MAX PLANCK INSTITUTE
FOR THE SCIENCE OF LIGHT

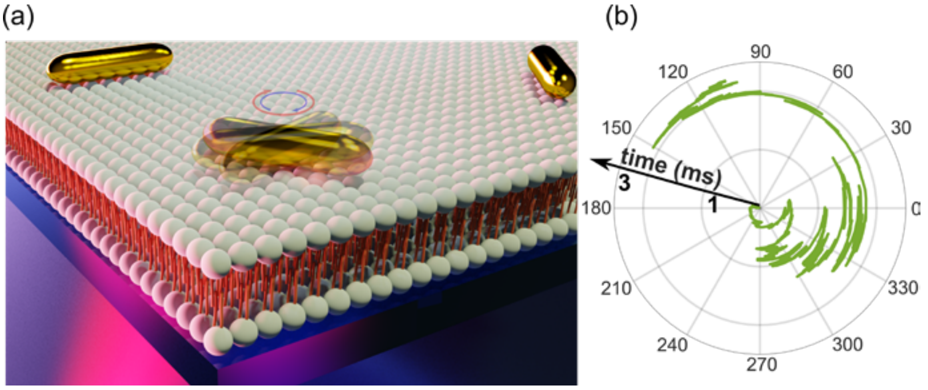
MPL News

MAX PLANCK INSTITUTE
FOR THE SCIENCE OF LIGHT
NEWSLETTER
ISSUE #16
FEBRUARY 2021

RESEARCH ARTICLE VS Sandoghdar Division

Fast rotational diffusion of a nanorod

The Brownian motion of a small particle can reveal important properties of its surroundings. For instance, the role of anomalous translational diffusion has awakened much interest recently. To carefully examine rotational diffusion in, e.g., biomembranes, one requires however more advanced experimental techniques and data analysis as well as higher temporal and spatial resolution. We recently studied the rotational and translational diffusion of a single gold nanorod linked to a supported lipid bilayer with ultrahigh temporal resolution of 2 µs using a custom-built polarization-sensitive dark-field microscope. The large number of trajectory points in the measurements with lateral precision of 3 nm and rotational precision of 4° allows us to characterize the statistics of rotational diffusion in unprecedented detail. The data show apparent signatures of anomalous diffusion, such as sublinear scaling of the mean-squared angular displacement and negative values of angular correlation function at small lag times. However, a careful analysis reveals that these effects stem from residual noise contributions and confirm normal diffusion.



(a) Schematics of a gold nanorod bound to a supported lipid bilayer on glass.
(b) Polar representation of a temporal zoom into a rotational trace.

Contact: mahdi.mazaheri@mpl.mpg.de
Group: Sandoghdar Divison
Reference: M. Mazaheri J. Ehrig, A. Shkarin, V. Zaburdaev, and V. Sandoghdar. Nano Lett. **20**, 7213-7219 (2020); doi.org/10.1021/acs.nanolett.0c02516

Ground-breaking ceremony for the new Max-Planck-Zentrum für Physik und Medizin

After years of preparation and planning, construction finally now begun on the building that will house the Max-Planck-Zentrum für Physik und Medizin (MPZPM). It will be sited in the grounds of the University Hospital, close to the river Schwabach in Erlangen.

The MPZPM ground-breaking ceremony. From left: Günter Leugering, Vice President Research at FAU, Florian Janik, Oberbürgermeister of Erlangen, Vahid Sandoghdar, MPL Director, and Heinrich Iro, Medical Director and Chairman of the Executive Board of the University Hospital Erlangen. Photo: Stephan Minx / MPZPM

Directors’ foreword

The last Newsletter appeared shortly after the outbreak of the COVID19 pandemic, and it is fair to say that we had no idea how the year would end. Looking back, we have been very fortunate to survive 2020 with minimal inconvenience. Everyone at MPL joined forces to keep the labs open while reducing the risk of virus infection. By creating a dynamic system of lab work, home office, online meetings, and proper measures for social distancing and disinfection, we managed to sustain our operation. We hope that 2021 will not disappoint us by presenting further surprises.

A major event of 2020 was the evaluation of MPL by our scientific advisory board. This is an established procedure in the Max Planck Society which takes places every three years. The evaluation was successfully carried out as the very first event in an online format. We are proud to say that MPL was judged excellent in all respects.

The online approach was soon adopted for many other activities, including our Distinguished Lecture Series, a new seminar program between MPL and the Max Planck Center in Ottawa, various workshops and symposia, teaching, etc. Nevertheless, we look forward to resuming personal exchange with our colleagues around the world.

An important milestone for Erlangen and MPL was reached last October by the groundbreaking ceremony of the building for the Max-Planck-Zentrum für Physik und Medizin. The new building on the campus of the Erlangen University Hospital is scheduled to open in 2024. The growth of MPL in this research direction is, however, already in full swing. The newest addition is Leonhard Möckl, who joined MPL from Stanford University last November to set up an independent group working at the interface of optics, biochemistry and medicine.

And MPL continues to evolve...for example we have recently embarked on an exciting new collaborative venture with the Academy of Fine Arts in Nuremberg. Watch this space!

Florian Marquardt Philip Russell

Jochen Guck Florian Marquardt Philip Russell Vahid Sandoghdar

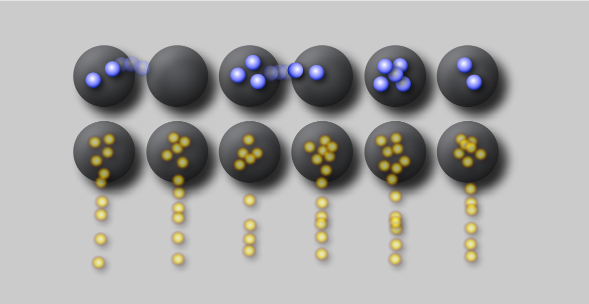
RESEARCH ARTICLES

NEWS

RESEARCH ARTICLE FM Marquardt Division

Kinetics of many-body reservoir engineering

Reservoir engineering (RE) provides a powerful way to exploit dissipative quantum dynamics. In contrast to uncontrolled dissipation, which destroys any quantum state of interest, the general framework of RE allows one to generate dissipative dynamics that prepare and stabilize quantum states. Recent first experimental advances illustrate the implementation of RE in many-body systems, such as quantum simulators based on superconducting circuits. Of particular interest in this context is the case of particle-number-conserving dissipation, since it can serve to cool a system at fixed particle number. However, a widely applicable, quantitative description of the emerging behaviour in a system of many particles subject to such a non-equilibrium reservoir is still missing. We have established a theoretical framework based on kinetic equations and noise spectra that can be used to describe the kinetics of many particles coupled to an engineered reservoir in a number-conserving manner. As an example, we show that the non-equilibrium steady state of a linear array of bosons can be described by a modified Bose-Einstein distribution with an energy-dependent temperature.



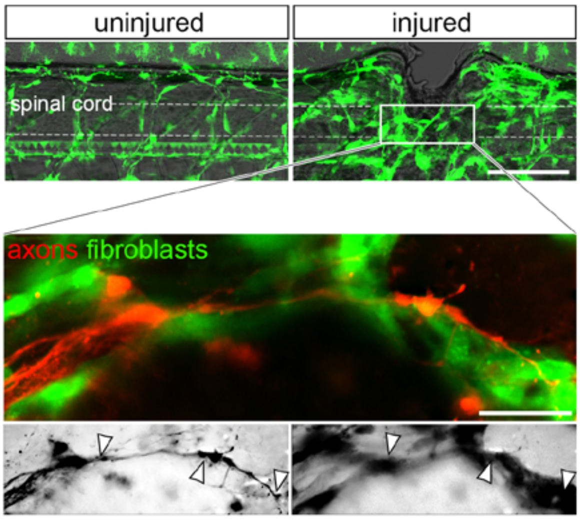
Many-particle system (upper chain of sites, with blue particles) coupled in a particle-conserving manner to a nonequilibrium bath (chain of driven cavities, with photons indicated in yellow).

Contact: hugo.ribeiro@mpl.mpg.de
Group: Marquardt Division
Reference: H. Ribeiro and F. Marquardt, Phys. Rev. Research **2**, 033231 (2020);
doi.org/10.1103/PhysRevResearch.2.033231

RESEARCH ARTICLE JG Guck Division

Specific composition of scar tissue permits nerve regrowth after spinal cord injury

Spinal cord injury results in lifelong paralysis because the severed nerve fibres (axons) fail to regrow across the lesion site. Among the mechanisms that limit axon regeneration in the mammalian central nervous system is scar tissue formation. Scars form due to excessive deposition of extracellular matrix (ECM) molecules by invading fibroblasts, and constitute a hostile environment to axon growth. Unlike mammals, zebrafish can efficiently repair damage to the central nervous system and regrow axons across the lesion site, leading to substantial recovery of swimming function. However, the difference that causes such opposite fates in man and zebrafish remained largely unknown. Using a panel of novel genetic tools, the Wehner group has identified a population of fibroblasts that – different to mammals – promote axon regeneration in zebrafish. In sharp contrast to their mammalian counterparts, zebrafish fibroblasts secrete a growth-promoting ECM in the spinal lesion site that is deprived of growth-inhibitory matrix molecules. Our study shows that the composition of the ECM in the scar is a key determinant of regenerative success in zebrafish versus inhibitory scarring in mammals. This insight might help one day to cure spinal cord injuries also in humans, by steering the ECM composition of the scar in the right direction.



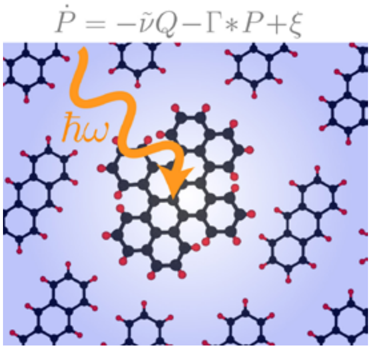
A specific fibroblast population in zebrafish (green) facilitates regrowth of injured nerve fibres (red) by depositing a regeneration-permissive scar tissue (not shown) in the spinal lesion site.

Contact: daniel.wehner@mpl.mpg.de
Group: Guck Division & Wehner Research Group
Reference: V. Tsata, S. Möllmert, C. Schweitzer, J. Kolb, C. Möckel, B. Böhm, G. Rosso, C. Lange, M. Lesche, J. Hammer, G. Kesavan, D. Beis, J. Guck, M. Brand, and D. Wehner, Developmental Cell **56**, 1–16 (2021);
doi.org/10.1016/j.devcel.2020.12.009

RESEARCH ARTICLE CG Genes Research Group

Molecule-photon interactions in phononic environments

Organic molecules embedded in solid-state host matrices have emerged as promising systems for quantum photonic technology. In particular, more recently, there has been interest in exploiting the strong inherent electron-vibration coupling in molecules for exploring optomechanical effects at the single-molecule level. In all of this, it is essential to understand the effects of temperature as well as the decoherence mechanisms taking place. In this collaboration with the Nano-Optics division at MPL, we have investigated the complex interplay between electronic, localized vibrational, phononic and photonic degrees of freedom in open solid-state molecular systems. The formalism predicts vibrationally-protected collective states for closely spaced molecules, and allows the imprint of molecular and crystal vibrations on the interaction with confined light modes to be quantified.



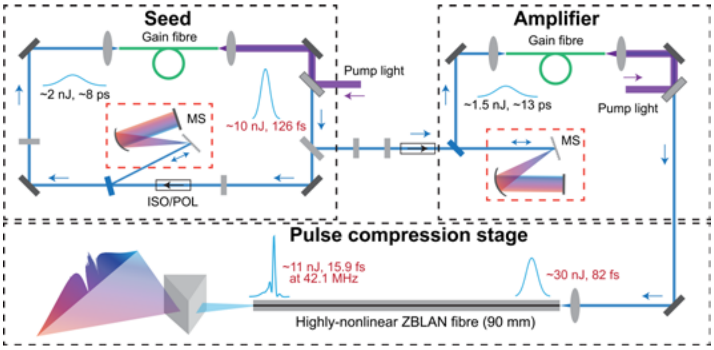
Molecules in a solid-state host matrix are electronically coupled to electromagnetic fields while vibrationally undergoing Brownian motion relaxation.

Contact: michael.reitz@mpl.mpg.de
Group: Genes Research Group
Reference: M. Reitz, C. Sommer, B. Gurlek, V. Sandogdhar, D. Martin-Cano, and C. Genes, Phys. Rev. Research **2**, 033270 (2020);
doi.org/10.1103/PhysRevResearch.2.033270

RESEARCH ARTICLE PR Russell Division

Sub-two-cycle mid-IR pulse generation in soft-glass fibre laser system

High-power ultrafast fibre lasers in the mid-infrared are of great interest because the fundamental vibrational bands of many important molecules have “fingerprints” in this spectral region. However, realization of such lasers has remained challenging for many years. In recent work, we designed and built a record-breaking mid-infrared fibre laser system by using intracavity-dispersion management, chirp-engineered amplification and higher order soliton compression techniques. The key elements are two grating-based pulse-stretchers, which introduce a large positive chirp on the mid-IR pulses in both the seed oscillator and power amplifier. The oscillator can directly generate ~100-fs pulses (~120 nm bandwidth). These pulses are amplified to an average power of ~1W and then compressed to ~16 fs in a short length of highly-nonlinear ZBLAN fiber, resulting in an octave-spanning spectrum from 1.8 µm to 3.8 µm. The sub-two-cycle mid-IR pulses generated in this three-stage fibre laser system have direct applications in fields such as molecular spectroscopy, frequency metrology, remote sensing, laser surgery, and optical diagnosis.



Three-stage mid-IR fiber laser set-up. ISO, isolator; POL, polarizer; MS, Martinez stretcher.

Contact: jiapeng.huang@mpl.mpg.de
Group: Russell Division
Reference: J. Huang, M. Pang, X. Jiang, F. Köttig, D. Schade, W. He, M. Butryn, and P. St. J. Russell, Optica **7**, 574-579 (2020);
doi.org/10.1364/OPTICA.389143

iSCAT news

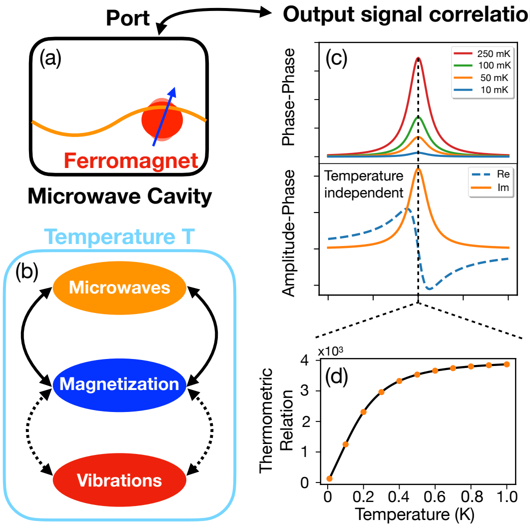
In a collaboration with Prof. Klaus Überla at the Virological Institute of the University Hospital Erlangen, the Sandoghdar Division has developed the first iSCAT microscope suitable for use in a biosafety level three (BSL3) laboratory – a "Viruscope". This instrument meets the requirements for studying not only SARS-CoV-2, but any type of high-risk pathogen. For more information contact michelle.kueppers@mpl.mpg.de, visit www.mpg.de/14660538/corona-virus-wirt-interaktion-iscat or read the research article entitled "Point spread function in interferometric scattering microscopy" in this issue. As announced in our previous issue, the inaugural iSCAT symposium took place May 26-28, 2020. Although of necessity held on-line, much positive feedback was received, and given the enthusiasm displayed by the attendees it is hoped the symposium will continue in the coming years, hopefully in-person.

Left: Exterior view of the Viruscope. Right: Internal view of the electronics and opto-mechanical components.

RESEARCH ARTICLE SVK Viola Kusminskiy Research Group

Magnon-phonon thermometry

The majority of experiments in quantum science and technology require low-temperature environments such as those afforded by dilution refrigerators. In these cryogenic environments, accurate thermometry can be difficult to implement, expensive, and often requires calibration to an external reference. In recent collaborative work with John Davis at the University of Alberta, Canada, we proposed a new kind of thermometer, based on a hybrid system consisting of a magnetic element inside a microwave cavity. The mechanical vibrations of the material couple to its magnetization via magnetostrictive interactions, in such a way that thermally driven vibrations are imprinted in the magnetization dynamics. Since when driven the cavity couples to the magnetization, the signatures of thermal vibration are transferred to the microwave signal exiting the cavity. The temperature can then be measured via noise cross-correlations, without need for external calibration. Combined with a simple low-temperature-compatible microwave cavity readout, this primary thermometer is a promising alternative for thermometry below 1 K.



(a) A hybrid system consisting of a ferromagnet loaded into a microwave cavity, which can be driven and probed via an external port. (b) Microwaves are coupled to the magnetization which in turns couples to the material vibrations. (c) Correlations in the output signal exhibit a temperature-dependent peak which, when compared with temperature-independent correlations, defines the thermometric relations in (d).

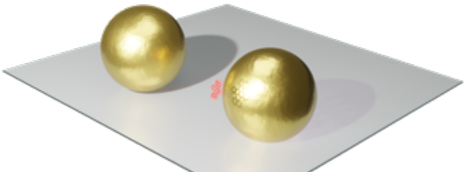
Contact: victor.bittencourt@mpl.mpg.de
Group: Viola Kusminskiy Research Group
Reference: C. A. Potts, V. A. S. V. Bittencourt, S. Viola Kusminskiy, and J. P. Davis, Phys. Rev. Appl. **13**, 064001 (2020); doi.org/10.1103/PhysRevApplied.13.064001

RESEARCH ARTICLE VS Sandoghdar Division

Letting a particle disappear

We can see objects because they scatter light. The scattering properties of objects are usually determined by their intrinsic material, shape, size and the surrounding medium. In a recent experiment, we were able to partially cloak a gold particle by bringing a single quantum emitter close to its surface. In this configuration, both the nanoparticle and the emitter (in our case a dye molecule) strongly affect each other's scattering behaviour through a coherent near-field interaction. This has the result of making the gold particle more transparent at the resonance frequency of the molecule. To protect the molecules from environmentally induced decoherence processes, they were embedded in a crystal prepared on a nanofabricated sample and operated at cryogenic temperatures (1.4 K). In the future, such a system could serve as a switch in optical circuits, using the molecule as a knob to control the optical response of the gold particle.

Contact: johannes.zirkelbach@mpl.mpg.de
Group: Sandoghdar Divison
Reference: J. Zirkelbach, B. Gmeiner, J. Renger, P. Türschmann, T. Utikal, S. Götzinger, and V. Sandoghdar, Phys. Rev. Lett. **125**, 103603 (2020); doi.org/10.1103/PhysRevLett.125.103603



A dye molecule partially cloaks a gold particle, resulting in a weaker shadow behind it.

Another five years of German-Canadian cooperation

We are happy to announce that, after a successful evaluation, the Max Planck Society has extended the funding of the Max Planck - uOttawa Centre for Extreme and Quantum Photonics for a further 5 years, until 2025. The centre provides a mechanism for researchers in 3 locations (MPL, MPQ in Garching and uOttawa) to strengthen their ties through workshops, exchanges and joint research projects. mpl.mpg.de/news-events/news-from-the-institute/news-detail/article/News/detail/another-five-years-of-german-canadian-cooperation/

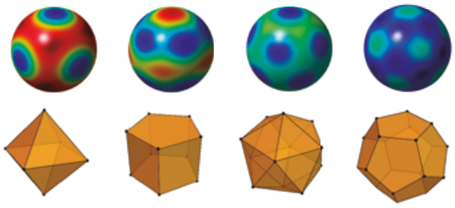
Welcome to new members

Lothar Kuhn joined MPL in July 2020, as Head of Communication and Marketing. Previously he worked as chief editor of the German edition of *New Scientist*, head of the science and technology news desk of *WirtschaftsWoche* and as deputy editor of *Edison*. He brings a wealth of experience to MPL in modern communication tools and social media. **Leonhard Möckl**, previously at Stanford University, arrived in November 2020 and is setting up an independent research group that will work at the intersection between optics, biochemistry, and medicine. He plans to deepen knowledge of fundamental cell biology and to translate the findings into therapeutic applications. In the autumn **Jule Murr** and **Tabita Ghete** joined the Zieske Research Group as laboratory engineers, and we also welcomed apprentice **Leonie Somann** as a member of the Front Office and Purchasing team.

RESEARCH ARTICLE GL Leuchs Emeritus Group

Extremal quantum states

The boundary between the classical and quantum realms has always been of great interest. A natural question arises: how quantum is a state? What makes one state more quantum than another? Is there a trait to which one can point and say "this embodies quantumness''? Rather than proposing a scale whose values would be associated with the degree of quantumness, we have looked at extremal properties. To this end, we examine quantities that are linked to intrinsic properties of any quantum state, such as Wehrl entropy or metrological power. We use these quantities to formulate extremal principles and determine in this way which states are the most and least "quantum". Moreover, the state of a quantum system can often be represented mathematically by points on a sphere. This type of representation is called a Majorana constellation. For coherent states, the constellation is simply a single point. Since these are the least quantum of states, the most quantum ones would have constellations that cover more of the sphere. The properties of these constellations have been thoroughly examined.



Majorana constellations of some of the most quantum states in various dimensions.

Contact: gerd.leuchs@mpl.mpg.de **Group:** Leuchs Emeritus Group
Reference: A. Z. Goldberg, A. B. Klimov, M. Grassl, G. Leuchs, and L. L. Sánchez-Soto, **AVS** Quantum Science **2**, 044701 (2020); doi.org/10.1116/5.0025819 (featured);
highlighted in, e.g.: phys.org/news/2020-11-quantifying-quantumness-mathematical-immense-beauty.html and www.space.com/quantifying-quantumness

Awards, appointments, honours

Congratulations to **Daqing Wang** on receiving both a 2019 Chinese Government Award for Outstanding Self-financed Students Abroad[1] and a 2020 German Physical Society (DPG) award[2] for his PhD dissertation Coherent *Coupling of a Single Molecule to a Fabry-Perot Microcavity*, and to **Michael Becker**, who received the 2020 Swiss Physical Society Award for Applied Physics[3] for his work on *Exciton dynamics and light-matter interaction of colloidal semiconductor nanocrystals*. Wang and Becker are both members of the Sandoghdar Division. **Meng Pang**, former team leader in the Russell Division, is recipient of an award within the highly competitive "1000 Talents Plan for Young Scientists" of the Chinese government. He is currently setting up a laboratory at the Shanghai Institute of Optics and Fine Mechanics. At a ceremony in October 2020, MPL Group Leader **Silvia Viola Kusminskiy** received the FAU's 2020 Teaching Award for Young Scientists (Natural Sciences). The award was presented by the President of FAU, Prof. Dr. Joachim Hornegger. **Maria Chekhova**, who heads an independent research group at MPL with interests in experimental quantum optics and sources of nonclassical light, has been appointed associate professor at FAU. She joins the Chair of Experimental Physics (Optics) in the Department of Physics. Congratulations also to **Xin Jiang, Nicolas Joly,** and **Birgit Stiller**, who in 2020 were elected Senior Members of The Optical Society (OSA).

Left: Joachim Hornegger and Silvia Viola Kusminskiy (photo credit: FAU/Iannicelli)
Right: Maria Chekhova.

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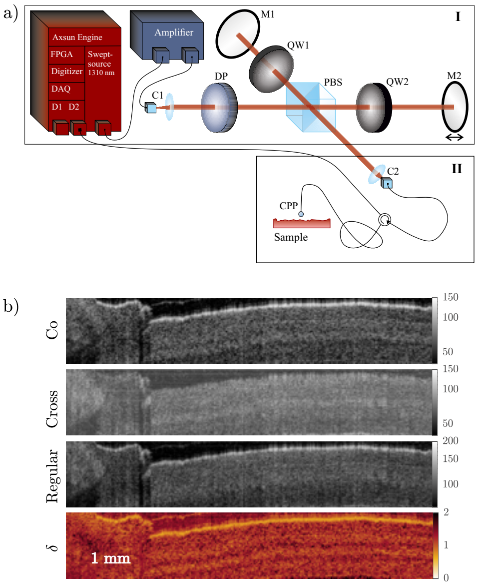
RESEARCH ARTICLE KS Singh Research Group



Novel input-polarisation-independent endoscopic cross-polarised OCT

Inspired by the need for robust systems for non-invasive optical biopsies in clinical settings, where the imaging systems need to be precise, insensitive to environmental changes, and convenient to operate, we recently reported the use of cross-polarised optical coherence tomography (OCT). The system works independently of the polarisation of the input illumination by introducing a depolariser into the illumination path (figure (a)). Despite its simplicity, the system performance is comparable to previously reported approaches, offering a sensitivity of 103 dB and a lateral resolution of 30 µm. The comparison of the fluctuations in illumination power with and without depolariser suggest that the depolariser introduces sufficient stability for the imaging under clinical conditions. The image of the nailbed of a human volunteer is shown in figure (b), illustrating the technique's ability to reveal the birefringence properties of tissue. The system can measure the birefringence of tissue independently of the source polarisation state, making it ideal for clinical imaging.

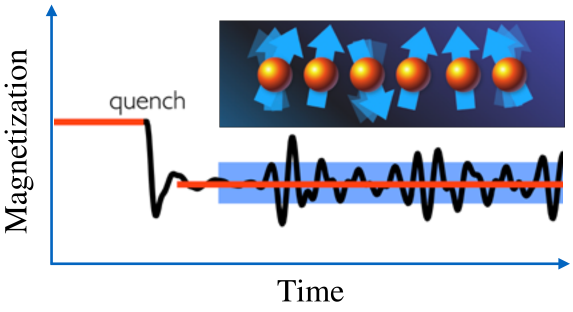
a) Endoscopy setup: I. OCT module; II. Endoscopy module with common-path probe (CPP).
b) Scan of the nailbed of a volunteer using the endoscopic system. Co-signal (co), cross-signal (cross), overall reflectivity (regular) and depolarisation ratio (δ).

Contact: kanwarpal.singh@mpl.mpg.de
Group: Singh Research Group
Reference: K. Blessing, J. Schirmer, G. Sharma, and K. Singh, J. Biophotonics **13**, e202000134 (2020);
doi.org/10.1002/jbio.202000134

RESEARCH ARTICLE FM Marquardt Division

Many-body dephasing in a trapped-ion quantum simulator

A fundamental question in thermodynamic and statistical physics is how a closed interacting quantum many-body system relaxes and dephases as a function of time. It is believed that a generic non-integrable quantum many-body system totally loses its initial memory after some decoherence time. In the thermodynamic limit, any observable relaxes to a constant described by standard statistical physics. However, it was realized that for a system of finite size, the observable never approaches a constant, but fluctuates persistently around its steady-state value. Our group had previously taken a significant step in this domain by identifying a generic physical mechanism ("many-body dephasing") and exploiting it to make analytical predictions for non-integrable models, which is notoriously challenging. In collaboration with the experimental group of Chris Monroe at the University of Maryland, this physics has now been demonstrated in a trapped-ion quantum simulator. Understanding the experiment required a significantly improved analysis, taking into account long-range forces and novel physical regimes. The experimental results are in good agreement with the predictions.



Schematic behaviour of the magnetization of a spin chain model after a quench.
The interaction between spins is initially turned off and abruptly turned on at a later time.
The magnetization displays persistent temporal fluctuations, even in the long-time limit.

Contact: lingzhen.guo@mpl.mpg.de
Group: Marquardt Division
Reference: H. B. Kaplan, L. Guo, W. L.Tan, A. De, F. Marquardt, G. Pagano, and C. Monroe, Phys. Rev. Lett. **125**, 120605 (2020);
doi.org/10.1103/PhysRevLett.125.120605

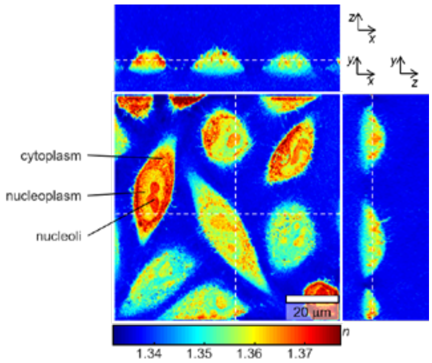
News about MPL staff

Tobias Utikal is the newly elected ombudsperson and **Shada Abu Hattum** has been appointed gender equality officer.

RESEARCH ARTICLE JG Guck Division

The cell nucleus is less dense than surrounding cytoplasm

The cell nucleus is a compartment within which essential processes such as gene transcription and DNA replication take place. It has been perceived as being much denser than cytoplasm, as it contains 2 meters of DNA, histones, and other proteins tightly packed into its membrane-bound micron-sized interior. So we were very surprised when measurements using optical diffraction tomography (ODT), an optical analogue of x-ray computed tomography, revealed the opposite. ODT measures the 3D refractive index distribution of specimens, which is linearly proportional to the mass density of most biomolecules such as proteins and nucleic acids. The results reveal that nucleoplasm is less dense than cytoplasm, while nucleoli—phase-separated membraneless compartments inside nuclei—exhibit significantly higher mass density. This did not change during progression through the cell cycle, even when we tried really hard to change it by drug-induced perturbation of the cytoskeleton and chromatin compaction. This robustness suggests that these density differences might be functionally relevant, and that they may be controlled by some as yet unknown mechanism that maintains them in both membrane-bound and membraneless compartments.



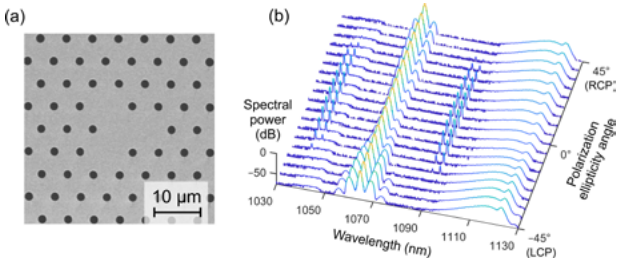
Cross-sectional slices of the 3D refractive index distribution of HeLa cells show that nucleoplasm has lower refractive index and mass density than the surrounding cytoplasm.

Contact: kyoohyun.kim@mpl.mpg.de
Group: Guck Division
Reference: K. Kim and J. Guck, Biophys. J. **119**, 1946–1957 (2020); doi.org/10.1016/j.bpj.2020.08.044

RESEARCH ARTICLE PR Russell Division

Cross-phase modulational instability of optical vortices in chiral three-core fibre

Modulational instability is a nonlinear phenomenon that occurs in many physical systems as a consequence of the interplay between dispersion and nonlinearity. In the context of fibre optics, it causes temporal break-up of an intense monochromatic pump wave, resulting in the appearance of a pair of spectral sidebands. A challenge in the field of multimode nonlinear fibre optics is the design of an optical fibre that supports vortex modes while offering widely engineerable group velocity dispersion. We report the first observation of cross-phase modulational instability of circularly polarized vortex modes in a chiral photonic crystal fibre with a three-fold symmetric core, formed by spinning the fibre preform during the draw. Under these circumstances, when the fibre is pumped by a superposition of left- and right-circularly polarized vortex modes, a pair of orthogonal circularly polarized sidebands of opposite topological charge is generated. When, on the other hand, a single circularly polarized mode is launched, the MI gain is zero and no sidebands are seen. These novel results are of great interest for fibre-based optical parametric amplification of vortex modes.



(a) Scanning electron micrograph of the chiral three-core PCF. (b) Cross-phase modulational instability spectra as a function of pump (1064 nm) polarization state at average power 10 mW. Stokes and anti-Stokes bands appear at 1091.8 and 1038.8 nm.

Contact: paul.roth@mpl.mpg.de
Group: Russell Division
Reference: P. Roth, M. H. Frosz, L. Weise, P. St.J. Russell, and G. K. L. Wong, Opt. Lett. **46**, 174-177 (2021); doi.org/10.1364/OL.413557
Editor's Pick: www.Osapublishing.org/OL/abstract.cfm?uri=OL-46-2-174

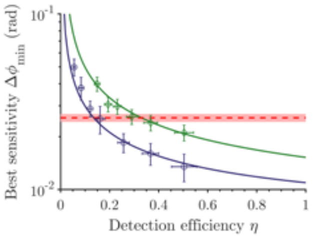
New Director at MPZPM

On August 1, **Kristian Franze** became one of the directors at the Max-Planck-Zentrum für Physik und Medizin (MPZPM), at the same time joining the Institute for Medical Physics and Microtissue Engineering at FAU. Franze's ground-breaking work concerns the interaction of mechanics with the nervous system. He came to us from the University of Cambridge in the UK, having previously studied veterinary medicine at the University of Leipzig, where he also received a PhD in physics.

RESEARCH ARTICLE MC Chekhova Research Group

Amplification protects fragile squeezed states of light from loss

Squeezing is a powerful resource in quantum optics, providing enhancements in sensing techniques such as interferometry, spectroscopy, magnetometry. Squeezed light is used to overcome the shot-noise limit, which is caused by the granularity of light and limits the precision of all classical optical measurements. The downsides of squeezing-based techniques are their susceptibility to loss and, especially, the lack of efficient detectors—sub-shot-noise measurements require detection efficiencies greater than 50%. A recent experiment with a squeezing-enhanced interferometer remedies these problems by introducing strong parametric amplification before detection. Amplifying the output photon number 600 times enabled phase measurements to be made at 6 dB below the shot-noise limit at detector efficiencies as low as 50%. Amplification also permitted sub-shot-noise operation even when the system losses were as high as 87%. The method will also help protect fragile squeezed states used in other types of quantum sensing.



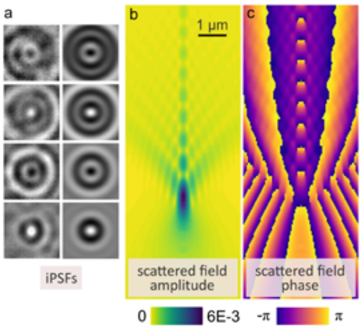
Phase sensitivity achieved with 220-fold (green) and 600-fold (blue) photon-number amplification, plotted versus the detection efficiency. The red dashed line shows the shot-noise limit.

Contact: maria.chekhova@mpl.mpg.de **Group:** Chekhova Research Group
Reference: G. Frascella, S. Agne, F. Ya. Khalili, and M. V. Chekhova,
in *Conference on Lasers and Electro-Optics*, OSA Technical Digest, postdeadline paper JTh4B.6 (2020);
doi.org/10.1364/CLEO_AT.2020.JTh4B.6

RESEARCH ARTICLE VS Sandoghdar Divison

Point spread function in interferometric scattering microscopy (iSCAT)

Interferometric scattering (iSCAT) microscopy is a powerful fluorescence-free technique, invented in our group, for sensitive detection of nano-matter such as individual viruses, proteins, nanoparticles and single molecules. In previous iSCAT studies the point-spread function (iPSF) was mostly approximated by a simple 2D Gaussian intensity function. We have now developed a quantitative description of the iPSF using a vectorial diffraction model to investigate the iPSF in tandem with rigorous FDTD simulations and experimental measurements [1]. We show that slight aberrations caused by the microscope cover-slide helps break the interferometric axial symmetry, thus allowing one to encode the 3D positional information of a nanoparticle [2]. We examine the iPSF under various imaging scenarios in a wide-field reflection iSCAT mode and put together a calibration-free unsupervised machine-learning algorithm, which extracts the height of a nanoparticle and validates the results against the rigorous physical model.



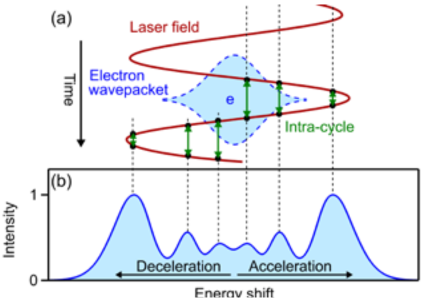
(a) Examples of experimental and modelled iPSF pairs.
(b, c) Scattered field and phase of a nanoparticle placed ~3 µm above the substrate.

Contact: reza.gholami@mpl.mpg.de **Group:** Sandoghdar Divison
Reference: R. Gholami Mahmoodabadi, R. W. Taylor, M. Kaller, S. Spindler,
M. Mazaheri, K. Kasaian, and V. Sandoghdar, Opt. Exp. **28**, 25969-25988 (2020);
doi.org/10.1364/OE.401374

RESEARCH ARTICLE PH Hommelhoff Max Planck Fellow Group (FAU)

Intracycle interference in electron-light interaction

In quantum mechanics textbooks, the wave nature of electrons is illustrated by the double-slit experiment. Interference of electron waves can be realized not only in the position-momentum domain but also in the time-energy domain. Recently we demonstrated theoretically that attosecond-scale interference occurs when an electron beam interacts with an optical field. The optical field accelerates or decelerates the electrons periodically, following its sinusoidal oscillation in time. When we focus on half an optical cycle, we find that there are pairs of timings separated by hundreds of attoseconds that yield the same amount of acceleration or deceleration, inducing interference in the energy domain. We proposed a scheme using a single-cycle optical field to experimentally observe this intracycle effect, free from other potential effects. Combined with a tailored optical field, intracycle interference can be used to coherently manipulate pulsed electron beams in electron microscopes or accelerators at time-scales shorter than half an optical cycle.

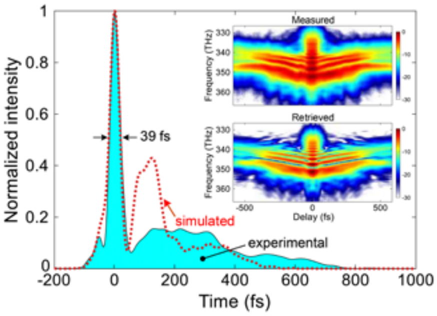


Concept of intracycle interference. (a) An electron wavepacket (blue) is periodically accelerated or decelerated by the optical laser field (red). Interference occurring within half an optical cycle (green arrows) leads to the modulation of the electron energy spectrum seen in (b).

Contact: peter.hommelhoff@fau.de
Group: Hommelhoff Max Planck Fellow Group (FAU)
Reference: Y. Morimoto and P. Hommelhoff, Phys. Rev. Research. **2**, 043089 (2020);
doi.org/10.1103/PhysRevResearch.2.043089

RESEARCH ARTICLE PR Russell Division

Raman conversion and pulse compression in H_2-filled hollow-core fibre



There is currently a lack of efficient lasers capable of delivering ultrashort pulses in the mid-infrared (MIR), limiting optimization of time-resolved spectroscopies in the molecular fingerprinting region and restricting the shortest wavelength achievable in high-harmonic generation. Although MIR fibre lasers based on rare-earth-doped glasses are a very active area of research, potentially offering robustness, compact dimensions, and high repetition rates, they are currently not yet as mature as their near-infrared counterparts, and are unable to deliver pulses shorter than ~100 fs. In recent work we report the generation of 39 fs pulses at 1.8 µm and few-100 kHz repetition rates with quantum efficiencies of 50% and without need for pulse post-compression, pumping with a commercial fibre laser at 1.03 µm. This is achieved by pressure-tuning the group velocity dispersion and avoiding Raman gain suppression by adjusting the chirp and modal content of the pump pulses. The approach is power-scalable, permits adjustment of the temporal pulse shape, and can potentially allow access to much longer wavelengths where current alternatives are fairly inefficient.

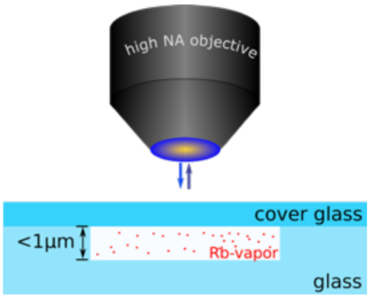
Experimental and simulated pulse shapes generated at 1.8 µm by stimulated Raman scattering in hydrogen-filled PCF, exhibiting a nearly transform-limited 39 fs-long temporal feature. The insets show the associated SHG-FROG traces.

Contact: david.novoa@mpl.mpg.de
Group: Russell Division
Reference: S. Loranger, P. St.J. Russell, and D. Novoa, J. Opt. Soc. Am. B **37**, 3550 (2020);
doi.org/10.1364/JOSAB.402179 (Highlighted in OSA's *Spotlight on Optics*)

RESEARCH ARTICLE VS Sandoghdar Division

Nanostructured alkali-metal vapour cells

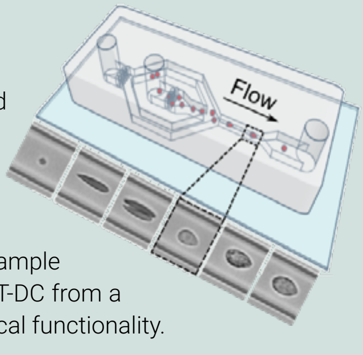
Interrogating atoms in the gas phase sets the current limits of temporal precision in atomic clocks and enables a plethora of laser spectroscopy and quantum optics experiments. In particular, alkali atoms such as rubidium have well understood electronic transitions which can be controlled and manipulated by external fields. Currently, most devices and experiments employ macroscopic vapour cells and use ensembles of atoms or bulky optical traps to maintain a small number of atoms at well-defined locations. In collaboration with the group of Charles Adams at Durham University, UK, we have miniaturized Rb-vapour cells using physically bonded glass surfaces. The design enables detection at high numerical apertures and also incorporates an integrated thin-film heating system. Using two-photon excitation, we interrogate atoms confined within a nanoscopic channel and observe atomic resonance linewidths that are more than an order of magnitude narrower than the Doppler width. Furthermore, we reveal a position-dependent vapour density within nano-channels, setting the ground for a scalable route towards room-temperature devices with single atoms within an interaction volume.



The rubidium-atom-vapour in the nanochannels can be imaged using total internal reflection fluorescence microscopy scheme or confocally.

Contact: vahid.sandoghdar@mpl.mpg.de **Group:** Sandoghdar Divisionn
Reference: T. F. Cutler, W. J. Hamlyn, J. Renger, K. A. Whittaker, D. Pizzey, I. G. Hughes, V. Sandoghdar, and C. S. Adams, Phys. Rev. Applied **14**, 034054 (2020);
doi.org/10.1103/PhysRevApplied.14.034054

Real-time deformability cytometry

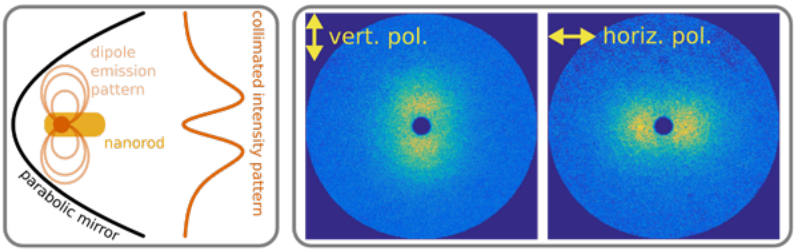


The Guck division and the Fraunhofer Institute for Manufacturing Engineering and Automation have been awarded 1.6 million Euros by the Fraunhofer Society and the Max Planck Society. The 'AutoRAPID' project is based on real-time deformability cytometry (RT-DC) developed by the Guck division. RT-DC is an image-based method for characterizing cell physical properties by flowing them through a microfluidic chip. The cells are deformed by hydrodynamic forces originating from the flow profile of a combined sheath and sample flow in a constriction channel region (see Figure). The aim of the project is to advance RT-DC from a research tool to an automated high-throughput screening platform with enhanced analytical functionality.

RESEARCH ARTICLE GL Leuchs Emeritus Group

Dipoles brought into line

A deep parabolic mirror is a viable tool both for focusing light onto an atom-like system with high coupling efficiency and for collecting photons emitted by the atom. As for any focusing device of finite size, the efficiency of both processes is optimal for a certain orientation of the atomic dipole. In the case of a deep parabolic mirror, optimum coupling is achieved for a linear dipole that is oriented along the optical axis of the mirror. A multi-group collaboration has demonstrated this important prerequisite with dot-in-rod nano-crystals – a type of solid state single-photon source. Ensembles of such nanorods have been trapped in the focus of a parabolic mirror using optical tweezers. The nanorods were aligned along the mirror axis by the longitudinal electric field of the optical trapping potential. Thanks to the high collection efficiency of the paraboloid, the 3D intensity pattern of the emitted photons could be projected onto a camera, verifying the alignment of the nanoscale dipoles.

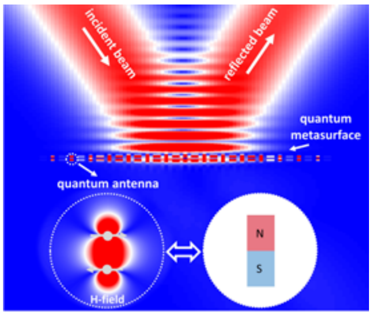


Left: Pictorial view of a nanorod aligned in a parabolic mirror. Right: Polarization-resolved images of the fluorescence photons after collimation.

Contact: markus.sondermann@mpl.mpg.de
Group: Leuchs Emeritus Group
Reference: V. Salakhutdinov, M. Sondermann, L. Carbone, E. Giacobino, A. Bramati, and G. Leuchs, Phys. Rev. Lett. **124**, 013607 (2020); doi.org/10.1103/PhysRevLett.124.013607

RESEARCH ARTICLE VS Sandoghdar Divison

Quantum metasurfaces



Schematics of a quantum magnetic metasurface composed of atomic dimers.

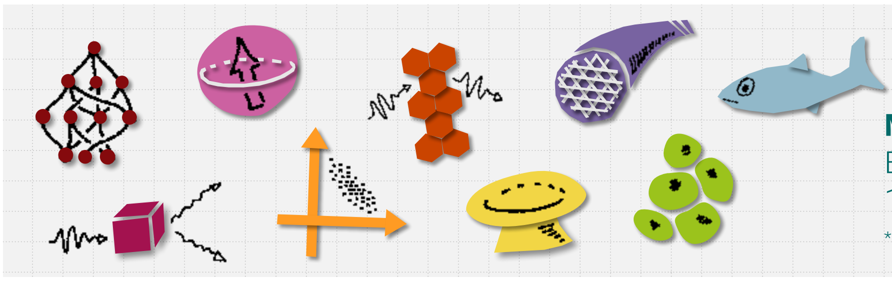
Natural atoms constitute the smallest and most fundamental optical antennas but they interact weakly with the magnetic field of light; this interaction is typically about two orders of magnitude smaller than its electric counterpart. To enhance the magnetic effects of light, we have proposed man-made quantum antennas and metamaterials based on the subwavelength arrangement of conventional quantum emitters with only electric dipole transitions. In particular, such a quantum antenna can enhance the decay rate of a magnetic transition in a close-by impurity by several orders of magnitude. Moreover, we show that a metasurface composed of a periodic arrangement of quantum antennas can strongly interact with both the electric and magnetic fields of light, thus forming electric or magnetic quantum mirrors. These quantum metamaterials can be experimentally realized using existing state-of-the-art technologies in cold atom manipulation or implantation strategies.

Contact: vahid.sandoghdar@mpl.mpg.de
Group: Sandoghdar Division
Reference: R. Alaee, B. Gurlek, M. Albooyeh, D. Martín-Cano, and V. Sandoghdar, Phys. Rev. Lett. **125**, 063601 (2020); doi.org/10.1103/PhysRevLett.125.063601

IMPRS-PL Annual Meeting

The Annual Meeting of the International Max Planck Research School Physics of Light took place October 21-23. Some 30 students, supervisors and external speakers met in a virtual setting for three days of learning, exchanging ideas and socializing. Students presented their work during talks and attended block lectures tailored to their needs. Of particular interest were invited talks by Prof. Sergio Leon-Saval (University of Sydney), Prof. David Miller (Stanford University) and Prof. Philipp Slusallek (Saarland University). An undisputed highlight was the round of discussions organized by the student spokesperson Mallika Suresh, during which students seized the opportunity to ask questions, on a variety of topics, of the invited panelists, who moved through different break-out groups, creating a very personal and engaging atmosphere. On the last day, IMPRS-PL alumnus Federico Belli (postdoctoral scientist at Heriot-Watt University in Scotland) presented insights into his work after leaving MPL, and Jasmin Graf was elected IMPRS student spokesperson for 2021.

Picture created by students during online social activities.



MAX PLANCK INSTITUTE
FOR THE SCIENCE OF LIGHT

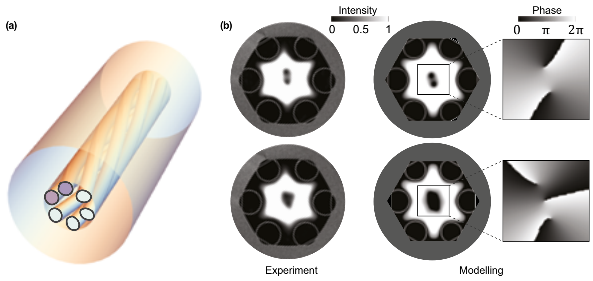
MPL Science Chat
Every 2nd Thursday*
15:00 via Zoom

*excepting dates with Distinguished Lectures

RESEARCH ARTICLE PR Russell Division

Excitation and Raman conversion of vortex modes in chiral gas-filled fibre

The characteristic ring-shaped intensity patterns and helical wavefronts of optical vortices (see figure (a)) make them useful in many applications. Here we report the excitation and efficient frequency conversion of vortex modes with one, two and three on-axis phase singularities in a chiral hydrogen-filled single-ring photonic crystal fibre (SR-PCF). Robust transmission of pure optical vortices is very difficult to achieve in an untwisted SR-PCF due unavoidable azimuthal imperfections in the fibre. In a helically twisted SR-PCF, however, the degeneracy between left- and right-handed versions of the same vortex mode is lifted, with the result that they are topologically protected against perturbations. A high damage threshold, along with launch efficiencies >75%, make these fibres ideal for nonlinear processes that require the polarization state and azimuthal order to be preserved over long distances. Vortex coherence waves of synchronized molecular motion carrying angular momentum are excited in the gas, permitting the angular momentum of the Raman bands to be tailored, even in spectral regions where conventional solid-core waveguides are opaque or prone to optical damage.



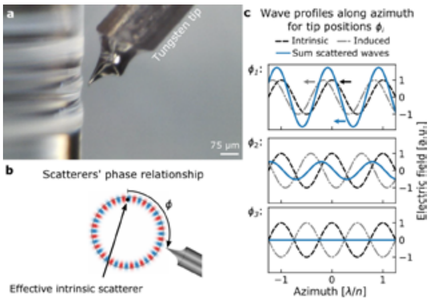
(a) Sketch of a chiral SR-PCF. (b) Intensity and phase distributions of vortex modes with two (upper) and three (lower) phase singularities, which separate from each other spatially due to asymmetries in the fibre microstructure.

Contact: david.novoa@mpl.mpg.de **Group:** Russell Division
Reference: S. Davtyan, Y. Chen, M. H. Frosz, P. St.J. Russell, and D. Novoa, Opt. Lett. **45**, 1766 (2020);
doi.org/10.1364/OL.383760

RESEARCH ARTICLE PD Del'Haye Research Group

Coherent suppression of backscattering in optical microresonator

Optical whispering-gallery-mode microresonators are used in a wide variety of applications, spanning many areas of photonics from classical and quantum information processing to metrology and sensing. In these resonators, some level of intrinsic backscattering of light is always present due to sub-wavelength imperfections in the surface and bulk material, causing light circulating in the resonator to scatter from one optical mode into the counterpropagating mode. For some applications, backscattering has a negative impact on the performance. In this work a method is introduced that allows the intrinsic backscattering in microresonators to be suppressed by more than 30 dB. A sub-wavelength tungsten tip (Fig. 1a and 1b) is introduced into the evanescent field of the resonator, causing the appearance of an additional counter-propagating wave. By precisely adjusting the position of the tip, the phase and amplitude of the backscattered light can be fine-tuned so that it interferes destructively with the intrinsic backscattered light, resulting in strong suppression of the backscattered signal.



(a) Micrograph sideview of the 3-mm-diameter whispering-gallery-mode rod resonator and chemically etched tungsten tip. (b) Phase relationship between the effective scatterer and the tip nanoscatterer (not to scale). (c) Illustrative standing wave profiles over a few cycles along the azimuth, showing that for an appropriate tip position Φ the total wave can be made to vanish (lowest panel).

Contact: pascal.delhaye@mpl.mpg.de **Group:** Del'Haye Research Group
Reference: : A. Ø. Svela, J. M. Silver, L. Del Bino, S. Zhang, M. T. M. Woodley, M. R. Vanner, and P. Del'Haye, Light Sci. Appl. 9, 204 (2020);
doi.org/10.1038/s41377-020-00440-2

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