MPL
Max Planck Institute
for the science of light

MPL News

MAX PLANCK INSTITUTE
FOR THE SCIENCE OF LIGHT
NEWSLETTER
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Symposium for the Science of Light 2018

A Symposium for the Science of Light took place 23rd to 26th July, in celebration of 150 years of optics in Erlangen, 15 years since the formation of the Max Planck Research Group at FAU and 1.5 years since MPL moved into its new building. After opening remarks by Gerd Leuchs, Frank Duzaar (Dean of the Faculty of Science at FAU) and Liz Rogan (Chief Executive Officer of the Optical Society), we were treated to 27 fascinating lectures on recent research by renowned speakers from all over the world. Overall the event was a great success, attracting some 300 attendees.

Directors' foreword

It has been an eventful 6 months since our last Newsletter, during which the institute has continued to flourish. We are very pleased to report that Jochen Guck, formerly based at TU Dresden, joined us on October 1st as MPL's 5th director. He will play a major role in the Max-Planck-Zentrum für Physik und Medizin (MPZ-PM), and will be accommodated in MPL's main building until the MPZ-PM building is ready, circa 2023. Two new Max Planck Research Groups have been approved, one on micro-endoscopy and related techniques, to be associated with MPZ-PM and currently being set up by Dr. Kanwarpal Singh (formerly at Harvard Medical School). The other will be headed by MPL alumna Dr. Birgit Stiller, who plans to rejoin us in April 2019.

MPL played a big part in Erlangen's hosting of the successful DPG Spring Meeting, organised locally by Prof. Peter Hommelhoff, who runs an MPL associated group at FAU. We are delighted to report that Peter has recently been awarded the status of Max Planck Fellow at MPL, which will bring him into even closer association with us.

In July we held a special Symposium for the Science of Light to celebrate three significant milestones in Erlangen optics, 150, 15 and 1.5 years ago. On September 14th MPL opened its doors to some 700 visitors from the general public, in celebration of the 70th anniversary of the founding of the Max Planck Society.

Further good news is that we now have a new head of administration, Dr. Dorothe Burggraf, who joined us in May from her previous position in Munich, and a new Public Relations manager, Patricia Staudacher-Sauer.

> **"The institute has continued to flourish.**

You can read more about some of these developments inside this Newsletter. We hope you enjoy it – and the new design!

Gerd Leuchs Philip Russell Vahid Sandoghdar Florian Marquardt

CONTENT

RESEARCH ARTICLE GL Leuchs Division

Free-space propagation of high-dimensional structured optical fields in an urban environment

A sketch of the 1.6 km free-space link over the city of Erlangen. The optical beam is transmitted over buildings, roads, and wooded areas.

Spatially structured optical fields have proven beneficial in a variety of systems, from sensing to information transfer. For future applications, a detailed understanding of the hurdles in real-world systems will become fundamentally important. For example, the propagation of light beams in free-space is an important challenge in many systems. Atmospheric fluctuations cause phase distortions, resulting in modal degradation. New channel models need to be established to predict the influence of such effects on higher-dimensional modes. In a collaborative project with the Universities of Glasgow and Ottawa, we examined the propagation of a set of Laguerre-Gaussian modes carrying orbital angular momentum (OAM) across a 1.6 km urban free-space link between two buildings above the city of Erlangen. We successfully sorted the different OAM modes and studied the intensity and phase distributions. We observed OAM cross-talk as well as a change of the measured average OAM for higher order modes, caused by vortex splitting before reaching the receiver. To overcome the challenges in a real free-space channel we conclude that these effects should be mitigated by adaptive optical techniques.

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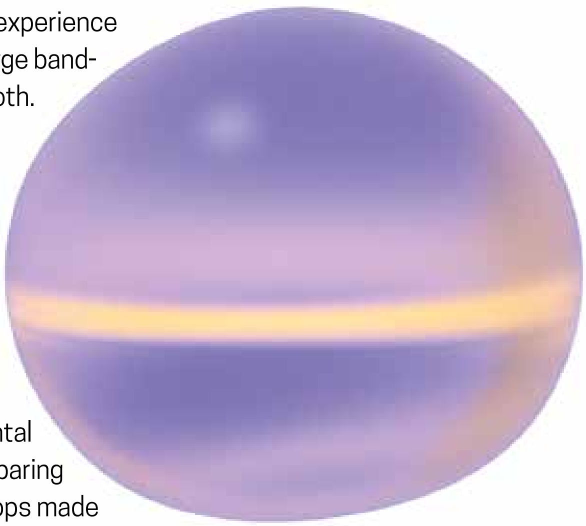
REFERENCE M. Lavery et al., Science Advances **3** (10), e1700552 (2017)
IMAGE SOURCE Google Earth

RESEARCH ARTICLE FM Marquardt Division

Light in a levitated helium drop

Imagine a single drop of liquid helium, levitated by a magnetic field. Light running around its equator will experience exceedingly small loss, since helium has a very large bandgap and the surface of the drop is clean and smooth. As a result, one would expect the drop to form a high quality optical cavity. At the same time, any surface deformations will shift the optical resonances, leading to a strong optomechanical coupling. In addition, and in contrast with other optomechanical systems, the rotational degrees of freedom couple as well. Recently, we have predicted these and other unconventional features of such drops, in collaboration with the experimental group of Jack Harris at Yale, who are currently preparing the experiment. In the future, one might study drops made of either superfluid helium-4 or normal fluid helium-3, manipulating and interrogating their dynamics via the light field.



A levitated helium drop may harbor light in a whispering gallery mode. The light will interact with the vibrations of the drop's surface.

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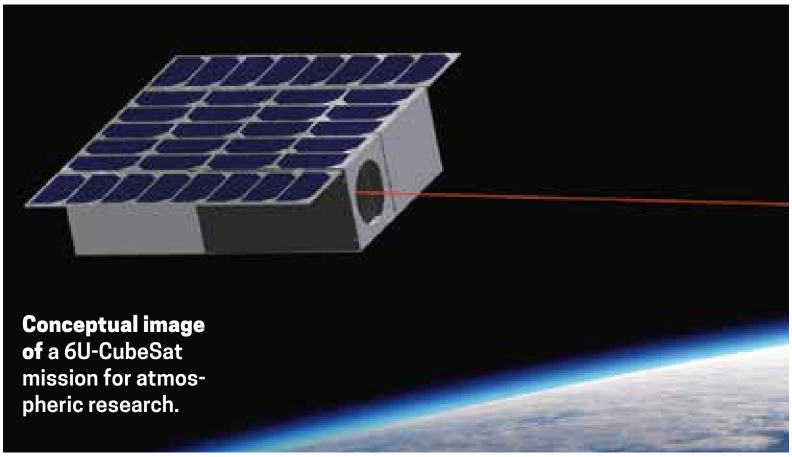
REFERENCE L. Childress et al., Phys. Rev. A **96,** 063842 (2017)

RESEARCH ARTICLE TDSU-2 TDSU-2 Optical Measurement Techniques

Spatial heterodyne interferometer for temperature measurements in the middle atmosphere



Conceptual image of a 6U-CubeSat mission for atmospheric research.

CONTACT klaus.mantel@mpl.mpg.de
REFERENCE M. Kaufmann et al., Atmos. Meas. Tech. **11,** 3861 (2018)

Understanding the atmosphere of the Earth, in particular the middle and higher regions, is important for improving climate projections. One of the least explored features of the middle atmosphere is gravity waves (i.e., buoyancy waves). Gravity waves couple different sections of the atmosphere, carrying momentum from the troposphere up to the mesosphere and even the thermosphere. A key quantity for characterising gravity waves is the atmospheric temperature. With the "**D**evelopment **I**nitiative for **S**mall **S**atellites **E**xploring **C**limate processes by **T**omography" (DISSECT), we aim to perform temperature measurements of the middle atmosphere by remote spectroscopy. The temperature is obtained by measuring the rotational structure of the emissions from the A-band of molecular oxygen at ~762 nm. As a measurement device, a spatial heterodyne interferometer, small enough to fit onto a nano-satellite (CubeSat), was chosen. By pointing the instrument's line of sight to the horizon, vertically resolved temperature profiles could be obtained. During the REXUS project 2017, the system passed its first successful flight test. An in-orbit verification mission on a Chinese technology demonstration satellite is scheduled for October 2018.

RESEARCH ARTICLE GL Leuchs Division

Quantum metrology at the limit with extremal Majorana constellations

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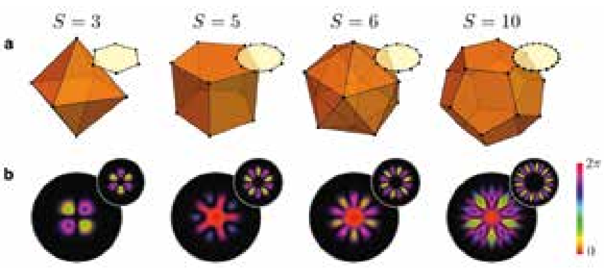
REFERENCE F. Bouchard et al., Optica **4,** 1429 (2017)

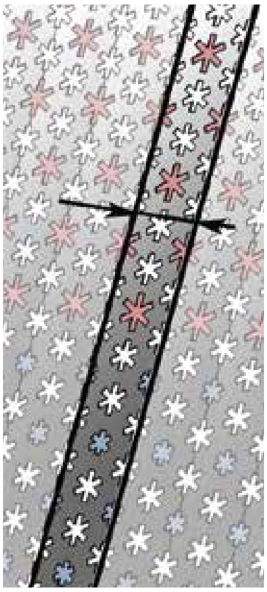
Quantum metrology allows remarkable improvements in the measurement accuracy of many physical parameters. An outstanding example is measurement of rotation, which plays a major role in applications such as gyroscopes, magnetometry, and polarimetry. When the rotation axis is known, NOON states are optimal for this task, achieving Heisenberg-limit scaling. We have recently found optimal states, which we dub the "Kings of Quantumness", for the case when the axis is unknown. In terms of the Majorana stellar representation, NOON states consist of equally spaced points along the equator of the Bloch sphere, whereas for the "Kings of Quantumness" the Majorana representation consists of points approximately uniformly distributed over the sphere. We have experimentally realized these states by generating up to 21-dimensional orbital angular momentum states of single photons, and confirmed their superior sensitivity for measuring a rotation about an arbitrary axis.



(a) Majorana constellations for the Kings of Quantumness (orange) and the NOON states (yellow) corresponding to spin S = 3, 5, 6 and 10. **(b) The Laguerre-Gauss** representation of the same states.

RESEARCH ARTICLE FM Marquardt Division

Snowflake topological insulator for phonons



A simple phononic crystal is a periodic piece of material where sound waves feel a bandstructure: waves inside certain frequency intervals cannot propagate (those inside the bandgap), making the material effectively insulating for sound at those frequencies. In our recent work, we have predicted a novel design that would allow to turn such a phononic crystal into a "topological insulator" for sound waves. Starting from a triangular lattice of snowflake-shaped holes, a straightforward checkerboard style modulation of hole sizes creates a bandgap that is topological in nature. What this means is that a sample with different domains of this modulation gives rise to unidirectional (so-called 'helical') edge states along the interface: one type of vibrations travels clockwise, the other counter-clockwise. Optomechanical tools can then be utilized to launch and read out the phononic excitations. This represents a very promising design for controlling sound transport at the nanoscale.

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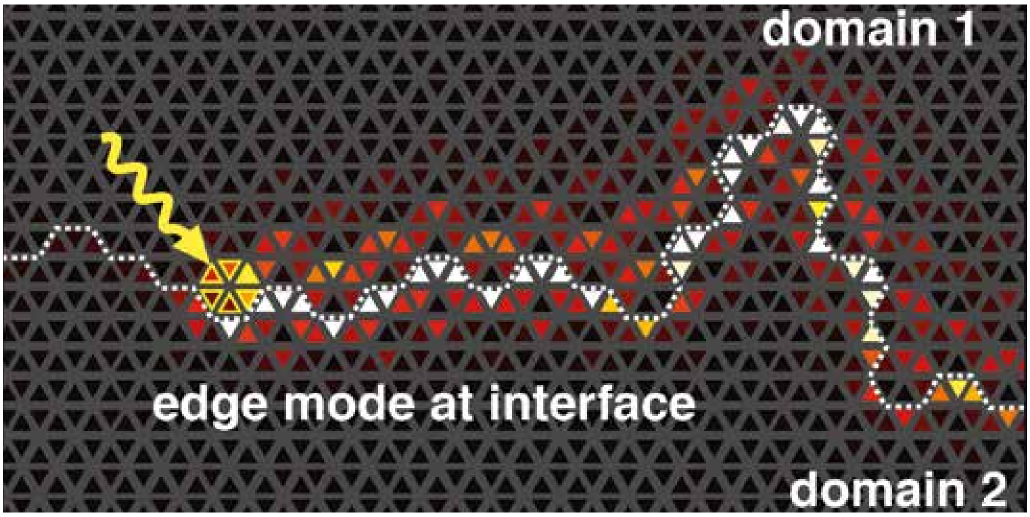
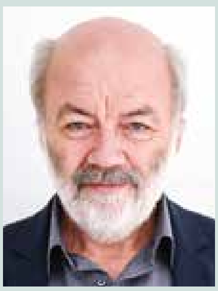
REFERENCE C. Brendel et al., Phys. Rev. B (Rapid Commun.) **97,** 020102 2018



A patterned 'phononic crystal' structure, with snowflake-shaped holes arranged in a lattice, can lead to topological transport of vibrations along edge mode channels. These channels arise at the interface between domains of different geometry.

Herbert-Walther Award 2018

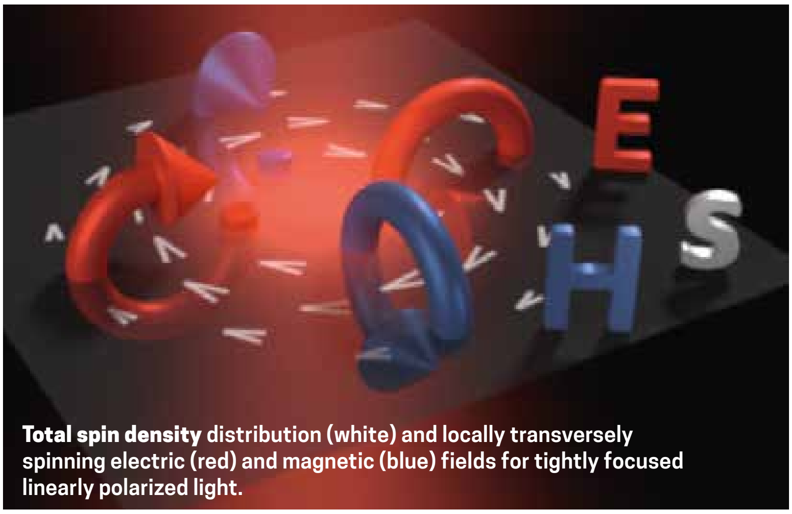
On March 7 2018, at a ceremony held during the Spring Meeting of the Deutsche Physikalische Gesellschaft (DPG), Gerd Leuchs received the 2018 Herbert Walther Award "for his pioneering and widespread scientific contributions ranging from ultrasmall focii of light to nonlinear optics, squeezed states of light and their



application in metrology and quantum information, as well as for a continuing commitment to the physics community, quantum optics and his students and team members". Sponsored jointly by the DPG and The Optical Society, the Walther Award was established in memory of Professor Herbert Walther, who played a pivotal role in the setting up of MPL.

RESEARCH ARTICLE GL Leuchs Division

Measuring the electric and magnetic transverse spin density of light



Total spin density distribution (white) and locally transversely spinning electric (red) and magnetic (blue) fields for tightly focused linearly polarized light.

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REFERENCE M. Neugebauer et al., Phys. Rev. X **8,** 021042 (2018)

Transverse spin describes electric and magnetic field vectors spinning around an axis perpendicular to the propagation direction of the light wave. Such three-dimensional polarization states occur naturally whenever light is strongly confined, typical examples being waveguide modes, surface plasmon polaritons and tightly focused light beams. Recently we have developed an experimental technique capable of sensing and distinguishing the electric and the magnetic components of transverse spin in tightly focused light beams. The approach relies on probing the local electric and magnetic spinning fields with a high-refractive-index nanosphere sitting on a glass substrate. The transverse spin of the excitation field induces spinning dipole moments inside the particle, which emits light in a directional manner. The evaluation of the characteristic emission patterns allows both the electric and the magnetic transverse spin density distributions to be reconstructed. For the case of tightly focused linearly polarized beams, the distributions of the electric and magnetic transverse spin densities have equal amplitudes, but are rotated with respect to each other by 90°. Radially and azimuthally polarized beams exhibit either purely electric or purely magnetic transverse spin, respectively.

RESEARCH ARTICLE MC Chekhova Research Group

Strong fluctuations enhance nonlinear effects

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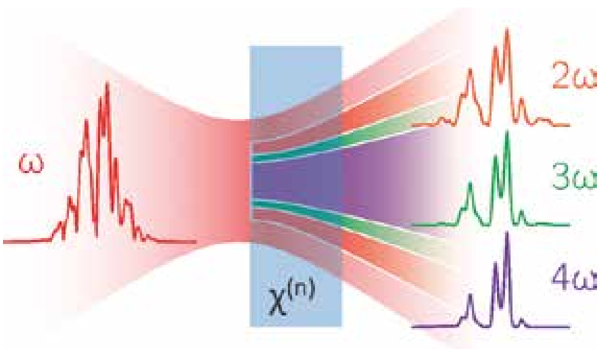
REFERENCE K. Yu. Spasibko et al., Phys. Rev. Lett. **119,** 223603 (2017).

Noise and fluctuations, although being a problem in most physics experiments, sometimes become a useful tool. Here we propose to use ultrafast photon-number fluctuations for enhancing nonlinear effects such as multiphoton absorption, ionization, polymerization, and generation of optical harmonics. We create 2nd, 3rd and 4th optical harmonics from picosecond pulses of broadband bright squeezed vacuum, obtained through high-gain parametric down-conversion. Compared to coherent pulses of the same duration, there is an efficiency enhancement of up to two orders of magnitude. The use of such fluctuating sources will be beneficial for multiphoton microscopy of fragile structures including biological objects: the sensitivity will increase dramatically without overcoming the damage threshold. It is worth noting that the generated harmonics, in their turn, are much 'noisier' than the incident radiation. Their pulse height distributions feature heavy tails typical of 'rogue waves' and suggest interesting applications in quantum optics.



'Noisy' light enhances both the efficiency of conversion to optical harmonics and their fluctuations.

RESEARCH ARTICLE PR Russell Division

Temperature sensing using a WGM-microlaser optically propelled inside a HC-PCF

Whispering-gallery-mode (WGM) resonators are versatile platforms for biological and physical sensing. Previous experiments have however been limited to stationary configurations which only allow single-point measurements. We have shown that a WGM microlaser, – a dye-doped polystyrene particle – can be trapped and optically propelled inside the core of a liquid-filled hollow-core photonic crystal fiber (HC-PCF). A 1064 nm CW-laser is used to trap and propel the particle, while its dopant is optically pumped by a pulsed excitation laser. Monitoring the spectral location of the lasing modes of the propelled microlaser allows the temperature profile along the fiber to be measured with mm spatial resolution. The demonstrated combination of particle propulsion in HC-PCF and WGM-based sensing opens up new perspectives for distributed sensing applications.

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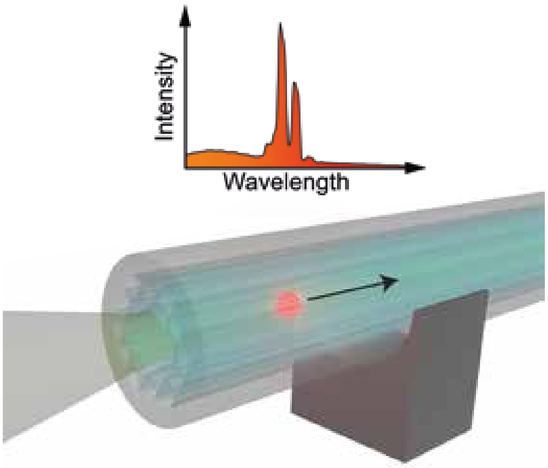
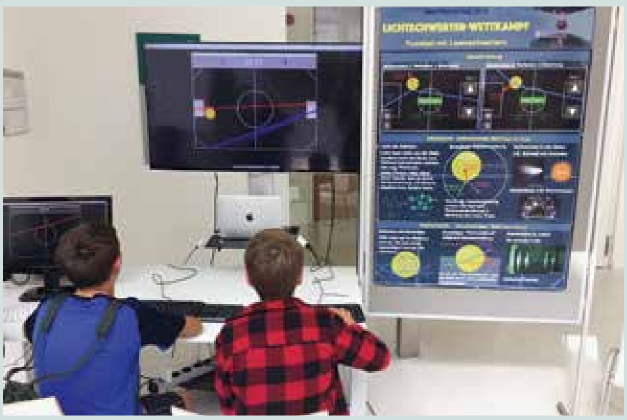
REFERENCE Zeltner et al.," Opt. Lett. **43,** 1479 (2018)



A lasing microparticle optically propelled within the core of a HC-PCF can be employed for distributed temperature sensing along the fibre.

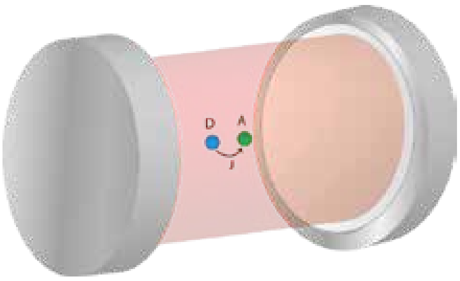
Laser swords on Max Planck Day

On September 14th MPL, along with all other Max Planck Institutes, opened its doors to the general public on "Max Planck Day". Some 700 visitors from Erlangen and the surrounding area came to the event, curious to find out about our research – and not least to inspect the new MPL building! By all accounts they greatly enjoyed their visit. More than 40 MPL scientists took part, offering laboratory tours and giving lectures on recent research to a packed auditorium. In addition, several live interactive demonstration such as a "laser sword football competition" and a "laser telephone" illustrated to young and old the fascinating science and technology of light.



RESEARCH ARTICLE CG Genes Research Group

Modification of resonance energy transfer by exploiting collective states



Donor-acceptor system embedded in an optical cavity.

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REFERENCE M. Reitz et al., Sci. Rep. **8,** 9050 (2018)

Förster resonant energy transfer between light-sensitive molecules (donor and acceptor) is a well-known near-field effect that plays a key role in, e.g., photosynthesis and organic solar cells. The main mechanism is an exchange of virtual photons provided by the electromagnetic vacuum. Standard treatments often overlook the inherent presence of collective decay processes, leading to superradiance and subradiance effects, that occur between donor and acceptor. We have recently shown that such effects can play an important role in enhancing the traditional scaling of the energy transfer mechanism for short distances (< 10 nm). Such dynamics can also be mimicked in confined electromagnetic environments such as optical cavities. The increased photon density of states combined with the delocalized character of photon and photon-matter hybrid states (polaritons) can lead to enhanced energy transfer rates that might also show a separation-independent scaling. This research is in line with current experimental and theoretical efforts aimed at designing novel materials with properties strongly modified by their strong coupling to the vacuum.

RESEARCH ARTICLE PR Russell Division

Gas-tunable third harmonic generation in tapered optical fibre

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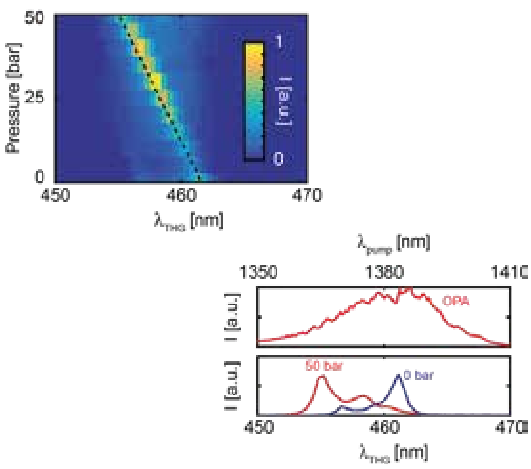
REFERENCE J. Hammer et al., Opt. Lett. **43,** 2320 (2018)

Micrometer-scale tapered fibres present an interesting platform for nonlinear optics, since tight light confinement can provide a very high effective nonlinearity, permitting the observation of nonlinear effects at moderate pump pulse energies. In such waveguides, the dispersion landscape and consequently the phase-matching condition can be adjusted by varying the diameter of the silica strand in the waist, allowing a specific nonlinear process to be targetted. In recent work we used tapered fibres for third harmonic generation, the goal being to reverse the process and generate triplet photon states. However, the strict phase-matching conditions impose fabrication tolerances that are not experimentally attainable. To circumvent this constraint we embedded the taper in a pressure-controllable gas, thus successfully demonstrating pressure-tuning of phase-matched intermodal THG in a sub-micron-diameter taper. By increasing the pressure of the surrounding argon gas up to 50 bar, the third-harmonic of 1.38 µm pump light could be tuned over 15 nm. This novel approach dramatically relaxes the stringent fabrication tolerances and may be applicable for other nonlinear processes in tapers.



Measured THG spectrum (upper) as a function of argon pressure for a taper diameter 679 nm. Lower: Pump and THG spectra for 0 bar and 50 bar (linear scale).

RESEARCH ARTICLE FM Marquardt Division

Linearized quantum theory around limit cycles

The theory of small (linearized) quantum fluctuations around classical steady states is a cornerstone in the analysis of nonlinear quantum-optical systems. Its simplicity, together with its accuracy for common experimentally accessible parameters, has turned it into the method of choice in most work on the subject. However, the technique has strong practical and conceptual complications when one tries to apply it to situations in which the classical long-term solution is time-dependent, a prominent example being spontaneous limit-cycle motion leading to periodic motion in phase space, as shown in the grey closed curve of the figures. We have succeeded in developing a linearization technique adapted for treating such situations. The method retains the simplicity and linear scaling with the size (the number of modes in the system) characteristic of standard linearization, making it applicable to large (many-body) systems. It provides a quantum steady state (represented in the left panel by its phase-space probability distribution) formed as a mixture of Gaussian states at each point of the classical trajectory (right panel).

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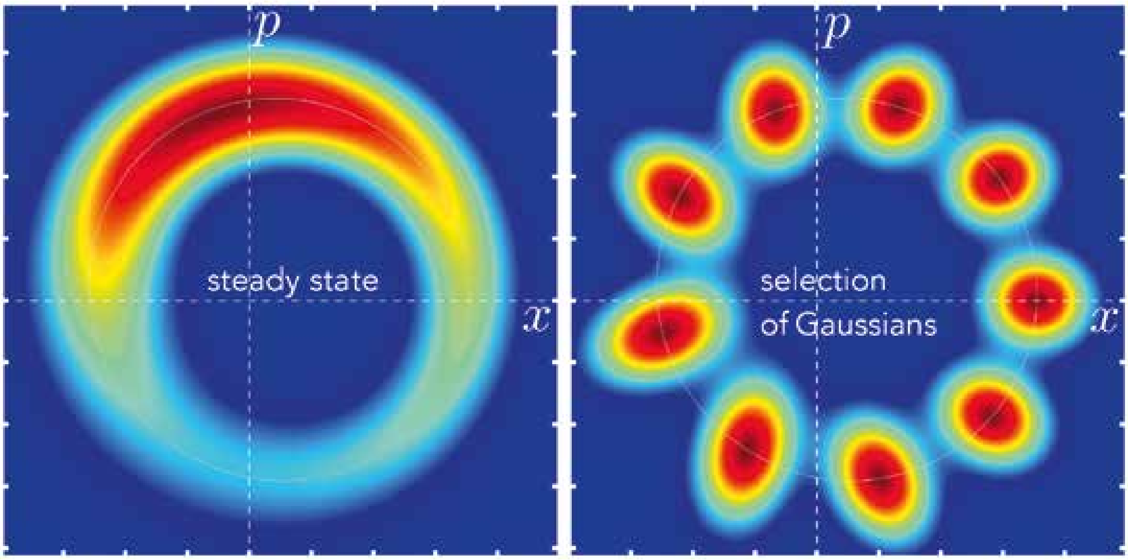
REFERENCE C. Navarrete-Benlloch et al., Phys. Rev. Lett.**119,** 133601 (2017)



The phase-space probability distribution around a limit cycle (left panel) can be formed as a mixture of Gaussian states along the classical trajectory (right panel).

Awards and prizes

At the Advanced Photonics Congress in Zurich in July 2018, Richard Zeltner (Russell Division) received the award for the best student paper in the category "Optical Sensors and Specialty Optical Fibres" for his paper "Whispering-gallery-mode temperature sensing with flying dye-doped particle in hollow-core PCF". At the 22nd Microoptics Conference, held at the University of Tokyo in December 2017, Philip Russell received an MOC Award of the Japanese Society of Applied Physics, and in May 2018 he was honoured with the Professor Maksymilian Pluta Award by the Photonics Society of Poland, which was celebrating its 10th anniversary.

Maurizio Burla, ETH Zürich

RESEARCH ARTICLE FM Marquardt Division

Continuum optomechanics

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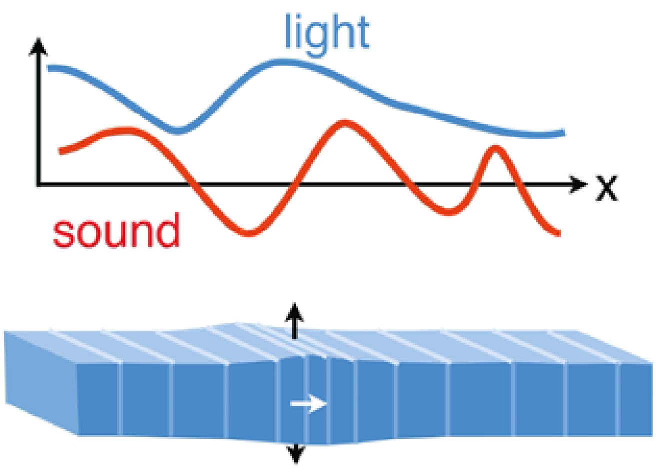
REFERENCE P. Rakich and F. Marquardt, New J. Phys. **20,** 045005 (2018)

In the field of cavity optomechanics, one exploits radiation forces to couple light and mechanical vibrations. As the name implies, an optical cavity is used to resonantly enhance the effects. However, there is a growing number of experimental platforms where light-vibration coupling can be studied in a similar spirit without any localized optical or mechanical resonances. Typical geometries include on-chip waveguides or suitably designed fibres (including designs invented in the Russell division at MPL). In recent theoretical work, we have written down the most general formulation of what might be called "quantum continuum optomechanics", where both the light field and the vibrational field propagate along a 1D continuum. Using symmetry consideration, we have been able to display all the possible coupling terms. Moreover, we connected this description to Raman and Brillouin scattering approaches. This work can serve as a foundation to explore generic effects that are important in any such system, including quantum and nonlinear phenomena.



Sound waves traveling along a 1D waveguide structure will lead to distortions that affect the propagation of light inside the same waveguide.

Retirement of Gerd Leuchs

After an extension of three years beyond the usual retirement age, Gerd Leuchs will finally step down as director at the end of March 2019. This represents the end of a memorable era in Erlangen optics, under the visionary leadership of Professor Leuchs, who conceived the idea of an Erlangen-based Max Planck Institute over 16 years ago, nurturing it first as a Max Planck Research Group at FAU and tending it until its successful transformation into a fully fledged Max Planck Institute in January 2009. MPL is delighted to announce that the MPG President, Martin Stratmann, has agreed to the establishment of a generously funded Emeritus Group for Gerd Leuchs, to be based at MPL. Additional funding will come from the Royal Society of New Zealand (a 3 year collaboration with the Dodd-Walls Centre), and a Russian Megagrant (3 years) with the Institute of Applied Physics of the Russian Academy of Sciences at Nizhniy-Novgorod.

RESEARCH ARTICLE PR Russell Division

Backward amplification of light

Backward stimulated Raman scattering permits amplification and compression of a frequency-downshifted Stokes signal, counter-propagating with the pump light. So far, however, it has only been observed when the Stokes signal is seeded in a controllable collinear environment. Here we report the first unambiguous observation of efficient noise-seeded backward stimulated Raman scattering in a hydrogen-filled hollow-core photonic crystal fibre. At high gas pressures the backward Raman gain is comparable to, but lower than, the forward gain. At high pump energies, however, the backward Stokes signal is experimentally and theoretically observed to be consistently stronger than the forward-propagating Stokes signal. In particular, quantum conversion efficiencies exceeding 40% to the backward Stokes at 683 nm from a narrowband 532 nm pump were achieved. We attribute this remarkable observation to the unique spatio-temporal dynamics of the interacting fields inside the fibre, which results in accumulation of the backward Raman molecular coherence close to the fiber input end, as shown in the figure, reaching peak values much greater than those of the forward coherence.

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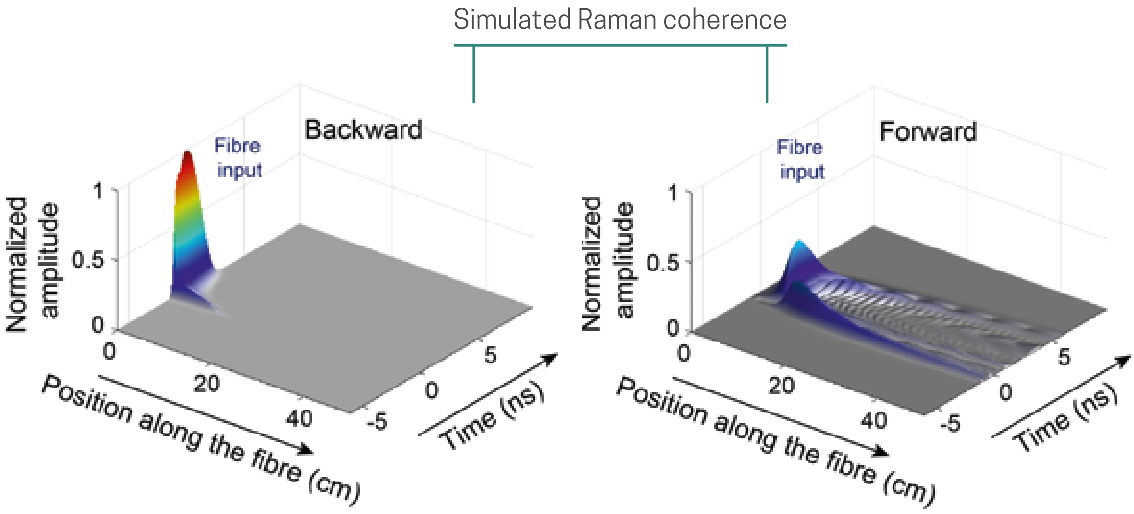
REFERENCE M. K. Mridha et al., Optica **5,** 570 (2018)



Evolution of the amplitude of the backward (LHS) and forward (RHS) Raman coherence. The backward coherence grows in strength towards the fibre input end, reaching a peak strength much higher than for forward SRS.

Arrivals and departures

We say a final goodbye to Marco Neisen, our previous head of administration. He has been helping out with advice during our search for a replacement. Goodbye also to Frau Dr. Elisabeth Träder, who ran MPL's administration during the interim period, and to Selda Müller, a highly valued member of MPL's public relations office. We wish them all the very best in the future and thank them for their great contributions to MPL.

We also welcome Public Relations manager Patricia Staudacher-Sauer and Frau Clara Mödl, institute safety officer.

In May 2018 we were very happy to welcome Frau Dr. Dorothe Burggraf as our new head of administration. She came to MPL from the Helmholtz Zentrum München in Neuherberg, where she was Leiterin des Fördermittelmanagements (funding manager). Dr. Burggraf holds a doctorate in biochemistry and has worked in basic research for ten years. She also completed an additional degree in finance.

RESEARCH ARTICLE PH Hommelhoff Associated Group (FAU)

The fastest current switching in a conductor

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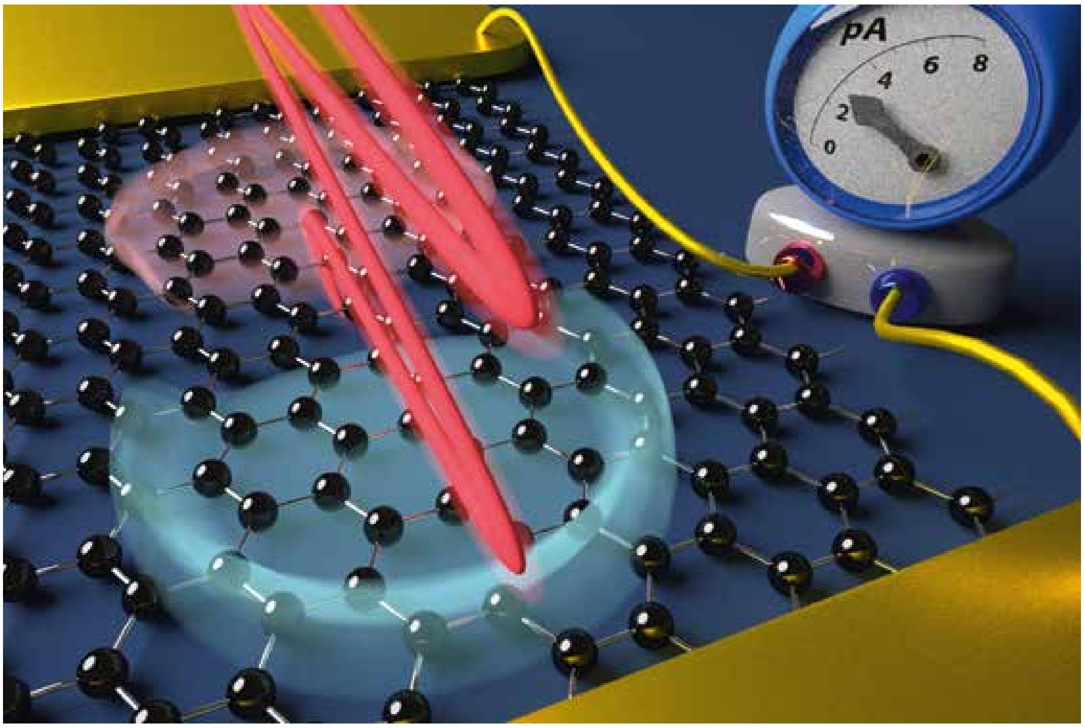
REFERENCE T. Higuchi et al., Nature **550,** 224 (2017)

"How fast can we generate a current?" is a fundamentally important question behind boosting the speed of electronics, since electronic data are transferred and processed via the flow of electrons. In a paper published in Nature, we have demonstrated a new approach for achieving ultrafast turning-on of currents in graphene, the atomically thin version of carbon, on the timescale of a femtosecond (1 fs = 10^{-15} s). The key mechanism involves driving electrons in graphene using the electric field of an intense ultrashort laser pulse. The resulting light-field-driven electron dynamics splits and recombines the electron wave function in graphene, leading to quantum-mechanical interference. The interference condition can be manipulated by adjusting the laser waveform, enabling switching on and off the current within a single optical cycle. These results represent a decisive step towards merging electronics and optics on one platform.



The shape of carrier-envelope phase-stable laser pulses (red waveform) can break the symmetry and induce an electric current in an otherwise fully symmetric layer of graphene (black spheres).

IMPRINT

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