MAX PLANCK INSTITUTE
for the science of light

Newsletter

n°7 | January 2014

FOUNDATION STONE CEREMONY

On 11th of July 2013 MPL laid the foundation stone of its new building in a ceremony in Staudtstraße, close to the southern campus of the Friedrich-Alexander Universität (FAU) in Erlangen. Vahid Sandoghdar, current Managing Director of MPL, opened the proceedings with a welcoming speech. This was followed by greetings from Dr. Ludwig Kronthaler, Secretary General of the Max Planck Society, Dr. Wolfgang Heubisch, former Bavarian Minister for Science, Research and the Arts, Joachim Herrmann, Bavarian Minister of the Interior, Prof. Dr. Karl-Dieter Grüske, President of FAU and Dr. Siegfried Balleis, Oberbürgermeister of the city of Erlangen. Among the many friends of MPL present at the ceremony was Nobel Prize winner Professor Roy Glauber from Harvard. ■

Inside THIS ISSUE

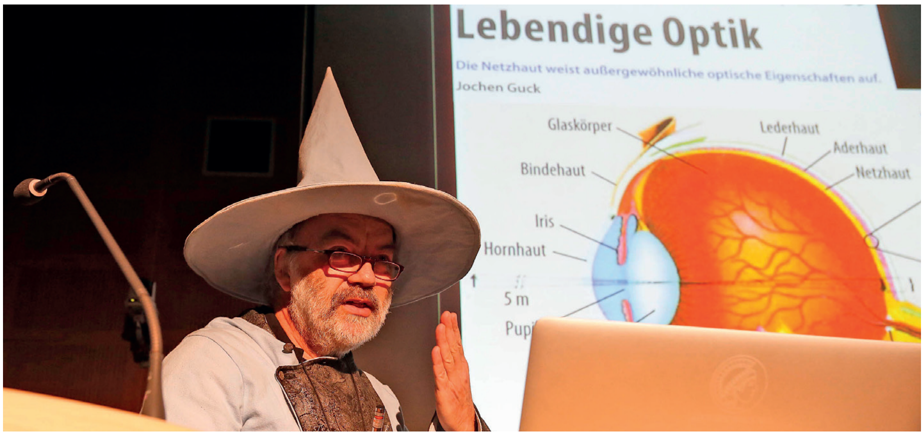


Foto: Hans von Draminski, Nürnberger Zeitung

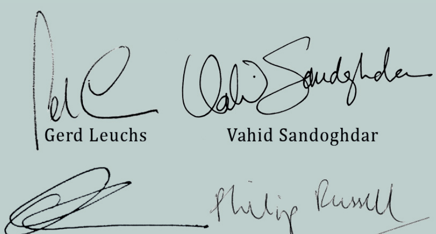
LONG NIGHT OF SCIENCE

The sixth "Long Night of Science", which took place October 19-20, 2013 in Nürnberg, Fürth and Erlangen, was a great success. Science-curious visitors came to find out what the local universities, research institutions and companies are up to. MPL also opened its doors, offering demonstrations of the fascinating effects that can be produced with light. Gerd Leuchs gave a public lecture at the FAU. His performance was streamed live to MPL so that it could be watched by visitors there. ■

Message FROM THE DIRECTORS

This is MPL's seventh Newsletter, printed just after our fifth anniversary in January 2014. Since the last edition, published in June 2013, a large excavation on the site of our new building has been gradually filling up and the concrete walls have by now risen well above ground. On the 11th of July 2013 the official ceremony for laying the foundation stone took place, with representatives from the Bavarian State Government, the City of Erlangen, the Friedrich-Alexander Universität and the Max Planck Society. On a day that was by turns sunny and cloudy, a live jazz band played in a marquee in the background, and many friends, colleagues and family members joined us to celebrate this important step in the development of MPL. During the ceremony a time capsule containing various items illustrating the work of MPL was sealed and will be buried in the new building. We hope to be able to move into our new quarters at the end of 2015.

Perhaps many of you already know that 2015 will also be the International Year of Light, supported by UNESCO and the United Nations. Naturally we at the Max Planck Institute for the Science of Light intend to play a role in this, promoting optics and photonics around the world. It coincides with a big initiative in the US – the National Photonics Initiative – and is a great opportunity to alert non-scientists to the importance of optics and photonics.

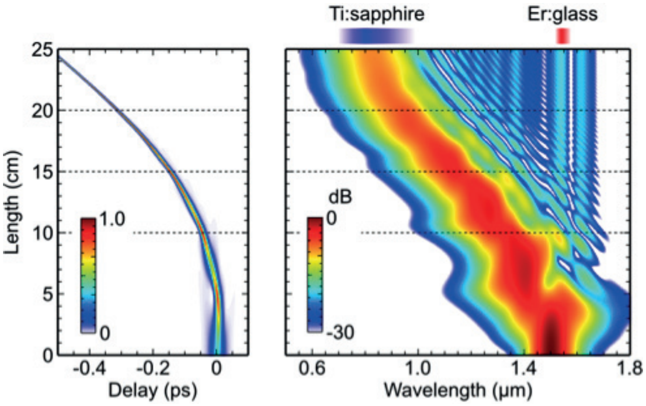


Gerd Leuchs Vahid Sandoghdar

Oskar Painter Philip Russell

RESEARCH *articles*

ULTRAFAST OPTICS IN HOLLOW-CORE FIBERS



The capture of ever-faster events, the conversion of light to higher frequencies and the attainment of strong effective nonlinearities are common themes in ultrafast optics. Although conventional optical fibers have provided remarkable advantages over bulk materials, gas-filled hollow-core fibre allows us to go to even more extreme intensities. By appropriate choice of gas pressure, the dispersion can be arranged to be anomalous at a pump wavelength of 1550 nm, permitting the excitation of a shape-preserving soliton, its duration being determined by the dispersion, pulse energy and core nonlinearity. Uniquely, a gaseous core makes these solitons possible even at ionizing intensities without damage to the system. A newly developed device enables a self-sustained interplay of extended ionization and soliton dynamics. Upon ionization, the abruptly dropping refractive index acts as a phase modulator, causing the soliton to experience a continuous upshift in frequency as it travels. The upshifting soliton adjusts adiabatically to the varying conditions at shorter wavelength by reducing its duration and increasing its peak intensity, causing further ionization. As a result, self-compression down to single-cycle durations together with simultaneous self-frequency-shifting by more than an octave can be obtained in an integrated all-fiber system. ■

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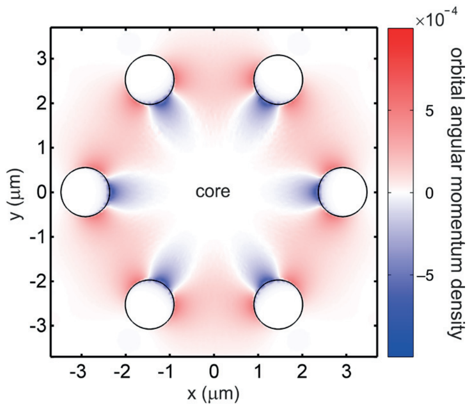
Group: *Russell Division*
Reference: W. Chang et al., Opt. Lett. **38**, 2984-2987 (2013).

OPTICAL ACTIVITY IN HELICALLY TWISTED PCF

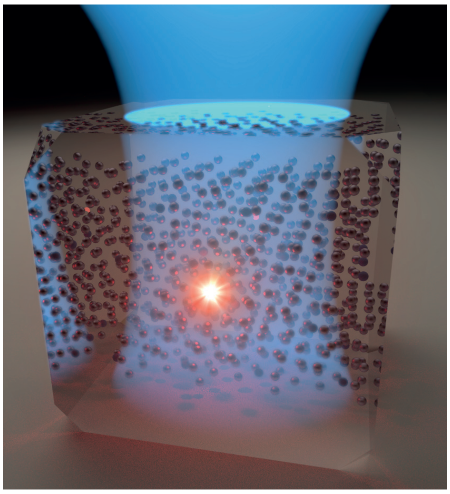
In a recent paper we showed theoretically and experimentally that continuously twisted solid-core photonic crystal fibre displays optical activity, the magnitude of the associated circular birefringence increasing linearly with twist rate. This is rather unexpected since there is no linear birefringence or anisotropy in the structure. A theoretical model based on symmetry properties and perturbation theory confirms that this is a non-resonant geometrical effect, which can only be understood if both spin and orbital angular momentum are considered. It turns out that the degenerate left- and right-circularly polarised modes of the untwisted PCF are not 100% circularly polarised but carry a small amount of orbital angular momentum caused by the interaction between the core mode and the hollow channels. The non-zero orbital angular momentum density close to the hollow channels in the vicinity of the fibre core (see figure) leads to a non-negligible contribution to the total angular momentum density and becomes dominant when circular birefringence is considered. Optically active twisted fibres are useful in applications such as current sensing and polarization control. ■

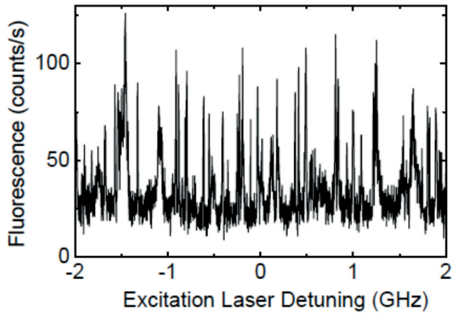


Contact: gordon.wong@mpl.mpg.de
Group: *Russell Division*
Reference: X. M. Xi et al., Phys. Rev. Lett. **110**, 143903 (2013).

FIRST HIGH-RESOLUTION SPECTROSCOPY OF SINGLE RARE-EARTH IONS IN A CRYSTAL

Solid-state emitters with atom-like optical and magnetic transitions are highly desirable for efficient and scalable quantum state engineering and information processing. Quantum dots, colour centres and embedded impurities have attracted a great deal of attention in this context, but influences from the surrounding matrix continue to pose challenges on the degree of attainable coherence in each system. An alternative solid-state platform builds on the optical detection and spectroscopy of single rare earth ions via their 4f intrashell transitions, which are well shielded from their environment. This leads, however, to long fluorescence lifetimes and thus weak emission, with the result that detection of rare earth ions through 4f transitions has proven to be elusive for more than two decades. By combining cryogenic high-resolution laser spectroscopy with fluorescence microscopy, we have now succeeded in spectrally selecting and spatially resolving individual praseodymium ions. The sharp lines in the figure display the fluorescence of individual ions within the inhomogeneous absorption spectrum of the sample. Access to the hyperfine levels via narrow-band lasers also allows us to prepare and read out information in single ions. Our results present a new solid-state system for single-emitter quantum optics. ■

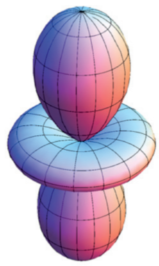




Contact: tobias.utikal@mpl.mpg.de
Group: *Sandoghdar Division*
Reference: T. Utikal et al., Nature Communications **5**, 3627 (2014).

QUANTUM VERSUS CLASSICAL POLARIZATION STATES: WHEN MULTIPOLES COUNT

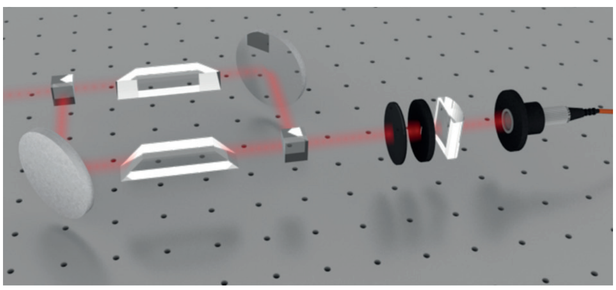
The standard notion of polarization comes from treating light as a beam. This suggests the existence of a well-defined direction of propagation and a specific transverse plane within which the tip of the electric field describes an ellipse. This polarization ellipse can be elegantly visualized by using the Poincaré sphere and is determined by the Stokes parameters. In the quantum domain, this classical setting can be immediately mimicked in terms of the Stokes operators, which can be obtained from the Stokes parameters by quantizing the field amplitudes. However, the appearance of hurdles such as, e.g., the presence of hidden polarization, shows that the resulting theory is insufficient. The root of these difficulties can be traced to the fact that classical polarization is chiefly built on first-order moments of the Stokes variables, whereas higher-order moments can play a major role for quantum fields. In this work we have developed a multipole expansion of the density matrix that naturally sorts successive moments of the Stokes variables. The dipole term, being just the first-order moment, can be identified with the classical picture, while the other multipoles (the figure shows one example) account for higher-order fluctuations. ■



Contact: lsanchez@ucm.es
Group: *Leuchs Division*
Reference: L L Sánchez-Soto et al., J. Phys. B: At. Mol. Opt. Phys. **46** 104011 (2013). The paper was chosen for IOPselect.

DIRECT MEASUREMENT OF THE SCHMIDT NUMBER FOR BIPHOTONS

Spontaneous parametric down-conversion is the most widely used source of entangled photons. Nevertheless, quantifying the degree of entanglement still proves a challenging task. The only operational entanglement measure that is routinely employed is the Fedorov ratio, namely the ratio of the joint state spectral width to the width of the correlations between the twin photons. It turns out, however, that this method of determining the degree of angular entanglement only works in the near- and far-field regions of the source and will fail otherwise. We have recently implemented an interferometric scheme that allows direct access to the spatial Schmidt number, which is a more fundamental entanglement quantifier and does not depend on propagation. In our set-up we exploit the fact that the more entangled a bipartite system is, the more incoherent are its subsystems. The Schmidt number is measured as the inverse visibility of interference observed in a modified Mach-Zehnder interferometer (see figure). ■



Contact: felix.just@mpl.mpg.de
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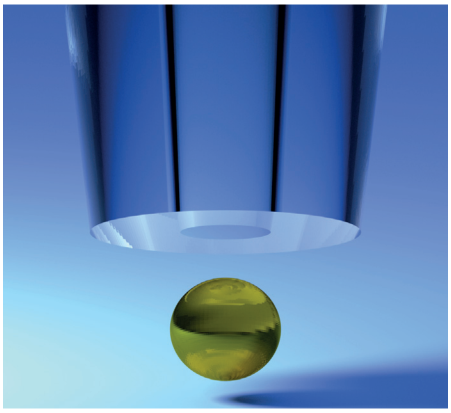
Reference: F. Just et al., New J. Phys. **15** 083015 (2013).

A SCANNING-PIPETTE ELECTROSTATIC TRAP FOR SMALL NANOPARTICLES

Although many clever trapping methods have been devised to tame nanoparticles and macromolecules, new methods are still in great demand for hanling different materials and environment. In particular, it is important to achieve contact-free trapping of ever smaller particles down to single proteins or clusters for times beyond seconds. The most established trapping technique, the optical tweezer, loses its effectiveness in this regime because the dipole force scales as the third power of the particle size so that trapping a particle of 10nm diameter requires about a million times more intensity than the commonly trapped



micron-sized particles. Last year we developed an electrostatic trap that is created in an aqueous medium between the aperture of a nanopipette and a substrate without any external potential. This is an extension of earlier on-chip work, which used polarization of glass surfaces in water to sculpt an electrostatic potential determined by the nanoscopic geometry. The scannable arrangement of a nanopipette allows us to trap, displace, or release various single particles such as gold nanoparticles and lipid vesicles at will. We plan to use this new technique for plasmonic applications and for trapping single proteins. ■

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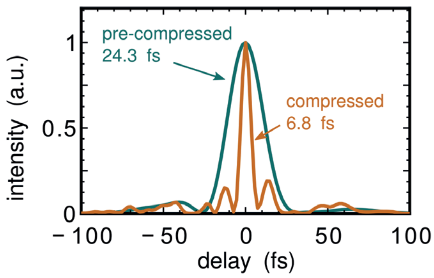
Reference: J.-T. Kim et al., Nature Communications **5**, 3380 (2014) .

COMPRESSING LIGHT – GENERATION OF STRIKINGLY SHORT PULSES

Laser pulses with extremely short durations (a few fs) are proving immensely useful in numerous scientific applications, such as the capturing of electron dynamics on extremely short timescales. By exploiting the unique qualities of noble gas-filled hollow-core photonic-crystal fibre (HC-PCF), we have demonstrated soliton self-compression of laser pulses down to durations of a few fs. In this process, the energy of a launched ~50 fs pump pulse at 800 nm is re-distributed adiabatically across a broad range of frequencies, merging in time into a single ultrashort pulse. This is possible because



of weak anomalous dispersion, self-phase modulation and the optical shock effect. Since the core is filled with an inert gas, substantially higher pulse energy ($\approx 10\ \mu$J) can be handled compared to traditional solid-core fibre. Moreover, HC-PCF provides much stronger light confinement than traditional glass capillaries, enabling the hollow core diameter to be down-scaled without impairing the optical transmission. This allows intensities of TW/cm^2 to be reached even at the moderate peak powers available from current generation high repetition-rate (hundreds of MHz) fiber and thin-disk lasers. The realization of a high average power, high repetition-rate ultrashort laser source is therefore one step closer. ■

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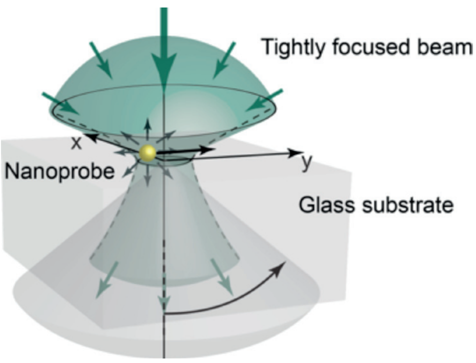
Group: *Russell Division*
Reference: K. F. Mak et al., Opt. Lett. **38**, 3592–3595 (2013).

MEASURING THE FULL VECTORIAL NATURE OF LIGHT ON THE NANOMETER SCALE

Tightly focused light beams with tailored field distributions find a wide range of applications in nano-optics, microscopy and imaging. Precise knowledge of such field distributions is of utmost importance. Measuring the fully vectorial distribution of the electric field of an optical wave is not an easy task, especially in the diffraction-limited focal spot of a high numerical aperture system. This is due to the deep sub-wavelength features exhibited by such a field distribution. We have demonstrated an experimental method and a theoretical analysis algorithm for measuring the three-dimensional field structure of highly confined



light. This technique, which we call "Mie scattering nanointerferometry", relies on angularly resolved measurement of the light scattered at a single plasmonic nanoparticle utilized as a scanning field probe (see figure). The interference between scattered and incoming light allows precise determination of the amplitude and relative phase distributions of all individual electric field components, hence providing detailed insight into the fully vectorial nature of the field distribution under study. No complex analysis of the scattered light field in terms of its polarization is required. This high resolution technique is easy-to-implement and highly compatible with standard microscopy systems. ■

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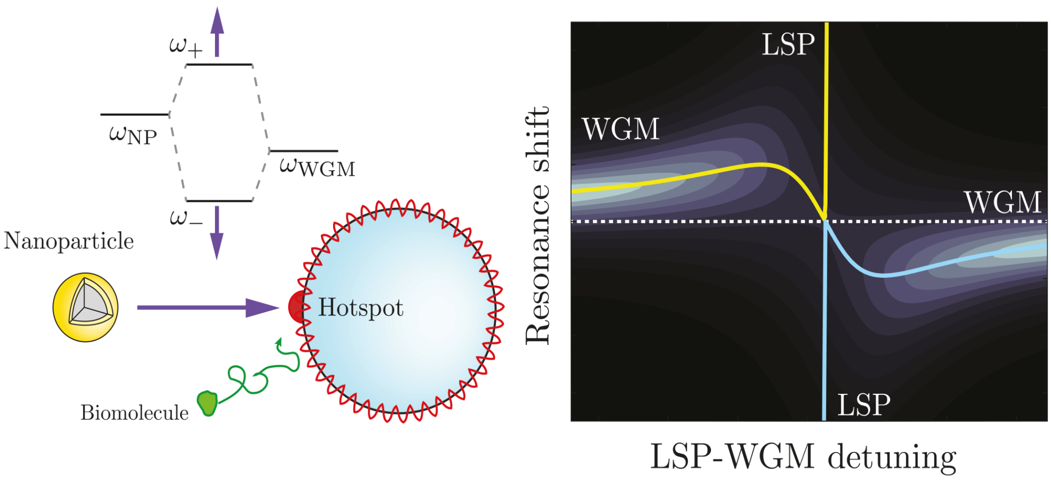
Group: *Leuchs Division*
Reference: T. Bauer et al., Nature Photonics **8**, 23–27 (2014).

HYBRID PHOTONIC-PLASMONIC RESONANCES FOR ENHANCED BIODETECTION



Whispering-gallery-mode (WGM) biosensors use high-Q optical resonances to detect, from a red shift in an excited resonance, binding of molecules and particles. Achieving sensitive and specific detection of individual viruses, DNA and proteins is important for implementing next-generation (on-chip) clinical diagnostic assays. Recently we have theoretically analysed photonic-plasmonic coupling between a WGM resonator and plasmonic nanoparticles as a means to push the detection envelope. Crossing of photonic and plasmonic modes for closely tuned WGM and localized surface plasmon (LSP) resonances was demonstrated (see figure). Resulting blue and red shifts of resonances are in agreement with experimental observations and afford multiplexing opportunities. Furthermore, nanoparticle induced resonance shifts were shown to be greatest when the LSP resonances were detuned by half the plasmon linewidth from the WGM resonance. At this optimal detuning, reactive coupling is maximised, leading to large near-field enhancements. Binding of biomolecules within these hotspots further tunes the WGM resonance in proportion to the enhanced intensity. Larger frequency shifts upon biomolecular binding are hence achievable with hybrid photonic-plasmonic resonators, putting single molecule detection within reach. ■

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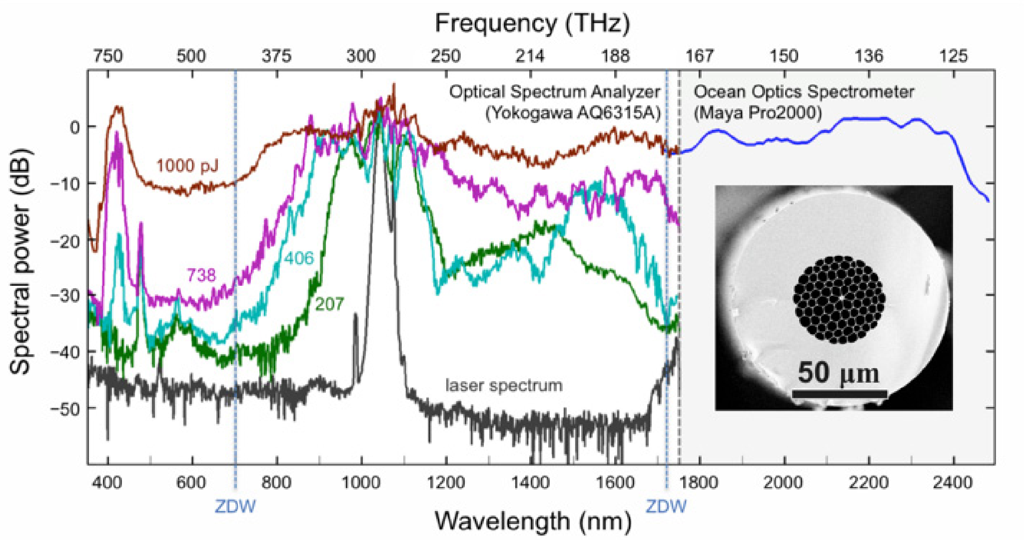
Group: *Biophotonics and Biosensing (MPRG)*
Reference: M. R. Foreman et al., Phys. Rev. A **88**, 023831 (2013).

CLOSE TO THREE-OCTAVE-SPANNING SUPERCONTINUUM GENERATED IN ZBLAN PHOTONIC CRYSTAL FIBRE



We report the successful fabrication, using advanced stack-and-draw techniques, of the world's first ZBLAN glass (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) photonic crystal fibre (PCF) with sub-micron features and a large air-filling fraction – considered by many experts to be impossible because of the narrow temperature range over which ZBLAN glass softens. By appropriate choice of core diameter, a close to three-octave-wide supercontinuum (10 dB-flat from 350 to 2500 nm) was generated by pumping with 140 fs, 1 nJ pulses at 1042 nm from an Yb^{3+}-doped KYW laser. Compared to previous work on supercontinuum generation in all-solid step-index ZBLAN fibers, which require pumping with pulses in the µJ or even mJ range due to low effective nonlinearity and a non-ideal dispersion landscape, these results represent a significant advance, producing a much wider spectrum. The availability of high-quality ZBLAN PCF opens up remarkable possibilities for the generation of ultra-broadband supercontinua. In addition, ZBLAN glass is an excellent host for rare-earth ions, suggesting the possibility of developing mid-infrared light amplifiers and coherent sources at MPL in future. ■

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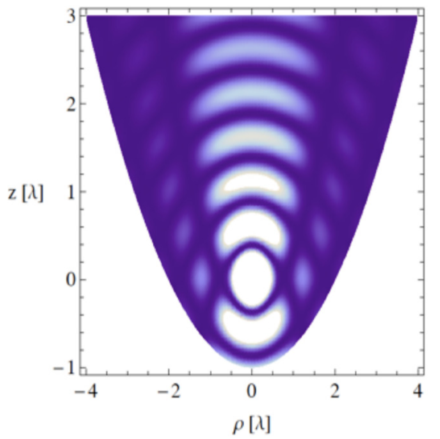
Reference: Post-deadline paper JTh5A.6, Advanced Solid-State Lasers (OSA Topical Meeting), Paris, Oct.27 – Nov.1, 2013

QED WITH A PARABOLIC MIRROR

The physics of strong light-matter coupling has attracted much attention over the last few years. Since the early nineteen eighties, single atoms have been coupled to optical cavities, leading to fundamental demonstrations of cavity quantum electro-dynamics (QED) in which the atom can excite only one or a few radiation modes. The opposite regime of free-space QED, where a continuum of modes is available, has recently also received notable recognition. In this case it is essential to increase the strength of the light-matter interaction: focusing light, matching the incoming field with the spatial and temporal atomic radiation mode, and tailoring the polarization pattern can improve the coupling to a nearly



perfect value. An intriguing intermediate situation between the single-mode and the continuum limit is the case of a large cavity, in which an atom couples to a large but not continuous number of modes. A parabolic cavity is a remarkable example of this, ensuring that light entering parallel to the axis couples to an atom located at its focus in a particularly efficient way. In this paper, we look into the QED of a two-level atom located at the focus of a parabolic mirror. We find the vector field modes that can couple efficiently to the atom (a density plot is sketched in the figure). In terms of them, we study the ensuing modifications of the spontaneous emission, as well as the quantum statistical properties of the generated photon. ■

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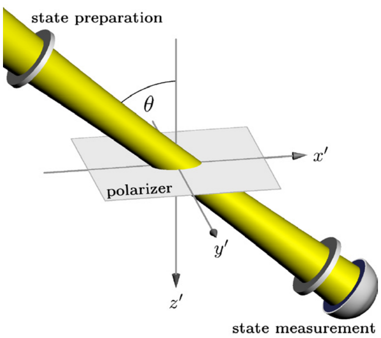
Group: *Leuchs Division*
Reference: G. Alber et al., Phys. Rev. A **88**, 023825 (2013). [selected as Editor's suggestion]

A REALISTIC VERSATILE POLARIZER MODEL

Polarizers are key components in both classical and quantum optics. Generally a polarizer is understood to project the light field onto a particular state of polarization. While the action of a polarizer is well known for normal incidence, surprisingly enough the behaviour of highly tilted polarizers is not so well understood. In connection with this, we have experimentally studied a polarizer made of oriented elongated nanoparticles embedded in a glass substrate. Close to the resonance, the electric field component along the long



axes of the particles is scattered and eventually absorbed. We refer to the long particle axis as the polarizer's absorbing axis. The projection of this global absorbing axis onto the local plane of the electric field can be interpreted as an effective absorbing axis. An intuitive rule of thumb states that the field component parallel to this effective absorbing axis must vanish. We applied this model to account for the physical nature of the nanoparticle polarizer, obtaining excellent agreement with experimental data. ■

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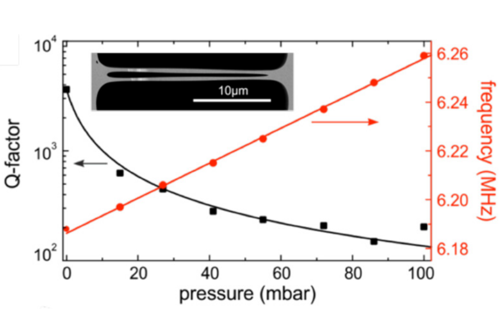
Group: *Leuchs Division*
Reference:Opt. Express **21**, pp. 27032–27042 (2013).

SQUEEZED FILM DAMPING AT THE NANOSCALE

The freely-suspended glass membranes in an evacuated dual-nanoweb fibre, driven at resonance by intensity-modulated light, exhibit a giant optomechanical nonlinearity. In recent experiments we investigated the effect of different gas pressures on the resonant frequency and Q-factor. As a consequence of the unusually narrow slot between the nanowebs (22 μm by 550 nm, the webs being ~440 nm thick), the gas-spring effect causes a pressure-dependent frequency shift that is ~15 times greater than typically measured in micro-electro-mechanical devices. On the other hand, squeezed-film damping causes the mechanical Q-factor to increase strongly as the pressure is reduced (see figure). The agreement between experiment and a model based on free-molecular energy transfer is remarkably good, especially since no free parameters are used. Squeezed-film damping and gas stiffness thus



play key roles in determining the resonant frequency and Q-factor of the mechanical resonances. The results also show that in the low pressure regime, which is of great interest in many optomechanical systems and devices, an analytical solution can be sufficient to describe the squeezed-film damping effect in real structures. ■

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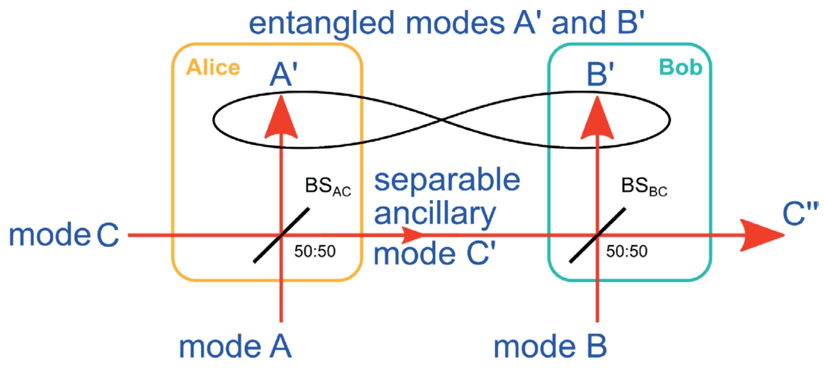
Group: *Russell Division*
Reference: J. R. Koehler et al., Appl. Phys. Lett. **103**, 221107 (2013).

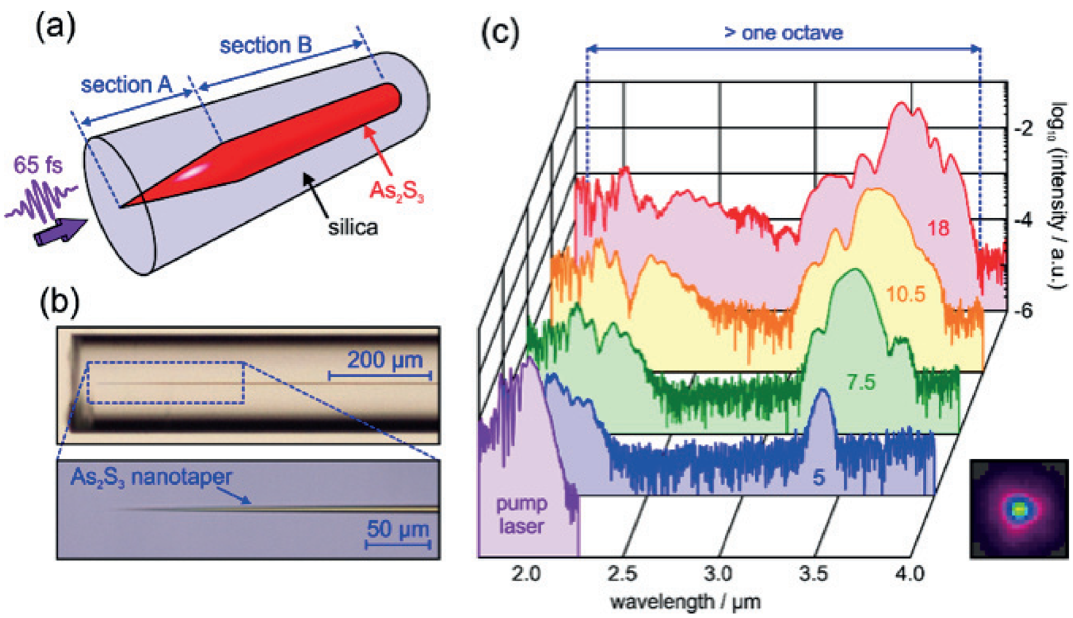
ENTANGLEMENT DISTRIBUTION WITH SEPARABLE STATES



Quantum measurement is the most counterintuitive phenomenon of the micro-world and this shows up most markedly in connection with entangled states. As a result quantum entanglement is a versatile resource for quantum information processing. An entangled quantum state of a composite quantum system cannot be described as the tensor product of separate quantum states of the subsystems involved (i.e., as an overall separable state). Quantum information protocols typically require the distribution of entanglement among separate parties. This is usually accomplished by direct transmission of entangled systems. In recent work we have demonstrated a protocol for entanglement distribution by a separable (i.e. unentangled) system. In this counterintuitive protocol, entanglement is distributed between two remote parties, Alice and Bob, with the help of communication via a separable auxiliary system C' (i.e., the ancilla state). Nevertheless, the state shared by the participants still contains non-classical correlations between the ancilla and the rest of the system, which are vital for the protocol to function. A third party David owns classical information about the preparation of the state, which he can distribute to enable the participants to recover the entanglement. This quantum protocol highlights the complex hierarchical structure of mixed correlated quantum states and the role that classical information plays in quantum information science. ■

Contact: christian.peuntinger@mpl.mpg.de
Group: *Leuchs Division*
Reference: C. Peuntinger et al., Phys. Rev. Lett. **111**, 230506 (2013).

MID-INFRARED SUPERCONTINUUM GENERATION IN As_2S_3-SILICA "NANO-SPIKE" STEP-INDEX WAVEGUIDE



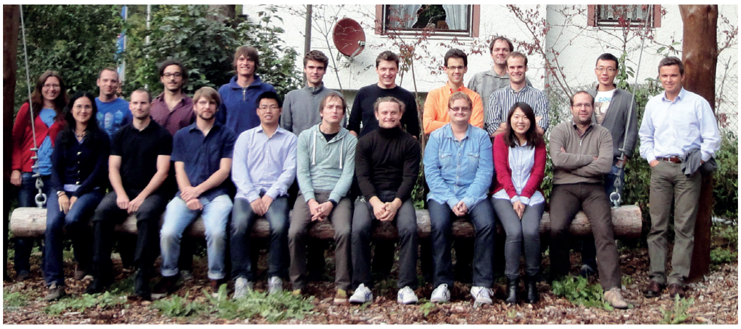
The bandwidth of a supercontinuum is limited by the window of transparency of the nonlinear medium – usually an optical fiber made from fused silica. To extend the spectrum beyond 2 μm into the mid-IR, the waveguide core must be made from materials that are transparent in this wavelength range. A capillary fibre with a 1 μm bore, one of its ends being tapered down to zero diameter, was pressure-filled with As_2S_3 glass. The resulting "nano-spike" (Section A in the figure) allows high launch efficiencies into the 2-mm-long uniform waveguide (section B). Ultrashort (65 fs) pulses at wavelength 2 µm, delivered from a Tm-doped fiber laser, are launched into the sub-wavelength As_2S_3 strand. Soliton fission and dispersive wave generation along the uniform section result in an octave-spanning supercontinuum out to nearly 4 µm at launched energies of only 18 pJ. This nano-spike device provides a unique means of solving the long-standing problem of efficiently coupling light into single-mode high-contrast step-index waveguides of sub-wavelength diameter. The spectra generated will have immediate uses in metrology and infrared spectroscopy. ■

Contact: shangran.xie@mpl.mpg.de
Group: *Russell Division (collaboration with IMRA Inc. and University of Rennes)*
Reference: N. Granzow et al., Opt. Exp. **21**, 10969-10977 (2013).

SECOND MPL AUTUMN ACADEMY

The second MPL Autumn Academy took place September 30 to October 2, 2013. As before, the aim of this two-and-a-half day event was to introduce BSc and MSc students to the fast moving field of optical sciences. The response was excellent. From more than 70 applications we selected 26 students and invited them to Erlangen for a packed schedule of lectures, laboratory visits and poster sessions. We were delighted that Prof. Cornelia Denz (WWU Münster), Dr. Jonathan Matthews (University of Bristol) and Prof. Florian Marquardt (FAU Erlangen) agreed to deliver invited lectures, despite their very busy schedules. Talks were also given by PhD students and group leaders at MPL as well as the MPL directors. The academy's social events were financially supported by a generous donation from Toptica GmbH. The next academy will take place September 29 to October 1, 2014. ■

IMPRS ANNUAL MEETING



The fourth Annual Meeting of the Erlangen IMPRS took place in Gößweinstein 16-19 September 2013. Invited lectures were given by Arno Rauschenbeutel (TU Wien), Allard Mosk (University of Twente), Alexander Rohrbach (Albert-Ludwigs-Universität Freiburg) and Oskar Painter (MPL). The program also included block lectures by IMPRS advisors Ulf Peschel and Maria Chekhova, as well as great talks and poster presentations by the IMPRS students. Best talk awards went to Michael Schmidberger and Robert Buschlinger, and Roland Lauter received this year's poster prize. ■

NEW EMPLOYEES

We warmly welcome Vanessa König, personal assistant to Oskar Painter and laboratory technician Alexander Gumann, a member of the Painter Division. Maksim Medvedev has joined the Mechanical Workshop and will focus on jobs for the Sandoghdar Division. ■

MATTHEW R. FOREMAN JOINS THE VOLLMER LAB

Dr Matthew Roy Foreman has been awarded an Alexander von Humboldt Fellowship. During his stay at the MPL he is planning to work on hybrid photonic-plasmonic micro-resonators for single molecule sensing. ■

OPTICAL IMAGING CENTER ERLANGEN (OICE)

In September 2013 the newly established Optical Imaging Center Erlangen (OICE) held a kick-off symposium and opened its doors to a newly renovated space on the Kussmaul campus of FAU. As well as providing a facility for microscopy, OICE will promote research, education and development in optical imaging with a strong emphasis on biomedical applications. The centre plans to work closely with MPL, the Graduate School of Advanced Optical Technologies (SAOT) and the Excellence Cluster Engineering of Advanced Materials (EAM) as well as the faculties of Science, Engineering and Medicine at FAU. OICE was initiated at FAU by Vahid Sandoghdar with support from the Alexander von Humboldt Foundation, SAOT and EAM. The new centre is an important step in extending the activities of MPL into the fast moving and exciting field of biophotonics. ■ Website: www.oice.uni-erlangen.de

NEWS IN BRIEF

The European Research Council (ERC) has announced the names of successful applicants for Advanced Grants in the sixth and final round of the Seventh Framework Programme. A total of 284 grants were approved, with funding of up to €3.5 million per grant. Ten grants were awarded to scientists at Max Planck Institutes, including **Gerd Leuchs**, who received an Advanced Grant.

Sanjay Srivastava has been named CSIR Young Scientist Award 2013. During his BOYSCAST fellowship with Silke Christiansen he worked on photovoltaic applications of silicon nano-structures.

Peter Hommelhoff has been awarded an ERC consolidator grant.

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