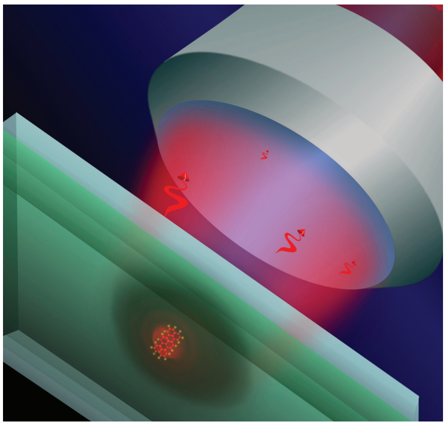
MAX PLANCK INSTITUTE
for the science of light

Newsletter

n°4 | March 2012

DESIGN FOR 99% EFFICIENCY IN COLLECTING PHOTONS FROM A SINGLE EMITTER

▸ Detection, spectroscopy and control of single optical emitters such as organic molecules, semiconductor quantum dots, and color centers have made rapid progress in the past two decades. Two examples of the most outstanding impact of this research field are the demonstration of single-photon sources and applications to single-molecule biophysics. Both these lines of research are limited by the intrinsically weak radiation of a single emitter and would, therefore, benefit from more efficient collection strategies. Over the years many groups have examined this issue in different ways, but the existing realizations fall substantially short of unity collection efficiency. Recently, we devised a planar metallo-dielectric antenna

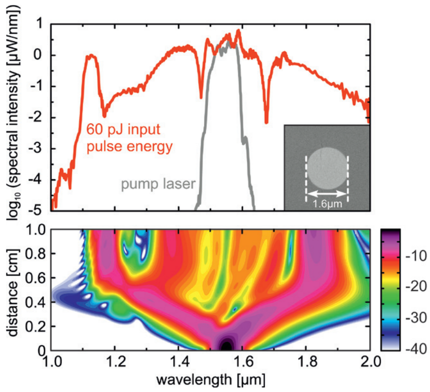


to redirect the emission into well-defined modes and achieved 99% efficiency in collecting photons from a single emitter with an arbitrary orientation of transition dipole moment. Some of the remarkable features of our design are broadband operation, no need for lateral nanofabrication and compatibility with essentially all materials. This work opens important doors in a wide range of contexts including quantum optics, quantum metrology, nano-analytics, and biophysics. ■

Contact: xuewen.chen@mpl.mpg.de
Group: *Sandoghdar Division*
Reference: X. Chen, S. Götzinger and V. Sandoghdar, Opt. Lett. **36**, 3545 (2011)

INFRARED SUPERCONTINUUM GENERATION

▸ By pumping molten chalcogenide glass into silica capillaries at high pressure, we were able to fabricate cm-long hybrid step-index waveguides with a highly nonlinear chalcogenide core only 1.6 μm in diameter, the silica cladding providing a sheath for the mechanically less robust chalcogenide glass. Upon launching ultrashort near IR-pulses into the chalcogenide



core, we observed an octave-spanning supercontinuum from 980 nm to 2000 nm. The experimental results are in good agreement with numerical simulations. The pressure-filling technique uniquely allows chalcogenide glasses to be integrated into silica fibres, leading to highly nonlinear devices with windows of transmission that can extend into the IR. Such hybrid fibre waveguides may be useful as IR supercontinuum sources for a variety of scientific and technical applications, such as mid-IR spectroscopy, microscopy, frequency metrology or optical coherence tomography. ■

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Group: *Russell Division*
Reference: N. Granzow et al., Opt. Express **19**, 21003 (2011)

Inside *THIS ISSUE*

Message FROM THE DIRECTORS

2011 was a busy and exciting year at MPL. Together with a large team from a Munich-based architect's agency and technical experts from the Max Planck Society, we specified various aspects of our planned new building. Issues ranging from vibration and temperature control, canalization of gases and the ventilation system as well as the landscaping of the surrounding grounds all had to be carefully planned and budgeted. We expect to move in 2015 and until then we will be expanding at our current site on the Siemens campus.

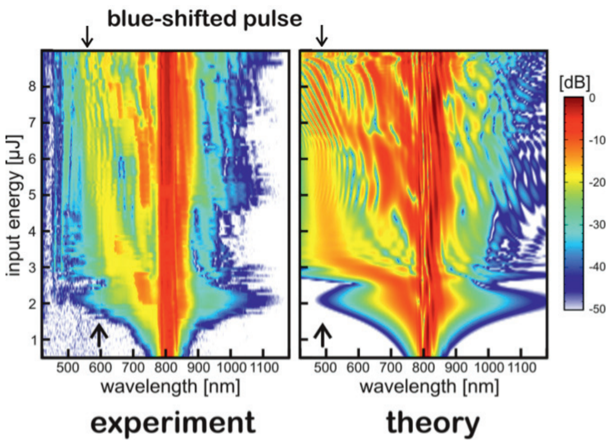
Last June experiments and equipment for the newly founded Nano-Optics Division were transported from Zurich to Erlangen (see photograph on the right). Together with the technical staff of MPL, the enthusiastic new members of the Sandoghdar group have done wonders in getting all the experiments up and running in a matter of just three months. We look forward to new exciting results from them. Having settled the third division, MPL has begun its search for a fourth director, guided by the Chemistry-Physics-Engineering section of the Max Planck Society. We hope to be in a position to make an announcement later this year.

In November 2011 we organized a symposium under the heading "Future Perspectives in the Science of Light", during the course of which we met with the Max Planck committee that is overseeing the future development of MPL. In a series of inspiring keynote lectures, leading scientists from Europe and USA gave their view of the future development of optics and photonics research in the 21st century (see page 8).

We wish all readers of this Newsletter a happy and successful 2012!

NONLINEAR FIBRE OPTICS IN THE IONISATION REGIME

Optically induced ionisation in gases pumped by energetic few-cycle pulses is commonly used to generate extreme ultraviolet light and produce attosecond pulses. On the other hand, glass-core photonic crystal fibre (PCF) has been remarkably successful in studies of soliton dynamics and supercontinuum generation. Here we use argon-filled hollow core PCF to study soliton-driven ionisation. The combination of anomalous dispersion and nonlinearity permits compression of 800 nm femtosecond pulses to the few cycle regime. When a sufficiently energetic pulse is compressed in this way it ionizes the atoms, causing a field-dependent lowering of the refractive index that does not recover within the duration of the pulse, i.e., it imposes a positive phase shift and consequentially a blue-shift in frequency.



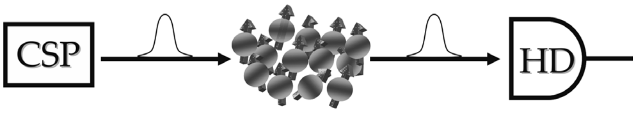
Blue-shifted pulses can be first seen at 2 μJ, and again at higher energies (~4 μJ). Analysis shows that these pulses propagate as solitons. In the experiments intensities of $\sim 10^{14}$ W/cm^2 are reached, with ionisation fractions as high as 0.5% and plasma interaction lengths of several cm. The ready accessibility of these extreme parameter ranges moves nonlinear single-mode fibre optics into the realm of high-field science. ■

Contact: john.travers@mpl.mpg.de
Group: *Russell Division*
References: P. Hölzer et al., Phys. Rev. Lett. **107**, 203901 (2011)

Heavy lifting during Vahid Sandoghdar's move to MPL.

HOW TO DECOMPOSE ARBITRARY CONTINUOUS-VARIABLE QUANTUM OPERATIONS

How can one implement an arbitrary quantum process from a small, finite set of experimentally realizable operations?



Lloyd and Braunstein's seminal work of 1999 partially answered this question. They gave the minimal requirements that the experimental gate set should satisfy, but a systematic and efficient approach has still been missing. In our recent work, we provide such a systematic recipe for an arbitrary operation acting upon arbitrarily many quantum oscillators (such as optical field modes). Our treatment brings the abstract notions of continuous-variable quantum computation close to experimental implementation. Accordingly, we present an explicit experimental proposal for a remarkably simple universal quantum information processor (see figure) using a conditional source (CSP) preparing quadratric (squeezed) and cubic optical states, an ensemble of atoms, and a homodyne detector (HD). The optical pulses emerging from the CSP interact once or a few times with the atomic ensemble and are eventually measured by the HD. Quantum information is stored, processed, and finally read out through the atomic ensemble. ■

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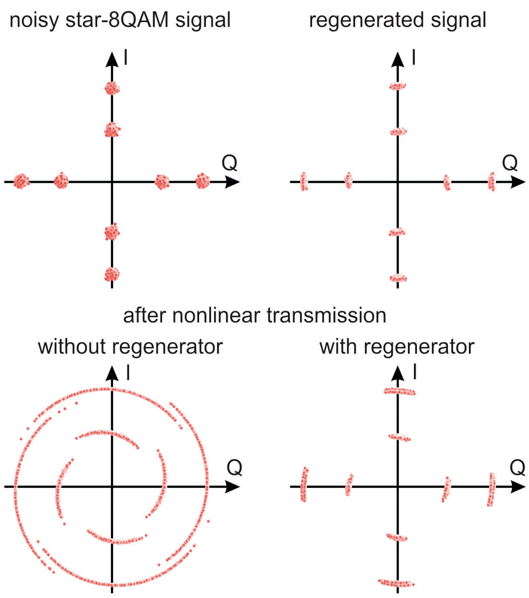
Group: *Optical Quantum Information Theory (Emmy Noether Research Group)*
Reference: S. Sefi, P. van Loock, Phys. Rev. Lett. **107**, 170501 (2011)

ALL-OPTICAL MULTILEVEL SIGNAL REGENERATION

Quadrature amplitude modulation (QAM) as a combination of multilevel amplitude- and phase-shift keying is one of the most promising options to increase the transmission capacity of optical fibre communication systems. Because of small state spacing, the QAM formats are very sensitive to amplitude and phase noise. A possibility of multilevel phase-preserving amplitude regeneration using a nonlinear amplifying loop mirror (NALM) has been demonstrated for the star-8QAM transmission format as an example. For quite efficient amplitude noise suppression at both amplitude levels simultaneously (see figure), optimization of the coupler splitting ratio and the directional phase bias in the NALM is all that is required, yielding at least 6 dB noise reduction in the high power amplitude state. Bit error ratio (BER) simulations show that in a transmission system, limited by nonlinear phase noise, such signal regeneration allows an increase of the fibre launch power by ~2 dB at a BER of 0.001 for state power ratios from 1:3 to 1:7. Further improvements in performance are possible by using a cascade of regenerators, each optimized for one amplitude state, or introducing amplifier gain nonlinearity in the NALM. ■



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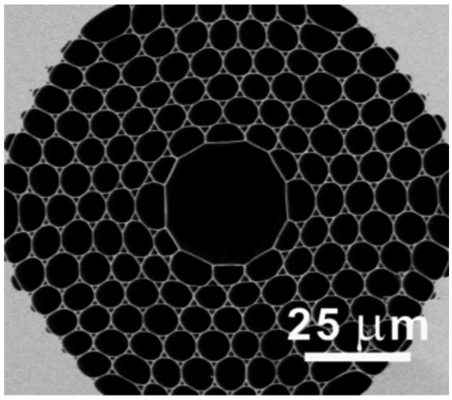
Group : *Leuchs Division*
Reference : M. Hierold et al., IEEE Photon. Technol. Lett. **23**, 1007-1009 (2011)

FIRST GUIDING HOLLOW-CORE PHOTONIC CRYSTAL FIBRE MADE FROM SOFT GLASS

Recently we successfully fabricated a soft glass (i.e., compound glass) hollow-core photonic crystal fibre offering single-mode guidance over a 750-1050 nm spectral window with a minimum loss of 0.74 dB/m. The fibre is made from a high-index lead-silicate glass (Schott SF6, refractive index 1.82 at 500 nm). Soft glasses based on heavy-metal oxides, fluorides and chalcogenides, are generally of interest for optical fibres due to extended mid-infrared transmission, higher Kerr nonlinearities and lower melting/processing temperatures. Making microstructured fibres from such glasses is however quite difficult owing to lower thermal stability and a narrower temperature range (< 50°C compared to ~300°C for silica) where the



viscosity is suitable for drawing. Until this report, successful fabrication of soft glass PCFs has been restricted to a few glass compositions, light guidance only being demonstrated in solid-core PCFs. The hollow core is formed from a 7-cell defect embedded in a highly uniform 6-layer cladding structure that resembles a kagomé-like lattice. The fibre shows single-mode guidance over the whole transmission range (750-1050 nm) despite having a large core diameter of ~30 μm. Finite-element calculations indicate that this single-mode behaviour is due to the fibre geometry as well as to the higher index of the glass material. ■

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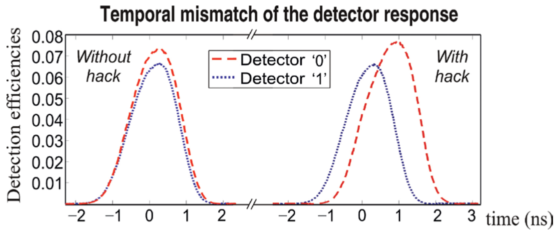
Group: *Technology Development & Service Unit: Fibre Drawing*
Reference: X. Jiang, et al., Opt. Express **19**, 15438 (2011)

DEVICE CALIBRATION IMPACTS SECURITY OF QUANTUM KEY DISTRIBUTION

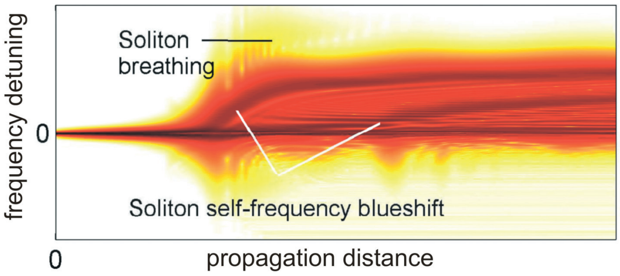
Quantum Key Distribution (QKD) offers unconditional security based on the laws of quantum mechanics: An eavesdropper *Eve* introduces errors while listening to the key-exchange between two legitimate parties, *Alice* and *Bob*, which gives away her presence. If however the theoretical model is not properly implemented, loopholes may arise that allow Eve to successfully breach the security. Most QKD systems routinely perform calibration sequences to ensure that various optical channels and components are properly aligned/synchronized. An inappropriately-implemented calibration may thus open a fatal security loophole. In recent work we have successfully demonstrated a hack to induce a large temporal detector efficiency mismatch in a commercial QKD system by deceiving a channel-length calibration sequence. The post-hack mismatch between the efficiencies $\eta_0(t)$ and $\eta_1(t)$ was almost two orders of magnitude higher (see figure). Employing faked states, we then also devised an optimal and realistic strategy for eavesdropping on the key, without alerting Alice and Bob. A countermeasure against this loophole was also suggested. Given that QKD aims to be the next disruptive technology for secret communications, it is vital that such loopholes in practical implementations are discovered and weeded out in time. ■



Contact: nitin.jain@mpl.mpg.de
Group: *Leuchs Division*
Reference: N. Jain et al, Phys. Rev. Lett. **107**, 110501 (2011)

BLUE-SHIFTING SOLITONS IN FIBRE-BASED GAS-PLASMA

When a hollow-core PCF is filled with ionisable gases, many interesting effects can be observed in the pulse propagation. A series of important phenomena were discovered in experiments performed in the Russell Division at MPL (Hoelzer et al., Phys. Rev. Lett. 107, 203901 (2011), see also the corresponding article in this newsletter), where short pulses were launched into a fibre with a so-called kagome-type cladding, that allows for broadband transmission. After initial compression, the pulse intensity increases above the ionization threshold, generating an electron plasma in the fibre core. This plasma exhibits a peculiar optical nonlinearity that produces a continuous soliton blue-shift, limited only by ionization losses. We have developed a theoretical model based on novel evolution equations, that are able to describe the above blue-shift (see figure, plotted in dimensionless units), plus a variety of new phenomena, such as non-local interactions between temporally distant pulses, modulational instability and special kinds of bound states held together by the plasma. ■



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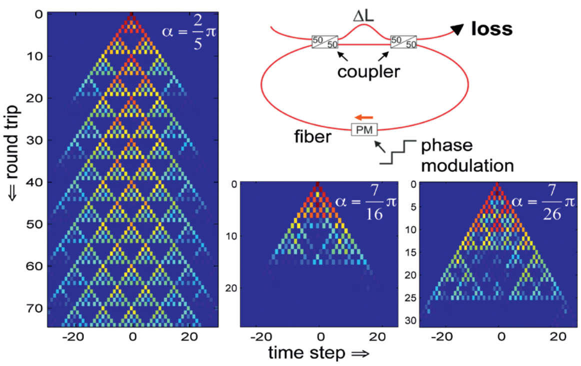
Group: *Nonlinear Photonic Nanostructures (MPRG)*
Reference: M. Saleh et al., Phys. Rev. Lett. **107**, 203902 (2011)

LOSSES BRING PHOTONS INTO FRACTAL ORDER

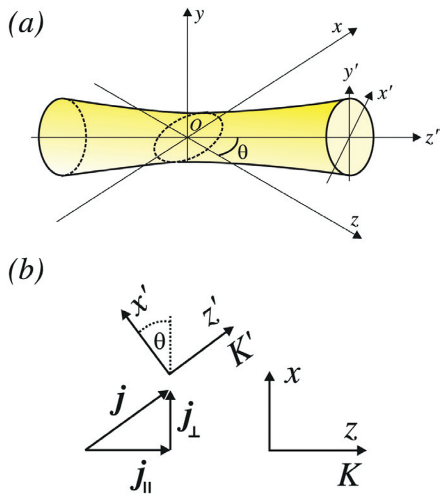
Usually losses in optics are considered a nuisance that has to be avoided. Here we demonstrate the unsuspected formation of beautiful fractal patterns in the presence of photon losses. Experiments were realized in a fibre loop setup using standard telecommunication equipment. In each round trip, photons can travel either a short or a long way resulting in the discrete spreading of a pulse pattern. In addition, some light gets lost at the open end of a coupler. If a temporally growing phase is applied in each round trip, an ordered pattern evolves. Starting with a single pulse, the resulting structures have similarities to the dynamics of cellular automata or to the famous Sierpinski triangle. The nature of the pattern can be tuned by varying the phase step α applied between subsequent pulses. The more irrational the phase step expressed in fractions of π, the more fractal is the evolving structure. In the future, this finding will help towards the generation of all-optical pseudo-random bit sequences. ■



Contact: alois.regensburger@mpl.mpg.de
Group: *Leuchs Division*
Reference: A. Regensburger et al., Phys. Rev. Lett. **107**, 233902 (2011)

GEOMETRIC SPIN HALL EFFECT OF LIGHT

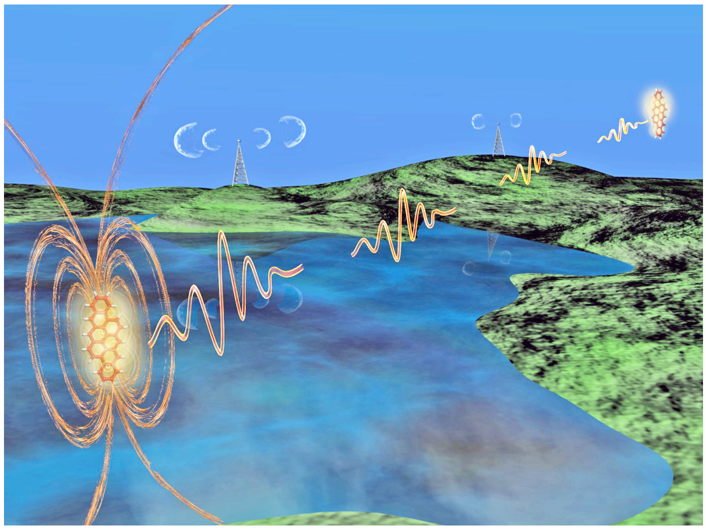
In modern physics, “Hall effect” identifies a broad class of phenomena comprising transverse displacement of an electric current in the presence of an external field (Hall Effect - HE), transverse movement of electron spins (spin HE), and the photonic version thereof, namely the spin Hall effect of light (SHEL). In its simplest manifestation, SHEL amounts to a transverse displacement of a light beam when refracted by an air-glass interface. Such a displacement occurs in a plane perpendicular to the plane of incidence, namely the plane containing the incident and the refracted beam, and depends on the light polarization. It was recently suggested that, even in the absence of a refracting surface, a transverse displacement of the intensity distribution of light (namely, of the flux of the Poynting vector) may be observed in a plane non-orthogonal to the main propagation of the beam *(a)*. This effect has a purely geometric nature and it is known as *geometric* SHEL (GSHEL). It appears whenever a beam possesses a non-zero transverse angular momentum *(b)*. The occurrence of GSHEL is not limited to light, and may manifest itself also in matter systems such as electronic and atomic beams. ■



Contact: andrea.aiello@mpl.mpg.de
Group : *Leuchs Division*
Reference : J. Korger et al., Appl. Phys. B **102**, 427-432 (2011)

TWO MOLECULES COMMUNICATE OVER LARGE DISTANCES VIA SINGLE PHOTONS

In our latest work, we realized one of the most elementary and oldest “gedanken” experiments in modern physics, namely, excitation of a single molecule with a single photon. Interaction of single atoms and single photons has been explored in the past two decades by using optical microcavities, but experiments with freely-propagating photons have been more demanding. To perform such studies, one requires a *bright* and *tunable* stream of single photons with a *narrow* bandwidth. A convenient source is a single emitter, but a typical atom, molecule, quantum dot, or color center can only emit a limited number of photons per second, and since only a fraction of these are collected by the usual optical elements, the remaining power is less than pW.



The next important challenge is to ensure that the precious single photons interact with the target molecule in an efficient manner. Interestingly, it turns out that if the incoming photons are resonant with the molecular transition, they confront scattering cross sections that are comparable to the area of the focused light beam. We had indeed already demonstrated, using classical laser light, that although a molecule is only about 1 nm large, it can intercept a large fraction of the incoming photons. To get to this regime, solid-state emitters have to be cooled to avoid broadening by thermal agitations.

In our experiment, we used two samples containing aromatic molecules embedded in organic crystals and cooled them to about 1.5 K. Single molecules in each sample were detected by a combination of spectral and spatial selection. To generate single photons, we excited a single molecule in the source sample to the first vibrationally excited state of the electronic excited state. After a rapid decay to the vibrational ground level, the molecule could emit one lifetime-limited photon at a time. The emitted single-photon stream was then directed toward the target sample at a distance of a few meters, where it was focused tightly. To tune the frequency of the incident photons to the transition of the target molecule, we exploited the Stark effect via gold microelectrodes on the sample. In this fashion, we succeeded in performing extinction spectroscopy on a single target molecule.

Our results provide the first example of long-distance communication between two quantum optical antennas in a manner similar to the 19th century experiments of Hertz and Marconi with radio antennas. In those early efforts, dipolar oscillators were used as transmitting and receiving antennas. In our recent experiment, two single molecules mimic that scenario at optical frequencies and via a nonclassical optical channel, namely a single-photon stream. This paves the way for further experiments in which single photons act as carriers of quantum information to be processed by single emitters in the solid state. ■

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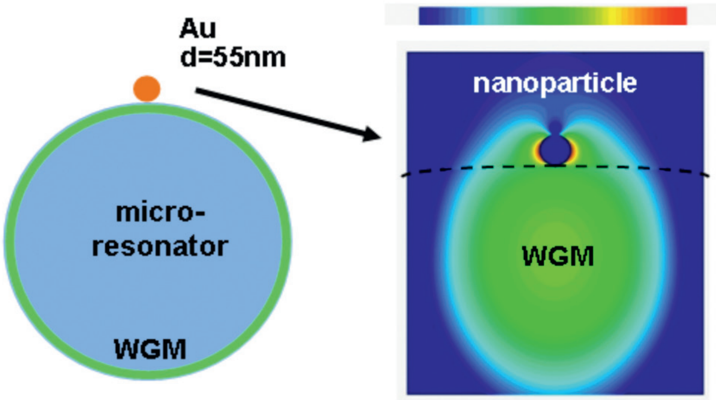
Group: *Sandoghdar Division*
Reference: Y. Rezus et al., Phys. Rev. Lett. **108**, 093601 (2012)

NANOPARTICLE-BASED PROTEIN DETECTION BY RESONANT MICROCAVITY

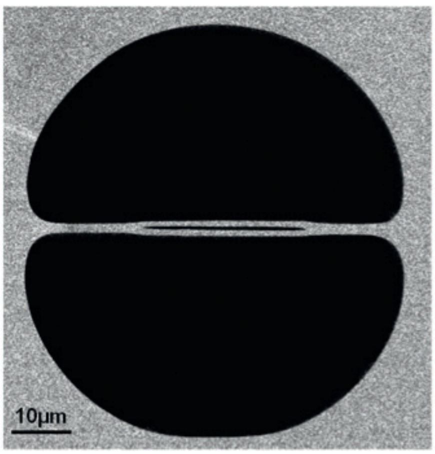
Label-free detection of single molecules has been a dream of biologists and biotechnologists. We have come one step closer towards achieving this goal by coupling optical resonators to nanoplasmonic structures. We use whispering gallery modes (WGM) in optical microsphere resonators to excite plasmon resonances in 55nm gold nanoparticles. Strong electromagnetic field strengths (hotspots, in red) are observed at the nanoparticle site, without significant impairment of the quality factor of the resonator. If a molecule binds to the hotspot location it tunes the resonance frequency of the optical resonator in proportion to the encountered field strength. The hotspots can provide large sensitivity enhancements, bringing label-free single molecule detection possibly within reach. Such detection capability is essential for designing next generation biosensors and elucidating the mechanisms of molecular machines. We have demonstrated this new sensing concept in collaboration with Penn State and Boston Universities in our recent cover paper in Applied Physics Letters. ■

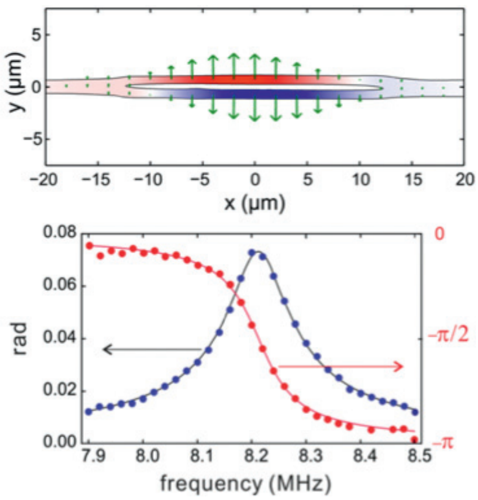


Contact: frank.vollmer@mpl.mpg.de
Group: *Biophotonics and Biosensing (MPRG)*
Reference: M.A. Santiago-Cordoba et al., Appl. Phys. Lett. **99**, 073701 (2011)

OPTOMECHANICAL INTERACTION AND NONLINEARITY IN DUAL-WEB FIBRE

Attractive or repulsive forces appear between two coupled waveguides when light is launched into them. So far, this has been explored in microstructures fabricated on silicon-on-insulator wafers. We have recently developed a new type of optomechanical device: an optical fibre consisting of two sub-micron thick parallel glass sheets ("nanowebs") separated by an air-gap of ~500 nm and suspended inside a fibre capillary. The nanoweb pair supports even and odd eigenmodes. In the case of the even optical mode the webs are attracted to each other, whereas for the odd mode they are pushed apart, although in both cases the refractive index rises with launched optical power – a phenomenon that we refer to as an optomechanical nonlinearity. It exceeds the Kerr nonlinearity by orders of magnitude and can be further enhanced by resonant excitation of the structure with light, amplitude-modulated in the vicinity of the mechanical eigenfrequency. The optomechanically induced web vibration results in dynamic changes in refractive index ~10,000 times higher than the Kerr effect. ■

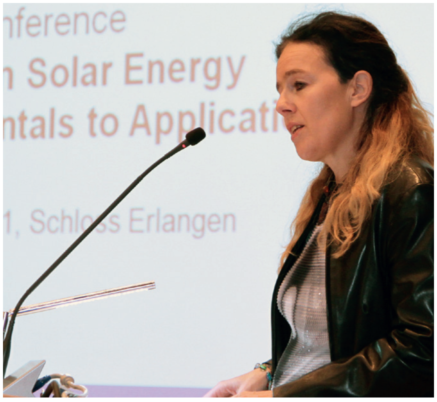




Contact: anna.butsch@mpl.mpg.de
Group: *Russell Division*
Reference: A. Butsch, et al., post-deadline paper PDPC3, Frontiers in Optics, San Jose (2011)

NEXT GENERATION SOLAR ENERGY SYMPOSIUM

The international symposium "Next Generation Solar Energy" (NGSE) took place on 12-14 December 2011 in Erlangen. The objective was to present a comprehensive survey of the current status and future research and development activities in the field. MPL was one of the hosts of this event together with the Cluster of Excellence Engineering of Advanced Materials (EAM), the Friedrich-Alexander-University Erlangen-Nürnberg (FAU), the Bavarian Center for Applied Energy Research (ZAE Bayern) and the Institute of Photonic Technologies (IPHT) in Jena. This successful event was organizationally supported by the Bayern Innovativ GmbH (Cluster Energy Technology). ■



PD Dr. Silke Christiansen (MPL)
Foto: Bayern Innovativ GmbH

HARRY POTTER CHRISTMAS LECTURE

This year, the physics department's Christmas Lecture took place on December 8 at the "Physikum", in a packed lecture hall G. Under the title "Harry Potter und das dunkle Geheimnis des Lichts", Gerd Leuchs and his co-workers took the audience on an entertaining journey through the fascinating world of optics. Both students and members of the general public followed Harry as he discovered polarization ghosts, flying dragons and secret messages, to mention only a few of his adventures. We would like to thank all of you who contributed to making this event a great success! ■

MIN JUN KIM JOINS THE VOLLMER LAB

Dr. Min Jun Kim from Drexel University has been awarded an Alexander von Humboldt Fellowship. As a PhD student at Brown University he held the Simon Ostrach Fellowship, thereafter working at the Rowland Institute (Harvard) as a postdoc. During his stay at MPL he plans to study the assembly and operation of multi-functionalized hybrid nanopore systems, as well as developing prototype systems for high-throughput single molecule analysis. ■

LONG NIGHT OF SCIENCE

The fifth "Long Night of Science" took place on the 22nd October 2011 in Nürnberg, Fürth and Erlangen and was a great success. Over 28,000 science-hungry 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 and answering questions such as: Can you make balloons burst by using a laser? What does a laser graffiti look like? A highlight was a visit to the Glass Studio where Ralf Keding produced Christmas decorations from molten glass. ■

IMPRS ANNUAL MEETING

The second IMPRS Annual Meeting was held 26-31 September 2011 at the Welcome Hotel in Bamberg. Invited lecturers included Miles Padgett (Glasgow University), Daniel Rückert (Imperial College), Eberhard Riedle (LMU, Munich), and Femius Koenderink (AMOLF, Amsterdam). Students and advisors took part in an extended poster session, a panel discussion and evening strolls in Bamberg's beautiful city centre. Eva Eibenberger received the best poster award and Christian Weis the award for the best student talk. ■

MPL NEW BUILDING

In February 2011 Fritsch+Tschaidse Architects, Munich, won the competition for the new institute building of MPL. Since then the planning process has got underway, involving a team of specialized engineers, the architect, the Max Planck headquarters and MPL as the future user. By December 2011 detailed plans were finalized and now await approval by the different authorities. If all goes well the call for tenders will be issued in the second half of 2012 and breaking ground will be in spring 2013. We expect to be able to move into the new building in summer 2015. ■

IMPRS EXTENSION

We are pleased to report that the Max Planck Society has approved a 6-year extension for the Erlangen International Max Planck Research School, which is now funded until the end of 2017. IMPRS-OPTIM offers an extended range of PhD topics through its new advisors Professor Andreas Tünnermann (University of Jena and Fraunhofer Institute for Applied Optics and Precision Engineering), Professor Vahid Sandoghdar, Dr Frank Vollmer and Dr Fabio Biancalana (MPL) and Professor Florian Marquardt (University of Erlangen-Nuremberg). Interested Masters students are encouraged to apply via our website www.mpl.mpg.de/imprs/ (submission deadlines 31st January and 31st July). ■

WELCOME TO DR SANJAY KUMAR SRIVASTAVA

Dr Srivastava from the National Physical Laboratory in India has been awarded BOYSCAST (Better Opportunities for Young Scientists in Chosen Areas of Science & Technology) fellowship. He plans to work with Silke Christiansen on photovoltaic applications of silicon nanostructures. ■

FUTURE PERSPECTIVES IN THE SCIENCE OF LIGHT

The aim of this symposium, which was held at MPL 24-25 November 2011, was to explore the views of leading scientists on the future development of photonics and optics in the 21st century. We were delighted that Javier Aizpurua (San Sebastián), Stephen Barnett (Strathclyde), Michael Fleischhauer (Kaiserslautern), Oskar Painter (Caltech) and Ian Walmsley (Oxford) were able to find time to visit us and give a series of inspiring lectures. The symposium was dedicated to Professor Tony Siegman, the well-known laser pioneer and Stanford professor who passed away suddenly in October. Tony was a good friend to MPL, being a valued member of the committees that helped shape it. ■

From left to right: Vahid Sandoghdar (MPI for the Science of Light), Stefan Hell (MPI for Biophysical Chemistry), Stephen Barnett (Strathclyde), Javier Aizpurua (San Sebastián), Michael Fleischhauer (Kaiserslautern), Oskar Painter (Caltech), Philip Russell, Gerd Leuchs (both MPI for the Science of Light). Missing on the picture: Ian Walmsley (Oxford).

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