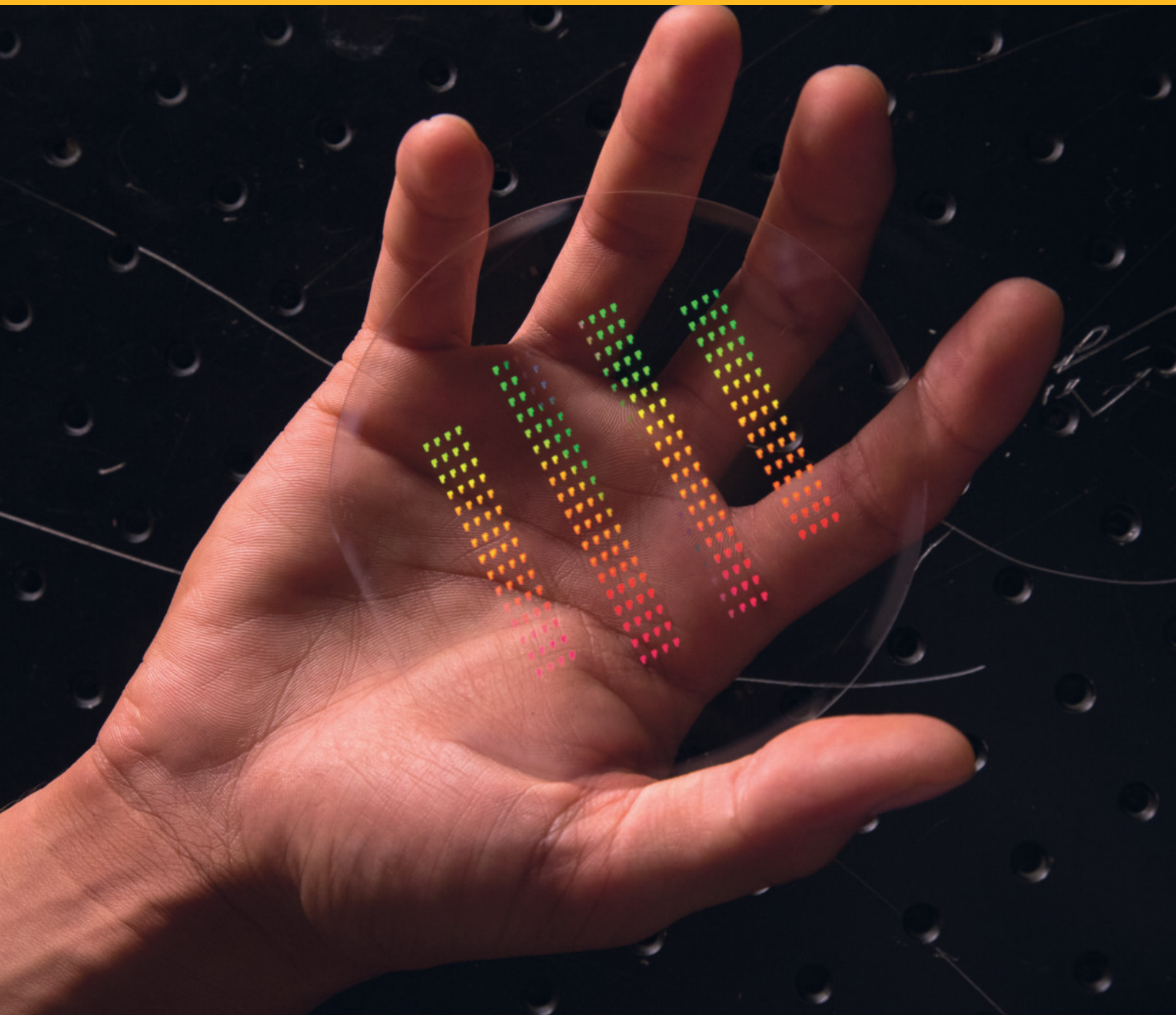


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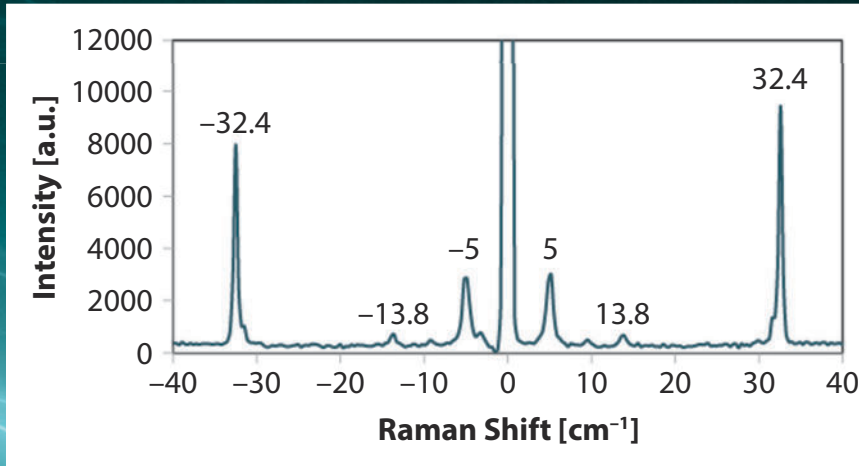
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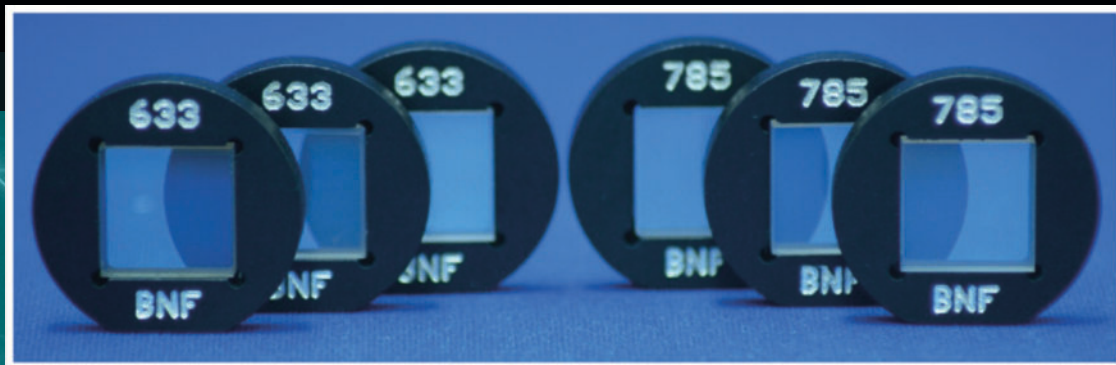


Raman spectrum of several layers of MoS_2 flakes measured at 633 nm with BragGrate™ Notch filters and single stage spectrometer

(data courtesy of : P. H. Tan, State Key Laboratory of SL and Microstr., Institute of Semiconductors, CAS, Beijing, P. R. China)

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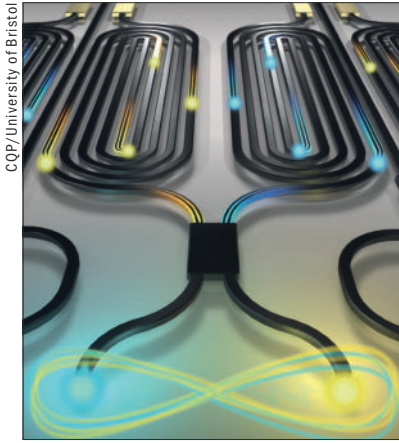
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Focus on: Optics & lasers

Welcome to this special focus issue of *Physics World*, which explores some of the latest research in optics and lasers. It includes a report from the UK research centre that is driving a new approach to quantum computing based on integrated photonic circuits, and explores other photonic research that could see particle accelerators shrunk to the scale of microchips. Indeed, the huge potential of the photonics sector in general is underlined in our keynote interview with the chief executive of Jenoptik, Michael Mertin. We also survey the advanced optics driving a new era of multifunctional 3D printing, the largest optical camera ever flown in space and the optical sensors that are changing the face of farming. Let us know what you think about any of the topics covered by e-mailing us at pwld@iop.org.

Matin Durrani, Editor, *Physics World*

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Sistine Chapel artworks see the light

Its enormous frescos have wowed tens of millions of visitors during the past five centuries, but from autumn this year the walls and ceilings of the Sistine Chapel in Rome will be revealed as never before. Lighting manufacturer Osram is in the process of installing 7000 LEDs in the famous building, each tuned in intensity and wavelength to provide the best possible viewing experience. Until now, the artworks have been lit via low-level natural light and metal halide lamps diffusing through glass windows to reduce long-term damage.

Based on measurements of the colour spectrum made at 280 points distributed over the chapel's surface, Osram engineers designed lighting rigs that combine radiation from standard red, blue, green and white LEDs in precisely controlled amounts to match the pigments in individual locations. The team is aiming for a near-perfect "colour-rendering index" – a measure of the quality of a light source relative to a reference such as the Sun – of 98 compared with 80 produced by standard indoor lighting.

The challenge, explains Osram project leader Mourad Boulouednine, was to improve the viewing experience massively without compromising on conservation. "We have convinced the Vatican that we have the right technology for this iconic project," he says. "These are



Governatorato dello Stato della Città del Vaticano

big deals – we're talking about a 500 m² artwork on the ceiling and other major works such as Michelangelo's *The Last Judgment*," he says.

LEDs emit no ultraviolet (UV) or infrared radiation, which is known to be one of the main causes of damage to pigments. Still, it took some time to convince Vatican conservators to take up the technology. The Osram team carried out stringent stress tests in the Vatican museum by exposing pigments to LED radiation with an illuminance of 200 000 lux – roughly double that produced by direct sunlight – for the equivalent of one year. The results showed that, under normal LED operating conditions of 50 lux or less, the priceless pigments on the chapel's walls would be safe for at least 1000 years – which addressed the Vatican's concerns. "First, they saw 3D effects and other

Illuminating
LEDs reveal unprecedented detail in the Sistine Chapel's ceiling.

details that the artists intended but that have never been seen before," says Boulouednine. "Then we did the stress test, and now there is not a single doubt."

Despite boosting the illuminance by a factor of five to 10, the new lighting rig is also expected to reduce power consumption for the Sistine Chapel by more than 60% thanks to the high energy efficiency of LEDs and careful direction of the light to ensure that artworks are uniformly illuminated without glare or light spill. Osram honed the technology last year at the Lenbachhaus Museum in Munich and is one of several lighting firms keen to get into the museum scene.

Last year, Philips installed some 750 000 individual LEDs in the refurbished Rijksmuseum in Amsterdam, while Toshiba LEDs are being used to illuminate the *Mona Lisa* and other famous works in the Louvre. "LED lighting in particular outlines the visual contrast and relief in the paintings," said Tim Zeedijk, who is head of exhibitions at the Rijksmuseum, in a statement. "A significant advantage of the new generation of LED lighting is that there is hardly any radiation of heat and no harmful UV being emitted. In addition, LEDs have a longer lifespan and require less maintenance than halogen lighting, which is more commonly used in museums."

Matthew Chalmers

Events

Physicists gear up for international year

Preparations are under way around the world for the 2015 International Year of Light (2015 IYL), which aims to promote the public and political understanding of the role of light in the modern world. Approved by the United Nations last December, the year will focus on the potential of technologies such as photonics to solve problems in energy, climate, health, communications and agriculture. It is also loosely linked to several anniversaries, ranging from the first studies of optics 1000 years ago to Einstein's work on the photoelec-



Come on in The optics and lasers community is being invited to join the 2015 International Year of Light.

tric effect in 1905 and the emergence of optical-fibre technology in 1965.

Ana María Cetto of the National Autonomous University of Mexico, who is a member of the 2015 IYL steering committee, admits that it would be hard to think of a broader subject for an international year, but thinks that is, in fact, the beauty of the idea. "Light concerns us all: there is ample room for all subjects or topics involving light and for everybody who wants to take part in the initiative," Cetto told *Physics World*. "In some countries the focus will be

more on the technological side, in others on the artistic or cultural one, in yet others on the scientific or educational one."

Physics will be central to the year's activities and many of the 35 countries that have signed up to the event have established national committees to coordinate events. According to Cetto, the response has been better than expected. "A major challenge will be to get all countries and people involved in some form or another, but we can only be optimistic," she says. A UK committee is being put together by the Institute of Physics, which publishes *Physics World*, and interested parties are invited to get in touch by e-mailing physics.society@iop.org.

Matthew Chalmers



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Space debris

Lasers put space junk under pressure

Collisions between pieces of space junk currently occur about once a year, but each one leaves more debris in its wake. That could lead to an environmental and financial catastrophe, says Craig Smith of EOS Space Systems in Canberra, Australia. “We appear to be exactly on track for an escalation of debris that in 20–25 years would make orbital space, or at least the most popular orbital slots, unusable,” he says.

An A\$20m (US\$19m) grant recently awarded to a consortium that includes EOS and the Australian National University will allow Smith and co-workers to tackle the growing problem of space junk using lasers. The idea has been around since the 1990s, with schemes based on very-high-energy laser pulses that cause ablation from an object’s surface. This causes a recoil that changes the velocity and thus the orbit of the object, but the required pulses are so powerful, explains Smith, that they can stimulate non-linear processes in the atmosphere and make it difficult for the light to reach its target.

The Australian team will explore a more subtle approach based on photon pressure proposed by researchers at NASA’s Ames Research Center in

Cleaning up

High-powered lasers fired from Mount Stromlo Observatory in Australia could prevent space-debris collisions.



California, which stops collisions happening by slightly changing the orbit of a debris object. “To do this we only need to change the velocity by about 1 mm s^{-1} , compared with $50\text{--}100 \text{ m s}^{-1}$ for ablation approaches to deorbit, which is within the reach of state-of-the-art laser systems,” says Smith. The technique will use adaptive optics, as used in astronomy, to concentrate light on the target, but the main challenge, he says, is to land and hold a laser beam on an object for up to seven minutes at a time.

The five-year project is one of several under way worldwide, including the European project “Clean-Space”. Claude Phipps of Photonic Associates in the US, who has been developing such techniques since 1995, says we need all ideas on the table. “After the film *Gravity* and the Iridium–Kosmos satellite collision, space junk has won people’s attention,” he says.

Matthew Chalmers

Biophysics

Biological boost for UK laser facility

Researchers at the Central Laser Facility (CLF) at Harwell Oxford, UK, have received a £1.5m (\$2.5m) grant to study biological samples in unprecedented detail. The funds, distributed by the Biotechnology and Biological Sciences Research Council, will be shared between the CLF’s ULTRA instrument (£0.9m), which uses lasers to probe molecular dynamics, and its OCTOPUS imaging facility (£0.6m).

ULTRA’s capabilities will be extended by a new instrument called LIFETIME, which will use ultrafast lasers to record changes taking place in a sample on timescales ranging from the very fast initial reaction (100 fs to 10 ps) to the slower millisecond-to-second timescales



In focus The CLF’s Functional Biosystems Imaging group is targeting biological imaging at nanometre resolution.

of follow-on reactions. Meanwhile, researchers at the OCTOPUS facility will commission a stimulated emission depletion (STED) microscope to achieve a lateral resolution of tens of nanometres, allowing them to study biological scaffolds, for instance.

“LIFETIME will interrogate kinetics and structural changes of biological systems spanning more than 10 orders of magnitude in timescale within a single experiment, on a single sample and under identical experimental conditions,” says Mike Towrie, ULTRA group leader. “This will allow a comprehensive study of many dynamic processes in biological systems in their whole complexity.”

Matthew Chalmers

Business Briefs

Nanoscribe is top for innovation

Laser-lithography specialist Nanoscribe in Germany has won SPIE’s 2014 Prism Award for the most innovative advanced-manufacturing product. The firm, a spin-out from Karlsruhe Institute of Technology, won the prize for its 3D printer “Photonic Professional GT” – a laser-lithography system that offers high performance, accuracy and speed-up for the fabrication of nano- and microstructures. The device combines two-photon polymerization and pivoted galvo mirrors to permit additive and subtractive manufacturing of polymers on a broad range of substrates and materials, and can etch complex structures with feature sizes as small as 160 nm on a write-area of up to 100 cm^2 (see pp17–18 for more about 3D printing).

Jenoptik keeps airbags in check

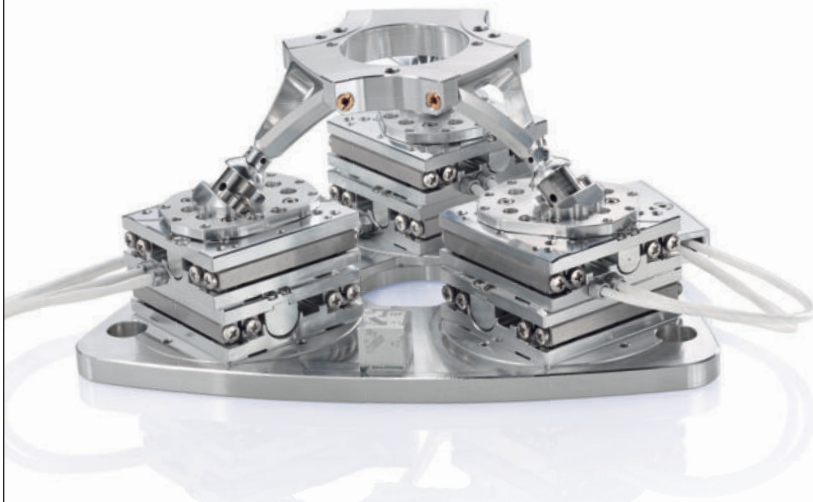
A laser-perforating system recently sold to Chinese automotive company YFV became the 200th such unit shipped by German optics giant Jenoptik. As a specialist in producing dashboards, YFV plans to use the device to create predetermined breaking points for airbag flaps. The technique works by generating a line of tiny perforations that weaken the material so that an airbag can break through and inflate during a collision, with sensors used to prevent the laser from severing the material. According to the firm, the system can rapidly process single- or multilayer materials and decorative layers made from plastic, textiles or leather. The type of perforation holes, their spacing and the shape of the perforated line are also adjustable.

Princeton Instruments eyes the Sun

Optical coatings developed by Princeton Instruments are helping NASA’s IRIS probe to capture unprecedented images of the Sun. Launched last year into a polar orbit where it will make continuous solar observations, IRIS is designed to study light in the far-ultraviolet (133.2–140.6 nm) and near-ultraviolet (278.5–283.5 nm) wavelength bands. The mirror coatings give the IRIS telescope a high reflectivity in the far-ultraviolet band while maintaining a fixed reflectivity in the near-ultraviolet band, to limit crosstalk, with the telescope having a low reflectivity in the visible and infrared bands. Coatings were also provided for several components within the IRIS spectrograph, including camera mirrors, fold mirrors, reimaging mirrors and collimating mirrors.

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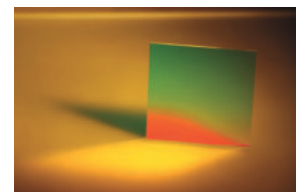
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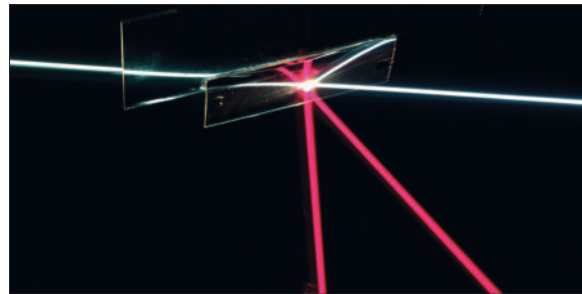
Research

New material offers angular control over light

A new material that filters light according to its direction of travel has been developed by physicists in the US and China. Made of alternating layers of two different transparent materials, the structure offers a simple way of controlling the direction in which light propagates. According to its inventors, the material could be used in applications from photography to solar energy (*Science* **343** 1499).

Light, microwaves and other electromagnetic plane waves are characterized by three fundamental properties: polarization, frequency and direction of propagation. Materials that filter light according to its polarization are commonplace, while photonic crystals can be used to select light according to its frequency. As for selecting light according to its direction of propagation, this is possible using lenses, mirrors and collimators, but miniaturizing such optical components into a practical device is difficult.

Yichen Shen, Marin Soljačić and colleagues at the Massachusetts Institute of Technology and Zhejiang University have now got round this



Weishun Xu and Yuhao Zheng

problem by creating a layered material that is transparent to light incident at a specific angle but reflects light coming in at all other angles. The operation of the device relies on the fact that light at a specific angle of incidence – known as “Brewster’s angle” – is transmitted completely through a transparent material.

This angle is related to the ratio of refractive indices of the material and the surrounding media, but when light is incident at a different angle, some – although not all – of it will be reflected. To increase the amount of light that bounces off the material, the team created alternating layers of materials with two different indices of refraction. If layers of similar mate-

Selective approach

This filter transmits white light incident at Brewster’s angle, while beams at other angles get reflected.

rial are separated by one-quarter the wavelength of the light, then light reflected from successive layers interferes constructively, with the result that nearly all of the light at angles other than Brewster’s is reflected.

The team’s device was created by sputtering 84 alternating layers of silica and tantalum oxide onto a silica substrate. By systematically varying the thicknesses of the layers from 70 to 150 nm, the device was made to work over a broad spectrum of wavelengths between 450 and 700 nm. The resulting “angular filter” is 8 μm thick and has an area of 2 × 4 cm.

The team found that about 90% of light is transmitted within 8° either side of the Brewster’s angle, which in this case is 55°, while nearly all of the light is reflected at all other angles. One possible application of the filter is in thermal solar-energy systems, which convert sunlight into heat that is then harvested to create electricity. It could also be used as camera filters that only admit light coming directly from the subject and reject light from background sources such as the sky.

Hamish Johnston

Applications

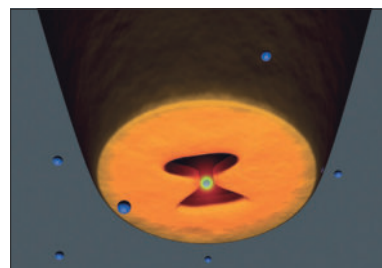
Optical tweezers grab nanometre-sized objects

Optical “nanotweezers” that can grasp and move objects just a few tens of nanometres in size have been created by researchers in Spain and Australia. The new tool is gentle enough to grab tiny objects such as viruses without destroying them, and works in biologically friendly media such as water. The nanotweezers could find a range of uses, from helping us to understand the biological mechanisms underlying diseases to assembling tiny machines (*Nature Nanotech.* **9** 295).

While nanometre-sized objects can be moved around using conventional optical tweezers, how precisely this can be done is subject to the diffraction limit – about 300 nm for visible light. However, this limit does not apply to “near-field” light waves, which exist near light-emitting regions and drop rapidly in intensity across distances that

Tiny impact

An artist’s impression of a polystyrene sphere held in optical nanotweezers created by near-field light near a bow-tie-shaped aperture.



Institute of Photonic Sciences

are much smaller than the diffraction limit. The new device, built by Romain Quidant at the Institute of Photonic Sciences in Barcelona and colleagues, consists of a near-field scanning optical microscope, which captures near-field light by scanning a tiny aperture just a few nanometres above an object of interest.

Turning such a microscope into optical tweezers involves firing laser light through the aperture, thus focusing it to a tiny spot of near-field light. As with current optical twee-

zers, the intensity gradient of the light across the spot draws tiny dielectric objects to the spot’s centre, where the electric field is strongest. Tiny objects can therefore be held and manipulated with nanometre precision, although experimental tests of this technique had, until now, never been carried out because it was thought that the concentrated light at the tip of the microscope would damage heat-sensitive objects or even the tip.

The new device can, however, be used to trap and manipulate light that is several orders of magnitude lower in intensity using a new technique called self-induced back action trapping, which adjusts the local field intensity in real time, based on the behaviour of the specimen. The team’s set-up involves a 1 μm-diameter optical fibre with an 85 nm-wide bow-tie-shaped aperture milled into its end. Using this device, the team was able to trap and hold polystyrene beads 50 nm in diameter suspended in water for longer than 30 minutes.

Katherine Kornei

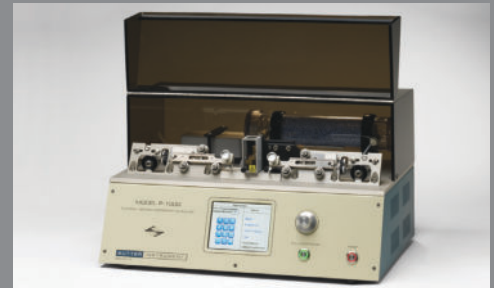
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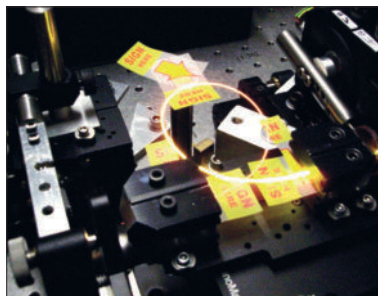
Devices

Powerful fibre laser shines in the mid-infrared

A new type of fibre laser that operates in the mid-infrared range has been designed by researchers in Australia. The device uses a dual-wavelength pumping approach that makes it 25 times more powerful than existing mid-infrared fibre lasers. It could also be cheaper to make and have a variety of applications, ranging from analysing greenhouse gases in the atmosphere to non-invasive medical diagnosis (*Optics Letters* **39** 493).

Despite the many advantages of mid-infrared lasers, building practical devices operating at these wavelengths has never been easy. Crystal lasers tend to be expensive and bulky, while fibre lasers are traditionally based on silica, which is opaque in the mid-infrared, requiring the use of more exotic glass fibres, such as ZBLAN – a type of heavy-metal glass based on zirconium fluoride. To make matters worse, mid-infrared transitions in rare-earth ions, such as

Pump me up
Prototype of the new mid-infrared fibre laser.



Ori Henderson-Sapir


erbium, are located high above the ground state – reducing the overall efficiency of any such device because of the difference in wavelengths between the emitted laser photon and the input pump photon.

The relaxing ions also tend to get stuck in relatively long-lived excited states on their way back down to the ground state, forming a “bottleneck” that can lower efficiency at best, or prevent further lasing at worst. To overcome these problems, a team led by Ori Henderson-Sapir from

the University of Adelaide exploited the bottlenecking phenomenon by using a relatively weak pump source to excite the ions to the low, long-lived excited state, before raising them to the most excited state with a second pump. When the ions relax to the long-lived state – emitting a photon as they do so – they can then be pumped up again, without delay.

“This method allowed an order of magnitude improvement in efficiency compared with other fibre lasers operating on this transition,” says Henderson-Sapir. The team’s laser produces more than 0.25 W at wavelengths of around 3.5 μm, with a significant peak in emissions at 3.6 μm. “To the best of our knowledge, [this is] the highest power, highest efficiency and the longest wavelength of a room-temperature fibre laser without using nonlinear effects,” he explains. The researchers are now developing the capacity to tune their laser’s output wavelength, with the aim being to create a system that is tunable between 3.3 and 3.8 μm.

Ian Randall

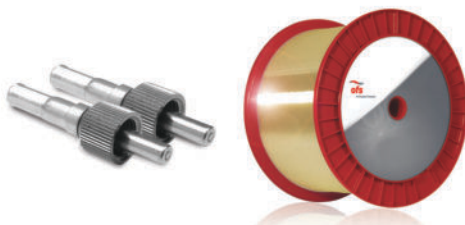


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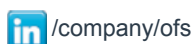
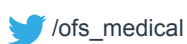
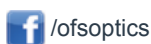
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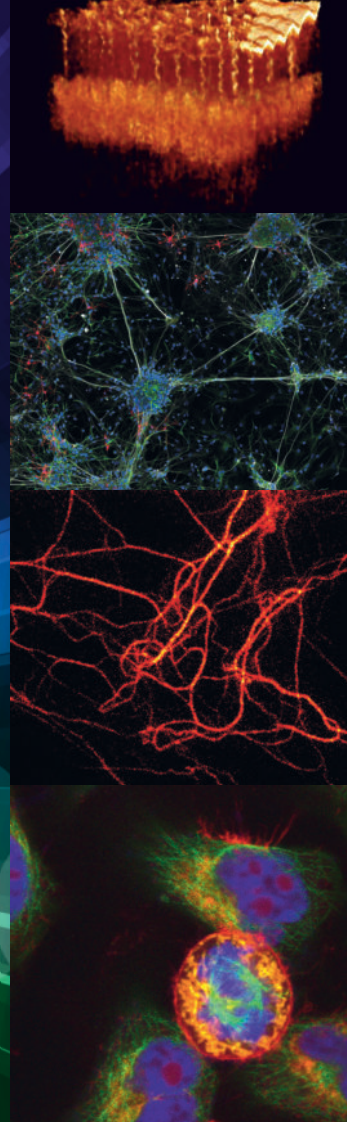
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Laser research

Ultrafast phase measurements could boost optical computing

Physicists in Germany have created the first compact electronic device that can measure the absolute phase of extremely short, attosecond-length light pulses. While the device is first expected to find use in laser labs, it could eventually be used in systems that use ultrashort light pulses to process information. The work was carried out by Ferenc Krausz and colleagues at the Max Planck Institute of Quantum Optics in Garching, near Munich (*Nature Photonics* 8 214).

Krausz's team generated and measured the first isolated attosecond light pulses back in 2001 and such pulses are now widely used to study the motion of electrons inside atoms in the burgeoning field of "attosecond physics". But while the technology used to create and characterize these pulses has improved over the past decade, measuring their absolute phase – which is essential for understanding rapidly varying opti-

cal signals – requires large and bulky equipment that cannot be easily deployed on a tiny device.

The new work builds on research carried out in 2013, when Krausz and co-workers showed that light can quickly turn an electrical insulator into an electrical conductor. By exposing a metal–dielectric–metal junction to an extremely short pulse of intense light, the team was able to measure a current flowing through the electrodes. The researchers found that the strength and direction of the current could be controlled by altering the waveform of the pulse – and it is this effect that the new device exploits.

The device works by tracking the sinusoidal variation of the electric field of light, which drives an oscillating current in the device at petahertz (10^{15}) frequencies. It can therefore take rapid "snapshots" of the shape of the oscillating light field, with the team making measurements on light



Thorsten Naeser

Quick thinking

A new phase detector could give us easier and better control of the waveforms emitted by lasers.

pulses lasting about a femtosecond (10^{-15} s). These pulses are used to generate attosecond (10^{-18} s) pulses in a process that requires precise knowledge of the absolute phase of the original femtosecond pulses. One advantage of the detector is that it is more compact than existing devices and does not need to be in a vacuum.

"[It is] easy to imagine it becoming a commercial device – a little black box – that other research groups can buy and use to measure the [light phase] from their lasers," says John Tisch of Imperial College London, who did not take part in the research. Although our understanding of the effect is still in its infancy, the device could be used to convert information encoded in light pulses into electronic data and allow signals to be processed at rates that are tens of thousands of times higher than today's digital electronics are able to achieve.

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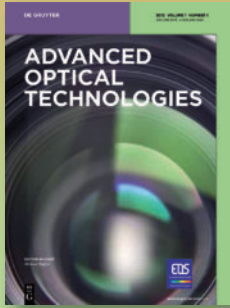
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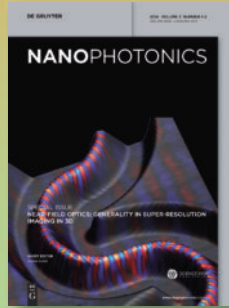
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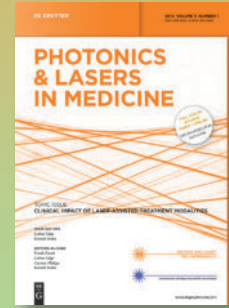
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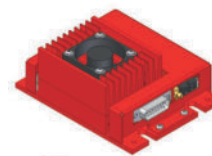
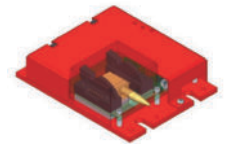


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Quantum engineering makes waves

Physicists at the University of Bristol in the UK are forging a new path to a quantum computer based on integrated photonic circuits, reports **Matthew Chalmers**

In a small, windowless laboratory in the Centre for Quantum Photonics (CQP) at the University of Bristol sits one of the most advanced computers on the planet. It is not much to look at: a series of bulky lenses, phase-shifters and other optical components bolted to a heavy-duty bench. It is not very smart either: the equipment's sole capability is to work out the prime factors of 21, and it takes several seconds to perform even that apparently simple task. In short, it is about as far removed from a modern microprocessor as you can imagine. Yet Mark Thompson, deputy director of the CQP, insists that his group is driving a revolution in photon-based quantum computing by squeezing all this optical circuitry onto a chip. "You'll be convinced of that by the end of the tour," he says confidently.

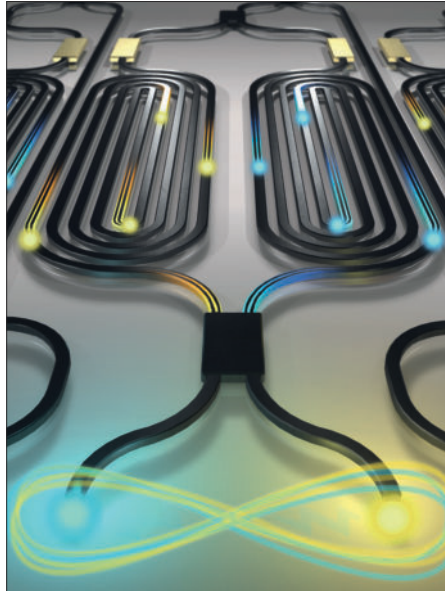
Quantum computers encode information in individual quantum states, as opposed to arrays of transistors. The horizontal and vertical polarization states of a photon, for instance, define a qubit that can be in an entangled state: a quantum superposition of both a "1" and a "0". By increasing the number of qubits, researchers can achieve an exponential increase in computational power compared with classical machines.

That could make a quantum computer unbeatable for certain problems such as factoring numbers and therefore poses a serious threat to modern data encryption, which is based on the inability of classical computers to factorize large numbers quickly. But a device that can factorize arbitrarily large numbers would require thousands – if not millions – of qubits working in concert. The Bristol set-up comprises just three qubits.

If physicists are to realize the dream of a universal quantum computer, they need to find new ways to scale up the number of qubits. And the most promising solution, says Thomson, is to merge quantum optics and photonic circuits into a new discipline called integrated quantum photonics. "We are the first in the world to do this," says Thompson.

Technology step change

Since 1995 quantum computers have been advancing at a rate of about one additional qubit per year. The record for photon-based approaches is currently about eight entan-



Entangled circuit Micron-scale waveguides can be configured to cause identical photons to interfere, constituting quantum logic gates.

gled photons, but these have met increasing competition from solid-state systems based on trapped ions or tiny superconducting circuits. The former holds the record for the largest number of entangled qubits in a single system – 14 – while the latter is the basis of the device recently unveiled by Canadian firm D-Wave, which it claims to be the world's first commercial quantum computer.

The CQP's first major result came in 2008, shortly after the group was founded. Using a glass chip etched with micron-wide channels, which guide photons along specific paths, the team demonstrated for the first time that quantum states of light could be made to interfere in an integrated circuit (*Science* **320** 646).

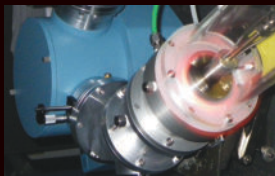
A similar glass-based chip is in use at the CQP today. Just a few centimetres

It is not yet clear whether ions, photons or some other physical system will win the race to a large-scale quantum computer

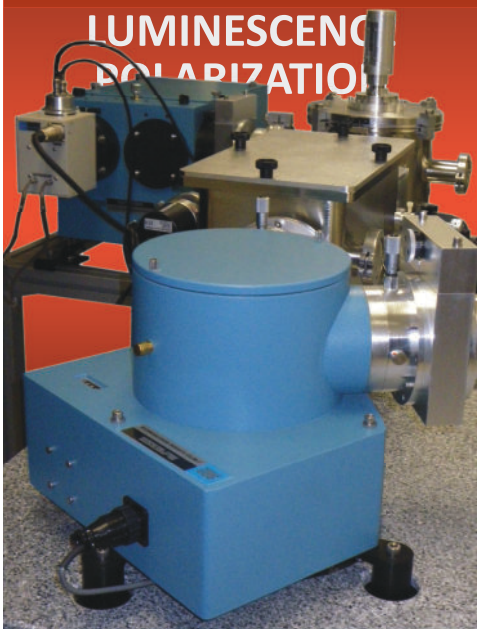
long and hooked up to optical fibres and electronics, the circuit causes two identical photons produced via laser parametric down-conversion to become entangled. The circuit then processes the photon states via a combination of beamsplitters and phase shifters that constitute a CNOT logic operation – a universal gate that is the quantum equivalent of a NAND gate, from which all classical logic gates can be built. In short, the chip can do everything that the group's nearby bulk-optics set-up can do but in a volume 1000 times smaller. The device is also much more easily configured to carry out different tasks, and has been the subject of more than half a dozen publications by the Bristol group in the past few years, including fundamental tests of quantum features such as non-locality (*Nature Photonics* **6** 45). Since last year the chip has even been made accessible online as an educational tool dubbed "Quantum in the Cloud" – a kind of quantum Raspberry Pi.

Being a two-qubit processor containing just a single logic gate, the chip is hardly a match even for the simplest of modern microprocessors. It is also a long way from a fully integrated device because neither the photon source nor the detector is incorporated into the glass architecture. Located on a neighbouring lab bench in the windowless room, however, is the Bristol group's answer to such limitations: a silicon quantum-photonics chip based on the same fabrication processes that are used in the microelectronics industry.

The speck of silicon is hidden behind electrical connections but its sophisticated channelled microstructure can be seen using a microscope. The trick behind this more recent device is that it integrates multiple photon sources into the same chip, which is the key to scaling up quantum computers with many more qubits. The circuit uses a single laser input via an optical fibre to pump photons into a tiny microresonator, which – owing to silicon's nonlinear properties – produces a continuous stream of correlated photons. Nobody before had ever put multiple sources on the same chip and then made them interfere, explains Josh Silverstone, a PhD student in the group. "There is no reason why, in the future, we couldn't put tens of thousands of components on here," he says.

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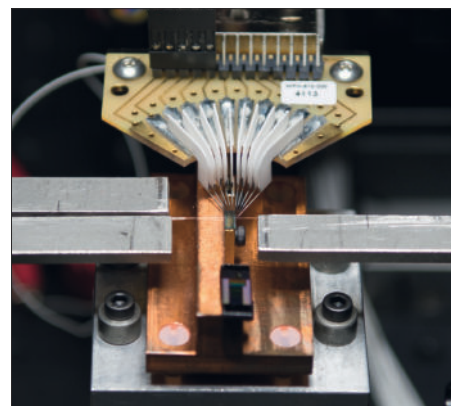
What is striking about the CQP's silicon chip, other than it being a million times more compact than an equivalent bulk-optics set-up, is that it is completely open to the environment. By contrast, most quantum-computing schemes must be isolated to protect the delicate quantum states from losing their coherence – the vast bulk of D-Wave's quantum computer, for instance, is a refrigeration unit. But because photons hardly interact with matter as they zip around the ultra-low-loss silicon waveguides, a photonic quantum computer could operate at room temperature. Currently, the output of the CQP's silicon chip is read out off-chip using a large superconducting detector that operates at cryogenic temperatures, but recently the group found a way to squeeze such detectors on-chip too.

In a third photonic chip in the Bristol lab, the team is working on the final photonic-integration step: putting the laser itself on-chip. While semiconductor lasers can be found in a standard DVD drive, getting them to mesh seamlessly with the rest of the quantum-photonic circuitry is a major challenge. This latest chip is not configured as a computer though. It is a prototype for a mobile system that the group recently patented with Nokia to guarantee secure transactions based on “quantum key distribution” – an established encryption technique that could render the assaults of a quantum-factoring algorithm useless because it relies on fundamental quantum logic to detect the presence of an eavesdropper.

“In the coming years we will start to see devices that can outperform a classical computer, but the first devices will not be for factoring because for that we need a full-scale universal quantum computer,” says Anthony Laing, a senior researcher at the CQP. “The first killer applications of quantum technologies beyond things like quantum communication and sensing are certain customized quantum simulations, perhaps for chemistry, which could allow us to design new types of materials or drugs by mimicking the behaviour of physical systems in a controllable setting.”

Blueprint for success

Quantum-optics groups worldwide are moving towards integrated circuits. “It is safe to assume it will become one of the pillars of quantum photonics, although bulk optical set-ups will persist for specific tasks,” says Max Tillmann of the Vienna Center for Quantum Science and Technology in Austria, who is developing a quantum device called a boson sampler using laser-etched circuits. Even so, it is not yet clear whether ions, photons or some other physical system will win the race to a large-scale quantum computer. “The unique



Quantum chips Silicon photonic circuits – like this one at the University of Bristol – could be the key to building large-scale quantum computers.

advantage of photons is their mobility and wide range of tunability in wavelength, which means all quantum communication between spatially separated quantum computers will be done with quantum photonics regardless of what the qubits are made from,” he says.

It is a peculiarity of research that has prevented the quantum and photonic communities from teaming up sooner, says CQP founder and director Jeremy O'Brien. “When I got my first job in a quantum-optics lab 12 years ago, the group had never used an optical fibre before, which speaks volumes about how some fields can become disconnected from each other,” he says. “Even the best photonics engineers wouldn't know what to do with our chips because we are working at the level of single photons.”

One of the main aims of the 75-strong group, which has an annual budget of around £20m (\$33m) and 18 industry partners, including D-Wave, Microsoft and Google, is to create a new generation of quantum engineers. To that end, the group has recently established the Centre for Doctoral Training in Quantum Engineering. There is a very big industry forming, says O'Brien, but the people who will populate it do not yet exist. “We aim to translate the UK's academic lead in quantum technologies into an economic lead, and the fact that the South West has the highest number of fabless integrated-circuit design units outside Silicon Valley could be a key part of the ecosystem surrounding us,” he says.

A five-year £270m investment into quantum technologies announced last year by the UK government will help bring about the transition from academic research to industry, says O'Brien – who is convinced that the first 1000-bit quantum computer will be a photonic one. “We now have a clear blueprint of how to build such a device and we can also capitalize on the remarkable technologies developed for the microelectronics industry,” he says.



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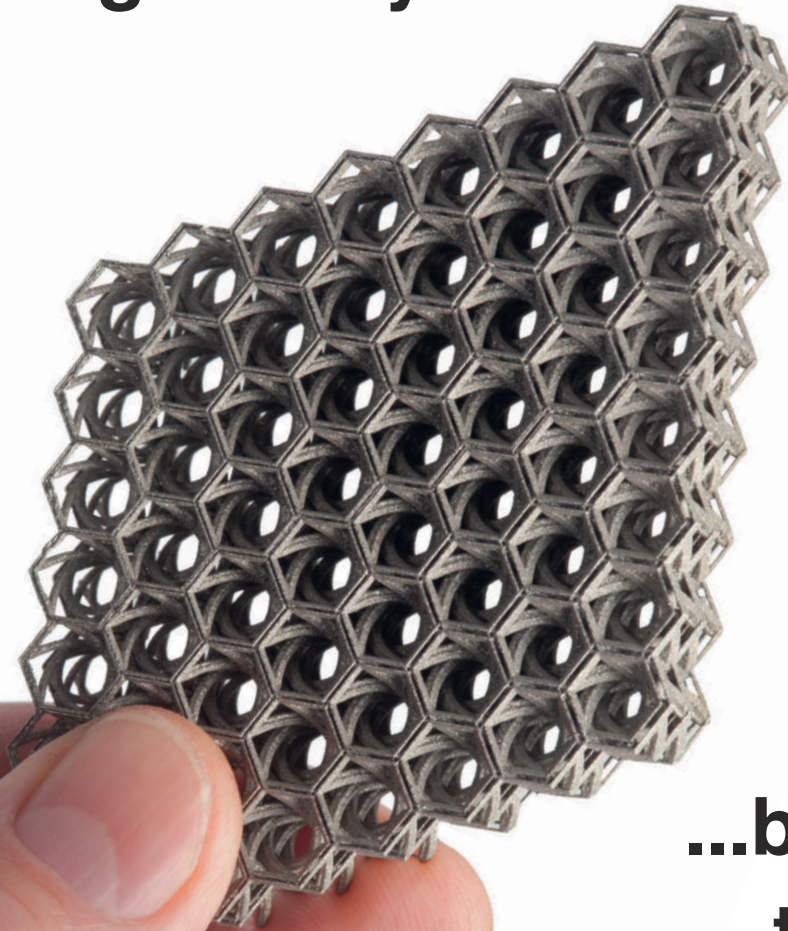
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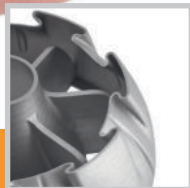
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3D printing: the next step

Multi-photon lithography and optical tweezers are among the tools driving a new generation of 3D printing that will allow multifunctional devices to be fabricated in a single processing step, explain **Richard Hague, Martin Baumers, Chris Tuck and Ricky Wildman**

The technique of 3D printing, more accurately known as additive manufacturing, has enjoyed extensive coverage in the media in recent years. Consumers will play an increasing role in manufacturing the products they use regularly, it is often suggested, perhaps even designing those products themselves. One frequently cited scenario involves consumers using free Web-based packages or mobile-phone photogrammetry applications to specify a design, then submitting it to a commercial 3D-printer operator who will carry out the manufacturing step and ship the product directly to them.

To a limited extent, this picture is already a reality. The commercial availability of low-cost 3D printers over the past five years has certainly allowed consumers to operate home-based manufacturing technology. Such low-cost platforms, which have come about because of the expiry of patents covering earlier prototyping systems, work on a principle called “filament extrusion”, in which a thin polymer thread held at a temperature close to its melting point is squeezed out from a small hole and deposited in raster fashion on a substrate. Consumers are also beginning to take advantage of commercial 3D-printing services, which use established industrial laser-based systems that generally work on the “powder bed” principle: a high-power laser scanned across an extremely thin bed of powder fuses a slice of a 3D object together, and the process is repeated to build up a volume.

Consumer devices bear little resemblance to their industrial additive-manufacturing counterparts, however. They tend to be able to deal only with a handful of extruded thermoplastic materials and – despite the “you can make anything” hype – are greatly limited in the size, resolution and complexity



Handy tool A 3D-printed functionalized prosthetic arm with electronic parts and nerve endings fabricated at the University of Nottingham.

of the parts that they can produce. Indeed, low-cost 3D printing makes up only a relatively small part of the overall 3D-printing industry: around 6% by revenue.

At the more established industrial end of the spectrum, however, the variety of printable material types has increased to include polymers, metals and ceramics. Such single-material addition is already an established manufacturing process in many sectors, including the hearing-aid industry, which manufactures millions of custom hearing-aid shells annually using stereolithography. Selective laser-melting technology has also recently been adopted by GE Avionics to produce metallic components in aero engines, while polymer laser-sintering technology is allowing firms such as FreshFiber to produce customized and complex designs for smartphone covers.

We expect that multifunctional 3D printing will be commercially available within the next 15 years, but there are major technical challenges ahead

Researchers are now exploring 3D-printing techniques that not only allow complex objects to be manufactured at low cost from almost any material, but will also enable objects with different functionalities to be printed in a single step. This next generation of additive-manufacturing technologies, which is rooted in advanced material-deposition systems and optical techniques, is being investigated by the Engineering and Physical Sciences Research Council’s Centre for Innovative Manufacturing in Additive Manufacturing at the University of Nottingham in the UK, which is undertaking internationally leading work in multifunctional 3D-printing research.

Beyond the hype

It might seem that 3D printing is a novel technology. In fact, the underlying principle – in which raw material is deposited layer by layer without the need for moulds, tools or dies – was first commercialized almost three decades ago. Originally developed for rapid design studies and prototyping, the earliest 3D-printing systems used an ultraviolet laser to selectively photopolymerize a liquid photocurable monomer resin, repeating the process layer by layer until the part is completed. Successive innovations since then have led to the spectrum of additive systems we know today, including the

Multifunctional 3D printing

low-cost extrusion-based machines as well as industrial systems based on fusing powders using infrared lasers.

As one of the leading research groups in this area, the 3D Printing Research Group at Nottingham is going beyond single-material 3D printing. Rather than incrementally improving existing single-material approaches, we are working on the next generation of systems capable of depositing multiple materials all at once. Doing so will enable the technology to leap beyond simple structural applications and allow the delivery of entire functionalized systems, such as 3D circuitry, drug-delivery systems and even biological tissue, within a single processing step.

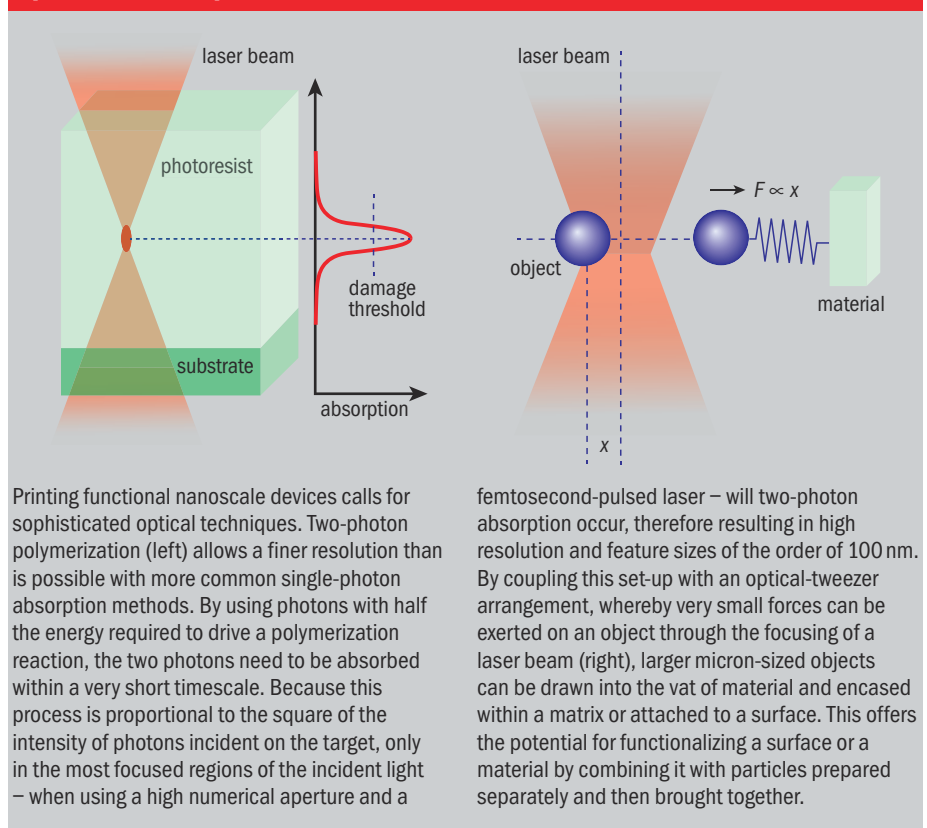
We expect that multifunctional 3D printing will be commercially available within the next 15 years, but there are major technical challenges ahead. These range from the accurate and reliable simultaneous deposition of different materials to the design of components and how best to integrate different materials for a given function. The variety of disciplines involved reflects the vastly different functional properties that could be printed directly into structural products: electrical circuitry, optical tracks, embedded sensors, energy sources, displays, antennas, chemical agents and even biologically active structures are just some of the many targets. A large part of research in this area is therefore focused on the search for functional 3D-printing materials.

New design approach

The first challenge, however, is to create a design methodology that enables us to integrate printed structures with lattices that contain functional components. Constraints within traditional manufacturing approaches, such as injection moulding or CNC machining, mean that, in general, it is not possible to fabricate the optimal shape for a given task. Instead, we are turning to algorithms that seek out the optimal shape or composition for a device taking into account weight, aesthetics and functionality in a single processing step.

A promising technique for depositing structural materials, especially engineering polymers, is drop-on-demand ink-jetting. This can take two forms: directly jetting a material that is suspended or in solution; and “reactive jetting”, whereby a monomer and catalyst are deposited separately and polymerization occurs *in situ* during the manufacturing process. This minimizes waste, reduces the need for solvents and opens up a wider range of materials that can be printed. Our group has printed nylon using this approach, but the current focus is on engineering materials that include polymethyl methacrylate, polyimides and polyurethane.

Optical techniques carve nanoscale features



Printing functional nanoscale devices calls for sophisticated optical techniques. Two-photon polymerization (left) allows a finer resolution than is possible with more common single-photon absorption methods. By using photons with half the energy required to drive a polymerization reaction, the two photons need to be absorbed within a very short timescale. Because this process is proportional to the square of the intensity of photons incident on the target, only in the most focused regions of the incident light – when using a high numerical aperture and a

femtosecond-pulsed laser – will two-photon absorption occur, therefore resulting in high resolution and feature sizes of the order of 100 nm. By coupling this set-up with an optical-tweezer arrangement, whereby very small forces can be exerted on an object through the focusing of a laser beam (right), larger micron-sized objects can be drawn into the vat of material and encased within a matrix or attached to a surface. This offers the potential for functionalizing a surface or a material by combining it with particles prepared separately and then brought together.

We are also investigating materials and deposition processes for conductive and dielectric systems, including highly novel research into the ink-jetting of metals with a melt temperature up to 1500 °C. This work, to be carried out in collaboration with the Netherlands-based manufacturer Océ, can potentially overcome limitations with conventional printed-electronics materials (such as their low conductivities), which currently rely on inks that have been loaded with nanoparticles of active materials such as silver.

One of the most exciting developments in this field is the creation of multifunctional structures at the nanoscale, which demands further improvements in the deposition resolution. At Nottingham we are developing a multi-photon lithography system that can produce arbitrary 3D structures of the order of 100 nm for advanced micro- or nanoscale applications, and using optical-tweezer technology to functionalize the structures deposited (see box). By coupling these two systems we can open the door to new nanoscale devices and structures, for example by providing the sensory input for embedded data-processing capability.

Dial-up medicine

Over the coming years multifunctional 3D printing will move beyond fundamental research towards new manufacturing

systems. Currently, we are at the stage of understanding the fundamental principles and challenges of multifunctional 3D printing, but it is clear that we need a joined-up approach between numerous disciplines – including physics, chemistry, optics, electronics, materials science, biology and pharmaceuticals. To this end, we are working with the School of Pharmacy at Nottingham to explore the 3D printing of pills and multiple therapeutics designed to release drugs at a rate that is personalized to the patient. This would lead to a radically decentralized business model in which drugs or implants could be distributively manufactured. It is envisaged that a medical practitioner would be able to “dial up” a treatment that is then made to a bespoke specification in a room next door, offering personalized care to patients at the point of need.

Multifunctional 3D printing promises genuinely new kinds of manufacturing processes with advanced capabilities, and ultimately a new generation of optimized and highly functional products. Supported by innovative business models, these products will set new standards in performance, efficiency and user-friendliness.

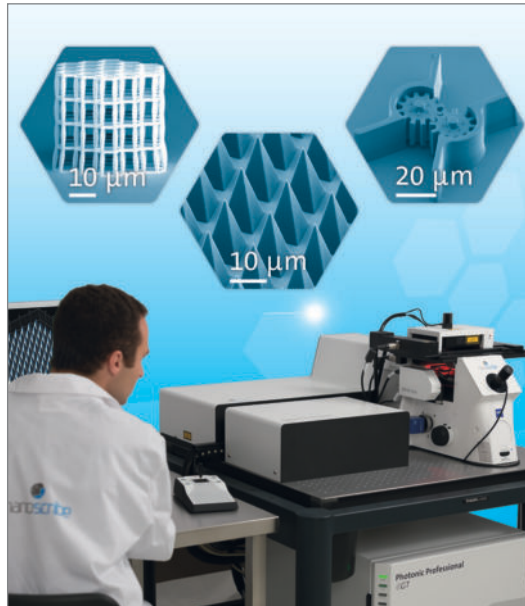
Richard Hague, Martin Baumers, Chris Tuck and Ricky Wildman are in the Faculty of Engineering at the University of Nottingham, UK (e-mail richard.hague@nottingham.ac.uk)

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The global market for 3D printing has a huge potential, especially in market segments where applications demand highly complex geometries or a high degree of individualization. Exactly for these demands, Nanoscribe offers 3D printers for the fabrication of true three-dimensional micro- and nanostructures with a previously unavailable freedom of design as well as photoresists and process solutions tailored to specific applications. The heights of structures produced by means of Photonic Professional systems range from a few hundred nanometers up to the millimeter range. Leading research institutes and universities in Europe, North America, Australia and Asia already appreciate the extraordinary quality and resolution of these high-tech 3D printers. They pave the way for a wide field of novel applications, e.g. in photonics, micro-optics, micro-fluidics or life sciences. The performance of the groundbreaking Photonic Professional GT system generation was emphasized most recently in February 2014 by being awarded a Prism Award in San Francisco, the „Oscar of Photonics“ in the category „Advanced Manufacturing“. The unrivaled 3D printer convinced the jury of its excellent performance, accuracy and tremendous speed. As an enabler for true

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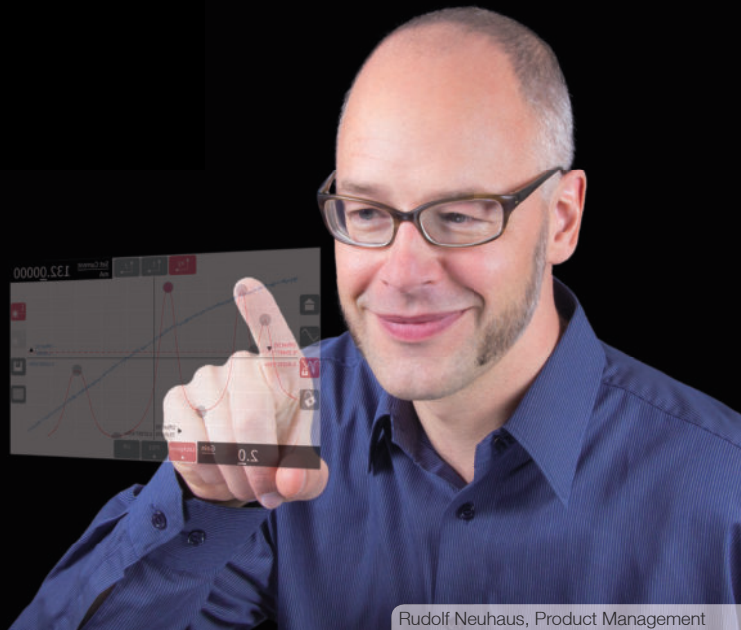
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Gaia set for galactic census

A state-of-the-art optical camera on board the European Space Agency's Gaia satellite is about to begin its five-year mission to chart the positions of a billion stars, writes **Matthew Chalmers**

On 19 December 2013, the largest digital camera ever flown in space was launched from the European spaceport in Kourou, French Guiana. Positioned at the cold and thermally stable "L2" gravitational point at an altitude of 1.5 million kilometres, the approximately £740m (\$1030m) European Space Agency (ESA) probe is now ready to begin its five-year-long mission to map the distance, brightness and velocities of about a billion stars in the Milky Way. The vast stellar catalogue will provide astronomers with an extraordinarily precise 3D map that will shed light on the origin, structure and evolutionary history of our galaxy.

The feat requires a telescope that is stable and powerful enough to pick out objects half a million times fainter than the human eye



Billion-pixel camera Gaia's optical plane uses 106 high-performance CCDs to convert faint starlight into electrical signals, which will be processed and beamed back to Earth at a rate of about 10 Mbits/s.

can see against a haze of background starlight. Thanks to some ingenious engineering and an enormous optical plane of 106 CCDs that packs almost a billion pixels into an area of 0.38m², Gaia can determine the position of an individual star with a precision of six micro-arcseconds – equivalent to resolving a penny on the Moon as viewed from Earth.

Mark Cropper of University College London (UCL), who worked on the project, says that, scientifically, there is nothing else of this scale up there. "Hubble had around 12 CCDs, but Gaia is an order of magnitude above that and much more than any other mission now or planned," he says. "Not long ago, people would fall on the floor laughing if you said you could do this, but ESA was bold enough to go for it."

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Optics in space

Astrometry is one of the oldest branches of science, with the first stellar catalogue compiled by the Greek astronomer Hipparchus more than 2000 years ago. Yet the difficulty in measuring the stellar parallax for distant objects – the apparent shift in a star's position as the Earth travels around the Sun, from which its distance can be calculated – has limited the reach of such surveys. Gaia follows in the footsteps of ESA's Hipparcos probe, which operated between 1989 and 1993 to chart the position of almost 120 000 stars with a precision of 0.001 arcseconds.

Gaia's superior capability stems from several factors, including the use of a highly thermally and mechanically stable silicon-carbide support structure to which all of its optical components are fixed. A large sunshield on the underside of the craft keeps the instruments cool and is one of Gaia's few moving parts. The need to reduce vibrations as far as possible also forced Gaia engineers to develop novel cold-gas thrusters that exert tiny forces to keep the craft in position.

Light entering two primary telescope mirrors set at an angle of 106.5° to each other travels through a combination of 10 mirrors with different shapes and sizes, which

extends Gaia's effective focal length to 35 m – some 10 times greater than the diameter of the satellite itself. The high-performance CCDs onto which the starlight is focused were designed, manufactured and tested by UK firm e2v. The company's image sensors have been used in more than 100 ground- and space-based telescopes – including Hubble, IRIS, Rosetta and Mars Curiosity Rover – but the sheer size of Gaia's optical plane and high-performance specifications presented the firm with unique challenges.

Rich astrophysics

During the production phase, particular focus was placed on achieving the required throughput of devices, says e2v's Gaia project manager Alan Walker. The facilities were highly automated and new test methods were developed, he explains. The e2v team also needed to make sure the CCDs could be closely arranged to minimize the dead space between adjacent devices in the array. "In addition to the screening acceptance testing, there was the usual mechanical, environmental, radiation and life testing to ensure that the array would survive the rigours that the Gaia mission would entail," says Walker.

Roughly two-thirds of the 106 CCD sen-

sors are devoted to Gaia's twin astrometry telescope, which will infer stellar distances. The rest are dedicated to Gaia's two other main instruments. One is a photometer made from two fused silica prisms that cause light to disperse, offering a measure of a star's spectral energy distribution and therefore temperature. The other is the radial velocity spectrometer (RVS), which will record the spectral signature of a star to determine its speed of travel in the line of sight and provide more detailed astrophysical measurements such as metallicity.

The RVS and photometer take Gaia's capabilities beyond basic cartography by revealing the luminosities and masses of hundreds of thousands of stars, from which their age and evolution can be understood. Extrasolar planets and exotic objects such as brown and white dwarfs will also come into spectacular view, plus Gaia will perform unique tests of general relativity. "There is not going to be a single astronomer who is not using Gaia data," says Cropper, who has spent the past 12 years participating in the development of the RVS with colleagues at UCL, ESA and Gaia prime contractors Astrium. "It will change our sense of consciousness about the Earth and our position in the universe."

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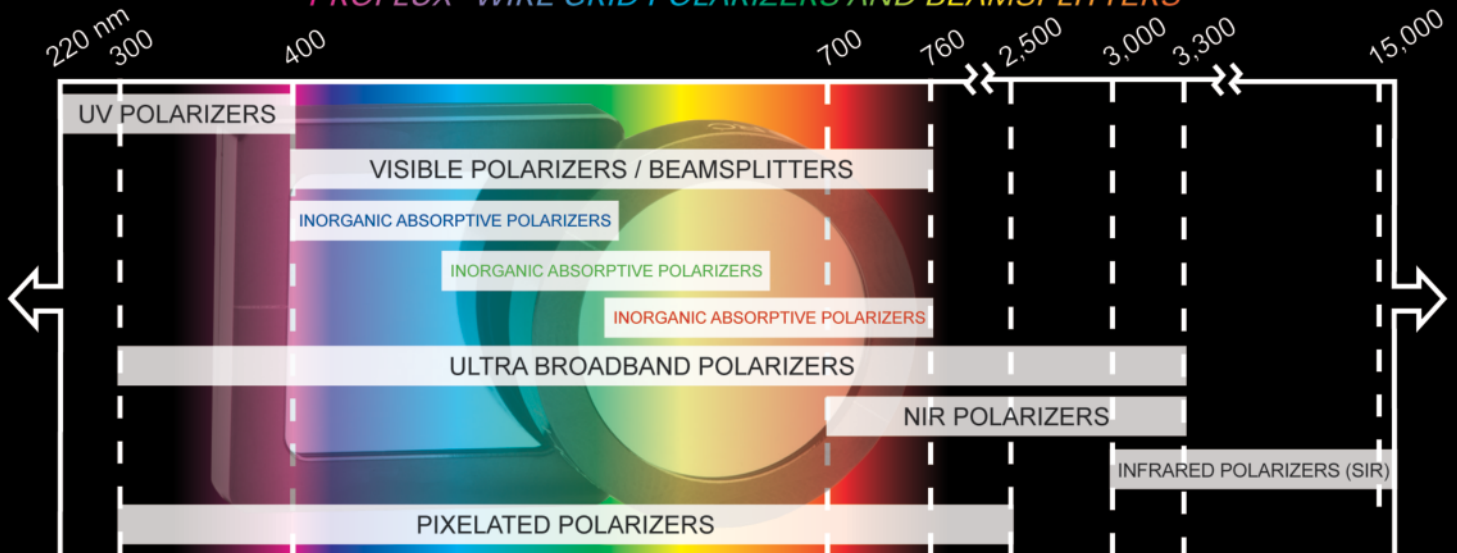


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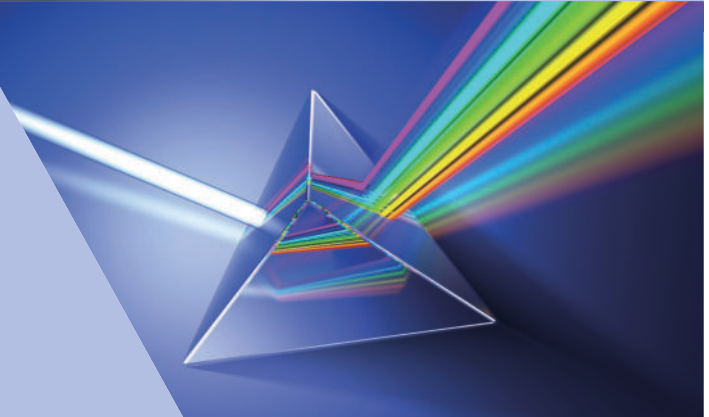
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Exploiting European photonics

As Europe's Horizon 2020 programme kicks off, **Michael Mertin** – president of Photonics21 and head of Jenoptik – explains why he expects strong growth in the European photonics sector

When and why was the Photonics21 Initiative established?

Photonics21 was founded in 2005 to address the heterogeneous nature of photonics. Unlike the situation in, say, the automotive industry, there are not just a few “big players” in photonics and there is no dominant country or technology. The aim of Photonics21 is therefore to unify the photonics community and to advise the European Commission (EC) on photonics research, development and innovation needs. Today, Photonics21 has around 2000 members representing more than 1000 companies or research institutes from all over Europe, from all industry branches and from everyone along the value chain, starting from basic research through to producers of highly complex systems and machines.



Bright future Jenoptik boss Michael Mertin expects that funding for Photonics21 will be €700m.

What has been achieved so far?

The EC has recognized the potential of photonics to increase Europe's industrial and innovative strength, and consequently declared photonics as a “key enabling technology”. This gives photonics a higher visibility and a higher priority on a political level, which impacts the funding of research and innovation activities in a positive way.

How does the platform relate to Horizon?

As a partner of the EC, Photonics21 is responsible for defining the Photonics Multiannual Strategic Roadmap, which sets the major research and innovation topics to be co-funded by the EC within Horizon 2020. The basis of the co-operation between the EC and the European photonics industry is a public private partnership (PPP), in which the private component commits to leverage

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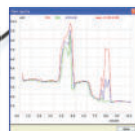
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Interview: Michael Mertin

the public funds by a factor of four. The expected funding for the PPP will be €700m (about \$1055m) for the seven-year-long framework, which is more than in the past.

Why are PPPs an effective approach for this sector?

There are several examples that show that project-based co-funding of R&D and innovation activities is highly effective. Funding schemes in Germany, for instance, enable large companies, SMEs and research institutions to join forces and develop new technologies and products supported by public funds. Knowledge is shared across organizations and the economic risk is split between different parties, benefiting all – including the broader economy and society – because more research can be carried out with lower levels of risk.

Is there still scope for blue-skies research?

The focus of the previous EC funding scheme, FP7, was mainly on scientific excellence, but with Horizon 2020 this will change. The goal of the industrial leadership part of Horizon 2020 is to support innovation, increase market uptake, stimulate private investment in research and innovation, and strengthen the participation of SMEs. Fundamental research will remain an important part, but now activities will go well beyond research. It's an acknowledgment of the fact that photonics innovation in Europe tends to get stuck in the stage between successful science and industrial deployments, where jobs can be created. Horizon 2020 aims to bridge this gap.

Which sectors in photonics have the largest growth potential?

It is difficult to pick out single market segments or technologies because the field of photonics is so diverse. What we can say,

however, is that the overall market for photonics is steadily growing at rates that are well above GDP growth. According to the *Photonics Industry Report 2013*, the global photonics market will increase to €615bn in 2020 – implying an average annual growth rate of 6.5%. Areas with a projected above-average growth are production technology, imaging and metrology, optical components and systems, medical solutions, and photovoltaics.

Will Horizon 2020 focus on particular areas?

The EC expects photonic solutions to address key societal challenges in Europe. Examples include new ways of detecting, treating and preventing major diseases while reducing care costs, for instance by developing mobile screening devices; laser-based high-throughput manufacturing technologies that allow mass customization, rapid manufacturing and zero-fault production; speeding up the development of organic LEDs by supporting the set-up of a pilot line for flexible substrates; and mid-infrared micro-sensors and other photonics solutions that enable higher levels of security and safety.

What have you learned from your Photonics21 presidency so far?

Making tough decisions in fully bottom-up-driven organizations is challenging but worth the effort. In the course of the preparation for the PPP we gave our governance structure a lot of thought to guarantee a fully inclusive and transparent process of how research and innovation topics are derived and prioritized. This new process enabled us to make tough choices to focus the available funds in areas where Europe has most to gain. This process required quite some effort, but it shows that the European photonics community is highly committed to our goals.

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Funding mechanisms are in place, supported by Fraunhofer UK Ltd, for collaborative, industry-linked PhD research at the Fraunhofer Centre for Applied Photonics in Glasgow, and partner institute Fraunhofer IAF in Freiburg, Germany.

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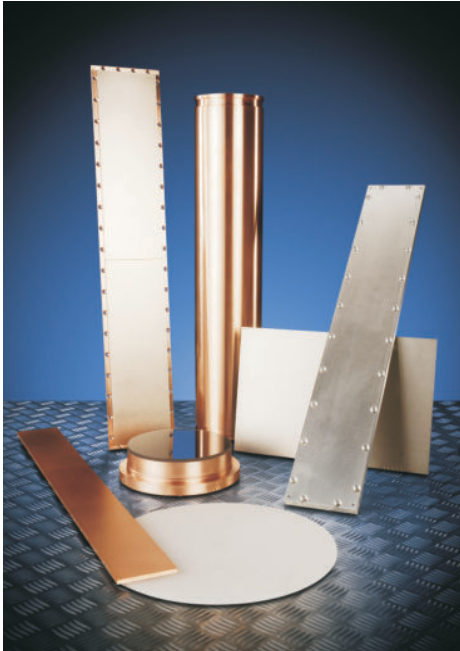


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Chip-scale accelerators

How to shrink an accelerator

Advanced photonics and techniques from the microchip industry are enabling physicists to develop light-based particle accelerators as small as a grain of rice, describes **Joel England**

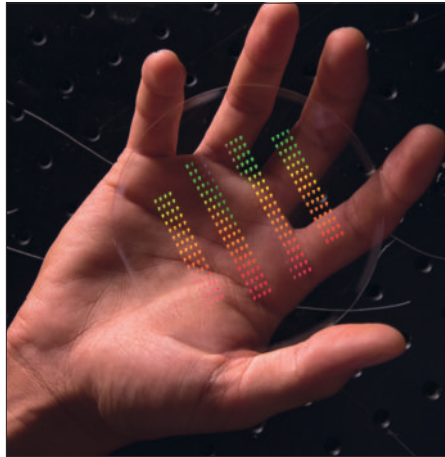
A modern laptop is 100 times smaller, a million times faster and 10000 times less expensive than the first general-purpose electronic computer built in 1946. This remarkable reduction in size and cost is largely down to semiconductor-fabrication methods that have been developed since the 1960s, which allow large and complex electrical circuits to be miniaturized onto tiny chips. But the technology is by no means limited to computers – the modern solid-state laser has benefited from a similar trend.

By combining state-of-the-art nanofabrication techniques with modern photonics and solid-state lasers, researchers are attempting to shrink some of the largest scientific instruments ever built: particle accelerators. This could lead to a new generation of compact and affordable machines for high-energy-physics exploration and X-ray science, and industrial devices for cancer therapy, food sterilization and security.

Conventional particle accelerators confine microwave energy in specially designed hollow metallic guides called radio-frequency cavities, which deliver a forward thrust to particles passing through them. As the microwave power is increased, the particles gain more energy. However, as is clear to anyone who has put a metallic object inside a microwave oven, the interior metal surfaces of a cavity begin to suffer electrical breakdown if the microwave power gets too high. This phenomenon leads to electrical arcs that can damage the machine, and limits the amount of energy that particles can gain over a given distance – a quantity called the accelerating gradient – to around 30 MeV/m. The only way to increase the energy of conventional accelerators is therefore to make them bigger.

In a research collaboration based at Stanford University and the SLAC National Accelerator Laboratory in California, US, we are using techniques from the microchip industry to make micron-scale accelerator structures from dielectric materials, which have high laser-damage thresholds and low ohmic losses. By accelerating particles using the energy from lasers instead of microwaves, gradients of billions of electron-volts per metre are possible. In principle, this would allow us to shrink conventional accelerators by a factor of 100 or more for a given particle energy.

The idea of using light to accelerate parti-



Light work Physicists envision that in the next 5–10 years a complete miniaturized particle-accelerator system could be built on a single wafer.

cles dates back to the 1960s, and since then a variety of all-dielectric, high-gradient structures have been proposed. But it is only recently that it became possible to fabricate the first laser-accelerator prototypes, thanks to high-power solid-state lasers, optical fibres and photolithographic techniques driven by the communications and semiconductor industries.

An alternative approach that has made impressive strides in recent years is plasma acceleration. When an ionized gas (or plasma) is excited by an intense laser pulse, it produces a wave that accelerates a trailing bunch of particles – similar to a surfer riding on the wake of a motorboat. Plasma accelerators use intense lasers that provide millions of billions of watts of peak power to excite the plasma wave, with one excitation occurring every few seconds.

By comparison, photonic-microstructure-based accelerators would use off-the-shelf tabletop lasers to produce millions of pulses per second with a high energy efficiency. This large number of pulses potentially allows micro-accelerators to operate with beam currents comparable to those in conventional accelerators, despite their tiny size, and such devices could also be mass-produced inexpensively.

The first demonstrations of chip-based photonic accelerators were carried out by the SLAC–Stanford collaboration in 2013. Graduate students Edgar Peralta and Ken Soong, respectively, fabricated the pro-

totype structures and developed the precision laser optics required to test them. Using photolithography, more than 200 individual accelerators were etched into a pair of bonded silica wafers. Each of the 1 mm² devices contains a channel as narrow as 400 nm, into which are etched a sequence of ridges and gaps. When illuminated by a laser, these ridges shape the laser field to produce a wave that can impart energy to a particle that arrives at the appropriate time (see figure on p29).

Because most applications require particle accelerators to operate at relativistic energies, we designed the micro-accelerators to produce a wave that will continuously accelerate particles travelling at near-light speeds. To demonstrate the effect, individual structures were carefully aligned in the path of a pre-accelerated electron test beam at SLAC, while being illuminated by a titanium-sapphire laser. Because the particles arrived in bunches that were longer than the 800 nm wavelength of the laser, some were accelerated and some decelerated depending on whether they arrived at the peak or at the trough of the accelerating wave.

High gradients

Our initial tests last year demonstrated accelerating gradients as high as 300 MeV/m (*Nature* **503** 91), but by further narrowing the width of the accelerating channel to enhance the accelerating field and using materials such as sapphire that can withstand higher laser intensities, it should be possible to increase the gradient by a factor of 10 or more. This would allow us, in principle, to shrink the entire 3 km-long SLAC linear accelerator to the size of a room, or to create lower-energy medical accelerators on a single wafer that would fit in your hand.

Alongside our ongoing experimental efforts, Peter Hommelhoff at Friedrich Alexander University in Germany and co-workers recently used an approach similar to ours to accelerate lower-energy (28 keV) electrons with gradients of 25 MeV/m (*Phys. Rev. Lett.* **111** 134803). The German group is also developing ways to fabricate sub-micron-sized particle sources that can be triggered using the same laser that powers the accelerators. Such a particle injector would negate the need for a conventional radio-frequency accelerator on the front end of the microchip accelerator, as was

Matt Beardsley/SLAC

Chip-scale accelerators

necessary in our experiments, and is vital for making on-chip devices that can accelerate electrons to sufficiently high energies.

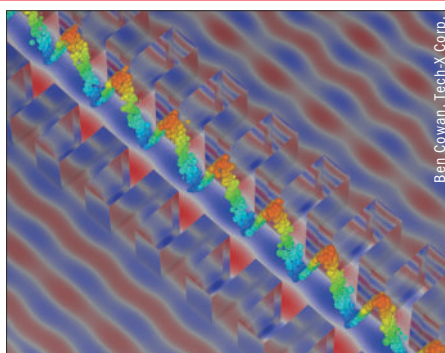
These first demonstrations of chip-scale accelerators are important steps, but a complete accelerator is still some way off. To reach useful particle energies, many of these tiny structures must be fabricated in succession and illuminated by a sequence of laser pulses that are precisely timed so that the particles see a continuous energy gain as they travel forward. The arrival times of the electrons and the laser must be synchronized to within a fraction of an optical period, corresponding to a few tens of attoseconds. This could be done, for instance, by introducing on-chip light guides with precise lengths that selectively funnel light into successive structures.

Another challenge is to avoid some of the particles being decelerated instead of accelerated. This requires that the incoming particles arrive in bunches that are separated by a distance equal to the wavelength of the laser and timed so that they all ride on the peak of the accelerating wave. Researchers at SLAC and Stanford have previously demonstrated a way to prepare the particles in this way using a laser to modulate the energy of the electrons followed by a magnetic compressor, which allows lower-energy particles to catch up with higher-energy ones. Accelerating these micro-bunched particles in unison at the peak accelerating field would also allow for monochromatic beams with a narrow energy spread, and we are now trying to integrate these approaches to design new particle sources that are optimized for testing micro-accelerators.

Similar techniques have been proposed to build a powerful source of pulsed X-rays for advanced crystallography research, for instance. By making on-chip laser-driven devices rapidly deflect rather than accelerate particles, a sequence of alternating deflectors in series would form an “undulator” that forces electrons to wiggle back and forth to generate bursts of synchrotron radiation. Such micro-bunched beams could potentially deliver X-ray pulses with durations of tens of attoseconds, allowing scientists to probe atomic and molecular dynamics on timescales three to four orders of magnitude shorter than present-day “conventional” X-ray free-electron lasers, such as the Linac Coherent Light Source at SLAC.

Industry appeal

We estimate that within the next 5–10 years tens of millions of electron-volts could be generated in an integrated device fabricated on a single 15 cm diameter wafer. To reach the billions or trillions of electron-volts needed for high-energy physics exploration, we will need to carefully align many such wafers in succession with sub-micron



Surfing a wave A computer simulation of particles in a microchip accelerator shows the accelerating (orange) and decelerating (blue) portions of the laser-induced wave in a nanostructured channel.

precision. This is straightforward when nanofabricating multiple devices on a single wafer, but more challenging if individual macroscopic objects are to be aligned. Consequently, in the next decade microchip accelerators will probably find their first applications in industry and medicine, where the required particle energies are in the much lower range of 1–20 MeV.

Companies that build accelerators for these sectors are beginning to express interest in commercializing the technology. Although the machines used in industry and medicine are smaller than high-energy colliders, they can still be the size of a room, weigh tens of tonnes and cost millions of dollars. Microchip-based versions could be sufficiently small and portable to allow endoscopic direct electron-beam cancer therapy, for instance. They could also enable more affordable medical X-ray sources for the treatment of clogged arteries, computed tomography (CT) scans and high-resolution imaging of biological tissues.

Similar devices for industry could provide a valuable X-ray source for non-destructive testing of products and materials, for instance by identifying cracks and deformations in hard-to-reach locations, or enabling new processes in the microchip industry by using multiple-beam X-ray lithography to rapidly “print” nanoscale patterns onto integrated chips. Accelerators for X-ray security screening of cargo and aircraft could also be made more widely available and, being smaller, capable of scanning larger areas or moving targets.

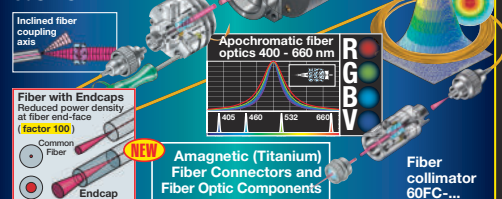
A number of these nearer-term applications are beginning to be explored and although the technology is not yet ready to compete with high-energy machines such as the 27km-circumference Large Hadron Collider at CERN in Switzerland, it is clear that photonic devices are a promising approach for the future of particle acceleration.

Joel England is a physicist at Stanford University and SLAC (e-mail england@slac.stanford.edu)

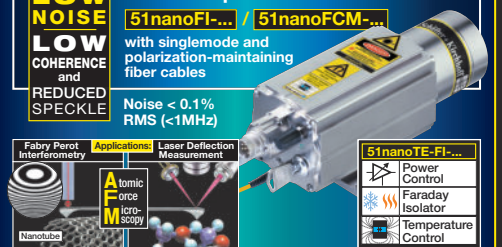
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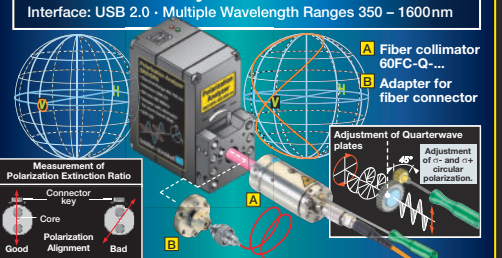
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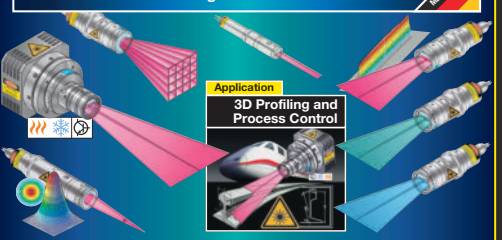
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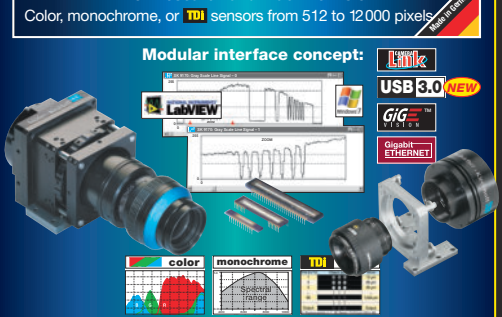
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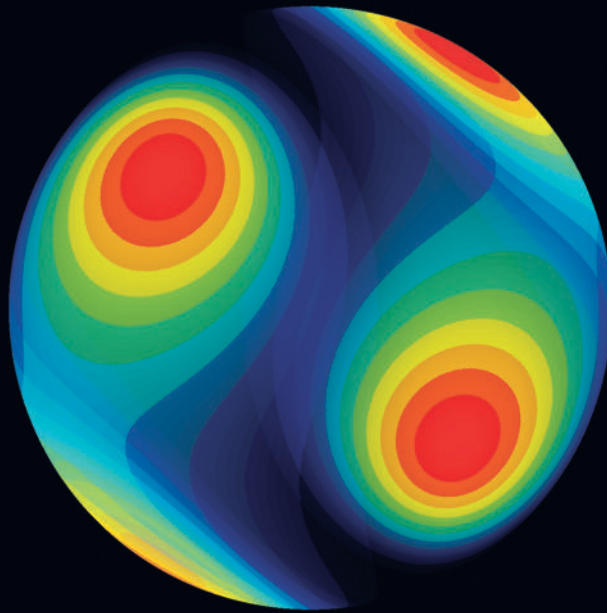


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Precision agriculture takes off

Optical sensors that can inspect and treat crops are helping farmers optimize their harvests by adjusting how much fertilizer they apply, finds **Martin Griffiths**

During the Second World War, the US military developed a method to distinguish real plants from enemy camouflage based on the way they react to light. Chlorophyll absorbs blue and red light while reflecting green, giving plants their colour. But plant cells also reflect infrared light, which is not energetic enough for photosynthesis, to prevent overheating. Therefore, while green camouflage looks the same colour as a plant to the naked eye, it appears dark on an infrared film, while vegetation appears white.

As remote sensing from satellites became possible in the 1960s, this princi-



Physics in the field Tractors fitted with commercial optical sensors can reduce the use of pesticides.

ple was developed into an index called the normalized difference vegetation index (NDVI), which relates reflectance in the

visible region to the infrared. The NDVI also provides a measure of how healthy a plant is based on its photosynthetic activity: an increase in the reflectance of red light indicates that a plant is not photosynthesizing as effectively as usual, perhaps because of drought or lack of nutrients. However, satellite NDVI measurements are also affected by atmospheric conditions, satellite geometry and the angle of incidence of the Sun's radiation.

Gauging a plant's needs

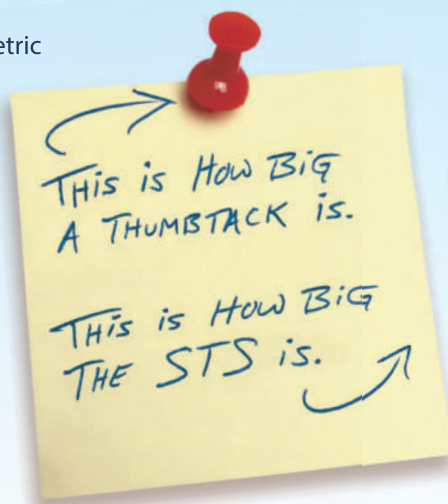
To get round these complications, in the 1990s plant scientists and agricultural engineers at Oklahoma State University in the US developed ground-based optical sensors. Their aim was to use NDVI measurements to gauge a plant's nitrogen needs, thereby allowing farmers to adjust the amount of fertilizer applied to a crop. Early sensors were passive and worked by measuring light reflected from the Sun,

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Optical sensing

which varies during the course of a day and with the level of cloud cover. In 1998, however, researchers developed active sensors using LEDs as a red and infrared source, and by 2002 US firm NTech Industries had commercialized the technology under the trademark "GreenSeeker".

Big business

Crop sensing has expanded rapidly in the last few years, with the acquisition of NTech by Californian firm Trimble in 2009 and the appearance of competitors such as Holland Scientific's Crop Circle and Topcon's Crop-Spec, which uses a laser diode rather than an LED source. In today's systems, several sensors are mounted along a boom attached to a tractor and readings are used to adjust the levels of fertilizer being applied in real time. A typical four-sensor GreenSeeker system costs in the region of \$10 000, but the resulting savings can be much bigger according to Trimble's Anna Hebert. "A farmer in Oklahoma saved more than \$32 000 in fertilizer costs in 2013 (\$24 per acre) and more than \$175 000 since he began using GreenSeeker in 2005," she says.

The next move for agricultural optics appears to be upwards. Andreas Burkart at the Jülich Research Centre in Germany is

leading a project to observe crops using a lightweight spectrometer made by US firm Ocean Optics aboard an unmanned aerial vehicle (UAV). "The dream of such an 'eye in the sky' is old," says Burkart, "but now UAVs can be readily purchased and configured so that even a biologist like me can operate one easily." The restricted payloads and flight times of UAVs make such systems more suitable for crop observation than treatment. Indeed, according to Michael Allen of Ocean Optics, the UAV device captures data about 20 times faster than with traditional ground-based techniques without causing any disturbance to the crops. "That's a huge advantage when you have to assess dozens of acres of cropland," Allen told *Physics World*.

The next step, says the Jülich team, is to use spectral data to reconstruct a full phenotype, including the size of plants, and the number and colour of their leaves. A UAV could then quickly scan an area containing several different varieties of a crop, such as barley, and assess how each performs in different conditions. Trimble launched its first UAV system targeted at farmers in January.

Unlike ground-based active optical sensors, measurements from the air rely on reflected light. But a recent project by a

multidisciplinary group at the University of New England in Australia aims to get the best of both worlds by mounting off-the-shelf active optical sensors on ultra-low-level aircraft flying 3–5 m above the ground.

Detecting disease

Researchers are also developing more advanced sensors. For example, the small amount of red light re-emitted after being absorbed in photosynthesis, known as chlorophyll fluorescence, can provide a sensitive indicator of plant stress. Optical techniques have even been demonstrated that can detect plant diseases before they can be ascertained any other way, allowing the preventative application of pesticides. By studying the reflectance spectra of sugar-beet crops infected with three different fungal pathogens, a team from the Institute for Crop Science and Resource Conservation at the University of Bonn in Germany has recently identified spectral features that are correlated with each disease.

"From online measurements of the fat content of milk to screening incoming materials for food manufacturing, optical solutions are becoming mainstream," says Allen. "Miniaturization and ease of use will drive more farmers to optical technologies."

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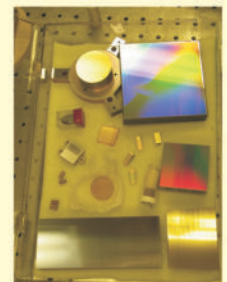
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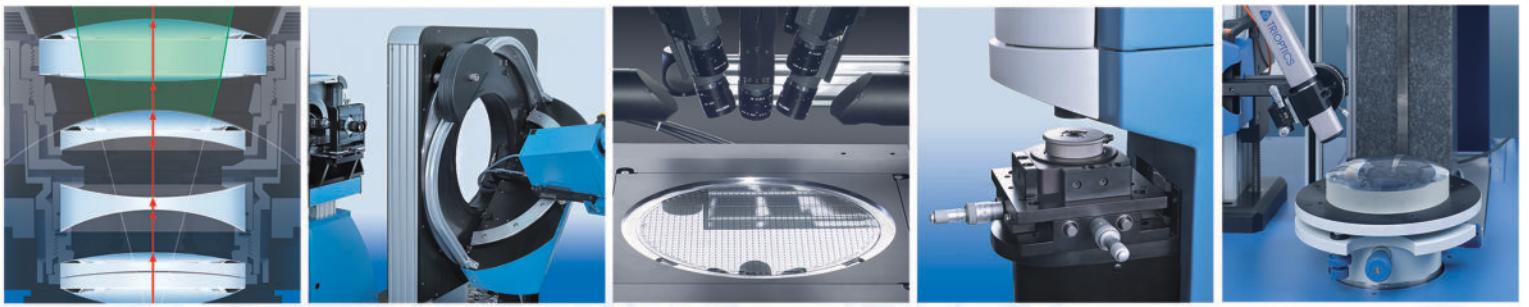
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