ONNA 2015

Workshop on Optical Nanofiber Applications:

From Quantum to Bio Technologies

25 - 28 May 2015, OIST Seaside House, Okinawa, Japan

Co-organisers

Síle Nic Chormaic (OIST Graduate University, Japan)

Kohzo Hakuta (University of Electro-Communications, Japan)

Luis Orozco (Joint Quantum Institute, University of Maryland, USA)

Gilberto Brambilla (ORC, University of Southampton, UK)

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Programme at a Glance

	24th Sunday	25th Monday	26th Tuesday	27th Wednesday	28th Thursday	29th Friday
9:00	Arrival and Dinner	Opening	Transfer to OIST	O. Benson 9:00–9:45	G. Brambilla 9:00–9:45	Departure from Seaside House
9:15		L. Orozco 9:15–10:00	F. Vollmer 9:15–10:00			
9:30						
9:45				B. Dayan 9:45–10:30	L. Tong 9:45–10:30	
10:00		J. Laurat 10:00–10:45	L. Yang 10:00–10:45			
10:15						
10:30				A. Schell	Y. Takeuchi	
10:45		BREAK 10:45–11:15	BREAK 10:45–11:15	BREAK 10:45–11:15	BREAK 10:45–11:15	
11:00						
11:15		F. Fatemi 11:15–12:00	T. Carmon 11:15–12:00	K. Hakuta 11:15–12:00	T. Tanabe 11:15–12:00	
11:30						
11:45						
12:00		J. Appel	OIST Campus Tour + Excursion + Conference Dinner	Y. L. Li	K. Nayak	
12:15		D. Holzmann		J. H. Kim	U. Tanaka	
12:30		LUNCH 12:30 –2:00		LUNCH 12:30 –2:00	LUNCH 12:30 –2:00	
12:45						
1:00						
1:15						
1:30						
1:45						
2:00		A. Rauschenbeutel 2:00–2:45		B. Li 2:00–2:45	M. Ding 2:00–2:45	
2:15						
2:30						
2:45		T. Aoki 2:45–3:30		S. Nic Chormaic 2:45–3:30	M. Sumetsky 2:45–3:30	
3:00						
3:15						
3:30		Y. Colombe		X.-C. Yu	A. Camposeo	
3:45		S.-P. Yu		S. Ozdemir	F. Xu	
4:00		BREAK 4:00–4:30		BREAK 4:00–4:30	Closing Remarks 4:00–4:30	
4:15						
4:30		poster preview I 4:30–5:15		poster preview II 4:30–5:15	BREAK 4:30–6:30	
4:45						
5:00						
5:15		poster session I 5:15–7:00		poster session II 5:15–7:00		
5:30						
5:45						
6:00						
6:30					BBQ DINNER 6:30–9:00	
7:00		DINNER 7:00–9:00		DINNER 7:00–9:00		

Sunday, 24 May

Arrival

Monday, 25 May

9:00	Opening	
9:15	T-1	Luis Orozco (JQI, University of Maryland, USA) Nanofibers for coupling atoms to superconducting qubits, a progress report
10:00	T-2	Julien Laurat (Laboratoire Kastler Brossel, France) Reversible storage of tightly guided light in an optical nanofiber
10:45	Break	
11:15	T-3	Fredrik Fatemi (NRL, USA) Exciting modes of tapered nanofibers
12:00	C-1	Jürgen Appel (University of Copenhagen, Denmark) Generation and detection of a Sub-Poissonian atom number distribution in a one-dimensional optical lattice
12:15	C-2	Daniela Holzmann (University of Innsbruck, Austria) Self-ordering and collective dynamics of transversely illuminated point-scatterers in a 1D trap
12:30	Lunch	
14:00	T-4	Arno Rauschenbeutel (TU Wien, Austria) Chiral interaction of light and matter in confined geometries
14:45	T-5	Takao Aoki (Waseda University, Japan) Tapered optical fibers with optimal shapes for quantum optics experiments
15:30	C-3	Yves Colombe (Universität Innsbruck, Austria) A nanofiber in an ion trap
15:45	C-4	Su-Peng Yu (California Institute of Technology, USA) 'Alligator' photonic crystal platform for atom trapping and strong light-matter interactions
16:00	Break	
16:30	Poster Preview I	
17:15	Poster Session I	
19:00	Dinner	

Tuesday, 26 May at OIST Campus

9:15	T-6	Frank Vollmer (MPI for the Science of Light, Germany) Detecting single molecules and their interactions with optical microcavities
10:00	T-7	Lan Yang (Washington University, USA) Whispering-gallery-mode resonators and their applications: from nanoscale measurement to parity-time symmetric photonics
10:45	Break	
11:15	T-8	Tal Carmon (Technion Israel Institute of Technology, Israel) Liquid optomechanics for giant quality factors
12:00	Campus Tour, Lunch, and Excursion	
19:00	Conference Dinner	

Wednesday, 27 May

9:00	T-9	Oliver Benson (Humboldt University, Germany) Quantum technologies in diamond: Chance & Challenge
9:45	T-10	Barak Dayan (Weizmann Institute of Science, Israel) Photon-Photon Interactions and Photonic Quantum Logic by Deterministic One-Photon Raman Interaction (DOPRI) with a Single Atom
10:30	C-5	Andreas Schell (Kyoto University, Japan) Emission enhancement with nanofiber Bragg cavities
10:45-	Break	

11:15	T11	Kohzo Hakuta (University of Electrocommunications, Japan) Cavity quantum electrodynamics on an optical nanofiber using photonic crystal structures
12:00	C-6	Ying Lia Li (University College London, UK) Cooling the Centre-of-Mass Motion of a Silica Microsphere
12:15	C-7	JunHwan Kim (JunHwan Kim, University of Illinois at Urbana-Champaign, USA) Magnet-free optical isolator using a fiber derived microresonator
12:30	Lunch	
14:00	T-12	Baojun Li (Sun Yat Sen University, China) Optical nanofiber drawing, device assembly, and applications in optofluidics
14:45	T-13	Síle Nic Chormaic (OIST Graduate University, Japan) Research update from the Light-Matter Interactions Unit
15:30	C-8	Xiao-Chong Yu (Peking University, China) Single nanoparticle detection and sizing using a nanofiber pair in aqueous environment
15:45	C-9	Sahin Kaya Ozdemir (Washington University, USA) Controlling light at the exceptional points with whispering gallery microresonators
16:00	Break	
16:30	Poster Review II	
17:15	Poster Session II	
19:00	Dinner	

Thursday, 28 May

9:00	T-14	Gilberto Brambilla (ORC, University of Southampton, UK) Nonlinear optics in optical micro- and nano-fibres
9:45	T-15	Limin Tong (Zhejiang University, China) Coupled microfiber/nanofiber-nanoparticle system
10:30	C-10	Yuki Takeuchi (Osaka University, Japan) Controlling the group velocities of light pulses in a fiber-coupled bottle micro resonator
10:45	Break	
11:15	T-16	Takasumi Tanabe (Keio University, Japan) Nonlinear optics using high-Q microcavities: Photonic crystal and whispering gallery mode cavities
12:00	C-11	Kali Prasanna Nayak (University of Electro-Communications, Japan) Efficient fiber-optical interface for nanophotonic devices
12:15	C12	Utako Tanaka (Osaka University, Japan) Charge measurement of tapered optical fibers with microparticles in a linear Paul trap
12:30	Lunch	
14:00	T-17	Ming Ding (BeiHang University, China) Nanostructured micro/nanofiber and related applications
14:45	T-18	Mikhail (Misha) Sumetsky (Aston University, UK) Nanophotonics of optical fibers
15:30	C-13	Andrea Camposeo (Istituto Nanoscienze-CNR, Italy) Optical waveguiding, gain and lasing properties of electrospun nanofibers for nanophotonics
15:45	C-14	Fei Xu (Nanjing University, China) Platform for enhanced light-matter interaction and miniaturizing fiber devices
16:00	Closing Remarks	
16:30	Break	
18:30	BBQ Dinner	

Friday, 29 May

Departure from Seaside House

T-1

Nanofibers for coupling atoms to superconducting qubits, a progress report

Luis A. Orozco

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Coupling of a neutral atomic ensemble to superconducting circuits via a magnetic dipole transition forms an interesting hybrid system. Here we present progress towards trapping cold rubidium atoms within 10 micrometers of a superconducting circuit using a cryogenically-compatible atom trap and a tunable, high-Q superconducting resonator. Evanescent fields around an optical nanofiber with 99.95% transmission form an atom trap for Rb suitable for a 15 mK dilution refrigerator. We study the coupling of the atoms to the mode and rhe dynamics of atoms near the nanofiber through conditional measurements of the intensity.

Work done in collaboration with: Jeffrey A. Grover[1], Jonathan E. Hoffman[1], Jongmin Lee[1], Sylvain Ravets[1,3], Pablo A. Solano[1], Steven L. Rolston[1], Guy Beadie[2], and Fredrik K. Fatemi[2].
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[2]*Optical Sciences Division, Naval Research Laboratory, Washington DC, 20375, USA.*
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T-2

Reversible storage of tightly guided light in an optical nanofiber

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Developing light-matter interfaces is a crucial capability with unique applications to quantum optics and quantum information networks. In this context, our group focuses on the development of quantum memories in cold, neutral atom clouds, using both electromagnetically-induced transparency (EIT) and DLCZ protocols. In a free-space implementation, we recently reported for instance the quantum storage of qubits encoded in the orbital angular momentum degree of freedom [1] and a multiple-degree-of-freedom quantum memory for structured light [2]. In this talk, I will focus on our demonstration [3] of slow light and optical storage at the single-photon level for the light tightly guided by a subwavelength-diameter optical fiber. This new setting is a promising alternative to free-space focusing, which limits the interaction one can obtain, and provides a novel platform for developing all-fibered quantum networks.

Our setup is illustrated in Fig. 1(a). A cloud of cold cesium atoms overlaps with a nanofiber suspended in the ultra-high vacuum chamber and connected to the outside by two teflon feedthroughs. The nanofiber is fabricated from a non polarization-maintaining fiber by the flame brushing technique. It exhibits a $2r = 400 \pm 20$ nm diameter over a length of 9 mm, longer than the cesium cloud. The silica-vacuum interface guides the hybrid fundamental mode HE_{11} along the nanofiber, which is adiabatically coupled via a tapered region on both sides. Since a large fraction of the energy travels in the evanescent field, the mode can be coupled to atoms in the vicinity. Theoretical studies have shown that this mode can propagate under EIT condition imposed by the surrounding medium without fundamental limitations [5].

The cesium cloud is released from a magneto-optical trap (MOT) cigar-shaped along the fiber by using rectangular coils. The experiment is conducted in a cyclic fashion. The current in the MOT coils is switched off, then, after a 4.4 ms decay of eddy currents, the trapping beams are turned off. Measurements are performed during 1 ms, while the cloud expands freely. After this stage, the trap is reloaded for 40 ms. The surrounding magnetic fields are measured by Zeeman microwave spectroscopy and cancelled with three pairs of coils. Compensation below 20 mG is obtained.

Figure 1(b) provides the storage results for a signal with a mean photon-number per pulse equal to 0.6±0.1. The pulses have been temporally shaped to an exponentially-rising profile with a full width at half-maximum of 60 ns. After optimisation of the control power for a trade-off between transparency and delay, an efficiency $\eta = 10 \pm 0.5$ % is obtained, therefore realizing a memory at the single-photon level in this fibered setting. Remarkably, the single-photon signal-to-noise ratio in the retrieved pulse is already equal to 20. Figure 1(c) finally shows the memory lifetime. Three concurrent decoherence mechanisms are involved and can be evaluated independently. The fit takes into account two dephasing mechanisms, i.e. residual magnetic field and motional dephasing, and the transit time of the atoms. The good agreement confirms that the decoherence mechanisms are well identified.

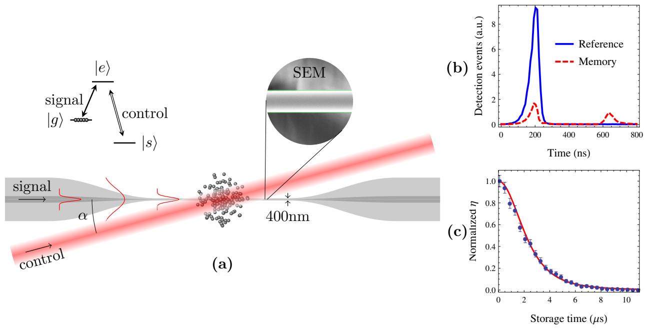

FIG. 1. (a) Setup. A 400-nm diameter nanofiber is overlapped with a large ensemble of cold cesium atoms. The signal to be stored is guided inside the nanofiber while the control propagates at the outside, with an angle $\alpha \sim 13°$. (b) Storage and retrieval. In the absence of control, the blue and purple points give the transmitted pulse without and with atoms respectively. The measured OD is equal here to 2. The red data corresponds to the memory sequence, showing leakage and retrieval. The black line indicates the control timing. The mean photon-number per pulse is 0.6 and the storage and retrieval efficiency is 10 ± 0.5%. (c) Normalized retrieval efficiency as a function of the storage time.

[1] A. Nicolas *et al.*, *A quantum memory for orbital angular momentum photonic qubits*, Nature Photon. **8**, 234 (2014).
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[3] B. Gouraud *et al.*, *Demonstration of a memory for tightly guided light in an optical nanofiber*, arXiv:1502.01458, PRL in press.
[4] D.E. Chang, V. Vuletić, and M.D. Lukin, *Quantum nonlinear optics – photon by photon*, Nature Photon. **8**, 685 (2014).
[5] F. Le Kien and K. Hakuta, *Slowing down of a guided light field along a nanofiber in a cold atomic gas*, Phys. Rev. A **79**, 013818 (2009).

T-3

Exciting modes of tapered nanofibers

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Optical nanofibers provide a rich platform for research into atomic and optical phenomena even when they support only one mode. Nanofibers supporting higher-order modes provide additional degrees of freedom to enable complex evanescent field profiles for interaction with the surrounding medium, but local control of these profiles requires nondestructive evaluation of the propagating fields. In this talk, I will describe the use of Rayleigh scattering for measuring light propagation in few-mode optical fibers. We image the Rayleigh scattered light to obtain a direct visualization of the spatial evolution of propagating fields throughout the entire fiber, including the transition from core-cladding guidance to cladding-air guidance. We measure local beat lengths by resolving the modal interference. These local beat lengths are steeply dependent on the fiber dimensions, and allow mapping of the fiber geometry with nanometer resolution. This diagnostic also enables real-time adjustment of the modal composition on the fiber waist by controlling the input field distribution.

T-4

Chiral interaction of light and matter in confined geometries

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When light is strongly transversally confined, significant local polarization components that point in the direction of propagation arise. In contrast to paraxial light fields, the corresponding intrinsic angular momentum of the light field is position-dependent - an effect referred to as spin-orbit interaction of light. Remarkably, the light's spin can even be perpendicular to the propagation direction. The interaction of emitters with such light fields leads to new and surprising effects. For example, when coupling gold nanoparticles or atoms to the evanescent field surrounding a silica nanophotonic waveguide, the intrinsic mirror symmetry of the particles' emission is broken. This allowed us to realize chiral nanophotonic interfaces in which the emission direction of light into the waveguide is controlled by the polarization of the excitation light [1] or by the internal state of the atoms [2], respectively. Moreover, we employ this chiral interaction to demonstrate nonreciprocal transmission of light at the single-photon level through a silica nanofiber [3]. The resulting optical diode is the first example of a new class of nonreciprocal nanophotonic devices which exploit the chiral interaction between quantum emitters and transversally confined photons.

References:

[1] J. Petersen, J. Volz, and A. Rauschenbeutel, “Chiral nanophotonic waveguide interface based on spin-orbit coupling of light,” Science **346**, 67 (2014).

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[3] C. Sayrin, C. Junge, R. Mitsch, B. Albrecht, D. O'Shea, P. Schneeweiss, J. Volz and A. Rauschenbeutel, “Optical diode based on the chirality of guided photons,” arXiv:1502.01549.

T-5

Tapered optical fibers with optimal shapes for quantum optics experiments

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Tapered optical fibers (TOF) have been utilized in various fields of optical science, because of the strong confinement of the guided mode to a subwavelength diameter and the large evanescent fields at the waist. For studies in quantum optics, particularly, it is important to minimize TOF losses to preserve the fidelity of quantum states of light. The non-zero taper angles in TOFs result in the power coupling losses from the fundamental guided mode to higher-order modes. Although TOFs with smaller taper angles have lower losses, they tend to be long and fragile. We have designed and fabricated TOFs with optimal shapes for minimizing the TOF lengths while maintaining low losses[1]. In this presentation, I will talk about the design and fabrication of these TOFs and quantum optics experiments[2] using these TOFs and microresonators being conducted in our lab at Waseda.

References

[1] R. Nagai and T. Aoki, “Ultra-low-loss tapered optical fibers with minimal lengths”, Opt. Express 22, 28427 (2014).
[2] S. Kato and T. Aoki, *poster presentation at ONNA2015*.

T-6

Detecting single molecules and their interactions with optical microcavities

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Our research is focused on the physics of biosensing, constructing microsystems for detecting molecules and their interactions. Of particular interest is the study of photonic microsystems with the goal of single molecule analysis. Taking detection to this limit is possible if the interaction of light is sufficiently enhanced. My laboratory at the Max Planck Institute for the Science of Light has now achieved such extreme enhancements in optical microcavities [1]. We demonstrate specific detection of single nucleic acids by monitoring frequency shifts in microsphere cavities. We detect down to single 8 mer (2.4 kDa) nucleic acid strands and less than 1 kDa intercalating small molecules. Matched and mismatched DNA strands are discriminated by their markedly different interaction kinetics. The technique can find various applications for monitoring biomolecular reactions which are difficult to study with other single molecule techniques.

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http://www.nature.com/nnano/journal/vaop/ncurrent/full/nnano.2014.180.html

T-7

Whispering-gallery-mode resonators and their applications: from nanoscale measurement to parity-time symmetric photonics

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Light-matter interactions are the fundamental basis for many phenomena and processes in optical devices. In this talk I will introduce and explain ultra-high-quality (Q) optical Whispering-Gallery-Mode (WGM) microresonators, in which light-matter interactions are significantly enhanced due to their superior capability to trap light field in a highly confined volume with low loss. WGM resonators have shown great promise for a variety of fields of science, spanning from optomechanics to on-chip microresonator lasers and ultra-sensitive label-free bio-chemical sensing. In this talk, after briefly introducing the physical concepts of WGM microresonators and their coupling with a microfiber waveguide, I will report recent progress in our group towards developing functional platforms using high-Q WGM microresonators and microlasers. First, I will present a recent discovery in using ultra-high-Q microresonators and microlasers for ultra-sensitive self-referencing detection and sizing of single virion, dielectric and metallic nanoparticles. I will also discuss using optical gains in a microlaser to improve the detection limit beyond the reach of a passive microresonator. These recent advancements in WGM microresonators will enable a new class of ultra-sensitive and low-power sensors for investigating the properties and kinetic behaviors of nanomaterials, nanostructures, and nanoscale phenomena. Then I will explain an interesting hybrid nanoparticle-resonator system in which the nanoparticles open a new channel to couple light from free space into high-Q WGM resonators. I will present two types of lasers, Raman and rare-earth-ions doped microlasers, achieved by free-space pumping of high-Q resonators via the nanocouplers. In the end, I will discuss exploration of fundamental physics, such as parity-time symmetry and light-matter interactions around exceptional point (EP), in high-quality WGM resonators, which can be used to achieve a new generation of optical systems enabling unconventional control of light flow.

T-8

Liquid optomechanics for giant quality factors

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While theory predicts photon lifetime in exceeding of 10 second for optical cavities, it is hard to make a solid device that does not have even a single missing atom in the crystal (dislocation), is free of thermal stress (for glasses), and without a single atom popping out of its perfectly smooth interface. In contrast with solids and quite the opposite, it is hard to imagine a liquid with an atomic-scale void or surface irregularity. To give it a quantitative scale, a Bohr-radius scale void, representing a missing liquid atom in liquids, will feel a compensating force that is 10^{16} times larger than gravity. In their inherent essence therefore, liquids permit what solids restrict in the effort for reaching giant quality factors.

I will review our recent experiments where optomechancial oscillations were excited in droplets. This can transform optics to enable dislocation free devices and transform quality factors to be giant.

T-9

Quantum technologies in diamond: Chance & Challenge

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Defect centers in diamonds have been studied extensively in the last years [1]. They represent single photon sources with stable operation even at room temperature. Additionally, their spin state provides a long decoherence time and can be controlled and read-out optically.

In this talk we focus on nitrogen vacancy (NV) centers in nanocrystalline diamond and how they can be integrated on a nanophotonic platform.

First, we introduce basic properties of nanodiamonds and discuss different methods to assemble fundamental nanophotonic devices [2]. The methods include scanning probe manipulation [3], direct laser writing [4], and nanoparticle trapping [5].

We will introduce first integrated quantum devices, which aim at collecting and directing a maximum number of photons. Specific problems of solid-state photon emitters, such as tuning of their emission wavelength and spectral diffusion will be discussed. Also a proposal [6] how to generate entanglement between two emitters at intermediate distance via coupling to a joined cavity mode is described.

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T-10

Photon-Photon Interactions and Photonic Quantum Logic by Deterministic One-Photon Raman Interaction (DOPRI) with a Single Atom

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I will present the recent demonstration of deterministic photon-atom and photon-photon interactions using a single atom coupled to a chip-based micro-resonator. Based on passive, interference-based nonlinearity which leads to Deterministic One-Photon Raman Interaction (DOPRI), this scheme swaps the quantum states of a single photon and a single quantum emitter (a ^{87}Rb atom, in our case), with no need for any control fields.

Beyond the ability to route single photons by single photons, this scheme can also function as a quantum memory and a photonic universal quantum gate. It can therefore provide a building block for scalable quantum networks based on completely passive nodes interconnected and activated solely by single photons.

Refs:

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T-11

Cavity quantum electrodynamics on an optical nanofiber using photonic crystal structures

Kohzo Hakuta

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We create 1D photonic crystal structures on an optical nanofiber, and extend the nanofiber quantum photonics to the cavity quantum electrodynamics (QED) regime. We have developed two types of method to fabricate photonic crystal structures on nanofibers. One is a direct fabrication method to create a series of nano-grooves/craters on a nanofiber using nano-machining techniques; focused ion beam machining or femtosecond-laser ablation technique. The other is a composite method to create a photonic crystal structure by combining a nanofiber with an external nanostructured grating. Essential ideas to create nanofiber cavities using the photonic-crystal structures are discussed systematically. Nanofiber cavities thus created are examined from the viewpoint of cavity QED. We experimentally demonstrate the cavity QED effect on a nanofibet in the Purcell regime using a composite photonic crystal cavity. We observe significant enhancement of the spontaneous emission rate into the nanofiber guided modes for single quantum dots. Detailed analysis will be given. Future prospects are also discussed.

T-12

Optical nanofiber drawing, device assembly, and applications in optofluidics

Baojun Li

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The development of nanotechnology in photonics offers significant scientific and technological potentials. It fosters the substantial efforts for exploring novel photonic materials, developing easy device fabrication techniques, reducing photonic device size, improving device integration density, and fabricating low-cost nanodevices. Since nanometer-scale optical fibers are highly desirable for applications in high density photonics, so miniaturization of photonic devices and applications are being intensively focused. In this talk, we present a type of nanofibers which were drawn by a one-step drawing process from the melt of novel poly(trimethylene terephthalate) (PTT), followed by presenting a number of devices assembled by flexible PTT nanofibers. As a promising application of nanofibers in optofluidics which is a new research field emerged in 2003 that combined microfluidics and optics (specifically nanophotonics), optical trapping and manipulation of particles/cells using the optical fibers will also be presented including assembly, migration, separation, delivery, arrangement, etc. As examples, Figure 1 shows a SEM image of a 6×6 nanosplitter formed by PTT nanofibers and optical microscope images of the guided red, green, and blue lights. Figure 2 shows the red, green, and blue lights in a 3×3 crossed structure form by PTT nanofibers with a white colour spot observed at the crossed junction (inset).

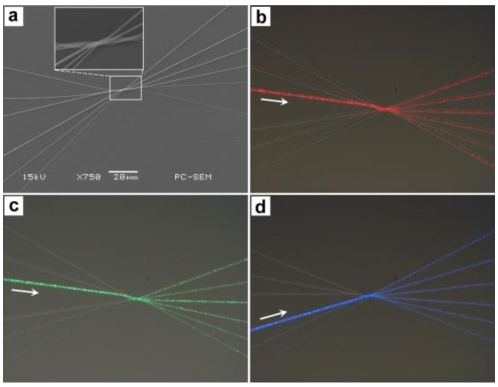

Fig. 1. (a) SEM image of a 6×6 nanosplitter with average diameter of about 486 nm. (b–d) Optical microscope images of the guided red, green, and blue lights, respectively. The arrows show the propagation directions of the lights.

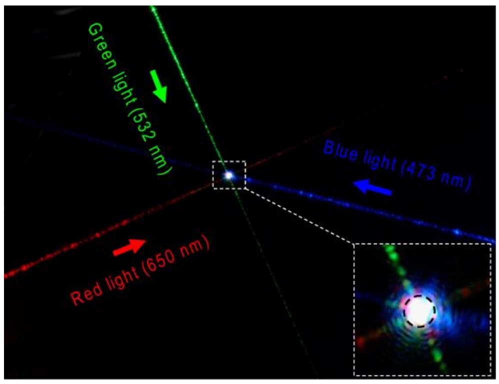

Fig. 2. Optical microscope image of the visible lights in a 3×3 crossed structure. The inset shows a magnified (×5) view of the white spot at the crossed junction. The arrows show the propagation directions of the lights.

T-13

Research update from the Light-Matter Interactions Unit

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Here, I will discuss the recent updates across the range of research topics pursued by the Light-Matter Interactions Unit at OIST. This will focus on work using optical micro or nanofibres for light propagation and will cover atom+fibre projects, particle manipulation work, and WGM resonators, such as microbubbles, for sensing applications.

T-14

Nonlinear optics in optical micro- and nano-fibres

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Optical micro- and nano- fibres (OMN) exhibit extraordinary properties as large evanescent field, high specific strength, high nonlinearity, strong confinement, flexibility, configurability, and easy connectivity to other fiberized components.

These properties have been used for a variety of nonlinear effects, including supercontinuum generation, second-, third- and one-third- harmonic generation, pulse shaping and nonlinear switching.

Moreover, in the last decade it was realised that OMNs could be easily manipulated to form a variety of novel resonators, namely the loop, knot and microcoil resonators, that combine the advantages of nano-photonics with the intergrability of standard fiberized optical components. This provided a new platform to observe enhanced nonlinear effects in OMNs.

In this talk I will discuss some applications in nonlinear optics of OMN and of OMN resonators and limitations to their practical exploitation.

T-15

Coupled microfiber/nanofiber-nanoparticle system

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Owing to its tightly confined waveguiding fields and large fractional evanescent fields, a waveguiding microfiber/nanofiber (MNF) is highly efficient for coupling exotic nanoparticles. Here we demonstrate the possibility of coupling the waveguiding photonic mode of a MNF with localized surface plasmonic resonance (LSPR) mode of a single gold nanorod (GNR). We show that, by embedding a GNR inside a polymer MNF, the waveguiding mode of the MNF can be converted into the LSPR mode of the GNR with high efficiency, providing a compact and efficient route to exciting a single GNR, as well as squeezing light into deep-subwavelength scale in all the three dimensions. Also, by placing a GNR on the surface of a glass MNF, and coupling the LSPR mode of the GNR with the whispering gallery mode of the MNF, we show the possibility of drastic reducing the linewidth of the LSPR via strong coupling, offering an opportunity for significant modification of LSPR in a GNR for deep-subwavelength photonic applications.

T-16

Nonlinear optics using high-Q microcavities: Photonic crystal and whispering gallery mode cavities

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Ultrahigh-Q microcavities are attractive for applications such as cavity quantum electro-dynamical devices (QEDs) and all-optical switches, all of which require strong interaction between light and matter. Among various high-*Q* microcavities, photonic crystal (PhC) nanocavities and toroidal whispering gallery mode microcavities are exhibiting the highest *Q*/*V*, where *V* is the mode volume of the cavity [1].

A photonic crystal nanocavity is a powerful device when we want to integrate cavity devices on a chip. One of the application is the cavity QED, where the cavity mode is coupled with the resonance of the quantum dots (QDs). In these studies, the position and the wavelength of a cavity must be finely-tuned to those of a QD, which is usually a challenging task. In addition, highly efficient coupling with the input and output waveguides is needed. To solve those problems, a method on creating a re-locatable and wavelength tunable nanocavity on a photonic crystal waveguide is developed by Y.-H. Lee *et al* [2]. It create a mode-gap confined cavity by contacting a tapered fiber on the top of the PhC slab. The cavity mode directly couples with the tapered fiber which enable high coupling efficiency. We follow their work but by employing a silicon PhC in order to study the maximum performance we can obtain with this scheme. We demonstrated that a nanocavity with a *Q* of 5.1×10^5 is obtained with a wavelength tuning accuracy of 27 pm. We also demonstrated that an extremely high-efficiency of 99.6% is possible with a loaded *Q* of 6.1×10^3. [3]

A silica toroidal microcavity is attractive for studying optical Kerr effect at a very low input power. Applications include low-power optical Kerr switch and frequency comb generation. Such applications are possible because the bandgap of the large and can reduce the multiphoton absorption. Recently we demonstrated an optical Kerr modulation at a very low 36 μW by using a cavity with a Q of 4×10^7 [4, 5]. By using these high-*Q* cavity we are also possible to demonstrate the generation of the Kerr comb [6]. The detail is discussed in this talk.

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T-17

Nanostructured Micro/nanofiber and Related Applications

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In the last decade, optical micro/nanofibers (MNFs) have attracted considerable interest because they offer a variety of enabling properties, including large evanescent fields, flexibility, configurability, high confinement, robustness and compactness. These distinctive features have been exploited in a wealth of applications ranging from telecommunication devices to sensors, from optical manipulation to high-Q resonators [1]. Nanostructures on the optical MNFs are very promising since the size of the device can be extremely small. With the development of nanostructuring methods, sub-wavelength feature sizes have been achieved [2]. In this talk, nanostructured optical MNFs and some related applications are discussed.

The first group of devices achieves two and three dimensions with nanostructured optical MNFs. Light was confined into a sub-wavelength dimension exploiting plasmons excited at the nanostructured optical MNFs tips to obtain high transmissivity. The improved transmission efficiency (higher than 10^{-2}) was achieved and effective confinements to 10 nm or smaller can be envisaged by decreasing the aperture size and slope angle. Three dimensional light confinement was proposed exploiting a Fabry-Perot microcavity formed by a MNFs grating similar to those used in distributed feedback lasers. MNFs were patterned using a focused ion beam (FIB) system. Strong three dimensional localization has also been achieved in plasmonic slot nano-resonators embedded in a gold-coated optical MNFs tapers. It shows high localization and strong enhancement (in excess of 10^6).

Light confinement in nanostructured optical MNFs was also widely used in sensing. A compact thermometer based on a broadband microfiber coupler tip showed a dynamic range spanning from room temperature to 1511ºC with a response time of tens of microseconds. An average sensitivity of 11.96 pm/ºC was achieved for a coupler tip with ~2.5 µm diameter. A temperature sensor which embedded fiber Bragg grating in a singlemode-multimode -singlemode (SMS) fiber was demonstrated with sensitivity of 145.5pm/ ºC. For refractive index sensing, a nanostructured SMS fiber tip refractive index sensor is proposed. An average sensitivity of 265 nm/RIU and a resolvable index change of 3.77×10^{-5} are obtained experimentally with a ~2.94 µm diameter SMS tip.

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T-18

Nanophotonics of optical fibers

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Nanoscale effects in photonic structures fabricated from pure optical fibres are reviewed. In contrast to those in plasmonics, these structures do not contain metal particles, wires, or films with nanoscale dimensions. Nevertheless, a nanoscale perturbation of the fibre radius can significantly alter their performance. I consider slow propagation of whispering gallery modes along the fibre surface. The axial propagation of these modes is so slow that they can be governed by extremely small nanoscale changes of the optical fibre radius. The described phenomenon is exploited in SNAP (Surface Nanoscale Axial Photonics), a new platform for fabrication of miniature super-low-loss photonic integrated circuits with unprecedented sub-angstrom precision [1].

Ultralow loss and dispersionless slow light delay line is one of the applications of the reviewed platform. In [2] this device was fabricated in the form of SNAP bottle resonator by the translation of the focused CO_2 laser beam along the fiber axis with a nonlinearly varied speed to arrive at the parabolic variation of the fiber radius. The deviation of the introduced radius variation from the exact parabolic was < 0.9 angstrom. In contrast to miniature delay lines considered previously, this delay line is not based on the periodic modulation of refractive index like in photonic crystal or coupled microresonator structures. The footprint of this device was only 0.12 mm^2. It exhibited the record large 2.58 ns (3 bytes) dispersionless delay of 100 ps pulses. The intrinsic (0.44 dB/ns) and full (1.12 dB/ns) loss of this device is more than two orders of magnitude smaller than losses demonstrated for miniature delay lines previously.

Next, the theory of slow light SNAP optofluidics is considered [3]. The concept is based on SNAP structures created at the thin-walled optical capillary. It is shown that these structures can perform comprehensive simultaneous detection and manipulation of microfluidic components. The developed theory shows that the microfluidic parameters can be determined from the spectrum of the SNAP structure. In addition, the optimized superposition of eigenstates of this structure can be used as a near-field optical tweezer for manipulating the microfluidic components.

Finally, I review the theory of a nanobump resonator, which has been recently introduced in [4] and is described at this workshop in [5]. This microresonator is formed by a nanoscale local deformation of the optical fiber surface. It is shown that a nanobump causes strong localization of whispering gallery modes near a closed stable ray at the fiber surface.

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C-1

Generation and detection of a Sub-Poissonian atom number distribution in a one-dimensional optical lattice

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We demonstrate preparation and detection of an atom number distribution in a one-dimensional atomic lattice with the variance −14 dB below the Poissonian noise level. A mesoscopic ensemble containing a few thousand atoms is trapped in the evanescent field of a nanofiber. The atom number is measured through dual-color homodyne interferometry with a pW-power shot noise limited probe. Strong coupling of the evanescent probe guided by the nanofiber allows for a real-time measurement with a precision of ±8 atoms on an ensemble of some 10^3 atoms in a one-dimensional trap. The method is very well suited for generating collective atomic entangled or spin-squeezed states via a quantum non-demolition measurement as well as for tomography of exotic atomic states in a one-dimensional lattice.

C-2

Self-ordering and collective dynamics of transversely illuminated point-scatterers in a 1D trap

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We study point-like polarizable particles confined in a 1D very elongated trap within the evanescent field of an optical nano-fiber or nano-structure. When illuminated transversely by coherent light, collective light scattering into propagating fiber modes induces long range interactions and eventually crystallisation of the particles into regular order. We develop a simple and intuitive scattering-matrix based approach to study these long-range interactions by collective scattering and the resulting light-induced self-ordering. For few particles we derive explicit conditions for self-consistent stable ordering. In the purely dispersive limit with negligible back-scattering, we recover the prediction of an equidistant lattice as previously found for effective dipole-dipole interaction models. We generalize our model to experimentally more realistic configurations including backscattering, absorption and a directional scattering asymmetry. For larger particle ensembles the resulting self-consistent particle-field equations can be numerically solved to study the formation of long-range order and stability limits.

C-3

A nanofiber in an ion trap

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I will present the experimental work done at the University of Innsbruck where an optical nanofiber is integrated to a macroscopic Paul trap where Ca+ ions are confined.

Our goal is to couple one or several ions to the evanescent optical field in the vicinity of the nanofiber, to eventually use the fiber as a bus between remote ion qubits. Since the ions are highly sensitive to electric fields, bringing them close to the nanofiber is an experimental challenge. I will present experiments conducted to characterize the charging of the nanofiber by using trapped ions as a field probe, and detail our efforts to control and minimize the charge of the nanofiber.

C-4

‘Alligator’ photonic crystal platform for atom trapping and strong light-matter interactions

S.-P. Yu*, J. D. Hood*, J. A. Muniz, M. J. Martin, Richard Norte, C.-L. Hung, Sean M. Meenehan, Justin D. Cohen, Oskar Painter, and H. J. Kimble
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Recent advances in nanophotonics provide new possibilities for optical physics [1-2]. The integration of free-space atoms with nanophotonic devices has progressed on several fronts, including nano-scale cavities [3] and dielectric waveguides [4]. Significant technical challenges exist for developing such hybrid atom-photonic systems, arising from the following requirements: (1) The fabrication is sufficiently precise to match waveguide photonic properties to atomic spectral lines; (2) atoms are stably trapped in close vicinity to nanophotonic structures to achieve strong atom-field interaction; (3) the optical addressing of nanophotonic structures is efficient for guided modes and free-space optics; and (4) the structures are tolerant to optical power required to support milli-Kelvin trap depths. We describe a nano-fabricated platform based on novel ‘alligator’ photonic crystal waveguide structures that meet aforementioned stringent requirements [5-6]. Here we present two different regimes achievable with our system: slow-light photonic crystal waveguides and high-finesse cavities using photonic crystal mirrors.

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C-5

Emission enhancement with nanofiber Bragg cavities

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The possibility to couple nanophotonics emitters like atoms [1], quantum dots [2] or defect centres [3] efficiently to optical nanofibres makes them a versatile device for constructiong single photon sources or quantum photonic networks. Another important tool are solid-state microcavities which ideally combine ultra-small mode volume, wide-range resonance frequency tuning, as well as lossless coupling to a single mode optical fibre. Using a combination of a nanofibre with a Bragg cavity, we developed an integrated system providing all of these three indispensable properties [4]. It consists of a nanofibre Bragg cavity (NFBC) with a mode volume of under 1 μm^3 and repeatable tuning capability over more than 20 nm at visible wavelengths. In order to demonstrate quantum light-matter interaction, we establish coupling of quantum dots to our tunable NFBC and achieve an emission enhancement by a factor of 2.7.

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C-6

Cooling the Centre-of-Mass Motion of a Silica Microsphere

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Light coupled from a tapered optical fibre is used to excite the morphology dependent whispering gallery mode (WGM) resonances of a silica microsphere-cantilever. Using the optomechanical transduction from the WGM, we feedback cool the centre-of-mass (c.o.m.) motion of this system from 300K to 4K at 1.5 mBar using a piezo stack. We aim to further test this 1D cooling scheme at lower pressures as well as replace the piezo element with the cavity enhanced optical dipole force (CEODF). We propose to combine one of these active cooling schemes with passive Doppler cooling in the orthogonal direction to provide damping in all c.o.m. degrees of freedom, using a single tapered fibre.

C-7

Magnet-free optical isolator using a fiber derived microresonator

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Time-reversal symmetry is a fundamental property of optical systems, leading to symmetric response independent of light propagation direction in a waveguide or a fiber. Thus, a break in time-reversal symmetry, i.e. non-reciprocity, is required for an optical isolator and circulator. Presently, optical isolation is achieved using the magneto-optic Faraday effect, but can be difficult to implement in many applications either due to fabrication challenges or an impact on other optical components from required magnetic fields. Our spherical microresonator device fabricated using a tapered fiber operates on acousto-optical principles and offers an alternative to Faraday isolators and circulators. Here, we provide the first experimental evidence of non-reciprocity, presented as an optical isolation, using a Brillouin optomechanical system. The effect is generated through opto-acoustic interaction with the unidirectionally-propagating spatiotemporal modulation created by an acoustic wave. This device could be implemented with an on-chip waveguide and microresonator using established on-chip fabrication recipes.

C-8

Single nanoparticle detection and sizing using a nanofiber pair in aqueous environment

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Rapid detection and sizing of nanoscale particles become of increasing importance for applications in various fields, such as in early-stage biomedical diagnostics and treatment, process control of semiconductor manufacturing, as well as in explosives and environmental monitoring. We demonstrate detection and sizing of single nanoparticles in aqueous environment using a pair of uniform optical nanofibers. Experimentally, step changes in the fiber transmission are obtained, which result from scattering by single polystyrene nanoparticles when they bind to the nanofibers surface one by one. The high detection sensitivity originates from the pronounced evanescent field of the optical nanofibers. Using the scattering method, sizing of nanoparticles with single uniform radius (~ 100 nm) and of mixed nanoparticles with two different radii (100 nm and 170 nm) are both realized, through statistical analyses to the step signals induced by nanoparticle binding events. These results agree well with the Rayleigh-Gans scattering theory by taking the inhomogeneous evanescent field of the nanofiber into account. Moreover, detection of single gold nanorods (diameter ~ 16 nm, length ~ 40 nm), is demonstrated by employing plasmonic enhancement.

Xiao-Chong Yu, Bei-Bei Li, Pan Wang, Limin Tong, Xue-Feng Jiang, Yan Li, Qihuang Gong, and Yun-Feng Xiao, "Single Nanoparticle Detection and Sizing Using a Nanofiber Pair in an Aqueous Environment," Adv. Mater. 26, 7462 (2014) (front cover)

C-9

Controlling light at the exceptional points with whispering gallery microresonators

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Whispering-Gallery-Mode (WGM) optical microcavities with their high-quality factors and microscale mode volumes have emerged as versatile platforms for exploring basic science and for fabricating functional devices. WGMRs represent open physical systems that are characterized by non-Hermitian Hamiltonians, and thus by appropriately steering the system parameters, their complex eigenvalues and the corresponding eigenstates can be made to coalesce giving rise to a degeneracy referred to as Exceptional point (EP). In this talk, we will present two applications enabled by driving coupled WGM microcavities through exceptional points. First, we will show parity-time (PT) symmetry and its breaking in a system composed of two coupled WGM microcavities, one of which is a passive resonator and the other is an active resonator with gain, balancing the loss of the other. We will show that broken phase enables localization of light in the active resonator, leading to nonlinearity-based nonreciprocal light transmission [1]. Second, we will show that controlling the loss contrast between two coupled passive resonators can bring the system to an EP where the total intracavity field intensity increases despite increasing loss [2]. This helps to control intensity-dependent optical processes by loss modulation. As an example we show that increasing loss first suppresses an existing laser, but then laser recovers back when the loss increases beyond a critical value. We will end the talk discussing some of the opportunities and challenges in the WGM research.

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C-10

Controlling the group velocities of light pulses in a fiber-coupled bottle micro resonator

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Whispering-gallery-microresonators have ultra-high quality factors (Q-factors) exceeding 10^7, which is suitable for performing cavity QED and many other studies [1,2]. Among those, controlling the group velocities of light pulses has attracted much interest for fundamental physics and the relevant applications, such as optical delay lines, storages, and enhancement of light-matter interactions. So far, slow and fast light phenomena have been demonstrated in single or arrayed microspheres and microrings [3,4,5]. Here, we report on controlling the group velocities of light pulses at a telecom wavelength in a tapered-fiber-coupled bottle microresonator with Q-factors exceeding 10^8.

Our bottle microresonators were fabricated by tapering a single mode optical fiber at two separated points using heat-and-pull technique [6]. The maximum bottle diameter was about 125 µm, and it was a few millimeters long. The group velocity is controlled by changing the distance between the tapered fiber and the bottle microresonator (i.e., controlling the ratio between the coupling loss and the sum of all other losses such as material absorption and scattering losses). We observed a maximum pulse advancement of 129.4 ns in the undercoupling regime and a maximum pulse delay of 251.7 ns in the overcoupling regime for the light pulses with a width of 333.3 ns (FWHM).

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C-11

Efficient fiber-optical interface for nanophotonic devices

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We demonstrate a method for efficient coupling of guided light from a single mode optical fiber to nanophotonic devices. Our approach makes use of single-sided conical tapered optical fibers that are evanescently coupled over the last 10 micrometers to a nanophotonic waveguide. By means of adiabatic mode transfer using a properly chosen taper, single-mode fiber-waveguide coupling efficiencies as high as 97(1)% are achieved. Efficient coupling is obtained for a wide range of device geometries which are either singly-clamped on a chip or attached to the fiber, demonstrating a promising approach for integrated nanophotonic circuits, quantum optical and nanoscale sensing applications.

Remarks: This work was done at Prof. Misha Lukin's group at Harvard, where I worked as a visiting scholar last year.

C-12

Charge measurement of tapered optical fibers with microparticles in a linear Paul trap

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We report charge measurement of tapered optical fibers with charged particles confined in a linear Paul trap. A tapered optical fiber is placed across the trap axis at a right angle, while polystyrene particles with the diameter of 1μm are trapped along the trap axis. We have found that there exists an equilibrium position for a positively charged particle at which the force produced by trap electrodes and that by the charged fiber are balanced. Assuming that the fiber in the trapping region can be regarded as a line charge, the charge per unit length of the fiber can be derived from the distance between the fiber and the particle and the magnitude of electric field generated by the end electrodes. It should be noted that the amount of the particle charge is not necessary for the derivation. The electric field at the particle is numerically calculated with a commercially available solver. We will show the measurement results of tapered fibers with different diameters and discuss the electric characteristics of tapered fibers. The method will provide information not only for a tapered fiber-integrated ion trap for quantum network but also for many of sensing applications.

C-13

Optical waveguiding, gain and lasing properties of electrospun nanofibers for nanophotonics

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The management of photon waveguiding, amplification, and optical resonances in nanostructured materials is currently the subject of intense experimental and theoretical investigations, aimed at understanding the interaction of light with sub-wavelength scale photonic structures. In this framework, polymer nanofibers [1-3] provide a unique platform for studying the optical properties of both individual nanostructures and arrays made of them.

Here we review our recent results on nanofibers for photonic applications, made by electrospinning. This process relies on the extrusion of a polymer solution through a metallic needle by electric fields. The versatility of the electrospinning process allows fiber size, morphology and macroscopic assembly to be tailored. Importantly, the high stretching rate of the polymer liquid jet during electrospinning allows for controlling the assembly of the active molecules in the fibers [4, 5], enabling the fabrication of fibers with anisotropic properties and the possibility of tailoring the optical properties of the produced nanostructures. In particular, we investigated the emission, waveguiding [6], gain and lasing properties of electrospun nanofibers made by polymers doped with optically-active chromophores and nanoparticles. The produced electrospun fibers featured emission and amplified spontaneous emission, with gain coefficients of tens of cm^{-1}. We also fabricated lasers based on fibers. Such results open interesting perspectives for designing and developing novel miniaturized photonic systems for optical sensing, light sourcing and detection integrating electrospun, multifunctional optical nanofibers.

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C-14

Platform for enhanced light-matter interaction and miniaturizing fiber devices

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We propose a reliable fabrication process enabling the integration of multiple functions in a single rod with one optical nano/microfiber (ONM), which represents a further step in the "lab-on-a-rod" technology roadmap. With a unique 3D geometry, the all-fiber in-line devices based on lab-on-a-rod techniques have more freedom and potential for compactness and functionality than conventional fiber devices. The proposed fabrication procedure involves wrapping-on-a-rod and nanopatterning techniques, which are applied directly to a separate rod rather than a tiny ONM. Following this approach, we demonstrate polarization-related function integration. By functionalizing the rod surface with a nanoscale silver film or graphene and tuning the coil geometry, a broadband polarizer, single-polarization resonator and modulator, respectively, are demonstrated.

P-1M

Limitation to maximum conversion efficiency of intermodal phase matching in real silica nanofibres due to intrinsic surface roughness

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The effect of intrinsic surface roughness due to frozen-in thermal oscillations on the efficiency of third harmonic generation in silica optical nanofibers is theoretically studied. Assuming a single periodic wave roughness, it was discovered that a 0.2 nm roughness induces a reduction in efficiency of 50% in a 1 mm optical nanofiber with the divergence increasing roughly quadratically with optical nanofiber length. It was discovered that the period of the surface waves does not have significant impact on the overall efficiency due to averaging effects, although the reverse is true for the location of the surface wave with respect to the phase matching radius. Simulations with a realistic optical nanofiber suggest that the intrinsic roughness of the surface wave limits the conversion efficiency to a maximum of 1%.

P-2M

Transient sensing of Au nanorods at plasmon frequency in aqueous solution using tapered optical fiber

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Tapered optical fibers have proven to be simple and sensitive platforms for the sensing of single nanoparticles down to sizes of tens of nanometers. In the past, sensing of single nanoparticles with fiber-tapers has relied primarily on the binding of nanoparticles to the optical fiber surface, thereby causing scattering induced reductions in transmitted light intensity. This method limits the lifetime and reusability of the sensor, as the binding of too many nanoparticles to the fiber-taper causes a complete loss of transmitted signal. In this paper, we present an aqueous sensing method which overcomes this difficulty by detecting gold nanorods of approximate dimensions 52 nm x 20 nm without binding to the fiber-taper. Using laser light at the plasmon frequency of the Au nanorods as our sensing signal, we are able to detect transient drops in transmitted signal intensity when sensing the nanorods in solution. The size and number of these transient events increase as the concentration of nanorods in the sensing solution is increased, indicating that the events are caused by the scattering of light as nanorods enter and subsequently leave the evanescent field around the optical fiber. Our sensing method opens the way to using tapered optical fibers as reusable and long lasting sensors for determining the concentration or size of nanoparticles in solution.

P-3M

Interfacing light and matter via optical nano fibers

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We aim to develop scientific as well as technical foundations towards the realization of a novel platform for light-matter interaction based on tapered optical nanofiber that enables to interface neutral atoms in its vicinity. Tapered nanofibers of diameter around half a micron are now routinely fabricated with high transmission (above 95%) in our lab. As a first experiment, such a nanofiber is made to overlap with cold atoms in a magneto-optical trap inside ultra-high vacuum. The light guided into the fiber can interact with the atoms via strong evanescent field in the tapered region of nanofiber. Since the beam mode area in this region is smaller than the resonant absorption cross-section of the atom, the probability of a photon to get absorbed by the atom increases, thus enhancing the strength of interaction. Large optical depth can be reached since the interaction length is not diffraction-limited as it is the case for a tightly focused free-space beam.

At the next stage, atoms from the magneto-optical trap will be loaded into a two-color optical dipole trap around the nanofiber. The dipole trap will be created by coupling blue-detuned and red-detuned laser fields into the nanofiber, the later being in a standing wave configuration. The red-detuned field mode will attract the atoms while blue-detuned field mode will repel the atoms away, such that the atoms will be eventually trapped longitudinally at the points of minimum potential around the nanofiber.

The interest of our group primarily lies in development of quantum memories and single-photon sources based on such cold-atomic ensembles. With our atom-nanofiber interface, we believe the memory efficiency, storage time and single-photon generation efficiency can all be greatly improved as large optical depth can be achieved. These experiments will take a step towards realization of all-fibered quantum network. Our interface is also a promising platform for experiments in non-linear quantum optics, quantum information science and technology, quantum communication and hybrid quantum systems.

P-4M

Liquid micro-resonators in air cladding with high quality factor in the near infrared

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We experimentally report on optical resonances in oil droplets with air cladding in the near infrared region. Reaching quality factors up to 10^7 radiation pressure as well as thermal effects were observed.

P-5M

Third-harmonic generation from graphene-clad microfibers

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We report on the studies of third-harmonic generation from graphene-clad microfibers. Graphene is highly absorbing material across entire visible spectrum, thus it exhibits very high third-order nonlinearity. By cladding the microfiber with graphene, the evanescent field outside the microfiber can efficiently interact with graphene, and the generated harmonic signal can be collected by the microfiber. We observed enhanced third-harmonic generation by direct comparing the signal from a bare microfiber and the microfiber with a graphene cladding length ~ 10 microns.

P-6M

Towards an fiber integrated magnetometer based on a single electron spin

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We report on our studies about the magnetic resonance of an electron spin in a single nitrogen-vacancy (NV) center coupled to a nanofiber. Such integrated nanofiber devices can play an important role in future quantum optical networks, as they offer the opportunity to initialize, polarize, and control electronic spins on the single electron level. In contrast to free space optical setups they are much smaller and more robust against disalignment. Hence, recently, many groups around the world have been working on realizing such structures [1-3].
In our experiment, we use a sharp tungsten tip to couple a nanodiamond to a nanofibre in a controlled way. By applying microwave radiation and a green excitation laser we are able to monitor the magnetic resonance of the NV center's spin optically through the fibre. In the current stage of our experiment the green excitation laser is focussed on the nanodiamond using a microscope objective, but we are working on more integrated solutions.
Such fully integrated magnetometers based on a single electron spin will possess a high sensitivity and probably can be used outside the controlled environment of a laboratory.

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P-7M

Enhanced refractive index sensor based on a combination of a long period fiber grating and singlemode-multimode-singlemode fiber structure

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Optical microfiber/nanowire-based photonic devices have been widely used in a range of sensing applications, including refractive index, stain, humidity, chemical gas and temperature. Optical fiber based refractive index (RI) sensors have attracted extensive attention due to their unique advantages such as immunity to electromagnetic interference, small size, high sensitivity, etc. The techniques used to implement fiber based RI sensing include a fiber Bragg grating (FBG), long period fiber grating (LPFG), surface plasmon resonance, tapered fiber and a singlemode–multimode–singlemode (SMS) fiber structure. Among these techniques, an SMS fiber structure has the advantages of simplicity and ease of fabrication and previous investigations have shown that an SMS fiber structure can excite and couple multiple modes to an SMF. For Bragg-grating-based sensors, which suffer from limited temperature- and strain-induced spectral displacements, is often required that one use complex interferometric techniques to detect these shifts. On the other hand, the LPFG is a promising technique for optical sensing and may exhibit wavelength blue-shift as the RI increases. If the two types of sensors are combined with each other, the sensitivity will be improved by monitoring the separation wavelength shifts between the resonant wavelengths of the LPFG and SMS fiber structures.

In this paper we investigate the use of a combination of LPFG and SMS fiber structures for RI sensing and show that the sensitivity achievable is higher than that of either of the structures alone. Our proposed technique has advantages of simple configuration, easy fabrication, and simultaneously measurement of both RI and temperature.

P-8M

Optical trapping and transport of polystyrene microsphere's evanescent wave on microfibers

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The manipulation of polystyrene microspheres using the evanescent optical field surrounding a silica microfiber is investigated. The microfiber is produced using a flame brushing technique from a standard single-mode optical fiber. It is observed that the polystyrene microspheres can be attracted and trapped along the microfiber by means of evanescent field, which provides both scattering and gradient forces. Scattering and gradient forces exerted on the microspheres also depend on the microsphere size where a larger number of polystyrene microspheres were seen attached to the microfiber if the microsphere size is smaller. The microspheres attached to the microfiber are also observed to be propelled along the microfiber in the direction of the propagating light. These results suggest that the proposed optical trapping mechanism can be used for manipulating and identifying minute biological objects such as bacteria, yeast, and organelles.

P-9M

Hybrid devices with semiconductor nanocrystals

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We are reporting on progress toward the coupling of optical nanofibers and more generally tapered waveguides to solid-state quantum emitters (semiconductor nanocrystals). Our approach relies on the development and study of various elementary building blocks in order to integrate them in original architectures.

We have recently demonstrated the coupling of a single non-blinking nanocrystal to the guided mode of a nanofiber.

In future development we plan to implement a fiber Bragg grating cavity around this single emitter in order to study cavity quantum electrodynamic effect with a solid state emitter.

P-10M

Geometrical profiling of a tapered optical fiber using WGM resonances

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Whispering gallery mode (WGM) microresonators (MRs) are attractive photonic devices due to their small mode field volume, narrow spectral linewidths and high Q-factors. Such MRs have been shown to have potential use in many areas, including studies of nonlinear optics, quantum electrodynamics and for low threshold micro lasers. One of the most promising applications of WGM MRs is in the area of optical sensing, where such resonators demonstrate a higher sensitivity than bulk fibre counterparts. The extreme sensitivity of WGM spectra to changes in the resonator shape and size make WGM spectroscopy a promising tool for geometrical profiling with diameter variations at the sub-wavelength scale. This method for characterization of fiber diameter has been originally proposed by Briks et al. Here we demonstrate application of WGM resonances for a highly accurate geometrical profiling of a tapered optical fiber.

For geometrical profiling of a tapered optical fiber, WGMs spectra were recorded as the tapered fiber under study was scanned along the perpendicularly positioned delivery microfiber. The tapered fiber under test acts as a cylindrical micro-resonator. The light coupling to the cylindrical micro-resonator is realized by the delivery microfiber placed in close contact with the fiber taper under test. Narrow WGM resonances are observed in the transmission spectrum of the delivery microfiber with a maximum Q factor of ~10^5. Spacing between the WGMs in the transmission spectrum is a function of the diameter of the tapered fiber under test. An accurate value for the frequency spacing of the WGM resonances is obtained from a Fourier analysis of the spectrum. The results of this approach are validated by comparing the taper geometry determined by WGMs spacing analysis with a microscopic measurements of the taper diameter.

P-11M

Localization of whispering gallery modes in a nanobump microresonator

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Different types of optical microresonators have been developed to date such as photonic crystal cavities, microspheres, microtoroids, microbottles, etc. In this paper we introduce and investigate a new type of microresonator, which we call a nanobump microresonator, explored in Surface Nanoscale Axial Photonics (SNAP), the recently developed platform for fabrication of ultralow loss integrated microresonator circuits at the surface of a silica fiber. Formation of SNAP microresonators is based on the sub-angstrom precise nanoscale deformation of the fiber which causes strong localization of whispering gallery modes (WGMs) circulating along the fiber surface. This deformation is usually introduced by annealing with a CO_2 laser beam. The local deformation of the fiber surface caused by the exposure of a stationary laser beam has the shape of a nanoscale-high bump which does not possess axial symmetry due to directional laser heating. Nevertheless, we show here that, under certain conditions, the corresponding violation of translation symmetry of the fiber causes strong localization of WGMs.

We present the theory of a nanobump WGM resonator which is based on the theory of WGMs localized near a stable closed geodesic developed in the mathematical theory of diffraction. It is shown that the eigenmodes of such microresonator are strongly localized near the closed ray at the fiber surface if this ray is stable. A simple condition for the stability of this ray corresponding to the appearance of a high Q-factor nanobump microresonator is found. Our theory confirms full localization of WGMs for the characteristic nanoscale height of the nanobump and its lateral dimensions ~ 10 – 100 μm, which is observed experimentally. We derive simple expressions for the characteristic axial width of the WGMs through the parameters of the nanobump. Our investigation is important for the design and fabrication of SNAP microdevices.

P-12M

Reconfigurable optical-force-drive chirp and delay-line in micro/nano-fiber Bragg grating

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The emergence of optical micro/nano-fiber (MNF) with a subwavelength diameter, which has ultra-light mass and an intense light field, brings an opportunity for develop fiber based optomechanical systems. In this study, we theoretically show an optomechanical effect in silica MNF Bragg gratings (MNFBGs). The light-induced mechanical effect results in continuously distributed strain along the grating. It is shown that the power-related strain introduces an optically reconfigurable chirp in the grating period. We develop new optomechanical coupled-mode equations and theoretically analyze the influence of the optical-force-induced nonlinearity and chirp on the grating performance. Compared with weak Kerr effect, the optomechanics effect dominated in the properties evolution of MNFBGs and significant group velocity reduction and switching effect have been theoretically demonstrated at medium power level. This kind of optomechanical MNFBG with optically reconfigurable chirp may offer a path toward all-optical tunable bandwidth of Bragg resonance and may lead to useful applications such as all-optical switching and optically controlled dispersion and slow/fast light.

P-13M

Optical binding in white light

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We experimentally demonstrate, for the first time, binding of aerosols with a variety of sizes and shapes in white light. The optomechancial interaction between particles is long range and at the underdamped regime. Incoherency allows mitigation of interference fringes to enable monotonically changing the distance between particles from 60 micron to touching - constituting a parametrically controlled testbed for transition studies at new scales.

P-14M

Single molecules coupled to nano-photonic structures

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In order to integrate single photon emission into nano-optical structures, coupling of single emitters to waveguides and resonators is investigated thoroughly by many research groups.
Our studies focus on single DBT molecules in a protective anthracene host matrix. The crystal matrix stabilizes the photon emission and reduces the intersystem crossing rates significantly, thereby reducing blinking and bleaching of the molecules under laser excitation. The robust shell also enables mechanical nano-manipulation techniques, which we developed to deterministically place single molecules.
We designed and fabricated on-chip plasmonic waveguides, efficiently connected to far-field in- and out-coupling ports via low-loss dielectric waveguides. The strong plasmonic interaction with the molecule emission enhances the coupling efficiency. The subsequent conversion to a dielectric waveguide mode allows for a simple application of the excitation light source and extraction of fluorescence photons.

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P-15M

Observation of magneto-optical effect with a spherical ferromagnetic-crystal optical cavity

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Optical whispering gallery mode (WGM) cavities are intensely investigated as a tool to implement highly efficient nonlinear optical processes based on their small mode volume and high-quality factor. While the studies of WGM photons interacting with mechanical modes or bulk phonons in the cavity are widely appreciated, less has been known for other collective excitations, such as magnon modes in ferromagnets. We study magnon-WGM photon interaction aiming at realizing an efficient and unique magneto-optical effect and exploring the possibility of laser cooling and quantum control of magnons.
Here we present experimental results on the WGMs in a spherical crystal cavity made of an insulating ferromagnet, yttrium iron garnet (YIG). A few ferromagnetic resonances at frequencies of several GHz are revealed with the microwave spectroscopy. We observe the interaction between the magnon mode and the optical WGM, which manifests itself as the enhanced Faraday rotation of the optical polarization at the WGM cavity resonances.

P-16M

Optomechanical Ramsey interferometry

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We adopt Ramsey's method of separated oscillatory fields to study coherences of the mechanical system in an optomechanical microresonator. The high-resolution Ramsey fringes are observed in the emission optical field, when two pulses separated in time are applied. We develop a theory to describe the transient optomechanical behavior underlying the Ramsey fringes. We also perform the experimental demonstration using a silica microresonator. The method is versatile and can be adopted for different types of mechanical resonators and electromechanical resonators.

P-17M

Storage of light in a nanofiber-trapped atomic ensemble

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The storage of a classical optical pulse is an important capability for the realization of all-optical signal processing schemes. Simple optical buffers can be extended to work as optical quantum memories in which quantum states of light can be stored and retrieved. Such quantum memories are crucial elements of a global quantum optical network. While the storage of light has been achieved with several systems, e.g., in ensembles of cold or ultracold atoms, the realization of efficient, long-lived fiber-integrated optical memories are still the subject of active research.
Here, we report on the progress of a novel implementation of a fiber-integrated optical quantum memory. We use an ensemble of cold cesium atoms that are trapped in the vicinity of a sub-wavelength optical nanofiber. Using electromagnetically induced transparency, we drastically slow down optical pulses that propagate in the optical nanofiber. We then demonstrate the storage and retrieval of weak optical pulses with an overall efficiency and characteristic memory lifetime largerly improved compared to existing fiber-integrated optical memories.

P-18W

Brillouin-scattering-induced transparency and non-reciprocal light storage in a silica microcavity

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Stimulated Brillouin scattering (SBS) is a fundamental interaction between light and traveling acoustic waves and arises primarily from electrostriction and photoelastic effects, with interaction strength several orders of magnitude greater than that of other relevant nonlinear optical processes. Here, we report an experimental demonstration of Brillouin-scattering-induced transparency (BSIT) in a high-quality whispering-gallery-mode optical microresonantor. The triply resonant SBS process underlying the BSIT greatly enhances the light-acoustic interaction, enabling the storage of light as a coherent, circulating acoustic wave with a lifetime up to 10 μs. Furthermore, because of the phase-matching requirement, a circulating acoustic wave can only couple to light with a given propagation direction, leading to non-reciprocal light storage and retrieval. These unique features establish a new avenue toward integrated all-optical switching with low-power consumption, optical isolators, and circulators.

P-19W

Coherent interaction of light and single molecules in a dielectric nanoguide

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Many of the currently pursued experiments in quantum optics would greatly benefit from a strong interaction between light and matter.
We present a simple new scheme for the efficient coupling of single molecules and photons. A glass capillary with a diameter of 600 nm filled with an organic crystal tightly guides the excitation light and provides a maximum spontaneous emission coupling factor (β) of 18% for the dye molecules doped in the organic crystal. A combination of extinction, fluorescence excitation, and resonance fluorescence spectroscopy with microscopy provides high-resolution spatiospectral access to a very large number of single molecules in a linear geometry. We discuss strategies for exploring a range of quantum-optical phenomena, including polaritonic interactions in a mesoscopic ensemble of molecules mediated by a single mode of propagating photons.

P-20W

Light-matter interaction in the vicinity of a photonic crystal nanofiber cavity

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In our previous works, we have demonstrated fabrication of photonic crystal nanofiber (PhCNF) cavities using a femtosecond laser. We have shown that thousands of periodic nano-craters are formed on the nanofiber by irradiating it with a single femtosecond laser pulse. In this work, we will present some preliminary results on light-matter interaction in the vicinity of a PhCNF cavity. Laser-cooled Cs-atoms prepared in a magneto-optical trap are overlapped with the PhCNF cavity. One of the cavity modes is tuned to the atomic resonance and the photo-absorption spectrum of the surrounding atoms is measured by sending a weak probe field through the PhCNF cavity. We have clearly observed an enhancement in the absorption signal, even though the finesse was only 9. We will also discuss the technical challenges and recent developments in the fabrication method and integration to laser-cooled atoms.

P-21W

Cavity-QED system with a fiber coupled cavity and laser cooled atoms

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A system with an atom coupled with a cavity photon, the so called cavity-QED system, has a fundamental importance on quantum optics, and is one of the most promising building blocks of the quantum computer and network. In this presentation, we discuss our experimental study on the cavity-QED system based on a fiber coupled optical cavity and laser cooled neutral atoms.

P-22W

Cavity QED on a nanofiber

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We realize cavity enhanced spontaneous emission for quantum emitters deposited on the surface of an optical nanofiber. We use a unique composite photonic crystal cavity (CPCC) method, combining a nanofabricated grating with the nanofiber itself. Quantum dots deposited on the nanofiber surface experience enhanced spontaneous emission at the cavity resonance wavelength. Our experimental measurements of the spontaneous emission enhancement factor correspond well with predictions based on numerical simulations. In addition to our results for quantum dots, we also discuss proposed extensions to the experiment using quantum emitters based on vacancy centers in diamond, where mainpulation of spin qubits is a possibility. We anticipate that the CPCC method may have applications to a variety of quantum information technologies from single photon sources to quantum switches and quantum memories.

P-23W

Towards non-Gaussian states in nanofiber trapped ensembles

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Atomic ensembles strongly coupled to the evanescent field of tapered nanofibers are an excellent atom-light-interface [1]. The preparation and characterization of genuinely quantum states in these ensembles is an important step towards the realization of quantum memories [2] and applications in quantum information processing or quantum communication networks.

The creation and characterization of a single excitation Fock state has recently been demonstrated in a dipole trapped cloud of 105 cesium atoms [3], though classical noise due to the large number of atoms required limits the performance. With our new nanofiber setup [4] we reach a much higher optical depth with about 1000 atoms. By exploiting the polarization dependent coupling of atomic emissions to the fundamental mode of the fiber [5], we in addition expect to significantly improve the state purity.

In a hybrid discrete-continuous approach, we will first create the atomic Fock state by detecting the heralding photon emitted by the single excitation. Subsequently, we perform quantum nondemolition measurement of the collective spin [3] employing dual-color heterodyne interferometry [4]. The non-classicality of the single excitation Fock state is then evident from the non-Gaussian quadrature probability distribution [6] as well as the reconstructed Wigner function, which takes on negative values. The measurement method can also be applied to even more exotic quantum states.

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P-24W

Deterministic switching of a Lambda system by single itinerant photons

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Extensive efforts have been made in a variety of physical systems to realize strong coupling between a single quantum emitter and a one-dimensional photon field provided by optical fibers and waveguides. In such one-dimensional optical systems, which are recently referred to as waveguide QED systems, interaction between an emitter and a photon is enhanced drastically due to the destructive interference between the incident field and the radiation from the emitter. This opens the possibility for deterministic control of quantum systems by individual photons. In particular, in a Lambda-type three-level system that has identical radiative decay rates from the top level and is coupled to a semi-infinite one-dimensional field, a resonant single photon deterministically induces a Raman transition in the Lambda system and switches its electronic state. This is applicable to a bidirectional quantum memory and a photon-photon quantum logic gate [1]. In this paper, we present our recent demonstration of such a Lambda system by utilizing the dressed states of a driven circuit-QED system. Applying continuous microwave to the Lambda system, we confirmed that the field amplitude vanishes completely upon its reflection (perfect absorption by “impedance matching”), and that input photons are down-converted by the Lambda system [2,3]. This indicates highly efficient switching of the Lambda system induced by individual microwave photons. We also show that the present system functions as a detector of single microwave photons [4].

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P-25W

Novel method of sub-wavelength thin gilm growth for single photon emission from dye molecules

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Single photons are very attractive for quantum information processing, given their long coherence time and their ability to carry information in many degrees of freedom. A current challenge is the generation of single photons in a photonic chip in order to scale up the complexity of quantum operations. Solid state emitters could offer this possibility. Quantum dots are one promising approach, but photons produced by different dots are generally distinguishable. Nitrogen-vacancy (N-V) centres in diamond are also promising, however it is challenging to place these in photonic circuits and the emitted photons have many frequencies. By contrast, dibenzoterrylene (DBT) molecules embedded in a thin film of anthracene (AC) at cryogenic temperatures produce a high yield of indistinguishable photons [1, 2]. DBT acts as a two-level system with a narrow 30 MHz near-infrared (785 nm) zero-phonon line [1]. We have proposed that a DBT molecule, deposited in the vicinity of a nanoscale waveguide, could emit these photons efficiently into the waveguide [3]. Conventional spin-coating methods [1] do not offer sufficient control over the surface coverage and the morphology of the AC crystal for deposition on photonic structures, while crystals grown with sublimation are too thick. Another method is needed.

In this paper we describe a new method for evaporating AC and DBT to produce crystals that are wide and thin. AC powder and DBT dissolved in diethyl ether are placed in a vial and heated close to the melting point of AC. The growth substrate covers the opening of the vial. 2D growth in the supersaturated vapour produces the crystals we require over the whole substrate. The crystals are typically several microns across and have remarkably uniform thickness, which we control between 20 and 150 nm by adjusting the growth time. The deposition is carried out in a glove bag in order to exclude oxygen, with a view to improving the photostability of the DBT molecules. Single DBT molecules are imaged in fluorescence using confocal microscopy. We analyse the polarization of this light to determine the alignment of the molecules with respect to the crystal axis. We aim to control the alignment of the molecules in order to maximise the coupling efficiency between the dipoles and the waveguide. We will present the single photon characteristics of this emission, including excited state lifetime, second-order correlation function, polarization, and photostability, as well as describing progress towards the coupling of photons to a silicon nitride waveguide.

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P-26W

Advantages of micro lensed fibers over microscope objectives for stimulation of whole mount mouse retina

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In this experiment we measure the response of retinal ganglion cells (RGCs) to light stimulation at low photon rates (<50 photons $\mu m^{-2} s^{-1}$) in an ex vivo preparation of mouse (C57bl/6) retina using a multielectrode recording system. Several means of stimulus delivery are compared. On the one hand a water immersion microscope objective (NA 0.3) is used to focus the beam of a 532 nm fiber coupled NDYAG laser directly onto the photoreceptor layer of the retina. On the other hand two types of micro lensed fibers are employed: (1) tapered cone lensed (TCL) fibers, providing a focused beam and (2) ball lensed (BL) fibers providing a near collimated beam. The spot size obtained by TCL fibers varies with the z position of the fiber tip significantly more than that of BL fibers.

Both fiber types offer major advantages over the traditionally used microscope objective approach. In case of TCL, when working with small spot sizes (<5 µm), the cost is at least one tenth of a comparable objective lens. BL fibers on the other hand eliminate the need for a costly, highly accurate z positioning systems.

Moreover, a purely fiber based system results in much less loss when compared to lens based ones (estimated < 30% vs. ≈ 50%) which is a crucial parameter in very low intensity light stimulation. This is owed to the fact that the number of reflective / absorbing surfaces is minimized by directly going from glass to water where there is small change in the index of refraction while in the case of a complex microscope objective the light goes from the fiber to air, the objective lenses' glass and then finally water.

In summary, the fiber based stimulation systems turn out to be much better suited for working with low photon rates as well as much more economical compared to lens based systems.

P-27W

Photonic quantum gates using multilevel atomic systems

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We propose methods for quantum gates between photons assisted by multilevel atomic systems. The atomic systems are supposed to be in a cavity or a one-dimensional waveguide. The methods can transfer a quantum state between a photon and an atom, and also work as quantum gates between consecutively input photons. The systems could be used as building blocks for universal quantum computation.

P-28W

Active formation of high Q nanocavity on photonic crystal waveguide assisted by nanofiber

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A photonic crystal (PhC) nanocavity has a high quality (Q) factor and an extremely small mode volume, and it is used for various applications including quantum optics and classical switching devices. However, it is generally difficult to fabricate nanocavity with precise resonant wavelength and position. In this study, we experimentally achieved high Q nanocavity having tunable resonance at arbitral position on a PhC waveguide. Our cavity was formed by adjusting a nanofiber close on the surface of a PhC waveguide. The presence of a nanocavity shifts the modegap of the PhC waveguide which allows the formation of a high-Q resonance with a Q of 5.1×10^5. We demonstrate that the resonance and position are able to control by changing the position of the nanofiber.

P-29W

Microfluidic chip based microfiber sensors

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Optical microfibers and nanofibers (MNFs) have been emerging as a novel platform for exploring fiber-optic technology on the micro/nanoscale owing to their outstanding properties including low waveguiding losses, tight optical confinement, strong evanescent fields, and widely tailorable waveguide dispersion. Among various MNFs applications, optical sensing has been attracting increasing research interest due to its possibilities of realizing miniaturized fiber optic sensors with small footprint, high sensitivity, fast response, high flexibility and low optical power consumption. Note that most of the previously reported evanescent wave sensors used MNFs suspended in air or mounted in a bulky volume flow chamber, thus, surface contamination and environmental factors are likely to affect the stability of these sensors. To address these issues, integrating MNFs with a microfluidic chip is an effective method to improve the stability and minimize the sample consumption, as the microfluidic chip does not only provide natural protection of the MNF, but also delivery of micro/nanoliter sample solution for the MNF. Herein, we demonstrate two types of microfluidic chip based MNF sensors for ultrasensitive absorption/fluorescence measurement and femtoliter detection volume fluorescence measurement, respectively.

P-30W

Cooperative effect between Stokes and anti-Stokes modes of nano-fibers stimulated by excited states of trapping atoms and its application

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We propose the cooperative effect between pump and Stokes (or anti-Stokes) modes in the Raman process in which the photons from pumping wave are cooperatively conversed in the Stokes mode in the process of the excitation of trapped atoms in the evanescent field of fiber optics. This effect takes place like in the cooperative process of the conversion of photons from pump mode to anti-Stokes field stimulated by atomic stream travelling through the cavity [1,2]. The similar situation can be created in nano fiber in process of Raman interaction of the pump field with the atoms trapped in the zone of evanescent field. In this situation the photons from the pump field can be cooperatively converted in the new anti-Stokes or Stokes modes of fibers as the function of the preparation of the atoms in the excited or ground state respectively. For descriptions of these cooperative processes we use the bi-boson operators which describe the cooperative conversion of the photons from the pump field into Stokes mode. This field of both modes (pump and Stokes) contains the second order coherence so that its properties are interesting from the classical point of view, because it contains the good amplitude and phase. From quantum descriptions this field is interesting because the second order coherence appears between the photons from the pump and Stokes modes.

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P-31W

Packaged silica and chalcogenide microspheres and their applications

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Significant progress has been made in the theoretical and experimental investigation of optical microresonators with different morphologies and functionalities over the past decade. Optical microresonators have shown potential as versatile basic building blocks capable of performing a number of key optical signal processing functions such as wavelength filtering, switching, regeneration and buffering, and also have been used as micro-lasers and wavelength-division-multiplexing (WDM) components and optical add-drop multiplexers.

In this research, a high quality silica microsphere with a diameter of circa 153 μm is fabricated using a CO_2 laser and coupled with two low-loss tapered fibers, both with diameters of 1.5 μm and fabricated using a fire brushing technique. Their relative positioning is optimized under an optical microscope and then fixed on a microscope slide using a low refractive index UV curable polymer. The use of a coating polymer significantly increases the mechanical alignment stability of the microsphere-fiber-tapers system. At wavelengths near 1550 nm, a high-Q mode of up to 0.9×10^5 can be efficiently excited via evanescent coupling from the input tapered silica fiber. This Q factor reported here for a packaged microsphere resonator coupled with two silica fiber tapers is very close to the theoretical material-limited Q factor. This indicates that the extra absorption and radiation loss resulting from the polymer packaging process is relatively low. The temperature dependence of the packaged silica microsphere add-drop filter has also been investigated in this work. The packaging technique offers the potential to develop low-cost, robustly assembled fully integrated applications including WDM, sensors, ultra small optical tunable filters and also integrated micro-lasers due to the simplicity of the fabrication process compared with a conventional costly photolithographic technique.

Also a high quality chalcogenide (As_2S_3) microsphere with a diameter of 110 μm is fabricated and packaged using a low refractive index UV curable polymer. The use of a coating polymer not only increases the alignment stability of the microsphere-taper system, but also acts as a modal filter, successfully removing some high order WGMs, as demonstrated both theoretically and experimentally. At wavelengths near 1549.5 nm, high-Q modes up to 1.8×10^5 can be efficiently excited via evanescent coupling from a 2 μm diameter tapered silica fiber. This is the highest Q factor reported to date for a chalcogenide microsphere resonator coupled with a silica fiber taper, despite the packaging with a polymer resulting in extra absorption and radiation loss. The photosensitivity of the packaged chalcogenide microsphere has also been investigated in this work, and we show that the photosensitivity of the device, which is useful for tuning, is still present and usable after the packaging process. The packaging technique offers the potential to develop low-cost, robustly assembled fully integrated all-optical switching & tunable filter devices due to the ease of the packaging process and the retention of photosensitivity.

P-32W

Polarization entangled photon pair generated by a fiber beam splitter

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The polarization entanglement of spatially separated photon pairs, generated by spontaneous parametric down conversion (SPDC), has been used in a variety of quantum experiments to demonstrate quantum teleportation, entanglement-based quantum cryptography, Bell-inequality violations, and others. These SPDC photon pairs are also entangled in their wave vectors being applicable for application of quantum imaging, photonic de Broglie wavelength measurement, quantum interference, and quantum lithography.
In our present work, we have proposed a scheme to generate polarization entanged photon pair using a fiber beam splitter, which simplifies the optical alignment compared with the case using a bulky standard beam slitter. The experimental result shows that the generated photon pairs are entangled in their polarization.

P-33W

Extending nanofiber quantum photonics to capillary nanofibers

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Recently, we have demonstrated cavity quantum electrodynamics conditions for single quantum emitters (QE) on the surface of a nanofiber, by constructing a cavity structure on the nanofiber using a novel composite method. The composite photonic crystal cavity (CPCC) was formed by combing the nanofiber and an external grating. Here, we present a unique method to place the QE inside the nanofiber to further improve the performance of the CPCC device. The method is to develop capillary nanofibers (liquid-core nanofibers) from conventional micro capillary fibers. We use water soluble colloidal quantum dots (QDs) for QEs. Placement of the QE inside the nanofiber is achieved by flowing the QD solution through the capillary nanofiber. We will discuss simulation and experimental results.

P-34W

All-optical switching using Kerr effect in a nanofiber-coupled whispering gallery mode microcavity system

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Whispering gallery mode (WGM) microcavities have an ultra-high quality factor and a small mode volume. In addition, it can be excited with ultimately small loss by using a nanofiber. These characteristics enable WGM microcavites to work as all-optical switches that are driven with small input power and with an ultimately small insertion loss. In this study, we achieved all-optical switching based on optical Kerr effect in a WGM cavity. Among various WGM cavities we employed a silica toroid microcavity that has a Q of over 100 million that can be fabricated on a silicon chip. We obtained all optical Kerr switching with an input power of 36 μW which is the record lowest value among all previously reported Kerr switches.

P-35M

All optical switching with cold Rb atoms using an optical nanofiber

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Switching a light beam using another light beam, called all optical switching, has the advantage of no mechanical movements involved in the process; this not only leads to a non-invasive way of switching devices, but could also be used for optical information processing, investigating concepts in quantum information science, etc. We demonstrate all optical switching with an optical nanofiber (ONF) embedded in a cloud of cold ^{87}Rb atoms. A probe beam of wavelength 780 nm and a control beam of wavelength 776 nm are passed through the ONF in a counter-propagating configuration. The probe beam is 14 MHz red-detuned from the 5 $S_{1/2}$ F=2 → 5 $P_{3/2}$ F′=3 transition, which is the same as the cooling beams used to create the magneto-optical trap, and the 776 nm beam is 14 MHz blue-detuned from the 5 $P_{3/2}$ F′=3 → 5 $D_{5/2}$ F″=4 transition in order to be at resonance. Powers used for the probe and the control beams are 100 pW and 100 nW, respectively. In the absence of the control beam the probe has 40% absorption; however, when the control beam is applied the medium becomes completely transparent to the probe as the atoms in the evanescent field of the nanofiber are excited to the 5 $D_{5/2}$ state, thereby reducing the ground state population in this region. Note that the cooling beams are at the same frequency as the probe and are continuously on. This ensures that the atoms are excited to the 5 $P_{3/2}$ state in order that the control beam can excite them further to 5 $D_{5/2}$. The control beam is switched on and off with a repetition rate of 5 kHz and a clear modulation of the probe beam is observed in the transmission.

P-36M

Selective excitation of higher order fiber modes and their interaction with cold atoms

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Injection of higher order modes (HOMs) into an optical nanofiber (ONF) should lead to interesting properties for atom trapping experiments. For example, a Laguerre-Gaussian beam of index 1 (LG_{01}), the so-called doughnut beam, can be used in such experiments to design new trapping geometries. This in turn improves sensing and control of the trapped atom positions. Moreover, such HOMs have a stronger evanescent field at the fiber waist compared to that of the fundamental mode. We demonstrated such effects in a previous study in which the additional guided modes, when one considers HOM propagation, improved the interaction between cold atoms and the evanescent field of an optical nanofiber designed to support up to the LP_{11} group. In the current work, we inject an LG_{01} beam into a few-mode tapered optical fiber and selectively separate the output into each of the LP_{11} group's four modes, namely TE_{01}, TM_{01}, $HE_{21,even}$ and $HE_{21,odd}$. We then investigate the contribution of each mode individually. The future aim is to use a combination of HOMs to design atom traps around ONFs.

P-37M

Optical trapping using plasmonic nanoring arrays

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We study the optical properties of hybrid gold nanodisk and nanohole arrays which demonstrate high plasmon resonance in the near-infrared regime (NIR) due to the device's high tunability. Tunability is achieved by varying parameters such as the periodicity, and dimensions of the different components of the arrays. The resonance modes of this hybrid design show a splitting to low and high energy modes caused by the interference of the disk and hole plasmons. Enhancement in the NIR is highly desirable for the purposes of biological sample manipulation where photo damage is low. Furthermore, grooves are added to connect the hybrid structures together, providing further enhancement of the local electric fields and therefore creating trapping sites. Characterization curves of the devices are obtained by collecting spectrometric measurements from the reflected light at the prism-water interface. The dependency on the incident angle and polarization is investigated during plasmon resonance frequency characterization and trapping experiments. Additionally, the fabrication procedure using electron beam lithography (EBL) is discussed.

P-38M

Investigation of two- photon excitation in cold and hot rubidium atoms

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The strong evanescent field intensity generated at the waist region of an optical nanofibre (ONF) for ultralow input powers (pW-nW range) makes such fibres suitable candidates for nonlinear optics and quantum interference effects in cold atoms [1]. Here we present near or on-resonance two-photon excitation spectroscopy in laser-cooled atoms (^{87}Rb) using an ONF and in thermal atoms (^{87}Rb) using free beams. Comparison of the spectral linewidths and line shapes in both cases will be highlighted. Using a two-photon excitation process we also study the impact of the high intensity light field on the atomic energy levels in terms of Autler-Townes splitting. Power levels needed to observe the nonlinear effect is orders of magnitude smaller in the cold atom setup using the ONF as compared to thermal atoms with free beams.

We use ^{87}Rb atoms and excite them from the ground state, $5S_{1/2}$ F=2 to the excited state $5D_{5/2}$ F” via an intermediate state $5P_{3/2}$ F’=3. In the case of cold atoms, both the 780 nm and 776 nm beams propagate through the nanofiber. De-excitation of the atoms from $5D_{5/2}$ to the $6P_{3/2}$ and then $5S_{1/2}$ produces 420 nm light which is used to probe the two-photon excitation process.

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P-39M

Fresnel atom microtraps from geometric apertures

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Microtraps for neutral atoms can be created by using the optical near field that appear when a laser beam diffracts on small, circular apertures in a thin screen. While usually the gradient forces required for trapping arise from a non-uniform field distribution over the laser beam cross section, in this nearfield situation they stem from the optical field non-uniformity due to the aperture. Such traps are capable of confining atoms to micron-sized regions and robust control over the trap parameters can be achieved by varying the intensity and detuning of the incident laser. In this work we show that other interesting potentials to control atoms on micro-sized scales can be created using the same principle and a variety of aperture geometries in the thin screen, namely circular aperture , annular aperture etc. And how the potential changes with modulated intensity.

P-40M

Optical binding of particles using higher order microfibre modes

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The light induced self-arrangement of trapped particles in optical fields is attributed to the binding effect. The binding effect occurs when a light field is incident on a group of particles. Each particle in the field acts as a source of scattered light and hence optical forces, which causes the system to reach a new equilibrium dictated by these optical binding forces[1]. Optical binding can be observed in many optical propulsion systems. Recently, Frawley *et al*. reported the propulsion of self-arranged particles where groups of silica micro particles were propelled along the surface of a nanofibre with a collective speed and stable inter-particle distances [2].

The work discussed above is based on the first fibre mode or fundamental mode (FM). However, for many applications, the evanescent fields of higher order micro/nanofibre modes (HOMs) show certain advantages, such as complex field distributions, larger evanescent field amplitudes and longer evanescent field decay lengths at the larger fibre diameters compared to that which can be obtained using the FM. Thanks to the recent improvements made in fabricating microfibres for HOMs [3] and the theoretical proposal for creating trapping sites using HOMs [4], some preliminary experimental works on the application of the HOMs for cold atom detection [5] and particle manipulations [6] have been reported. Understanding the behavior of different order modes and their interactions with micro/nano objects is necessary for further study in the field of optical manipulation for both colloidal particles and biological samples, and also in the field of cold atom trapping.

Motivated by the works listed above, we studied the binding effect of varying numbers of polystyrene particles under the evanescent field of the HOMs. The changes to the particles' speeds caused by optical binding effects between propelled particles are analyzed. To support the experimental results, a theoretical analysis was also provided to explain the obtained phenomena. The preferred particle position versus fibre diameter was studied.

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P-41M

Nanostructured micro- and nanofibres for optical trapping

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Optical waveguides with dimensions close to, or smaller than, the wavelength of the guided light, produce evanescent fields which extend beyond their physical boundaries, and have become a subject of much interest in the field of optical manipulation since their realization by Kawata *et al.*[1]almost two decades ago. The evanescent field produced from simple waveguiding structures has been applied, largely, to the propulsion and trapping of micro-sized polystyrene/latex particles or nano-sized gold/silver particles, as well as the size- and refractive index-sorting of particles. In the case of polystyrene or latex particles, the low dielectric contrast of the trapping systems, coupled with the finite decay length of any given optical waveguide system, prevents the propulsion of nanoparticles made from these materials without the use of high input intensities. Recently optical micro- and nanofibres (MNFs) have been used in optical manipulation. MNFs, consisting of cylindrical optical waveguides with diameters ranging anywhere from a few microns to hundreds of nanometers, are an attractive solution to trapping problems as they are robust, can be introduced to different environments in a non-destructive manner, and are easily interfaced with a vast number of existing optical devices. By modifying the structure of an MNF through the introduction of a nano-sized cavity at the MNF waist, a region of increased electric field intensity is created. This device can be applied to various problems in sensing and particle or atom trapping. Here, we look at the application of this slotted tapered optical fiber (STOF) to the trapping of nanoparticles. Counter-propagating electric fields are used to trap 100 nm fluorescing particles at the slotted region of the STOF, and, by recording both the transmission of the trapping laser beam and imaging the cavity region, trapping events can be observed. The geometry of the STOF allows for high coupling of light emitted by particles within the cavity into the guided modes of the STOF. Therefore, we also monitor the transmission of fluorescent nanoparticles by collecting their emitted light as another means of detecting the presence of successful trapping events.

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P-42W

Anisotropic ring plasmonic arrays for nanoparticle trapping

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Since the advent of optical tweezers there have been significant efforts to achieve trapping and manipulation of nanoscale objects. The field confinement exerted by metal nanostructures, in particular by double nanohole apertures, has been shown to efficiently localize the field and enable optical trapping of few nanometer-size particles[1]. At the same time, plasmonic arrays, as opposed to isolated subwavelength structures, create multiple trapping sites[2]. Moreover, varying the lattice constant provides an additional parameter for spectral tuning of the trapping device[3]. Here we propose anisotropic nanoring arrays, based on a combination of double nanoholes[1] and ring plasmonic arrays[2]. We further perform spectral characterization of the arrays. These structures exhibit a strong polarization anisotropy, and benefit from tunable red-shifted plasmon resonances[3] for both nanoscale trapping and microscale manipulation. Increasing the inner diameter of the rings shifts the array resonant transmission towards the infra-red, improving both trapping efficiency and sensitivity, which are two parameters of particular interest in biological and diagnostic applications. Finally, we discuss preliminary results for nanoparticle trapping.

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P-43W

Pressure tunable microbubble resonator as an external reference to a laser

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Narrow linewidth laser source with frequency tunability is highly imperative in many areas of modern science research. Through the time of developing laser sources, many methods were invented for fine tuning frequencies. Among them, external resonator is one widely used way. Fabry-Perot etalon is a most popular external resonator. The laser can be locked in by feedback control which is a mature technique in many laser applications. Miniaturizing the external cavity reference has a great significance in practice, such as whispering gallery mode (WGM) microresonators. In toroidal WGM resonators it was demonstrated that both the coupled power and wavelength of the pump laser can be locked to the WGMs [1]. Whereas similar lock in control with tunable capability in fused silica microresonators [2] was also demonstrated. Although tunability was large, it was at the expense of high hysteresis in repeatability. Here by using a microbubble WGM cavity [3] as the external reference, we demonstrated a proof of principle of laser tuning by pressure. By locking the 1550 nm laser to WGM of the microbubble using Pound-Drever-Hall method and changing the internal aerostatic pressure of the microbubble, the laser can be tuned at a shift rate of 7 GHz/bar and a tuning range up to 20 GHz. Compared to [2], aerostatic pressure tuning is nearly linear [4], which guarantees an excellent repeatability. Long term stability and noise profiles of such tuning were also investigated and discrepancies are observed to be very low.

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P-44W

Pressure tunable microbubble and coupled-mode-induced transparency

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We reported an improvement of quality (Q) factor in microbubble resonator fabricated by co-propagating CO_2 laser beams from microcapillaries. The Q factor remains 10^6 to 10^7 even for submicron wall thickness microbubble. By finite element method (FEM), the calculated Q is only one magnitude higher than the experimental results. As a direct application, we show an aerostatic pressure tunability of the whispering gallery modes (WGMs). The sensitivity reaches 18 GHz/bar at telecommunication communication band (1.55μm) for the first time, while the resolution of the pressure sensing is proved as 1.3mbar.

We also studied the difference of the sensitivities for different radial order WGMs in the microbubble theoretically using FEM. Due to the differences of light paths for different order modes, those radial modes experience different frequency shifts at same pressure changes, due to the strain and stress effect of the inner pressure. It is proved that the strain effect which changes the size of the microbubble plays the dominant role and the sensitivity differences increase when the microbubble wall is thinner. An experimental measurement further confirms it.

In a thin-walled microbubble, by aerostatic pressure tuning, the first order WGM shifts across the second order mode with about 2 bar pressure. While the modes cross, a coupled-mode-induced transparency window can be observed on the transmission spectrum. The dynamics was analyzed by coupled mode theory for such microbubble-tapered fiber coupled system, where the coupling between the two different order modes are originated from the coupling to the fiber taper mode. The theory satisfied with the experimental results quite well. This work shows that it is possible to achieve a fully controllable Fano and EIT-like system in a single WGM resonator, and it can be a future development for improving the resolution of aerostatic pressure sensing applications in the microbubble resonators.

P-45W

Small numbers of atoms close to optical nano-fibres

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We study the coupling between a row of atoms and the guided modes of an optical nano-fibre in a configuration where the axis of the fibre is aligned perpendicularly to a row of regularly separated ^{133}Cs atoms. This can, for example, be realised when bringing a nano-fibre close to a one-dimensional optical lattice prepared in a Mott insulator state. In general the emission characteristics of an atom into a nano-fibre mode depends on the radius of the fibre, the position of the atom, the wavelength of the transition and the orientation of the dipole. We show that nano-fibres make it possible to achieve atomic resolution in the lattice and to identify unoccupied sites. We also show that the small size of the fibre combined with an enhanced photon collection rate can allow for the attainment of large and reliable measurement signals.

Secondly, we investigate how self-trapping can be induced from the interference of coherent off-resonant light scattered by a small number of atoms close to a nano-fibre. When atoms are sitting inside the reach of the first fundamental mode of the fibre, and coherent laser light is scattered from them, the resulting fibre field provides a longitudinal potential, which acts back on the atomic distribution. In our scenario, the back-action of the atoms on the confining field is non-negligible and can lead to self-trapping.

P-46W

Er:Yb doped microbubble laser

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Here we experimentally explore for the first time the idea of a silica microbubble or microcapillary resonators coated with a layer of laser glass in this case Yb:Er doped phosphate glass. This is realised by the fact that the two glasses have different melting points. The Er:Yb doped glass outer layer is pumped at 980 nm and lasing is observed at 1535 nm. Thermal tuning of the lasing mode over 70 GHz is achieved by flowing air through the cavity. The idea of gas/liquid flow sensing using the concept of a “hot cavity” is discussed and preliminary measurements and characterisation of the system is presented.

P-47W

Compact system of optical tweezers/nanofibres/nano plasmonic structure for particle trapping and manipulation

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Optical tweezer technique can be used to gently trap and manipulate small objects, which has many applications in biological sciences. Recently, optical nanofibre has been proposed as an efficient method for multi-microparticle trapping and prolusion.[1] In this work, we first discuss new optical techniques for trapping and manipulating micro-objects using a micro- and nano-fibre (MNF) in combination with an optical tweezer. We investigate the optical dynamic interaction of single and chains of trapped particles in the evanescent field of the fundamental mode (FM) and higher order modes (HOM) of the MNF.[2-3] Three-dimensional trapping, control, and rotation of particles are demonstrated around the MNF by using counter-propagating FM and HOM waves.

To enhance the capabilities to selectively trap and monitor the objects from micron down to nanometer scales, we integrate a nano slot into a nanofibre. The small-gap between the dielectric elements of a nano slot-fibre results in high local electric field confinement, offering new possibilities to trap and control multiple nanoparticles that have diameters of less than 100 nm along the nano slot region of the nanofibre.[4]

We finally address the possibilities to trap dielectric nanoparticles of 10-50 nm with the combination of a sub-wavelength nano-metallic aperture array and an optical tweezer system. We study optical properties of this plasmon-like resonant surface using hybrid gold nanodisk and nanohole annular aperture arrays. Tunability from the visible to the near-infrared region of resonance modes was demonstrated due to the change of the coupling of electromagnetic interactions between nanohole and nanodisk plasmons. Experimental results on optical trapping of single and multiple nanoparticles of less than 30 nm are demonstrated using this hybrid array.

This work is essential for future studies on three dimensional trapping and precise control of long-range and large scale of complex biological molecules in aqueous solutions.

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