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SPECIAL ISSUE ON THE SCIENCE OF LIGHT

Guiding light | Light for bio-imaging | Light for brevity | Controlling light at the nanoscale | Extreme light | Quantum light

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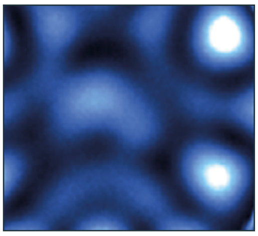
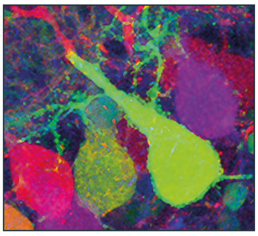
Cover picture: Girl making Rangoli design and decorating with oil lamps for Diwali, an ancient Hindu festival. ©iStockPhoto
Special issue on the science of light, pages 12 to 39.



▲ PAGE 13

Guiding light



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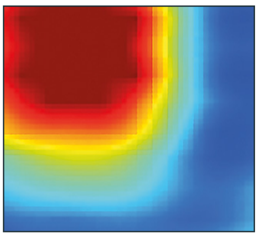
Light for bio-imaging



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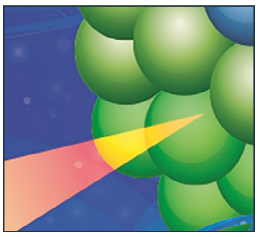
Light for brevity



▲ PAGE 31

Extreme light

EPS EDITORIAL

NEWS

HIGHLIGHTS

FEATURES

ANNUAL INDEX

BOOK REVIEW

OPINION

[EDITORIAL]

EPS and Physics for Development
Your help is needed

We all agree that EPS is a European Society for European physicists and that there is certainly more to be done to further improve its structure and its impact on scientific excellence and science policies.

On 2nd October a well-attended meeting with the presidents or representatives of about 25 National member societies took place in Brussels. It was an opportunity to share mutual information and concerns, listen to excellent talks on the role of EU organizations and on lobbying for science. Nevertheless all this commitment should not prevent us to think also of the acute problems encountered by our colleague physicists in developing countries of other continents such as Africa. Lack of funding, lack of public awareness, lack of institutional framework for research, lack of laboratory equipment and means for teaching. I was recently in Kenya visiting a public high school and some laboratories at the University of Nairobi, which is one of the well-functioning Universities and was impressed by the commitment of the people and a good organization. But the need for better lab equipment, for well-trained teaching staff and for the search and promotion of talented students of both genders is still very large. These countries are certainly already engaged in developing institutions dedicated to scientific research and technological innovation as they recognize their importance in achieving national and international competitiveness, but the way is still long.

The awareness of EPS for Physics for Development dates back to 1981 with the creation of the interdivisional group on Physics for Development (IGPD) by H. van Regemorter. In spite of continuous efforts this group has always been short of proper funding for its activities. Information on its mission and projects can be found in the new web site of the group (www.physdev.org).

To help funding some focused and well planned projects we need your support with personal commitment but also your financial help. This is why a Special Activity Fund has been set up to collect donations and support specific activities that are not in the main stream of EPS and cannot be financed within the EPS budget. At the beginning EPS will match each donation by the same amount until a total of € 50,000 is reached. The way how to donate can be found on our EPS website. It is important to state here that this Fund will be supervised by an independent group of persons, external to the EPS Executive Committee and checked regularly by an external audit.

We are well aware of the many different foundations acting for the development of science, the sharing of knowledge and contributing also to environmental and social problems but this does not prevent us physicists to participate and contribute our fair share.

These countries recognize the importance of scientific research and technological innovation in achieving national and international competitiveness, but the way is still long.

Hopefully this new initiative will be appreciated by all our members and be a further demonstration that our Society is always looking for new ideas, challenges and remains dedicated to the promotion of scientific excellence at all levels. Now your action and support is needed. In particular the valuable help from young physics students as well as from retired physicists, ready to spend some time for a good purpose, would be highly appreciated. We are also looking for your constructive comments and initiatives, helping to make your Society as lively and appealing as possible. ■

Christophe Rossel
President of the EPS

▾ Christophe Rossel talking about physics to students at a girls' high school in Nairobi.

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EPS HISTORIC SITES

The Institute of Radium Research

Boltzmanngasse 3, Vienna, Austria

On May 28th, 2015, the 21st EPS Historic Site Plaque was unveiled in front of the building Boltzmanngasse 3 in Vienna by Luisa Cifarelli, Chair of the EPS Historic Site Committee and past president of EPS, and Anton Zeilinger, the President of the Austrian Academy of Sciences.

Applying for the election of this first EPS Historic Site in Austria has been a double obligation to me: On the one hand I had myself been a doctor-grade's candidate at the Institute of Radium Research; on the other hand, I wished to assume my responsibility as the Director of the European Centre for the History of Physics ECHOPHYSICS, which has obtained on permanent loan from the University of Vienna the complete historical collection of the Institute for Radium Research—to be shown to the public at the ECHOPHYSICS exhibition on *Radiation and Mankind* at Poellau Castle in Styria, Austria.

Why had an EPS Historic Site to be dedicated at the building Boltzmanngasse No. 3 at all?

The Austrian Academy of Sciences had intended this institute to become their Institute for Radium Research right from the outset. From its inauguration in 1910, the very purpose of this research institution – the first institute worldwide of this kind – had been to explore the physical properties of the radioactive element radium discovered earlier in 1898. Following its example, the radium institutes in Prague, Paris and Saint Petersburg were established several years later. Imposing success had been fast in coming. The major contributions of Victor F. Hess, the discoverer of cosmic radiation, of George de Hevesy and Friedrich Paneth, the inventors of the use of isotopic tracers in the study of chemical processes, as well as those of Marietta Blau, pioneer in nuclear-emulsion detectors, all these achievements were completed at Boltzmanngasse 3. More could be added to the listing – yet do I wish to point out the three prerequisites, which this "house for the element of radium" brought in and which have led to the innovative potential of the Institute.

First, substantial capital had been invested: The generous donation by Karl Kupelwieser covered all the costs involved to erect the premises and to provide the complete instrumental equipment. In his proposal letter to the Academy, Kupelwieser pointed out that he wanted to prevent his country to "expose herself to the shame" of not conducting research in the new field of radium – Austria holding the monopoly on this fascinating element.

▲ From right to left: Caslav Brukner, Anton Zeilinger, Luisa Cifarelli, Margit Fischer, Eberhard Widmann, Peter M. Schuster. [Image source: SMI, Vienna]

Second, there has been this extraordinary atmosphere of collegiality. Exner — who had been revered by Schrödinger as the "Father of the Austrian School"— gathered around himself a circle of highly gifted young physicists, among whom are to be named Benndorf, Hasenöhrl, Hevesy, Kohlrausch, Meyer, Paneth, Przibram, von Schweidler and Schrödinger, all of them being not only the "Exner's sons" as von Schweidler had put it but who, moreover, were "also brothers with each other". And Stefan Meyer, the first Director of the Institute for Radium Research from its being established in 1910, continued this cordial solidarity. There was more: this new radium research had an interdisciplinary character and comprehended physics at highest priority, but also chemistry, geology, atmospheric research, and last but not least medicine. The institute was internationally oriented and hosted many famous scientists and also famous guests from abroad (Otto Hönigschmid, Hans Petterson). Possibly the atmosphere at the institute gained profit from its 50% of female scientist colleagues, an unparalleled gender balance at the time.

The third and to me as a physics historian the most impressive characteristic has been the meticulous way in which they had elaborated their discoveries at the Radium Institute. Victor F. Hess' procedure was typical: his extremely accurate and strict method of working combined with his scrupulous checking of hypotheses might best be put to the point through the motto for life he had given to his step-grandson: "Never assume!" At this Institute the scientists commonly practised the obstinacy to persevere in investigating one sole subject until the research work was fully concluded — for Hess it was about 'radioactivity and electrification in the air', a self-chosen life-lasting restriction which made him carry out tedious and assiduous measurements leading to his giving evidence of the existence of cosmic rays.

And this distinctive spirit has been felt by all who entered the house at a later time. Even ourselves fierce youngsters, the doctor-grade's candidates, experienced the exceptional atmosphere when entering the room of Professor Berta Karlik where she sat at her records, always deeply absorbed and nearly immersed in a sea of delicate flowers she adored.

Today the history of this building is being continued, under new names for the two institutes of the Austrian Academy of Sciences that it houses: The Stefan Meyer Institute for Subatomic Physics (SMI) and the Institute for Quantum Optics and Quantum Information Vienna (IQOQI Vienna).

The festive ceremony of unveiling the EPS Historic Site plaque was hosted by these two institutes. After the opening by the two directors, Eberhard Widmann of SMI and Caslav Brukner of IQOQI Vienna, a brief description of the history of the Institute for Radium Research was given by Peter M. Schuster, Chair of the History of Physics (HoP) Group of EPS. His talk was followed by short speeches of Martina Malyar, the district leader for the Boltzmanngasse 3, Luisa Cifarelli and Anton Zeilinger. The event also hosted Austria's First Lady Margit Fischer, representatives of the Austrian scientific community and numerous students and was concluded with a visit to the laboratories of the two institutes and a celebratory colloquium at the Austrian Academy of Sciences. ■

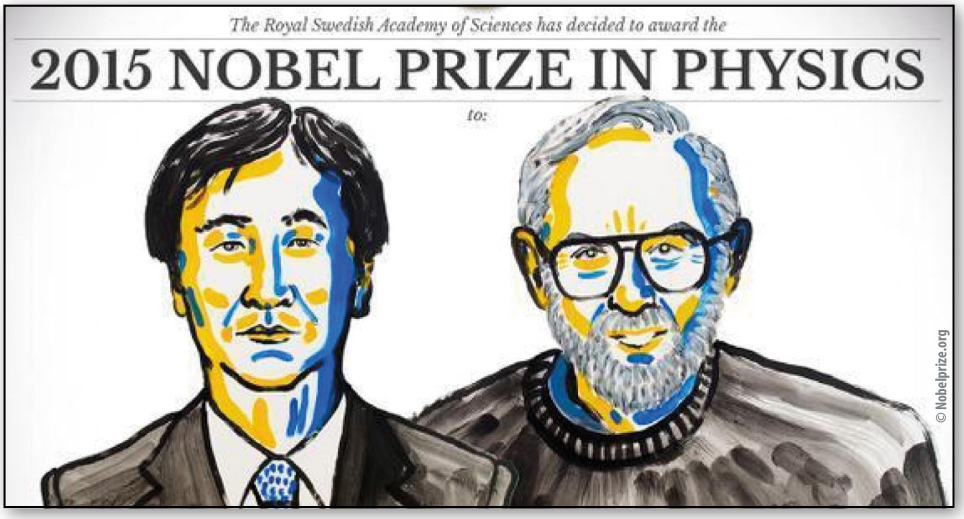
Peter M. Schuster
Director of Echophysics
Chair of the EPS History of Physics Group

▼ An actual view of the former Institute for Radium Research of the Vienna Academy of Sciences [Image source: © Blaschnek, Vienna]

The 2015 Nobel Prize in Physics

The 2015 Nobel prize in physics was attributed to Takaaki Kajita from the Super-Kamiokande (Super-K) experiment in Japan and to Arthur B. McDonald from the Sudbury Neutrino Observatory (SNO) in Canada *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*.

The SNO and Super-Kamiokande experiments had previously received the prestigious Giuseppe and Vanna Cocconi Prize of the EPS in 2013 *"for their outstanding contributions to the solution of the solar neutrino puzzle by measuring the flux of all neutrino flavours from the Sun"*.



The oscillations originate from a pure quantum mixing phenomena made possible if the neutrinos have masses: the neutrino quantum states that propagate with a definite mass are different from the neutrino quantum states of a definite flavour produced in weak interactions. If one generates neutrinos of a given flavour from a source, say for example electron-neutrinos from the sun, they will act as a linear combination of neutrino states of definite masses which propagate towards the detector on earth. The mixing evolves during propagation and neutrinos of different flavours can be detected.

The Super-K experiment is a large underground water Cherenkov detector located in the Mozumi mine under Mount Kamioka near the city of Hida in Japan. The SNO experiment is a heavy-water (deuterium) Cherenkov detector located in Vale Inco's Creighton Mine near Sudbury, in Canada.

Takaaki Kajita, now director of the Institute for Cosmic Ray Research at the University of Tokyo in Japan, played a leading role in the analysis of the data that lead to the Super-K discovery. He showed that an anomaly in the atmospheric neutrino flux could be interpreted in the context of neutrino flavour oscillations. Arthur B. McDonald, now University Research Chair at Queen's University in Canada, led the SNO experimental project. With SNO, and looking at the sun where electron-neutrino species are abundantly produced, Arthur B. McDonald was able to detect the products of the interaction of each of the three flavours of neutrinos with the deuterium detector target. This enabled a separate measurement of the flux of electron-neutrinos and of the sum of muon- and tau-neutrinos. In this way it resulted that the sum of neutrino species detected on Earth corresponds to the expected flux emitted by the Sun, while the flux of electron neutrinos on Earth is greatly depleted.

These results have provided revolutionary insight into the properties of neutrinos. The "Neutrino Physics" has now evolved into a scientific field of its own, with series of underground-based and accelerator-based experiments attempting to disentangle the neutrino mass hierarchy and mixing parameters, and searching for a possible contribution of the neutrino sector for the matter-antimatter asymmetry in the Universe.■

◂ Takaaki Kajita and Arthur B. McDonald ©icrr.u-tokyo.ac.jp ©snolab.ca

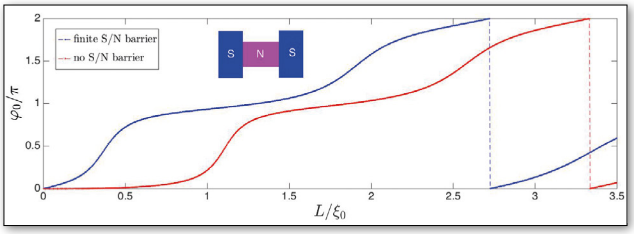
Yves Sirois and Mauro Mezzetto
On behalf of the EPS HEPP Board

Highlights from European journals

CONDENSED MATTER

Revealing the microscopic origin of φ_0 Josephson junctions.

A spontaneous dissipationless current (supercurrent) can flow in a superconducting ring even in the absence of a magnetic flux, if the ring is interrupted by a so-called φ_0 junction. In the present work the authors present a full microscopic theory that explains the appearance of the anomalous φ_0 phase in junctions with an intrinsic spin-orbit coupling (SOC) and a spin-splitting field like the exchange field in ferromagnets. The SOC generates the spin precession of moving particles, and, in addition, it causes a spin-dependent deflection of electron trajectories. The latter can be interpreted in terms of an effective spin- dependent SU(2) magnetic field that in normal systems is the origin of the intrinsic spin Hall effect and the existence of spin currents in the equilibrium state. A finite φ_0 in a Josephson junction is directly related to the appearance of an equilibrium spin current with a spin projection parallel to the exchange field. These findings are the first steps towards spin-orbitronics with superconductors by making a natural connection between charge-spin conversion in dissipative and superconducting structures. ■



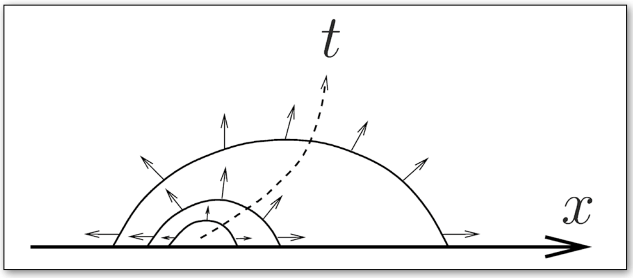
▲ The dependence of φ_0 on the length L of the N bridge (see inset) with an intrinsic SOC and spin-splitting field.

■ **F. S. Bergeret** and **I. V. Tokatly**, 'Theory of diffusive φ_0 Josephson junctions in the presence of spin-orbit coupling', *EPL* **110**, 57005 (2015)

MATHEMATICAL PHYSICS

Ever-growing disturbances leading to freak waves

Physicists like to study unusual kinds of waves, like freak waves found in the sea. Such wave movements can be studied using models designed to describe the dynamics of disturbances. The authors have focused on finding ways of best explaining how wave disturbance occurs under very specific initial conditions that are key to the genesis of these disturbances. They looked for solutions to this puzzle by resolving a type of equation, called the nonlinear Schrödinger equation. It is solved by applying a method designed for studying instabilities tailored to these initial conditions. Their approach makes it possible to locate exactly where and how pertinent information used to identify disturbance patterns can be extracted from localised disturbances' characteristics. The findings have been published recently. They therefore contribute to a better understanding of the complex dynamics of systems subjected to such disturbances. For example, they could be used to better understand waves appearing on fluid surfaces, whose evolution is influenced by gravity, or light waves propagated in optical fibres.■



▲ A schematic one-dimensional illustration of the spatiotemporal evolution of the envelope of wave-train in the absolutely unstable case.

■ **S. Coulibaly**, **E. Louvergneaux**, **M. Taki** and **L. Brevdo**, 'Spatiotemporal wave-train instabilities in nonlinear Schrödinger equation: revisited', *Eur. Phys. J. D* **69**, 186 (2015)

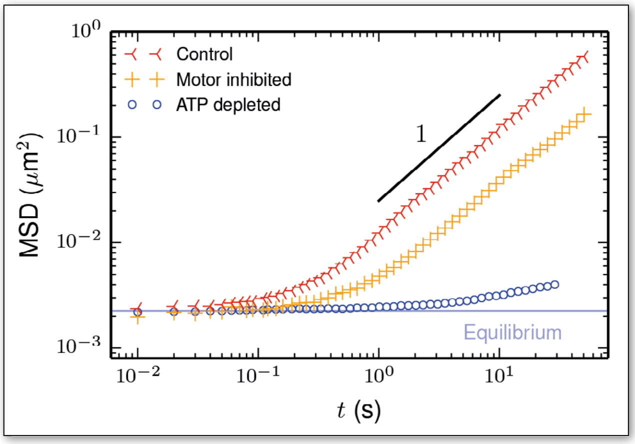
BIOPHYSICS

Activity–driven fluctuations in living cells

Living cells operate far from equilibrium due to the permanent injection of energy provided by ATP supply. The dynamics of the intracellular components is driven by both thermal equilibrium fluctuations, and active stochastic forces generated by the molecular motors.

To sort out genuine nonequilibrium fluctuations from purely thermal effects, we inject tracer particles in ATP depleted cells. By testing the fluctuation-dissipation theorem (FDT), we identify these cells as an equilibrium-like reference in which the tracers remain locally confined by the elastic cytoskeletal network that permeates the cytoplasm. In contrast, we highlight a violation of the FDT and a diffusion-like motion at long time scales in untreated and selective motor inhibited cells. Removing the thermal contribution in the tracer fluctuations, we estimate the spectrum of the active forces. Eventually, we report non-Gaussian tails in the tracer displacement distribution as a result of directed motion events.

▾ Mean square displacement of tracers in living cells.



We recapitulate theoretically the observed fluctuations by modeling the dynamics with a confining harmonic potential which experiences random bursts as a result of motor activity. This minimal model allows us to quantify the time scales of the active forces, along with the energy injected by the ensuing fluctuations. ■

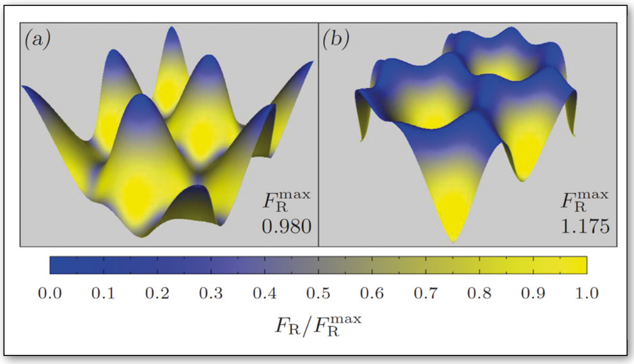
▪ **E. Fodor**, **M. Guo**, **N. S. Gov**, **P. Visco**, **D. A. Weitz** and **F. van Wijland**,
'Activity-driven fluctuations in living cells', *EPL* **110**, 48005 (2015)

CONDENSED MATTER

Shaping the hilly landscapes of a semi-conductor nanoworld

A new study reveals how hexagonal-patterned, self-organised hill structures emerge in 2D at the nanoscale due to redeposition following semi-conductor bombardment with low-energy ions.

Nanoscale worlds sometimes resemble macroscale roller-coaster style hills, placed at the tip of a series of hexagons. Surprisingly, these nanohills stem from the self-organisation of particles – the very particles that have been eroded and subsequently redeposited following the bombardment of semi-conductors with ion beams. Now, a new theoretical study constitutes the first exhaustive investigation of the redeposition effect on the evolution of the roughening and smoothing of two-dimensional surfaces bombarded by multiple ions. The



▴ Redeposition on hexagonally arranged dots.

results demonstrate that the redeposition can indeed act as stabilising factor during the creation of the hexagonally arranged dot patterns observed in experiments. These findings have been published recently. ■

▪ **C. Diddens** and **S. J. Linz**,
'Continuum modeling of particle redeposition during ion-beam erosion', *Eur. Phys. J. B* **88**, 190 (2015)

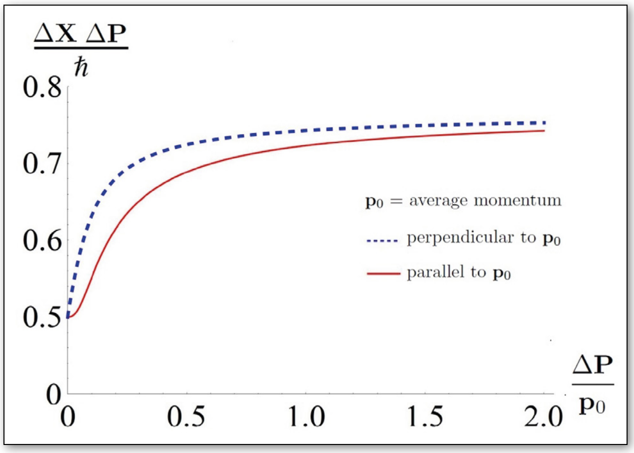
QUANTUM PHYSICS

Single-photon observables and preparation uncertainty relations

The escalating requests for highly accurate manipulation of single photons call for an appropriate description of their observables. The authors provide a unified procedure for treating all single-photon observables in terms of Positive Operator-Valued Measures (POVMs), allowing for the evaluation of corresponding probability distributions.

The suppression of longitudinal (or equivalently 0-helicity) photon states is identified as a projection from an extended Hilbert space onto the physical one, carrying an irreducible spin-1 mass-0 representation of the Poincaré group.

▾ Increase of uncertainty relations for circularly polarized Gaussian states as a function of the momentum spread. In the paraxial limit (ΔP→0) ħ/2 is retrieved.



POVMs are naturally obtained by applying such projections to Projection-Valued Measures (PVMs) associated to operators well-defined on the extended Hilbert space. Such operators are inherited from the familiar relativistic description of spin-1 massive particles and simply adapted to photons.

Results show that PVMs of momentum and helicity remain unaltered, while those of position and spin are turned into POVMs by the projection, reflecting their intrinsic unsharpness.

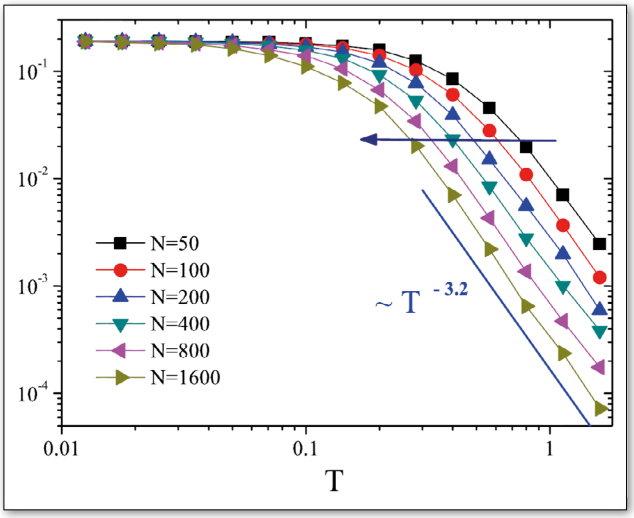
Finally, evaluation of uncertainty relations for position and momentum and probability distribution of spin over a broad class of physically relevant states is done, leading to new quantitative and experimentally measurable results. ■

G. Guarnieri, **M. Motta** and **L. Lanz**,
'Single-photon observables and preparation uncertainty relations', *J. Phys. A: Math.Theor.* **48**, 265302 (2015)

STATISTICAL PHYSICS

Law governing anomalous heat conduction revealed

Study finds the law governing how heat transport scales up with temperature.



▲ Heat conductance as the function of temperature T for different lattice size N=50; 100; 200; 400; 800 and 1600.

How heat travels, matters. Yet, there is still no consensus on the exact physical mechanism that causes anomalous heat conduction—despite the existence of previous numerical simulation, theoretical predictions and experimental observations. Now, the authors have demonstrated that electron transport depends on temperature. It follows a scaling governed by a power law—and not the exponential scaling previously envisaged. These findings were published recently. Heat conduction depends on the internal energy transferred by microscopic diffusion and collisions of particles, such as electrons, within a given body. Anomalous heat conduction can be best studied in a particular kind of model: one that accounts for the thermal transport in a one-dimensional (1D) lattice. In this study, the chosen 1D model is dubbed the coupled rotator lattice model. The authors systematically investigated how heat conductivity changes with temperature. This approach led them to the thesis that heat conductivity correlates with a power law, instead of an exponential scaling as previously predicted. Further, this phenomenon occurs without a transition temperature above which the heat conduction is normal and below which it is anomalous. ■

Y. Li, **N. Li** and **B. Li**,
'Temperature dependence of thermal conductivities of coupled rotator lattice and the momentum diffusion in standard map', *Eur. Phys. J. B* **88**, 182 (2015)

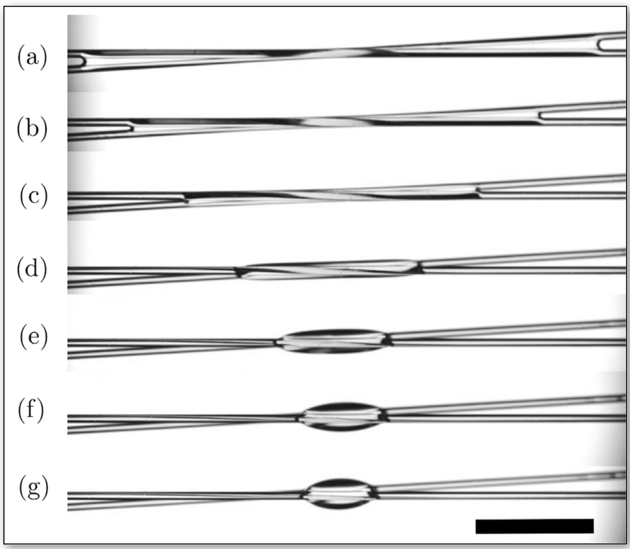
LIQUID PHYSICS

Improving insulation materials, down to wetting crossed fibres

Scientists model the manner in which a liquid wets fibres, gaining useful insights for improving glass wool properties.

Sandcastles are a prime example of how adding a small amount of liquid to a granular material changes its characteristics. But understanding the effect of a liquid wetting randomly oriented fibres in a fibrous medium remains a mystery. Relevant to the building industry, which uses glass wool, for instance, this phenomenon can be better understood by studying the behaviour of a liquid trapped between two parallel fibres. It can either remain in the shape of a drop or spread between the fibres into a long and thin column of liquid. Now, the authors have demonstrated that the spreading of the liquid is controlled

▼ Evolution of the morphology of a drop of silicone oil on two touching crossed fibres.



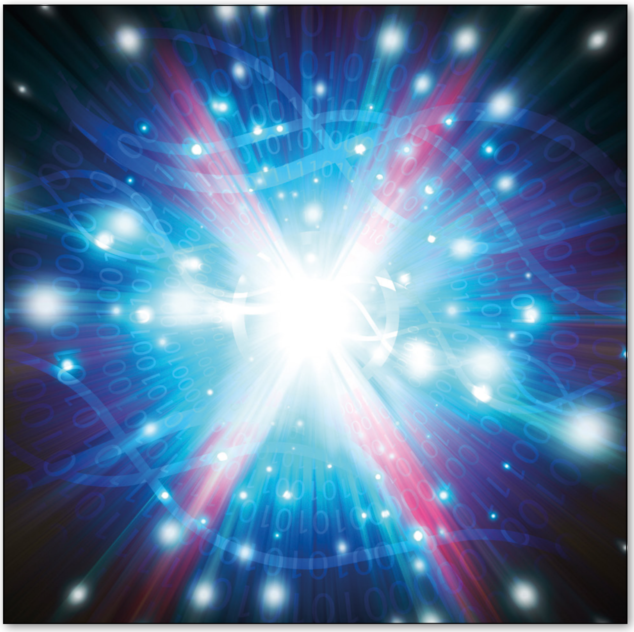
by three key parameters: the amount of liquid on the fibres, the fibres' orientation and the minimum distance between them. These findings, based on experimental and modelling work, were published recently. ■

■ **A. Sauret**, **F. Boulogne**, **B. Soh**, **E. Dressaire** and **H. A. Stone**,
'Wetting morphologies on randomly oriented fibers',
Eur. Phys. J. E **38**, 62 (2015)

OPTICS

New way of retaining quantum memories **stored in light**

A novel way of stopping light in a state that stores information encoded in photons, opens the door to applications in quantum information processing.



▲ Quantum information stored in photons can be preserved by confining light.

The authors have now developed a way to confine light. This is significant because the approach allows quantum memories stored within photons to be retained. These findings have been published recently. The results may herald the advent of a multitude of hybrid, optoelectronic devices relying on the use of quantum information stored in photons for processing information that can be used in communication networks or quantum computing.

Indeed, stopping and storing light for a duration ranging from a few seconds to a few minutes is key for quantum information processing. Unfortunately, certain media induce a loss of coherence of the light, due to effects of the surroundings, which, in turn, affects the integrity of the quantum information stored in photons. This new study focuses on understanding the propagation properties of the electromagnetic wave associated with light to learn how best to stop it.

Previous attempts at stopping light showed it was possible to stop light for an entire minute. They dramatically slowed down light's progression via interaction within its propagation medium. In contrast, the authors here rely on electric and magnetic polarisation to predict the conditions under which light could be confined. The authors' theoretical approach is based on controlling the speed at which the light's energy flows in order to stop it. At the same time, they also predict what it takes in terms of energy density to reach a stage where the electromagnetic waves constitutive of light can be stored, particularly in a medium in which waves travel at different speeds or are absorbed. ■

■ **N. Sun**, **J. Chen** and **D. Tang**,
'Stopping light in an active medium', *Eur. Phys. J. D* **69**, 219 (2015)

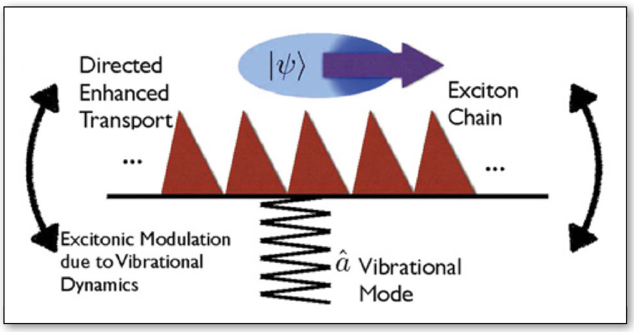
QUANTUM PHYSICS

A new scheme for **directed coherent transport**

Energy transport at the nano/quantum scale has a long history of research, with significant interest being paid in the debate over whether quantum coherence plays a role in the efficiency of exciton transport in photosynthetic complexes. Much attention has also turned to improving energy transport for man-made energy harvesting systems and nanodevices, such as in solar cells and quantum dot arrays.

Achieving directed quantum transport permits far superior collection of the deposited energy. The study of quantum ratchets shows how directed energy transport is achievable in quantum dot arrays. Recent experimental work on light harvesting molecules have implicated the role of discrete mechanical modes in enhancing the energy transport through dipole arrays, but say less about directed transport. Here the authors bring together these two apparently unrelated models to present a scheme for a new type of quantum engine. Utilising both excitonic and vibrational motions it

▼ Schematic of the vibrationally rocked excitonic quantum ratchet



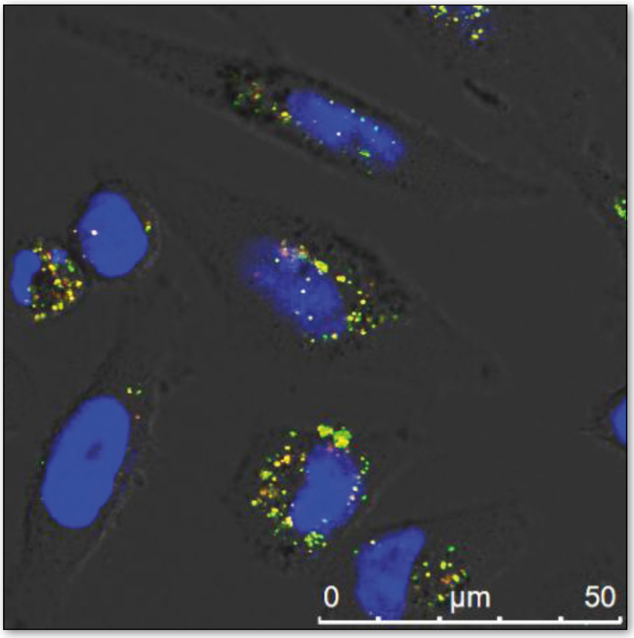
is shown that the resulting coherent mechanical dynamics causes directed enhanced energy transport towards one end of the exciton chain. The quantum engine is autonomous, requiring no external pumping or modulation but works off the initial charge on the exciton chain which excites the vibrational motion. ■

■ **C. R. Myers**, **G. J. Milburn** and **J. Twamley**, 'Vibrationally assisted quantum energy pumps', *New J. Phys.* **17**, 093030 (2015)

BIOPHYSICS

Gold-diamond nanodevice for **hyperlocalised cancer therapy**

Gold nanorods can be used as remote controlled nanoheaters delivering the right amount of thermal treatment to cancer cells, thanks to diamond nanocrystals used as temperature sensors.



▲ Colocalisation studies with confocal fluorescence microscopy and acidotropic probes show particles trapped in the lysosomes of the living HeLa cells

Precise targeting biological molecules, such as cancer cells, for treatment is a challenge, due to their sheer size. Now, the authors have proposed an advanced solution, based on a novel combination of previously used techniques, which can potentially be applied to thermal cancer therapy. The authors presented in this work an improved sensing technique for nanometre-scale heating and temperature sensing. Using a chemical method to attach gold nanorods to the surface of a diamond nanocrystal, they have invented a new biocompatible nanodevice. It is capable of delivering extremely localised heating from a near-infrared laser aimed at the gold nanorods, while accurately sensing temperature with the nanocrystals. The novelty of this study is that it shows that it is possible to use diamond nanocrystals as hypersensitive temperature sensors with a high spatial resolution—ranging from 10 to 100 nanometres—to monitor the amount of heat delivered to cancer cells. ■

■ **P.-Ch. Tsai**, **O. Y. Chen**, **Y.-K. Tzeng**, **Y. Y. Hui**, **J. Y. Guo**, **Ch.-Ch. Wu**, **M.-Sh. Chang** and **H.-Ch. Chang**, 'Gold/diamond nanohybrids for quantum sensing applications", *EPJ Quantum Technology* **2**, 19 (2015)

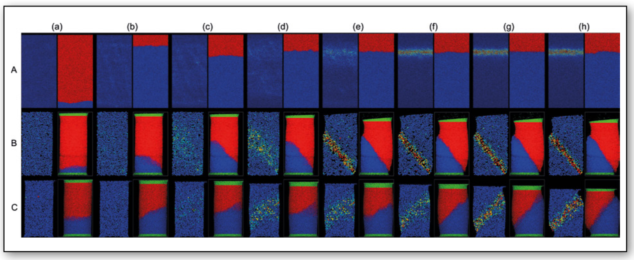
MATERIAL SCIENCE

Force transmission bottlenecks as determinants of shear bands

The formation of shear bands (or 'strain localisation') is a key attribute of degradation and failure in soil, rocks, and other amorphous and crystalline materials. Their deleterious effects on material performance is well known, though on the other hand their rich pores provide important conduits for flow in petroleum and natural gas recovery from shale and tight rock formations. Despite intense research efforts, their origin and mechanisms of evolution have proved elusive. Here, patterns discovered from data on sand and discrete element simulations suggest that the early localization of bottlenecks in force transmission is the root cause of shear bands in dense granular media. This mechanism was shown to initiate early in the loading history for initially (globally) homogeneous samples. The finding paves the way for early prediction of failure and highlights promising avenues to explore ways to change its course from inception. ■

■ **A. Tordesillas**, **S. Pucilowski**, **S. Tobin**, **M. R. Kuhn**, **E. Andò**, **G. Viggiani**, **A. Druckrey** and **K. Alshibli**, 'Shear bands as bottlenecks in force transmission', *EPL* **110**, 58005 (2015)

▼ Particle rotations and minimum cut from start to end of loading history (columns (a) to (h)): simple shear DEM simulation (row A) and triaxial compression of Caicos Ooid (row B) and Ottawa (row C) sand. Particles with high (low) rotations are coloured red (blue). The minimum cut lies at the blue-red interface; green particles identify source/sink nodes.



INTERNATIONAL YEAR OF LIGHT 2015

FOREWORD ON THE SPECIAL ISSUE ON THE SCIENCE OF LIGHT

FROM THE EDITORS

It is a great pleasure to present the last EPN issue of this year, a special double issue devoted to light as a tribute to the International Year of Light and Light-based Technologies (IYL2015). We are delighted that Dr. Luc Bergé, Chair of the Quantum Electronics and Optics Division of the European Physical Society (EPS), was willing to act as Guest Editor for this special issue. We are grateful to him and all contributing authors for their efforts to create an attractive and exceptional issue having **Light** as its leitmotiv. We hope that the issue you now hold in your hands will provide pleasant and interesting reading.

Victor R. Velasco and Jo Hermans

FROM THE GUEST EDITOR

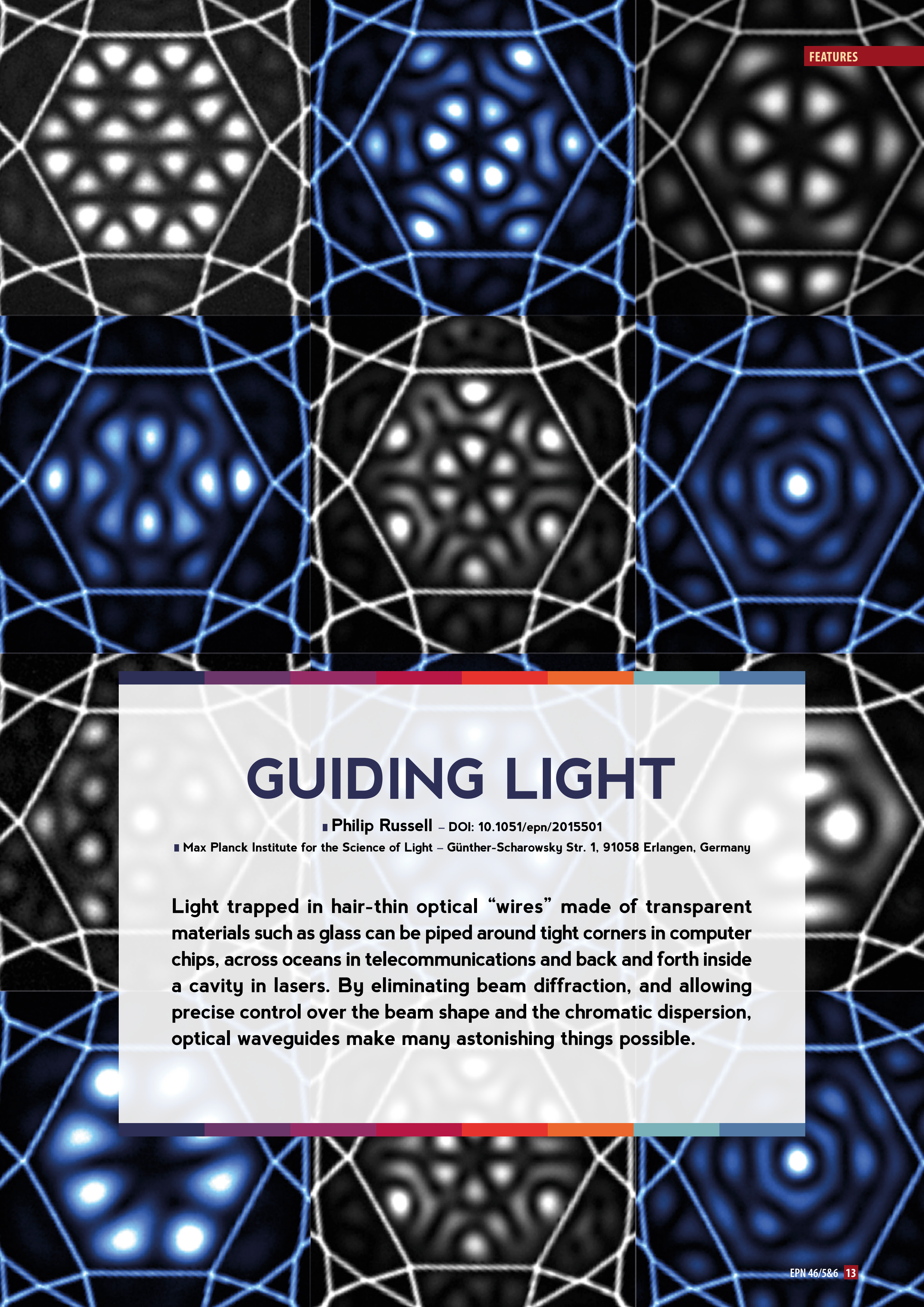
"Let there be a Year of Light " – With these words the Secretary General of the United Nations, Ban Ki-moon, officially launched through a video message the International Year of Light during its Opening Ceremony held in the UNESCO Headquarter in Paris, the 19th of January 2015. Light is indeed everywhere: First supplied by the sun for mankind, light is an essential vector of life, inspiration and progress, for Nature through photosynthesis as well as health and well-being, for the artists of all cultures, for reducing poverty and offering alternative sources of energy, and for inspecting and thus opening new areas in all fields of science. The International Year of Light and Light-based Technologies will have been an exceptional opportunity to engage with leaders in science, technology, culture and politics; initiate partnerships between the scientific, public and private sectors; bring knowledge to people and improving their access to information and sustainable development in all parts of the world.

Looking at this ambitious perspective, I am sincerely honoured and pleased to serve as Guest Editor for this Special Issue of Europhysics News dedicated to the Science of Light. All along this year the Quantum Electronics and Optics Division of the EPS has supported this tremendous event every day, through the organisation of the broadest conferences devoted to light in Europe, by attributing prestigious prizes in optics and photonics, and promoting new events for young researchers throughout the world. The Science of Light is like a white light composed of many distinct vibrating colours: One field of physics composed of several branches evolving with their own seminal discoveries. It was difficult to choose which of them could be best selected to offer a broad state-of-the-art in optics. Limited by six feature articles, my choice is by no means exhaustive, but it gives the readers different outlooks and promising applications of light in modern branches of photonics. I also asked outstanding and world-famous authors to write these feature articles, which they willingly accepted. Therefore, you will enjoy reading the articles by Philip Russell, President of The Optical Society (OSA) on photonic crystal fibres; Jörg Bewersdorf from Yale University on super-resolved fluorescence microscopy; Anne L'Huillier, laureate of the UNESCO L'Oréal and Emmy Noether EPS Awards, on attosecond science; Martin Frimmer and Lukas Novotny on the fascinating properties of light at the nanoscale; and Gérard Mourou, co-inventor of the chirped-phase amplification technique, Jonathan Wheeler, and Toshi Tajima, discoverer of plasma-based particle acceleration, on the next generation of ultrapowerful lasers and their future capabilities to create matter from vacuum. Last but not least, the quantum nature of light is not omitted and nicely addressed from the teleportation viewpoint by Nicolas Gisin, awarded by the John Bell Prize in 2009, Sébastien Tanzilli and Wolfgang Tittel.

I deeply thank all these great names for accepting my invitation and for their kindness in delivering their article on time. All of them contribute to pushing forward the frontiers of knowledge in the Science of Light.

So, Let there be Light!

Luc Bergé



GUIDING LIGHT

Philip Russell – DOI: 10.1051/epn/2015501

Max Planck Institute for the Science of Light – Günther-Scharowsky Str. 1, 91058 Erlangen, Germany

Light trapped in hair-thin optical "wires" made of transparent materials such as glass can be piped around tight corners in computer chips, across oceans in telecommunications and back and forth inside a cavity in lasers. By eliminating beam diffraction, and allowing precise control over the beam shape and the chromatic dispersion, optical waveguides make many astonishing things possible.

◂P.13 : A gallery of the modes guided in a hollow core PCF

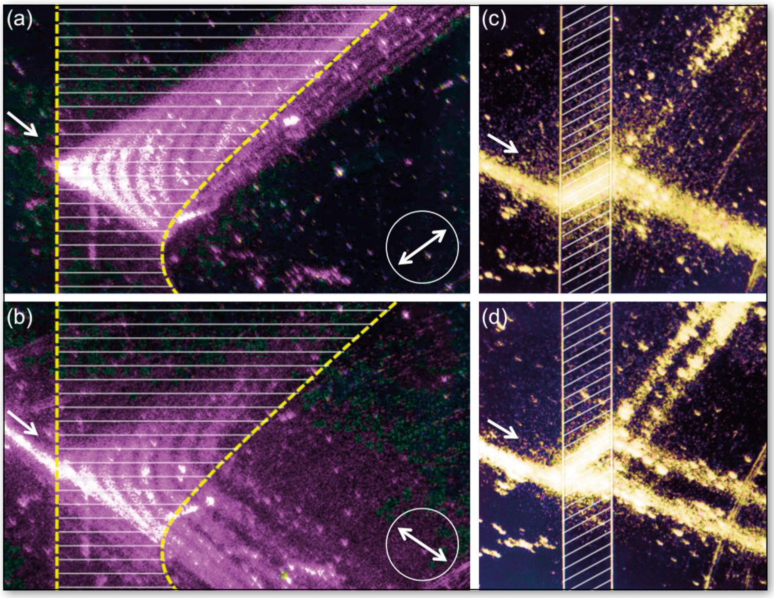
Nanometres and femtoseconds

Left to its own devices, light scatters everywhere. It is the ultimate radar, exploring every cubic micron of a room in a tiny fraction of a second and relaying the information almost instantaneously to the eye. Since an optical cycle is only a few femtoseconds in duration, light can at the same time be used to follow some of the fastest events in the natural world. It can thus be used to probe phenomena in four dimensions—three spatial and one temporal—with astonishingly high resolution. Its ability to follow ultrafast events also means that it can be used to encode information at ultra-high data rates. Understanding, taming and making use of these extraordinary properties has occupied scientists for hundreds of years, culminating in the invention of the laser over 50 years ago, a breakthrough that has stimulated for example the creation of the world-wide-web, whose interconnecting strands are glass optical fibre waveguides capable of transmitting signals at terabit rates under oceans and across continents, and laser machining, which has transformed precision manufacturing world-wide.

Bending light around corners

The success of optical fibre lies in its ability to overcome the natural tendency of light to diffract and travel in straight lines in free space (although occasionally it takes a curved path, for example when reflected by an inversion layer of hot air trapped on a sun-baked road surface, giving rise to a mirage). In 1841 Swiss scientist Jean-Daniel Colladon, by directing a beam of sunlight into a stream of water issuing from a tank, was the first to show scientifically that total internal reflection could be used to force light to turn a corner [1]. Irishman John Tyndall further popularised this experiment in a demonstration at the Royal Institution in London in 1870. Glass fibre optics is a lineal descendant of these early experiments, and its history makes fascinating reading [2], starting with the pioneering work of Snitzer [3] and followed shortly afterwards by Kao's 1966 prediction that glass fibres could be used for telecommunications [4].

▾**FIG. 1:** Diffraction and refraction of TM-polarized photonic Bloch waves in single-mode periodic planar waveguide of tantala on glass. The narrow white lines indicate the direction of the corrugations. **(a)** Narrow beam impinges on boundary and excites a diffracting Bloch beam; a polarizer is used to select the upward-progressing harmonic of the Bloch wave, revealing a pattern of hook-shaped fringes. **(b)** Rotating the polarizer to block the upward-progressing harmonic reveals the complementary set of fringes. **(c)** Negative refraction of a narrow beam inside a periodic region. **(d)** Double negative refraction for a slightly different incident angle.



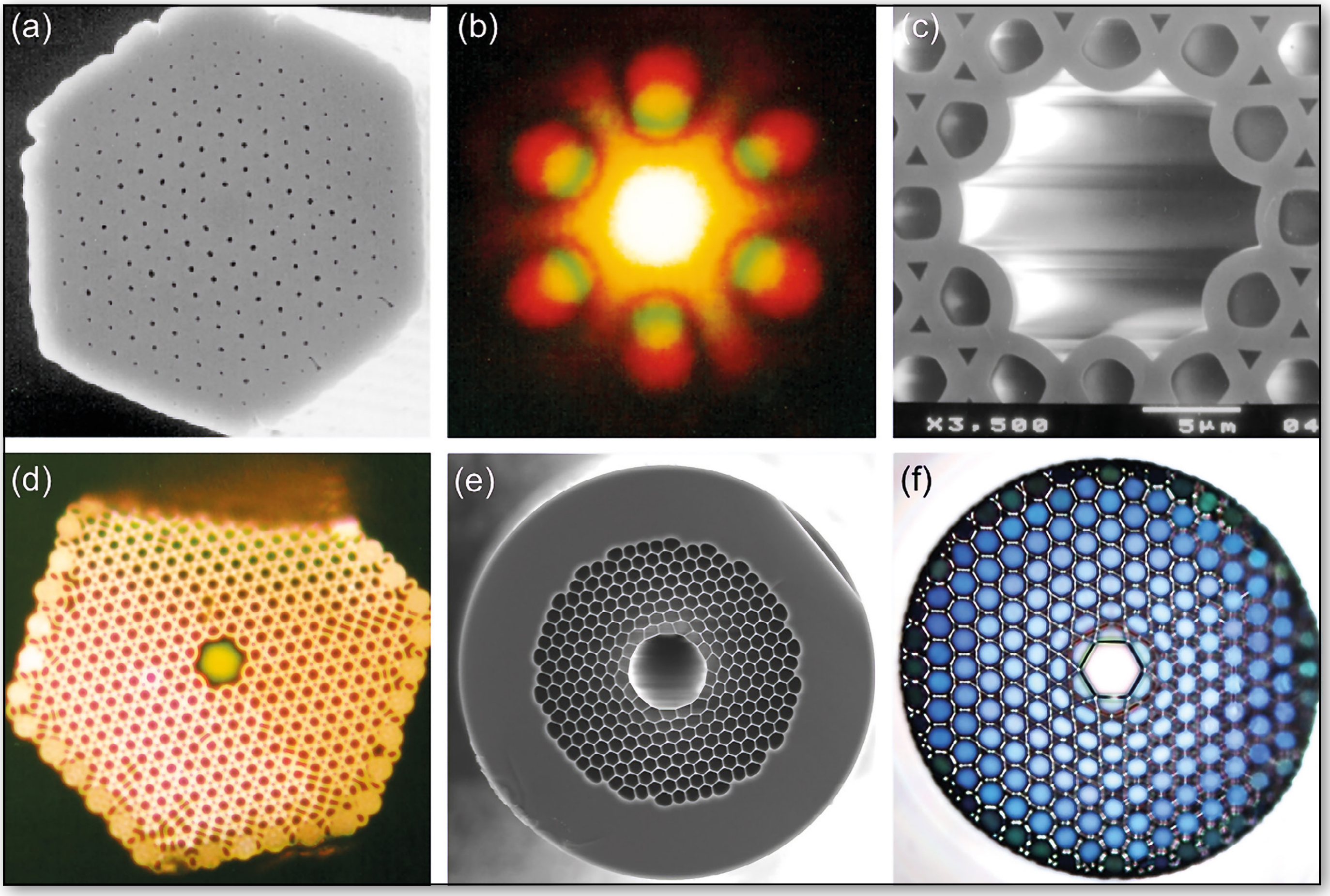
Integrated optical circuitry

The arrival of the laser, a source of coherent optical radiation not dissimilar in nature to a pure microwave or radio signal but at a much higher frequency, inspired scientists in the late 1960s at Bell Laboratories in the USA to explore trapping light in thin films and strips of dielectric material placed on a low index substrate [5]. By integrating many components on one platform, they aimed to miniaturise bulk optics in much the same way as electronic components have been integrated on to microprocessor chips. This led to the invention of devices such as prism and grating couplers, wavelength division multiplexers, Bragg mirrors and distributed feedback lasers (many of these were inspired by microwave devices).

Integrated optical components are now routinely used in the rapidly growing field of silicon photonics, where the remarkable facilities in silicon foundries are applied to the manufacture of integrated optical chips.

One of the members of the original Bell Labs team was Reinhard Ulrich, who in 1970 moved to the Max Planck Institute for Solid-State Research in Stuttgart, Germany, where in 1975 (stimulated by Brillouin's book on wave propagation in periodic structures [6]) he embarked on a set of beautiful experiments involving the often-counter-intuitive behaviour of visible photonic Bloch waves in thin dielectric films etched with multiply periodic structures (Fig. 1). Borrowing tools from electronic band structure, he and his group used this elegant two-dimensional system to observe effects such as negative & positive refraction, zero diffraction and the exquisite field patterns created by the interference of guided Bloch waves—topics that are closely related to (and predate) the fields of photonic crystals and metamaterials [7] [8]. The field of guided wave "photonic crystals" is now very active, though the pioneering early work of Ulrich's group is not often recognised.

The biggest success story of guided wave optics is, however and of course, single-mode fibre (SMF) used in optical communications. Perfected in the 1980s, and offering extremely low transmission losses (~0.2 dB/km), SMF has close to ideal properties. It has also found



▲FIG. 2: Gallery of PCF structures. **(a)** The first solid-core PCF. **(b)** Far-field pattern of endlessly- single-mode PCF guiding white light. **(c)** The first hollow-core PCF and **(d)** the near-field pattern at its endface when white light was launched. **(e)** State-of-the-art hollow core PBG PCF. **(f)** Kagomé-style hollow core PCF guiding white light.

important uses in structural monitoring of, *e.g.*, buildings, ships, aircraft, bridges, chemical plants and oil wells. Such fibre sensors make use of miniature Fabry-Pérot and Mach-Zehnder resonators, Bragg and long-period fiber gratings—and nonlinear optical effects such as Brillouin and Raman scattering. Indeed, experimental nonlinear optics has itself benefitted hugely from the availability of SMF, which made possible for the first time the observation of many effects within a near-perfect one-dimensional system that offers diffraction-free propagation at high intensities while allowing precise tailoring of the dispersion.

Emergence of holey (with an 'e') fibres

By 1991, fibres seemed as close to perfect as anyone could wish. Nevertheless, the story was not at an end. At that time it was suggested that low-loss guidance of light in a hollow core might be possible if one could create a two-dimensional "photonic bandgap" (PBG) crystal of microscopic hollow channels in the cladding of an optical fiber [9]. The challenge would be to design a suitable structure and, not least, work out a way of making it.

After several attempts in the period 1991 and 1995, the first working photonic crystal fibre (PCF) was drawn from a preform constructed by stacking 216 silica capillaries in a tight-packed hexagonal array around a central solid core (Fig. 2). The fibre guided by a kind of modified total internal reflection and led to the discovery of "endlessly single-mode" PCF which, if it guides at all, only supports the fundamental mode [9].

In endlessly single-mode PCF, the fundamental modes of the glass channels around the core have refractive indices lower than the fundamental core mode, which is therefore trapped by the equivalent of total internal reflection. Higher order core modes, on the other hand, have lower indices and are able to leak away between the hollow channels. This modal filtering effect was in fact predicted in an early 1974 paper on single-material fibres [10].

Group velocity dispersion

It was soon realised that, compared to SMF, solid-core PCF offers much greater control over group velocity dispersion (GVD)—the effect that causes the velocity of a pulse to change with its central frequency.

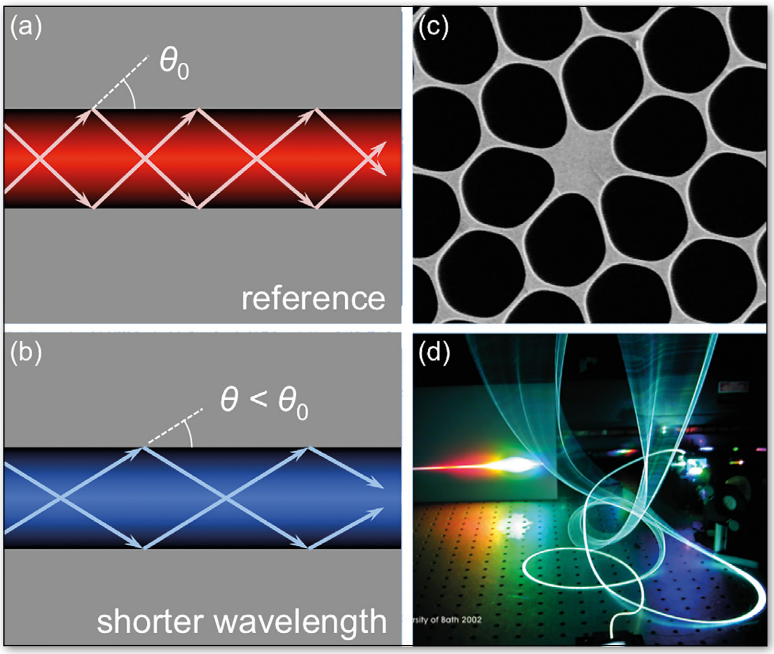
Consider a hollow planar waveguide formed by two flat mirrors spaced d apart. Rays of light can be trapped by zig-zagging to and fro between them, and there seems no particular reason why certain angles should be favoured. As d gets smaller, however, the wave nature of light begins to reveal itself. Upward and downward travelling rays interfere, producing a pattern of fringes, parallel to the mirrors, with a spacing that depends on the ray angle θ (see Fig. 3). When only one fringe fits between the mirrors, the waveguide is resonant with the light and a fundamental mode forms. If the vacuum wavelength λ falls, θ has to fall to maintain the same fringe width, which reduces the number of bounces per metre and causes the group velocity to increase (at the same time the phase velocity decreases, causing the modal refractive index to rise).

A hollow waveguide has anomalous GVD, *i.e.*, pulses at a higher (bluer) frequencies always travel faster (Fig. 3). If the core is filled, however, its anomalous dispersion is either reinforced or reduced, depending on the GVD of the filling material.

10,000 times brighter than the sun

In PCFs with micron-sized solid glass cores surrounded by hollow channels, the geometrical dispersion is strongly anomalous, which counterbalances the normal dispersion of the glass and shifts the zero dispersion wavelength from 1.29 μm (its value for silica-based SMF) into the visible. This creates ideal conditions for generating octave-spanning supercontinua (Fig. 3), and forms the basis for a revolutionary range of extremely bright white-light sources [11], with multiple applications from frequency metrology to hyperspectral imaging [12]. Recently a dispersion-tailored small-core PCF was drawn from the fluorozirconate glass ZBLAN and used to generate a spectrum extending from 200 nm to beyond 2 μm in wavelength (Fig. 4). A remarkable feature of this source is that, unlike silica-glass, the ZBLAN glass shows no sign of degradation in the UV, even when operating for many hours at high brightness [13].

▾ **FIG. 3: (a)** Fundamental mode of a narrow waveguide is formed by the interference of upward and downward rays. **(b)** For shorter wavelengths the number of bounces per unit length falls, resulting in an increase in group velocity. **(c)** Solid-core PCF with very strong anomalous waveguide dispersion, permitting the 1.29 μm zero dispersion wavelength of silica to be shifted into the near IR. **(d)** Iconic photograph of supercontinuum generation in a silica PCF (taken by Will Reeves when he was a PhD student at the University of Bath).



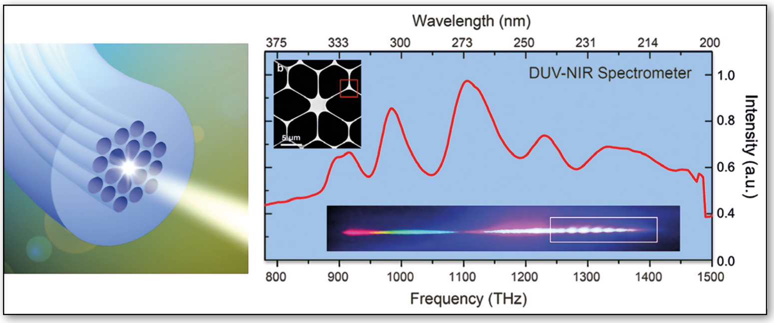
Gas, glass and ultrafast light

As a result of self-focusing through the electronic Kerr effect (which causes the refractive index to increase with intensity), a laser beam can reach field strengths sufficient to ionise the gas. The release of free electrons creates a negative index change that opposes the Kerr effect. The resulting balance of focusing and defocusing, together with the GVD of the medium, leads to self-guidance of light (known as "filamentation" [14]) and provides a means of channelling a laser beam up into the atmosphere to probe, *e.g.*, for environmental pollutants.

Hollow core PCF offers for the first time a low-loss linear means of guiding light in a narrow (~20 μm) channel filled with gas (Fig. 2). This has triggered the emergence of a new generation of versatile and efficient gas-based nonlinear devices, based on "anti-resonant-reflecting" (ARR) PCFs that do not possess a full two-dimensional PBG but provide ultra-broad-band guidance at losses of 1 dB/m or less. Examples of ARR-PCFs include structures with a kagomé lattice cladding or a single ring of hollow channels around the central hollow core. ARR-PCFs are particularly suited to ultrafast nonlinear optics because they can accommodate the bandwidth needed to support fs pulses, and—a first for fibre optics—the GVD can be adjusted simply by changing the gas pressure. Since more than 99.9% of the light travels in the hollow core, they have a damage threshold of more than 10^{14} W/cm^2, some 100 times higher than in glass. These features have led to a number of dramatic results, including efficient generation of few-cycle pulses by soliton self-compression of ~1 μJ, ~30 fs pump pulses, and bright widely-tunable UV light sources extending deep into the vacuum UV [15].

Twisted light

Solid-core PCFs continue to find new applications. For example, the non-circular transverse microstructure has a remarkable effect when a PCF is twisted continuously (by thermal post-processing or by spinning the preform during fibre drawing). This creates orbital angular momentum (OAM) states in the cladding that couple to the core mode, creating sharp dips in the transmitted spectrum at wavelengths that scale with the twist rate – an effect that can be used to measure mechanical twist. Twisted PCFs with cores placed in a ring equidistant from the axis have the unique property of preserving the magnitude and sign of the orbital angular momentum over long distances, *i.e.*, they are OAM-birefringent [16].



▲ **FIG. 4:** A remarkably bright and stable band of deep ultraviolet light is generated in a small-core ZBLAN PCF with carefully tailored dispersion.

Son et lumière

Another emerging field is that of optoacoustic devices, where the light itself drives mechanical resonances in the glass core. The tight confinement of both acoustic and optical energy within a small PCF core creates a very strong interaction. One of the first experiments in this direction involved pumping the GHz acoustic core resonance in a PCF with two laser signals, spaced apart in frequency by the acoustic frequency. The action and back-action of sound on light resulted in the generation of a GHz frequency comb. This effect has recently been used to stably mode-lock a fibre soliton laser at the 126th harmonic (2.1 GHz) of its round-trip frequency (16.8 MHz) [17]. These ideas are now being explored in the context of silicon integrated optics [18].

Concluding remarks

In this short account it has been not possible to cover all aspects of optical waveguides—I have focused mainly on photonic crystal fibres. Perhaps, though, it is worth mentioning that hollow core PCF has been proposed as a "low-latency" means of transmitting information, since optical signals travel ~1.5 times more quickly in air [19]. Applications include high frequency stock-market trading and communications between high performance computers. Overall, it is certain that waveguides, as a vital ingredient in state-of-the-art optics and photonics, will continue to play a key role in fundamental and applied research, as well as commercial products, for the foreseeable future. ■

About the Author

Philip Russell is a founding Director at the Max-Planck Institute for the Science of Light (MPL), a position he has held since January 2009. He obtained his D. Phil. (1979) degree at the University of Oxford. His interests currently focus on scientific applications of photonic crystal fibres. He is a Fellow of the Royal Society and the Optical Society of America (OSA) and has won several awards including the 2000 OSA Joseph Fraunhofer Award/Robert M. Burley Prize, the 2005 Thomas Young Prize of the IOP, the 2005 Körber Prize for European Science, the 2013 EPS Prize for Research into the Science of Light, the 2014 Berthold Leibinger Zukunftspreis and the 2015 IEEE Photonics Award. He is OSA's President in 2015, the International Year of Light.

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LIGHT FOR BIO-IMAGING

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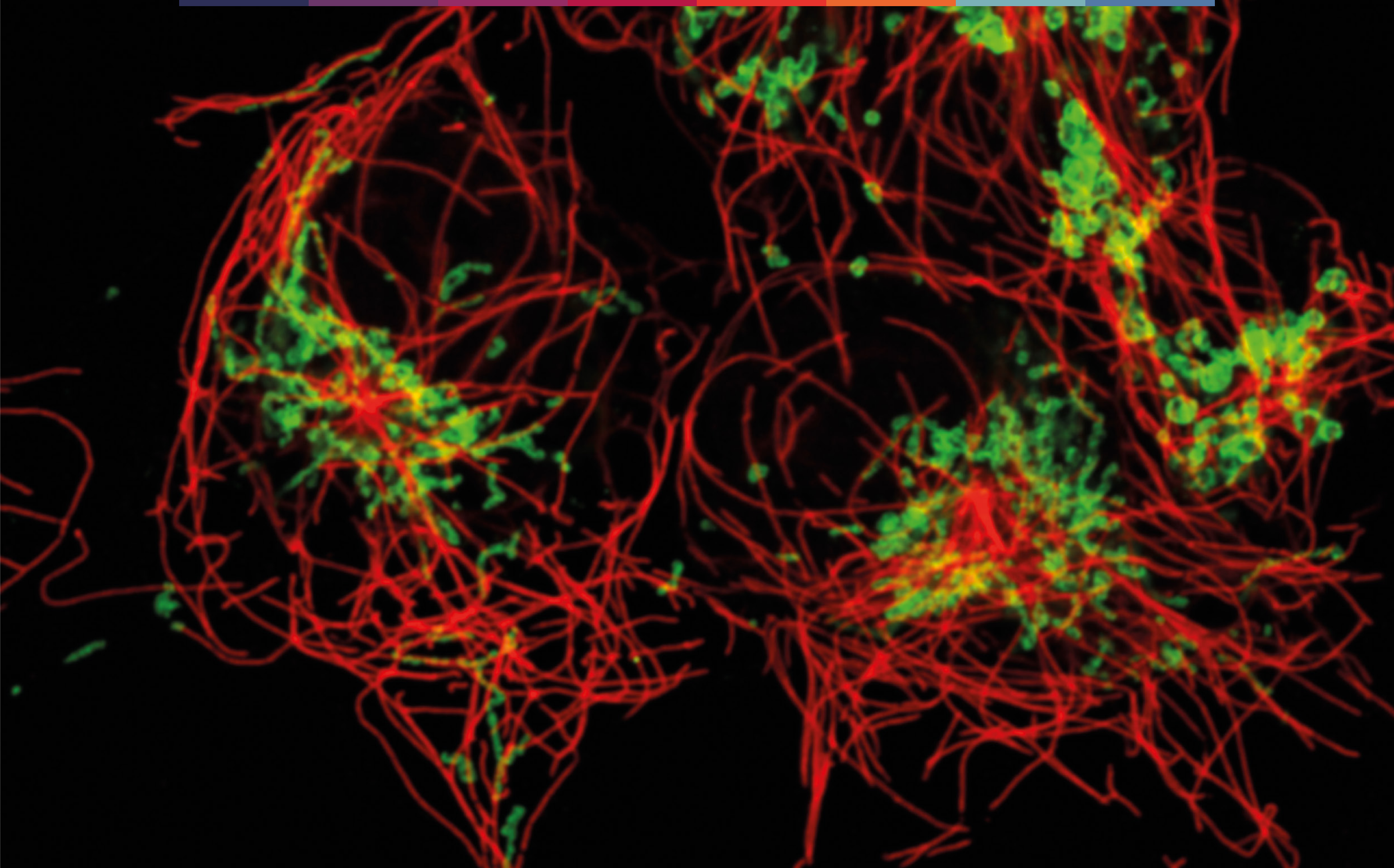
The biological sciences have seen tremendous progress over the last decades - sequencing the human genome is just one example - and biology has been proclaimed to be the scientific discipline of the 21st century [1]. These advances have been enabled through tools developed by physicists. Light and light-based technologies, in particular, have been of utmost importance to this progress.



Light technology and biology: a long-standing partnership

Already the discovery of the first cells and the emergence of the field of microbiology in the 17th century were closely linked to progress in optics at the time. It was their pioneering work in the construction of microscopes that allowed Robert Hooke and Antonie van Leeuwenhoek to identify cells in cork sections and find bacteria and other microorganisms, respectively. Towards the end of the 19th century, the mathematical description of optics by Ernst Abbe and others allowed to produce higher quality optical instruments, a development which coincided with the discovery of sub-cellular structures such as chromosomes and the Golgi apparatus. In the 20th century, the invention of phase contrast microscopy by Zernike and the development of laser scanning microscopy, enabled by the invention of the laser, provided new contrast mechanism and imaging modalities in microscopy. Photon detectors sensitive enough to detect single fluorescent molecules and optical tweezers which can pull at single molecules with piconewton forces by means of highly focused laser beams have led to the thriving field of single-molecule biophysics. Even more recently, breaking the diffraction barrier of light in far-field optical microscopy, which has been awarded by the 2014 Nobel Prize in Chemistry (fig. 1), has increased the resolution of light microscopes by another order of magnitude and now allows for the first time to visualize nanoscale dynamics in living cells.

Similarly, progress in optical technology has provided new tools for medical diagnostics and treatment. Examples include the development of endoscopy beginning in the early 1800's and range to more recent innovations such as optical coherence tomography, the optical equivalent of ultrasound imaging which has been enabled by the emergence of bright, low-coherence light sources such as ultrashort laser pulses. Laser scalpels and photodynamic therapy in which a photosensitive drug is applied that, upon application of light, becomes toxic to targeted cells, for example cancer cells, are examples for medical treatments enabled by light.

Light Technology in Biology: More than Just Optics

Over the last century, the nature of the technological breakthroughs that have contributed to new biology has changed. The initial milestones were primarily in classical

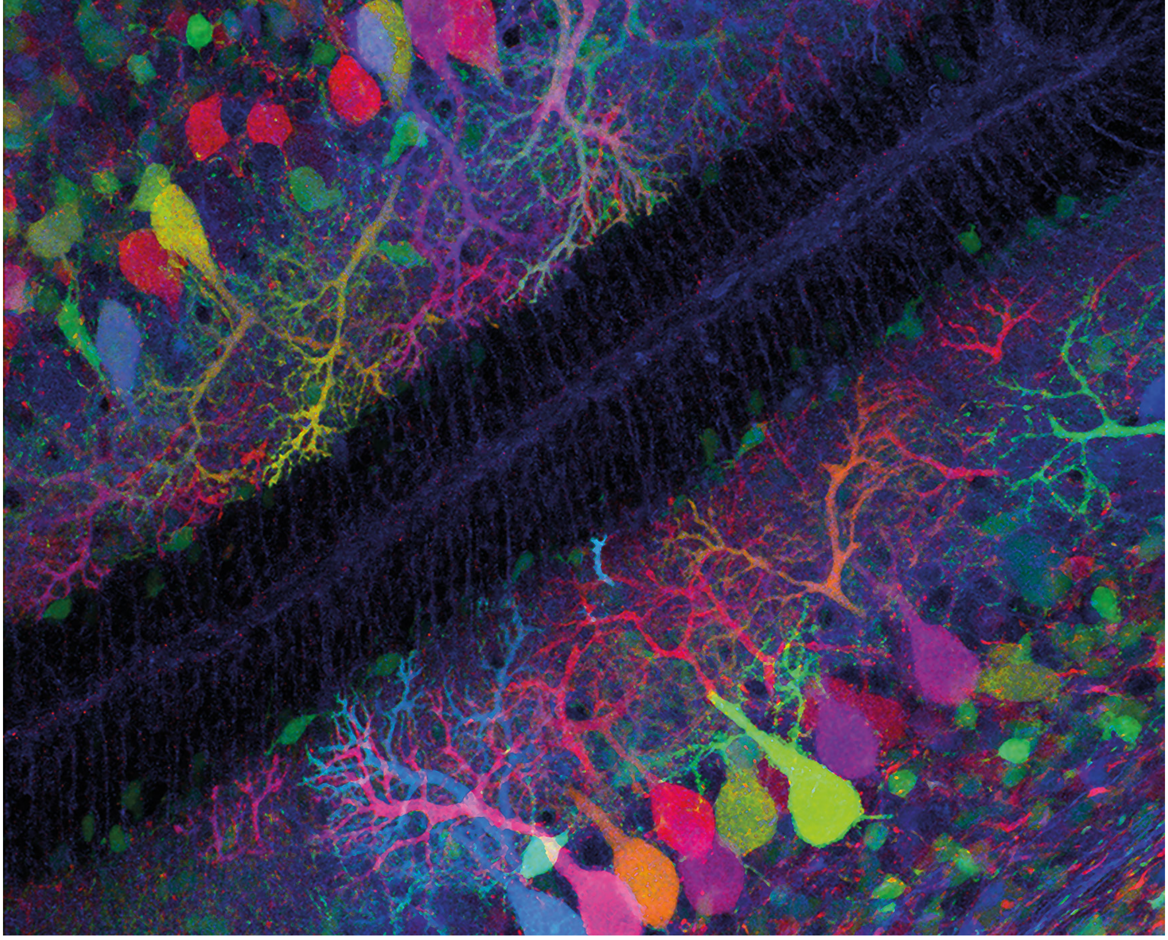
BOX: OPTICAL NANOSCOPY

For more than 100 years, diffraction was considered to be the ultimate barrier in far-field optical microscopy limiting its resolution to about half the wavelength of light [2]. From a pure optics point of view, this still holds true: it is impossible to create a focus of light in the far field of a lens where the majority of the energy is concentrated in a spot significantly smaller than this limit.

Around 1990, Stefan Hell realized that a possible solution to this problem must lie in the interaction of light with the sample, or more concretely, in exploiting the quantum mechanical states a molecule can be in [3]. By getting a molecule into a different, measurable state, it can be distinguished from all other molecules, even if they are closer than the diffraction limit. Using stimulated emission to switch molecules between a fluorescent excited state and the non-fluorescent ground state (fig. 3a), and applying it in a ring around the excitation focus of a laser scanning microscope (fig. 3b,e), Hell and co-workers could demonstrate that, even in far-field microscopy, fluorescence emission can be restricted to a spot much smaller than the diffraction limit (fig. 3c,f) [3]. Modern Stimulated Emission Depletion (STED) 'nanoscopes' achieve about 25 nm resolution in biological samples, about one order of magnitude below that of the best conventional far-field optical microscopes. In fact, the resolution in STED microscopy and related techniques is limited only by how well one can switch molecules between states and eventually by the size of the molecules.

Instead of switching molecules in a spatially targeted manner at the edges of a laser focus, one can alternatively take advantage of stochastic switching, or 'blinking', of individual molecules to overcome the diffraction limit. Based on technological advances pioneered by W.E. Moerner [4], Michel Orrit [5] and others to detect single fluorescent molecules, and the discovery of photoswitchable fluorescent molecules, this concept was realized in 2006 by Eric Betzig, Sam Hess, Xiaowei Zhuang and colleagues [6-8]. Individual molecules are recorded with a camera as they randomly emit bursts of photons (fig. 3h,i). In contrast to STED microscopy, where the location of the emitters is known *a priori* through the position of the laser focus, in this latter group of techniques the molecule positions have to be determined from the recorded data by fitting a model function to each diffraction-limited molecule image (fig. 3h-j).

Current research in both families of techniques, for example by our research group (fig. 4) [9], aims at optimizing optical nanoscopy for imaging of living samples with multiple stainings at different colors in three dimensions.



◂ **FIG. 2:** Fluorescence microscopy image of a mouse brain section. Using a sophisticated genetic approach, each Purkinje nerve cell produces a different ratio of cyan, yellow and red-coloured fluorescent proteins which provides a unique identifier for each cell and allows to trace neuronal networks in the mouse brain [10]. Figure reproduced with kind permission by J. Lichtman.

optics: lenses were improved to the theoretical limits and phase contrast methods that exploit interference phenomena of light were invented. With new devices derived from quantum electronics, in particular the laser and electronic photon detectors becoming readily available, the focus changed to implementing these devices into biological instrumentation, reflecting the progress in the physics and physical technology of the time and forming the field of biophotonics.

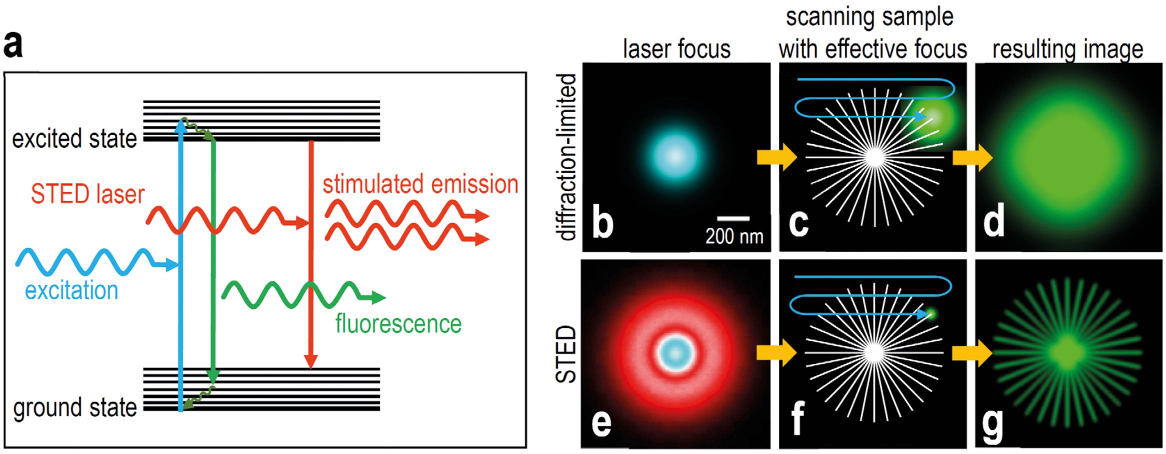
More recently, starting at the end of the 20th century, major breakthroughs emerged primarily at the interface between light and biological samples. The development of antibody-based labelling techniques allowed to specifically highlight nearly every biological structure or protein of interest in a cell with fluorescent molecules. The discovery of green fluorescent proteins (GFPs) and their blue, yellow and red cousins which can be genetically linked to virtually any cellular target of interest boosted live-cell fluorescence microscopy dramatically. The versatility of this new labelling technology, complemented by new detectors sensitive enough to measure the weak fluorescent signal and technology to keep cells in a culture dish alive on a microscope stage, has led to the dominance of fluorescence microscopy as the primary imaging tool in biological imaging (fig. 2).

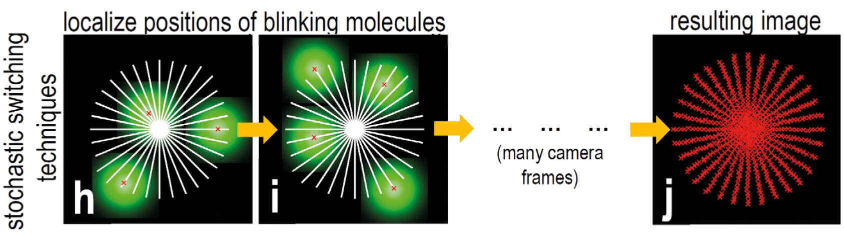
Moreover, the entrance of versatile molecular probes as major actors on the biological imaging stage significantly expanded the number of parameters to play with and led to inventions previously unimaginable: the diffraction barrier in optical nanoscopes could be broken by taking advantage of the photophysical switching properties of fluorescent molecules (see Box), bioluminescence based on the enzyme luciferase is used to study tumor growth in mice, the new field of optogenetics utilizes photoactuator molecules such as channelrhodopsin to manipulate brain circuits of laboratory animals and essentially 'control their mind' by light. Even genomes can be sequenced by detecting single fluorescent molecules in zero-mode waveguides. Biophotonics has become a truly interdisciplinary venture.

The Future of Light in Biological Research is Bright

Living in a world flooded by photons, organisms are well adapted to light in many aspects. Evolution has found means to harvest the energy of light (chlorophyll), detect light to sense the surrounding (photoreceptors and eyes), actively communicate through light and color (bird feathers and bioluminescence in fireflies), and even deal with the negative effects of photodamage (pigmentation and DNA repair mechanisms). These multifaceted interactions outfit a large molecular toolbox that is continuously utilized by

▾ **FIG. 1:** Eric Betzig, Stefan W. Hell and W.E. Moerner shared the Nobel Prize in Chemistry 2014 "for the development of super-resolved fluorescence microscopy". © Nobel Media AB. Photos: Alexander Mahmoud



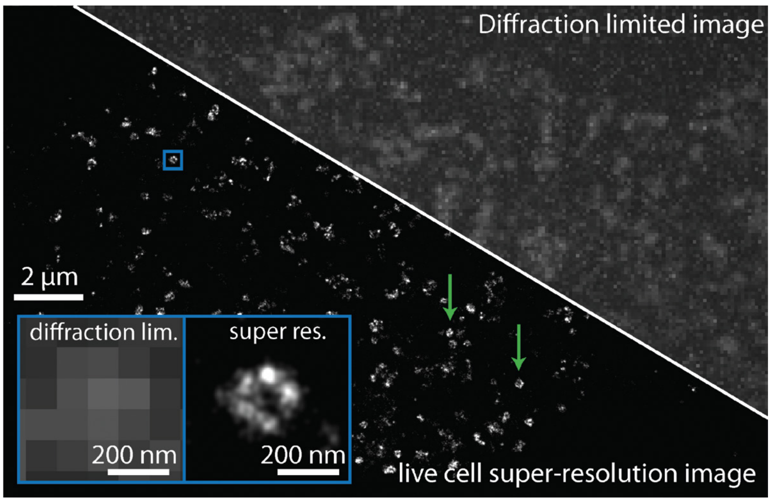


▸ **FIG. 3:** Concepts of Optical Nanoscopy. **(a)** Jablonski diagram of a typical fluorescent molecule showing the transitions used in STED microscopy. **(b-g)** Image formation in a conventional laser scanning microscope **(b-d)** and in a STED microscope **(e-g)**. Overlaying the regular excitation focus (b) with a ring-shaped STED focus **(e)** for stimulated emission which can deplete excited states in a saturating manner leads to a much smaller remaining effective focal spot **(f)**. **(h-j)** Concept of stochastic switching optical nanoscopy. Random, sparse distributions of single molecules are imaged in usually thousands of camera frames **(h,i)**. The computationally determined positions are combined to form a diffraction-unlimited image **(j)**.

the research community to inspire and create novel technologies for biophotonics. An end to this development is not in sight with many of the most exciting developments, for example optogenetics, being just a few years old.

At the same time, optical technology itself is making fast progress which has a positive impact on the development of biological applications: billions of smartphones have given most humans access to high-quality cameras which can be adapted to biodiagnostic usage with little effort. Lasers, LEDs, cameras and other detectors become more powerful every day. Data storage and analysis get cheaper, faster and more accessible, for example through cloud services. All these get implemented into the next generation of optical instrumentation for biological applications making them better, faster and more reliable.

▾ **FIG. 4:** Example of a state-of-the-art optical nanoscopy picture showing clathrin-coated pits, scaffolding structures involved in internalizing extracellular cargo into a cell, in a live HeLa cell. Figure: Fang Huang.



With these developments already in the pipeline, it is safe to predict that light technologies will continue to have a fundamental impact on the advancement of biological research and improving our health. ■

About the author

Joerg Bewersdorf earned his doctoral degree in physics in 2002 under the mentorship of Dr. Stefan Hell. He is now an Associate Professor at Yale University where he works on the development of optical nanoscopy and its biomedical application. Joerg Bewersdorf discloses financial interest in Bruker Corp.

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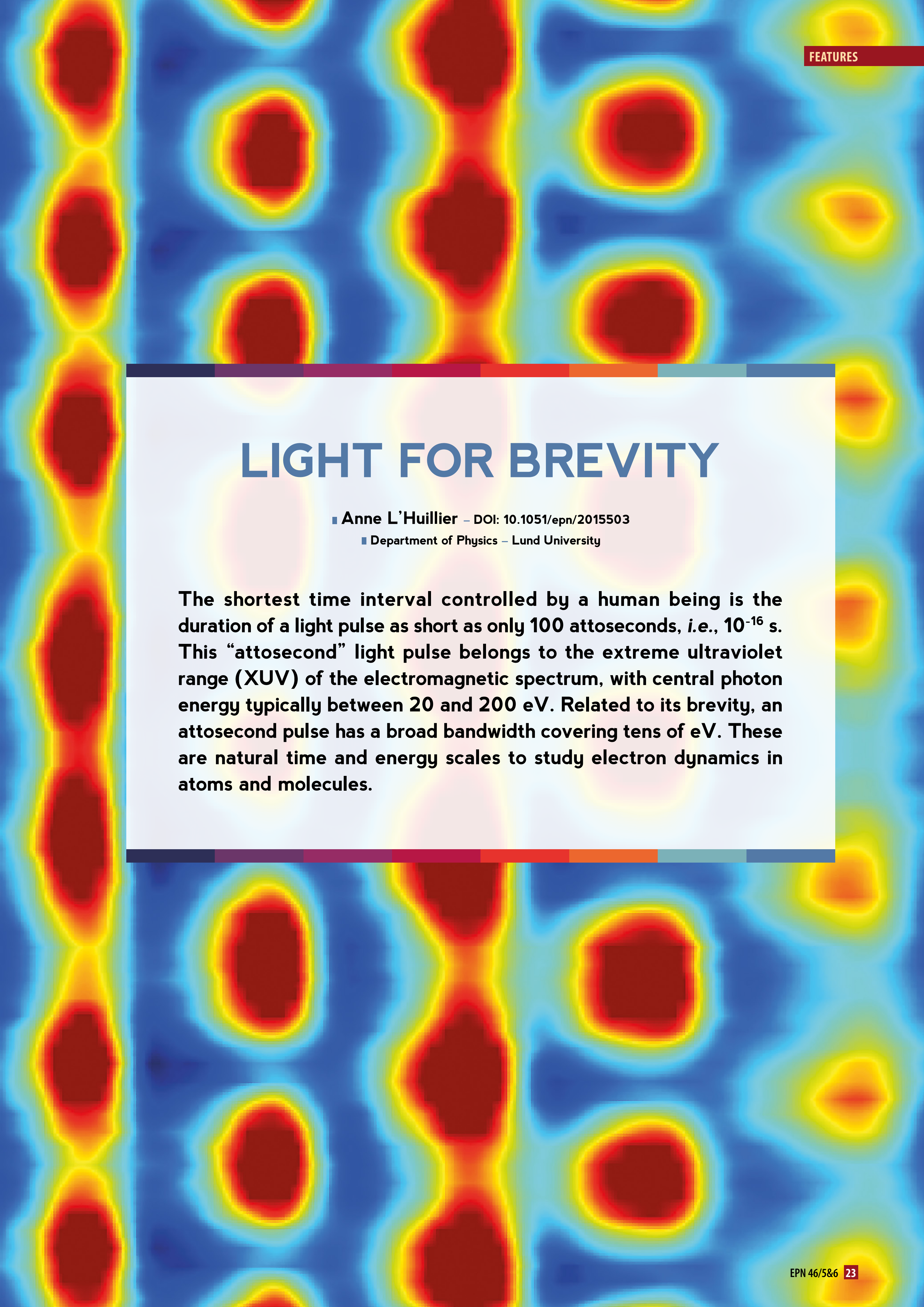

LIGHT FOR BREVITY

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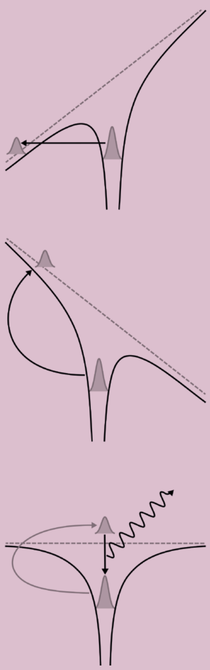
The shortest time interval controlled by a human being is the duration of a light pulse as short as only 100 attoseconds, *i.e.*, 10^{-16} s. This "attosecond" light pulse belongs to the extreme ultraviolet range (XUV) of the electromagnetic spectrum, with central photon energy typically between 20 and 200 eV. Related to its brevity, an attosecond pulse has a broad bandwidth covering tens of eV. These are natural time and energy scales to study electron dynamics in atoms and molecules.

This feature article introduces the physics of attosecond pulses generated through high-order harmonic generation in gases to a general readership. We will also try to answer the question: what can we measure with such short pulses and what can we learn that we don't already know.

Brief historical background

In the late 80s, scientists observed the emission of high-order harmonics of an intense laser focused into a gas cell [1,2]. Not only did the intensity of these harmonics not decrease with their order, forming a "plateau", but their number was high, reaching more than one hundred and thus covering a large bandwidth. It was suggested that if all these harmonics were emitted "in phase" their interference would lead to the formation of very short pulses. This suggestion was rapidly supported by a theoretical understanding of the single atom response to a strong laser field (Box 1) [3,4], as well as of propagation effects in the nonlinear medium (Box 2) [5]. It took, however, almost fifteen years to demonstrate experimentally the existence of these ultrashort pulses. In 2001, the first train of attosecond pulses was observed at the *Laboratoire d'Optique Appliquée* in France [6], while the first isolated attosecond pulse was produced and measured at the Technical University of Vienna [7]. Since then, the number and diversity of attosecond sources, as well as their applications, is expanding worldwide [8].

BOX1: SINGLE ATOM RESPONSE –THE THREE STEP MODEL



The laser field induces a distortion of the atomic potential so that an electron can be ionized by tunnel effect. When the laser field changes sign, the electron is attracted towards the ionic core. It may return with a high kinetic energy and be captured by its parent-ion. The electron recombines with the remaining ground state and an XUV photon is emitted. Everything happens within a laser optical cycle, ~ one femtosecond (10^{-15} s) and the emitted light pulse has a width of ~200 as. This coherent phenomenon follows the oscillations of the laser field and is repeated at each optical half cycle. Interference between consecutive attosecond pulses results in a frequency comb of high-order (odd) harmonics.

Versatility of attosecond sources

An interesting aspect of attosecond sources based upon high-order harmonic generation (HHG) in gases is their versatility. The radiation consists of a frequency comb of high-order harmonics, corresponding in the time domain to a train of attosecond pulses. It is possible to select a single harmonic, to generate a single attosecond pulse or to use the HHG frequency comb, thus keeping a high frequency resolution while benefiting from the underlying attosecond time structure. Single attosecond pulses can be generated using extremely short laser pulses (below 5 fs) in combination with spectral selection of the high-energy part of the spectrum [7]. It is also possible to manipulate the laser polarization (polarization gating) [9] and to spatially streak the attosecond pulse train emission (lighthouse [10] and noncollinear optical gating techniques [11]).

The performances of attosecond sources vary by orders of magnitude depending on the lasers used to drive them. Figure 1 (graph) shows the energy per harmonic pulse around 20 eV as a function of the laser repetition rate. The diagonals indicate the average harmonic power. The take-home message of this picture is that harmonics can be generated with similar conversion efficiency (about 10^{-5} in this case) both using high-energy lasers at low repetition rate and high-average-power lasers, with a few μJ laser energy at MHz repetition rate. HHG sources can be vastly different as shown in the photographs of Fig. 1 and should be designed for specific applications. There is also a lot of effort being devoted to the extension of HHG sources to higher photon energies, in the soft X-ray range, in particular using mid-IR sources [12].

Probing ultrafast dynamics

The pulse duration and photon energy of attosecond pulses correspond to the characteristic time and energy of excitation processes in atoms and molecules. Heisenberg's principle gives for example a time $\tau=\hbar/\Delta E\approx 60$ as for an electronic transition with energy $\Delta E=10$ eV. One could think of attosecond pulses as flashes of a camera filming the ultrafast motion of electrons in matter. The absorption of a pulse starts a process (for example, ionization or chemical reaction) and the absorption of a second pulse, delayed relative to the first, stops it. By varying the delay between the pump and probe, the movement can be reconstructed. However, this classical image of a pump/probe technique should be modified since the moving electrons are also waves or more precisely wave packets (wave-particle duality). The measurement of ultrashort electron dynamics which is made possible by attosecond light pulses in general implies the determination of the amplitude and phase of electronic wavepackets, which can be done either in the time domain, or equivalently, in the spectral domain. One of the techniques used for such phase and amplitude measurements, based upon interferometry, is illustrated in Box 3. It was first developed for the characterization of attosecond pulses and dubbed RABITT (Reconstruction of Attosecond Bursts by Interference of Two-photon Transitions) [6]. The technique often used for the measurement of single attosecond pulses, called streaking, is also based upon cross correlation between the XUV pulse and the fundamental field, however, at higher laser intensity [8]. In both cases, phase and amplitude measurements reflect the properties of the exciting field and of the ionization process used in the measurement. The characterization of attosecond pulses requires either to neglect the influence of ionization or to assume it known from other measurements or theoretical calculations. Conversely, the ionization dynamics can be determined if the attosecond pulses are well known or if their influence can be accounted for in the measurement. We illustrate below one fascinating application of attosecond pulses, the measurement of photoionization (or photoemission) time delays [13-15], opening a new area of research, which we called "ultrafast atomic and molecular physics", by analogy with ultrafast optics.

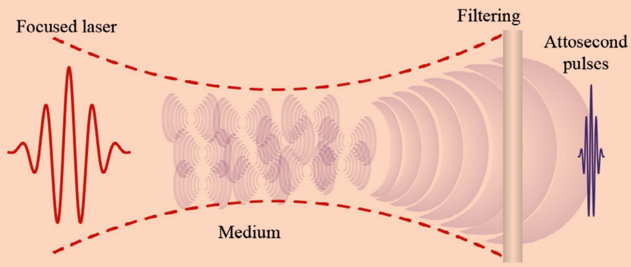
Ultrafast atomic and molecular physics

In ultrafast optics, an ultrashort pulse going through a dispersive medium will acquire a group delay due to the fact that the different frequency components of the pulse travel through the medium at different velocities. It can be calculated as the derivative of a spectral phase, dependent on the dispersion and length of the medium. Similarly, an electronic wavepacket created by absorbing an attosecond pulse will acquire a group delay when propagating through the atomic or molecular potential. This delay is the derivative with respect to energy of the phase of the photoionization probability amplitude.

The interferometric method presented in Box 3 allows us to determine the variation of this group delay across the spectrum of the attosecond pulses and/or to compare different ionization mechanisms if they are initiated by the same pulse. Figure 2 shows for example measurements of the difference of photoionization time delays in the 3s and 3p shell of argon. So far, we have "only" been able to answer simple questions such as: which of the 3s or 3p electron wavepacket is coming first out of the potential [14] or how long does it take for two electrons to be ejected [16]. With improved spectral range and temporal precision, we will get much more insight into the dynamics of correlated electrons in matter, *e.g.* close to resonances [17,18,19]

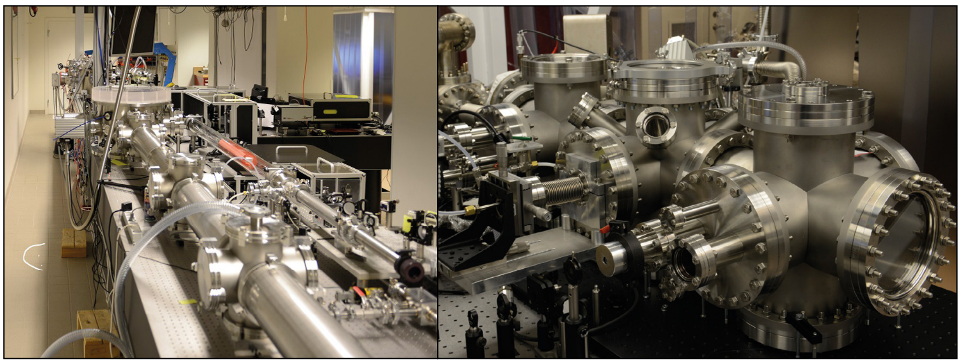
In conclusion, one of the most interesting applications of attosecond pulse technology might be the possibility to measure phases (or phase derivatives) of quantum mechanical probability amplitudes. Such measurements, combined with intensity (or cross section) determinations allow us to

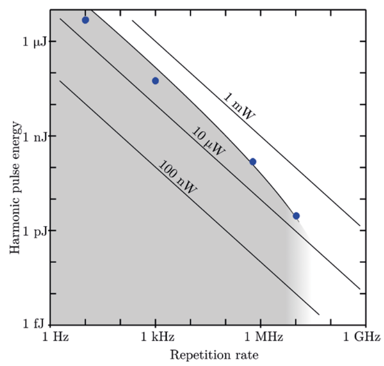
BOX2: MANY-ATOM RESPONSE - PROPAGATION IN THE NONLINEAR MEDIUM

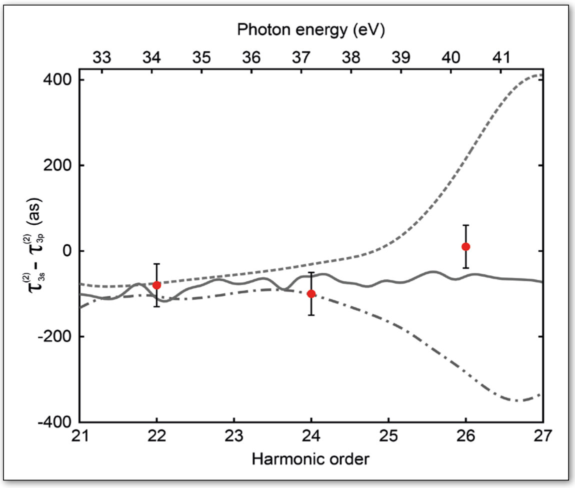


A laser is focused into a gas medium and induces a strong nonlinear atomic response. The emission from all the emitters adds coherently along the laser propagation direction. Phase matching depends on four contributions, the neutral gas dispersion, the dispersion induced by the presence of free electrons in the medium, the Gouy phase variation due to laser focusing, and the intrinsic dipole response. In general, the phase velocity at harmonic frequencies is superluminal since the refractive index above the ionization threshold is below one. A few percent ionization in the medium is necessary (and sufficient) to ensure that the phase velocity of the fundamental field matches that of the harmonic field. A filter is often placed in the beam to eliminate the fundamental field. Finally a detection gas is used for characterization as well as for applications (Courtesy of Marcus Dahlström).

▼ FIG. 1: Left: Long (15 m) attosecond beamline driven by a 200 mJ 40-fs 10-Hz Ti-Sapphire laser system. **Middle:** Compact, table-top, 200 kHz-repetition rate attosecond source driven by an OPCPA laser system. **Right:** Graph showing the average power reached in one harmonic at 20-30 eV photon energy (grey). The experimental measurements (blue dots) are from (left to right) E. Takahashi *et al.*, *Optics Lett.* **27**, 1920 (2002); E. Constant *et al.*, *Phys. Rev. Lett.* **82**, 1668 (1999); S. Hädrich *et al.*, *Nat. Phot.* **8**, 779 (2014); S. Hädrich *et al.*, *Light Science and applications* **4**, e320 (2015) (Courtesy of Christoph Heyl).







▸ **FIG. 2.** Difference between photoionization time delays in the 3s and 3p shells in Ar [14]. The experimental measurements are the red dots. The lines refer to calculations using different approximations such as Random Phase Approximation (dashed line), Muticonfiguration Hartree-Fock Theory (solid line) [D. Guénot *et al.*, *Phys. Rev. A* **85**, 053424 (2012)], Time Dependent Density Functional Theory (dot-dashed line) [G. Dixit *et al.*, *Phys. Rev. Lett.* **111**, 203003 (2013)]. These calculations show quite different results at high energy (40 eV) close to the Cooper minimum of the 3s shell where correlation effects between the 3s and 3p subshells are important. Note that the indicated values need to be corrected for the influence of the IR field to deduce the photoionization time delays. (Courtesy of Diego Guénot and David Kroon)

completely characterize electron wavepackets in the spectral or temporal domain, giving thus access to the temporal dynamics of the electron wavepacket. The door is now open to the investigation of more complex problems such as the dynamics of electrons in inner shells or the transfer of charge in molecules [20]. ■

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About the author

Anne L'Huillier is professor in Atomic Physics at Lund University since 1997, and leader of a research group in attosecond science. After a PhD at the University Pierre et Marie Curie in 1986, she was researcher at the Commissariat à l'Energie Atomique, Saclay, France until 1995 when she moved to Sweden. She has made numerous contributions to the field of high-order harmonic generation in gases and its application to attosecond pulse generation. She is member of the Royal Swedish Academy of Sciences since 2004.

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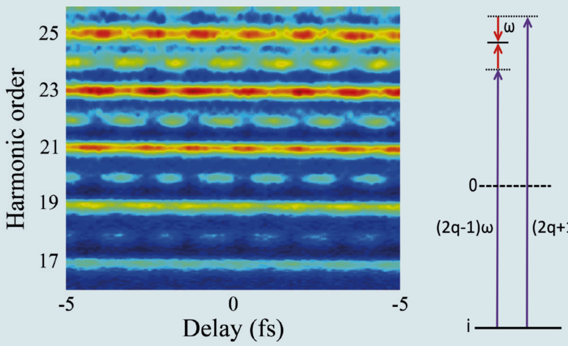
BOX3: ATTOSECOND INTERFEROMETRY

An optical Mach Zendher interferometer is used to generate attosecond pulse trains together with a small fraction of the infrared (IR) laser field used for the generation, with a variable time delay. Both XUV and IR fields are focused into a detection gas including an electron spectrometer. Ionization of the gas by the HHG frequency comb leads to electron peaks with energy equal to $n\hbar\omega - I_p$, where n is an odd integer and I_p the ionization energy. The absorption or emission of an IR photon leads to sideband peaks at energies $n\hbar\omega - I_p$, with n even. Because two quantum paths lead to the same final state, the probability amplitudes interfere and the electron signal oscillates as a function of delay between the XUV and IR pulses. Our measurement consists in measuring the phase of these oscillations,



as a function of energy. The measured phase offset is the phase difference of the complex amplitudes of the two quantum paths leading to the same final state. This includes the phase difference between consecutive harmonics as well as a phase difference induced by the two-photon ionization process.

CONTROLLING LIGHT AT THE NANOSCALE

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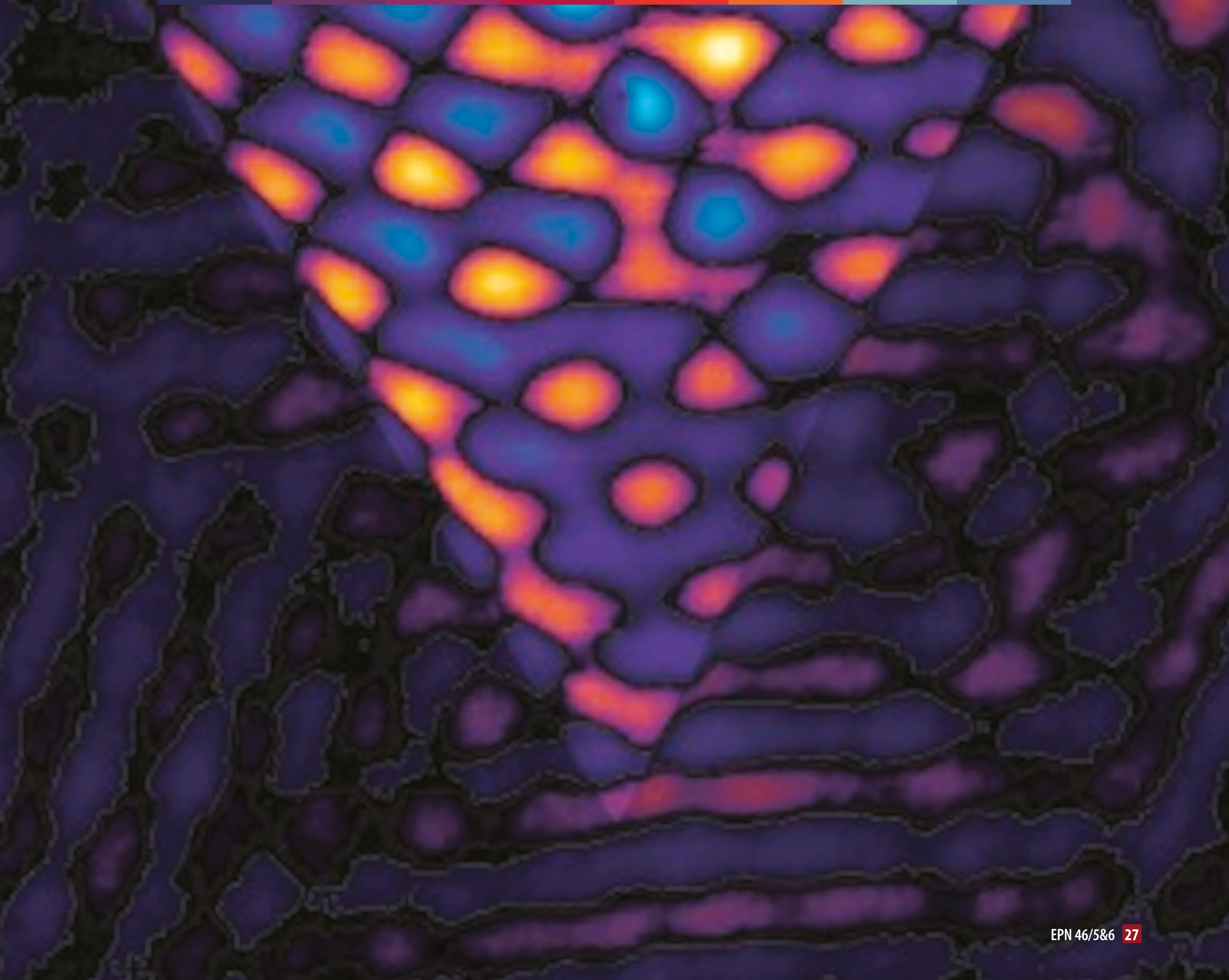
Nanophotonics aims to control light on length scales smaller than the wavelength. By harnessing the interaction of light with matter, nanophotonics has allowed to mold the flow of light and control its emission and absorption on a length scale of just a few nanometers.



◂P.27: Optical near-field on a laser-irradiated monocrystalline gold triangle. The image has been recorded with scanning near-field microscopy and illustrates the electromagnetic near-fields forming standing waves on the metal surface. Image credit: Bradley Deutsch.

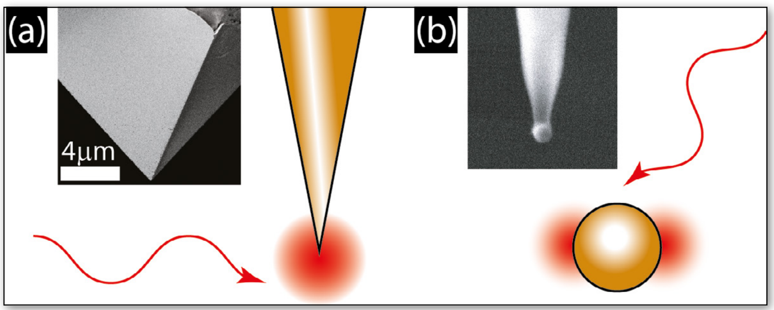
In optics, lenses and mirrors are used to redirect the wavefronts of light. Due to diffraction, propagating radiation cannot be localized to dimensions much smaller than the wavelength. However, by including non-propagating fields, better localization is achievable. Nanophotonics is the science of controlling the interaction of light and matter on length scales smaller than the light's wavelength [1]. This vibrant field has created artificial materials molding the flow of light in previously unknown ways, allowed spectroscopy at the nanometer level and created light sources emitting single photons at a high rate. Instead of a comprehensive review [2], this article presents both the challenge and the promise of nanophotonics. We introduce the optical antenna as the paradigmatic tool of nano-optics and provide two illustrative examples.

The challenge and the promise of sub-wavelength optics

The challenge of manipulating radiation on length scales smaller than the wavelength arises directly from Maxwell's equations. They predict the existence of electromagnetic waves travelling in vacuum at the characteristic speed of light. A principal concept of wave physics is interference, which allows focusing of travelling waves [2]. Importantly, the smallest focus which can be generated with propagating waves of wavelength λ is limited to about $\lambda/2$. This limit is called the Abbe diffraction limit and for visible light is around 200 nm. Accordingly, sub-wavelength optics is referred to as nanophotonics.

The desire to control electromagnetic fields at the sub-wavelength scale arises from the fact that light is both an ideal carrier for information as well as an extremely powerful probe. Spectroscopists harness the interaction of light with matter to gain insight into matter's properties. The building blocks of matter are atoms and molecules and spectroscopy provides insight into their internal structure and dynamics.

▾FIG. 1: (a) Sketch of a metallic tip irradiated by a laser beam, creating strongly localized near-fields at its apex. The inset shows a scanning electron micrograph of a pyramidal gold nanotip used as an optical antenna. (b) Sketch of a metallic nanoparticle illuminated by a laser. The polarization of the particle creates strong near-fields in its close proximity. The inset shows a scanning electron micrograph of a gold nano-particle with a diameter of 100 nm attached to the end of a glass tip.



Assume that we are interested to optically probe the properties of a single molecule. Two criteria need to be satisfied. First, the interaction strength between the light field and the molecule must be large enough to detect the signature of the molecule. This interaction strength will scale with some power of the electric field strength at the molecule's position. According to Abbe's diffraction limit, the light from any source can only be focused to a volume of about λ^3, which poses a limit on the achievable light-matter interaction strength. Second, in order to probe a single molecule, we need to spatially resolve the molecule against all other optically responsive species in its surrounding. Accordingly, the diffraction limit imposes a limit both on the spatial resolution and the light-matter interaction strength achievable. Manipulating and focusing electromagnetic fields beyond the diffraction limit is therefore a prerequisite in order to probe matter at the single-molecule level in the crowded environments where, for example, the biochemical processes of life happen, or at the extreme integration densities of next-generation computing chips.

Optical antennas

The key to such subwavelength focusing and control is also found in Maxwell's equations. While their only physical solution in a homogeneous medium are propagating waves, at material boundaries another type of solution is allowed: the evanescent wave [1]. An evanescent wave decays exponentially away from the interface. The decay length can be much shorter than the wavelength. One method to localize evanescent waves in three dimensions is to exploit the lightning-rod effect. A lightning rod is a conductive rod with a sharp tip. When the rod is charged, strong fields are generated at its apex. Similarly, when shrunk to the nanoscale, a sharp metallic tip irradiated by a laser beam creates strong localized near-fields at its very apex, as illustrated in Fig. 1(a). In essence, such a tip acts as an optical antenna [3]. The antenna is a concept well known from electrical engineering. Antennas are devices for radiating or receiving radio waves. By extending the definition of a radio-antenna to the optical frequency regime, optical antennas mediate the emission of light from a local source or the detection of light by a local sink. Optical antennas therefore boost light-matter interaction by bridging the mismatch in length scales between the size of the emitter or receiver (about 1 nm for a molecule) and that of the propagating radiation set by its wavelength (which is of the order of 500 nm for visible light).

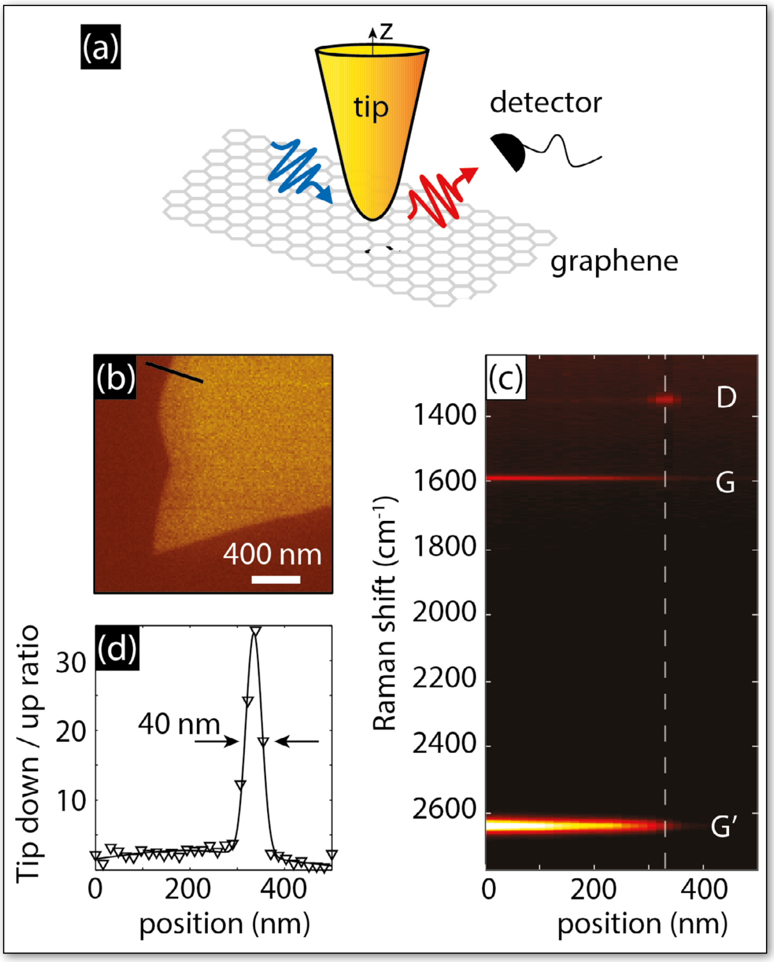
The lightning rod is not the only device from electrical engineering which has inspired the nanophotonics community. Particles of diameter small compared to the wavelength and irradiated with a plane wave get polarized and thereby scatter the incoming fields. In close proximity of the particle, these scattered fields are dominated by evanescent waves, which create hot-spots of strong light intensity in close proximity of the particle, as illustrated in Fig. 1(b). One can boost the amplitude of these evanescent fields by using a noble-metal nanoparticle which supports plasmons, collective excitations of conduction electrons. Excited at its plasmonic resonance with a driving field, such a noble-metal nanoparticle can effectively focus radiation to a volume smaller than the diffraction limit.

Just like their radiofrequency counterparts, optical antennas not only focus incoming radiation to small volumes, but equally serve as transmitting devices, boosting the power radiated by an otherwise inefficient oscillator of sub-wavelength size [4]. In the following, we present examples illustrating both sharp tips and nanoparticles acting as optical antennas.

Tip-enhanced Raman spectroscopy

One of the most impressive examples of nanophotonics enabling spectroscopy at the nanometer scale is tip-enhanced Raman spectroscopy (TERS) [6]. In Raman spectroscopy, a laser beam is sent at a material where it creates phonons, vibrational excitations of the atomic lattice. The scattered photon is shifted in energy relative to the excitation light by the phonon energy. As illustrated in Fig. 2(a), in TERS a sharp metallic tip illuminated by a laser beam is raster-scanned across a surface [5]. With the hot-spot of the electromagnetic field at the tip end being only a few nm^3 in size, via the spectral content of the inelastically scattered Raman signal, a superresolution image of the vibrational properties of the species on the surface is acquired.

A particularly illustrative application of TERS is the characterization of two-dimensional materials like graphene. The superior spatial resolution provided by TERS allows to map defects and local strain in such materials, a feat not achievable with conventional far-field techniques. Figure 2(b) shows a false-color topography plot of a graphene flake (bright region) acquired by scanning a sharp metallic tip at a constant distance across the surface. At the same time as the topographical information is acquired, the Raman scattered light is collected and spectrally analyzed. Figure 2(c) shows an intensity plot of Raman spectra for tip positions along the black line in Fig. 2(b). Three different bands are clearly resolvable. The bands termed G and G' are present in the flake. These bands are the signatures of vibrational modes of the pristine graphene flake. Interestingly, there is another signature, called the D-band, generated by defects in the graphene lattice, which only shows at the very edge of the flake, which represents a defect. To illustrate the resolution provided by the technique, Fig. 2(d) shows the D-band signal as a function of position. Clearly, the D-band signal is strongly localized to within 40 nm around the flake's edge, while it is absent in the center of the flake, which accordingly is defect free. This measurement clearly illustrates the ability of TERS to characterize material properties with a spatial resolution not achievable with conventional microscopy techniques.

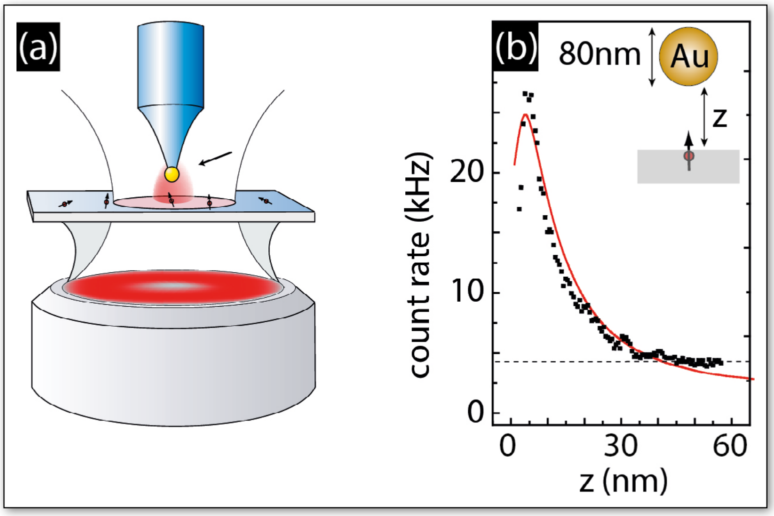


▲ **FIG. 2: (a)** Schematic of a TERS experiment with a graphene layer as a sample. The tip effectively focuses the excitation light (sketched in blue) at its apex. In an inelastic scattering process (red), photons are generated at characteristic Raman sidebands relative to the excitation wavelength. **(b)** Topography scan of graphene flake. **(c)** False-color plot of the Raman spectrum as a function of position on the graphene flake. The G and G' bands are characteristic for graphene and are present in the center of the flake while at the flake edge, the D-band appears. **(d)** Raman-signal enhancement in the D-band due to presence of the tip as a function of position along black line in (b). The D-band signal is localized to within 40 nm around the flake's edge. Figure adapted from Ref. [5].

Spontaneous-emission control

A striking example of the power of optical antennas is their application to control spontaneous emission. A molecule can be promoted to an excited state via the

> **Nanophotonics is the science of controlling the interaction of light and matter on length scales smaller than the light's wavelength**



▲ **FIG. 3: (a)** Schematic of experiment demonstrating the fluorescence enhancement provided by an optical antenna. The antenna is a gold nanoparticle with a diameter of 80 nm attached to the apex of a sharp glass tip, as shown in the inset of Fig. 1(b). This tip is brought in contact with a sample on an optical microscope holding fluorescent molecules dilute enough, such that a single molecule can be addressed. **(b)** Fluorescence enhancement of a single molecule as a function of its distance to the nanoantenna. On a length scale of about 20 nm the photon detection rate is boosted by a factor of about eight by the optical antenna. Figure adapted from Ref. [8].

absorption of a photon. After a certain typical time, termed the fluorescence lifetime, the excited molecule returns to its ground state under the emission of a photon. Interestingly, this fluorescence lifetime is not solely determined by the quantum mechanical properties of the molecule. Instead, the environment determines the number of channels available for the photon generated when the molecule transitions from its excited state to the ground state. Therefore, by tailoring the environment in which a quantum emitter is located, it is possible to control its decay rate. This fact

"By extending the definition of a radio-antenna to the optical frequency regime, optical antennas mediate the emission of light from a local source or the detection of light by a local sink"

was first realized by E. M. Purcell in 1946 [7]. With the decay rate limiting the maximum number of photons available from a single emitter per unit time, such decay-rate engineering is of paramount importance to enhance the efficiency of light-emitting devices and to build the next-generation light sources for secure and high-speed optical data transmission. Figure 3(a) illustrates an experiment demonstrating the working principle of a simple optical antenna, a gold nanoparticle with a diameter of 80 nm [8]. Such a particle is attached to a glass tip, which can be positioned with nanometric precision above a sample surface. The sample holds fluorescing molecules dilute enough, such that only a single molecule is optically excited. Figure 3(b) shows a measurement of the fluorescence intensity recorded as a function of distance between the nanoparticle and the molecule. Upon approaching the optical antenna to the molecule, the detected intensity is boosted by almost a factor eight within a distance of merely 20 nm. The observed brightness enhancement relies on two effects. First, the optical antenna effectively focuses the excitation light in its close proximity. Accordingly, the molecule is excited more efficiently by the pump light. Second, the optical antenna reduces the lifetime and therefore boosts the photon emission rate of the molecule. This experiment is a striking example of controlling the brightness of a fluorescing molecule by simply changing its relative location within its photonic environment by a sub-wavelength distance.

Conclusion and outlook

Nanophotonics provides a powerful toolset for spectroscopists and microscopists from the material and biological sciences. A current focus at the field's forefront is the study of light-matter interaction at the atomic and sub-atomic length scales. A major challenge for nanophotonics beyond the purely scientific playground will be to meet its promises when it comes to real-world mass applications like light management for optical computing, the realization of cheap but efficient solar cells and optical sensing. ■

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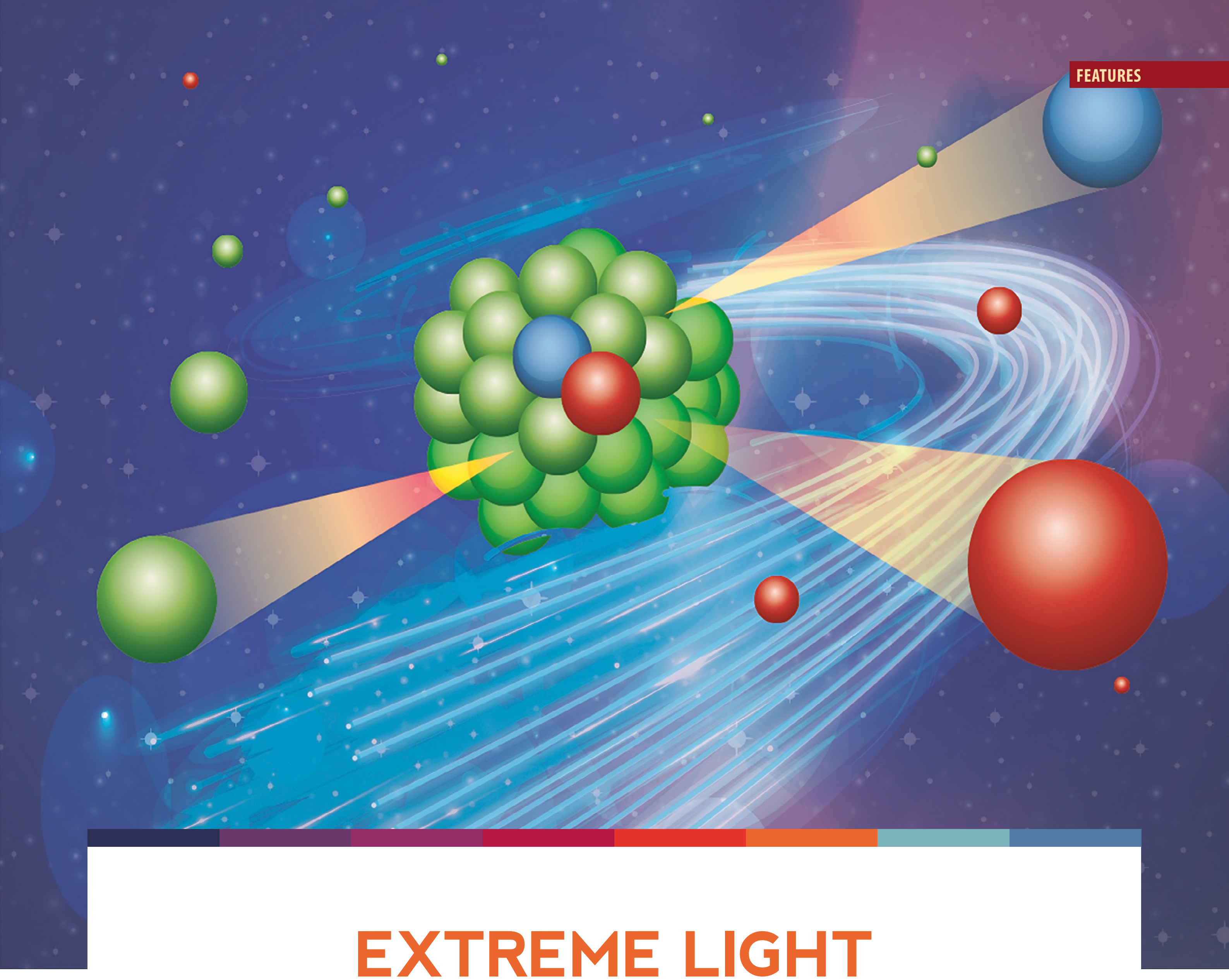

EXTREME LIGHT

AN INTENSE PURSUIT OF FUNDAMENTAL HIGH ENERGY PHYSICS

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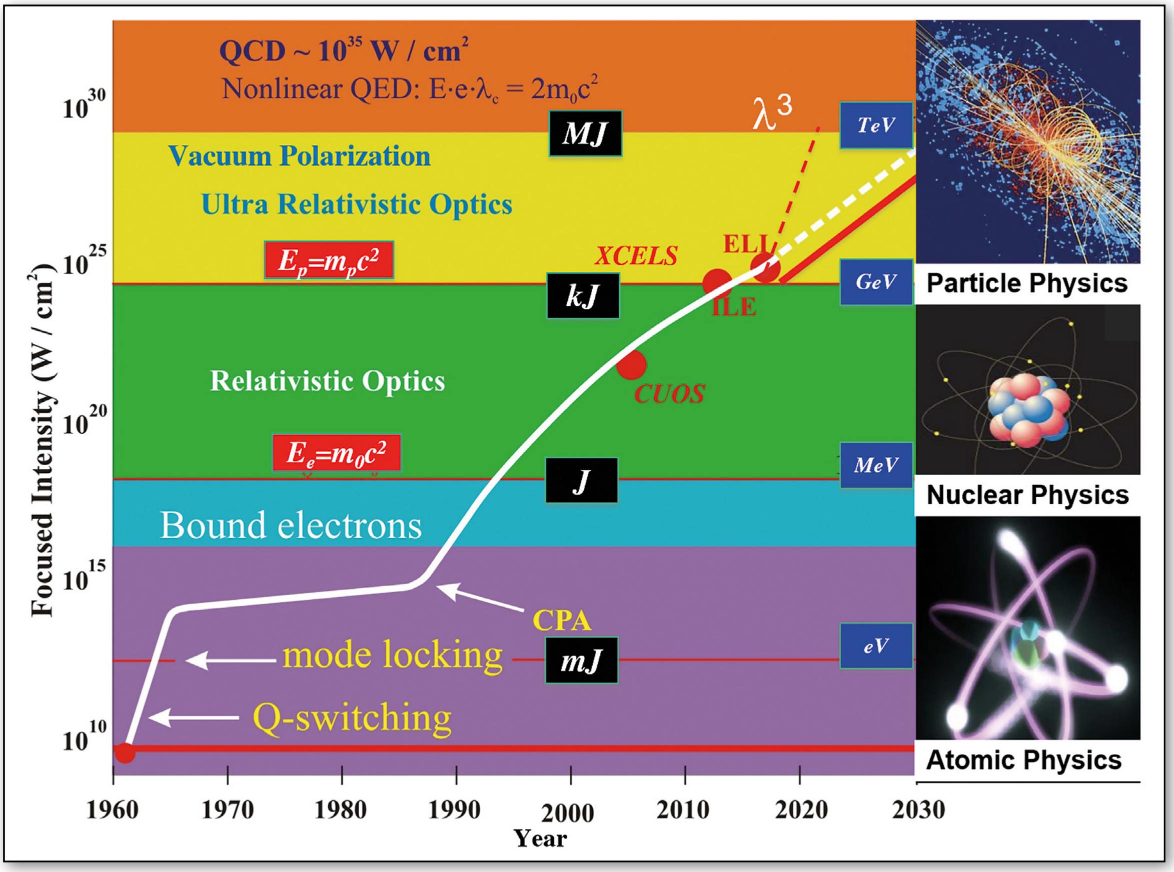
By the compression of petawatt pulses to multi-exawatt, a new route for the generation of Schwinger intensities capable of producing high-energy radiation and particle beams with extremely short time structure down to the attosecond-zeptosecond regime is being presented. Far from the traditional laser investigation in the eV regime, this laser-based approach offers a new paradigm to investigate the structure of vacuum and applications to subatomic physics.

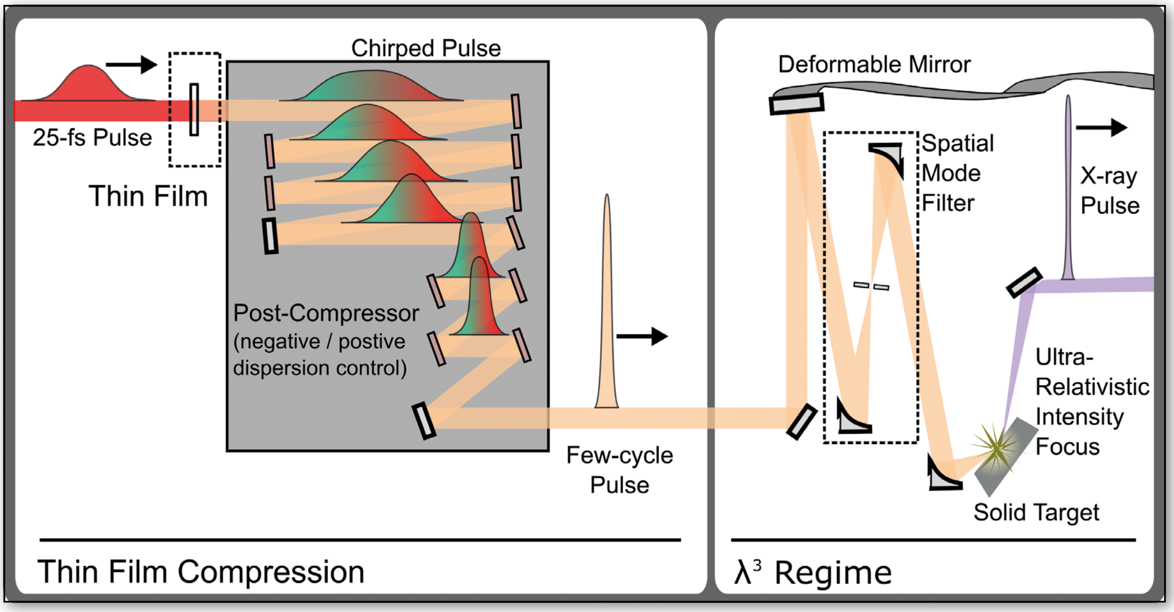
Over the past 30 years peak laser power has progressed to the petawatt (10^{15} W) and is expected soon to reach 10 PW. A level considered as the limit not only in power but also in size and cost. Recently, it was realized that the peak power could not be increased only by increasing the energy but by dramatically decreasing the pulse duration to the subattosecond time scale while maintaining the energy at the 10-1000 J level, corresponding to peak power improvement of several thousand times. The extraordinary large peak power will provide accelerating gradient 6 orders of magnitude higher than can be accomplished with RF based accelerators. Fundamental subatomic physics and applications have been hitherto, mainly driven by high energy fermionic beams and it is heady to think that a 10 km TeV accelerator could fit on the top of one finger. This is a feat likened to electronics where over the same period of time (1950-today) centimeter sized vacuum tubes have been replaced by the nanometer-scale transistor. This opportunity will radically transform the laser field hitherto centered mostly in atomic physics or eV physics. A revolution to the field will make accessible new regimes of physics dealing with the physics of TeV energies and beyond, cosmos acceleration, vacuum nonlinearities, light-mass weak coupling fields such as, dark matter and dark energy, nonlinear QED and QCD fields, radiation physics in the vicinity of the Schwinger field, zeptosecond dynamical spectroscopy of vacuum, as well as affordable proton sources for proton therapy . For scientists the applications will be innumerable, based in particular on laser wakefield acceleration (LWFA) providing abundant sources of protons, neutrons, neutrinos, muons, and gamma-rays [2].

The Ultra-Intensity Pursuit

Since its invention the laser has been ideally suited to focus on atomic physics, or eV physics of electronic interactions. With the advent of Chirped Pulsed Amplification (CPA) [3] and later Optical Parametric CPA (OPCPA) there has been a considerable leap in peak power and intensity of 6 to 8 orders of magnitude, peaking from 10^{15} W/cm^2 to 10^{22} W/cm^2 or 4 orders of magnitude above the level where the electron quiver energy equals the rest mass energy of the electron, associated with pulse intensities of 10^{18} W/cm^2. Above this limit is the relativistic regime of the electron and the threshold for subatomic

▾ **FIG. 1:** Laser Intensity through the years. Note the steep slope in intensities that occurred during the 1960s. This period corresponded to the discovery of most nonlinear optical effects due to the bound electron. We are today experiencing a similar rapid increase in intensity opening up a new regime in optics dominated by the relativistic character of the electron freed through photoionization. A few years ago we called it high intensity when the electron in a quiver energy was around 1 eV. Today high intensity corresponds to electron quiver energies of the order of mc^2 ~0.5 MeV. The dashed line corresponds to what could be obtained with significant increases in beam size or by increasing the number of beams. The red-dashed line corresponds to the "short cut" obtained using the double-compression technique.





▲ **FIG. 2:** Two Stages of Compression. The Thin Film Compression stage relies on the interplay between the spectral broadening produced by self-phase-modulation and the group velocity dispersion necessary to stretch the pulse in a sub-millimeter, large aperture material. The combination of both effects contributes to create a linearly frequency-chirped pulse with increased spectral content compared to the initial pulse that can be compressed using dispersive elements such as chirped mirrors. The second stage of compression requires delivery of the single-cycle pulse with appropriate tight focusing quality to produce and apply a compressed pulse with an ultra-relativistic intensity to a solid target plasma emitting X-rays by up-conversion.

physics including nuclear and particle physics. The next intensity level leads to a quiver energy equal to the proton rest mass, or 10^{25} W/cm^2. It is these enormous intensities that are attempted to be delivered by the various large-scale European laser infrastructures such as those being built at ELI, LMJ and Apollon, as well as others in Russia, China and Korea. These facilities rely on CPA/OPCPA technology housed in 100 m size buildings and have reached the affordable limits to modern techniques in terms of size and cost. To explore the regime up to the Schwinger intensity (10^{29} W/cm^2) —defined as the intensity threshold for vacuum electron-positron pair production—requires an additional 3-4 orders of magnitude increase in pulse energy and is well beyond what is currently affordable. A radical change in technology is required to truly make this dramatic leap.

The method proposed is to efficiently compress pulses with tens of joules to sub-attosecond (10^{-18} s) durations and tightly focus over a spot size such that the peak intensity will be in the Schwinger range of 10^{29} W/cm^2. Note that by using a Fourier-Heisenberg argument, the subattosecond pulses are composed of a spectral range containing keV energy X-ray photons. The strategy that we have adopted for the efficient production of high energy subattosecond pulses is done in two steps depicted in Figure 2. The compression technique will first shorten a typical 20 fs, 20 J near-infrared (NIR) pulse into a single-cycle while maintaining upwards of 15 J of energy. The second step utilizes a relativistic plasma mirror to drastically compress the pulse from 2.5 fs to the attosecond and even the zeptosecond (10^{-21} s) regimes.

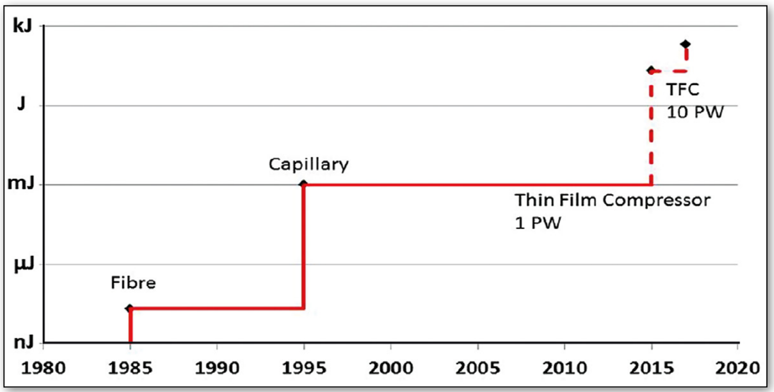
Current compression techniques rely on a fused silica hollow-core capillary, filled with noble gases for the spectral broadening required but the resulting pulse energies from these schemes are typically limited to the sub-mJ level. To go higher in energy, bulk compression was attempted by Corkum and Rolland [4] with the pulse free-propagating rather than guided. The pulse was relatively long around 90 fs with an input energy of 500 μJ leading to an output pulse of 100 μJ in 20 fs. As the material nonlinearity is strongly influenced by changes in the beam intensity, this scheme is impaired by the Gaussian intensity profile of the beam. A non-uniform broadening develops compounds with small-scale intensity features. These make the pulse impossible to compress uniformly except in the peak region of the beam that can be considered as constant. This crucial limitation to the efficiency frustrated the initial attractiveness of this arrangement.

To solve the uniformity problem we have recently proposed a new scheme for compression to the single cycle regime suited for high energy pulses in the tens of Joules level. This Thin Film/Plate Compressor [5] relies on the fact that current high energy and short pulsed lasers are designed to produce top hat pulses in amplitude and phase for efficient energy extraction. Using thin and inexpensive sheets of plastic, or alternatively thin, sub-millimeter glass plates, it has been shown through numerical simulations that we can produce identical self-phase-modulation across the beam that would lead to a uniform pulse compression. Plastic is the ideal candidate as it is much cheaper to fabricate than quartz and glass at the required thicknesses of a fraction of a millimeter but modern glass making may allow for appropriate candidate substrates as well. The large aperture (~0.5 m) material must be capable of withstanding high intensity laser shots without breaking while being easily replaceable as it degrades with use. Note that the thickness needs to be uniform but not necessarily flat to be effective as the nonlinear material. Numerical simulations were carried out assuming a plastic film interacting with a laser similar to that recently commissioned at the CETAL PW laser facility based at the Institut National de Laser, Plasma et Radiophysique (INFLPR) in Magurele, Romania [5, 6] and experimental plans are underway to test the conclusions of these simulations. This CPA laser system is designed to deliver 27 J of energy within 27 fs yielding a 1 PW laser pulse at a wavelength of 800 nm. Once focused to a diffraction limited size this single cycle pulse should belong the so called Relativistic λ^3 regime [7].

“This laser-based approach offers a new paradigm to investigate the structure of vacuum and applications to subatomic physics using ultrashort, coherent keV x-ray.”

The application of such a relativistic intensity field to a solid target plasma is what gives rise to the dramatic compression and photon up-conversion of the ultrashort NIR pulse to an even shorter X-ray pulse. A laser-driven reflective surface within the plasma that moves in and out under the influence of the incident pulse acts as a so-called relativistic mirror. In this relativistic regime Naumova *et al.* [7] predicts a reflected pulse duration T—compressed by the relativistic motion of the mirror toward the pulse—scaling as $T = 600\ (attosecond)/a_0$. Here a_0 is the normalized vector potential of the laser pulse, which is unity at 10^{18} W/cm^2 and scales as the square root of the intensity. Considering the scaling for an incident intensity of the order of 10^{22} W/cm^2 the pulse reflected from this high efficiency relativistic mirror is predicted to be compressed and necessarily up-converted in photon energies to achieve coherent keV X-ray pulses at the exawatt (10^{18} W) level power. A modest 1 J of reflected energy contained within an attosecond pulse duration is sufficient to produce an exawatt pulse. Any compression achieved below this timescale relaxes the energy requirements to produce similar powerful pulses.

▾ **FIG. 3: Evolution of Pulse Compression in the single cycle regime. Early work by Grischkowsky *et al.* [9] compression technique which relies upon the nonlinear response of a material to a high intensity pulse within a single mode fiber. In their experiment a picosecond pulse with nJ energy was further compressed to a duration of tens of femtoseconds. This work triggered an enormous interest that culminated with the introduction by O. Svelto, F. Krausz et al [10] of a fused silica hollow-core capillary, filled with noble gases and demonstrated that a 20 fs pulse can be further compressed to 5 fs, or 2 cycles of light, at 800 nm. Due to the energy losses associated with coupling the laser pulse spatial mode into a single-mode fiber or hollow-core capillary the resulting pulse energies from these schemes are typically limited to the sub mJ level.**



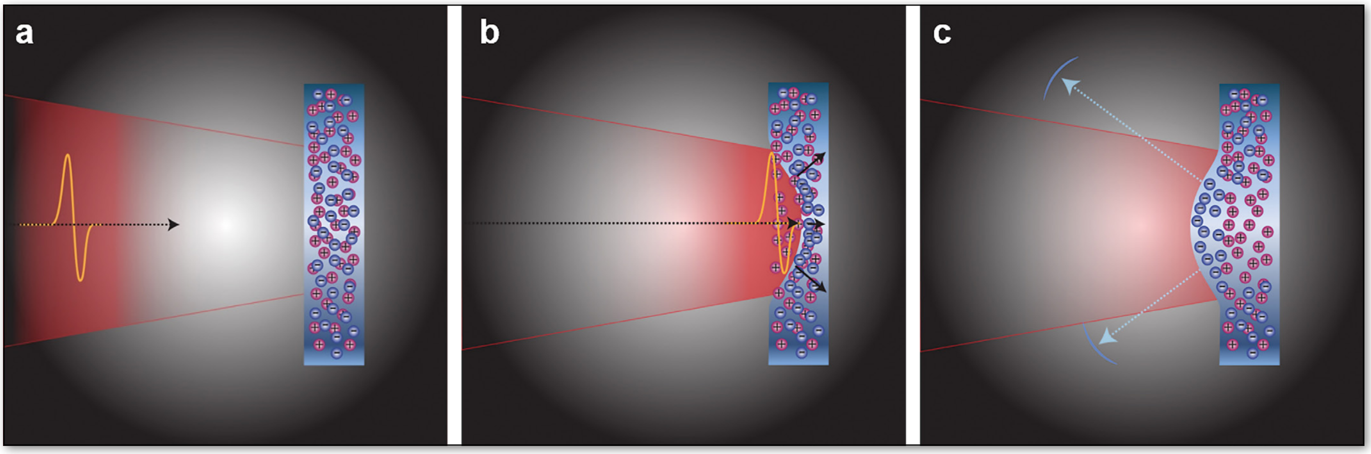
Applications of High Energy, Short Pulses

Nonlinearity of Vacuum. A coherent, exawatt x-ray pulse that can be focused tighter than current NIR laser systems is capable of reaching the Schwinger intensity and produce sizable nonlinearities in vacuum due to the expected pair production. This is even though the nonlinear index of refraction of vacuum is 18 orders of magnitude smaller than that of a typical optically transparent medium such as glass. In treating the pair production process as a nonlinear index it is fascinating to imagine the physics of vacuum nonlinearity to pulse compression, self-focusing and the generation of filaments in vacuum analogous to those produced in air by NIR pulses [8]. The properties would be limited by "vacuum breakdown" or pair creation as the intensity approaches 10^{29} W/cm^2.

Giant Laser Wakefield Acceleration in Solid: CERN on a chip! The high frequency photons offer the advantage of driving wakefields in high density matter. The critical density of a plasma, n_c, is defined by a given laser frequency and increases with increasing photon frequency or energy. For 1eV optical photons, n_c is about 10^{21} /cc, while for X-ray photons of 10 keV n_c is about 10^{29} /cc and is well above solid densities. In LWFA, the energy gain is limited by the critical density of the plasma with the high intensity LWFA energy gain given by

$$\varepsilon_e = a_0^2\, mc^2 (n_c/n_e),$$

where n_e is the electron density. Therefore going to a higher photon energy allows for a greater achievable energy gain. An important benefit of a higher density plasma is that it supports a larger acceleration gradient. Shifting to extreme X-ray driven wakefield acceleration dramatically allows the acceleration to larger energies to be achieved over shorter distances suggesting TeV energies over centimeter distances. The accelerating lengths of the order of TeV/cm are 10^3 times larger than previous results achieved for optical lasers in gases and 10^6 times that of current radiofrequency technology. They suggest acceleration performances to levels achieved only at CERN,



▲ **FIG. 4:** Reflection from a Relativistic Mirror. **(a)** A high intensity single-cycle pulse encounters a solid target plasma and **(b)** pushes the plasma electron critical density surface further into the plasma until the laser field reaches equilibrium with the electrostatic potential that has developed between the displaced electrons and stationary ions to pull the critical surface back so that **(c)** a portion of the incoming pulse is compressed as it is swept up by its encounter with this relativistically moving reflective surface. Deformations in the target surface due to the shape of the focus help to spatially isolate portions of the reflected beam.

in Geneva not over kilometers, but over a few centimeter focus and supported by a laser facility such as the PW level facilities currently being built.

Conclusion

Modern high peak power laser producing PW and 10PW pulses with top hat distribution, combined with Thin Film/Plate Compressor could have the capability to produce 100 PW pulses with single cycle or 2.5 fs. Focused on a spot size limited by the laser wavelength, their interaction with solids is expected to generate attosecond or even zeptosecond multi-exawatt pulses in the X-ray regime with the acumen to drive giant acceleration in crystal in the TeV/cm regime. This would form the basis of an all-optical high energy physics field providing the means to investigate vacuum structure, dark matter, dark fields and the like. In addition the technology could underpin new compact sources of protons, neutrons and muons with applications in fundamental physics and societal applications like proton therapy or nuclear waste transmutation. ■

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Gérard Mourou is a Professor Haut College at the École Polytechnique and Director of the International center for Zetta-Exawatt Science and Technology (IZEST). He is also an Emeritus Professor of the University of Michigan. He is the recipient of numerous awards including the 2009 Charles H. Townes Award from The Optical Society.

Toshiki Tajima is the Norman Rostoker Professor at University of California at Irvine and is well known as the inventor of laser electron acceleration in 1979. He is Deputy Director of IZEST, Chairman of International Committee for Ultrahigh Intensity Lasers (ICUIL), and spokesman of the Collaboration THEXAC (Transformative High Energy X-ray Acceleration in Crystal). He has received many awards, including most-recently the 2015 Enrico Fermi Prize.

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QUANTUM LIGHT:

THE PUZZLING PREDICTIONS OF ENTANGLEMENT ARE COMING OF AGE

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Entanglement is the physical property that marks the most striking deviation of the quantum from the classical world. It has been mentioned first by the great Austrian Physicist Erwin Schrödinger in 1935 (an introduction to this and other quantum phenomena is given in [1]). Yet, despite this theoretical prediction now being 80 years old, and the famous experimental verifications by Alain Aspect dating back to the early eighties [2], entanglement and its use entered mainstream physics as a key element of quantum information science [3] only in the 1990's.

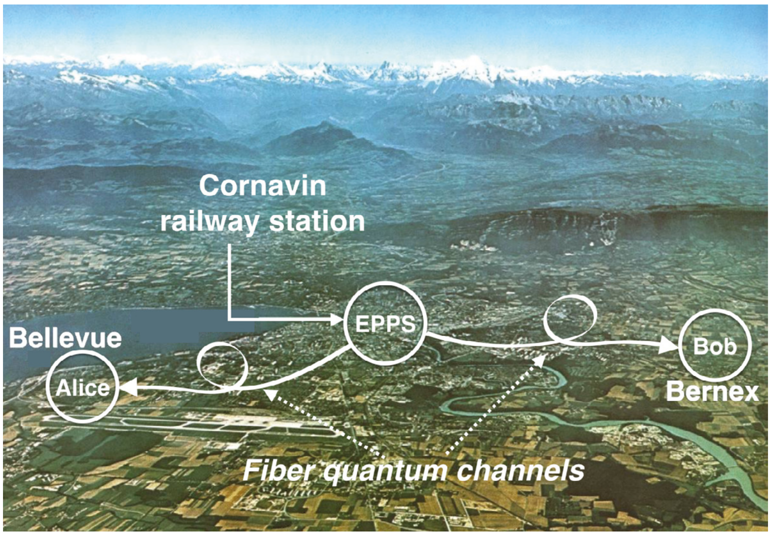
The academic research into entanglement nicely illustrates the interplay between fundamental science and applications, as well as the need to foster both aspects to advance either one. For instance, the possibility to distribute entangled photons over tens or even hundreds of kilometers is fascinating because it confirms the quantum predictions over large distances, while quantum theory is often presented to apply to the very small (see Figure 1). On the other hand, entanglement enables quantum key distribution (QKD) [1]. This most advanced application of quantum information processing allows one to distribute cryptographic keys in a provably secure manner. For this, one merely has to measure the two halves of an entangled pair of photons. Surprisingly, and being of both fundamental and practical interest, the use of entanglement removes even the necessity for trusting most equipment used for the measurements [5]. Furthermore, entanglement serves as a resource for quantum teleportation (see Figure 2) [1]. In turn, this provides a tool for extending quantum key distribution to arbitrarily large distances and building large-scale networks that connect future quantum computers and atomic clocks [6].

In the following, we describe the counter-intuitive properties of entangled particles as well as a few recent experiments that address fundamental and applied aspects of quantum teleportation. While a lot of work is being done using different quantum systems, including trapped ions, colour centres in diamond, quantum dots, and superconducting circuits, we will restrict ourselves to experiments involving photons due to their suitability for building future quantum networks.

Entanglement – a puzzling consequence of quantum theory

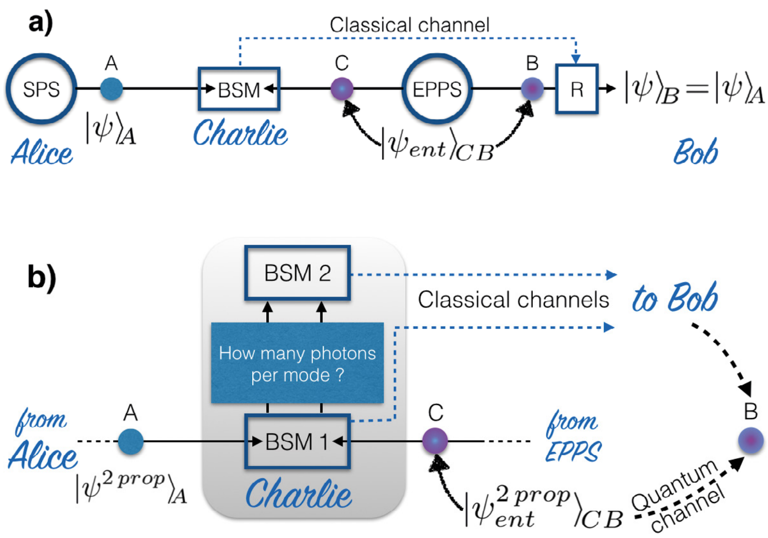
Entanglement manifests itself through highly, if not perfectly, correlated results of measurements performed on particles that can in principle be arbitrarily far away – say, one on the earth, and one on the moon. If we consider two photons and their polarization as an example, quantum theory describes, and experiments confirm, that photon 1 might be found horizontally polarized, and photon 2 vertically polarized. Or vice versa. What is more, one might also find that one photon is polarized at 45° and the other one at -45°. All what is known in advance is that the two photons are orthogonally polarized.

What is particularly discomforting about these correlations is that they cannot be explained by attributing properties to the individual photons that determine, irrespective of what happens to the other photon, how each will respond to its measurement. Entangled particles behave in unison, regardless of their separation and even if they are measured simultaneously. The result of a quantum measurement is random, but, somehow, this



▲ **FIG. 1:** Long-distance entanglement distribution. A source, located at the Geneva-Cornavin main railway station, distributes entangled photon pairs emitted at a telecom wavelength to two remote villages (Alice's and Bob's station located in Bellevue and Bernex, respectively, in the Geneva back-country). Those two user stations are more than 10 km apart, and are connected to the source through commercial fiber optics quantum channels. This experiment reported the first tests of entanglement distribution and nonlocality in the real world [4]. Entanglement can be further exploited for establishing secret sequences of bits (*i.e.* secret keys) finding applications in cryptography. EPPS: entangled photon pair source.

▼ **FIG. 2:** Quantum teleportation. **(a)** The original scheme. Initially, a source (EPPS) produces a pair of polarization entangled photons. Those photons are referred to as C and B, and are prepared in a state represented by $|\psi_{ent}\rangle_{CB}$. Photon C is given to Alice and photon B to Bob. Photon A, emitted on Alice's side, whose polarization, represented by $|\psi\rangle_A$, should be teleported onto photon B at Bob's, is measured jointly with photon C. This joint measurement, called Bell-state measurement (BSM), reveals, loosely speaking, the difference in the electric field directions, without telling the individual directions. For instance, if we find that A and C are orthogonally polarized, and knowing from the original entanglement that the polarization of photon C is orthogonal to that of photon B, we find that the electric field of photon B must point in the same direction as that of photon A before the measurement. Note that the outcome of the BSM could also have been different, for example, A and C are identically polarized. Similar reasoning would then lead to the conclusion that photon B's polarization is orthogonal to that of photon A. Therefore, rotating it back would also allow one to perfectly recover the original polarization encoded into photon A. In short, the BSM, possibly followed by a well-defined rotation of the (unknown) polarization of photon B, allows one to teleport without error the property "polarization" from photon A onto photon B. EPPS: entangled photon pair source; SPS: single photon source; R: polarization rotator. **(b)** Teleportation of two properties. This scenario is comparable to that described in a) with, however, the possibility of teleporting two quantum properties coded on the same original single photon. In this case, the single BSM is replaced by two cascaded joint measurements, one for each property, but the second one is conditioned on the success of the first one.



random event manifests itself at both locations. Einstein called this "spooky action at a distance", though there is no real action from one side onto the other [7]! But while the question of how to understand this invisible, non-local tie remains intriguing, the tie enables applications of quantum communication such as teleportation.

Quantum teleportation – a surprising possibility

Suppose you see a beautiful sculpture in a museum and you would like to have the same at home. Unfortunately, you can't take it with you. However, you can accurately measure all its properties — *e.g.*, its shape (height, length and depth) — and then reproduce an identical copy for your living room. But this "measure-and-reproduce" strategy would fail if the sculpture were a photon. Indeed, for the case of a quantum object, the quantum no-cloning theorem [1] tells us that perfect copying of, say, the photon's polarization is impossible.

Quantum teleportation, proposed in 1993 and first experimentally demonstrated at the Universities of Rome and Innsbruck in 1997, allows the flawless transfer of a property between two quantum particles – *e.g.*, two photons – without running into a contradiction with the no-cloning theorem (see [8] for a recent review article). As explained in Fig. 2a, it requires three particles – one whose property is to be teleported (A), and two that are originally entangled (C and B). The comparative measurement of the property of the first photon with that of one member of the entangled pair allows transferring it from the first photon onto the second member of the pair. This measurement – the so-called Bell-state measurement – is named after the Northern Irish Physicist John Bell, who has played a seminal role in establishing the science of entanglement. The first photon loses its property during this measurement, that is, there is no 'copying' during teleportation. Moreover, the transfer does not happen instantaneously (something that is often claimed erroneously in the non-scientific literature), and hence there is no contradiction with another pillar of modern physics either – that of special relativity.

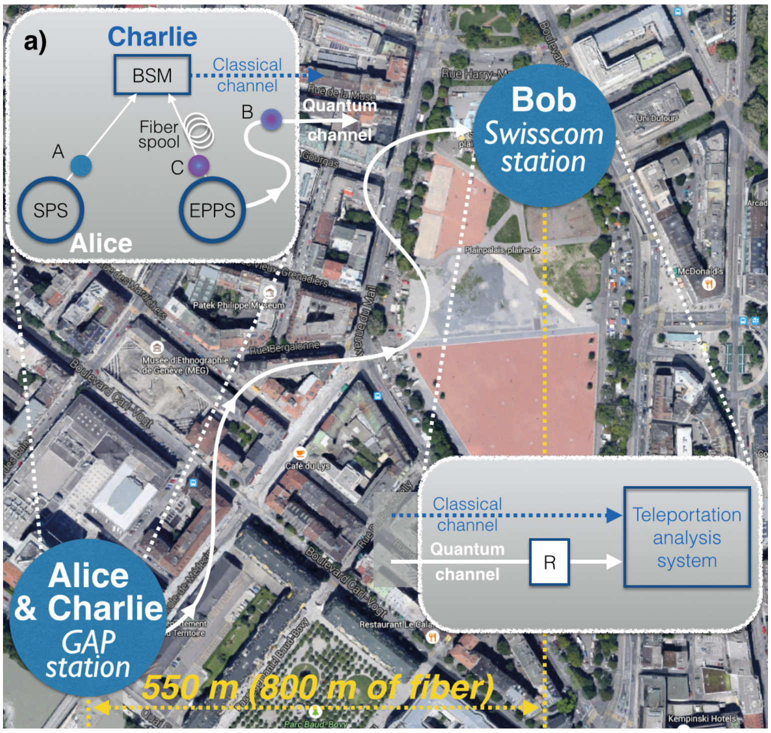
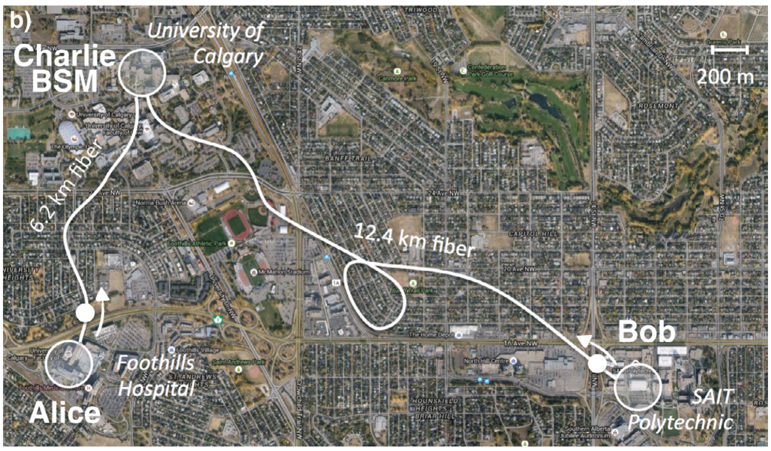


FIG. 3: Extending the reach. a) The 2007 Geneva teleportation experiment as an example in which photon B is already outside the lab when photon A is created, and continues to travel before being measured at Bob's [10]. b) The Calgary Bell-state measurement as an example in which photons A and C are travelling a long distance before being jointly measured.



An application of quantum teleportation - extending the reach

Only five years after its discovery, it was realized that quantum teleportation is not only an intriguing manifestation of the puzzling predictions of quantum theory. Together with the possibility to transfer properties from flying photons onto stationary particles (*i.e.*, to create quantum memory for light), it allows establishing entanglement over theoretically arbitrarily long distances by means of quantum repeaters [8]. This would allow building ultra-long-distance QKD links as well as quantum networks across countries, continents, or even the globe.

The first step in this direction was demonstrated in 2003 at the University of Geneva, when the photon that received the teleported property (photon B in Figure 2a) was sent over 2 km of spooled, standard telecommunication fiber before being measured [9]. This demonstration was extended in 2007 to more than 800 m of deployed fiber that was part of the Swisscom fiber network [10] (see Figure 3a). In this experiment the receiving photon was already hundreds of meters away when the qubit to be teleported was prepared. More recently, the transmission distance of photon B was extended to more than 100 km of air by researchers at the University of Vienna as well as the University of Science and Technology in Hefei [8].

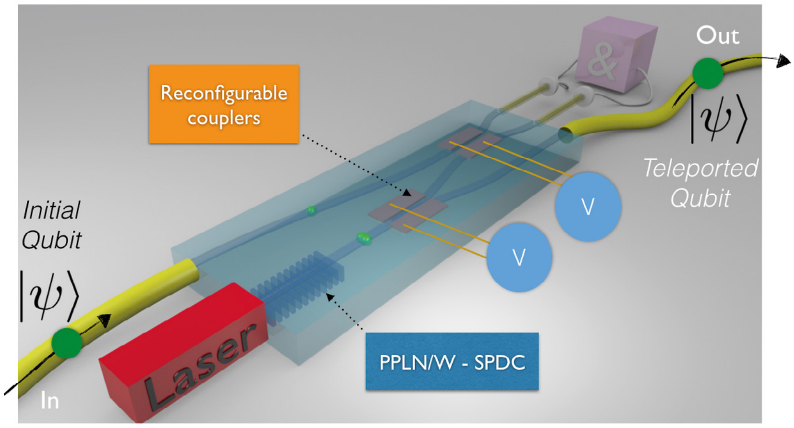
The next step is to extend the distance over which the other two photons (photon A and C in Fig. 2a) travel before meeting for the Bell-state measurement. However, due to the difficulty of avoiding any modification of either photon during transmission, this challenge has not yet been met outside a well-controlled laboratory. An important step in this direction has been the recent demonstration by researchers at the University of Calgary of a Bell-state measurement – not a full quantum teleportation experiment – with photons that have been created at different places within the city of Calgary and travelled through the standard telecommunication fiber network before being measured [11] (see Figure 3b).

Another key achievement on the path towards a quantum network has been last year's teleportation at the University of Geneva of a property from a photon into a rare-earth-ion doped crystal, which stored it for 50 nanoseconds [12]. Notably, both photons that took part in the Bell-state measurement travelled over 12.5 km of spooled fiber, thereby also meeting the above-described requirement for building extended quantum networks. This demonstration built on the previous observation that such crystals are suitable for storing members from entangled photon pairs, which was reported in 2011 by researchers in Geneva as well as in Calgary [13].

A fundamental question – teleportation of multiple properties

With very few exceptions, all quantum teleportation experiments to date demonstrated the transfer of a single property of one particle, *e.g.*, the polarization of a photon. However, objects encountered in our every-day life are composed of many elementary building blocks, *e.g.*, many atoms, each of which being described by several properties. A natural question is therefore if one can teleport more complex quantum systems as well. Indeed, this is possible. A first guess may lead to the idea of teleporting all properties individually in a straightforward generalization of the scheme shown in Figure 2a. This guess is correct – most surprisingly even if the properties are entangled!

However, in the case of teleporting several properties encoded into the same particle, there is an interesting twist – at least in the scheme employed by researchers from the University of Science and Technology in Hefei in 2015 to transfer the angular orbital momentum and the polarization of a single photon [14]. As shown in Figure 2b, it requires, as an intermediate step, the confirmation that exactly one photon traveled along each of the two paths connecting the measurement that teleports the first property (the orbital angular momentum) with the measurement that teleports the second one (the polarization). Obviously, the use of standard single photon detectors is not a viable solution, as the photons would be destroyed during the measurements. But interestingly a standard "single property teleporter" does the job. Indeed, a successful Bell-state



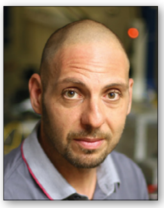
▲ **FIG. 4:** On-chip teleportation. The on-chip teleporter developed in Nice in 2012, as a telecom-compatible elementary plug-in. A source of entangled photon pairs and routing circuitry are integrated on a single photonic substrate enabling on-chip teleportation of an incoming photon. Entangled photon pairs are produced on-chip by means of spontaneous parametric down-conversion (SPDC) out of nonlinear periodically poled lithium niobate waveguide (PPLN) section. V = Applied voltage on the electrodes of the integrated directional couplers in order to route the photons appropriately by means of electro-optics capabilities.

measurement does not only transfer a property from one photon onto another photon (a process that is not distinguishable from the direct transmission of the original photon through the teleporter), but also confirms that the photon existed! This idea generalizes from two to any number of properties: an n-property teleporter requires an (n-1)-property teleporter as a plug-in, which itself requires an (n-2)-property teleporter, *etc.* Figure 4 shows a fully integrated "on-chip" realization of a one-property teleporter, developed at the University of Nice [15], that would constitute a good starting point for building such a nested scheme.

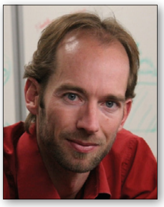
As one can see from these insights into current research, many fundamental problems related to entanglement and teleportation remain to be solved. Furthermore, on the application side, the connection of distant nodes into quantum networks, which will enable provably secure communication and networked quantum computers, will remain an important challenge for many years to come. One thing is clear: this highly multi-disciplinary field will continue to be exciting! ■

About the Authors

Nicolas Gisin is a Professor and Director of the Department of Applied Physics at the University of Geneva. His activities range from foundations of quantum physics to applications in quantum communications.



Sébastien Tanzilli is a CNRS Research Director at the University Nice Sophia Antipolis. He aims at exploiting integrated photonics as an enabling technology for quantum communication and fundamental quantum optics.



Wolfgang Tittel is a Professor and Chair for Quantum Secured Communication at the University of Calgary in Canada. He aims at exploiting entanglement as well as rare-earth doped crystals and fibers to establish long-distance quantum communication links.

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[Letter to the Editor]

by Frank Israel, Sterrewacht Leiden

Dear Editor,

The article: "Light, cosmic messages from the past" in *EPN* 46-4 contained two small errors.

- Sanduleak was not a star but a person. Nicholas Sanduleak was an American astronomer of Rumanian origin who published in 1970 a catalogue of stars in the Large Magellanic Cloud. The precursor of SN 1987A was listed in this catalogue and is referred to as Sk -69 202a (or Sanduleak -69 202a).
- The supernova remnant Cas A was observed for the first time in the 20th century, not in 1680. The supernova explosion that created the remnant occurred at some time in the 17th century, but there are no unequivocal records of its occurrence. The very bright star was probably obscured by dense clouds of dust in the line of sight. ■

The author responds

We agree with the comment that the blue supergiant star, progenitor to supernova 1987A in the Large Magellanic Cloud was officially named Sanduleak -69° 202. We apologize for the sloppiness.

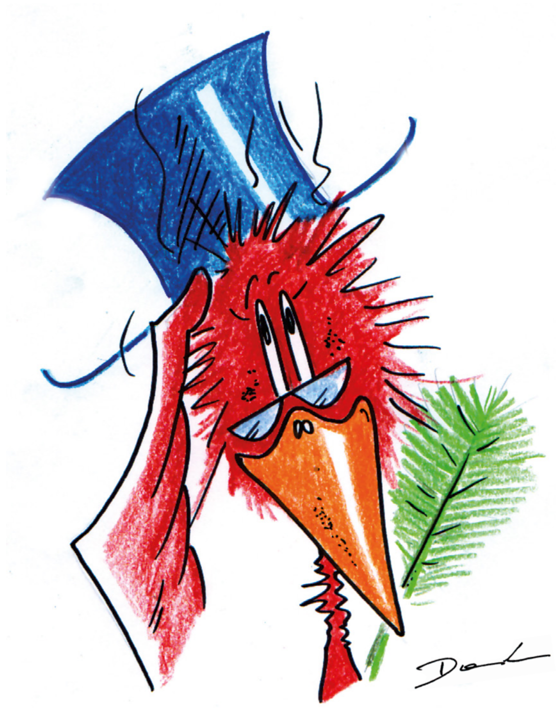
To the second comment, we agree that the remnant of Cas A is officially first observed in the 20th century as a radio source. Optical and x-ray observation identified that source to be an expanding supernova remnant of a supernova that has exploded about 340 years ago (from today). There have been frequent discussions and arguments ever since if that remnant is associated with a suddenly appearing and short-lived bright star that was observed in 1680 by the British Astronomer Royal John Flamsteed at(or near) that location. (David W. Hughes: Did Flamsteed see the Cassiopeia A supernova?, *Nature* 285, 132-133 (1980). That possible observation is what we have been referring to. ■

M. Wiescher and K. Langanke

by L.J.F. (Jo) Hermans
Leiden University, The Netherlands - Hermans@Physics.LeidenUniv.nl - DOI: 10.1051/epn/2015507

Dipping bird

Most readers will probably recall having seen this funny bird, in one form or another: the Dipping Bird, or Drinking Bird. It is an astonishing gadget which – for some laymen – seems to be a perpetual motion machine. And indeed, it looks like one. The bird balances for a while in a near-vertical position, then gradually bends over to a glass of water, takes a sip, flips back to its original position and starts the show all over again. Indefinitely, so it seems.



What is going on here? The set-up essentially consists of a glass bulb – the bird's body – containing a coloured liquid in which a glass tube is immersed. Its upper end forms a second bulb – the bird's head – which is covered with felt or some other cloth that absorbs water easily. Upon tipping over and 'drinking' the bird's head gets wet and starts cooling down by evaporation. So, the upper bulb becomes the coldest spot in the set-up. As a result, some of the vapour inside starts to condense in the upper bulb. Since the corresponding vapour pressure is lower than it is in the lower bulb, the liquid is sucked upward in the tube, thereby shifting the centre of mass upward – until it tips over, allowing the bird to 'drink'. In the near-horizontal position, some of the vapour will be allowed to pass over the liquid, so that pressure equilibrium is restored and the liquid flows back down. The show can now start all over again as long as the head is wet. Indeed, even if we remove the glass of water, the bird will carry on for an hour or so.

This is not the full story, however. If the coloured liquid were water, we would need a pretty large temperature difference to raise the liquid by some 10 cm: almost exactly 10 °C at room temperature. So this is not going to work. We need a fluid with a lower boiling point – and, consequently, a steeper vapour pressure curve at ambient temperature. Dichloromethane (CH_2Cl_2) is found to be a good choice. Its boiling point is 40 °C and we need only a bit less than 1 °C to pull the fluid up by 10 cm, which is about the distance required to make the bird tip over.

Now what about the perpetual motion aspects? Where are we putting in energy? Not in the coloured liquid, because the net energy for the closed evaporation-condensation cycle is zero. However, the heat of vaporization of the water needs to be supplied by the environment. In other words: the device works by maintaining a temperature difference between the bird's body and its head. So, after all, our dipping bird turns out to be a simple heat engine. But – let's admit it – quite an elegant one. ■

ANNUAL INDEX VOLUME 46 - 2015

AUTHOR INDEX

MATTER INDEX

by Herman C.W. Beijerinck
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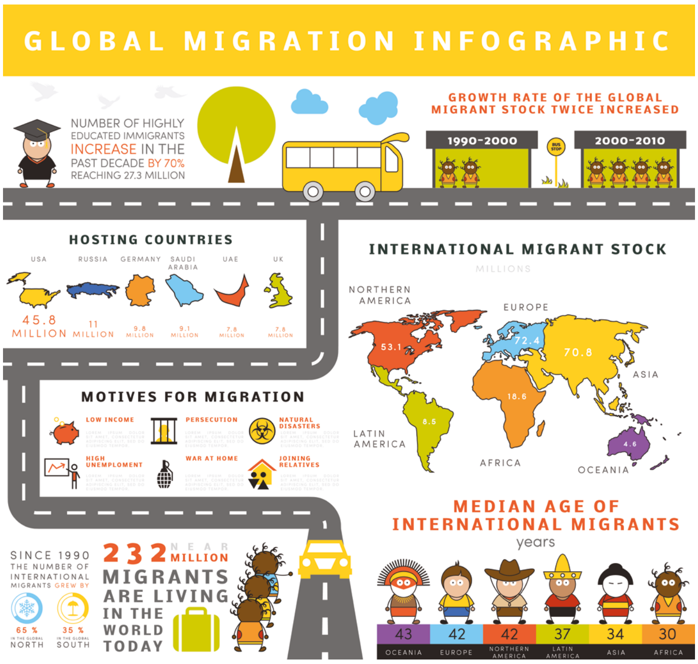
Physics and politics: a happy marriage?

Physics and politics: at first sight an unhappy couple, but we should know better. Think of Angela Merkel, a physicist trained in the former East Germany but now the most powerful player in the European Union. As an independent mind in a slightly xenophobic Europe that is afraid of the migration of people from Syria, she is opening the borders of Germany and investing in housing and jobs. What can we learn from fellow physicist Angela Merkel?

First, let us keep in mind that immigration is the motor of history. Without immigration, Homo sapiens would still be in Africa, with Neanderthals' running Europe. Without immigration, the USA would still be a minor country without a global role. Second, integration is always tough to handle because it is based on a mind-set of 'us' versus the 'others'. Prejudice plays an important role in rejecting immigration. Third, when the first two steps have been taken, innovation is the result. Just look at the names of the founding fathers of successful start-ups like Facebook, Google and Tesla, most of them do not go back to the founding fathers of the original colony.

Look at the USA with its huge waves of immigrants that were integrated in society. These immigrants were poor and lacked education in most cases, but were highly motivated to start a new life in uncharted territory. They imported a gene pool of DNA of entrepreneurship and daring. In my opinion this is the basis of the strong entrepreneurial spirit of the USA, as compared to Europe.



The 'haves' stayed at home, the 'have-nots' with guts left for the new frontier. Evolution is slow in its usual track; immigration with its strong and immediate selection of an entrepreneurial gene pool evolves at a faster pace in a country with new opportunities and new challenges.

In physics, immigration has also been very successful. In the northern European countries, a majority of the PhD students is from Eastern and Southern Europe, with Asia as a runner-up. The fraction of foreign PhD's in The Netherlands is close to 60 to 70%. Most of them stay in The Netherlands, fully integrate and land in high-tech jobs at Shell, ASML or equivalent. Also in the USA physics depends heavily on a pool of foreign PhD students.

Do we in Europe want to miss out on this opportunity of opening our borders for a wave of highly motivated immigrants from Syria? Let us open our minds, not as charity but as wise people that accept the course of history and put it into perspective. Let us open up our economy to build new housing, incorporate this new work force and invest in schooling of their families. Immigration from Syria is not a problem but a challenge with a beautiful future.

EPS can help to speak its mind and remember society of the above message. Physics has a strong international tradition with full acceptance of scientists from all over the world. Physics helped many Jewish scientists to leave Nazi-Germany, a limited effort in numbers but a good example for society. Society would be better off with a few more of these values on its mind. ■

The Energy-Climate Continuum: Lessons from Basic Science and History

Where will we end up if we do not change direction in global energy trends? Scientists should take the lead in informing society on problematic and delicate issues, such as energy supply, environmental and climate changes, making difficult things understandable.

If you were to ask a member of the public about the meaning of the 450 climate change mitigation scenario, they might wonder, "What on earth has this to do with us?". Indeed, not so long ago scientists were considered a closed society living in ivory towers, spending much of their time in exotic laboratories and academic institutions. Nowadays, there is a growing commitment of scientists to share our knowledge and opinions with society. Scientists should take the lead in informing society and policy-makers on problematic and delicate issues, such as energy supply, environmental and climate changes. This book addresses the threats and opportunities facing the global energy systems, explaining in a readable way how strongly the energy and climate debates are interconnected.

The best strategy to succeed in science should be based on our capability to explain the laws of nature in a transparent way. Antoine Bret explains in his book the science behind the energy-climate continuum problem, trying to make difficult things understandable, illustrating facts with the feeling of orders of magnitude.

The book covers physics fields with relevance for all energy technologies and their impact on climate, including:

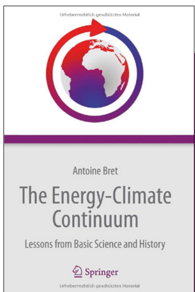
- ✓ The energy problem in a world presently dominated by the use of fossil fuels, how we know the influence of their usage on climate and introducing elements of climate modelling.
- ✓ Elements of solution by non-fossil energy sources pointing out: a) the impact of replacing conventional fossil or nuclear energy sources by intermittent renewable energy sources, b) the development of massive energy sources, like fission/fusion, since the dominance of fossil fuels must decline, c) the requirements for fossil power plants and technologies to reduce CO_2 emissions and feasibility of large–scale CO_2 storage, and, d) physical capabilities of energy storage systems.
- ✓ History as a learning strategy, where the issue of energy has a direct impact on economic capacity and social stability.

It is clear that we are facing an energy transition phase with new global drivers like climate change and globalization. Indeed, we need a society with a critical knowledge that should understand how much energy based on fossils we need to substitute compared with previous transitions, which are much greater than at any other time. The quest for energy is a global endeavour and new energy strategies require technologies for energy production, storage, conversion, transmission and savings.

The book, which is very much worth reading by everyone who wants to understand the present energy-climate debate, shows that we need the development of all potentially viable options for low-carbon energy, promoting research and favouring innovation without jeopardising the security of energy supply. The reader will find some clues to form an opinion and to answer key energy-related questions like: "Where will we end up if we do not change direction in global energy trends? What are the energy options and their pros and cons? What is the impact of energy on social stability?"

Energy is the life-blood of today´s society, and new strategies for the development of sustainable energy sources are needed to reduce energy-related carbon emissions. We cannot afford to delay further actions to tackle climate change if the long-term target of limiting the global average temperature increase to 2 °C, as analysed in the 450 scenario [the 450 referring to a parts-per-million (ppm) concentration of carbon dioxide (CO_2) in the atmosphere], is to be achieved at a reasonable cost.

But we should be realistic: the need for new strategies for energy generation, conversion and storage is a colossal challenge. A global challenge where the dynamics of energy markets are increasingly due to population growth, increase in economic output and energy demand. A global challenge that would require a multi-decade approach, keeping a coherent and sustained energy policy that strengthens the mutually beneficial relationship between education, research and innovation. ■



ABOUT

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REVIEWED BY

Carlos Hidalgo

Opinion: The crystal ball and basic research

Jo Hermans is emeritus professor of physics at Leiden University and Science Editor of Europhysics News

During my academic career, the research that I did was mostly curiosity-driven. This work was rewarding, exciting and at times even thrilling. But when asked what the useful applications were, I really didn't know how to respond. Nowadays my answer is: '*How could I know? You should ask my grandson*'. The reason is, of course, that there is – almost always – a considerable time lag between fundamental research and its applications.

Take Wilhelm Conrad Röntgen who was experimenting with high-voltage cathode-ray tubes back in 1895. He observed a strange kind of radiation which had the astonishing property of passing through various substances which are opaque for visible light. This included the hand of his wife (when seeing her skeleton she seems to have exclaimed: '*I have seen my death!*'). He called this unknown radiation 'X-rays', a term which persists to this day. Now, more than a century later, X-rays are routinely used in Medicine, both in diagnostics and therapy.

A second example. Nuclear Magnetic Resonance (NMR) was originally explored to better understand the atomic structure. Isidor Rabi was awarded the Nobel Prize for his work on NMR in 1944. Although NMR has developed into a unique scientific tool in its own right, the technique became famous much later after it was realised that the relaxation time of protons in the human body depends on their environment. Magnetic Resonance Imaging (MRI), as the medical application has been coined, is now a leading technique in medical diagnostics. But its practical application requires superconducting magnets, and superconductivity is another result of curiosity-driven research. Kamerlingh Onnes discovered this phenomenon by accident while he was studying the behaviour of electrical resistance at low temperatures back in 1911.

In this International Year of Light the most appropriate example is the Laser. Charley Townes – well-known for his work on microwave spectroscopy – laid the foundation for the Laser when he realised that stimulated emission in a cavity would lead to amplification. To show this in the lab proved to be an uphill battle, because his department chairman did not believe in the project. One day he came into Townes's office with Isidor Rabi (!). As Townes writes in '*How the Laser happened*', they said: "*You should stop the work you are doing. It's not going to work. You know it's not going to work. We know it's not going to work. You're wasting money. Just stop!*" Fortunately Townes was stubborn enough to continue, and he and his students had the first Maser working in 1954. Once the proof-of-principle was given, he worked out the theory for the optical case together with his brother-in-law Arthur Schawlow, and in 1960 the first operating Laser was produced by Theodore Maiman.

One would think that this success was recognised early on as an important achievement. That was not the case. It's even worse. There was a famous quip at the time, that 'the laser is a solution looking for a problem'. Now, more than half a century later, we cannot imagine life without the laser. Our groceries are scanned by a laser at the cash register, our bags at the airport are scanned by lasers, we play our CDs and DVDs using a laser, high-speed digital data transfer through fibres uses lasers, laser eye surgery, you name it.

It is impossible to predict the pay-off of fundamental research

Conlusion: it is impossible to predict the pay-off of fundamental research. There is no such thing as a crystal ball. If politicians and other decision makers doubt the value of pure research and want instant gratification, we should remind them of the good old motto: making predictions is difficult, especially where it concerns the future. ■