FEBRUARY 2021
ISSUE 310

Electro Optics

Photonics business, applications & technology

Commercialising Quantum

New technologies set sites on global challenges

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In the Art of Making Lasers

Electro Optics



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Electro Optics is published 10 times a year by Europa Science Ltd, 4 Signet Court, Cambridge, CB5 8LA, UK
Tel: +44 (0)1223 221030 Fax: +44 (0)1223 213385 Web: www.europascience.com ISSN: 0013-4589

LEADER
JESSICA ROWBURY

Quantum-ready

Each year, quantum photonics seems to gain more momentum.

Spie, for example, is holding a 'Quantum West' conference for the first time this year, which will take place alongside the online Photonics West event in March.

And with so much joint industry-academic activity happening – with results set to transform a plethora of applications – the growing anticipation seems justified.

On page 14, Keely Portway details the progress of various projects in the UK and across Europe, funded through UK and EU government funding programmes that both surpass £1bn.

A correlated photon pair source and a photon counting camera, a fluorescence imaging device and a gas sensing lidar instrument are just a few of the products on the horizon, although significant engineering challenges remain before we commonly see quantum products in the commercial market.

Also in this issue, we have a feature on making EUV lithography – another heavily-funded technology sector – more affordable for small and medium enterprises, the benefits of which have not yet been accessible to smaller firms. Read more on page 10.

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POSTMASTER: Send address changes to Electro Optics, PO Box 437, Emigsville PA 17318-0437.

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FOCUS BUSINESS & RESEARCH NEWS

IN BRIEF

Following Brexit, the UK will be a full associate member of the next **Horizon Europe** collaborative research and development funding framework. The UK will also join a range of other EU programmes including Euratom, European Space Agency (ESA) inc Copernicus, European Institute of Innovation and Technology, Joint Research Centre and European Research Infrastructure Consortium.

Hamamatsu Photonics UK and **Medical Technologies Innovation Facility (MTIF)** have partnered to allow customers to use Hamamatsu's functional drug screening system (FDSS) µCell, the first to be made available in the UK in this way. The agreement is expected to accelerate the development of new medical and pharmaceutical therapies.

Luna Innovations has bought OptaSense from parent firm QinetiQ for £29m. OptaSense delivers fibre optic distributed monitoring solutions for pipelines, oilfield services, security, transport and utilities monitoring systems. With enhanced distributed acoustic sensing intellectual property and expertise, Luna aims to create a significantly larger company.

PIC spectral sensors earn investment

Two firms developing NIR chip-based sensors have received funding to push towards mass manufacturing. Dutch start-up MantiSpectra has received investment from public-private partnership PhotonDelta and independent VC investor Innovation Industries, while Dresden-based pilot Senorics is set to receive more than €2m from the Development Bank of Saxony.

MantiSpectra, a recent spin-off from Eindhoven University of Technology, is developing a chip-based near infrared (NIR) spectral sensor. By using photonic integrated chips (PICs), MantiSpectra is able to make their sensors cheaper, smaller and easier to use.

The investment will allow MantiSpectra to expand the team and industrialise the product, a standalone spectrometer, targeting the agri-food sector at first, and other sectors in years to come.

Maurangelo Petruzzella, managing director and co-founder of MantiSpectra, said: 'With this investment MantiSpectra is able to make the next steps to bring this promising technology to the market. This includes attracting highly qualified personnel to expand the team and industrialising and scaling up the product and manufacturing processes.'

Sander Verbrugge, general partner of Innovation Industries, added: 'MantiSpectra has the potential to play an important role in mass adoption of affordable, miniaturised spectrometers.'

Senorics, a spin-off from the University of Technology Dresden, develops chip-based photonic sensors for material analysis. Because its chip is monolithic and has no dispersive elements, optical or mechanical parts, it is robust against vibrations and shocks. The chip is around the size and height of a one cent coin, making it easy to integrate in a range of devices for varying applications.

Senorics founder and CEO Ronny Timmreck said in a statement that the next step in making its NIR sensors ready for the mass market is the construction of a pilot line. With the support of the Saxon Ministry of Economics, the company can promote the industrialisation of its technology and build a pilot facility to produce the sensors in Dresden.

Fluorescence microscopy method expands dynamic processes study

Scientists at the Institute of Post-LED Photonics (pLED), at Tokushima University in Japan, have developed a fluorescence microscopy method for studying dynamic biological processes.

The fluorescence lifetime microscopy technique uses frequency combs and no mechanical parts to observe dynamic biological phenomena. The work was published in *Science Advances*.

Conventional fluorescence microscopy only captures fluorescence intensity, which can vary depending on experimental conditions and the concentration of the fluorescent substance.

The new method measures both fluorescence intensity and lifetime. It does not require mechanical scanning of a focal point, but instead produces images from all points in the sample simultaneously, enabling a more quantitative study of dynamic biological and chemical processes.

Professor Takeshi Yasui, who led the study at pLED, said: 'Our method can be interpreted as simultaneously mapping 44,400 light stopwatches over a 2D space to measure fluorescence lifetimes – all in a single shot and without scanning.'

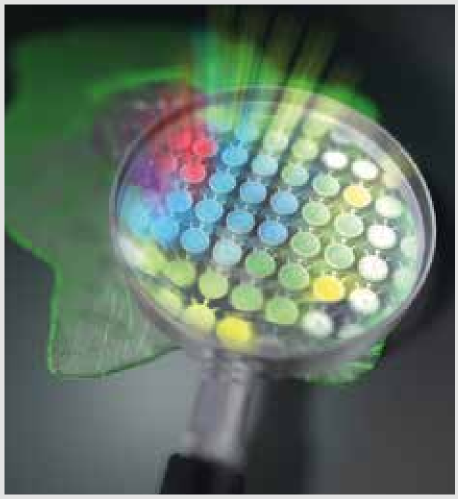
Thanks to its speed and high spatial resolution, the scientists believe the microscopy method will make it easier to exploit the advantages of fluorescence lifetime measurements.

'Because our technique does not require scanning, a simultaneous measurement over the entire sample is guaranteed'

'Because our technique does not require scanning, a simultaneous measurement over the entire sample is guaranteed in each shot,' Yasui added. 'This will be helpful in life sciences, where dynamic observations of living cells are needed.'

In addition to providing deeper insight into biological processes, this new approach could be used for simultaneous imaging of multiple samples for antigen testing, which is already being used for diagnosing Covid-19.

When a fluorescent substance is irradiated with a short burst of light, the resulting fluorescence does not disappear immediately but decays over time in a way specific to that substance. The fluorescence lifetime microscopy technique uses this phenomenon – which is independent of experimental conditions – to quantify fluorescent



Institute of Post-LED Photonics

2D arrangement of 44,400 light stopwatches enables scanless fluorescence lifetime imaging

molecules and changes in environment. Fluorescence decay is extremely fast. To capture it, the scientists used an optical frequency comb as the excitation light for the sample. The fluorescence is focused onto a high-speed single-point photodetector, and the measured signal used to calculate the fluorescence lifetime.

An optical frequency comb is essentially a light signal composed of the sum of many discrete optical frequencies with a constant spacing between. The target sample is irradiated with a pair of excitation frequency comb signals, which decompose into individual optical beat signals (dual-comb optical beats) with different intensity-modulation frequencies, each carrying a single modulation frequency. Each light beam hits the sample on a spatially distinct location, creating a one-to-one correspondence between each point on the the 2D surface of the sample (pixel) and each modulation frequency of the dual-comb optical beats.

Due to its fluorescence properties, the sample re-emits part of the captured radiation while preserving the frequency–position correspondence. The fluorescence signal captured by the photodetector is mathematically transformed into the frequency domain. The fluorescence lifetime at each 'pixel' is calculated from the relative phase delay between the excitation signal at that modulation frequency, versus the one measured.

Using optical frequency combs in microscopy techniques holds promise for developing novel therapeutic options for various diseases, the scientists say.

Silicon PIC processor delivers faster data speeds

A team of international scientists has demonstrated an initial prototype of a photonic processor using tiny rays of light confined in silicon chips that can process information much more rapidly than electronic chips and also in parallel – something traditional chips cannot do.

The discovery, made by researchers at Oxford, Münster, Exeter and Pittsburgh universities, École Polytechnique Fédérale (EPFL) and IBM Research Europe, was published on 6 January in *Nature*.

Machine learning and AI applications make use of vast troves of data. Our data is increasing exponentially and using this data to create information requires computer processing. The capabilities of conventional computer processors are not sufficient to keep up with this demand.

But now this international research team has developed an approach and processor architecture which provides a potential avenue to perform these tasks at high throughput – essentially by combining processing and data storage functionalities onto a single chip – so called in-memory processors, but using light.

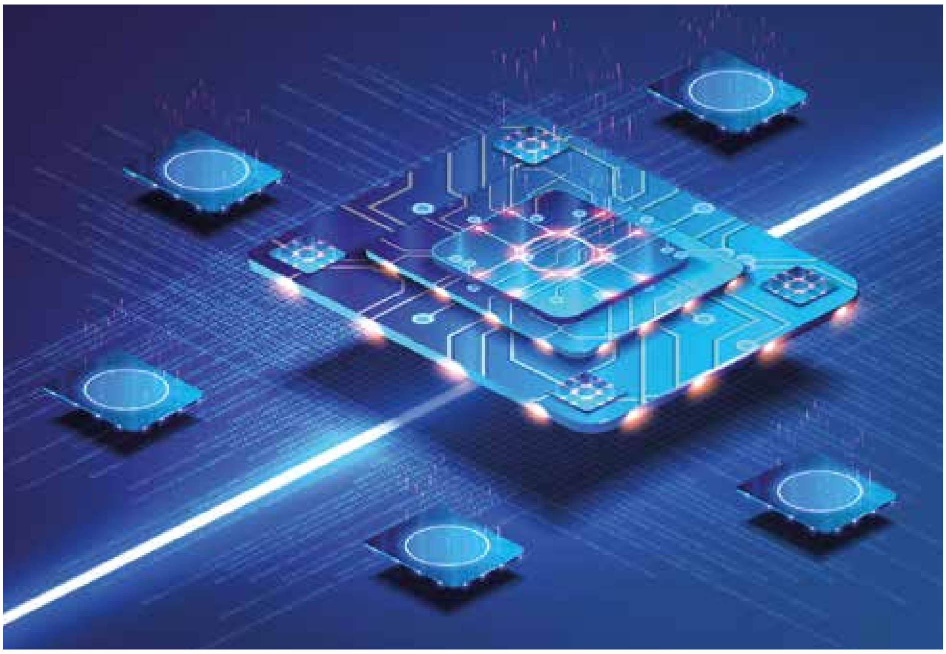
Senior co-author Wolfram Pernice, at University of Munster, one of the professors who led the research, said: 'Light-based processors for speeding up tasks in the field of machine learning enable complex mathematical tasks to be processed at high speeds and throughputs.

'This is much faster than conventional chips, which rely on electronic data transfer, such as graphic cards or specialised hardware like TPUs (Tensor Processing Unit).'

The team implemented a hardware accelerator for so-called matrix-vector multiplications. Such operations form the backbone of neural networks (a series of algorithms which simulate the human brain) that are used to compute machine learning algorithms.

Using light allowed the team to use multiple wavelengths of light to do parallel calculations, since light has the property of having different colours that do not interfere. However, to do this, they used yet another recent invention, a chip-based frequency comb, as a light source.

Professor Tobias Kippenberg, at EPFL, said: 'Our study is the first to apply frequency combs in the field of artificial neural networks. The frequency comb provides a variety of optical wavelengths which are processed independently of one another in the same photonic chip.'



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'Our study is the first to apply frequency combs in the field of artificial neural networks'

Once the chips were designed and fabricated, the researchers used a convolutional neural network for the recognition of handwritten numbers. These networks are a concept in the field of machine learning inspired by biological processes. Used primarily in the processing of image or audio data, they currently achieve the highest accuracies for classification.

Johannes Feldmann, now based at Oxford University's Department of Materials, said: 'The convolution operation between input data and one or more filters – which can identify edges in an image, for example, are well suited to our matrix architecture'.

Researcher Nathan Youngblood added: 'Exploiting wavelength multiplexing permits higher data rates and computing densities, i.e. operations per area of processor, not previously attained.'

Professor David Wright, of the University of Exeter, who leads EU project Fun-Comp, which funded this work, said: 'This work is a real showcase of European collaborative research. While every research group involved is world-leading in their own way, it was bringing all these parts together that made this work truly possible.'

The results have a wide range of potential applications, such as: in AI where more data can be processed simultaneously while saving energy; more accurate, and hitherto unattainable, forecasts and more precise data analysis; in clinical settings, where the photonic processors can support the evaluation of large quantities of data for diagnoses; in self-driving vehicles, rapid evaluation of sensor data can be enhanced; IT infrastructures such as cloud computing can be expanded by providing more storage space, computing power and applications software.

Abu Sebastian, senior co-author who oversees the efforts on emerging computing paradigms at IBM Research Zurich, said: 'One of the key differentiators for an in-memory photonic processor compared to its electronic counterpart is the ability to parallelise in the frequency domain, making it particularly well-suited for computational primitives such as convolutions.'

Professor Harish Bhaskaran, senior co-author at the Department of Materials, Oxford University, said: 'While the current work provides a pathway towards implementing such processors in the photonic domain, many daunting scientific and technological challenges remain. This is what makes this field an exciting and fast-moving area of research.'

Burst of colour: laser TV at CES 'better than cinema'

Chinese consumer electronics firm Hisense has introduced an RGB laser light source architecture for its TriChroma Laser television range, offering an 'extremely wide' colour gamut.

The display technology was unveiled at the Consumer Electronics Show, held virtually in January.

In a keynote address at CES, Dr Liu Xianrong, chief scientist of Hisense Laser Display, explained that the technology packages and controls separate lasers to produce purer colours. The new light source achieves a 128 per cent improvement in RGB colour. It also attains a 20 per cent brightness enhancement at the pixel-level, with a 430-nit picture brightness, exceeding that of a regular television.

In addition, with the colour gamut coverage reaching up to 151 per cent of the DCI-P3 film colour standard, it is almost 50 per cent beyond that of high-end cinema.

The laser televisions range from 75- to 100-inch. They are also equipped with AI smart cameras to facilitate interactive activities such as online karaoke and fitness.

Hisense will release more laser TV models this year, and projects a promising market share in 2021.

What is a laser TV?

Rather than comprising a single television unit, laser TVs require a screen and projector to operate.

Hisense introduced its first-generation model at CES 2015.

Hisense

For Hisense' 100-inch L5 4k laser TV, the projector only needs to be 19cm from the screen

In 2020 the firm's overseas sales went up 288 per cent for laser televisions across 17 countries, including the US, Mexico and Australia.

Last year the firm introduced its L5 laser TV, available in 75 and 100-inch sizes. For the 100-inch model, the projector only needs to be 19cm from the wall. The screen also rejects ambient lighting, enabling it to be viewed clearly in bright conditions.

With less harmful blue light, the L5 is certified as a low blue light hardware solution. It is equipped with a built-in sensor that detects if an object passes too close to the light source, reducing the light's strength and automatically powering off the console to avoid damage to a person's eyes.

Photonics West switches to online format

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As a result of the pandemic's ongoing disruption to international travel, Spie will be hosting Photonics West as an interactive, virtual conference this year from 6 to 11 March.

The event – North America's largest optics and photonics technology conference – usually takes place in San Francisco, California.

Each year Photonics West showcases the latest in applications, technologies, and discoveries in optics and photonics.

The virtual format will include two digital exhibitions in addition to the Lase, Bios, Opto and Quantum West conferences.

In addition to the plenary sessions and conference presentations, the virtual format will include networking opportunities and other special events. All conference presentations and manuscripts will be accessible after the conference via SPIE's digital library.

Spie CEO Kent Rochford said: 'The Spie Digital Forum platform was developed to help people share results and make connections during the pandemic, and we continued to fine-tune our virtual platform and digital offerings throughout 2020.

'We'll be implementing the latest improvements during Photonics West and are excited to release them to our attendees, presenters and exhibitors.

'These forums, as always, ensure the professional discussion, innovation sharing, and networking opportunities that the Spie community values and relies on to advance its research, product development and engineering collaborations.'

John Greivenkamp, 2020 Spie President, said: 'It's been a challenging year for our entire community, and I know that I am not alone in my desire to meet in person to exchange ideas, research, technological advances, and new products.

'The Spie Digital Forum platform was developed to help people share results and make connections during the pandemic'

'We are hopeful of being able to gather in person later in 2021. In the meantime, I invite you to join us online at one or more of these dynamic conferences and look forward to seeing you there.'

In addition to Photonics West, the following Spie 2021 conferences will also be held via the organisation's Digital Forum platform: AR/VR/MR; Advanced Lithography; Medical Imaging; and Smart Structures + Nondestructive Evaluation.

Prism Award finalists announced

Innovations in the fields of quantum, manufacturing, healthcare, smart sensing and autonomous transportation have been selected as finalists for the Prism Awards.

The annual event, now in its 13th year, recognises industrial innovation in photonics in multiple categories. It will take place during Photonics West in March.

Emerging companies Lumedica and Qnami and returning Prism champions WaveOptics and nLight will share the stage, alongside industry stalwarts such as IPG and Osram. Judges reviewed 149 applications from 18 countries.

'The finalists vying for the 2021 Prism Awards represent exciting innovations in the optics and photonics industry,' said Spie CEO Kent Rochford.

'In a year when R&D has been understandably challenged, we still see tremendous work from our community, in terms of developing products that enable healthcare, make our planet safer and cleaner, and improve manufacturing, while also looking into the future to continue to impact and enhance our daily lives.

'We congratulate all the applicants for the research, development, and perseverance necessary to bring a sellable technology to market and look forward to recognising the winners early next year.'

Here's a full list of the Prism Award finalists and their competing technologies:

Life Sciences
Augmentiqs Medical, Augmentiqs 1000;
IPG Photonics, YLPF-FlexO;
OmniVision Technologies, OVM6948 CameraCubeChip

Manufacturing
BMF (Boston Micro Fabrication), microArch S240;
IPG Photonics, LightWeld 1500;
nLight, AFX

Medical Devices
Endofotonics, Spectra IMDxTM;
Lumedica Vision, OQ EyeScope;
Norlase, Lion

Quality Control
Ophir, LBS-300HP-NIR;
Teledyne Dalsa, Linea HS 32k TDI camera;
RoadVista, StripeMaster 3 retroreflectometer

Quantum
Aurea Technology, quantum entangled twin photon source;
Element Six, DNV-B1TM;
Qnami, Qnami ProteusQ

Safety and Security
Alakai Defense Systems, situational awareness for first responders (SAFR);
Cubert, Ultris 20 hyperspectral camera;
RaySecur, MailSecur mmWave scanner

Software
Amphanov, Immersive Photonics Lab;
Beijing JCZ Technology, Ezcad laser processing software;
OptoTest, OPL-CLX software suite

Smart Sensing
Luxmux, ultrawide tuneable Fabry Perot laser;
mirSense, new QCLs from 10µm to 17µm;
nanoLambda, digital nano spectrometer;

Transportation
AEye, AEye 4Sight M;
Lumotive, X20 lidar;
SLD Laser, LaserLight W-IR SMD

Vision Technology
Gamma Scientific, NED-LMD waveguide tester;
Osram Opto Semiconductors, 550 aperture PowerBoost VCSEL;
WaveOptics, WaveOptics waveguide platforms

PRISM AWARDS

Upholding the law

Keely Portway discovers how lasers are being used to advance Moore's law, and how this technology could become more accessible to SMEs

Fraunhofer ILT

The EUV source at Fraunhofer ILT's Excimer facility delivers 40W at 13.5nm

Moore's Law came into being more than 50 years ago, when a research specialist at American semiconductor company, Fairchild Semiconductor, suggested that the number of transistors in dense integrated circuits could double every two years.

That specialist, Gordon Moore, consequently predicted that the speed and capability of computers would also increase every two years. Moore's prediction has since been used in the semiconductor world for planning and product development, and has been a near-reality ever since. This has been driven by advances in photolithography, one of the key technologies behind size reduction of computer chip components.

While there is not a definitive consensus about when, or if, Moore's law will come to an end, there has been speculation that semiconductor advancement has slowed in the past 10 years. However, in the last two years, manufacturers of this technology have developed new, mass-fabrication practices, for which lasers play a crucial role.

Some recent market predictions appear to dispute the slowing of semiconductor development altogether. The Semiconductor Industry Association recently announced that global sales of semiconductors totalled $113.6bn in the third quarter, an increase of 11 per cent on the previous and a 5.8 per cent increase year-on-year. Looking ahead, Technavio's Global Semiconductor Market 2020-2024 report forecasts that the global market size will grow more than $90bn by 2024.

Driven by 5G

Technavio's report states that major market growth came from the integrated circuits segment last year, which is expected to experience the fastest growth during the next five years, largely because of the growing investments in telecommunication network deployments, including 5G networks.

The most recent, and arguably one of the most famous, examples is the iPhone 12. The new smartphone features what Apple calls the world's first processor built from 5nm transistors: the A14. The processor was supplied to Apple by Taiwan Semiconductor Manufacturing Company (TSMC), for use in its smartphones, tablets and Mac computers. It is anticipated that the transistors – which are about the width of 25 atoms – will also begin to appear in some of the leading PCs, servers and smartphones from multiple vendors in the next year.

To put the size of the transistors into context – and return to Moore's Law – there are about 171 million of them laid out over every square millimetre of the chip. This has been possible thanks in no small part to Dutch firm ASML.

'The cost of the systems is exorbitant right now and it is not going to become cheaper any day soon'

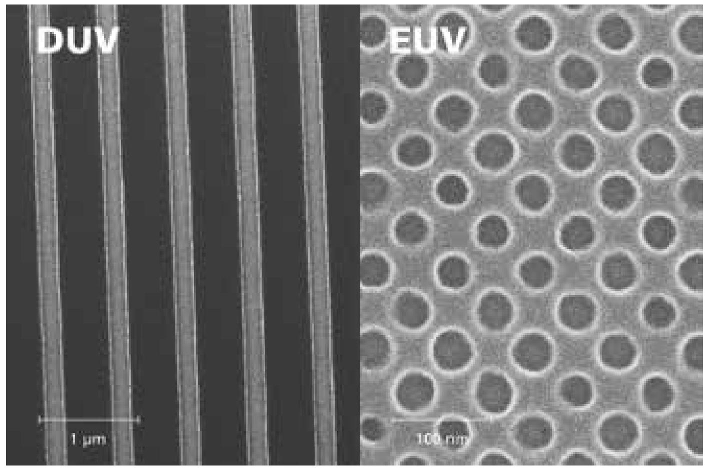
The lithography system manufacturer developed a technique to carve circuitry patterns into silicon via extreme ultraviolet (EUV) lithography – and this is where lasers earn their stripes. Back in 2018, laser manufacturer Trumpf described at Epic's Executive Meeting on Industrial Lasers how it was using CO_2 lasers to develop EUV lithography systems for this purpose. Dr Andeas Popp, a project head at Trumpf Photonic Components, explained that this new application of CO_2 lasers will be key for taking the next step in Moore's law. This is because the size of semiconductor structures on chips are approaching atomic dimensions – something that has been made possible by complex exposure processes enabled by lasers.

To the limit

Previously, exposure processes had been performed using UV radiation generated by 193nm excimer lasers. But this wavelength range faces limitations when producing


Fraunhofer ILT

At Fraunhofer ILT, a laboratory system for EUV has been built to process wafers with a diameter of up to 100mm



Fraunhofer ILT

Nanostructures with 300nm (left) and 28nm (right) half-pitch, created using DUV and EUV technology respectively

structures less than 10nm in size. For structures in the range of 5nm, exposure at shorter wavelengths in the EUV range must be used to provide the resolution necessary for their fabrication.

Trumpf collaborated with ASML, its subsidiary Cymer and optics giant Zeiss, to develop the systems. The EUV lithography technology quickly generated interest from major semiconductor manufacturers, according to the company, with such end-users placing orders for the systems, to ramp up their mass production throughout 2018 and 2019.

TSMC was one such company, and is now sole supplier of the A14 processor to Apple. Samsung is also putting the technology to good use, and is set, alongside Qualcomm, to imminently reveal a new processor for Android phones. Then there is Intel, which is reportedly looking to start using the technology this year.

Counteracting the cost

But what about start-up companies, or those of a smaller or medium size (SMEs)? The ASML machines cost in excess of $120m (£90m) each, which is high even compared with other semiconductor industry tools.

This has led many speculators to argue that, because the cost of a single EUV layer on a chip is about three times the cost of a layer that uses traditional processing, this cancels out the benefits of transistors this size.

Moreover, Moore's Law historically yielded 40 per cent reductions in transistor cost, but the benefit from this new technology will be closer to around 10 per cent. In addition, by prohibiting smaller businesses and start-ups from accessing the technology, the cost could also prevent more new and exciting developments reaching the market.

To help counteract this problem, Fraunhofer ILT is developing technologies for the production of nanostructures that start-ups or SMEs can also afford. The idea, revealed Dr Serhiy Danylyuk, team leader of EUV and DUV technology at the institute, is to generate periodic structures via the interference effects of coherent radiation, like the achromatic Talbot effect. In the near field – less than 500µm behind a mask – an intensity distribution is created with which microlithographic structures can be produced.

Danylyuk explained: 'The cost of the systems is exorbitant right now and it is not going to become cheaper any day soon. So, we got thinking that we could try to scale down and make it possible for SMEs.'

Scientists at the institute are doing this using a KrF excimer laser at a wavelength of 248nm to generate structures with a period of several hundred nanometres. This was tested with a Leap150K laser system from Coherent. In a photoresist, 180nm wide lines can be generated with a period of 600nm. With higher energies of 250mJ/cm², silicon on glass can also be ablated with similar dimensions. The technology is also well suited for the ablation of PET plastic surfaces on a 300nm scale.

The principle also works with wavelengths in the EUV, as used to produce the 5nm transistors. The institute developed its own beam source for this purpose, the FS5440. This is based on a gas discharge, and can generate the required radiation at 13.5nm wavelength. It is also much more compact than the laser-based EUV source used in large-scale industrial facilities.

'There are three main cost factors in EUV technology,' continued Danylyuk, 'the point of source; the optical system, which is extremely expensive and technologically advanced in the large scale; and, of course, the positioning system, which places high demands in the nanometre range. We thought that smaller laser sources would be the best thing. We are basically happy to use any kind of source, depending on customer requirements, but we believe our own plasma source to be the cheapest.' →


Apple

The iPhone 12 features the world's first processor built from 5nm transistors, thanks to laser technology

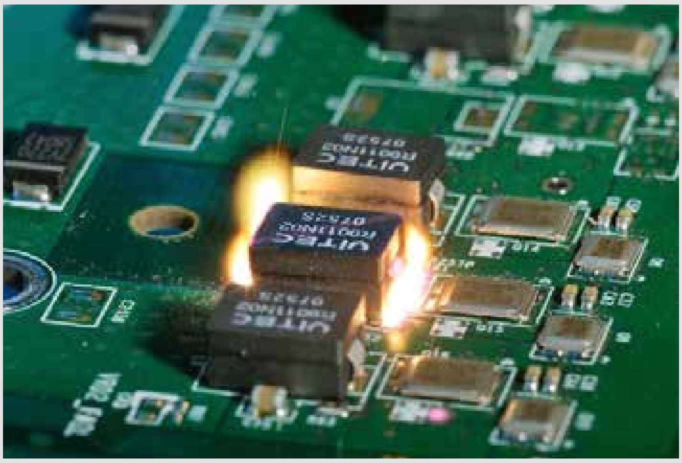
Next-generation urban mining

Fraunhofer ILT has spent the past four years heading up the completed EU project ADIR, which saw lasers being used to process electronics at the end of their lifespan.

The project was launched with the aim of developing a completely new, sustainable and automated method of recycling electronic devices by disassembling them and recovering the valuable raw materials they contain.

It's eight partners from three countries sought to reduce the EU's dependency on natural resources, cut the need for costly imports of raw materials, and demonstrate technologies for inverse production.

The new recycling concept focuses on the elements tantalum, neodymium, tungsten, cobalt and gallium. Found in virtually every modern electronic device, these metals are valuable due to their scarcity, their cost – which in some cases is close to €250/kg – and the tremendous difficulty of recovering them from used electronic devices in a cost-effective way.



Fraunhofer ILT

Lasers can recover valuable raw materials from end-of-life devices

The disassembly method relies on an intelligent combination of laser technology, robotics, vision systems and information technology. Lasers are used to perform key tasks such as identifying what each component consists of, as well as desoldering or cutting components out of the board in a fast, non-contact process.

The procedure was proven to be an efficient way to recover strategically important materials of high economic value on an industrial scale. 'We disassembled around 1,000 mobile phones and more than 800 large computer printed circuit boards, from which we recovered several kilograms of components for recovery,' confirmed ADIR's manager Dr Cord Fricke-Begemann. 'We were able to gain between 96 and 98 per cent of the tantalum.'

With the project now being completed and the concept's economic viability proven, the partners have already attracted interest from industry – having found an initial set of partners willing to put their methods into practice, while continuing to seek further candidates.

The advantages of the new recycling concept go beyond a more efficient use of raw materials. According to Fraunhofer ILT, it has the potential to reduce Germany's dependence on shipments of raw materials from other regions, by offering new opportunities to introduce inverse production technologies. These are required to establish closed material cycles for a future sustainable economy.

There is still room for improvement in the concept, however. According to the project partners, smart automation concepts could be used to speed up the dismantling processes for the housing of mobile phones to get access to the printed circuit board, the battery and magnetic components.

→ Masks or mirrors?

Transmission masks were used as an alternative optical scheme to reduce the amount of mirrors required in the system.

'We worked on a simpler scheme, using transmission masks not as expensive as mirrors,' said Danylyuk. 'We developed these in-house and it means we can use maybe one or two mirrors in the system, not nine. This is not necessarily as scalable as using reflective masks, but if you are an SME going for smaller volumes, this approach could work. The mask is positioned in the vicinity of the wafer, and we can demagnify the structure by a factor of two.'

In terms of cost, while Danylyuk acknowledged that, while it may never reach the thousand-dollar mark, the system under development will still be significantly more accessible than those currently available. 'I think we will be looking at low six numbers,' he said. 'It depends on the requirements on the source side.'

Discussing the challenges of working toward such a technology – which has been in development at Fraunhofer ILT for almost 10 years – Danylyuk said: 'It's probably hard to go to the resolution of 5nm and below with this technology, but we are looking at a sub-20nm scale already, and whether SMEs need such a small resolution. It should be scalable to 10nm but it's challenging, both from a mass-manufacturing and a positioning point of view. Systems have to become more expensive if you want to drive to single nanometre precision. Somewhere we need to make a cut and say "that's perhaps not what SMEs would need anyway".'

An additional challenge for the institute came with the positioning of the mask. 'We had to position it in a sub-millimetre distance to the wafer, and make sure that the distance is maintained over the full wafer size,' said Danylyuk. 'So we developed a technology for maintaining dynamic distance. Our system is currently working with 100mm wafers, and there is no reason why it cannot go larger, but the medium size is what many of the SMEs are comfortable with, and there is a lot of technology available for this wafer size.'

Ready and waiting

So, how do SMEs get their hands on this technology? 'Everyone is welcome to use our facility to test this technology,' said Danylyuk. 'Depending on the end-use, we can also speak with our partners about how

'Fraunhofer ILT is developing technologies for the production of nanostructures that start-ups or SMEs can also afford'

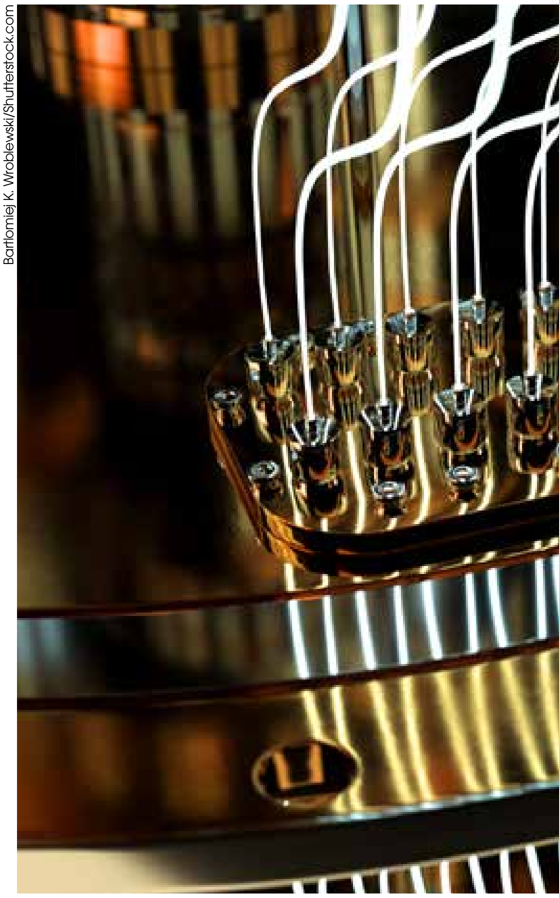
to bring the technology to the market. This way, people can get an idea of whether it is suitable for them, and what kind of effort is needed to bring it into their facility.'

It is also worth noting if, after taking these steps, SMEs still feel that the technology is out of their reach, there are other options available. 'If the cost is still too high, they could consider using far ultraviolet (FUV) as the laser source,' said Danylyuk. 'It uses a similar technology and the same type of approach that we use in EUV, but with FUV – and this may not give you the sub-10nm structures, rather 100 to 150nm – the technology is more scalable by using commercially available UV laser sources.

'So, for people who may only need to use structures on the scale of under 200nm, with different materials, we can offer the development of lithography-based UV, and also direct laser structuring technology.' EO

Photonics' quantum quest

Keely Portway looks at some of the latest developments in quantum science, and what they could mean for the commercial space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Quantum science has prompted much excitement in recent years, promising benefits such as a scalable platform for communication and information processing tasks.

Much of the work in quantum photonics has historically been behind the scenes in research laboratories and academic institutions. But, there has been a huge amount of investment in recent years to help deploy quantum technology into commercial applications such as computing, communications and sensing.

The UK and Europe have large quantum funding programmes. The European Commission's quantum flagship programme launched in 2018, with the commision promising to contribute €1bn of investment over 10 years. The UK's national quantum technologies programme (NQTP) launched in 2014, and has already reached the £1bn investment milestone through joint government and industry funding.

Lynn Gladden, chair of the NQTP programme board, explained its strategic intentions: 'Much has been achieved in the first five years of this pioneering programme due to excellent science, extraordinary collaboration and the dedicated UK community. But we must not lose sight of the fact that the science is far from done and significant engineering challenges remain. We must continue to build on our efforts, rather than lose momentum to provide continuity in these challenging times and help the sector to reach its full potential.'

Perfect 10

In line with this, the UK has seen the launch of its largest quantum computing programme to date: the Discovery project. This was launched by a collaboration of nine UK quantum industry organisations and represents a £10m research programme to address the current barriers to commercial quantum computing.

Photonics and quantum systems supplier M Squared is co-ordinating the project alongside partner organisations Oxford Ionics, ORCA Computing, Kelvin Nanotechnology and TMD Technologies, and academic institutes including Glasgow, Strathclyde and Oxford universities, as well as the National Physical Laboratory (NPL).

Graeme Malcolm, M Squared CEO and founder, explained: 'Cross-sector investment is proving critical for progressing the UK's quantum computing capabilities. Innovation is a journey and we are on a collective mission to help tackle the world's most pressing problems, from climate change to healthcare. Together we are commercialising novel science. Innovation and the development of new technology is central to our approach.'

> 'We must not lose sight of the fact that... significant engineering challenges remain'

At present, the consortium believes that there are several viable approaches to commercialising quantum computing. The project will specifically address three methods enabled by photonics: neutral atom, ion trap and optical qubits. These approaches represent the state-of-the-art in demonstrated hardware; however, the consortium acknowledges that there are still a number of barriers to commercial deployment, such as the challenge of increasing both qubit fidelity and qubit scalability.

A commercial breakthrough

The programme is designed to demonstrate a shift from fundamental, academic activity to scalable, commercial implementations.

Malcolm explained: 'The project will help the UK establish itself at the forefront of commercially viable photonics-enabled quantum-computing approaches. It will enable industry to capitalise on the government's early investment into quantum technology and build on our strong academic heritage in photonics and quantum information. The coming era of quantum technology will play a major, transformative role in both the economy and society alike.'

So, what could this role look like? It is clear that 'quantum' is something of a buzzword, but what is it about this technology which, at its heart, harnesses the behaviour of tiny particles, that creates such excitement?

For Gladden, this is obvious: 'These remarkable technologies,' she said, 'are an integral part of the UK's future digital backbone and its manufacturing base that the nation requires, unlocking innovation across sectors to drive growth and help

'These remarkable technologies are an integral part of the UK's future digital backbone'

build a resilient, prosperous, secure nation.'

Malcolm is of a similar mind. 'Quantum technology,' he said, 'has the potential to completely transform everything we do from a societal and scientific perspective. It could open up entirely new possibilities and ways of working.'

While he believes that we are beginning to see more commercial applications of this technology, the next stage in its development is to focus on scaling-up production and bringing it fully into the commercial arena.

Gravity check

This is something that M Squared has been working toward, and has developed a number of devices for use in commercial applications. One of the first, in 2017, was its quantum gravimeter for the measurement of gravity. This, believes Malcolm, can help pave the way for new applications in many sectors.

The project was co-funded by Innovate UK under the NQTP programme, and the company worked with Professor Kai Bongs' group at the University of Birmingham.

Malcolm explained: 'A quantum gravimeter can detect and measure atomic interference, a manifestation of wave-particle duality that matter can display when it is in a quantum state at temperatures just above absolute zero. It uses quantum technology to bring precision to gravitational measurements and the detection of gravitational fields of hidden objects.'

Among the economic, social and environmental benefits that such a device could bring in the future, Malcolm envisages applications in several sectors 'from the detection of new oil and gas deposits, surveying unknown underground infrastructures such as pipes and cables, even monitoring the water table,' he said. 'If we can transfer the technology into accurate seismic mapping, it could be used to predict natural disasters, from avalanches and volcanic eruptions to tsunamis.'

In 2018 the company developed what it believes was the UK's first quantum accelerometer for navigation, alongside a team from Imperial College London.

This is a self-contained navigation system which sends and receives signals from satellites orbiting the Earth. It does not rely on any external signals such as global navigation satellite systems (GNSS), including GPS.

Lighting the way

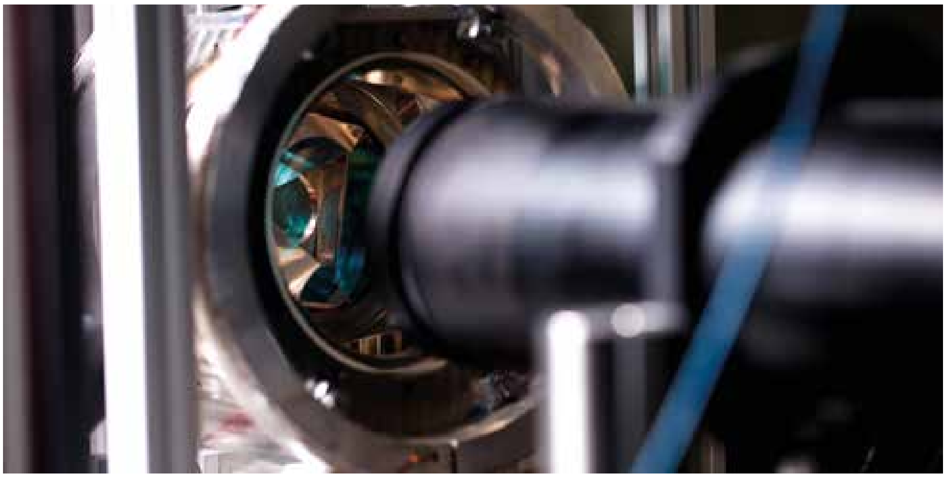
Malcolm sees this as important because satellite signals can become unavailable if there are blockages from tall buildings. Systems relying on GNSS can also be jammed, imitated or denied – preventing accurate navigation. The new system uses quantum mechanics to describe how the atoms move when they are ultra-cold. As the atoms fall, their wave properties are affected by the acceleration of the vehicle. Using an 'optical ruler', the accelerometer is able to measure these minute changes very accurately. To make the atoms cold enough, and to probe their properties as they respond to acceleration, very powerful lasers that can be precisely controlled are required.

Meanwhile, the company's strontium lattice clock was designed to create the world's first commercially available and →

M Squared

Using an 'optical ruler', the accelerometer is able to measure minute changes very accurately

M Squared



The quantum gravimeter, launched in 2017, could help pave the way for new applications

fully integrated optical frequency atomic clock. It is designed to be compact, transportable, easy to use and based on optical lattice technology. It will achieve frequency uncertainties below 10-17, which is considered to be a level unprecedented on the global market.

Some other projects have already been brought to market via the NQTP's Quantum Enhanced Imaging Hub. These include a correlated photon pair source and a photon counting camera for use in research activities; fluorescence imaging technology of molecular processes with impact on medical research; and a gas sensing lidar for fast and accurate leak detection.

Malcolm said: 'Introducing devices such as these to the commercial market is a significant step towards bringing quantum technology into the real world. The huge promises of quantum technologies are already starting to become tangible.'

Halfway there

Quantum technology work has also continued at pace, with the European Commission's quantum flagship programme now at the mid-point of its 'ramp-up' phase. The programme has amassed a number of projects using quantum technology in different applications.

There are currently four projects in the field of communications, with the Civiq project focusing on telecommunications. Specifically, on cost-efficient, high-integration and high-performance quantum communication technologies to deploy continuous-variable quantum key distribution (QKD) into the optical telecommunication network infrastructure.

Civiq gained funding from the European Union's Horizon 2020 research and innovation programme, and brings together 21 partners, including those from major telecoms, integrators and developers of QKD.

Photonic integration circuits (PICs) are becoming more widely viewed as a key technology for this work. Recently, Spanish SME fabless company and project partner, VLC Photonics (now part of Hitachi High Tech), designed an Indium Phosphide photonic integrated circuit (PIC) specifically for secure quantum communications in the network.

Tip the scales

As in the UK, reaching scale economies is a key ingredient when it comes to meeting the growing demands for quantum applications. Therefore, exploiting semiconductor photonic integration technologies could help to bring strategic opportunities for chip-scale module fabrication, as well as supporting design innovation.

VLC is actively involved in the Civiq project, facilitating the transformation

'The huge promise of quantum technology is already starting to become tangible'

of a fairly bulky optical system that was developed in a laboratory into a PIC layout. This is specifically in a standard 4x6mm^2 cell-size, in order to be flexible enough to satisfy the different requirements from QKD system partners. The chips can then be fabricated through a JePPIX multi-project wafer of the InP foundry of Fraunhofer HHI, another partner of the project.

The first generation of continuous-variable QKD transmitter was devised by system partners Instituto de Ciencias Fotónicas (ICFO), Centre National de la Recherche Scientifique (CNRS), Max Planck Institute for the Science of Light (MPL), Technical University of Denmark (DTU) and Huawei Technologies, together with Fraunhofer and VLC.

It consists of a low-linewidth laser and the modulator PIC, which includes a high extinction electro-absorption modulator, an IQ modulation scheme and a variable optical attenuator. The compact design provides a compromise between system complexity, redundant optical paths for monitoring the performance and electrical paths distribution for driving the components.

After VLC has provided the chip design and Fraunhofer has fabricated it, the modulation system of the transmitter will be characterised by VLC, ICFO and CNRS to consider its functionalities as an independent component device.

The next stage will see the integrated narrow linewidth laser, currently being developed by Fraunhofer, integrated in the transmitter. It can then be used in continuous-variable QKD systems developed within Civiq to meet network security demands.

In other news

Other communications projects under the flagship programme have achieved breakthroughs towards high efficiency and multiplexed quantum memory technologies, enabling the storage of quantum information, quantum money, QKD, digital signatures and secure quantum cloud computing. They have specified, modelled and validated construction technologies for three different types of quantum random number generation, and they have developed advanced components systems for quantum communication for use in several different areas, including QKD and quantum networks.

There has also been a great deal of work on quantum in the fields of sensing and metrology, with four current projects taking place. One of these has already helped towards the development of quantum sensors based on NV-diamond centres, for applications such as in the automotive industry, and medical instrumentation (Asteriqs). Another project has made advances in quantum metrology and sensing through microelectromechanical systems (MEMS) technology using five different types of sensors, as well as innovative integration and packaging technologies (Macqsimal).

A third project has achieved homogeneous layers of ultra-shallow NV centres to build sensors that will enable much safer and more accurate medical imaging (Metaboliqs). The fourth has made progress toward the next generation of extremely accurate integrated and compact optical quantum clocks (Iqclock).

A further 12 projects are currently under way, spanning the fields of computing, simulation, basic science and co-ordination of flagship activities. **EO**

Fibre lasers help manipulate atoms to make quantum inertial sensors

The gradiometer team at the University of Birmingham have developed the World's most portable quantum gravity gradiometer, with NKT Photonics' Koheras fibre lasers one of the keys to success when making these compact quantum instruments

The progress made in atom manipulation over the last two decades has allowed researchers to use the quantum properties of matter to make accurate inertial sensors. The best sensitivity in absolute gravimetry comes from quantum sensors, which joins the clocks for accurate measurements given by quantum instruments. Other types of quantum sensors make highly accurate measurements such as rotation, acceleration, magnetic field, or light.

Quantum instruments are built according to the recipe: a sensor head, where the atoms are kept in an ultra-high vacuum environment to be interrogated; magnetic field environment, made of coils and magnetic shields to control the magnetic field applied on the atoms; a laser system, to cool and manipulate the atoms through the different steps; a microwave chain, to generate the frequencies required for the laser system; and a controller, to define the sequence and collect the data.

Using quantum gravity gradiometers to measure density fluctuations

Gravity gradiometers are used to map the underground density anomaly by measuring the gradient of gravity, which gives the same information as gravity with less signal at long distances but more sensitivity to density fluctuations.

To do so, the vertical acceleration of two spatially separated clouds of cold atoms are put in a quantum superposition and recombined by the same interrogation laser. This allows the suppression of common-mode noise between the two clouds, which allows gradiometers to perform measurements in noisy environments such as onboard vehicles.

The quantum gravity gradiometer is the preferred choice for industrial transfer because quantum instruments demonstrate high performance and common-mode suppressed gradiometers can perform measurements in different environments.

The University of Birmingham leads the UK Quantum Technology Hub for Sensors and Timing and has developed 79 collaborative projects with the industry. One of the major goals is to develop compact field quantum gravity gradiometers with a technology readiness suitable for industrial development.

Atom interferometry requires fast frequency modulation, a narrow linewidth, and low noise

The quantum gravity gradiometer of the University of Birmingham is based on cooled Rubidium-87 atoms. A cloud consisting of 108 atoms is cooled and trapped by laser beams. The cloud is cooled through different steps, first via magneto-optical trapping, then by performing optical molasses to reach 4 µK. To cool the atoms, the laser frequency is red-detuned from the atomic transition.

For interrogation, vertically aligned laser beams put the atoms into a quantum superposition state. Then, after an evolution time, they are recombined by laser pulses (of a few µs).

The output state of the interferometer, read by fluorescence, depends on the ability of the laser frequency chirp to compensate for the changing Doppler shift induced by the acceleration of the atoms in freefall.

As the laser frequency must be kept stable, the laser seed is (text removed) locked to a rubidium transition using a spectroscopy cell. The laser intensity, the laser

BoostiK linecard

BasiK MIKRO

linewidth, and the laser frequency directly impact the interferometer phase, so the laser system needs to be as good as possible in order not to add extra noise. The University of Birmingham partnered with Photonic Solutions in the UK to supply NKT Photonics' Koheras BasiK E15 fiber laser as the laser seed for their interferometer. The fast frequency modulation of up to 8GHz, sub kHz linewidth and low phase and relative intensity noise characteristics of the laser were all critical to the performance of the of the interferometer.
The instrument requires a fast frequency modulation (100 MHz in 1 ms) and a narrow linewidth (1 kHz). Moreover, the polarisation extinction ratio must be high, as the atomic transition efficiency depends on the polarisation.
Another driving force in the design of the instrument was portability and the telecom technology of the Koheras BASIK E15 and the 2 W Koheras BOOSTIK amplifier module allow for a compact, robust, and transportable instrument.

The University of Birmingham are also using more recent cold atoms tools, such as moving lattices. They are investigating how best to interrogate atoms with a large momentum transfer, e.g. using the high-power frequency-doubled laser system Koheras HARMONIK.

Compact systems enable more applications

The current field gradiometer from the University of Birmingham is the world's most portable quantum gravity gradiometer, designed to detect under-surface. This instrument shows a useful application for civil engineering for non-destructive underground mapping. It is already in industrial transfer process with the UK **EO**
www.photonicsolutions.co.uk/product-detail.php?prod=5935

Sensors go quantum

Gemma Church explains how Hübner Photonics is helping to put pieces of the puzzle in place for next-generation novel quantum sensors

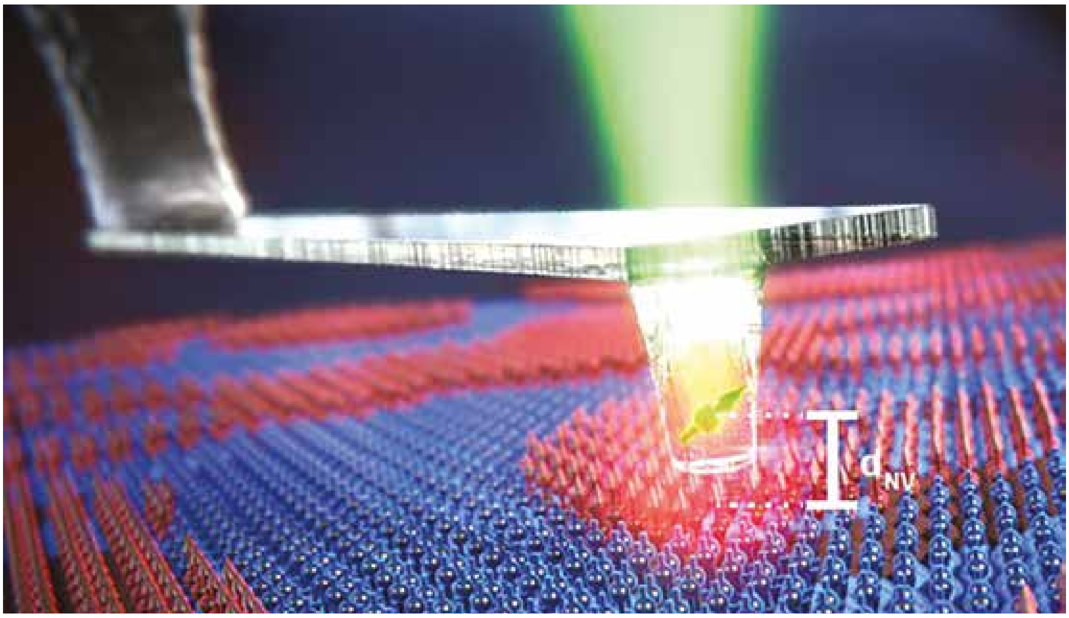
Sensors are a staple of modern technology, collecting the swarms of big data now fuelling our devices and connecting the internet of things (IoT). These sensors typically rely on physical and chemical effects to transform a measured quantity into an electrical signal. Now, advances in quantum sensors are forging the way for new, innovative sensing technologies.

Dr Niklas Waasem, regional sales manager and application specialist at Hübner Photonics said: 'It is expected that quantum sensors will be used for many applications in the future, for example, building precise gyroscopes for self-driving cars, or brain-machine interfacing via precise magnetic-field sensing on the head.'

In essence, quantum sensors rely on the behaviour of subatomic particles, zooming down to the atomic scale where classical physics breaks down and the rules of the quantum world take over.

First-generation quantum sensors are already used in many commercial applications such as nuclear magnetic resonance spectroscopy and magnetic resonance imaging.

However, recent advances in quantum technologies are taking things one step further, opening up a world of possibilities. These next-generation developments provide 'higher sensitivity and resolution, and new measurement modalities which are not reachable with classical sensing techniques,' according to Dr Waasem. 'Many techniques are based on the measurement of the behaviour of single quantum states. The evolution of these states can be extremely sensitive to external properties.'



Courtesy of the Quantum Sensing Group at Basel University

An artist's rendering of an all-diamond tip containing a single-electron spin quantum sensor at its apex. The spin is used to measure the magnetic field at a distance of dNV ~20 nm over a sample surface, where dNV defines the ultimate imaging resolution of the approach

Quantum gravimeters, for example, are one type of quantum sensor. They provide an unprecedented level of sensitivity to determine and detect underground structures, such as voids or cavities. This technology could have major implications in the construction industry, which currently relies on expensive, time-consuming exploratory digging to survey potential building sites.

Quantum gravimeters use a laser to cool atoms to just above absolute zero. These atoms are then accelerated vertically in a vacuum and then allowed to fall back to Earth. This trajectory is measured, where tiny gravitational fluctuations signal a change in the underground structure.

The technology is also being used to monitor volcanoes, where a network of quantum gravimeters can give far more accurate readings of magma movements under the Earth's crust. And this is just the tip of the iceberg. There are many other quantum sensor technologies under development.

Nanoscale quantum magnetometry

Recently, the University of Basel spin-out Qnami commercialised a quantum microscope system, where specialised diamond tips are used to measure magnetic fields with spatial resolutions on the nanometre scale.

This work has important implications for nanotechnology and electronics, including 'the characterisation of multiferroics and antiferromagnets, which are expected to become key contenders for next-generation electronic devices,' according to Dr Waasem.

Instead of sensing an atom's response to gravity, the quantum sensor detects the Zeeman splitting of a spin state in a magnetic field. Dr Waasem explained: 'Usually, the experiments begin by bringing the quantum centre into a defined state. Afterwards, the state is manipulated using microwaves and the actual sensing begins: the quantum state evolves. After this 'sensing interval' the new quantum state is detected.

'The development of the state depends on the property to be measured, for example, the magnetic field. Thus, by comparing the initial and end state of the quantum centre, one can make conclusions on what external influences it "felt" during the measurement time. This way, these "external influences" can be measured.'

Single-electron spins of NV centres in diamond are an emerging quantum sensor technology for nanoscale applications. These devices exhibit excellent sensitivity and nanoscale resolution for imaging and sensing of magnetic fields and other quantities, including electric fields or temperature. What's more, these diamond tips can detect single-electron spins in cryogenic environments and under ambient conditions. This removes the need for cooling equipment, freeing up these quantum sensors for a broader range of applications.

This is a key step forward. Many of today's quantum sensors are 'bulky and expensive tools,' according to Dr Waasem, who added: 'There are many developments going on in parallel, for example, finding new or suitable quantum centres for certain sensing tasks.'

Research into quantum sensing technologies is focused on several core areas. There are many candidates for quantum centres such as single atoms, ions, molecules, quantum dots, defects in 2D materials, diamond, or other materials, each of which requires further investigation.

This has a knock-on effect where the technologies surrounding the quantum sensor also require development.

Dr Waasem explained: 'With it comes the need to improve techniques for capturing or cooling these quantum centres and techniques for initialising, manipulating, and reading out single quantum states. This drives the development of new lasers and electronics, as well as miniaturisation and finding ways to allow mass production.'

> **"The evolution of quantum states can be extremely sensitive to external properties"**

This is an important point. Quantum sensors rely on the availability of specialised components, lasers, electronics and microscopy hardware. To initialise the spin state of the quantum centre and read it out, for example, requires precisely tailored laser-light pulses. These pulses must work in a defined emission spectrum with fast switching times of under 10ns, and a high on/off extinction ratio.

Until recently, these laser pulses were generated by combining a continuous-wave laser and an acousto-optical modulator (AOM). However, these setups are difficult to align, and the systems they use are bulky, expensive, and sensitive to shocks and temperature inconsistencies.

Laser diodes with direct intensity modulation are an alternative solution, thanks to their modulation capabilities, as well as precise real-time intensity control without the need for an external modulator.

The HTCure technology from Hübner Photonics, for example, enables the production of lasers providing these features and ruggedised micro-optical setups in general, making them suitable for use in harsh environments. This helps Hübner Photonics' partners commercialise sophisticated lab setups.

This is just one example of how the world of quantum sensors is moving into the mainstream. In a recent white paper Hübner Photonics explained how fast low-noise lasers and electronics have supported the commercialisation of nanoscale quantum magnetometers. Further breakthroughs promise to transform quantum sensing technologies into a versatile range of sensor products.

Hübner Photonics will continue to work in this important, dynamic research field, as Dr. Waasem concluded: 'Hopefully, many continued and new collaborations – with research groups, spinouts from quantum labs, as well as industry partners to tailor the performance of our lasers to their requirements – will continue.

'With this, we can enable the development and production of more compact, rugged and reliable high-performance quantum sensors.' **EO**

Cavity ring-down spectroscopy: Optical interruption method opens up MIR spectroscopy applications

Researchers at the VTT Technical Research Centre of Finland have developed optical interruption of a mid-infrared quantum cascade laser, which could cut costs of a sensitive type of spectroscopy

Cavity ring-down spectroscopy (CRDS) is one of the most sensitive types available. It can detect a wide variety of molecules at extremely low levels of concentration, making it suitable for a range of applications from monitoring air quality and atmospheric gases to the detection of harmful substances and medical diagnostics.

Until recently the widespread adoption of the technology has been limited by the costs of both the components and the complexity of the setup. However, the development of a room temperature quantum cascade laser (QCL), and the fall in price of mid-infrared lasers, drivers and optics, means that the scope for the application of CRDS has grown significantly.

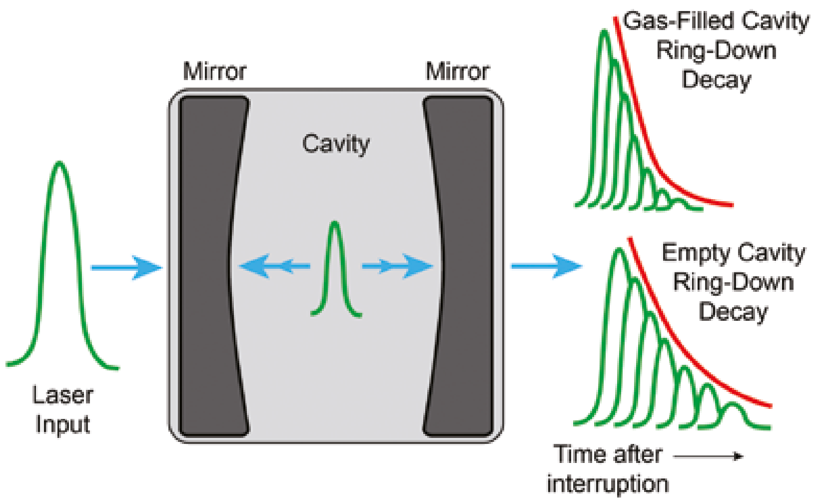
There have also been important innovations in the setup of CRDS.

As a new white paper from Wavelength Electronics explains, the recently-developed method of optical interruption of a QCL for CRDS using a near-infrared laser diode could drive down the costs even further, and most importantly, without impacting the sensitivity or reliability of the results.

Wavelength Electronics

QCL1000 OEM QCL Driver

Wavelength Electronics



Cavity ring-down spectroscopy schematic

CRDS is based on the time it takes for laser light to decay in a high-finesse optical cavity after the light injection has stopped. The laser light is reflected between two high reflectivity concave mirrors with a cavity between them, and when enough light is detected in the cavity, the laser is interrupted, and a ring-down event is started. No mirror reflects light perfectly, and when the light into the cavity is interrupted, the decay of the light leaking can be measured with a detector.

The speed of the decay is accelerated according to the molecules trapped in the cavity, and by comparing the ring-down time with the ring-down time of an empty cavity the absorption coefficient can be inferred, with different molecules having unique absorption coefficients and spectra. The mid-infrared light enabled by the highly tailorable QCL, also known as the fingerprint region of the infrared spectrum, makes CRDS particularly sensitive as it consists of many of the best absorption transitions of some of the most important molecules. It provides a cleaner spectrum and more distinct peaks and troughs for the absorbed sample.

CRDS is also particularly sensitive thanks to the thousands of trips a pulse of light may make between the mirrors during the decay process. This can equate to the light travelling a few kilometres in the multi-pass cavity before it decays, with the long distance travelled in the sample gas ensuring better measurement precision.

CRDS measurements are independent of the stability of the laser itself, because the laser is interrupted. This makes the interruption of the laser one of the most important aspects of the CRDS setup. For the CRDS to be as sensitive and reliable as possible it is necessary to have a quick and clean interruption of the laser.

Jeremiah Hashley, technical writer at Wavelength Electronics, explained its importance: 'The interruption of the laser is one of the most critical parts of the spectroscopy. You want the laser to be interrupted quickly, so that the ring-down decay can start almost immediately after you've started the interruption, and then get a clean exponential decay of that signal. The better your interruption is, the more sensitive your spectroscopy is.'

A poor interruption may lead to either poor detection with oscillations in the decay signal, or even failure to measure the ring-down event at all.

While there are several existing methods for interrupting the laser, each has its own particular disadvantages: fast current modulation of the laser can reduce the light build up in the cavity, creating a poor signal-to-noise ratio and decreasing the sensitivity of the spectrometer; acousto-optic modulators are expensive in the mid-infrared range, and add complexity to the apparatus; and a fast current step requires a fast QCL driver, which is very effective in interrupting the laser, but can also be expensive.

What is required is a way of interrupting the QCL without the excessive additional cost or loss of precision. This is what researchers from Finland have developed with a new design for the optical interruption of a QCL laser in CRDS.

Researchers from the VTT Technical Research Centre in Finland have successfully demonstrated that a fast interruption can be achieved without loss of performance by using a near-infrared laser diode to modulate the QCL on cavity build-up. The near infrared emission quickly interrupts the QCL into the cavity, with a small frequency shift sufficient to interrupt the light in a high finesse cavity.

The results of the optical interruption were found to be comparable with typical current modulation methods of electrical interruptions, albeit at a lower cost, requiring reduced bandwidths from the QCL driver, and increasing the speed with which the QCL driver returns to the original frequency. The reduced bandwidth required of the QCL driver has the potential to reduce the costs and complexity of CRDS, while the potential increased rate of ring-down events means that they can accurately be repeated.

"The less noise you have the better the signal will be, the cleaner it will be, and the easier it will be to detect"

Stability is essential for the proper operation of the lasers and the repeatability of the results. In the Finnish experiment the necessary precision control was provided by Wavelength Electronics' laser drivers: the LDD200 laser diode driver was used to drive current to the near infrared laser diode, and the QCL1000 OEM driver was used to drive the current to the mid-infrared QCL. Hashley described the contribution he thought that Wavelength Electronics' drivers had made to the experiment:

'Wavelength Electronics' laser drivers provide low noise and stable current to the lasers at a relatively low cost. These are high performance drivers with very low noise, and noise is critical when using any kind of spectroscopy setup,' Hashley said. 'The less noise you have the better the signal will be, the cleaner it will be, and the easier it will be to detect.'

Optical interruption is undoubtedly an exciting area of development in CRDS, and an important step in the drive to making CRDS practical and affordable wherever there are potential applications.

But, as Hashley pointed out, this is an ongoing process: 'Using optical interruption allows for quick and clean ring-down events to make the CRDS experiment successful with good detection rates and repeatable results. Reducing the cost and simplifying the experimental setup are driving factors in future research to make this method useful in a variety of applications.'

As the CRDS apparatus is simplified and the costs lowered, without the loss of sensitivity or reliability, an increasing range of applications starts to open up in a wide variety of settings. It seems highly likely therefore, that CRDS will crop up more often in the future, whether with breath analysis in medical settings, greenhouse gases in the stratosphere, or to help counter terrorism. **EO**

EPIC NEWS

EPIC
European Photonics Industry Consortium

News from Epic
By Carlos Lee, director general
www.epic-assoc.com

Epic recruits head of photonics market research

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I have always believed in the importance of access to market analysis to understand a market's ecosystem, the key players and trends. We believe that market reports should not only be accessible to large companies who can afford them, which is why Epic has been providing free reports to member companies. And the interest among members is huge. Every year more than 900 individuals download reports from the Epic extranet.

Given that 86 per cent of our members are small companies, we have provided this feature in one way or another since the creation of Epic. The association's founder, Tom Pearsall, used to produce reports himself, writing about lighting and photovoltaics. We then decided to partner with market research firms to outsource the development of a report or buy existing reports and make them available to members. We also bought reports from firms outside our network, but were very disappointed with the quality.


Tracey Vanik

For several years, Epic has had in its membership companies that help other firms understand markets. For instance, Yole Développement, Tematys, LightCounting, fibeReality and also specific market consultants such as Vision Ventures.

However, many markets of interest to Epic members are too specific, or too niche, to warrant established research firms' time in producing entire reports on them. Epic members also have specific questions that may not be addressed.

This year, Epic will publish a list of 10 market reports. To produce these, our new head of photonics market research, Tracey Vanik, will speak with Epic members to determine what topics and questions they would like to see in these reports. She will work with existing market research firms and consultants, which will research and write the reports, acting as the middle person between the market research companies and our members.

"Vanik will act as the middle person between market research companies and our members"

Tracey has previously worked with TacticalTeam, a sales development company that resolves problematic sales. Before that, she was with RHK, a telecommunication analysis company where she became the chief technologist through her work with emerging optical routed networks, 10GigEthernet, and high-speed component applications. Her forecasts blended emerging components, systems, and applications, coupled with adoption potential.

Vanik likes to say that 'the working Excel spreadsheets were rather ugly, but the refined results were more accurate in contrast to traditional hockey-stick forecasts'. While at RHK, she also worked with several Venture Capital groups evaluating potential investments. You can contact her directly at **tracey.vanik@epic-assoc.com**


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Functionalising complex shaped optics



Dr Kristin Pfeiffer, Pallabi Paul, and Dr Adriana Szeghalmi have developed conformal coating processes for functionalising strongly curved optics

Optical components in numerous applications rely on functional coatings to obtain various levels of performance. Such coatings are used in applications ranging from unique astronomical systems to high-volume devices and consumer products such as eyeglasses, cameras and lidar systems. Many of these functional coatings, including anti-reflection (AR) coatings, dichroic mirrors, beam splitters and filters, consist of multiple layers of high and low refractive index oxides, including TiO_2, HfO_2, Al_2O_3 and SiO_2. According to publicly available information, the global market volume of AR coatings alone is around $4bn and increasing.

Light incident on any surface is partially reflected. These reflections must be suppressed to enhance the performance of optical devices. In a multilayer AR coating, there is a reflected beam at each interface. The interference of these reflected beams enables the propagation of light to be manipulated as desired.

Destructive interference makes it possible to nearly eliminate the reflection from transparent surfaces, such as glass or plastics, for specific spectral ranges. Therefore, the coatings must have precisely defined film thickness compositions; individual layers have thicknesses in the range of a few nanometres up to several hundred nanometres, depending on the target AR property.

Plastic optics pose a challenge

Thermoplastics such as poly(methyl methacrylate) (PMMA), polycarbonate and polystyrene are widely used for producing various optical elements such as freeform surfaces, aspheric lenses, Fresnel lenses and many other diffractive optical elements. In general, these substrates can be manufactured in complex shapes with significantly reduced cost compared to glass substrates by the injection moulding method. Thanks to being lightweight, optical components made of plastics are an important substitute for glass optics.

PMMA in particular, which has a high transmission (approximately 92 per cent) in the visible spectrum (400 to 700nm), excellent hardness, and a high Abbe number, is extensively used in precision optical manufacturing. However, precision coatings on plastics are rather challenging because of the crack formation and low adhesion of the dielectric coatings to the polymer surface. Since the parameters of optimised processes for glass substrates cannot be directly transferred to plastics, explicit polymer-specific research is required to functionalise these materials.

Existing approaches

Different deposition methods based on wet chemistry, physical vapour deposition and chemical vapour deposition techniques have been applied on PMMA and other plastic substrates to try to enhance their optical functionalities.

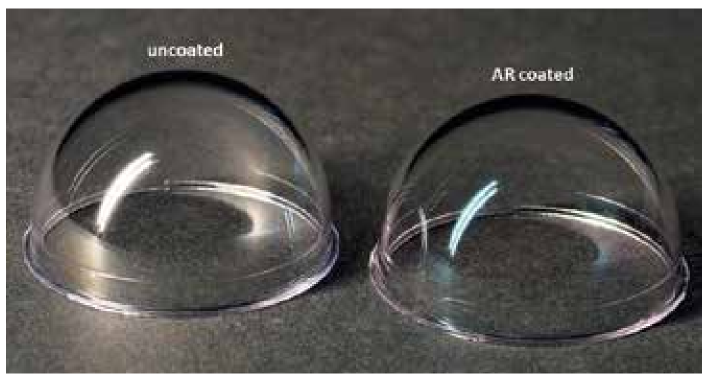
These include the sol-gel method, ion- and plasma-assisted evaporation and sputtering processes, and plasma-enhanced chemical vapour deposition.

Previous research also suggests that applying a special direct current glow discharge plasma pre-treatment, or creating a vacuum ultraviolet protection layer by boat evaporation prior to the plasma ion-assisted depositions, can improve the adhesion of thin films on PMMA.

Several other approaches, involving moth-eye structures by plasma-assisted etching, full wafer and roll-to-roll nano-imprint lithography (NIL), layer-by-layer assembly of hollow silica nanoparticles and porous quarter wave coating with colloidal nanospheres, have also been demonstrated for AR coatings on plastics.

The environmental stability of nanostructured AR coatings however is rather limited, restricting their usage to the inner surfaces of optical systems.

Optical components with complex shapes



Uncoated (left) and AR-coated dome (right) having significantly reduced residual reflection from each surface of the dome

Our solution

Nowadays the shape of numerous optics is becoming increasingly complex. For such strongly curved substrates, atomic layer deposition (ALD) becomes the most promising coating technology to achieve a conformal coating with excellent thickness control[1]. With it, multilayer thin film coatings can be applied to manipulate the transmittance and reflectance of the optics based on the optical interference effect between the reflected beams at each interface.

We have developed various high and low refractive index oxides that can be applied widely in optical coatings. Thermal and plasma-enhanced ALD (PEALD) processes have been optimised successfully for Al_2O_3, TiO_2, and SiO_2 materials for coating plastics. We have also analysed the influence of process parameters on the uniformity, optical and mechanical properties, and environmental stability of the resultant coatings.

It is challenging to optimise ALD processes towards adhesive and crack-free films on PMMA. A low deposition temperature at around 60°C is preferential for temperature-sensitive PMMA substrates, as the polymer starts degrading at around 80°C. Additionally, these films should be homogeneous, uniform in thickness, and dense for application in optical coatings.

We found that employing longer purge times and extra pump down steps during the creation of a thermal Al_2O_3 protection layer, along with the proper tuning of plasma parameters, resulted in adhesive and crack-free films on PMMA substrates. Upon achieving the desired optical properties of the films – dispersion behaviour, optical losses and mechanical stability – a possible route for optical coatings for the visible spectral range was established via thermal ALD and PEALD processes[2].

While uncoated PMMA substrates have a reflectance of nearly 8 per cent in the visible range, this has been reduced to below 1.2 per cent for the 420 to 670nm spectral range by applying a double-sided AR coating with an average reflectance of 0.7 per cent[2]. The optimised ALD coatings show good adhesion

"Our conformal coatings can be applied on a range of highly curved glass and polymer substrates"

to the PMMA substrates even after a climate test in a high-humidity and high-temperature chamber. These results enable a possible route by ALD to deposit uniform, crack-free, adhesive and environmentally durable thin film layers on sensitive thermoplastics such as PMMA.

Subsequently, the 3D conformal growth of ALD films was exploited on PMMA domes – highly demanding complex shaped substrates. Moreover, both surfaces can be coated simultaneously by ALD, which compensates for the relatively slow growth rate in ALD technology. ALD provides the flexibility to functionalise arbitrary surface geometries, even without having any in situ monitoring or complex substrate rotation.

The lower of the two pictures shows the visual appearance of an uncoated and an AR-coated dome, with the reflections clearly visible at both outer and inner surface. This AR coating is designed to maintain a blue colour independent of the viewing angle[3]. The reflectance becomes faint after coating. In order to make the substrates nearly invisible, a higher performance AR functional coating can be applied. Such broadband and angle insensitivity, however, rely on ultra-low refractive index, nanoporous or nanostructured top layers[4], which are relatively fragile. The reflectance is reduced to below 0.5 per cent in the visible spectral range at 0° to 45° angles of incidence. Even at steep viewing angles, the reflectance must be very low.

Conclusion and future steps

Our conformal coatings can be applied to various optical specifications on a range of substrates, both glass and polymer. They can be realised for highly curved substrates such as freeform components, ball and half-ball lenses, domes and high aspect ratio nanostructures such →

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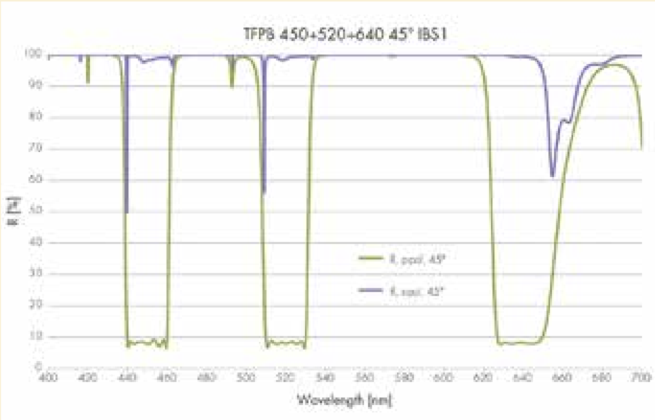

Trichroid Thin Film Polarisers

Laser Components began production of optical coatings in 1986. Since production began, we have been committed to consistency, quality and constant development. We now have E-beam, IAD and IBS technology and are well equipped for challenging custom coating designs tailored to specific applications.

Our latest development is a trichroid thin-film polariser (TFP), which makes it possible to simultaneously separate the polarisation of three wavelengths. These optics have excellent reflectivity for s-polarisation in blue (450nm), green (520nm) and red (640nm) light, with p-polarisation being almost completely transmitted. These TFPs may be used to combine linearly polarised laser beams from different sources of the same or different wavelength, or conversely to separate unpolarised light at three wavelengths into the two polarisations.

This complex and challenging design is produced using our ion beam sputtering (IBS) facility, which enables particularly compact layer structures with good reflectivity.

Further information: www.lasercomponents.com/uk/request/request-form-laser-optics/

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Coating service capabilities from Spectrogon

Spectrogon's Coating Service capabilities (400-20, 000nm) for OEM customers include:

- **Antireflection (AR) coatings:** Single and multilayer coatings; Broadband AR coatings; Extended BBAR coatings; Laser line AR coatings and dual wavelength AR coatings.
- **High reflective coatings**: Metallic high reflective coatings; Dielectric laser line HR coatings; and dielectric HR coatings.
- **Beam splitter coatings**: 400-20, 000nm

Send us your requests at:
www.spectrogon.com/contact-us/requests/coatings

→ as gratings or photonic crystal fibres.

Domes especially are difficult to coat with conventional technologies, due to their highly curved convex outer surface and deeply concave inner surface. Hemispherical and hyper-hemispherical dome-shaped windows are applied to protect equipment for optical remote sensing, such as automotive and terrestrial lidar systems, and optical communication, such as laser communication systems. Wide-angle dome ports are ideal for applications in surveillance and security camera systems, as well as submersible camera systems for underwater photography and underwater photogrammetry. For all these purposes, the dome-shaped windows act as an additional optical element, for which high transmission is required in the desired wavelength range. This high transmission can be realised by conformal AR or filter coatings.

The perspective of ALD for such optical applications is promising, since high efficiency on complex substrates has been demonstrated; however, scalability and throughput are critical aspects towards future applications. In the next phase, we will gradually scale up the optimised ALD technology and evaluate the application in industrial use with prospective project partners. Higher throughput and process transfer will be evaluated in corresponding industry-related ALD batch tools. Further challenges involve improving the mechanical stability of optical components, and coating development for various polymer materials. **EO**

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MANUFACTURING AND SERVICES

Picomaster-H range of lithography systems

Sitech supplies the new Picomaster-H range of high resolution, single-beam direct-write lithography (SB-DWL) hologram and lens mastering systems from dutch firm 4Pico Litho.

The systems can write any kind of micron or sub-micron structured surface directly onto photoresist plates over areas up to 500 x 500mm (8.5 x 8.5in) in size.

The PicoMaster-H is the ultimate direct-write lithography mastering tool for small and medium formats, such as security holograms and OVDs; diffractive 'rainbow' patterns; Fresnel lenses; Fresnel 'bas relief' images; zero colour 'platinum' patterns and images; micro-lens arrays; and 2.5D, greyscale, optical micro-structures.

The PicoMaster-H turnkey systems require no additional and expensive options to expose all kinds of 2.5D, greyscale, seamless, micron and sub-micron-scale structured surfaces.

Each system comes with a 405nm laser, 225nm high-resolution mode, professional 4,096 greyscale mode, three software-selectable spot sizes/resolutions, an optical real-time auto-focus system, and PicoHLD, a user-friendly hologram, diffractive pattern, and Fresnel lens design and composition program. Sitech's Pattern Generator, which generates random shape and gradient 'pillars of light' patterns for optical security and packaging applications, is also present.
www.sitech.co.uk

LASERS AND DIODES

PT403 picosecond laser

Ekspla has introduced a new tunable wavelength picosecond laser that provides from 210 to 2,300nm output wavelength from one box.

The new PT403 series laser integrates a picosecond 1KHz repetition-rate DPSS pump laser and optical parametric generator into a single housing. Compared with other two-box systems, the PT403 delivers an almost two times smaller footprint, much shorter installation time, better stability and other substantial benefits.

The all-in-one-box solution features all components in one compact housing, for better overall stability as it eliminates all causes for misalignment between the separate units of the pump laser and optical parametric generator.

The PT403's optical design is optimised to produce low divergence beams with moderate linewidth (typically $<8\text{cm}^{-1}$) at approximately 15 to 20ps pulse duration. Featuring 1KHz repetition rate, the PT400 tunable laser is a versatile cost-efficient tool for scientists researching various kinds of disciplines.
www.ekspla.com

Cobolt 05-iE single frequency laser

Hübner Photonics has introduced the Cobolt 05-iE, an all-integrated model of compact and powerful single frequency lasers across the wavelength range 355 to 1,064nm.

In the series, all control electronics are contained in the laser head, eliminating the need for an external controller. The all-in-one Cobolt 05-iE means less complexity, fewer parts and an overall significantly reduced system footprint, thus simplifying the use and integration of the laser both for system integrators and researchers.

All Cobolt lasers are manufactured using HTCure technology and the resulting compact hermetically-sealed package which provides a very high level of immunity to varying environmental conditions, along with exceptional reliability.
www.hubner-photonics.com

PHOTONIC INTEGRATED CIRCUITS

OptoCplrLT glass chip

Optoscribe has released the OptoCplrLT, a monolithic glass chip for low-loss coupling to silicon photonics (SiPh) grating couplers.

OptoCplrLT is designed to overcome fibre-to-SiPh photonic integrated circuit (PIC) coupling challenges to enable high-volume automated assembly and help drive down costs. Created using Optoscribe's high-speed laser writing technique, OptoCplrLT features low-loss light turning curved mirrors, which are uniquely formed in the glass, to direct the light to or from SiPh grating couplers. This prevents the need for bend-tolerant fibre solutions, which are often expensive, challenging and have some significant limitations in size and profile.

To help address footprint challenges, OptoCplrLT has a low-profile interface of less than 1.5mm in height, which allows compact interface layouts that alleviate packaging constraints. It is also compatible with industry-standard materials and processes; for example, the glass chip has a coefficient of thermal expansion matched to the silicon chip, helping to maximise performance.
www.optoscribe.com

ANALYSIS, TEST AND MEASUREMENT

Vector line of display view angle testers

Gamma Scientific has introduced its Vector line of display view angle testers. The colour testers integrate multiple spectroradiometers into a compact module to provide accurate, high-speed, and reliable display measurement from multiple angles simultaneously. Solutions are available with three, four, five and six angles, including a flicker meter.

This solution for display measurement provides laboratories, R&D and production lines the ability to gain more insight into their products with a single snapshot, as well as see how their products will be perceived by the human eye in real-life conditions. This will enable complete spectral analysis to help characterise displays and improve display design, development and quality control.

The standard GS-1164 four-angle spectroradiometer from Gamma Scientific has the capability of delivering simultaneous measurements from 0°, 30°,45°, and 60°. It lets manufacturers optimise product quality, while increasing efficiencies and decreasing costs.
www.gamma-sci.com

Phemos-X C15765-01 semiconductor failure analysis system

Hamamatsu Photonics has developed a new semiconductor failure analysis system called the Phemos-X C15765-01, a single unit that uses visible to near-infrared light to analyse semiconductor defects.

This is possible thanks to a newly mounted multi-wavelength laser scanner that applies the company's optical design technology. Using multi-wavelength light efficiently enables the high sensitivity and high resolution essential for localising semiconductor failures. This will improve failure analysis efficiency in diverse semiconductor devices that will be in high demand, such as devices whose circuit line width keeps shrinking, as well as power semiconductors that control electrical power more efficiently than ordinary semiconductor devices.

The Phemos-X is available from 1 April.
www.hamamatsu.com

LW-series of beam collimators

Optical Surfaces has released a new series of beam collimators designed for modulation transfer function (MTF) testing of optical systems.

Benefiting from a lightweight design and new assembly technique, the LW-series of beam collimators combine high stability, high performance and short delivery time, all at a competitive price.

The series incorporates a low expansion off-axis parabolic mirror, manufactured to better than lambda/10 p-v surface accuracy. The optics within the beam collimator are secured by the use of stress-free mounts and come pre-aligned for optimum performance.

The off-axis design of LW-series beam collimators produces no central obscuration, ensuring highly efficient transmission is obtained.
www.optisurf.com

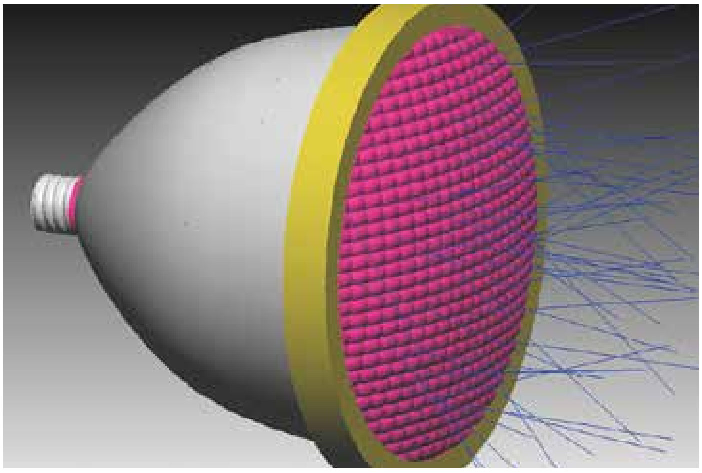
SOFTWARE

LightTools illumination design software 9.1

Synopsys has released version 9.1 of its LightTools illumination design software, which expands LightTools' comprehensive features and workflows for illumination optics design with new tools to model and analyse light detection and ranging (lidar), AR/VR and biomedical systems.

Additionally, version 9.1 introduces a distributed simulation module that increases the speed of computation-intensive ray tracing, as well as improved optomechanical interoperability with Dassault Systèmes' Solidworks 3D CAD software.

The feature and workflow enhancements in LightTools are tailored to help engineers focus on solving complex design challenges and delivering optical systems to market sooner. Solidworks users working on optical designs can expect to speed up source characterisations. Engineers developing lidar systems can more easily perform time-of-flight analysis. And development of advanced applications for AR/VR, displays and medical devices is improved with LightTools' polarisation analysis.
www.synopsys.com



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Clear path to a bigger future

Carlos Lee, EPIC's director general, talks to Koichiro Ikeda, president and CEO of Isuzu Glass

Kochiro Ikeda wants to 'change the mindset' as his company looks to expand beyond Japan

What led to you becoming CEO of Isuzu Glass?
Having graduated in Economics, I worked for a few years for an accounting firm until 2004, when I joined Isuzu Glass as finance manager. I worked in sales and gained a lot of experience in the material development of glass. Between 2007 and 2009, our business expanded considerably, and we set up a factory in China. Unfortunately, our projected markets and sales didn't materialise and in 2014 we were bought out by a venture capital group.

In the previous couple of years, I had put a lot of effort into finding new customers and partners to inject capital into the company, and when we were finally bought out, the VC wanted me to stay on as CEO.

How has the company developed in the last six years?
The workforce has grown to 80 and we now have more than 200 customers, 60 per cent in Japan and 40 per cent abroad. One of our main aims has been to internationalise the company and find more overseas customers. To this end, in addition to our head office and factory in Osaka, we've set up sales offices in Los Angeles and Frankfurt.

We've also expanded or range of products in two main categories: firstly, optical filters for applications in opto-electronics, office automation equipment, photography, lighting and medical equipment; and secondly, glass moulded lenses, which include integrated and micro lens arrays, aspheric lenses, and a variety of other moulded lenses for the medical, sensing, UV LED, laser and 3D printer markets.

What have been your main challenges as CEO?
Until recently Isuzu Glass, like many other Japanese companies, had a closed mentality, and a major challenge has been to change the company culture to make us more open minded about communicating and collaborating with foreign customers. Of course, language is a problem but with our offices in the US and Germany this is less of an issue. What's more problematic is how to change the mindset of the people here in Japan.

"In the near future we'd be interested in collaborating with a larger company in Europe"

What are your plans for Isuzu Glass over the next 10 years?
In order to develop new markets in Europe and the United States, we will increase sales of moulded lenses, improve our development and sales capabilities in optical filters, and expand our speciality glass materials business. Although our manufacturing capacity is not currently so big, we're growing quickly and in the near future we'd be interested in collaborating with a larger company in Europe to find synergies and scale up our manufacturing.

We're particularly impressed with the progress Europe is making with Industry 4.0 and the ongoing digital transformation.

Hopefully, as we're now a member of EPIC, finding a collaborator in Europe will be much easier. EO

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Isuzu Glass's head office and factory is in Osaka, but it also has offices in Frankfurt and Los Angeles