sensors and Actuators

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As a combination of fiber optics and nanotechnology, optical micro/nanofibers (MNFs) exhibit diameters close to or smaller than the wavelength of guided light. These tiny MNFs guide light with low loss, tight optical confinement, and large fractional evanescent fields, making them an attractive platform for optical sensing and actuation. We utilized MNFs as artificial optical nerves, leveraging their guided-to-radiation modes transition under external stimuli to enable their sensing capability. We developed a skin-like optical tactile sensor with high sensitivity (1870 kPa^{-1}), low detection limit (7 mPa) and fast response (10 us), demonstrating its potential applications in physiological monitoring, human-machine interfaces, and intelligent robotics [1]. For weak force sensing applications, we developed a self-sensing nanofiber cantilever with ultra-low stiffness, achieving an ultrasensitive microforce balance with a nanonewton-scale working range (0-11.2 nN) and piconewton-level resolution (3.3 pN) [2]. For single nanoparticle detection in fundamental physics and biological applications, we developed a single nanoparticle sensing chip by embedding nanofibers into microfluidic channels, enabling highly sensitive detection and analysis of nanoparticles with varying diameters (100-1000 nm) and biological samples (exosomes and yeasts) [3]. On the other hand, leveraging the high energy density, high tensile strength, and small bending radius of nanofiber tapers, we developed compact photoactuators with large deformation, fast response, and strong gripping capability, laying the foundation for integrated sensing-actuation optical devices [4].

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The quantum cooperative description of photons in Raman emission

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ABSTRACT

In this work the theoretical description of the quantum cooperative aspect of the interaction of atoms, molecules and biomolecules with the active medium of the cavity is presented. In particular, cooperative effects between two cavity modes are examined. The optical cavity being characterized by the rather high quality factor Q in which the lifetime of photons dominates over the lifetime of atoms excited in biquantum Raman (R) resonance. In this paper, for the description and analysis of Raman emission, the quantum generator was selected as the object of research at the conversion of low energy photons into higher energy photons in the process R of the cavity. At the same time, the correlation function between photons is obtained as a result of the analysis of the statistical properties between Stokes and anti-Stokes photons.

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Ultra-thin silicon nitride micro wheel-resonator for enhanced light-atom interaction

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Room-temperature atomic vapor cells demonstrate lower technical complexities and better compatibility with photonic integrated circuits (PIC). In spite of less precision and control over individual atoms, thermal atomic vapor holds the possibility for realizing non-classical light source, small-scale atomic clocks, and quantum memories as some of the major building blocks of a hybrid atom-nanophotonic network. Despite thermal atoms suffering from low density, short transit times, and large linewidth broadening due to thermal motion, a strong coupling between optical field and the atoms can compensate these drawbacks, allowing an atomic vapor cell based cQED platform to display quantum interference effects. In this work, we propose to enhance the light-atom interaction with an ultra-thin wheel resonator. We present the design, fabrication, and characterization of the resonator with high optical quality factor of $Q_{in} = 6.6 \times 10^5$ at 780 nm. We anticipate the strong evanescent field can allow for enhanced light-atom interaction, achieving a high Purcell factor of 97.5.

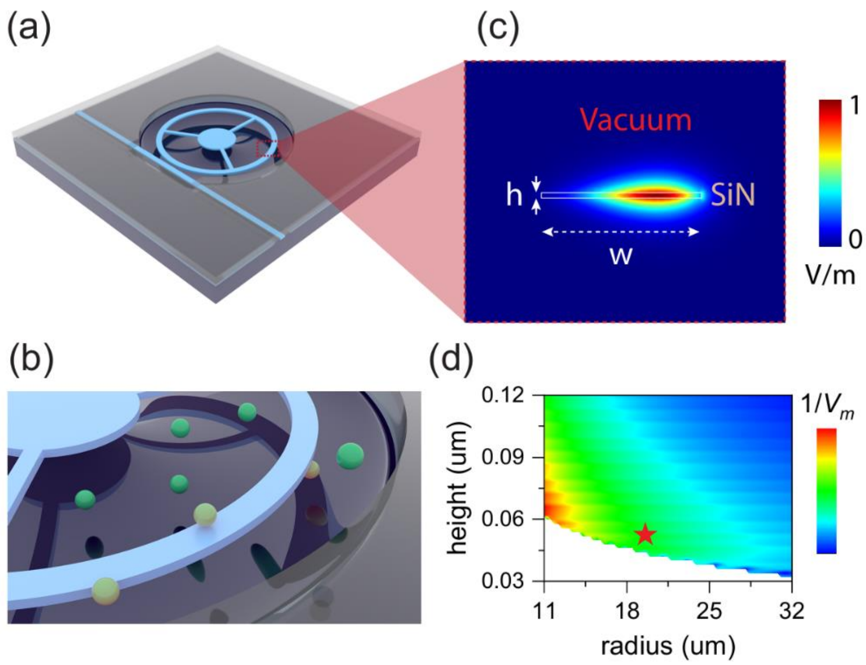

Fig.1. Coupling a microwheel resonator to atomic vapor in its evanescent field. (a) 3D model showing the design of the microwheel resonator. (b) Zoom-in of the microwheel indicating interaction with close-by atoms. (c) Cross-sectional simulation of the optical field for a TE-mode supported in the microwheel resonator. (d) FDTD simulated $1/V_m$ as a function of ring radius r and height (thickness) h. The width of the ring is fixed at 2 μm.

Impact-parameter selective Rydberg-Rydberg collision by optical tweezers

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Optical tweezers are tightly focused beams of light used to trap and manipulate microscopic particles. A recent study has demonstrated a novel use of a tweezer to accelerate a neutral single atom [1]. This control of spatially localized wavepacket of an atom accelerated to a desired velocity opens new avenues to study atomic and molecular collisions with selected impact parameter and collision velocity. This contrasts to typical collision experiments in a gas of atoms, for which the effects of impact parameter and collision velocity are averaged over. Moreover, the effects of collisions are often quantified as a change in electronic excitation through inelastic scattering by measuring (field-)ionization after collisions. Optical tweezers provide a new probing scheme that gives access to elastic Rydberg-Rydberg scattering for the first time.

In the current experiment (Fig. 1) two rubidium atoms are initially in the ground state. The projectile atom A is accelerated by an dynamic optical tweezer while the target atom B is trapped in a static tweezer. After de-activation of optical tweezers, both atoms are optically excited to an $nS_{1/2}$ Rydberg state followed by a collision. After some time dlay the atom B is de-excited to the ground state before the static tweezer is reactivated. The atom B can be recaptured by the tweezer unless the momentum transfer caused by the collision pushes the atom out of recapture zone. The recapture probability, $P_B(b; n, v)$, can be used to extract the collisional cross section between two Rydberg atoms.

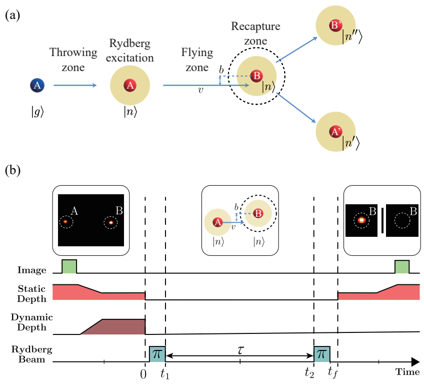

Fig.1 (a) Schematic of the Rydberg-atom collision experiment. (b) Experimental procedure: two atoms A and B initially captured with static optical dipole traps from a cloud of $^{87}\mathrm{Rb}$ atoms. Atom A is transported to the dynamic trap followed by an acceleration until reaching a desired collision velocity. After all traps are deactivated, a π-pulse is applied to excite both atoms to a Rydberg state with $n \simeq 50$. After a collision another π-pulse de-excites the atoms before a trap is reactivated to recapture the atoms.

The measured data agree quite well with the simulations, in which the electronic excitation dynamics of each atom is approximated by a two-level system for an elastic collision and the motion of atom follows the classical equations of motion. The obtained cross section is indeed sensitive to the size of recapture zone. An additional comparison to quantum mechanical scattering theory indicates that the interference between atomic trajectories may become observable in the limit of small recapture zone of the tweezer.

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