MAX PLANCK INSTITUTE
for the science of light

Newsletter

n°9 | December 2015

SIEGMAN INTERNATIONAL SCHOOL ON LASERS

Just a few weeks ago MPL hosted the second OSA Siegman International School on Lasers in Amberg, close to Nuremberg. Co-managed by OSA and MPL (the local organisers were Bettina Heim, Tina Schwender, Nicolas Joly and Philip Russell) and funded by the OSA Foundation, IPG Photonics and the Max Planck Society, as well as several companies and foundations, the school brought together students and internationally recognized academic and industry leaders in the field of lasers and their applications. We are pleased to announce that it was a tremendous success. The lectures covered a wide range of different topics, immersing 82 graduate students from around the world in a packed program of lectures, networking events, professional development programs, poster presentations and discussions on research and industrial development. In numbers: 119 applications were received, 82 students from 28 countries attended (24 of whom female) and 100% of all requests for financial support towards travel and subsistence were met. A full summary of the school can be found at www.osa.org/siegman, where you can view the complete list of lecturers, together with photos and information on next year's school, which will be hosted by ICFO – The Institute of Photonic Sciences in Barcelona, Spain. ■

Inside THIS ISSUE

SYMPOSIUM PHYSICS AND MEDICINE

On February 26th and 27th MPL held a symposium on Physics and Medicine at the medical school of the Friedrich Alexander University in Erlangen. Sixteen international invited speakers reported on a wide range of methods and concepts from theoretical and experimental physics that can be applied to the study of fundamental problems in biomedical research. Topics included cell mechanics, physics of cancer, nanophysiology, photoacoustic and multiphoton microscopy, analytics of blood cells, pattern formation in cells, virus infection, chip-based studies, neurophotonics and wavefront shaping for deep tissue imaging. A wonderful audience of some 150 scientists and medical doctors from Erlangen and abroad engaged in lively discussion during lectures, breaks and poster sessions. The symposium provided lots of valuable insight for the planned Max Planck Centre for Physics and Medicine in Erlangen. ■

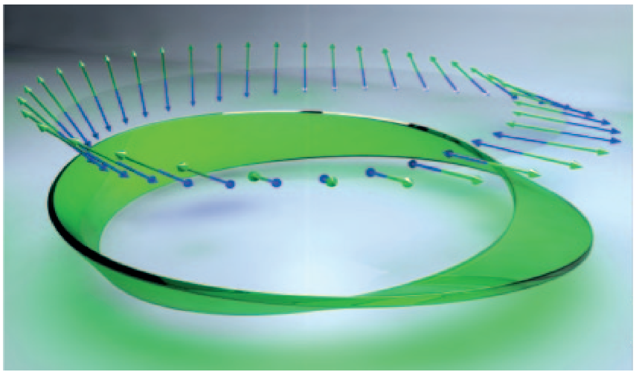
Message *FROM THE DIRECTORS*

As the International Year of Light (IYL) 2015 nears its end—you can read about MPL's IYL-light-themed street theatre in the pages of this Newsletter—the MPL New Building is nearing completion. With its outward slanting western wall and its elegant black windows it resembles a cruise ship setting off into the nearby forest. The landscaping of the grounds is also underway, so that externally at least the building is beginning to look fully clothed. Internally, however, it is far from ready. We will have to wait until late spring 2016 before we can move in—the complex internal infrastructure of such a high tech building takes time to plan and install, requiring many detailed discussions between the installation engineers and the MPL scientists, coordinated by Klaus Gagel, MPL's head of Technical Services. What else has happened since the last Newsletter? At the start of August MPL hosted the second OSA Siegman International School on Lasers in Amberg, east of Nuremberg. It was a huge success, and we'd like to take this opportunity to thank the invited lecturers for a series of inspiring talks, as well as all those organisations and individuals who contributed financially to supporting the students, who came from all over the world. MPL has won funding from the German *EXIST-Forschungstransfer* program to set up the commercial spin-out *ultralumina*. Headed by MPL alumnus Patrick Uebel, the company aims to commercialise a range of deep and vacuum ultraviolet light sources based on photonic crystal fibres. Finally, in the New Year we hope that the appointment procedures for new directors heading the 4th and the 5th divisions will make good progress. Watch this space!

Gerd Leuchs   Vahid Sandoghdar   Philip Russell

RESEARCH *articles*

BENDING AND TWISTING LIGHT'S POLARIZATION INTO A MÖBIUS STRIP



If one end of a paper strip is twisted by 180° and both ends are glued together, a fascinating object is created – a Möbius strip. The introduction of a half-twist has striking consequences for the strip properties. For example, it has only one side and a single edge or boundary (see Figure). We all have already seen Möbius strips in the form of sculptures or drawings, or maybe have even constructed one ourselves. Nevertheless, it seems quite counterintuitive that these objects can also be formed by the polarization of light. A decade ago, Isaac Freund theoretically proposed the occurrence of these unusual optical topologies in interfering light beams. Recently, we proved the existence of optical polarization Möbius strips experimentally for the first time. In the lab, we focused a superposition of two polarized light beams tightly, resulting in the creation of nanoscopic versions of Möbius strips. We took advantage of a nano-probing technique developed in the group to measure the distribution of the electric field in the focal plane. By retrieving the local polarization ellipses from the electric field information, we unveiled the hidden Möbius strips formed by the ellipse axes (see arrows in Figure). ■

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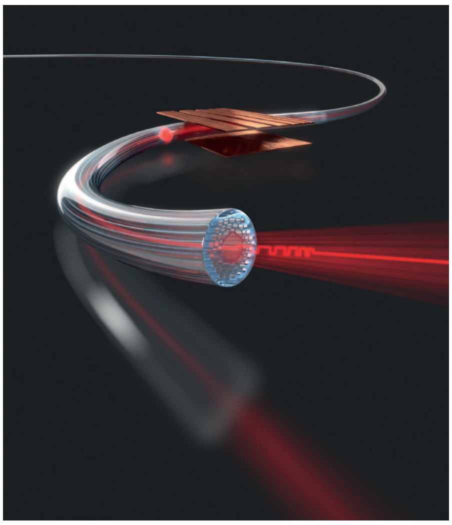
Reference: T. Bauer et al., Science **347**, 964-966 (2015).

FLYING PARTICLE SENSORS

Optical fibre sensors make use of diverse physical effects to measure parameters such as strain, temperature and electric field. We have recently introduced a new class of reconfigurable fibre sensor, based on a 'flying-particle' optically trapped inside a hollow-core photonic crystal fibre, and illustrated its use in electric field and temperature sensing with high spatial resolution. The electric field distribution near the surface of a multi-element electrode was measured with a resolution of ~100 µm by monitoring changes in the transmitted light signal due to the transverse displacement of a charged silica microparticle trapped within the hollow core (see Figure). In another experiment, Doppler-based velocity measurements are used to map the gas viscosity, and thus the temperature, along a hollow-core photonic crystal fibre. The flying-particle approach represents a new paradigm in fibre sensors, potentially allowing multiple physical quantities to be mapped with high positional accuracy over kilometre-scale distances. ■



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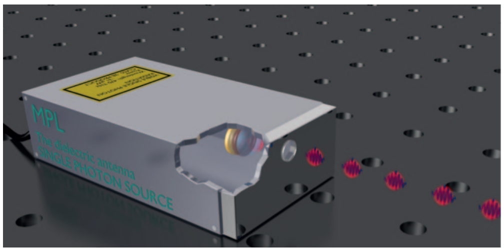
Group: *Russell Division*
Reference: D. S. Bykov et al., Nature Photonics **9**, 461–465 (2015).

WHEN EVERY PHOTON COUNTS

Single-photon sources are desirable resources for a variety of applications, ranging from quantum information processing to metrology. A single emitter, like a single atom or a quantum dot can, in principle, be used as the central element in such a device, and indeed, this has been demonstrated by many groups over the past two decades. However, the low efficiency in collecting the emitted photons makes its impossible to tell when a single photon will arrive. In other words, success of previous work has been more to ensure that one never has more than one photon at a time but not that one has a photon at a given time! In recent work we tackled the problem of photon collection by designing a metallo-dielectric antenna structure that allows >99% of the photons emitted from a single emitter to be collected by a microscope objective. In the experiment we use single CdSe/CdS quantum dots in a thin polymer film (PMMA/PVA) sandwiched between a sapphire substrate and a gold mirror. We measure the performance of the antenna by investigating the angular emission pattern from a quantum dot at room temperature. The experimental results show remarkable agreement with theoretical predictions, leading us to the conclusion that the antenna indeed has a photon collection efficiency exceeding 99%. Such an antenna might be the key element for realizing a deterministic single-photon source that can deliver several tens of millions of photons per second. ■



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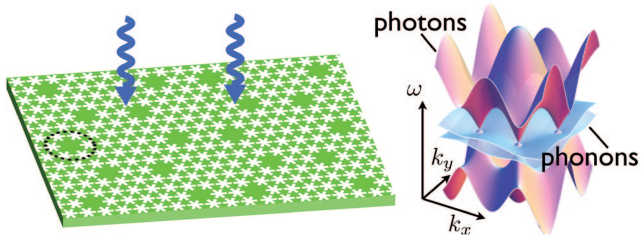
Reference: X.-L. Chu et al, Optica **4**, 203-208 (2014).

OPTOMECHANICAL DIRAC PHYSICS

Photonic crystals can be designed to have artificial defects, at which light gets trapped and forms an optical mode, similar to a macroscopic optical cavity. This concept can be extended to produce localized vibrational modes as well in the same piece of material, as demonstrated in recent years by various groups. The result, sometimes called an optomechanical crystal, features strong interactions between light and sound. We are building on this idea, investigating its potential for future optomechanical metamaterials, where many such optical and vibrational modes are arranged in a periodic lattice. These systems would represent a platform where photons and phonons travel on a lattice and interact with each other. This gives rise to a photon/phonon band structure whose properties are controlled in-situ by the intensity and frequency of the laser illuminating the whole sample. The figure shows the case of a honeycomb lattice, where the photon-phonon polaritons acquire the typical Dirac cone bandstructure of massless relativistic particles. ■



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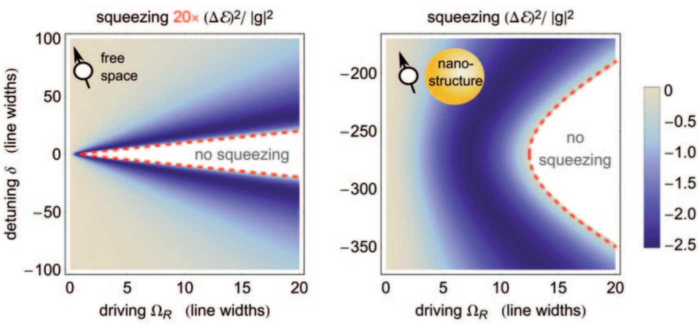
Reference: M. Schmidt et al., New Journal of Physics **17**, 023025 (2015).

NANOSTRUCTURES AND QUANTUM EMITTERS TOGETHER MAKE LIGHT MORE PRECISE

The noise arising from the quantum nature of light imposes fundamental limits in technologies as diverse as bioimaging, spectroscopy, or gravitational wave detection, where extreme precision becomes crucial. Squeezed states of light allow such noise to be overcome. Currently, sources of squeezed light still commonly rely on the nonlinear response of macroscopic systems, despite some recent advances on the microscopic scale. As a further step in this direction, we have investigated, in a collaboration with the National Institute of Optics (CNR-INO) in Florence, Italy, a novel source of squeezed light made from just a single emitter, such as a single atom, coupled to an optical nanostructure. The nanostructure both acts as an enhancing antenna and modifies the intrinsic quantum properties of the emitter. This interplay can generate squeezed light several orders of magnitude brighter than could be obtained from the emitter alone, and can cover a significantly wider spectral range (see Figure). The work provides a bridge between sources of squeezed light and nanoscale optics, paving the way for their integration in nanophotonic devices. ■



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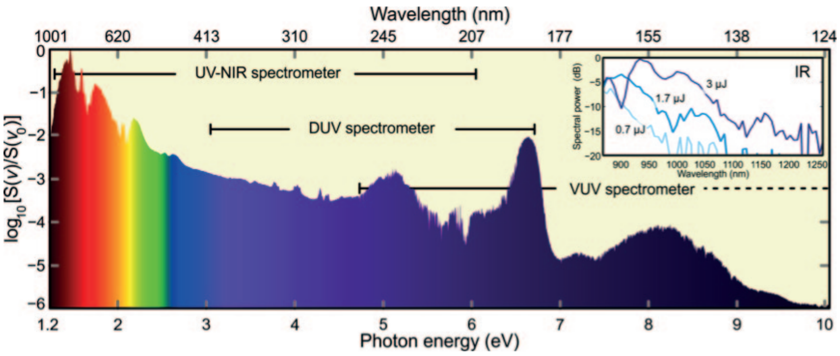
Reference: D. Martin-Cano et al., Phys. Rev. Lett. **113**, 263605 (2014).

VACUUM-ULTRAVIOLET TO INFRARED SUPERCONTINUUM IN HYDROGEN-FILLED PHOTONIC CRYSTAL FIBRE



Although supercontinuum sources are readily available for the visible and near infrared, and recently also for the mid-IR to deep-UV, many areas of biology, chemistry, and physics would benefit greatly from the availability of compact, stable, and spectrally bright deep-UV and vacuum-UV supercontinuum sources. Recently we have succeeded in generating a bright supercontinuum, spanning more than three octaves from 124 nm to beyond 1200 nm (see the inset), in a hydrogen-filled kagomé-style hollow-core photonic crystal fibre. Few-microjoule, 30 fs pump pulses at wavelength of 805 nm are launched into the fibre, where they undergo self-compression via the Raman-enhanced Kerr effect. Modelling indicates that before reaching a minimum subcycle pulse duration of ~ 1 fs, much less than one period of molecular vibration (8 fs), nonlinear reshaping of the pulse envelope, accentuated by self-steepening and shock formation, creates an ultrashort feature that causes impulsive excitation of long-lived coherent molecular vibrations. These phase modulate a strong VUV dispersive wave (at 182 nm or 6.8 eV) on the trailing edge of the pulse, further broadening the spectrum into the VUV. ■

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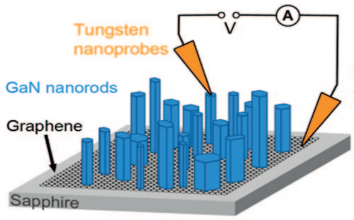
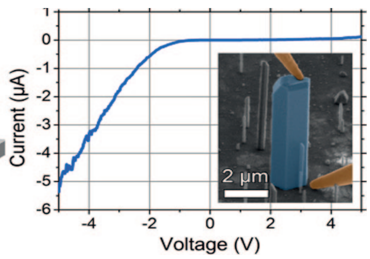
Reference: F. Belli et al., Optica **2**, 292-300 (2015).

GROWING GAN NANOSTRUCTURES ON GRAPHENE

GaN and its In- or Al-alloys, all direct bandgap semiconductors, are ideally suited for a wide range of opto-electronic applications. It has been shown that not only layer stacks but also three-dimensional (3D) architectures of micro- and nanorods can be grown and outperform their 2D counterparts, showing faster growth rates and fewer lattice defects. For integration into an optoelectronic device a top and bottom contact is required. The insulating sapphire substrate prevents simple back-contacting of rods so that complex, yield and performance-hampering schemes must be used. As a possible workaround, we transferred graphene (a good electrical conductor) on to the insulating sapphire prior to GaN rod formation. In a recent publication we report on the use of this technique in solid-state-lighting (SSL). Correlated Raman measurements and scanning electron microscopy imaging reveal that the GaN rods grow on defective graphene where GaN rods can nucleate at dangling bonds. Using a nanoprobe it was possible to demonstrate conductivity between the as-grown GaN rods and the graphene back contact. This study has implications on further developments in the SSL markets. ■





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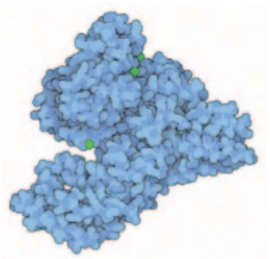
Reference: M. Heilmann et al., Crystal Growth & Design, **15**, 2079–2086 (2015).

THERMAL CHARACTERIZATION OF BIOPOLYMERS

The structure of biopolymers is known to change with temperature, affecting for example the activity of enzymes and the folding of proteins. We have now shown that such structural changes can be monitored using highly sensitive “whispering gallery mode” (WGM) optical biosensors. To achieve this goal, we have devised a technique to temperature-stabilize the WGM sensor system, by adding glycerol to a WGM glass microsphere placed in an aqueous sensing environment. The temperature stabilized WGM sensor was utilized to track structural changes in biopolymers, by monitoring frequency shifts associated with optical polarizability change. Using this sensing method, structural changes in albumin protein (see Figure) could be resolved for only one degree in temperature variation. Such highly sensitive detection of structural change can have many important applications: in single molecule studies, for thermodynamic investigations of biological systems, and for monitoring temperature-dependent reaction kinetics. ■



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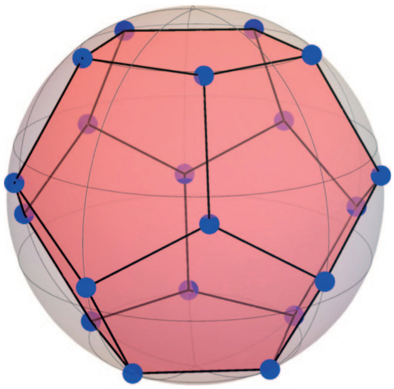
Reference: E. Kim et al., Applied Physics Letters **106**, 161101 (2015).

QUANTUM CONSTELLATIONS

Shortly before disappearing in mysterious circumstances at the age of 32, the Italian physicist Ettore Majorana invented a beautiful, yet largely ignored, representation of finite quantum systems. A pure state of spin S is expressed as a set of 2S points on the unit sphere: the Majorana constellation. This provides an intuitive method to study these systems from a purely geometric perspective. As a result, the Majorana representation has emerged as a most useful tool in many different fields. Spin coherent states are the most classical states, in the sense that they point "somewhere" as much as possible. The Majorana constellations for these states collapse to a single point. In this project, we attempt to characterize what states might serve as the opposite of coherent



states. Such states, which point "nowhere", can be considered as the kings of quantumness. The associated Majorana constellation consists of a set of 2S points distributed in the "most symmetric" fashion over the sphere. This relates closely to other problems, such as Thomson's or spherical *t*-designs. Apart from their indisputable geometrical beauty, there surely is plenty of room for applications of such states, the generation of which has started at MPL. ■

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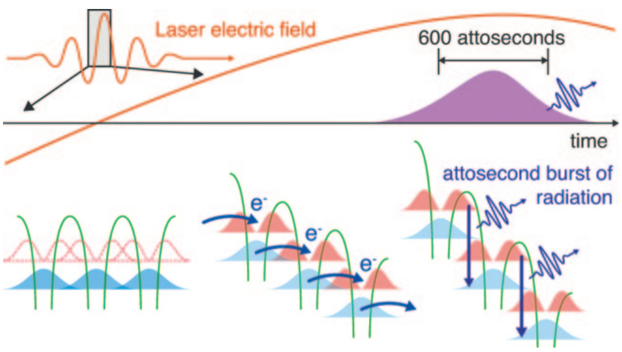
Reference: G. Björk et al., Physical Review A **92**, 031801(R) (2015).

STRONG-FIELD PERSPECTIVE ON HIGH HARMONIC RADIATION FROM BULK SOLIDS

To record the dynamics of a fast moving object, short pulses of light are used to record a series of "frozen" pictures. In the case of electrons in materials, typical timescales are of the order of attoseconds (a billionth of a billionth of a second), so that attosecond light pulses are required. So far they have been generated as high-harmonics of a strong laser pulse in gaseous media. In this study, we propose to generate such extremely short pulses in a solid-state medium, opening up the prospect of a compact solid-state device. To this end, we have clarified theoretically the mechanisms of high-harmonic generation from crystals by treating the electric field of a laser as a quasi-static strong field. Under these circumstances, electrons in periodic potentials form dressed states, known as Wannier-Stark states. The energy differences between the dressed states determine the frequencies of the radiation. The radiation yield is determined by the magnitudes of the current matrix elements between the dressed states. With a proper high-frequency filter an extremely short part of the radiation, reaching the attosecond timescale, can be extracted. ■



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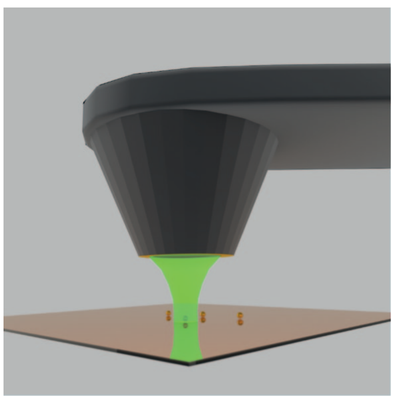
Reference: T. Higuchi, et al., Phys. Rev. Lett. **113**, 213901 (2014).

A CANTILEVER-BASED SUB-λ^3 MODE-VOLUME OPTICAL MICROCAVITY

Microcavities have been popular for a number of applications, ranging from micorlasers, cavity quantum electrodynamics studies and sensing. Enhanced coupling in the cavity is usually achieved via a high quality factor. This, however, severely limits the operating bandwidth of the cavity. Using small radius of curvature micromirrors, we have succeeded in creating a very small microcavity that accommodates high Purcell factors while maintaining a THz operating bandwidth. Using focused ion beam milling, we fabricated a concave micromirror of radius of curvature 2.6 micrometers on the tip of an



atomic force microscope cantilever. The micromirror faces a planar dielectric mirror to form a plane-concave microcavity with a mode volume of only 0.8 λ^3. The sensitivity of this microcavity to small perturbations is demonstrated by detecting the modification of the cavity resonance by a 80 nm gold particle. This type of a microcavity has the capability to strongly modify radiation emitted by a single molecule in a crystal, effectively turning it into a two level system, but it can also be used to detect biomolecules such as viruses. ■

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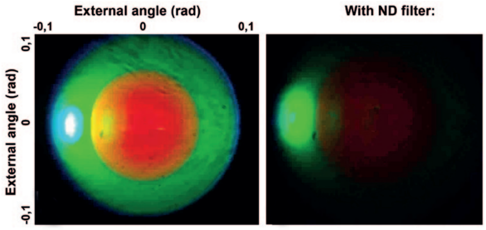
Reference: H. Kelkar et al., Phys. Rev. Applied **4**, 0504010 (2015).

GIANT TWIN BEAMS DIRECTED BY THE POYNTING VECTOR

In high-gain parametric down-conversion, the strongest emission is along the pump beam, namely along its energy propagation direction. If the pump undergoes spatial walk-off, a certain direction is selected out of the familiar 'rainbow' of rings – the one given by the pump Poynting vector. Along this direction, we observe a strong spatially single-mode beam, with its twin generated along the phase matching direction. A similar effect occurs in the temporal domain: the emission is strongly enhanced for wavelengths that are group-velocity matched with the pump. In both cases, an enhancement of more than two orders of magnitude is observed. Based on the spatial walk-off effect, we have constructed a new type of optical parametric generator. Up to 30% of the pump photons are converted into the signal beam, which is nearly single-mode spatially and tunable over the range 1400-1700 nm. Conveniently, its twin is in the visible wavelength range and is anti-correlated with the signal beam in wavelength and correlated in photon number. ■



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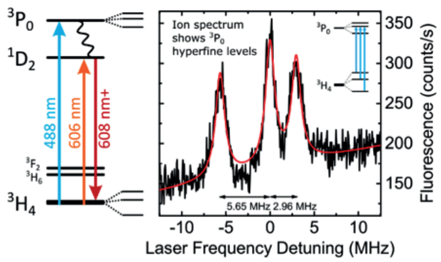
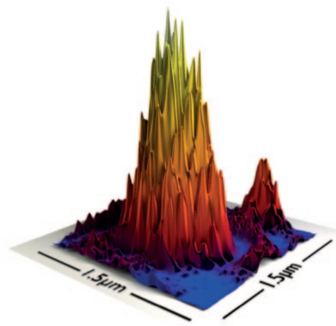
Reference: A. M. Perez et al., Nature Comm. **6**, 7707, (2015).

SINGLE RARE-EARTH IONS IN A NEW LIGHT

Over the last two years single rare-earth ions doped into a crystal have emerged as a new species of solid-state quantum emitter. The unrivalled long coherence times of these ions represent an important step towards scalable quantum memories. In 2013 we demonstrated the first detection of single praseodymium ions in a YSO crystal using high-NA cryogenic microscopy. By tuning a narrow-band laser over the $^3H_4$-$^3P_0$ transition, single ions could be isolated from a large inhomogeneously broadened ensemble. Recently, we have expanded the accessibility of our system to a second scheme, where both excitation and detection are now achievable via the $^3H_4$-$^1D_2$ transition, which is more commonly studied. We have further studied the arrival statistics of the emitted photons, which provides the final proof of the quantum nature of the system. By improving our sample preparation technique, we have also significantly reduced the strain/stress-broadened single ion linewidths down to 1.26 MHz, thus resolving the excited state hyperfine-splitting. ■





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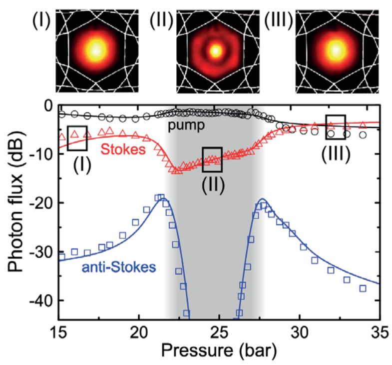
Group: *Sandoghdar Division*
Reference: E. Eichhammer et al., New J. Phys. **17**, 083018 (2015).

DRAMATIC SUPPRESSION OF RAMAN GAIN IN HYDROGEN-FILLED HOLLOW-CORE PCF

In 1964 Bloembergen and Shen predicted that gain in Raman-active media, i.e. the exponential amplification of Stokes signals down-shifted with respect to the pump frequency by a transition frequency of Raman-active molecules, could be coherently suppressed if the rates of phonon creation and annihilation exactly balance. This only occurs if synchronous, collective molecular oscillations, i.e., phonon coherence waves created by pump-to-Stokes scattering, are identical to those annihilated in pump-to-anti-Stokes scattering. In free space, this can only be accomplished over limited interaction lengths via non-collinear geometries. In contrast, by using a gas-filled kagomé-type hollow-core PCF, we demonstrate the first dramatic suppression of the Raman gain over long collinear path-lengths in hydrogen. This is achieved by operating close to the pressure-tunable zero dispersion point of the fibre, where the conditions for coherent gain suppression are fulfilled. Thus, at a precise pressure, generation of Stokes and anti-Stokes bands in the fundamental mode is entirely suppressed (see Figure), allowing other processes such spontaneous Raman scattering to be investigated in regimes of high luminosity. This study may have implications in quantum information and particle micromanipulation. ■



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Group: *Russell Division*
Reference: S. T. Bauerschmidt et al., Phys. Rev. Lett. **115**, 243901 (2015).

THIRD MAX PLANCK CENTRE IN NORTH AMERICA OPENS AT UNIVERSITY OF OTTAWA

May 26th, 2015: The University of Ottawa signs a formal partnership with the Max Planck Society establishing the Max Planck-University of Ottawa Centre for Extreme and Quantum Photonics. The third Max Planck Centre in North America, it will link two of the world's foremost research teams in optics and photonics, covering activities such as the development of very high intensity laser sources, a quintessential technology for future advanced manufacturing processes, optical methods for quantum information science for use in secure data transmission over optical fiber systems and the fabrication of devices for use in classical and quantum photonics. The cornerstone of this partnership will however be the international exchange of young scientists between Canada and Germany, giving them the opportunity to explore different scientific cultures early on in their professional development. The principal investigators from the University of Ottawa in the new centre will be Professor Paul Corkum, National Research Council-Canada Research chair in attosecond photonics, Professor Robert Boyd, Canada Excellence Research chair in quantum nonlinear optics and Pierre Berini, University Research chair in surface plasmon photonics. The principal researchers from Germany include Professor Ferenc Krausz, Max Planck Institute for Quantum Optics in Garching as well as the three MPL directors. ■

OSA STUDENT CHAPTER: FIELD TRIP TO OSRAM

A highlight of the OSA Student Chapter activities this year was a field trip to OSRAM in Regensburg. The 30 participants first attended a talk on research and development at OSRAM Organic Light Emitting Diodes. Next they visited OSRAM Opto Semiconductors, where after an introductory talk on light emitting diodes (LEDs) they went on a guided tour of the LED fabrication facilities. In the afternoon they had a get-together in a beer garden with view over the old town of Regensburg. ■

PANEL DISCUSSION ON DATA SECURITY

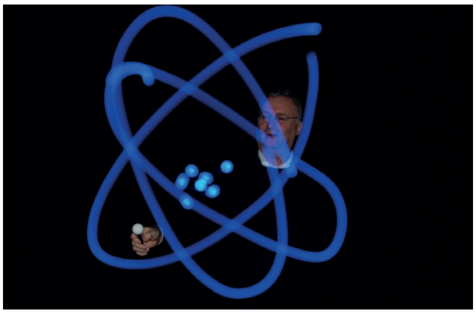
On May 7, 2015 the Museum of Communication in Nuremberg hosted a Max Planck Forum, an evening event that is open to the public. The topic of the session was the currently hotly debated issue of internet security. Gerd Leuchs and Michael Backes, Professor at the Saarland University and Max Planck Fellow at the Max Planck Institute for Software Systems in Saarbrücken, outlined their views on the subject. In an introductory talk, Michael Backes sketched the manifold aspects of data security including computer safety, while Gerd Leuchs focused on cryptography and on the current research into algorithm and information-theory based security. In the subsequent panel discussion, it became apparent that it is extremely difficult to prevent private data from being accessed by powerful eavesdroppers such as the intelligence services. In the lively discussion that followed, it became clear, however, that the first step is to increase user awareness of the security risks so that they can modify their behaviour. ■

6TH IMPRS ANNUAL MEETING

The sixth annual meeting of the IMPRS Physics of Light took place in Gößweinstein from October 5-8, 2015. Invited lectures were given by Anne Sentenac (L'Institut Fresnel), Jean-Michel Gérard (Institute for Nanoscience and Cryogeny, CEA), Mikael Käll (Chalmers University of Technology) and Albert Stolow (University of Ottawa). The programme also included two block lectures by Peter Hommelhoff (FAU) and Christoph Marquardt (MPL) as well as student talks, poster presentations and a panel discussion. Ankan Bag (Optics & Information) was awarded the prize for the best student talk and Ramin Beravat (Photonic Crystal Fibre Science) received the best poster award. ■

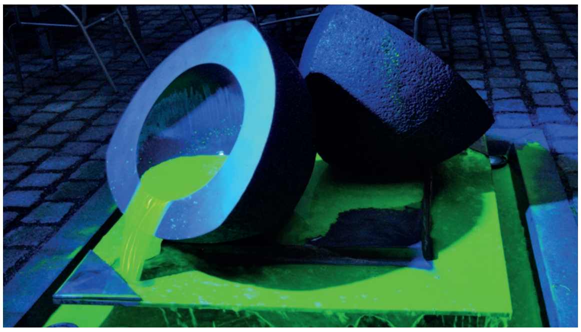
LONG NIGHT OF SCIENCE

The 7th "Long Night of Science" which took place October 24, 2015 in the conurbation of 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 up its doors, offering demonstrations of the fascinating effects that can be produced with light. Visitors could even paint with light. ■



DIE.LICHTBÜHNE

In 2013, the year 2015 was declared by the United Nations General Assembly to be the International Year of Light and Light-based Technologies (IYL2015). The goal of this global initiative is to "highlight to the citizens of the world the importance of light and optical technologies in their lives, for their futures, and for the development of society". die.Lichtbühne ("light stage") was MPL's main public outreach activity in IYL2015. At city centre locations, passers-by were invited to visit the MPL booth, listen to exciting short presentations and witness a number of different experiments with light, each with a different scientific focus. In total we held six very successful events in the Erlangen pedestrian precinct, during the "Blaue Nacht" (a famous public art event in Nürnberg) and at FAU's "Schlossgartenfest". ■



NEW EMPLOYEES

We warmly welcome Dr Katrin Bauer (Vahid Sandoghdar's new PA), Carolin Gacha-Avdic (who takes over the running of the Welcome Center), Mulugeta Aron (in charge of planning the relocation to the new building), Hannes Wirth (technical services) and Renate Bastuck (accounting). ■

NEWS IN BRIEF

- **Peter Banzer** is the new IMPRS coordinator, replacing **Tijmen Euser** who has been appointed to a lectureship in physics at the University of Cambridge.
- **Bettina Heim** becomes MPL's new Scientific Coordinator.
- **Michael Krüger** receives the Max Planck Society's Otto Hahn Medal.
- **Curtis Menyuk** wins Humboldt Research Award and will be a guest in the Russell Division.
- **Vahid Sandoghdar** is elected fellow of the Optical Society (OSA).
- **Harald Schwefel** is now senior lecturer in physics at the University of Otago, New Zealand.
- **Richard Taylor** receives an Alexander von Humboldt Fellowship.
- **John Travers** has been awarded an ERC Starting Grant.
- MPL will host the **23rd Central European Workshop on Quantum Optics** in 2016.

Imprint

Publisher:
Max Planck Institute
for the Science of Light
Günther-Scharowsky-Str. 1 / Bldg 24
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