THURSDAY EDITION

THURSDAY, FEBRUARY 18, 2016

SPIE. PHOTONICS WEST | optics.org

PHOTONICS WEST. SHOW DAILY

Startup Challenge
Double Helix has winning in its DNA

Credit: Adam Resnick

Credit: Doug Cody

QCLs and quantum dots among Prism winners

A terahertz source based on quantum cascade lasers (QCLs), cadmium-free quantum dots for display and lighting applications, and laser technology for digital cinema projection were among last night's winners at the annual Prism Awards.

Parisian firm Lytid claimed the honors in the scientific lasers category for its QCL-based "TeraCascade", while UK-based Nanoco Technologies was recognized in the materials and coatings division for its development of cadmium-free quantum dots. Lytid beat off tough competition from high-power laser diode developer Lasertel and KMLabs in its division.

Other Photonics West exhibitors to receive Prisms at the Marriott Marquis Hotel included diode laser firm Necsel, thanks to its collaboration with household name Dolby and digital display specialist Christie on a completely new 3D laser cinema projector. Necsel provides lasers operating at six different wavelengths, creating what is described as a high-contrast, immersive 3D experience. Dolby provides the 3D glasses.

Miniaturized spectrometers are a strong theme at this year's exhibition and Finland's Spectral Engines won in the detectors and sensors category with its tiny wireless infrared analyzer, described as a "spectroscopic lab in your pocket."

Sticking with infrared sensors, another Photonics West exhibitor - First Light Imaging - won for its "C-RED One" short-wave IR (SWIR) camera. Combining mercury cadmium telluride detectors with "noiseless" amplification, it is said to be the fastest scientific low-noise SWIR camera in the world.

Another exhibitor, LightFab, was rewarded for its development of a laser 3D printing system capable of both two-photon polymerization and selective laser etching. The German company beat off competition from Coherent and Onefive in the industrial lasers category, while Biodesy's Delta claimed the Prism for biomedical instrumentation with its "Real Eye Nano" system for eye tracking in MRI scanners.

Liquid crystal polarization gratings from Boulder Nonlinear Systems that are tipped to revolutionize the world of galvos and gimbals in defense and aerospace applications won in the optics and optical components category, and 4D Technology's "Flexcam" – specifically designed to aid the challenges of roll-to-roll process metrology – beat Neaspec's miniature FTIR and Physik Instrumente's precision alignment engine for photonics integration in the "other metrology instrumentation" division.

DON'T MISS THESE EVENTS TODAY

INDUSTRY EVENTS

Basics of laser material processing workshop
(8-10 AM, Room 102, South)

Photonics Industry update
(9:15-9:45 AM, Room 103, South)

Photonics West exhibition
(10 AM-4PM, North & South halls)

Prism Awards for Photonics Innovation, award winners at exhibition

Silicon photomultiplier workshop
(10 AM-12 Noon, Room 102, South)

Startup Alley
(11 AM-1 PM, Room 102, South)

Supply Chain workshop
(1:30-3 PM, Room 102, South)

See the technical program and exhibition guide for more details on daily events. Conference registration may be required. Industry events are open to all registration categories, except where noted.

Read daily news reports from Photonics West online: spie.org/PWnews

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New fibers and diodes set to disrupt laser industry

Advances in photonic crystal fibers and three-dimensional nanofabrication techniques point to a promising future for basic research and applications in laser technology — and high-power semiconductor lasers are in the process of disrupting a fragmented industry, according to speakers at the LASE plenary session Wednesday.

Even 20 years after they were invented, photonic crystal fibers remain a vibrant technology that's promising for a myriad of applications. "You can do many, many things with these fibers," said Philip Russell of the Max Planck Institute for the Science of Light in Germany, who first developed the fibers in 1996, in an interview for the *Show Daily*. "It's up to your imagination."

Conventional optical fibers confine and guide light with total internal reflection. Photonic crystal fibers, however, employ a new mechanism, using a periodic network of hollow channels that surround the fiber's core, which can be either hollow or solid glass. The hollow channels allow for precise control of the light even across large distances.

Such precise control has opened up many potential uses. Fibers with hollow cores enable faster transmission of data, since light travels quicker through air. By converting short pulses of infrared into a bright, broad band of light, solid-core versions of these fibers have led to new kinds of supercontinuum sources, important for a host of uses, such as spectroscopy and microscopy.

One of the most important recent applications of these fibers is the generation of vacuum ultraviolet light, which is immediately absorbed by oxygen in the air. A photonic crystal fiber's hollow core can be filled with gas. By adjusting the pressure of the gas, researchers can tune the properties of the light, such as the group velocity dispersion, traveling through the fiber.

Russell's team is now starting a company to develop these new vacuum UV light sources.

Orbital angular momentum (OAM) can be derived from twisting the channels in the fiber in a helical arrangement, Russell said. The design resulted in previously unexpected dips in transmission spectra, or "globs of light that are sort of stuck between the hollow channels." The helical Bloch wave that is created results in a new kind of birefringence, "OAM birefringence," which could be useful for laser tweezer applications.

Fibers with solid glass cores show strong optoacoustic effects, making them useful for mode-locking lasers at high repetition rates. When light travels through the glass core, it generates acoustic vibrations, which in turn modulate the light. This feedback process produces rapid pulses of light at the resonant frequency of the core's vibration.

"Someone needs to manufacture and sell these things," Russell told the audience.

Typical mode-locked lasers require electronics to create and stabilize such high-frequency pulses. But with photonic crystal fibers, you get stable, high-frequency pulses without any electronics—a much simpler proposition, Russell said.

This rapidly progressing field is a rich one, he said. "It's like a big playground for physicists and engineers."

(l to r) Satoshi Kawata, Scott Keeney, Philip Russell. Credit: Adam Resnick.

3D nanofabrication

Today, most nanofabrication techniques happen in two dimensions, by modifying and manipulating a surface using methods like lithography, deposition, and etching. But three-dimensional nanofabrication can open up all kinds of possibilities, from developing tiny machines and devices that treat diseases to metamaterials with new properties, said Satoshi Kawata of the University of Osaka and RIKEN.

In 1997, Kawata's team devised a technique called two-photon photopolymerization to create a three-dimensional figure of a bull as small as a blood cell. The method involves a near-infrared femtosecond laser that penetrates a photopolymer solution. The laser solidifies the liquid at the focus of the beam.

By moving the beam, the researchers can draw whatever three-dimensional object they want. In 1998, for example, they used this technique to create nanoscale data-storage devices.

This same drawing method can be used to photoreduce ions of gold or silver in a liquid solution. By reducing the metal ions, a laser beam can draw a 3D metallic nanostructure, such as an antenna array.

This technique is limited, however, if you want to fabricate larger structures with nanoscale precision. One way to make such structures is by growing them, Kawata said. In 1999, he found that by firing a UV laser into a photopolymerizable resin, he could induce the growth of optical fibers. Like water carving out a system of rivers and streams, the fibers branch off and merge. This way, you can create a large structure without having to drill or cut individual fibers.

Most recently, Kawata is using these self-growth techniques to create metallic fractal metamaterials. He starts with silver nanoparticles on a glass substrate, all in a silver ion solution. A laser beam heats the metal, which helps reduce the ions floating nearby, turning them into silver atoms that latch onto the nanoparticle. Soon, the particle grows into a needle with branches sprouting from its sides. These nanoforests, as he calls them, could form metamaterials with new kinds of useful properties.

Kawata said these techniques could possibly be used to make micromachines for inside the body. Although it's still too early to know for sure what the new properties might be and how these metamaterials may be used, they show the potential of nanofabrication in 3D, Kawata said.

> "It's like a big playground for physicists and engineers."
>
> PHILIP RUSSELL, LASE PLENARY SPEAKER

Future of lasers

Scott Keeney, president/CEO and co-founder of nLight Corp., brought the LASE plenary session to a close on a very practical, real-world note, saying that he believes the laser industry is finally starting to come into its own.

Keeney spoke about the disruptive effects of high-power semiconductor lasers, telling the audience that advanced manufacturing would be among the big applications for these lasers, as well as microfabrication for the consumer and medical markets. Additive manufacturing, while a promising field, "needs significant improvements" in economics, he said.

"Volume has become more important," he said, now that dramatic improvements in reliability have been achieved. For example, in many areas fiber lasers are replacing CO_2 lasers, he added.

"We've just hit our stride with respect to technology improvements and cost improvements," he told the *Show Daily*.

The current laser market is fragmented, he said, filled with many relatively small companies. Although the market is still immature, there will continue to be many opportunities for growth — thanks to the industry's own version of Moore's law.

Maintaining the current pace of advancement will also require continued progress in material science, automation processes, optical designs, and in lowering costs. Still, Keeney is optimistic that the growth will continue.

Returning to the theme of disruption, Keeney ended his talk with a Chinese proverb: "When a bird's nest is overturned, no egg can remain intact."

RICH DONNELLY AND MARCUS WOO

Smart phone diagnostics "transforming" healthcare

The high-quality optics and associated on-board processing power of smart phones provide a versatile platform for the developers of biomedical solutions for low resource settings. That was the headline theme of BiOS conference 9699 on Saturday morning, chaired by David Levitz from MobileODT in Israel.

Topics ranged from the digital detection of biomarkers for high-sensitivity, low-cost diagnostics by Selim Ünlü (Boston University), DNA imaging by smart phone microscope presented by Qingshan Wei from Aydogan's Ozcan's group at UCLA, and the NutriPhone – a commercial device developed out of David Erickson's Cornell University research group and presented by Seoho Lee. Ozcan's group has also developed a phone-based colorimetric microplate reader for point-of-care testing, as detailed by Brandon Berg.

The NutriPhone is currently funded by a five-year, $3 million US National Science Foundation grant. Lee said: "Our NutriPhone is transforming the way we monitor individual health around the world. This adaptation of an iPhone or Android smart phone combines nanofabricated lab-on-chip technology with a range of apps that enable the monitoring of test subjects' nutrition, notably the presence of vitamin B12 in blood and the adverse impacts of inadequate diet."

UCLA's colorimetric microplate reader features a 3D-printed attachment with 24 blue LEDs operating at 464 nm, and 96 plastic optical fibers that each scan a well in the 8 x 12 cell sampling array. Integrated with the phone handset the whole system is about the same size as a house brick – for younger readers, that's about the same as a cell phone of 1980s vintage.

Microplate based enzyme-linked immunosorbent assays (called ELISAs) are widely used for various nanomedicine, molecular sensing, and disease screening applications; multiwell plate batched analysis dramatically cuts diagnosis costs per patient.

Berg said that his team's relatively simple and economical testing system – which allows rapid processing and good "machine learning" potential – compared favorably in lab tests with much more expensive and larger clinical spectrophotometers.

"We have compared our device at UCLA's Clinical Microbiology Laboratory with samples of mumps IgG [antibodies], measles IgG and the herpes simplex virus IgG," he said. "Our conclusions are that our device can read a 96-well plate at short distance and without significant distortion. There is less than a 20% deviation from equivalent tests using the clinical spectrophotometer. Our smart phone based system gives positive/negative accuracy determinations with more than 98.5% accuracy."

MATTHEW PEACH

Versatile hyperspectral camera reads checks and balances

Corning's hyperspectral imaging (HSI) application development kit (ADK), shown at the company's exhibition booth, is being aimed at product inspection and fraud detection. Supported by a family of HSI sensor modules, the kit covers spectral ranges from visible to LWIR. For example, the bench-based vis-NIR ADK (pictured here, scanning a forged check) includes a patented high-sensitivity HSI module configured for push-broom scanning.

Double-checked: Corning's hyperspectral imager for fraud prevention.

The ADK can also be configured for fieldwork; the vis-NIR scanner can be fitted with a plug-and-play optical scan head incorporating a servo mirror that can acquire complete hyperspectral data sets from scenes ranging in distance from a few meters to multiple kilometers. This standalone sensor is controlled by HyperC+ software installed on a tablet, included with the package.

Another variant, also on display on Corning's booth in the South Hall, the nanoSHARK is an HSI system designed for deployment on board a compact UAV. Fitted with Corning's vis-NIR nanoSPEC sensor, the system weighs just 1.7lb (770 g), including battery, storage and navigation system.

—

Corning has also entered into a joint development agreement with Lithuania's Altechna to develop new types of laser processing solutions for glass. The partners said their motivation was "emerging opportunities for ultra-strong, ultra-thin, and ultra-clean glass."

MATTHEW PEACH

NAVITAR SET TO ACQUIRE HYPERION

US-based ultraviolet and infrared precision optics firm Navitar is to acquire fellow Photonics West exhibitor and custom optical assembly provider Hyperion, the two firms revealed in San Francisco.

Saying that the deal would create an "optical design powerhouse" with four engineering, design and production facilities across the US, Navitar will gain expertise in the design of deep-ultraviolet and extreme ultraviolet (EUV) lithography systems. Key system vendor ASML is expecting to ship at least six of its developmental EUV systems this year, with more advanced tools destined for mass production of silicon chips following in 2017.

Expected to close in the current quarter, the merger agreement follows Hyperion's recent expansion through the 2014 acquisitions of AMF Optics and American Diamond Turning. They have now been consolidated into AMF, which has an ITAR-registered facility in Woburn, Massachusetts. Navitar said that all personnel and facilities will be maintained post-acquisition.

Hyperion cofounder Russ Hudyma added in a company announcement: "Navitar's international presence and vertical integration will enable the team to reach more customers, speed up the design and prototyping process, and ensure our best-in-class solutions reach our customers on time and on budget."

MIKE HATCHER

EXHIBIT NEWS IN BRIEF

Hamamatsu says it has raised the bar for its line of "scientific CMOS" cameras, increasing the quantum efficiency of the devices to 82%. The cameras are finding use in cutting-edge applications like neurophotonics. Earlier this week Stephanie Fullerton, a neuroscientist employed by the company to "help translate what biologists need into things our engineers can make", showed images of brain activity in fruit-fly larvae that the Hamamatsu cameras had captured. "The next wave is scientific CMOS," Fullerton said.

Coherent CEO John Ambroseo said that the best years were still ahead as the laser company celebrated its golden anniversary with a champagne reception at the Moscone Center. Fifty years after setting up in a Palo Alto laundry room, this year sees the firm launching its usual raft of new products – including picosecond and femtosecond sources for micromachining, and a new 250 mW version of its 405 nm OBIS laser aimed at flow cytometry and confocal microscopy.

Limoges, France, exhibitor **Leukos** showed off its new ultra-compact OEM supercontinuum laser. Measuring 130 x 85 mm and weighing just a kilo it offers high-temperature performance up to 50˚C, a wavelength range of 320–2400nm, and pulse energies up to 3 μJ. Intended applications include metrology, spectroscopy, LIDAR and imaging.

Superlum from Cork in Ireland presented its new swept-wavelength tunable laser, the Broadsweeper BS-930-1-HP. The source is based around a quasi-collinear acousto-optic tunable filter in an external fiber ring cavity. Designed for applications in biomedical imaging, optical metrology, interferometry and OCT, the laser offers 15 mW of power across a 135 nm-wavelength range between 880 and 1010 nm.

Hot on the heels of its launch of the Tangor industrial 100 W femtosecond laser, **Amplitude Systèmes** debuted its Mango optical parametric amplifier. It is designed to complement the company's high-power, ultrafast lasers. "This new platform gives access to a new range of wavelengths (210–11000 nm) at unprecedented repetition rates," the company stated. Pulse duration is less than 300 fs.

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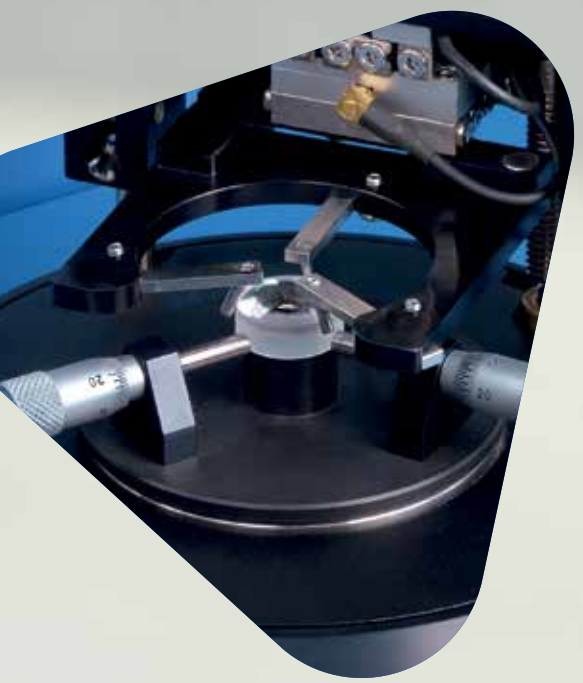

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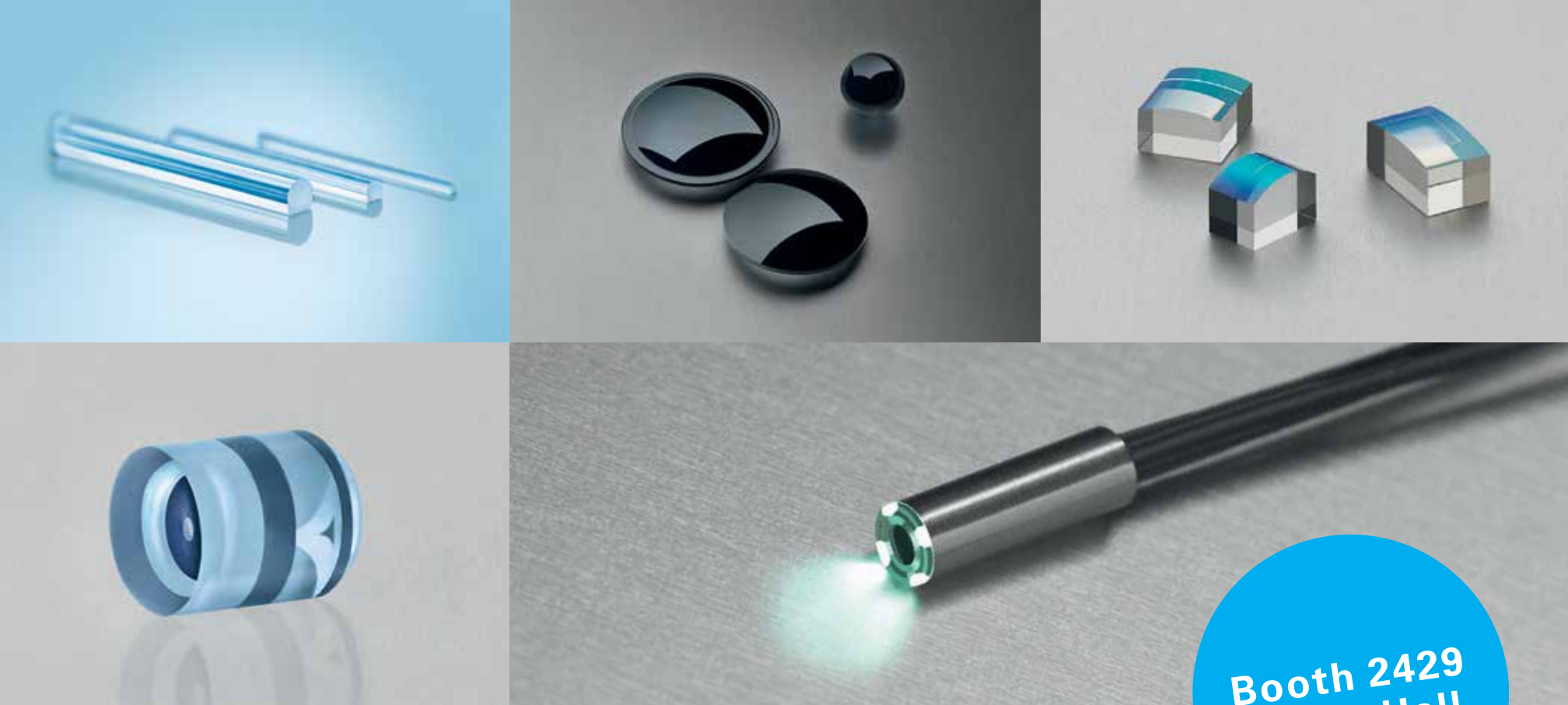

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Optical coherence tomography: a $10 platform?

While advances in OCT expand the technique's use in biomedicine, the prospect of new cost-effective approaches may herald a revolution outside the clinic.

The impact of optical coherence tomography (OCT) in ophthalmology is testament to the technique's exceptional suitability for imaging below the surface of accessible tissues. And despite a quarter-century of productive deployment, it is evident – not least from this week's BiOS conferences – that new ways to exploit OCT's capabilities continue to be developed.

One current example is the extraction of useful information from the speckle patterns that appear in, and sometimes bedevil, many imaging methodologies when the light path interacts with biological materials in motion - blood cells, for instance.

"In the past the objective was to eliminate speckle, but there have now been several breakthroughs in understanding what can be learned from speckle across different imaging techniques," commented Martin Leahy of the National University of Ireland, Galway, who chaired a panel discussion entitled *Speckle In Biomedical Optics* during this week's symposium.

"In principle, the variation in speckle over time can give an indication of the speed of blood flow through vessels, helping to identify the locations where active blood flow is taking place and whether it is fast or slow," he explained.

This general principle has spurred the gathering of data from speckle specifically seen by OCT when living tissues are imaged - the subject of another dedicated BiOS session. Topics included mapping transverse capillary flow speed using OCT speckle signals, and the factors influencing the creation of shadow-artefacts in microcirculation imaging.

A $10 OCT system

But alongside these clinical advances, a major development in the use of OCT in new and wider markets is taking shape, based on the prospect of workable instrumental platforms potentially priced at just a few dollars. "The starting point was the realization that the optical units in a DVD pick-up drive now cost very little money, but nonetheless share some core components with an OCT system," said Leahy. "We envisaged building OCT platforms exploiting these low-cost items."

Compact Imaging, a California start-up with strong connections to Irish research centers including Leahy's NUI Galway group, has developed a modified version of the architecture usually employed for time-domain OCT, intended to fit the bill. Christened multiple reference OCT (MR-OCT), Compact Imaging's initial working model used a voice coil extracted from the optical pick-up head of a DVD player, and the company believes the heart of mass-produced MR-OCT units can be made with similarly convenient components. CTO and co-founder Josh Hogan brings expertise from that field, having previously developed low-cost DVD+RW optical storage technology for HP Labs.

Compact Imaging's CTO and co-founder, Josh Hogan, whose background is in developing small, low-cost optoelectronics – including optical storage devices at HP Labs. Photo: Compact Imaging.

"One factor in our favor is that the processing power in mobile platforms, such as smart-phones and tablets, is advancing so rapidly," commented Leahy. "Given their abilities at computation and display, we are confident that those tasks can be separated from the optical systems of the OCT platform and handled elsewhere."

The question of obtaining a light source suitable for such a low-cost unit does remain an issue, given that the broadband sources used in clinical OCT systems carry hefty price tags. Identifying the right markets should provide the answer. "Again, the parallel is with CD and DVD drives," Leahy noted. "Once both the technology to build DVD drives around semiconductor lasers and suitable markets for those units numbering in the tens of millions were developed, the price dropped to single-digits."

Biometric security

So where exactly might the markets for similarly large quantities of OCT systems actually emerge? Biometric security is one likely candidate. The traditional surface fingerprint used for identification purposes can be readily spoofed, but the "primary" fingerprint pattern - first created in the womb and lying just below the skin's surface - provides a more cast-iron proof of identity. Examining that pattern could make banking and other financial systems more secure, or be used for identity checks on travelers. As Leahy noted, border security is unlikely to become a shrinking market any time soon.

That kind of business may prove crucial to a $10 OCT system in advanced economies, but the positive impact in more personal applications could be just as significant. Over six billion people have no access to the expensive healthcare technology available to many in the developed world, so reaching them with OCT would perform a clear global good.

OCT's heartland of ophthalmology provides one possibility: a simple system designed to yield single significant measurements - perhaps the thickness of the retina - rather than the wider array of complex parameters or detailed images captured by full clinical systems, could help identify the symptoms of particular eye diseases at low cost.

"Age-related macular degeneration affects retinal thickness, and can do so very rapidly, potentially over a period of just a few days," said Leahy. "A cost-effective way to assess at-risk individuals more regularly and with less inconvenience could spot the disease before it becomes irreparable, and allow prompt treatment."

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UK backs 'spooky' quantum tech to emerge from the lab

Technology roadmap developed under £270M project outlines likely commercial applications of devices able to harness quantum effects.

Stroll around the Photonics West exhibition and you'll be surrounded by quantum technologies – after all, any laser or transistor operates by exploiting the laws of physics that govern the realm of the very small. So when the UK government announced in late 2014 that it was going to throw £270 million into the development of "quantum technologies" there was a certain amount of, ahem, uncertainty. What exactly was being envisaged?

A year on, not only is the answer to that question becoming much more evident, it is also clear that photonics technology – in various forms – is right at the heart of things. In November 2015, the national program to develop real-world technologies based on the "spooky" effects of quantum phenomena celebrated its first year with a packed-out event at The Royal Society in London.

Held just a week after the new Quantum Metrology Institute (QMI) at the National Physical Laboratory (NPL) officially opened, the National Quantum Technology Showcase included a dozen table-top exhibits of largely photonics-based prototypes that indicated the kinds of applications that it is hoped will become fully commercial before the end of the initial five-year funding period.

They included cameras able to see around corners, optical atomic clocks, interferometry-based gravity imagers, quantum encryption for consumer devices employing photonic integrated circuits (PICs), and potential building blocks for future quantum computers.

David Delpy, previously CEO of the Engineering and Physical Sciences Research Council (EPSRC) and now chair of the quantum technology network's strategic advisory board, kicked off the showcase with a call for extensive industry collaboration and engagement with the likely end users of commercial equipment based on quantum physics.

"Our vision is to develop a world-leading position in quantum technologies," Delpy told delegates. "When the world thinks about quantum technology we want them to think about the UK."

Referencing a palpable buzz amid the Royal Society's iconic marble halls and wood-paneled rooms, he added: "Something has changed. We are completely full."

Industry engagement key

Delpy also stressed the level of industry engagement that the network's four individual quantum "hubs" are working to stimulate, saying: "Industry has been embedded right from the outset. [This] program is a combination of academic and business partners and we want commercial support. The £270 million [initial, five-year UK government funding for the network] is just a kick-start."

> "The strategy is to make the UK the go-to place for quantum technologies."
>
> RICHARD MURRAY, LEAD TECHNOLOGIST FOR EMERGING TECHNOLOGIES AND INDUSTRIES AT INNOVATE UK.

Acknowledging the potential for some creative tensions between academic and industry partners, Delpy noted that the inherent ambiguity of "spooky" technology is not something that industry would naturally gravitate towards.

However, industry is very visibly represented in the quantum network. Its special interest group is chaired by e2v Technologies' CTO Trevor Cross, and more than 160 companies are already involved in the four hubs. Cross was optimistic about the future translation of quantum science into tangible commercial products:

"We're at a point in time when a new raft of functionality will lead to new technologies," he told delegates at the Royal Society. "This is happening right now, and supply chains are beginning to take shape. This is more than a technology 'push'."

Quantum key distribution (QKD) for highly secure communications is already a commercial, albeit expensive, reality. The UK's quantum hub based at York is aiming to develop much cheaper versions of the technology and to deploy a secure quantum network in Bristol and Cambridge. Photo: EPSRC.

Quantum roadmap

The quantum technology program has been set up deliberately to combine some relatively "quick wins" – for example the single-pixel cameras for methane imaging being developed at the Glasgow-based QuantIC hub, which is led by the optics professor and Photonics West conference committee member Miles Padgett – with the much longer-term goals of building quantum computers.

The intention is to demonstrate several real-world applications of quantum technology within the initial five-year funding time frame, and thus be in a strong posi-

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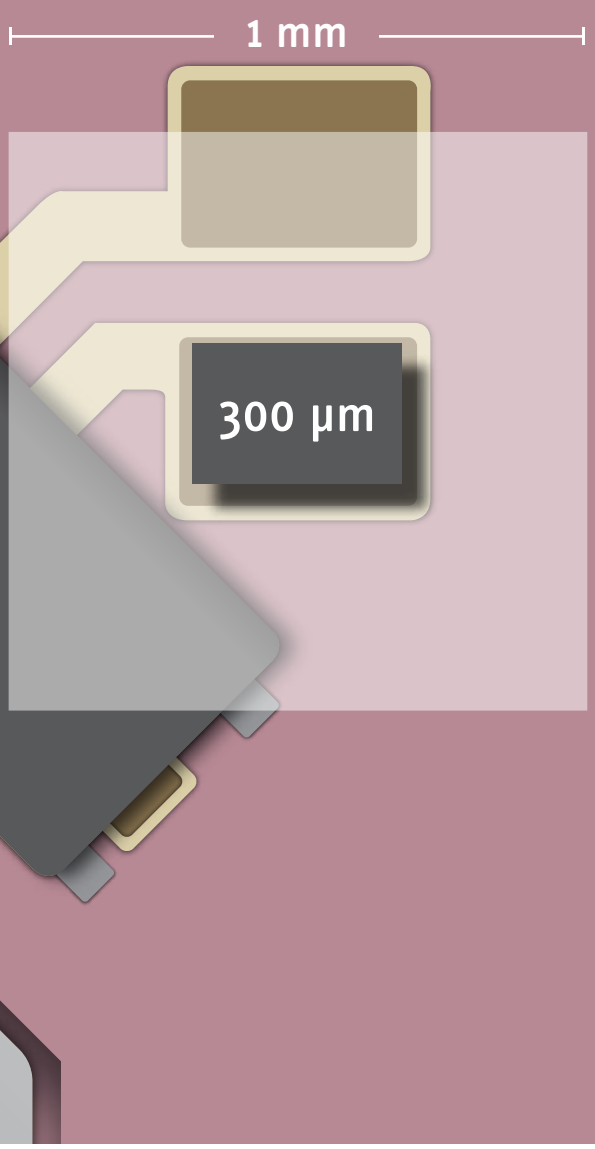

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Quantum Tech continued from page 09

tion to attract more funding subsequently.

Appearing on BBC national radio on the morning of the Royal Society showcase, Padgett hailed the strong industry connection, highlighting that 20% of the initial QuantIC funding had been set aside to be allocated by its industry partners.

"My personal experience is that [interacting with industry] has been incredibly stimulating," he said. "It makes you think about problems differently, and it is thinking differently about things that leads to scientific creativity."

Industry is set to play an increasingly important part in funding as the technology and applications develop,

Not just any camera: this prototype imaging system, under development at QuantIC hub partner Heriot-Watt University, could aid security services with the ability to see around corners. Photo: EPSRC.

with Cross and Delpy both looking for close engagement with systems companies and end users, as well as high-performance component makers (and Photonics West exhibitors) like e2v and M-Squared Lasers.

To that end, the Cross-chaired special interest group has compiled a quantum technology "roadmap" outlining key target markets, and the current status and challenges facing applications like atomic clocks, gravity and magnetic sensors, quantum encryption and computing.

In his introduction to that document, drawn up after a series of workshops involving funding agencies, academic partners and the private sector, Cross writes: "This roadmap is for anyone with an interest in this emerging sector, particularly business."

He continues: "It shows companies where new opportunities in quantum technologies overlap with their interests and helps them understand how these new applications could drive their growth."

Innovation game

Helping to drive that industry involvement is Richard Murray, lead technologist for emerging technologies and industries at Innovate UK. His non-technological answer to the question "what is a quantum technology" is to explain that while devices like lasers and transistors harness quantum *states* (rather than quantum *effects*), the new program is about developing devices that create and manipulate quantum states. Two key areas to exploit are quantum superposition – where something can exist in two places simultaneously – and entanglement, where atoms (or photons) can be connected at distance. These quantum effects have not yet been commercialized to any significant extent.

Murray says there is a widely held belief that the only way these technologies can become commercial is if companies are heavily connected with the program. The job of Innovate UK is to generate that commercial interest; to connect academia with industry, aid the development of real products, and help with networking and road mapping activity. Crucially, £32 million of the total pot of money invested in the quantum technology network is available for industry-led efforts. Murray stresses that industry involvement is at the core.

He sees two key reasons for the undoubted "buzz" surrounding the quantum topic in the UK. "One is that companies are becoming more aware, companies that are involved in optics, vacuum technologies, electronics etc.," he told *Show Daily*. "Also, academics are looking to engage with the community [and establish] good collaborations with SMEs." At this early stage of the initial five-year effort, stand-out achievements include the groups looking to develop gravity sensors and imagers – technology with potential applications detecting underground pipes and subterranean sinkholes.

Prompted by the UK Defence Science and Technology Laboratory (DSTL), which is likely to represent the "first adopter" of this technology, Murray reports that a strong industry collaboration is forming around the Birmingham-led hub focused on quantum sensors under the leadership of Professor Kai Bongs. "The companies involved have the ambition to sell products," Murray says. "They see applications in space and in consumer markets."

"The quantum sensing devices being developed at the University of Birmingham are already at the early demonstrator/prototype stage, and the university is partnering with a number of different companies to help them to identify business cases for adopting these technologies," Murray adds. "Two examples of these companies are e2v technologies and RSK."

e2v, long established as a supplier of high-end sensors used in space imaging (sensors on board the Hubble Space Telescope, the New Horizons Pluto probe and the Gaia galaxy-mapping mission stand out among a raft of high-profile deployments) is working very closely with

> "The notion that 'this technology is coming' will not be enough."
>
> RICHARD MURRAY, LEAD TECHNOLOGIST FOR EMERGING TECHNOLOGIES AND INDUSTRIES AT INNOVATE UK.

the Birmingham hub to develop quantum gravity sensors for a variety of space and defense applications. "The quantum technologies program has allowed e2v to bring the development of these new quantum technologies in-house, which will allow them to develop products, and the understanding that they need to develop products for themselves," Murray said.

Environmental consultancy RSK already uses non-quantum gravity sensor devices to assess ground conditions on construction and other geological sites. It is working on the "Sigma" project, funded through an

continued on page 13

Quantum Tech continued from page 11

Innovate UK call, to model and test quantum gravity sensing devices, and compare them to existing commercial sensors. That ought to help ensure that the quantum technology developed, which should offer greater sensitivity, operability and reliability over existing devices, will meet users' needs. "Together, these programs are looking to create a full supply chain for future quantum technologies, where technologies are developed within a commercial environment to meet a customer need," Murray sums up.

Valley of death

Overcoming the "valley of death" between lab development and commercial success is of course a much-covered topic, and there are some concerns that the UK's quantum technology effort could fall into the trap of creating a technology push without the required market pull. While Murray admits that the quantum program is risky, he also believes that the combination of public-sector and private-sector partners involved in the projects are pulling in the same direction. "The best way is to have a flexible approach and be open to new ideas – even if not successful at first," he says, suggesting that some fundamentally entrepreneurial thinking is being fostered.

One common observation is that while the UK is very strong in some technology areas – aerospace and pharmaceuticals the most obvious – it does lack key players and OEMs in other high-tech sectors like electronics. Murray points to the close involvement of BT, for whom the quantum key distribution (QKD) application led by the York hub is the main focus, and says that these big

> "This roadmap is for anyone with an interest in this emerging sector, particularly business."
>
> TREVOR CROSS,
>
> CTO AT E2V TECHNOLOGIES.

players will be needed to pull applications to a large scale. But that does not necessarily require the involvement of UK companies. "The strategy is to make the UK the go-to place for quantum technologies," said Murray, also indicating a certain international element within the program. He points out: "It means an opportunity to grow our strengths here and a good chance to create the potentially large companies of the future with disruptive technologies. But also to attract big global players from outside the UK."

Murray adds that, ultimately, the idea is to create a global industry for quantum technologies, and to collaborate internationally. "The ambition is that if the right environment and infrastructure is created, then the UK will be attractive to large global companies and systems integrators," he says. "The UK is working closely with the European Commission, which is very interested in quantum technologies." One example here is a collaboration under the Future and Emerging Technologies (FET) element of Horizon 2020. "There is an appetite for FET to be more industry-focused, and to make it similar to what we are doing in the UK," Murray added. "The EC wants the FET to be proactive with industry."

At the Royal Society showcase, a common observation was that the quantum technologies program resembled

Photonics is at the heart of many of the innovations under development at the UK's four quantum "hubs". The National Physical Laboratory (NPL) is working on new compact atomic clocks that exploit the unusual properties of hollow-core optical fiber. Photo: EPSRC.

a "five-year program with a ten-year vision". Murray acknowledges that to justify a decade of funding, the network will have to provide clear evidence of its effectiveness within the initial five-year period. "Simply the notion that 'this technology is coming' will not be enough," he admits. "We will have to have evidence that, for example, companies are being created, technologies have become commercial, so early wins are important."

The likely "low-hanging fruit" applications in gravity sensing and atomic clocks will at first be augmented by some of the basic components of quantum technologies, for example single-photon sources and ultra-stable lasers from the likes of M-Squared, which already has a heavy involvement in the quantum network. Even this can be very lucrative, says Murray, estimating a total market already standing at £1 billion for laboratory experiments aimed at pushing the quantum science base.

Metrology lends credibility

It is clear that investors – including those allocating government money for research – require solid numbers as well as credible science to back up any future spending decisions.

Underpinning that credibility will be the Quantum Metrology Institute (QMI), which is charged with developing new measurement techniques and fundamental standards under the auspices of the National Physical Laboratory (NPL).

Formally opened by local member of parliament Tania Mathias (a medical doctor who also sits on the UK parliament's science and technology committee) last November, the QMI will host a national center for testing and validating quantum technologies "to secure the confidence and investment necessary to commercialize new products".

Sir Peter Knight, the quantum optics professor from Imperial College, London, who is chairing the QMI, said at the time: "Because quantum technologies are based on very advanced and extraordinary physics, validation is crucial to getting investors and industry on board to accelerate the commercialization of them.

"As the UK's home of measurement, with over one hundred years' experience in helping new technologies make the jump from lab to market, NPL is the best place for this testing and validation to be conducted to ensure that the UK can start benefiting from amazing new technologies as soon as possible."

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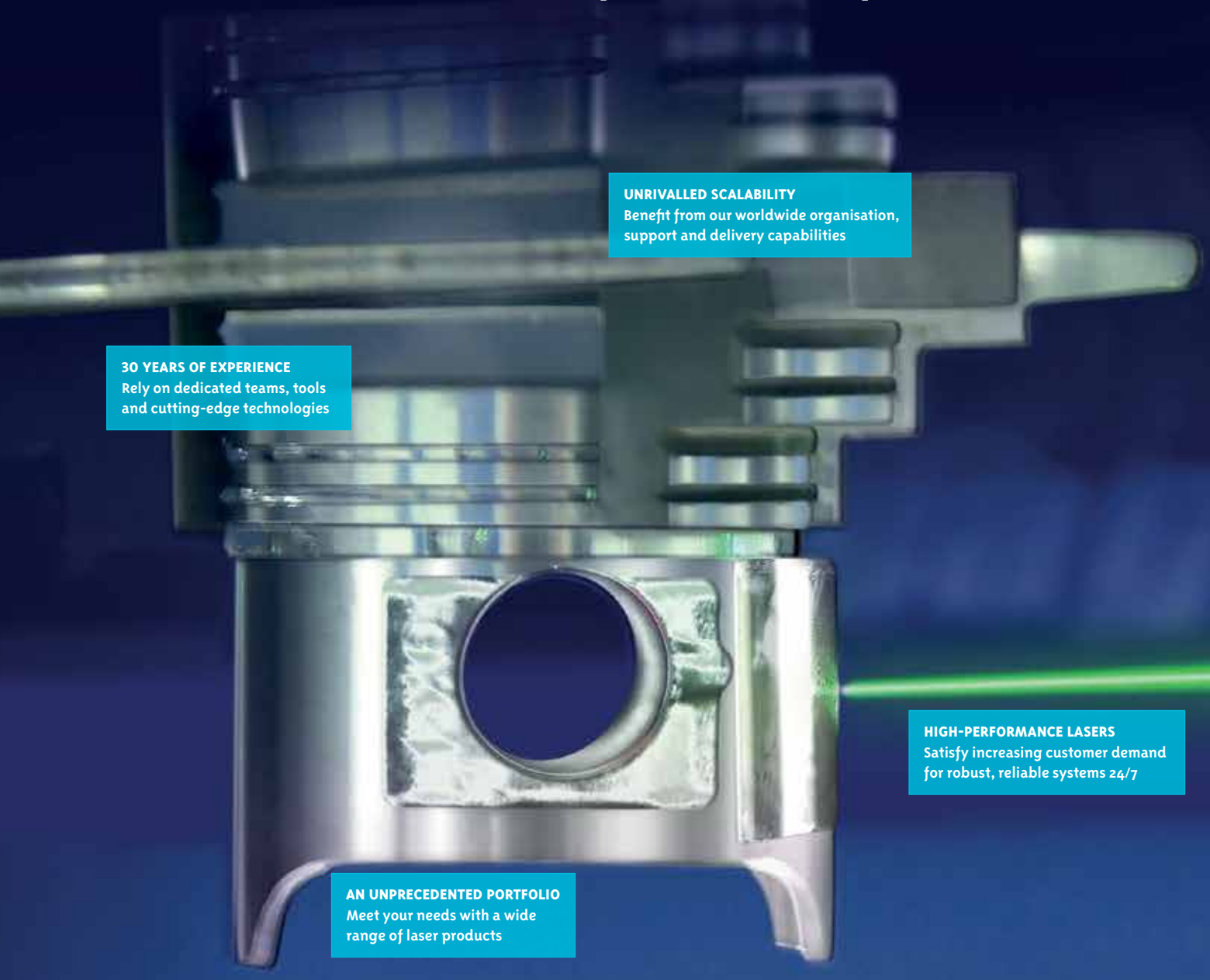

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ELI Beamlines prepares for first firing next year

Petawatt-scale sources with unprecedented features are expected to begin test-firing from 2017.

The front of the ELI Beamlines building near Prague, which hosted an official opening ceremony in late 2015. First light for the "L1" laser is currently anticipated in around a year's time. Photo: ELI Beamlines.

In October 2015, the ELI Beamlines international laser research center, currently being developed at three sites across Eastern Europe, opened its first facility near Prague, Czech Republic. The center, which will house some of the world's most powerful lasers, with intensities ten times higher than those achievable elsewhere, is financed by the European Union via structural funds and also by the host country.

The other two ELI sites to follow in the coming years are known as ELI-ALPS, in Hungary, and ELI-NP, in Romania. When complete in 2018, The ELI facilities will together have received an investment exceeding €850 million ($925 million), assuming budgets stay on track, mainly from the European Regional Development Fund. Research operations, starting in 2018, will be unified under the new European Research Infrastructure Consortium, also known as "ELI-ERIC".

The new ELI Beamlines building is sited in the Prague satellite town of Dolní Břežany, which is set to become to a high-tech hub. When complete, new facility will focus on the development of short-pulse high-intensity lasers and laser-driven secondary sources of radiation and accelerated particles. They will then be used for molecular, biomedical and material sciences, dense plasmas, warm dense matter, and laboratory astrophysics. ELI Beamlines consists of four separate buildings, accommodating offices, laboratories, a multi-functional space with lecture theater and a café and the principal element: a massive concrete box, comparable in size to a football pitch, housing the laser hall itself.

Georg Korn, chief scientist at ELI Beamlines. Photo: ELI Beamlines.

"The heart of ELI Beamlines research and development projects will be a quartet of unique high-power lasers, which will gradually be installed over the next few years," explained Professor Georg Korn, scientific and technology manager and chief scientist at the site. "Our researchers will utilize these powerful, high-repetition-rate lasers for this wide range of high-field physics experiments, with their focused intensities up to 10^{23} W/cm², such as are needed for investigating fundamental and sometimes exotic physics."

"We have now finished the first construction phase of the ELI Beamlines center and opened the administrative and multi-functional building. Now we want to present our experimental halls, which are being prepared for the installation of laser systems."

First light

The four planned laser systems (named "L1" to "L4") are still in development in cooperation with other European and US-based laboratories, although work has started on putting "L1" in place. The lasers will be installed from early 2016 until the end of 2017.

"The ELI Beamlines facility will be a high-energy, high repetition-rate laser pillar of the overall ELI project," said Korn. "It will provide pulses from four laser systems, which could be used in various combinations. To meet the requirement for high repetition rates, three of these lasers will employ state-of-the-art-and-beyond technologies of diode-pumped solid-state lasers for driving broadband amplifiers. The fourth, multi-kilojoule laser will use a newly-developed flash lamp technology with an actively cooled gain medium that will lead to an augmented shot rate."

He added, "We have now started to install the first laser, L1, ready for alignment and for some small-scale initial experiments. L1 should be installed and up and running by the end of 2016 and first light will be seen at the beginning of 2017."

Laser specifications

L1 beam line: A high-repetition-rate laser system firing high-energy ultrashort femtosecond laser pulses at 1kHz. It is based on amplification of picosecond pulses in broadband optical parametric chirped pulse amplification (OPCPA) and compressed to 20 femtoseconds using chirped mirrors. The pump lasers are based on Yb:YAG thin disk technology. L1 is a complete in-house development, which will eventually result in a 100mJ sub-20fs 1kHz laser that could not be bought "off-the-shelf". It will be completely diode-pumped by a short pulse pump laser from Trumpf Scientific. This 1.5 picosecond pump laser is based on OPCPA while the ELI team is building the femtosecond laser's OPCPA stages.

L2 beam line: A laser system using diode-pumped, cryogenically-cooled Yb:YAG lasers for pumping of nanosecond OPCPA amplification stages. The system is designed in partnership with the UK's Rutherford Appleton Laboratory to operate at least at 10Hz and to deliver petawatt class pulses with 20 femtoseconds pulse duration. State-of-the-art Yb:YAG crystal growth technology as well as a new cryogenic system has been developed in order to advance the performance of the pump laser.

L3 beam line: This represents what the development team calls the "absolute cutting edge" performance of any diode pumped lasers in its class. The laser is designed to deliver peak power in excess of one petawatt and thanks to novel ways of handling high average power and diode pumping can fire 10 times a second (10 Hz). This "High Repetition-Rate Advanced Petawatt Laser System" (HAPLS) is being developed and constructed in close cooperation with California's Lawrence Livermore National Laboratory.

L4 beam line: This system will operate with up to 40x higher energies than the L3 system. The flash lamp pumped technology will enable this system based on actively-cooled laser glass to reach very high pulse energies in excess of 1500J per pulse and reach peak powers up to the unprecedented 10 petawatt level with a highly augmented shot-rate of one pulse per minute, thanks to new amplifier cooling. One of the unique features of this system is the possibility of a dual output of 1800J nanosecond pulses with temporal pulse shaping and 150J, 1 petawatt femtosecond pulses with precision programmable delay.

Recruitment schedule

Korn also gave a status update on the recruitment of the 250-strong ELI Beamlines team: "We still need to fill a few posts but most of the key positions are now filled. We have a nice mix of international research staff – more than half of the total originate from outside of the Czech Republic. It's not an easy task to hire so many specialists in a short time, so when it doesn't make sense to hire a staff member we are using consultants."

Even at this relatively early stage, several world records have already been broken during the development of laser systems. For example, the L3 laser, which ELI Beamlines is developing together with Lawrence Livermore National Laboratory, will be using the brightest laser diodes ever manufactured.

Another notable technological development activity is the P3 chamber, which is the largest experimental chamber so far developed for civil and academic research of laser plasma in the world, as well as the delivery of the High Harmonic Generation device, which generates ultrashort coherent pulses of extreme-UV radiation for material research and applications in biomolecular sciences, such as for imaging of biological samples with high temporal and spatial resolution.

Asked about the key performance indicators for the ELI Beamlines facility, Korn said: "Satisfied customers will be the ultimate test. And the signs are already positive at this early stage: We believe we have already had a positive effect on the Czech Republic's scientific community with various partnerships established with the Czech Technical University and the Charles University in Prague, for example, as well as many others in the wider European and global research community."

Even before the first shot has been fired, ELI Beamlines has agreed and is now planning numerous research collaborations with the likes of the universities of Oxford, Uppsala, Osaka and Hamburg, the Japan Atomic Energy Agency, Rutherford Appleton Laboratory, IOQ Jena, Lawrence Livermore National Laboratory, to name a few.

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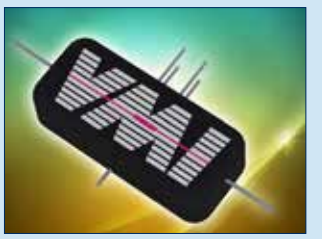

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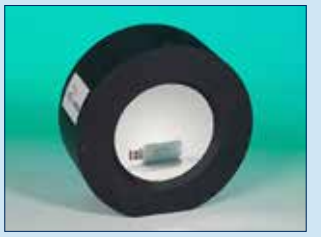

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Christopher Pinzone Joins Thorlabs

Christopher Pinzone joined Thorlabs Quantum Electronics (TQE) in Jessup, MD in October 2015 as Director of Epitaxy. One of the pioneers of commercial MOCVD epitaxial wafer growth, Chris' achievements include growing the first room temperature CW laser directly on silicon, bringing CATV analog DFB lasers to market, and developing a new, patented technique for direct wafer bonding of InGaAs to silicon. Pinzone co-founded Ahura Scientific in 2002, a venture-capital-backed startup that developed and produced the world's first handheld Raman and FT-IR spectrometers for rugged field service, culminating in a sale to Thermo Fisher Scientific in 2010.

"We are excited to have Chris' expertise on board," said Peter Heim, Chief Technology Officer at TQE. "He has deep roots in the global epitaxy community that go back to his time at Bell Labs. His leadership will be key to our efforts to provide epitaxial services to both industry and academia."

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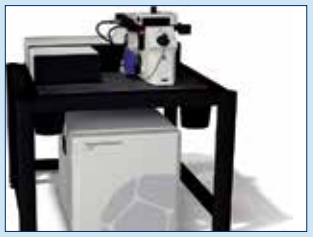

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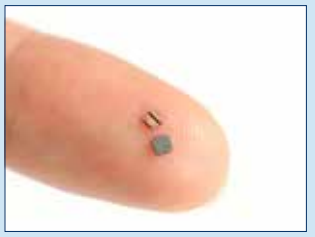

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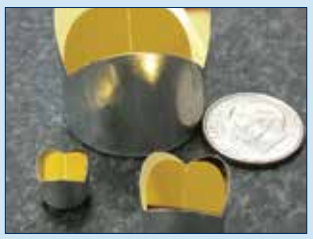

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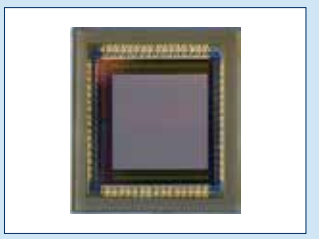

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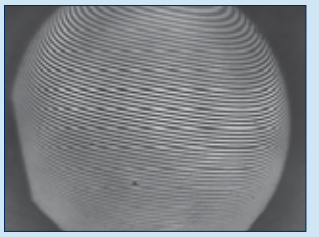
Please see the VFI-2000 at Photonics West 2016 – Arden Photonics booth #5543.



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IYL 2015: Spontaneous activities spread the word of photonics

Organizer-in-chief John Dudley reflects on an extraordinary year.

Shortly before this year's Photonics West exhibition opened for business, UNESCO's International Year of Light (IYL) was drawing to a close, with a three-day celebration down in Mexico. During the year, the global event embraced all aspects of light with the grand aim of promoting the importance of photonics and its benefits to all the citizens of the world.

A key figure who helped to drive IYL at many levels from education to politics, via diplomacy, networking, business and even entertainment, is Professor John Dudley, as chair of the IYL's steering committee. The New Zealander's day job, which he has somehow managed to maintain while jetting to the various IYL gatherings is at the Université de Franche-Comté, Besançon, France, where he heads the optoelectronics and photonics research group of the FEMTO-ST Laboratory.

Dudley has been amazed by the response and enthusiasm of innumerable individuals, companies and organizations worldwide that have often spontaneously decided to take a part in the IYL, whether it is the French education department, the Australian Scouts or the Ghanaian government, all of whom have piggy-backed on IYL to help spread the message.

"We can't even total the full number of events yet – possibly at least 10,000 separate activities in 130 countries could be a starting estimate," he said in December. "But whatever the number, we can safely assume that the International Year of Light has reached tens of millions of people. There have been all sorts of events that even the local country organizers haven't got to see, from Europe, to the Philippines to Africa and beyond." UNESCO awards the themed years, such as chemistry and astronomy, but Dudley feels that light has been the highest-profile topic to date. "It has shown the power of UNESCO to bring people together," he added.

The IYL logo, projected onto the Globe of Science and Innovation at CERN. Photo: CERN.

The IYL has provided opportunities to interrupt the routines of influential figures not usually associated with photonics and bring them together into a new and informative context. At last year's Laser World of Photonics expo in Munich, for example, UNESCO organized a gathering of ambassadors and senior UN attachés from across Africa and took them on a guided tour of the show. Dudley, who was on the tour himself, commented, "We met a range of CEOs and technologists from the likes of Trumpf and other major companies, so the delegates could return to their countries with greater knowledge of the opportunities offered by photonics, better armed to spread the benefits."

Another major objective of IYL was raising awareness of light poverty. "We spend billions trying to address the consequences caused by poverty," said Dudley, "but we spend very little on the things that could stop it altogether. When you consider that allowing young people to learn about the world for themselves – democratizing education is so important and is not possible without light at home – then we have to solve the problem of providing access to reliable lighting for them.

"The idea of using IYL as a progress lever led to the creation of Energy For All, which involves multi-national NGOs and the lighting manufacturers Osram, Siemens and Philips. This group is lobbying to reduce light poverty so that, ideally, there will be light for everyone who needs it by 2030. That's an amazing outcome of IYL that will continue long after we have finished."

Looking at some of the local IYL activities he had been able to discover, Dudley references a few examples: "Ghana is a good example of significant achievement. It did not have the word photonics on its agenda at all just four years ago, but it has become one of the leading promoters. Ghana hosted a major regional conference on light technology for West Africa in September 2015. Another example is in South Korea, where the National Assembly held a special information session on light-based technologies to pass on the knowledge to ministers."

France, Dudley's country of residence and also the headquarters of UNESCO, has recently decided to extend the IYL from February to the end of the school year in mid-2016. "It doesn't make sense to stop this activity at the end of the year," he said.

Education about light-related topics, he believes, continues to have an important role not just to empower nations but also to bridge divides and perhaps to even solve conflicts. The opening ceremony of the IYL in January 2015, at UNESCO's headquarters in Paris, took place just a few days after the *Charlie Hebdo* terrorist attack, before of course the same city suffered further atrocities in November.

Associated with the IYL was an exhibition called 1001 Inventions, which celebrated some of the earliest innovations using light by the Islamic scholars and scientists of Egypt and the Middle East more than 1000 years ago. It was centered around Ibn al Haytham, the pioneering mathematician and astronomer, who was also influential in developing the photonics sciences of his day.

Dudley sees an opportunity to use photonics to bridge political and cultural divides. "There is now the need to push harder the need for education to combat extremism," he said. "The organizers of 1001 Inventions contacted me desperately after the first attack to say we all need to work harder and they want us to be involved even more so in 2016 to try to do things to solve these problems."

1001 Inventions presented IYL events throughout the

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Middle East and the Persian Gulf. There are also some new partnerships In China, to promote the wider issue of the Middle East and its educational history. The social entrepreneurs of 1001 Inventions are trying to spread a message of peace, highlighting the scientific successes of the "Golden Age" of Islamic invention.

Dudley believes that the reach and impact of IYL has been truly global: "From the local to the regional, national, and international it has been a huge success," he said. "It's also been interesting to see how the different players and bodies have responded. For example, the Lighting Industry Association (UK) organized a cultural light event in which it lit up ten UNESCO world heritage sites around the UK & Northern Ireland. Philips organized round-tables, the International Association of Lighting Designers has organized many events, to name a few.

"Associations such as the IEEE Photonics Society, the APS, SPIE, OSA have often worked together to achieve larger scale. It's good to see the rapprochement and improving dialogue between these groups in a common mission."

Political reach and legacy

Dudley also believes that amid all of the "soft power" promotion, IYL has achieved serious traction at a political level. Besides the globetrotting and outreach, he has also spoken alongside Nobel laureates at major scientific-political events, notably the executive board at UNESCO's headquarters. "One of my aims has been to bring hardcore science into the political arena. I believe it has been a success that we will see more interaction between politicians and scientists."

One of the key issues has been bridging the language gap so that politicians and scientists can better understand each other. As an example, Dudley said: "Consider the word theory. In science [this] is a model used to describe reality, but to a politician a theory is something not proven; to a scientist evidence is something that is fact confirming a theory, while to a politician evidence can be an argument that may or may not be true.

"There now thousands of politicians worldwide who have seen talks by the likes of Eugene Arthurs, myself or other IYL speakers who have made people aware of such vocabulary differences and the need very early in the conversation to be unambiguous. Politicians in my experience are far more receptive to clear opinions than you might think if you have good arguments to back them and if you give them easy take-aways."

Dudley believes that the legacy from IYL will be substantial and long-lasting, especially with younger people and students around the world. "People who might not otherwise have done so have learnt about science and especially photonics," he told *Show Daily*. "We may not see immediate measurable benefits but I am confident that in ten time years we will see young scientists doing work in this area as a consequence of having seen a presentation in 2015."

The calendar year may be over but the work of IYL will not cease with the closing ceremony. The UNESCO team and its myriad offshoots worldwide have developed many resources, including websites, diverse educational materials, posters, booklets and the like. Dudley commented: "We will be meeting in the early part of 2016 with the major stakeholders to see how we can continue what has worked in IYL, to see which partners wish to continue to work together and to see how UNESCO can continue to support them. People have realized that the IYL has opened up a great route or door, and we have illuminated a path to the future. Now it's up to us to walk that path."

MATTHEW PEACH

Cadmium or cadmium-free? That is the question

Quantum-dot-enhanced TV screens look great but mostly rely on cadmium to deliver spectral purity. Can cadmium-free alternatives live up to expectations?

Quantum dots (QDs), fluorescent nanoscale semiconductor particles, typically measure anywhere between 10 and 100 atoms in diameter – or about one-thousandth of the width of a human hair. When excited by an external light source, the color of the light that they re-emit depends on the size of the particle. So by carefully tuning that size, it is possible to control the spectrum of light re-emitted. By combining QDs with existing display light sources, display manufacturers have found ways to reproduce color accurately.

As a result, QDs have rather suddenly become the latest big advance in the displays industry, with a growing number of manufacturers incorporating these brilliant tiny semiconductors into their backlight units (BLUs). Manufacturers including big-hitters Sony, Samsung and Philips claim improved color purity compared with conventional phosphor-based LED-backlit LCD screens, driven by the QDs' ability to convert blue LED light to very specific reds and greens – in the process offering more vibrant and realistic color reproduction than traditional LCD technology.

Despite the obvious attractions of QDs, their incorporation of cadmium has always been an issue, and there is currently a heated debate about whether or not to prohibit the use of cadmium-based versions of the technology in display screens. Cadmium is of course a highly toxic and carcinogenic heavy metal, meaning its use has been strictly regulated under the European Union's 'Restriction of Hazardous Substances' (RoHS) directive. And while a number of exemptions recognize the metal's usefulness for various optical applications – including in high-quality microscope lenses and cadmium telluride solar panels – there are sharply conflicting views over whether these exemptions should be extended to include TVs and other displays.

Going cadmium-free: the alternatives

One of the key developers and producers of cadmium-free QD (CFQD) technology is the UK-headquartered Prism Award finalist Nanoco Technologies, whose QDs are instead based on indium. As its VP of business development Steve Reinhard explains, CFQDs can be incorporated into an array of electrical and electronic equipment, including displays and lighting, to produce what he describes as 'fully RoHS compliant products.'

"Early in Nanoco's history, we recognized that the market would inevitably turn away from quantum dots containing cadmium and other toxic heavy metals," Reinhard told *Show Daily*. "To future-proof our business, we pivoted our research and development strategy to focus on enabling the creation – and, importantly, the large-scale creation – of cadmium-free quantum dots."

Nanoco's patented seeding process utilizes the molecules contained in a cluster compound as the nucleation sites for nanoparticle growth – in the process avoiding the need for a high-temperature injection step. Particle growth is maintained by the periodic addition of precursors at moderate temperatures until the desired particle size is reached. According to Reinhard, the inherent element of control in this process means that it is easy to scale up for volume production. He claims that it provides "the best, most reliable route for the production of cadmium-free quantum dots."

In terms of cadmium-based QDs, one of the major manufacturers is Boston-based QD Vision, initially set up around ten years ago as a spin-out to exploit ground-breaking work in the area at the Massachusetts Institute of Technology (MIT). The company's "ColorIQ" product for edge-lit displays works by placing QD material in a hermetically sealed glass optic that sits atop the blue LEDs in the LCD backlight unit. According to John Volkmann, chief marketing officer at QD Vision, it provides a very affordable way to bring much wider color gamut capability to standard LED screens.

"Most people don't realize it, but today's displays can only show about a third of the colors the human eye can see," he adds. "QD-based displays show more than 50% more colors than today's TVs and monitors, and are on path to deliver a lot more than that in the foreseeable future."

Volkmann claims that the cadmium selenide dots produced by QD Vision deliver a wider color gamut than cadmium-free alternatives. Using industry-standard benchmarks, he adds, displays based on cadmium selenide QDs "show over 10% more colors than those based on indium phosphide." Volkmann also states that the firm's cadmium selenide-based edge optic solutions are cheaper and more stable in high heat and flux conditions, meaning that they can be placed closer to the LEDs.

"As a result, you need to use about one twentieth the material of an indium phosphide-based solution – sometimes referred to as 'cadmium-free'," he said.

Claims and counter-claims

Until the European Commission and other global legislative bodies reach a decision over the issue, it is likely that the row over the relative merits of cadmium-based and cadmium-free QD technology will continue to rage. Even so, in view of the steadily growing global restrictions on the use of cadmium in general, Nanoco believes manufacturers will increasingly turn to cadmium-free QD options.

"The technology to create cadmium-free quantum dots is here today, thanks to our scientific innovations," claims Andrew Gooda, supply chain and compliance director at Nanoco. "It's only natural to believe the market will fully reject the use of products containing cadmium over time."

In contrast, Volkmann insists that the cadmium-based QD Vision technology is in fact the more environmentally friendly option – by virtue of the fact that the production process is less energy-intensive than the alternative.

"Cadmium selenide-based QD displays are more energy-efficient," he says. "In lab tests, changing only the quantum dot material, cadmium selenide-based QD displays consume a minimum of 20% less energy than indium phosphide-based QD displays. In fact, tests show that cadmium selenide-based QD displays are significantly more energy efficient than any other wide color gamut technology available today – including red/green phosphor, OLED and indium phosphide QDs – while producing the benefit of a much wider color gamut."

Volkmann also claims this efficiency means that cadmium selenide QDs have the potential to save Europeans more than €3 billion every year in energy costs, equivalent to nearly seven million tons of avoided carbon dioxide emissions.

"Because fossil-fuel-burning electrical production plants are a leading source of free cadmium in the atmosphere, cadmium selenide-based QD displays result in a net reduction in free cadmium in the environment," he claims. "More specifically, 1.5 milligrams of cadmium selenide in a typical 55-inch display leads to a net 40 milligram reduction in free cadmium over the average life of a television.

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Prism Award finalist Nanoco Technologies has pioneered the development of cadmium-free quantum dots, as an alternative to the cadmium selenide nanomaterial that is starting to make an impact in the displays industry. It is working closely with key licensee Dow Electronic Materials to establish a base for mass production in Korea. The plant in Cheonan should be ready to supply customers in the current quarter. Image: Nanoco Technologies.

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"Said another way, QD displays based on indium phosphide actually lead to more free cadmium in the environment than those using cadmium selenide. It may seem counterintuitive, but it's true."

Environmental issues aside, a fair amount of dispute also relates to the relative cost and performance of the competing technologies. According to Tony Sun, a research analyst at consultancy Lux Research, although cadmium-based and cadmium-free displays both improve the color performance of displays, adding cadmium-based QDs to a 55-inch LCD TV 'will cost $50 to $100 more than a regular screen.' Sun says that, in the past, cadmium-containing QDs have tended to generate purer colors than cadmium-free at a lower cost, but points out that cadmium-free QD developers such as Nanoco claim to be able to achieve 'similar performance to cadmium-based QDs at a similar cost.'

"The overall performance of cadmium-based QDs has stayed relatively the same in the past two years and the technology is rather mature now," says Sun. "The key challenge for cadmium-based QDs lies in the regulation of cadmium usage. Cadmium-based QD could be regulated or even banned in regions like the European Union."

Sun adds that it is a little early to judge any environmental impact, saying: "Cadmium-free QDs' claim of performance and [being] cost competitive [with] cadmium-based QDs needs to be verified, as environmental advantages will only come into play if they can also compete on cost and performance."

Bright outlook

Whichever side the debate over the use of cadmium ultimately falls on, the future for QD technology does look extremely positive. QDs of all flavors are energy-efficient, bright and versatile, making them a true platform technology – there is now a growing range of applications extending from displays to lighting (see box-out), photovoltaics and bio-imaging. Sun expects the overall QD display market to grow at a compound annual growth rate (CAGR) of 60% through 2020 – with the technology beginning to penetrate some mid-to-low end TVs as well as high-end models.

"For display applications, QD manufacturing will enter a fast scaling-up process," says the analyst. "Thus, im-

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Cadmium-free QD technology in lighting

Beyond their burgeoning application in displays, QDs could also find use in a range of other major applications, including lighting. Steve Reinhard, VP of business development at Nanoco Technologies, reports that the company is seeing a 'large market pull' in the field of solid-state lighting. He says QDs, acting as a narrow-band red phosphor, are able to produce excellent color quality without the large loss in efficiency typically seen with red phosphors.

"So we see QDs and QD-enabled products entering markets where color quality and specificity of the light spectrum are paramount – horticulture, medicine and lighting for retail and museums and galleries are just some examples," Reinhard told *Show Daily*. In late 2015, Nanoco and the UK lighting company Marl launched four products incorporating QD technology, said to be the very first cadmium-free QD lighting products to hit the market.

It may take a while, though. Fabian Hoeltzenbein, lead analyst for lighting at the consultancy firm IHS Technology, points out that this market is still very much in its infancy, and warns that it could be difficult to go beyond niche uses.

"The benefits of using a QD layer in LED products are strong – mostly in terms of light quality and light temperature – and closely controllable light color for specialist applications," he says. "The mainstream adoption of QD lighting will largely depend on its price, but in the short and medium term the only realistic applications are high-end retail and hospitality, and some specialty applications such as horticultural lighting, where having controllable, high-quality light is the most important factor."

Over at rival analyst firm Lux Research, Tony Sun suggests that technology developers will need to solve the key issue of short lifetimes with QDs in lighting applications in order to achieve success.

Cadmium continued from page 27

proving yield will be a major topic for QD developers."

Gooda clams that, with QDs, LCD screens finally have the capability to rival and even outperform next-generation organic LED displays when it comes to color. In his view, QDs also have the advantage of presenting an "easy solution" for display manufacturers to integrate into their products – whereas OLED production requires either a completely new facility or a total overhaul of an existing production line, QDs can be incorporated within the existing LCD infrastructure.

Lux Research analyst Tony Sun, who predicts that the market for QD-enhanced displays will grow at a compound annual rate of 60% through 2020 to become a $5 billion global market. Photo: Lux Research.

"Furthermore, the flexible nature of QD technology, as these particles are easily tunable, is applicable to all sizes of displays – from large, high-definition TVs to smaller devices like tablets and mobile phones," he adds.

Like analysts, Volkmann is predicting significant growth for the use of QDs in TVs, monitors and other displays. "The core value proposition of QDs – wider color gamut – is visible to the consumer and employable with relatively low incremental cost to the manufacturer. Wider color gamut is a natural complement to other display innovations such as greater pixel density and high dynamic range," he says.

"Also look for a trend towards bringing the QD material closer and closer to the light source – with a goal of making it part of the LED. At that point, the universe could extend well beyond displays into lighting and other applications."

It appears that QD Vision has convinced others of that commercial potential. In November, the firm said it had raised another $22 million in finance, led by China-based Tsing Capital and chemical giant BASF's venture capital enterprise. As part of the deal, QD Vision signed a new joint agreement with BASF to develop QD-enhanced backlights and a color filter for use in LCD displays.

"The two companies will target growing demand for wide color gamut technologies, particularly those focused on achieving the Rec. 2020 color standard," QD Vision announced. "Wide color gamut technology will enable displays to show millions more colors than today's UHD or 4K displays."

CEO Mustafa Ozgen added: "This latest infusion of capital signals investor confidence in QD Vision and the strong growth potential of the quantum dot market. We have established solid industry leadership in color performance, low energy use, environmental safety, and affordability of our Color IQ technology."

John Volkmann, chief marketing officer at Boston-based QD Vision, claims that the superior energy efficiency of cadmium-based QDs leads to less free cadmium being released into the environment through burnt fossil fuels. Photo: QD Vision.

And it also appears that Volkmann's counter-intuitive claims of superior environmental credentials are cutting some ice. Tsing Capital reckons itself to be China's "leading cleantech venture capital firm", and managing partner Michael Li said: "QD Vision has demonstrated its commitment to developing energy efficient, environmentally friendly quantum dots for LCD displays, and the company has distinguished itself as the preferred choice of Chinese TV manufacturers. [It] is a natural fit for our China Environmental Fund."

BASF representatives are similarly effusive, saying that they expect the QD's to find "widespread application" in next generation LCD screens. "The fact that current standard LCD technology is capable of displaying only around a third of the colors a human eye can see indicates the improvement potential in this field," added Jeff Knight, the senior VP responsible for BASF's electronic specialties business. "Combining QD Vision's Color IQ technology with BASF's competencies in color filters will allow us to jointly develop advanced display materials matching next generation display color standards."

ANDREW WILLIAMS

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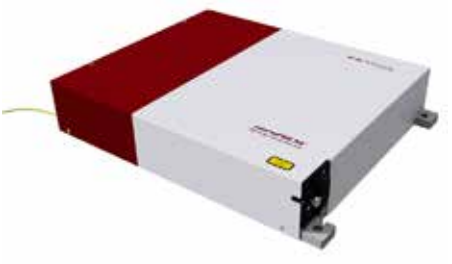

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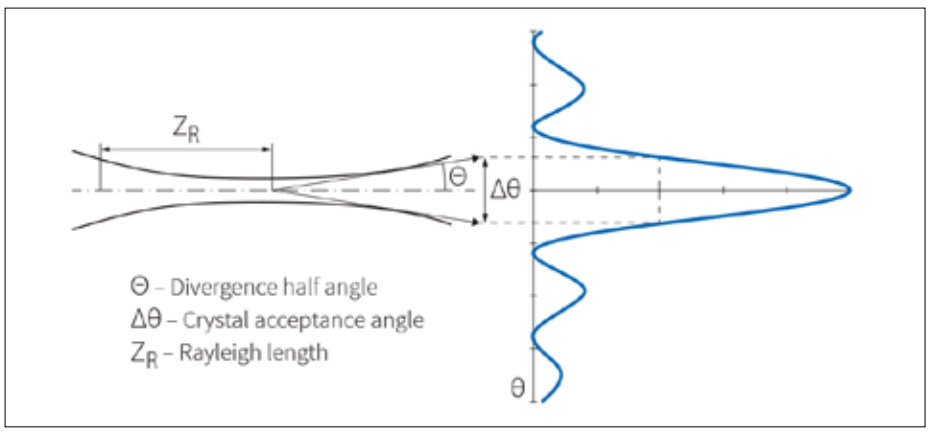

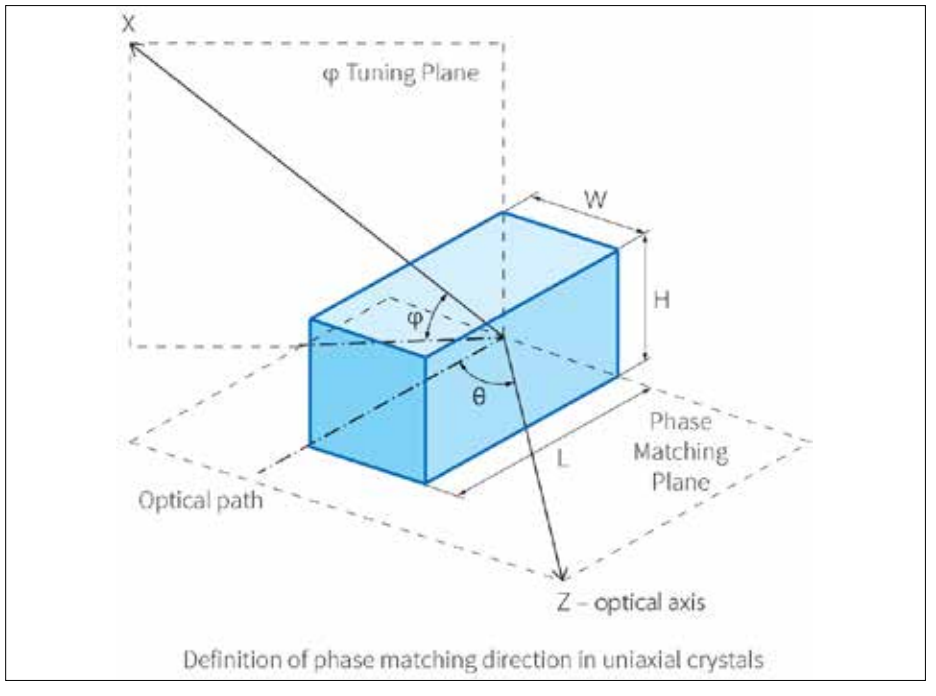

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Versatile Measurement Systems for Objective Lenses and Camera Modules

TRIOPTICS offers customers maximum versatility with a combined test system for objective lenses as well as for camera modules. The system is based on the ImageMaster® HR technology – the industry standard for testing the image quality of objective lenses. An additional ProCam® object generator converts the ImageMaster® HR into a test system for measuring the image quality of camera modules. The exchange of the object generator is quick and user friendly giving customers the flexibility to use either the ImageMaster® HR or the ProCam® Test R&D functions alternately.

ImageMaster® HR for testing image quality of objective lenses

The ImageMaster® HR is a fully equipped quality test station for medium sized sample lenses. Its modular and upgradeable design enables the measurement of the image quality (MTF) and a wide range of other optical parameters for today and future needs. The instrument is used in R&D labs as well as in quality assurance or in production. The unique vertical setup of the ImageMaster® HR is space saving and ensures the most convenient and accurate positioning of the sample lens mounts. With the collimator on the precise swinging arm an ultra-wide field angle of ± 105° can be measured for infinity conjugate samples. An upgrade for finite testing can easily be adapted to the system with an additional motorized stage and object generator.

ProCam® Test R&D for camera module testing

The ProCam® Test R&D is a versatile measurement device for testing various image quality parameters of camera modules. It does not only feature on-axis but also a wide off-axis angle range of up to ±110°. The computer-controlled test target distance can be freely selected from finite distances to infinity using a focusing collimator. The ProCam® Test R&D can be used for many different types of camera modules. This high flexibility makes the test instrument an ideal solution for comprehensive measurement tasks in R&D environment.

Both systems the ImageMaster HR as well as the ProCam® Test R&D are available for various wavelength ranges.

Measurement parameters

The ImageMaster® HR and the ProCam® Test system measure the following parameters of visual and infrared lenses:

- MTF on-axis and off-axis
- Effective Focal Length (EFL)
- Distortion
- Field curvature
- Lateral and longitudinal chromatic aberrations
- Etc.

Additional functions for assembled camera modules:

- Determination of shift
- Tilt and defocus of the sensor

Please visit **www.trioptics.com** or contact us at **sales@trioptics.com** for more information about our product range.

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TRIOPTICS

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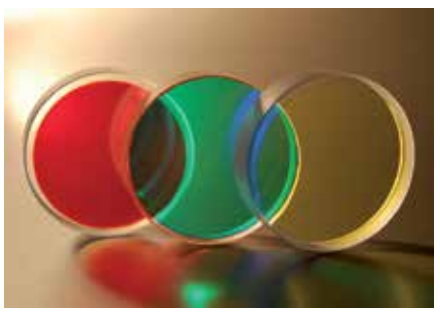

NANEO is specialised in the production of custom made optical coatings for high quality optics in industry and science. If your needs are spectrally, technically or environmentally demanding - NANEO should be your first solution.

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Respect, reliability make for great workplaces

Offices and laboratories for optics and photonics professionals are great places to work because of the passion, teamwork, and collegiality of co-workers, and it's a bonus that the pay is so good.

Those were the key findings from the 6th annual SPIE Optics & Photonics Global Salary Report and the consensus of three early-career professionals on an industry panel at Photonics West Wednesday morning.

The new salary report, available in a pre-release version at the SPIE Career Center booth 1100 in Moscone South, found that 96% of survey respondents are highly satisfied with their jobs, 95% find their work meaningful, and 93% enjoy the respect of their co-workers.

Respect from co-workers was ranked the top benefit of an ideal workplace in the survey, followed by opportunity for advancement, flexible work hours, paid vacation, and high pay.

"You can love your work, but if your co-workers are mean to you, you're going to hate going to work," said Christina Willis, a laser scientist at Fibertek.

Willis was joined on the panel discussing "great workplaces" in optics and photonics by Nishant Mohan, director of product management and marketing at Wasatch Photonics' systems division, and Aaron Weinroth, vice president of technology commercialization at Tornado Spectral Systems.

Moderator Adam Resnick, left, with panelists Christina Willis, Aaron Weinroth, and Nishant Mohan. Credit: Courtney Rambo

Co-workers show their respect for each other by being reliable and willing to help others solve problems, even when not assigned to a project, the panelists said.

All three agreed that teamwork, mutual respect, and dependability were highly important in their own work experiences. "I am doing my best when I know someone is depending on me," Mohan said.

The panelists and audience members noted that it was unusual that high pay was only #5 on the list of valuable job benefits and speculated that the reason was because the typical pay in the field is already sufficiently high.

The median salary for full-time employees is $62,433, according to the new SPIE report, down slightly from $64,000 in 2015, with the aerospace sector again offering the highest median salaries, $102,300.

"The variety is what's interesting," Weinroth said when asked about a typical workday. "There are no two days that look alike."

Asked by moderator Adam Resnick of SPIE if there was a "special sauce" that employers could create to have a satisfied workforce, the panelists agreed that it wasn't that easy.

"Be careful looking for that sauce," Mohan said. "Happiness is mostly inside you."

The salary report is available online at SPIEcareerCenter.org, and the final version will be updated by early March.

KATHY SHEEHAN

3-PHOTON IMAGING FOR OVARIAN CANCER

Advances in ultrafast lasers are helping University of Arizona (UA) scientists develop new multi-photon techniques that could help detect ovarian cancer at an early stage.

Jennifer Barton, interim director of UA's "BIO5" multi-disciplinary institute, said during an invited talk at the *Diagnosis and Treatment of Diseases in the Breast and Reproductive System* conference Saturday that the poor survival rates for the disease were largely because ovarian cancer is so difficult to diagnose.

Ideally, gynecologists would like to use a non-invasive, high-resolution imaging technique on ovaries and fallopian tubes – where many ovarian cancers are thought to originate – to a depth of 10 mm.

The UA team has been working on various multi-photon imaging schemes to achieve that, and with more ultrafast fiber lasers coming onto the market, Barton believes it will be possible to miniaturize a system with distal optics into a 3mm-diameter laparoscope suitable for clinical applications.

MIKE HATCHER

Industry leaders see silicon photonics sales taking off

Silicon photonics is always on the conference agenda at Photonics West, whether as the subject of research lab advances, usually involving most of the Greek alphabet, or "will it – won't it take off?" market analysis debates. Tuesday's panel session covered both sides, with input from industry names that are working at the business end of this emerging technology.

In the week before this event, analyst Lightcounting had published a market report that bluntly argued that silicon photonics (SiP) would not disrupt the market until 2020. But some panel members did not feel that the market was stalled, arguing that SiP sales were happening and that research and business were already locked in a virtuous cycle.

Philippe Absil, imec. Credit: Matthew Peach

Philippe Absil, 3D and Optical Technologies Department director at Belgian research lab imec, invited would-be system developers to make use of his fab facilities; the organization performs much open SiP R&D, and some production.

In November 2015, imec and the University of Ghent claimed a breakthrough advance for integrated photonics by fabricating an array of laser diodes on a large silicon wafer like those used in volume semiconductor production. Absil said, "imec is doubling its silicon photonics fab resources this year, and we invite all fabless companies to come and use our facilities. We have over the past two years already served eight different silicon photonics customers."

Peter De Dobbelaere, vice president of engineering at Luxtera, talked about the quickly changing market conditions and how they are driving the uptake of silicon photonics applications, particularly for the fast-growing cloud-based communications sector.

"The growth of cloud services and data centers are both factors that are driving silicon photonics," he said. "Companies like Amazon Web Services and Microsoft Cloud are still growing fast. We can see that photonics is moving closer towards ASICs," referring to application-specific integrated circuits. "Ultimately, we will see transceivers being integrated into chipsets, which is why silicon photonics is becoming more important to these markets."

Douglas Gill, a researcher at IBM's Thomas J. Watson Research Center, noted that a certain number of wafers have to go through the foundry to support the ecosystem around silicon photonics. "You can do a myriad wondrous and beautiful things with silicon photonics," Gill said. "But unless you have the wafer projects in volume, that technology is not going to blossom and grow in the way that it really can."

He added, "IBM has developed a commercial sub-100 nm monolithic silicon photonics platform, which supports multi-25 Gbit optical engines for reach beyond where VCSELs can typically deliver – beyond, say, 500 m. This is a result of a decade of research in a commercial foundry, and we now have a second stage of our 25 Gbit demonstrator in the works."

Joan Fong, staff engineer at Mellanox, a supplier of end-to-end Ethernet and InfiniBand interconnect solutions, described how her company's silicon photonics-based interconnect solutions are increasing data-center efficiency by providing high throughput at low latency.

Asked whether she agreed with the Lightcounting forecast that silicon photonics would not disrupt the market until 2020, Fong said, "Five years ago, I would have agreed with that analysis, but not now. Silicon photonics systems are already transmitting at above 100 Gbit/s rates.

"Silicon photonics is currently picking up. It's in real production and making real sales."

MATTHEW PEACH

Photoacoustics "coming of age" as clinical trials grow

Introducing a packed-out opening session on clinical applications of photoacoustic imaging (PAI), conference chair Alexander Oraevsky said that the technology was "really coming of age". Seventeen years after the first BiOS conference on the topic, he now expects the field to grow quickly as the emphasis shifts towards technology transfer and clinical imaging.

Appropriately enough for Valentine's Day, the Sunday-morning session soon turned to matters of the heart.

Speaker Jie Hui from Purdue University described a high-speed PAI system built in collaboration with the Shanghai Institute of Optics and Fine Mechanics and others that is able to recognize fatty lipid material building up inside arteries. That molecular information is beyond the capability of standard angiogram and optical coherence tomography (OCT) imaging, which can indicate the extent to which an artery is occluded, but not the chemical composition of the blockage.

The intravascular system takes advantage of the high absorption of lipids at a wavelength of 1.7 microns, using it to "map" the presence of lipid material coating the inside of the arterial wall. Measuring only 36 x 27 x 10 cm, Hui said that the design is sufficiently compact for clinical use. Tested on an *ex vivo* coronary artery, it produced imagery to a depth of 6 mm, including the entire artery wall. Next up for the team will be *in vivo* tests on pigs, which should happen later this year.

Oraevsky's fellow conference chair Lihong Wang is one of the pioneers in the field, and his group represented strongly, using PAI to measure the flexibility of blood vessels – or "vascular elasticity" – for potentially diagnosing conditions that could lead to thrombosis, strokes or heart attacks. Wang's Washington University in St. Louis team has so far tested the system on human fingers, detecting changes in vascular elasticity in small blood vessels at a depth that conventional imaging techniques cannot access.

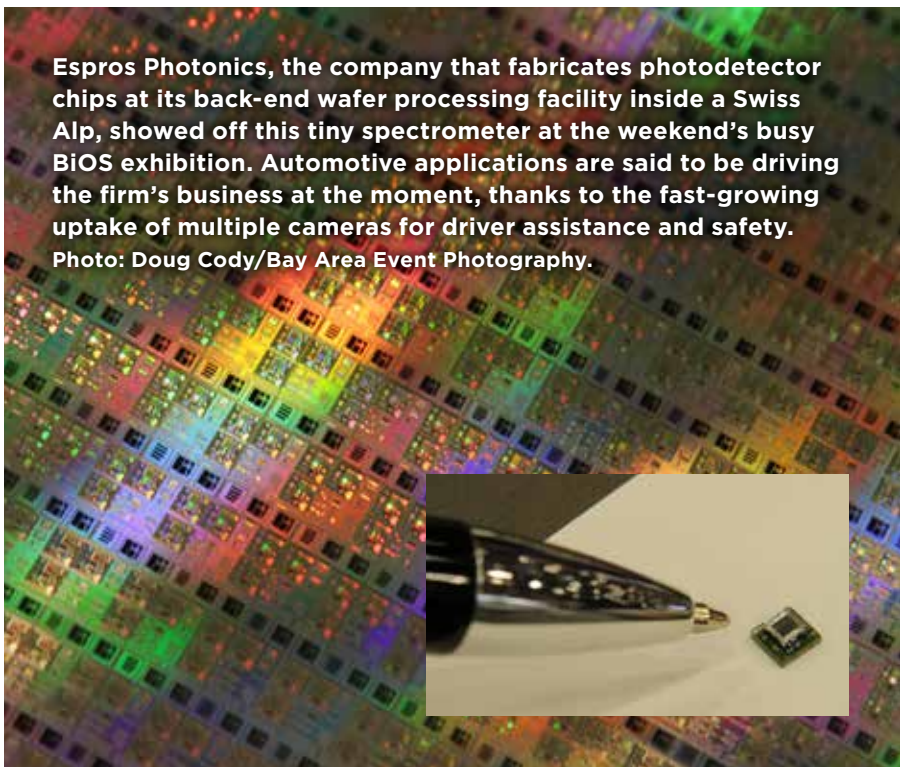
PAI systems are also shrinking in size, thanks to innovations like the ultra-compact diode module developed by Quantel (note a correction to our Tuesday edition: Quantel's presentation was made by Andreas Kohl, not Olivier Rabot as stated). Wang's group has developed a hand-held imager that is able to measure the depth and volume of melanomas non-invasively. Knowing the depth to which a malignant lesion has grown is critical for effective removal. Conventional biopsies can underestimate that depth, but in a small study on humans the group's new setup was able to image the depth of tumors up to 5 mm in diameter, showing good correlation with conventional histology analysis. In tests on mice, the system was also able to monitor the rapid rate of melanoma growth.

MIKE HATCHER

BERLINER GLAS SEEKS NEW SCANNER APPS

Berliner Glas showed off the latest version of its hand-held digital dentistry imager at the weekend's BiOS Expo - with a full-blown scanner from key customer Sirona Dental Systems on hand to demonstrate just how quickly the technology can map and create a digital impression of patients' teeth.

The new hardware is the first to both visualize and measure hard and soft tissues in completely digital fashion, and is used to prepare crowns far more quickly than is possible with conventional impression molds. Berliner Glas says that precise alignment of prism components and detectors in the white-light probe is the key to its performance. While the company has an exclusive deal with Sirona for the dental application, it is now seeking to adapt the technology for other biomedical uses such as endoscopy.



Espros Photonics, the company that fabricates photodetector chips at its back-end wafer processing facility inside a Swiss Alp, showed off this tiny spectrometer at the weekend's busy BiOS exhibition. Automotive applications are said to be driving the firm's business at the moment, thanks to the fast-growing uptake of multiple cameras for driver assistance and safety.
Photo: Doug Cody/Bay Area Event Photography.

3D PRINTING MARKET: GOOD NEWS AND BAD NEWS

There was bad news, good news and yet more bad news for the use of lasers in 3D printing applications, announced Monday at the Pennwell-organized Lasers and Photonics Marketplace conference running parallel to Photonics West.

This was the provocative introductory remark by Allen Nogee, analyst at Strategies Unlimited, as he delivered his annual review of the global photonics market.

"You have all heard the hoopla about 3D printing and it is a market that everybody here really should be watching," he said. "The first bad news is that 3D printing today is taking away some of the revenue from laser systems and the conventional subtractive manufacturing technologies that use them. It is not a big drop, but I am seeing it in some medical manufacturing applications.

"The good news is that certain 3D printing systems, especially metal 3D printers, use lasers," Nogee continued. "Last year, I counted at least 800 units of laser sintering systems being shipped. These machines typically have up to four lasers, ranging in power between 200W and 1kW, which can be either CO_2 or fiber lasers. That business is growing."

But his second piece of bad news is that lasers might not always be a part of these 3D printing systems. "We are seeing it now, that the problem is speed; laser-based systems tend to be slower and are often used for prototyping rather than for full-scale manufacturing.

"Users want a faster version of that capability. So there is work in progress on new systems that will use infrared lamps instead of lasers to melt the metal. We cannot assume that 15-20 years from now these 3D printing systems will continue to have lasers inside. Maybe they will, maybe not."

Nogee then looked at the recent performance of the 3D printing business, plotting the revenues of three public companies – Protolabs, 3D Systems and Stratasys. He added: "In 2014 there was a lot of growth but, in its own right, the laser sintering business has been doing fantastically." Nogee also noted that the lion's share of 3D printing systems developers is based in Europe, where the manufacturing industries are so far taking to the technology more enthusiastically than in the US.

MATTHEW PEACH

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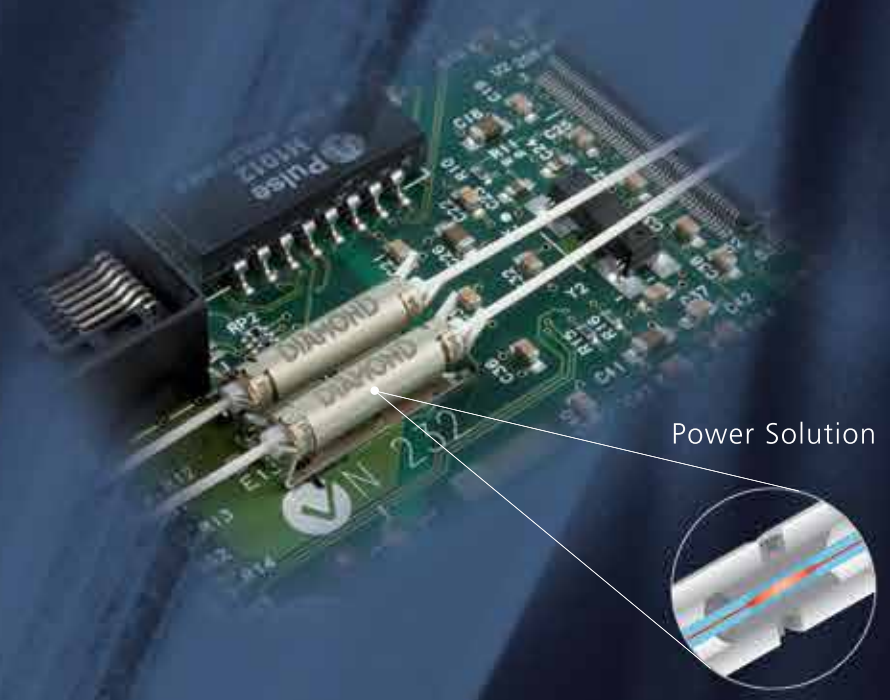

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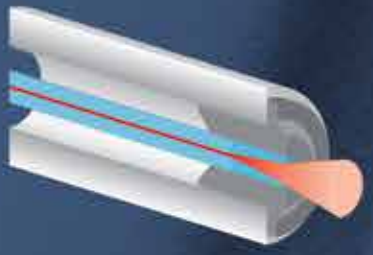
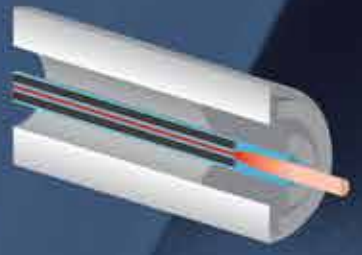
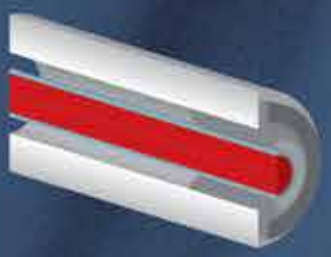


PSf Free Space (Diverging)



PM-PS Collimated Polarization Maintaining



PSm (Power Solution Multimode)

PM (Polarization Maintaining)

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